

The nature of engineering and science
knowledge in curriculum:
A case study in thermodynamics

By

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Abstract

The study explores the nature of disciplinary knowledge differences and similarities between the sciences and the engineering sciences as these appear in curriculum texts. The work is presented as a case study of curriculum knowledge in thermodynamics, and the epistemic properties are investigated in four sub-cases in mechanical engineering, chemical engineering, physics and chemistry. Data was collected from prescribed undergraduate textbooks in the four disciplinary fields.

The work is theoretically informed by two fields of scholarly work: the sociology of educational knowledge (in particular the work of Basil Bernstein) and the applied philosophies of science and engineering science, in order to develop a theoretical framework for analysis of the data. The framework allows the study to move beyond the typical binary classification of the sciences as 'hard-pure' and engineering sciences as 'hard-applied' disciplines. Starting from broad teleological considerations, the philosophical concepts of specialisation, idealisation and normativity are explored and developed into modalities and modal continua of variance to allow investigation of the epistemic differences and similarities in the recontextualised disciplinary knowledge from these contiguous conceptual fields.

The empirical study identifies important differences in thermodynamics curriculum knowledge in terms of specialisation, normativity and idealisation across the broad disciplinary fields, rendering more complex Bernstein's notions of singulars and regions. The epistemic modalities and modes provide a way to conceive in more detail how the professional engineering science knowledge is orientated towards its field of practice. Curriculum knowledge in the engineering sciences is shown to be remarkably different from the knowledge in the sciences: both mechanical and chemical engineering knowledge emphasise particulars, rather than universals, have stronger normative aspects, and employ a limited form of idealisation in their commitment to physical realisability. By contrast, knowledge in the sciences is more universal, normativity is incidental, and idealisation is used expansively. In addition, the research findings suggest a negative correlation between idealisation and normativity as epistemic modalities: a commitment to normative concerns in the engineering sciences constrains the extent to which knowledge idealisation is pursued, compared to what is observed in the bodies of science curriculum knowledge. Furthermore, over and above differences in curriculum knowledge between the broad fields of science and engineering science, discernible variation exists between the engineering sciences investigated, raising cautions against a monolithic view of curricular epistemic properties across broad disciplinary areas.

Acknowledgements

The castle of Cair Paravel on its little hill towered up above them; before them were the sands, with rocks and little pools of salt water, and seaweed, and the smell of the sea and long miles of bluish-green waves breaking for ever and ever on the beach. And oh, the cry of the seagulls! Have you ever heard it? Can you remember? — C.S. Lewis, *The Lion, the Witch and the Wardrobe*

Embarking on doctoral studies later in life means that one is perhaps a little more aware of just how many others have walked the road with you to bring you to this point.

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Sola Gratia

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Chapter 1 Introduction

Well, you've got me searching for, searching for the philosopher's stone.

Even my best friends... they don't know that my job is turning lead into gold.

— Van Morrison, *The Philosopher's Stone*

The expansion of modern industrial economies is linked to innovation and technological development. In this endeavour engineering functions as a crucial driver (Thursby, 2014), and is pervasive in almost every aspect of the economy, from transportation to communication; from manufacturing and construction to healthcare and computing. Engineering continuously has to evolve to meet the demands of ever-changing needs in society, and respond with innovation to the pressing problems of humankind. For this reason, governments, in particular in the developed world, invest significant resources in research and development in the engineering sector. A recent review of economic return on investment in the United Kingdom (Rosemberg *et al.*, 2015) illustrates the importance of the engineering sector with an estimated £280 billion in gross value added (GVA) by the sector during 2011, representing 20% of the UK's total GVA for that year.

The work of engineering graduates and postgraduate engineering research serves to advance product development in many economic sectors, and Rosemberg *et al.* (2015) argue that sectors with high concentrations of engineering graduates report higher than average levels of innovation activity and productivity. The role of the engineer is consequently central in any country's economy, and the development of critical technical skills can hardly be over-emphasised in a country's attempt to retain or improve its global competitive edge.

It is therefore a concern that shortages in the training of engineers are reported widely: the 2015 Technopolis report (Rosemberg *et al.*) reports a stasis in the number of engineering graduates in the UK over the previous eight years, in spite of growing demands to address the skills shortage. Similarly, in the USA, concerns have been expressed that, even though there has been an increase in the number of engineering graduates produced over the last few years, only 4% of the total number of undergraduate degrees currently awarded are in engineering fields. This compares unfavourably to an average of 13% in European countries and 23% in key Asian countries (Thursby, 2014). South Africa's shortage of engineering professionals is also a national concern (Erasmus & Breier, 2009). In 2005 the country had one engineer per 3166 citizens, compared to other developing countries like Brazil and Malaysia with one engineer per 227 and 543 citizens respectively (Lawless, 2007). This shortage has not shifted in any

significant way: there are eleven engineering professions in the top twenty professions on the 2014 National Scarce Skills List (Department of Higher Education and Training, 2014).

Reasons for the persistent shortages of engineers are numerous and varied depending on the national context, but behind these figures is a deep-seated concern about retaining engineering students and ensuring successful graduation from engineering programmes (see for instance the concern expressed by Wormley (2003) about the high national attrition rates of around 40% from undergraduate engineering programmes in the USA). The current shortages in engineering graduates become even more pressing in the light of the rapid pace of technological change. Artefact production cycle times continue to shrink, and older technologies are being replaced at an ever-increasing rate (Committee on the Engineer of 2020 Phase II, Committee on Engineering Education, & National Academy of Engineering, 2005). It is therefore unsurprising that engineering education research has grown in stature and output over the last two decades as researchers try to understand the many issues that affect student success in engineering programmes (Borrego & Bernhard, 2011; Jesiek, Newswander, & Borrego, 2009; Olds, Moskal, & Miller, 2005; Zhang, Anderson, Ohland, & Thorndyke, 2004).

Much of the literature in the growing field of engineering education research has tended to focus attention on issues around the teaching of engineering in the context of the engineering classroom (Borrego & Bernhard, 2011). See for example the work of Rugarcia *et al* (2000) offering “tools [for] engineering professors who wish to become better teachers...” (p.2), and “teaching methods that work” (Felder, Woods, Stice, & Rugarcia, 2000, p. 27). Others have focused on the teaching of specific topics or skills, for instance, the review article on teaching engineering design in capstone projects by Dutson *et al.* (1997). In addition there is research on problem-based and project-based teaching of engineering content (Beddoes, Jesiek, & Borrego, 2010; Mills & Treagust, 2003). In addition to this emphasis on pedagogy in engineering education research, some researchers take student learning as the starting point, often providing evidence of student satisfaction to support their approach (Felder, Brent, & Prince, 2011; Felder, Felder, & Dietz, 1998).

Another line of engineering education research focuses on curriculum design, often with a particular slant towards industry expectations of graduate engineers’ knowledge and skills sets (Lang, Cruse, McVey, & McMasters, 1999; Nair & Patil, 2009), or engineering graduate attributes, as shown in the reports commissioned by professional bodies in the UK, USA and Australia (Committee on the Engineer of 2020 Phase II *et al.*, 2005; King, 2007; Spinks, Silburn, & Birchall, 2006). Aligned to this, is work done on the influence of professional bodies charged

with the accreditation of engineering programmes on the content of the curriculum (Felder & Brent, 2003; International Engineering Alliance, 2014; Patil & Codner, 2007).

1.1 Rationale for the study

Conceptual content for engineering curricula is drawn from a number of different knowledge areas (Engineering Council of South Africa, 2014; International Engineering Alliance, 2013): the basic sciences, mathematical sciences, engineering sciences, design, and different complementary studies. These disciplinary fields are characteristically treated by curriculum designers as though they were simply a collection of content units that describe the *shape* of a curriculum without much regard to the *nature* of the disciplinary knowledge represented. Any concern about coherence is typically limited to topic progression, rather than relationships between knowledge fields. The question raised by the shape of the typical curriculum is whether differences in epistemic properties of the different disciplinary fields are significant enough to present a challenge for students as they move through the curriculum.

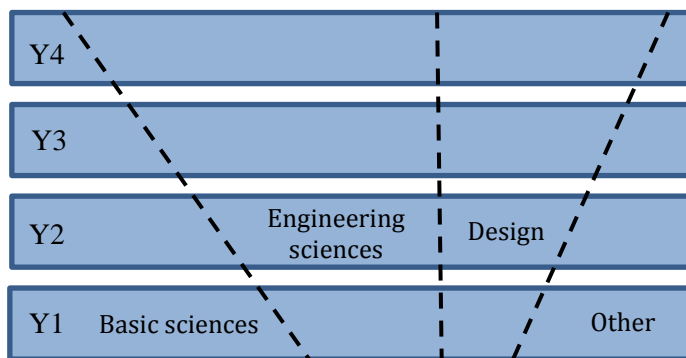


Figure 1-1: Structure and shape of a typical undergraduate engineering curriculum

One obvious feature of the typical engineering curriculum depicted in Figure 1-1, is a shift in focus in the curriculum: the amount of basic science content decreases as students progress through the curriculum, and the engineering science conceptual content increases to become by far the most prominent aspect of the curriculum. It is this disciplinary knowledge that students have to call on in their capstone design courses, integrating the principles and concepts mastered in the engineering science courses with a high level of complex problem-solving. The influence of engineering science knowledge is therefore probably even more significant than Figure 1-1 suggests. The shape of the typical professional curriculum in engineering suggests that students are expected to make a transition from the basic (or pure) sciences to knowledge in the engineering sciences as they continue through their engineering curriculum. In addition, in accordance with universities' high view of disciplinarity, the pure science content early in the curriculum is often taught by discipline specialists, i.e. physicists and chemists, rather than by engineers. This means that disciplinary differences can be quite pronounced, and it is not

unreasonable to expect substantial implications for curriculum design (and perhaps also for pedagogic practice).

By nature, professional curricula tend to include an emphasis on skills and competencies, and there is therefore a real risk of neglecting the epistemic features of the technical knowledge that forms the bedrock of expertise in the professions. I argue in chapter two with the sociologists of knowledge that knowledge-blindness in curriculum design is the result of a current (over-) emphasis on graduate attributes, skills and competencies, and the work done here consequently seeks to contribute to conversations around professional knowledge.

The point of departure in this study is therefore an examination of the fundamental disciplinary *knowledge* differences (and similarities) that have to be negotiated in a curriculum transition from the sciences to the engineering sciences. A desire to understand the nature of the epistemic properties of valued *disciplinary knowledge* in engineering science, compared to those in science, as these appear in an engineering curriculum, is the focus of the investigation described in this thesis.

In the rest of this introductory chapter I do the following: first I locate the research study briefly in two bodies of scholarly work: the sociology of educational knowledge and the applied philosophies of science and engineering science. I then describe the research design, giving a broad-strokes account of the development of an analytical framework for the empirical work. This is followed by a fairly substantial overview of the way in which scientific knowledge and engineering science knowledge have developed and related to each other in history, starting with the very early predecessors of what we call science and engineering today, to the emergence of engineering science after the Industrial Revolution, and the trajectory of the knowledge into university curricula. Chapter one concludes with an outline of the organisation of the rest of the thesis.

1.2 Locating the study

The research problem this thesis attempts to address is understanding the nature of the differences and similarities between the recontextualised disciplinary knowledge in science and engineering science curricula. This is important because of the implications these may have for the education of science and engineering students, which, in the context of this thesis with its emphasis on knowledge, essentially involves inducting students into the disciplinary knowledge.

The nature of the relationship between engineering and science has been the topic of scholarly consideration over time: researchers such as Channell (2009), Houkes (2009), Layton (1974, 1976, 1987) and Radder (2009b) give examples of some of the discussions. However, as discussed more comprehensively in chapter two, relatively little theoretical work has been done to provide a reasoned and grounded account of the relationship between engineering and science knowledge, and much of the research lacks empirical corroboration. The work described in this thesis aims to contribute to the conversations about a theoretical underpinning of the disciplinary differences and similarities, and, in particular, to establish an 'empirical turn' for the theoretical concepts developed.

In his influential 1973 paper, Biglan discusses the organisation of the modern university in departments according to subject fields or disciplines. At the root of this organisation lies an implicit belief about the uniqueness of disciplinary fields, even as inter- and multidisciplinary approaches to problems are furthered. The binaries hard/soft and pure/applied proposed by Biglan (1973) provided an early approach to disciplinary distinction for other sociologists to build upon (Becher, 1989, 1994; Becher & Trowler, 2001; Kolb, 1981). To broaden the scope of the theoretical work that could specifically speak to the problem of the nature of disciplinary knowledge, it was necessary to consider other literature.

1.2.1 Considering the sociology of knowledge, with a focus on education

The theoretical work of British sociologist Basil Bernstein provided a valuable starting point for thinking about disciplinary differences and their potential impact on curriculum knowledge. He developed a range of theoretical constructs that allows for describing knowledge as it functions in educational processes. In Bernstein's terms, both engineering science and basic science are examples of vertical discourses with methodically ordered hierarchical knowledge structures. These conceptual ideas ground the notion of disciplinarity in a theoretical framework, even though by themselves they do not yet allow for the exploration of potential differences between the disciplines considered in this study. In fact, one of the major challenges faced in the research described here is the close proximity of the fields: of all the different kinds of knowledge fields incorporated in engineering, engineering science is the field where knowledge in engineering and science could reasonably be expected to share most common ground. Real and tangible differences here would provide convincing evidence of embodied differentiation of knowledge. Furthermore, research results discriminating enough to identify differences and similarities in these contiguous fields of knowledge could be useful in relation to other disciplinary fields.

The Bernsteinian notions of *classification*, *singulars* and *regions* (1977, 2000) were important concepts to consider in the research described here. Classification refers to the extent of

boundary creation and maintenance; in the case of the thesis, of the boundaries around disciplinary knowledge fields. It allows for an exploration of the relations *between* categories, rather than merely focusing on the characteristics of the enclosed. For Bernstein, classification, with its reference to boundary maintenance, regulates the social division of labour (Bernstein, 1981), as well as the specialisation implied in distinguishing between disciplines. The notion of *specialisation* became a crucial concept in developing an instrument for data analysis in the thesis, as set out in chapter three.

Classification is important for understanding two further concepts in the Bernstein oeuvre, the notions of *singulars* and *regions*. The science disciplines of chemistry and physics are considered typical singulars in the Bernsteinian tradition (stronger classification and boundary maintenance), while the engineering sciences (mechanical and chemical engineering) are examples of regions (weaker classification and boundary maintenance). This distinction between regions and singulars was useful as a first pass to differentiate between knowledge in science and engineering. However, there is consensus amongst Bernsteinian sociologists that the notions of singulars and regions have been left largely un-theorised by Bernstein and those working in the broad Bernsteinian tradition. For this reason, the concepts are challenging to operationalise directly, and lack definition as analytical tools. This argument is expounded in chapters two and three of the thesis.

Bernstein theorised the educational process (the circulating of knowledge in transmission and acquisition) in the development of the Pedagogic Device as “a ruler for consciousness” (Bernstein, 2000, p. 28), and a description of the way the “outside becomes the inside...” (Bernstein, 1987, p. 563). In the process he developed a sociology of knowledge that allowed for differentiating between ‘new’ knowledge becoming part of the canon of a discipline in the field of production, the recontextualising of this knowledge through a process of delocation and relocation into curriculum knowledge in the field of recontextualisation, and finally the acquisition of knowledge through pedagogic practices in the classroom in the field of reproduction.

For a researcher, it is therefore methodologically important to clarify the positioning of a study in terms of these three levels. The empirical data described in this thesis was collected from curriculum texts, and is therefore recontextualised disciplinary knowledge. The extent and nature of the relationship between curriculum knowledge and the underlying disciplinary logic has been debated in the literature (see the discussion in chapter two), and the work done in this study contributes to conversations around the scope of disciplinary traits discernible in recontextualised knowledge.

Bernstein's work on knowledge in educational settings was extended by a number of different scholars over recent years – see for instance theoretical work done by Johan Muller with *contextuality* and *conceptuality*, empirical work done by Suellen Shay on curriculum knowledge typologies, and Karl Maton's Legitimation Code Theory (LCT). However, these theoretical tools are limited in their potential to manage the fine-grained distinctions in the data from the closely related fields investigated in this thesis. It was therefore necessary to turn to another body of literature: the applied philosophies of science and engineering which concern themselves with the nature of the disciplines and their various epistemic properties. This was considered next as a potential source of theoretical concepts that would make analysis of the data possible.

1.2.2 Considering the philosophy of engineering science and science

Various philosophers counsel against essentialist delineations of the disciplines: Houkes (2009) cautions against an oversimplified polarisation of the goals of the disciplines as “truth vs usefulness” (p.312), and others contest the notion of “truth” as the aim for science (see van Fraassen's (1977, 2001) use of “empirical adequacy” rather than “truth”). Radder (2009b) warns against descriptions of science that disregard the high value placed on actions that generate empirical knowledge in addition to theoretical knowledge. Others point out that technological activities often generate new theoretical knowledge (Layton, 1974; Vincenti, 1990), and that the design of artefacts and processes for specific purposes is also valued in the empirical sciences (Gooding, 1990). All of this suggests that a nuanced approach is needed in any discussion of differences between engineering and the sciences, and that a simplistic preoccupation with goals and aims does not take one beyond a superficial distinction.

A first obvious position to take is to reiterate the commitment to consider *knowledge* rather than all disciplinary practices. The focus is therefore on epistemic differences and similarities, or the degree of “epistemic emancipation” (Houkes, 2009, p. 309) in the disciplines. Houkes points out that there is a lack of empirical studies in this area, and intriguingly suggests that it might be possible to probe epistemic emancipation empirically if differences could be found in the way the disciplines approach certain epistemic practices. Two such epistemic practices, idealisation and normativity, are explored further in this thesis.

Modelling (or more generally idealisation) is an important epistemic activity in both science and engineering science. This involves the intentional (Weisberg, 2007a) and selective (Van Fraassen, 2010) distortion of knowledge for specific purposes. One of the questions explored in the research described in this project is whether there is any evidence in the data for differences in the way idealisation is employed in the sciences and engineering sciences, as alluded to by scholars like de Vries (2010), Hansson (2007) and Pirtle (2010).

The second concept employed from the philosophy of technology in this thesis is normativity. Normativity is often centred on the artefactual nature of technology. Franssen (2009), for example, argues from the perspective of the kinds of statements that are made about the functionality (or malfunction) of artefacts which includes evaluating the fitness-for-purpose, and the expectation that the artefact 'ought' to function in a particular way. Another view is that artefacts themselves have a dual nature that involves intentionality (Dancy, 2006): they are constructed for a precise purpose, and in addition there is a purposeful process involved in their construction. Radder (2009c) goes beyond the artefact in his view that technology, including engineering, is inherently normative. He sees artefacts as a part of a functional system that includes its future potential, its realisability in a particular environment and the intentions of the human participants in the technology. In terms of the work covered in this thesis, Houkes (2009) suggests the possibility of qualitative differences in evaluative or normative emphases in the knowledge in science and engineering knowledge.

These notions of normativity and idealisation from the philosophy of science and engineering science, as well as specialisation from sociology, became important conceptual tools in developing the analytical framework for this study.

1.3 Research Design

The research study described here uses a case study approach: thermodynamics knowledge in four disciplinary areas, two sciences (chemistry and physics), and two engineering sciences (mechanical engineering and chemical engineering), is analysed as it appears in five undergraduate university textbooks. The research design is strengthened by the symmetry of the two fields, and also by the fact that more than one discipline in each of the encompassing fields of science and engineering science was considered. This made it possible to consider variations not only between science and engineering science, but also variations within the four fields. The conceptual content covers the same nominal content across the four disciplines: the first two laws of thermodynamics. It has to be emphasised that the major focus in the study is *the nature of engineering science knowledge*, and how it is different from knowledge in the sciences as exemplified in the recontextualised curriculum knowledge. There is therefore a sense in which knowledge in the sciences is treated as the backdrop or foil for the investigation into the nature of engineering science as found in the curriculum.

The study described in the thesis had two main tasks. Firstly, a set of theoretical constructs had to be developed into an analytical framework that would be discriminating enough to distinguish empirical differences between contiguous disciplinary fields of knowledge. Secondly, an empirical study had to be conducted to explore disciplinary knowledge differences

and similarities in a systematic way, applying the theoretical framework developed to data units consisting of disciplinary knowledge units.

1.4 Development of an analytical framework

The starting point for developing the framework was an intuitive proto-understanding of the broader purposes or fundamental values of the comprehensive *disciplines* of science and engineering (rather than the disciplinary knowledge), and from there to move to explore implications of these for different aspects of the *knowledge*, and also for the relationships between them. The philosophical constructs were important for this task.

One of the basic premises underlying work in science is *regularity in the world* it investigates and attempts to describe. The same holds true for engineering as well, but there is an even more fundamental presupposition for engineering and technology than cause and effect in the world. Engineering aims to change the natural world in an intentional manner to suit the needs of humankind, and the fundamental underlying presupposition for this purpose is that *the world is not immutable*, but capable of being transformed and manipulated to meet human needs (Rogers, 1983). This particular teleological orientation of the *discipline* of engineering results in a *knowledge* orientation towards functionality and problem solving, namely, to exploit regularity in the world to bring about change. By contrast, the *disciplinary* teleological orientation in science is to understand, describe and explain the natural and modified world. This results in a *knowledge* orientation in the sciences that is theory-focused, where concepts carry meaning as part of a theory that maps the regularity of the world. The “epistemic destiny” of knowledge in science is “the pursuit of increasingly abstract and general propositions” (Muller, 2009, p. 208).

The research task was to track the knowledge orientations of the disciplines in empirical work. This involved a process of refining the broad categories identified from the sociology of knowledge and the applied philosophies of science and engineering. The process is explained in chapters two and three of the thesis, and it involved clarifying an analytical instrument in which specialisation, idealisation and normativity were cast as *knowledge modalities*. With the modalities still too data-distant to be useful in the empirical work, further finer-grained distinctions needed to be developed. The knowledge modalities were next conceptualised as ranging along continua of variance, called *modes* in the study. The specialisation modality varied along a universal – particular modal continuum, the idealisation modality changed along an abstract-ideal theorisation – physical realisability continuum, and the normative modality varied along an incidental – constitutive modal continuum.

Applying the analytical framework to empirical data revealed complexities in the instrument in the levels at which the modalities operate and relationships between modalities. The study also gave insight into the Bernsteinian concepts of singulars and regions, it complexified the differences and similarities between curriculum knowledge in engineering science and the sciences, and provided a contribution to an empirical turn in the philosophy of science and engineering science.

1.5 Historical overview of the development of knowledge in engineering science and science

This section presents a selective consideration of a historical trajectory of the modern Western understanding of science and engineering science knowledge.

The purpose of the historical overview is four-fold. First, my purpose is to trace the unfolding of and changes in the *relationship* between science and the technical sciences as they emerged over time (Mitcam & Schatzberg, 2009; Oldenziel, 2006). The relationship has not been uncontested, and the history provides particular insight into this argument. Channell (2009) suggests that the relationships between scientific and technological knowledge can be thought of as either independent, dependent or interdependent. He argues that throughout history examples of all of these models can be found, but that there are periods when a particular model seems to dominate. Secondly, I trace particular developments in the history, for example the shift from knowledge building as a purely rational activity to one where experimentation plays a central role. In the third place, the overview tracks milestones in the historical development of some of the conceptual content explored in this thesis. See for example the progression from the earliest discovery and intentional use of fire, to ways to think about heat, temperature, and efficiency. In this context the emergence of thermodynamics is traced alongside the development of the steam engine. Finally, this section provides a brief account of the progression of the science and engineering science disciplinary knowledge into formal education institutions.

Because of the particular purposes of the historical overview as explained above, some disclaimers are in order: it is not meant as an exhaustive account of the history of science and engineering, and any number of omissions can be pointed out, such as a limited exploration of ancient Greek, Arabic, Persian and other eastern thinkers and their work. The historical story is told with the specific aim of pursuing key milestones in the trajectory of the relationship between science and engineering science, and the parallel tracing of the development of concepts important in thermodynamics. Furthermore, the discussion is structured around

different periods in history to characterise development in these eras. The time periods are approximate, starting from a pre-science and pre-technology (or pre-engineering) period, and are not meant to suggest clear and water-tight boundaries. There are obvious overlaps, and some of the individuals in the historical story are ahead of their contemporaries, forerunners of a time to come. Finally, the focus here is on the way *knowledge*, concepts and information develop historically, rather than on the professions or practices of scientists and engineers, and any use of the term ‘engineer’ or ‘scientist’ denotes a loose, common-sense understanding of the terms.

1.5.1 Prehistory to 500 CE: Craft

For much of humankind’s history the early precursors of technology and science (craft and natural philosophy) existed quite independently from each other, with very little influence on each other (Channell, 2009; Rogers, 1983).

Early human ancestors began using tools at least the last 2.6 million years ago (Smithsonian's National Museum of Natural History, n.d.)¹. For most of this time the tools were rudimentary implements fashioned from stone, bone and antler, and it was only at the end of the last glacial period as humans evolved from primarily hunter-gatherers to farmer-herder societies that there were advances in the making of tools. Rogers (1983) argues that this came with a growing realisation for humans that their environment need not simply be endured, but that it could be changed and controlled, a recognition of “the fundamental presupposition upon which all technology is based” (p. 7). However, humankind was still very far removed from anything that could appropriately be called ‘technology’. Scholars have proposed that tool-making was a mixture of fortuitous accident, invention and manipulation skills. For this reason the pre-history of technology is considered to be craft.

The widespread *controlled use* of fire is dated to approximately 125 000 years ago, with some claims of evidence for the first controlled use as early as 1.5 million years ago (Gowlett & Wrangham, 2013). Fire used in this way influenced the behaviour of humans: activities were no longer confined to day-time, fire could be used for cooking, and evidence has been found of its craft use to shape stone tools around 72 000 years ago. This last use is of interest here in the early association it provides between discovery in the natural world (fire) and its application (in

¹ The recent (2011) discovery on the shores of Lake Turkana in Kenya, of stone tools dated 3.3 million years ago has cast doubt on previous belief that *Homo habilis* were the earliest tool-makers, and scientists now suggest that some of the earlier predecessors of modern humans (genus *Homo*) were more sophisticated than previously believed (Harmand *et al.*, 2015).

tool-making). With time, tools were constructed from different materials, first bronze (around 3500 BCE) and later iron (around 1400 BCE).

Other craft practices that gradually developed early in human history were the use of clay pots to store grains, milling grain, spinning, paper-making in China, and the weaving of reeds for various uses (Rogers, 1983). These various developments have in common the fact that they arose in response to a particular need identified in primitive social groups.

As human social groups grew in size, people started to congregate in cities, and building skills developed. (It is important to emphasise that development as described here happened unevenly, and that in some areas there remained hunter-gatherers, and others to function in agrarian ways). In fertile regions, people had time freed up for different activities. With larger social groups it became possible for humans to specialise in tasks, and the division of labour found its way into society. Rogers (1983) describes the rise of a group of people he calls engineers/architects/priests who oversaw the building of pyramids and temples, from around 2600 BCE.

The period from around 1000 BCE to 300 BCE was a productive period for growth in inventions, especially in Greece: people discovered how to smelt iron, and invented the potter's wheel, lathes, clocks, pumps and the waterwheel (Rogers, 1983). Artisans had high standing in society. The Roman era (from around 300 BCE) was a time during which free slave labour was plentiful, and large diverse building projects were embarked upon². Sophisticated transport and water supply systems were built and the early precursors of today's civil and military engineering arose. The closest record we have of any systematic attempt to relate practice to theory from this period is Vitruvius' *Ten books on Architecture* from the first century BCE during the reign of Julius Caesar (Illies & Ray, 2009). It contains practical rule-of-thumb advice, and is an early hint of craft's potential to mature into what would later be called the start of 'technics'.

Vitruvius' work was an exception though, and typically craft knowledge was applied to specific situations as needs arose, with virtually no attempt made to generalise the knowledge. For this reason, historians treat this time of human development as the period of the mechanical or manual arts.

² Some, like Rogers (1983), argue that Roman reliance on slave labour led to dramatic improvement of existing technologies, but resulted in suppressed innovation, and contributed to technological stagnation in the Roman Empire.

1.5.2 3 000 BCE to 1400 CE: Natural Philosophy and the mechanical arts

Whereas craft knowledge resulted in historically identifiable artefacts and practices, it is more difficult to trace the inception of what later came to be recognised as ‘natural philosophy’, characterised by abstract thinking. Rogers (1983) attempts to do this in his broad sweep through early history, with a description of the development of primitive language, and the use of clay tablets (around 3 000 BCE), initially to represent numbers and later language.

However, historians agree that the Greeks around 1 000 BCE should probably be credited with early abstract thinking on topics like the *properties* of numbers and triangles, lines and points in mathematics, and the *nature* of fire (as opposed to the *use* of fire). It is this concern with asking questions and seeking for answers about the ultimate nature of the physical world that characterises the start of natural philosophy (McClellan & Dorn, 2006). This period also sees the origin of logical deduction and arguing from proof in the work of Euclid and the Pythagoreans, crucial for the development of mathematics and later scientific thought. The basic premise that characterises this period is a recognition of regularity in the natural world, leading to the conceptualisation of cause and effect, as opposed to assigning events exclusively to the capricious acts of gods (Rogers, 1983). Thales of Miletus (*circa* 7th century BCE) is credited with first formulating the early science-like question about the nature of all things, suggesting water as the most elemental of substances (McClellan & Dorn, 2006). Others grappled with the same question: Anaximander (610-546 BCE) believed that there had to be something more fundamental than water that resulted in the opposites of wetness and dryness, heat and cold. Empedocles (495-430 BCE) took this further, and is credited with the influential and quite enduring notion of the four classical elements of earth, fire, water and air. Leucippus and Democritus (around the 5th century BCE) were the first atomists with their conviction that everything consists of tiny, indivisible particles which they called atoms (Gaukroger, 2006; McClellan & Dorn, 2006).

Changes also came on other fronts during this period: the Pythagoreans introduced abstract mathematics into natural philosophy, and with their refinement of the “crude arithmetic of the marketplace... they made the concept of number central to their view of nature” (McClellan & Dorn, 2006, p. 62).

This early form of philosophical thought was characterised by contested relations between the importance of mind and body: Platonic thought emphasised the importance of the mind in reaching an understanding of the nature of the world. Plato (*circa* 428 – 348 BCE) believed that the material world (and therefore any form of practice) provided but a shadowy representation of the true nature of the world that could only be grasped by the mind (Channell, 2009;

McClellan & Dorn, 2006). This view was countered to some extent by Aristotle (384 – 322 BCE) with the attention he gave to the material world and the world of the senses. However, the social class barriers of the time reinforced the division between intellectual and manual work (Channell, 2009).

There were hints in the work of Archimedes (c. 287 – c. 212 BCE) of what could be achieved by experimentation: he invented pulleys, hydraulic screws, and instruments of war (McClellan & Dorn, 2006). However, he saw these as mere ‘toys’, and in Platonic style placed a higher value on the work he did on calculating the ratio of the circumference of a circle to its diameter, and the mathematical description of mechanical devices. He made use of idealisation in his thinking: forces were idealised to work on a single point at the ends of a lever that rested on an idealised fulcrum (this early use of idealisation in abstract thinking is important in the context of this thesis). Heron of Alexandria (10 – 70 CE) was another natural philosopher of the time who appears to have done experimentation. His description of an aeolipile is often cited as the earliest record of a primitive mechanical device using steam power (See Keyser’s (1992) exposition of various arguments around this).

New forms of formal education arose during the time of Charlemagne (742 – 814 CE), and monastic and cathedral schools became places of learning for the clerics (McClellan & Dorn, 2006). The first western medieval universities appeared in the 12th century, in Bologna, Paris and Oxford. The seven liberal arts formed the curriculum, with pride-of-place given to the trivium (Latin grammar, logic, and rhetoric) and the lesser valued quadrivium (arithmetic, geometry, astronomy, music theory). Over time the curriculum developed to include the three Aristotelian philosophies (natural philosophy, metaphysics and moral philosophy or ethics). The seven mechanical arts (weaving, weapon foundry, navigation, agriculture, hunting, medicine and drama) were not taught in the medieval university. This curriculum structure reflected a stark division in academia, traces of which are still evident to this day (Muller, 2009) with the trivium representing the work of the mind, and the quadrivium the work of natural philosophy. The absence of the mechanical arts in the medieval university reflected the low esteem in which the practical arts were held. Muller (2009) describes the medieval university as “forthrightly anti-utilitarian” (p. 206), and the liberal and mechanical arts developed effectively independent of each other.

Formal education in a university was not an option for craftspeople. The skills of the mechanical artisans were passed on in an apprenticeship system. A teenage boy entered an apprenticeship with a master to learn the trade for a period as long as fourteen years, after which he was allowed to practice his trade as a journeyman to earn a living. Once established, a journeyman

could apply to a guild to be recognised as a master craftsman and be allowed to take on apprentices. Guilds operated in medieval society to protect the economic interests of their members and to regulate the quality of work produced. Guilds were powerful groups in society, controlling the pricing of goods and services in towns, and even blocking import of goods into towns that would compete with local products (See the work of Epstein (1998) and Swanson (1988) for a critical discussion of the role of guilds in society).

The social and intellectual barriers between the natural philosophers and craftspeople of the time remained in place. However, some changes were developing: Roger Bacon, a Franciscan friar (1214-1292), was a scholar of Arabian and Greek manuscripts, and is considered by some to be one of the first natural philosophers to emphasise the role of experimentation (McClellan & Dorn, 2006), not only for confirmation of knowledge arrived at by reason, but also to discover some practical uses for that knowledge. Furthermore, the work of the monks (the literate scholars of their time) and their engagement in manual labour resulted in a gradual shift towards an understanding of the dignity of (manual) work. “Ora, Labora et Lectio” refers to the Benedictine division of the day into prayer, labour and study of the scriptures.

The period described here therefore saw significant advances in abstract thinking that later became natural philosophy, with some early tentative ventures into experimentation alongside the intellectual work. For the most part though, there was a firm divide between intellectual and practical work, underpinned by stark social class differences between natural philosophers and artisans.

1.5.3 1500 CE to 1750 CE: The dawn of science and technics

There were several factors that contributed to the gradual shift from natural philosophy to something beginning to approximate scientific thought³. It is interesting to note that this process was largely aided by developments in the mechanical arts, which at the same time steadily progressed into something more methodical (described as ‘technics’ by historians).

The polymath Leonardo da Vinci (1452-1519) played an important role in this development. The breadth of his contribution as a Renaissance artist and his work as an inventor-engineer pushed the boundaries of the intellectual and cultural worlds of his time. Channell (2009) describes how he used the artist’s fixed-point-of-perspective approach (a Renaissance development) to analyse and draw detailed technical diagrams of machines. As one of the literate artist-engineers (others were Alberti, Brunelleschi and Francesco di Giorgio Martini), he

³ The first use of the term ‘scientist’ (by analogy to the term ‘artist’) is traced to 1839, but a more widespread use only came decades later (Cardwell, 1994).

functioned as a bridge to transform the mechanical arts into a more “systematic form of knowledge that could be abstractly studied and shared” (Channell, 2009, p. 123), and it became an advantage for craftspeople to be literate.

The late Middle Ages saw a proliferation of scientific work, especially in astronomy. With the publication of his book at the end of his life (1543), *On the Revolutions of the Heavenly Spheres*, Copernicus launched the ‘scientific revolution’ (McClellan & Dorn, 2006). He proposed a heliocentric universe, with a moving earth rotating every day on its own axis and completing an annual journey around the sun. Copernicus was, in a sense, “the last of the ancient astronomers, not the first of the moderns” (McClellan & Dorn, 2006, p. 209), as he neither made any new observations, nor set out to prove his theory. He hypothesised a simpler, more elegant system that agreed with observations made by others before him (mainly the retrogradation of the planets). This was a radical break with the geocentric view accepted in just about every culture of the day, and had an enormous influence on natural philosophy and astronomy at the time. Brahe (1546-1601), who never accepted heliocentricity, and Kepler (1571-1630), followed with detailed empirical measurements and calculations, relying heavily on the skills of artisan instrument makers.

Francis Bacon (1561-1626) has been described as “the Father of Experimental Philosophy” (Urbach, 1987, p. 185), and as the one who, “more than anyone else” (Gaukroger, 2004, p. 1), advocated the transformation of natural philosophy into what later came to be understood as science. Bacon argued that natural philosophy should be about discovering laws of nature and physical causes, and result in ‘effects’, or a *scientia operativa* which he describes as an inductive process of actively engaging with nature, and gradually moving from the particular to the general, in “a pyramid or hierarchy of increased generality” (Vickers, 1992, p. 502). Bacon’s notion that natural philosophy (scientific) knowledge is cumulative (i.e. that knowledge builds) was also new for his time. It requires that scientific knowledge be thought of as paradigmatic (Vickers, 1992). Bacon believed that “the generality of one’s assumptions should be increased only gradually and should be proportioned at every stage to the available evidence” (Urbach, 1987, p. 192). In Bacon’s work, pure intellectual inquiry was united for the first time with a call for empirical investigation of phenomena, and this brought the start of a closer relation between the mechanical arts and natural philosophy.

This closer cooperation between the mechanical arts and the natural philosophers is striking in the large number of inventions that became available for scientific work. The slide ruler (Bissaker), logarithms (Napier), a mechanical adding machine (Pascal), telescopes, the compound microscope, vacuum pumps and the barometer are examples of inventions in the

course of the 17th century. Some of these inventions were directly dependent on the skills of master craftspeople, such as lens grinders.

Improved capabilities of instruments like the telescope had a significant impact on the work of scientists of the day. While Galileo (1564-1642) is probably most famous for his work in astronomy and the consequences of his support for the Copernican heliocentric model⁴, another, perhaps lesser known, contribution he made was his thinking about the way in which the *performance of machines* was judged. At the time, machines were evaluated qualitatively in terms of the workmanship of the machine and for the way they appeared to function “by cheating nature” (Channell, 2009, p. 125). By contrast, Galileo believed that machines operated by using natural forces and transforming them for some useful purpose. He developed an approach that allowed him to calculate how this transformation took place for an ideal machine, and by comparing this to how actual machines transformed forces and motion, he was able to assess quantitatively the performance of actual machines. This very early approach to what later became known as efficiency, shows why it is “impossible to overestimate the importance of Galileo’s profound insight” (Cardwell, 1994, p. 87). Another important contribution made by Galileo was his ability to abstract a general principle from the particular instance via idealisation, for example, by studying the way bodies moved down different inclined slopes, he was able to postulate the motion of a body to be continuous and unchanging in the absence of other forces like friction.

The time period described here therefore brought changes in the way the burgeoning sciences and technics related to each other: the increase in experimental work in the sciences relied heavily on technical instrumentation, and technics itself became more methodical. Another consequence of the changing relationship between natural philosophy and the mechanical arts at this time in history was that people started to argue that the (products of) mechanical arts could be used to explain natural philosophy. This led to the development of a mathematical-mechanical view of the world by scientist-philosophers like Descartes (1596 – 1650), Newton (1643 – 1727), Hobbes (1588 – 1679), Boyle (1627 – 1691) and Leibnitz (1646 – 1716) (Channell, 2009).

However, these advances in scientific thinking have to be kept in perspective. McClellan & Dorn (2006) warn against imagining the so-called scientific revolution simply as a period of triumphant progress in the nascent sciences. This was also the period during which “the ‘occult’

⁴ Tried and convicted by the Inquisition for heresy, Galileo was forced to recant and spent the last nine years of his life under house arrest. Over time the Catholic Church’s stance changed, but it was only in 1992 that Pope John Paul II formally acknowledged “the error of the theologians of the time” (Robinson, Sweeney, & Gill, 2006, p. 169).

sciences of magic, alchemy and astrology” (p. 203) flourished. Chemistry’s “deep roots in traditional alchemy” (McClellan & Dorn, 2006, p. 300) with its “mystical and spiritual elements” (p. 85) hindered any radical restructuring of the subject field during the ‘scientific revolution’ of the 16th and 17th centuries, and it was only in the 18th century that chemistry developed a theoretical base with the (erroneous) phlogiston theory (phlogiston was regarded as the active product released in every combustion reaction). The downfall of the phlogiston theory finally brought about what McClellan and Dorn (2006) call the “chemical revolution” (p.300). This came with Lavoisier’s (1774) careful accounting of reactants and products in combustion reactions, and his empirical argument that combustion took something out of the air, rather than adding something (phlogiston) to it. However, progress was so slow that even Priestley, who is credited with the discovery of the element oxygen, died in 1804 without accepting the ‘new’ chemistry. Some (see Rogers, 1983) contend that this slow pace of scientific theory development at that time was the reason why chemistry had comparatively little influence the start of the Industrial Revolution. The development of fundamental theoretical ideas on the role of molecules in reactions (Avogadro, 1776-1856), atomic weights (Cannizzaro 1826-1910) and the early conception of a Periodic Table of elements (Mendeleev, 1834 - 1907) were mostly 19th century ones.

1.5.4 1760 to 1850 CE: The Industrial Revolution

The Industrial Revolution, estimated to have run from around 1760 till around 1820 to 1840, was a period of transition towards mechanisation of industrial processes, with concomitant social developments such as the urbanisation of society, the rise of the factory system with machines replacing manual labour, and an increase in global trade. Iron, coal and steam became crucial resources (McClellan & Dorn, 2006).

Waterwheels were the dominant machines in the late 17th, early 18th century, and converted the energy from free-flowing water for useful tasks like milling flour or grinding wood pulp. With the increase in industrialisation that came with the Industrial Revolution there was a greater concern about productivity and the efficiency of machines. John Smeaton developed a method for investigating properties of the waterwheel (such as the type of wheel, flow and head of the water, the load on the wheel, etc.) in a deliberate and systematic way to find the most efficient type of machine. This approach came to be known as ‘parameter variation’, and became an important technique much later in the engineering sciences (Vincenti, 1990).

In keeping with the focus on thermodynamics in this thesis, the emphasis in this section is on the development of the steam engine. It will be shown here how the steam engine had its inception, improvement and development originating from the ‘shop floor’, driven by the need

to solve practical problems. In fact, in arguments against the primacy of science in the science-technology relationship, the steam engine is often cited as an example of a case where technological knowledge and developments clearly lead scientific understanding and knowledge. The role played by the patent law system in constraining and enabling innovation in the history of the steam engine is a fascinating thread of the story, and I attempt to draw attention to this where appropriate.

The pressing problem of the time was how to deal with water in tin and coal mines, which severely limited the depth to which the mines could be worked. In 1698, Thomas Savery patented an early steam engine, based on Papin's 1679 'bone' (steam) digester, an early precursor never patented. In his patent, Savery described his engine as an invention that could be used for "raising water by the impellent force of fire" (Savery, 1827, p. 7) to drain mines. It effectively worked by displacing the water by the force of vacuum, had no piston, no moving parts, and did not transmit its power to any external device. For these reasons some do not regard it strictly as an engine (Tortella, 2009; Watson, 2013). There were severe limitations on the height to which it could 'raise' water (only around 7 m). It wasted heat in warming up the water that was being transported, and the soldered joints in the second stage could not withstand the pressure of the high pressure steam, which led to safety concerns. Note these early normative concerns of safety and energy wastage around the working of the machines.

Cardwell (1994) describes how the reform of the patent system in England had an impact on developments during the Industrial Revolution, and therefore also indirectly on the development of engineering science knowledge. In the case of the steam engine, Savery's original patent protected the invention for 14 years, extended by an Act of Parliament (the Fire Engine Act) for a further 21 years, in spite of the failure of the engine as a practical solution. The patent rights meant that Newcomen had to form a partnership with Savery to implement his ideas for improvement. Newcomen was a tradesperson, a trained ironmonger with knowledge of the properties of metals and familiar with the limitations of iron. He developed a design that used atmospheric pressure to drive a piston, avoiding the dangers of high-pressure steam. The engine design was complex, and historians argue that there are signs that the development was an incremental process, responding empirically as problems arose (Cardwell, 1994). Savery's patent remained in place until 1733, and resulted in a virtual monopoly on working steam engines for the duration of the patent.

The process of arriving at a functioning practical steam engine that could finally be used to pump water from mines was a tortuous journey, and historians of science and technology tell the story in various ways. Cohen (2010), for example, emphasises the role of theory: he argues

that Papin's device was the result of the theory of atmospheric pressure being "completed", which allowed for thinking about how this could be "harness[ed] through the conversion of fuel into a working stroke" (p.477). He admits, however, that it is a long way from "theoretical practice" to "*practicable* practice" (p. 478, emphasis in the original). McClellan & Dorn (2006) strongly disagree with this kind of interpretation of the role of scientific theory in the development of the steam engine: "...the actual design of the steam engine owed nothing to science" (p.283). They argue that, even allowing that the notion of atmospheric pressure's use as a potential force for motion was "in the air," the complex mechanics of Newcomen's working engine evolved through "intuition, tinkering, and a stroke of luck" (p. 283), rather than application of theory. (Note the slightly dismissive comment by Cohen of this type of work as "artisanal improvement ... of experimental science" (p. 477)).

In spite of its widespread commercial use, there were serious design difficulties with the Newcomen engine. James Watt was the next artisan-engineer to contribute to the development of the steam engine. He started out working as an instrument-maker at the University of Glasgow where he spent some time repairing a Newcomen engine that belonged to the department of Natural Philosophy (Muirhead, 1858). Watt realised that a considerable amount of energy was wasted in the Newcomen engine's primitive single piston and cylinder design. The process was slow (only one oscillation every five seconds, according to Currier (2015)), which further hampered the effectiveness of the engine. Watt made numerous improvements over time, but the two most important ones were the addition of a condenser and the development of a second power stroke. The separate condenser eliminated the need for repeated heating and cooling of the single cylinder by expelling the steam from each stroke into a separate cooling condenser. The second improvement effectively sealed the steam in the main cylinder, allowing the piston shaft to move through an airtight seal. This meant that the steam first pushed the piston to the top of its stroke, and afterward propelled the piston in the opposite direction. This dual action doubled the fuel efficiency of the steam engine (Currier, 2015). By then efficiency was a major concern, and this was given impetus by commercial interests and the patent system.

One major drawback of the steam engine (compared to the waterwheel) was the lack of rotary motion. In yet another example of the impact of patent rights, James Pickard took a twelve year patent on the flywheel-and-crank rotary motion steam engine he had developed (Marsden & Jones, 2004) in 1780. Watt and his partner Boulton had to work around this potentially ruinous (for Watt and Boulton) limitation by developing a sun-and-planet gear system, evading Pickard's crank system patent until its expiry.

Watt's engine operated at relatively low pressure, and the next logical development came with the development of high pressure engines. This was initially strongly opposed by Watt and Boulton by enforcing the monopoly of their patent and actively preventing others from building high-pressure engines. Boldrin and Levine (2008) argue that there was very little change in fuel efficiency during the time of Watt's patent, with a fivefold increase in fuel efficiency of the steam engine in the 25 years following the expiry of the patent. The advantages of the high-pressure engines were obvious: the new engines could be made smaller and were therefore more economical. Smaller engines were suitable for transportation and powering other machines, accelerating the mechanisation of many industrial processes.

The discussion this far has focused on the way in which the developments in the steam engine were artisan/engineering driven; knowledge was practicable and focused on the physical realisability of the artefact. It often grew from a trial-and-error approach to improving the artefact (Boon & Knuuttila, 2009). The next section looks at how knowledge of a different kind developed at this time.

1.5.5 Emergence of the engineering sciences: thermodynamics as an example

The engineering sciences arose during the 18th and 19th centuries as the product of the political, social, economic and intellectual changes brought about by the Industrial Revolution (Channell, 2009). There was a growing realisation that technical knowledge needed to be developed from the practicable, tinkering knowledge that resulted in working artefacts, into something more systematic and theory-based, which could be extended beyond a specific context (Banse & Grunwald, 2009).

Channell (2009) calls the development of thermodynamics "one of the most significant developments in the emergence of the engineering sciences" (p. 132). Thermodynamics theory resulted from the study of the steam engine, but very early on there was a realisation that the theory did not depend on a particular theoretical conception of heat, "making thermodynamics a true engineering science" (Channell, p. 133). This was soon extended; energy and entropy were recognised as universal concepts applicable beyond heat phenomena to many every-day, scientific and technological events and processes -- from the efficiency of power stations to the evolution of stars; from the cooling down of a cup of coffee to the probabilistic likelihood of events. This represents an interesting shift in the way practical shop floor type knowledge became more general and systematic.

The first use of the term “thermodynamic” appears in William Thomson’s (Lord Kelvin) (1849) report on Sadi Carnot’s work to the Edinburgh Royal Society: “A *perfect* thermo-dynamic engine of any kind, is a machine by means of which the greatest possible amount of mechanical effect can be obtained from a given thermal agency.... and so to complete the theory of the motive power of heat.” (p. 118, emphasis in the original). There are several aspects of interest here: features of idealisation (the notion of a “perfect” engine), the universalised engine “of any kind”, the normative idea of evaluating the “mechanical effect,” and the concern with the theory of the “motive power of heat”. It is an indication of a shift to a more systematic, theoretical way of thinking about the implications of the operation of steam engines from the shop floor of the industrial workshops.

The Industrial Revolution brought in its wake an urgent demand for more and better sources of power, and therefore an increased interest in improving the steam engines by understanding the principles on which they function. In 1768, Smeaton conducted the first parameter variation studies (a uniquely *engineering* analytical process, according to Vincenti (1990)) on a model steam engine. By the end of the 18th century, Watt was trying to calculate the amount of work done by his steam engine, or the ‘duty’ of the engine (Cardwell, 1994), a process that was problematic because of the way in which steam expanded in the engine. One of Watt’s assistants eventually built a meter that recorded the pressure changes throughout the stroke of the engine, leading to the development of pressure-volume diagrams that became a standard feature of thermodynamics.

However, the person who contributed most to understanding the thermodynamic processes at work in steam engines was the French military engineer, Sadi Carnot. His contribution (*Reflexions on the Motive Power of Fire* published in 1824) came more than 100 years *after* the invention of the steam engine launched the Industrial Revolution in Britain. The epistemic purpose for Carnot’s work was the desire for an understanding of the theoretical limits of the performance of a heat engine (Boon & Knuuttila, 2009) – today we would call this the efficiency of the heat engine. In 1824, Carnot wrote, “In spite of the many advances that have been made with the heat-engine... the theory of its operation is rudimentary, and attempts to improve its performance are still made in an almost haphazard way” (1986 [1824], p. 61, as quoted in Boon & Knuuttila, 2009). This is an illustration of how technological developments in many cases lead the scientific understanding of the processes, an example of “technology setting the agenda for scientific research” (McClellan & Dorn, 2006, p. 305).

Boon & Knuuttila (2009) point out that, unlike theoretical explanations in the typical ‘pure’ sciences, the engineering science starts from a practical problem⁵, in this case the efficiency of a heat-engine. Carnot was the first to think of the steam engine as a *heat* engine, rather than a pressure engine, as most of his contemporaries saw it and where they focused their attention for improvement (Cardwell, 1994). Carnot’s crucial insight was to set out to understand ‘steam power’: ‘water power’ was well understood at the time, but the behaviour of steam (for example the rapid increase in pressure with an increase in temperature) was not understood in the context of the steam engine at the time. He described a ‘perfect’ heat engine: a set of conditions under which a heat engine functioned at maximum efficiency. ‘Perfection’ (an idealisation) is here conceptualised in terms of the ever-present normative concern of efficiency. Carnot was able to demonstrate that his ideal theoretical cycle was independent of any particular theory of heat (and independent of the properties of any particular working fluid). The knowledge is generalised and extends beyond the immediate practical problem that saw its inception. At the time, Carnot supported a material theory of heat: heat is a caloric fluid that produces work as it flows from a hotter to a colder body. By the 1850s, the material (caloric) theory of heat had been replaced by a mechanical understanding of heat, and Joule (1818 – 1889) argued that heat was converted into work (the notion that both heat and work are different forms of energy came a little later in the work done by Thomson and Rankine). Clausius (1822 – 1888) was able to reconcile the new theory about heat to the growing body of thermodynamics theory by postulating that some of the heat is converted into work, and that the rest of the energy is dissipated at a lower temperature. He introduced the term “entropy” to refer to this dissipated energy, nature’s ‘penalty’ (Lindsay, 1959) for energy transformations. Clausius defined the concept of ‘internal energy’ and formulated the two laws of thermodynamics: the First Law states that the energy in the universe is constant, and the Second Law that the entropy in the universe tends towards a maximum (Massoud, 2005).

On the chemistry front, J. Willard Gibbs (1839 – 1903) made major contributions to thermodynamics theory in his work on thermodynamic equilibrium, effectively launching the field of physical chemistry in the late 1870s. One of Gibbs’ most important contributions was the move towards a statistical mechanical approach to thermodynamics.

At this point, with the emergence of thermodynamics as an example of an engineering science, I conclude the historical overview. I next turn to the recontextualisation of the knowledge into curricula for educating discipline specialists.

⁵ This is an important distinction, explored further in the following chapter: although engineering science, as a science, is interested in explaining and understanding, the *fundamental purpose* (‘telos’) is always response to a perceived human need and a problem.

1.5.6 History of education in the sciences and engineering

Education in the sciences and engineering follows a trajectory parallel to the conceptual development of the knowledge in the disciplinary fields as described in the previous sections. Education here involves a systematic process of inducting potential new disciplinary practitioners into the valued disciplinary knowledge.

As discussed earlier in this chapter, the early natural philosophers concerned themselves with questions and answers about the fundamental meaning and nature of the world; they focused on mathematics, geometry and other forms of logical reasoning to resolve general problems. The purpose of this kind of thinking was “to idealize problems so their solutions could be universally applied to descriptions of nature as a whole” (Channell, 2009, p. 118). These kinds of activities were practiced by the elite of society, and once universities emerge in the Middle Ages, the typical natural philosopher was literate and university-educated. This also meant that there was a tradition of disseminating the knowledge via manuscripts.

The crafts, or ‘mechanical arts’ on the other hand, were practiced by people concerned with practical problems that were unique, and the rule-of-thumb techniques that were developed usually applied to specific situations. Very few of the early practitioners had a university education: knowledge was gained through experience, and only very seldom was writing used to circulate the knowledge. Craftspeople usually mastered their arts as artisans in apprenticeships (see for instance Epstein, 1998). Artisans were only allowed to practice as members of a guild, and apprenticeships became the first form of non-religious education in the Middle Ages. The influence of the guilds was strong throughout the Industrial Revolution.

A point of contact with the history of the steam engine is the career of James Watt, who studied instrument-making in London before settling in Glasgow to set up a business as instrument-maker. His application to become a member of the Glasgow Guild of Hammermen was rejected because he had not served the seven year apprenticeship required by the Guild, even though there were no other qualified instrument-makers in Scotland that could oversee his specialised craft. The need of the University of Glasgow for an expert to maintain and repair their astronomical instruments provided a way around the stand-off, and he was employed by the university, rather than working as an independent artisan (Carnegie, 2005).

The Industrial Revolution brought rapid development in various technological fields, and Channell (2009) describes the development of different institutions that focused on the dissemination of technological knowledge like the Masonic Lodges and Mechanics’ Institutes. Engineering colleges were established, such as the École Polytechnique in Paris in 1794, with

polytechnics also established in Vienna, Prague, Karlsruhe, Munich, and later the Military Academy at Westpoint in 1818), the Rensselaer Polytechnic Institute in 1847, and the Massachusetts Institute of Technology in Boston in 1861 (Layton, 1971).

Channell (2009) describes the important role Scotland played in the development of the engineering sciences: the strong cultural links with both England and France, enabled the Scots to bring together the empirical emphasis from England with the strong mathematical-theoretical focus of the French. A central figure here was W.J. M. Rankine whose work in thermodynamics and mechanics by at the University of Glasgow brought about “an integration between science and technology” (see the description of the “harmony” brought about by the engineering sciences in Channell (1982, p. 52)). Layton (1971) argues that by 1900 the engineering sciences constituted unified, recognisable bodies of knowledge in different conceptual fields. This development of identifiable, structured engineering science knowledge strengthened and consolidated the education of engineers in the polytechnics and engineering colleges, and by 1900 training in engineering colleges had virtually replaced apprenticeship training (Layton, 1971).

The elitist orientation of the traditional liberal arts colleges and universities initially blocked the introduction of technical education into the classical colleges, and Case (2013) points out that engineering had some difficulty gaining recognition in the university. However, the surge in the building of canals, railroads and manufacturing industries increased the demand for skilled workers, and the technical colleges grew in stature. At the same time, the growing recognition of the role of technology in industry and the economy also brought a gradual change in the nature of the science (previously natural philosophy) presented in the colleges and universities. As the sciences became more empirical (Noble, 1977), there was a gradual change in the relationship, with the (now more empirical) science and engineering education moving slightly closer together.

With time, concerns grew about the wide range of non-standard qualifications offered by the polytechnics and colleges, and there was a growing realisation that engineering education needed to move into a formalised academic environment (Case, 2013). This was not an easy, unimpeded process. As the sciences became more accepted in the academy, science educators often aligned themselves with classical disciplines against the technology educators (Noble, 1977). To overcome the resistance present in the liberal arts colleges, it became necessary for the engineering education offered to become ‘academised’, shifting from a ‘shop’ culture with its singular emphasis on practical solutions to practical problems, rules-of-thumb heuristics, and less systematic tinkering, towards a curriculum where science and mathematics knowledge

played a more prominent role. This was most pronounced in the 'newer' branches of engineering like chemical and electrical engineering. Noble (1977) points out that the first teachers in chemical engineering programmes were chemists, rather than chemical engineers. These realities about chemical engineering (the fact that it is a 'younger' discipline, as well as the stronger earlier link with chemistry in the original teachers of the discipline) provide an interesting perspective on some of the findings from the research described in this thesis.

Harwood (2006) describes two aspects of the 'academic drift' or 'academisation' of the technical education towards a stronger 'science orientation' at the time of entering the academy: one was a social process of 'upgrading' the education to gain more status, and the other a cognitive shift where science and mathematics became more prominent in the engineering practice. That this should coincide with the emergence of engineering sciences (like thermodynamics), was indeed fortuitous for engineering education. Case (2013) argues that once engineering education made the shift into the academy, the engineering science content in curricula increased. The academic teachers of the engineering sciences were also the knowledge producers in their research, and the degree of specialisation strengthened. These changes in engineering curricula did not always coincide with demands and desires of the industry employers of engineers (Noble, 1977), and led to very different kinds of engineering education across institutions and continents. Harwood (2006) describes how some institutions attempted to recreate the 'shop culture', whereas others offered a completely theoretical education, or 'school culture'. Still others, like Cornell, offered a 'sandwich' approach that interspersed science and mathematics education with industrial shop experience.

Case (2013) argues that the development of engineering as a profession played an important role in the development of engineering education curricula. In this the trajectory for engineering is different from the 'older' professions like law and medicine where professional identity is embodied in the claim to a specialised body of knowledge. By contrast, industry employers of engineers and the interests of corporate capital (Noble, 1977) became (and still are) important influences in engineering curricula. Divall (1994), for example, describes a complex process in the case of chemical engineering education which meant that business interests were integrated in educational programmes via the influence of professional societies and so-called 'consultants' who were experts responsible for the design of chemical plants. There was a need for the early chemical engineers to distinguish their profession from chemistry and mechanical engineering in the scaling up of laboratory processes to industrial ones, and a distinctive academic training was one way of doing this. This resulted in a much closer and, therefore, perhaps less contested relationship with industry.

In closing this section it is pertinent to point out that contestation of engineering curricula continues unabated: Bernstein (1990) described this general process as a struggle for the control of the pedagogic device by dominant groups in society. There are concerns about whether university curricula produce enough engineering graduates, and whether these are graduates of the 'right' kind: do they have the appropriate skills and knowledge sets for the workplace? The role and influence of professional engineering bodies have increased with their accreditation processes, see for example the 'outcomes-based' accreditation granted by professional bodies that are signatories of the international Washington Accord, offering mutual recognition of engineering qualifications (Case, 2014). Case argues that this move towards outcomes-based accreditation is the result of an industry demand that engineering graduates need to be able to "deliver value from their first day in the workplace" (p.144). The urgency expressed here finds its way into conversations about curriculum change around problem-based and project-based curricula, usually based on an assumption that it is possible to teach and learn best in contexts that mimic 'authentic' workplace environments.

Not everyone agrees with these assumptions: sociologists of educational knowledge (Muller & Young, 2014; Wheelahan, 2014; Young, 2013; Young & Muller, 2010) express concern when a focus on competencies and skills comes at the expense of 'powerful' knowledge in the curriculum (see the more detailed discussion in the following chapter). Case (2014) cautions against curricula that take the 'real' world as the defining organising principle, as in the case with problem-based learning, rather than taking seriously the epistemic organisation and the characteristics of the valued disciplinary knowledge. It is to this conversation that the study described here aims to contribute in its investigation into the nature of similarities and differences in disciplinary knowledge.

1.5.7 Concluding remarks on the historical overview

In this section, I traced the lines of development followed by the two broad disciplinary streams of science and engineering science, through their antecedents of natural philosophy, craft and technics, and converged on the emergence of the engineering sciences at the time of the Industrial Revolution.

The overview traces aspects of the complex relationship between science and engineering, and shows how at times in human history they existed separately and independent of each other, and at other times one or the other led in the relationship, setting up hierarchies (more on this in chapter two). The historical story also gives insight into the development of the nature of the disciplines as we find them today: emphasising the role of experimentation, the importance of a structured theoretical base to lead understanding of natural and artefactual phenomena, the use

and role of idealisation in extending knowledge beyond the particular, and the importance of normative concerns (or lack thereof) in the disciplines. I briefly looked at the trajectory of recontextualised disciplinary knowledge into academic curricula for the purposes of educating disciplinary neophytes. In particular, the historical account focused on a specific body of knowledge, namely thermodynamics, and milestones in the conceptual development were signalled as these illustrated various stages of disciplinary knowledge development.

At the end of the historical story the task at hand is now to find ways of investigating *how* disciplinary knowledge in the sciences and engineering sciences are similar and different, and the extent to which they carry in their curricular recontextualisation a reflection of disciplinary characteristics.

1.6 Roadmap to the thesis

This chapter lays the foundation for the thesis. It presents a broad introduction to the research problem, justifies the methodological approach and offers a selective tracking of the relationship between science and engineering science in history, with an emphasis on the development of conceptual content that refers to knowledge in thermodynamics. The chapters that follow here examine and describe these aspects in detail: chapter two critically locates the study in literature on the sociology of knowledge and the philosophy of science and engineering science. Chapter three presents the research design, and shows the development of the analytical instrument. In chapters four to six, the theoretical tools developed in the preceding chapter are applied to analyse data from five thermodynamics textbooks. A condensed overview of the data coding decisions are presented in Appendix A. Chapter seven presents a discussion of the findings and implications of the thesis. The study is consolidated in the concluding chapter.

Chapter 2 Review of relevant literature

There are more things in Heaven and Earth, Horatio, than are dreamt of in your philosophy.

—William Shakespeare, *Hamlet*

Emile Durkheim's observation that the progression of modern society would bring a parallel and correlated increase in the division of labour in society and therefore greater specialisation and differentiation, hardly needs articulation. Muller (2012) argues that this increase in specialisation and differentiation is carried largely by developments in the scientific and technological fields.

It is this specialisation of the division of labour in society, in particular the differentiation into science and engineering, that functions as the backdrop to the study described in this thesis. In this chapter, I discuss literature from the sociology of knowledge and from the philosophy of science and engineering that speak to possible ways to describe and understand the disciplinary differences in the knowledge of these different, but related fields. The work done in the thesis focuses narrowly on the disciplinary *knowledge*, rather than on the practices and characteristics of the disciplinary practitioners. Furthermore, the particular interest is the nature of engineering science knowledge, with knowledge in the sciences functioning in juxtaposition.

2.1 The academic disciplines

One of the most innocuous, and yet fundamental, features of the organisation of tertiary institutions, is its structuring around academic disciplines. In a seminal study of the way academic departments at modern universities operate according to subject matter, Biglan (1973) proposes three dimensions to differentiate between disciplines: the extent to which a paradigm exists, the degree to which application is important, and the role of "life systems" (p. 201) in the discipline. He uses "paradigm" in the Kuhnian sense (1962) to refer to agreement about theoretical disciplinary knowledge, and approaches to typical problems in the disciplines (Smit, 2012). "Hard" disciplines have a high degree of paradigmaticity, which is lacking in the "soft" disciplines⁶. Biglan furthermore uses the "pure-applied" dimension to contrast disciplines such as agriculture, education and engineering and their concern for application, with disciplines such as chemistry and English, where application of the knowledge is less relevant. The third dimension (a concern with life systems) is not relevant to the current study, but the

⁶ Muller (2009) points out that the terms "hard" and "soft" were used by Bertrand Russell (1914) (hard and soft data), and also by Storer (1967) (the extent of the use of mathematics), and Price (1970) (citation patterns), before Biglan.

other two dimensions have enabled scholars to develop two sets of binaries to describe disciplinary areas: “hard/soft” and “pure/applied”. The natural sciences (for example physics and chemistry) are accordingly considered typical examples of hard-pure disciplines, with the humanities like languages and history typified as soft-pure. The science-based professions like engineering and medicine are examples of hard-applied disciplines, and education could be considered a soft-applied discipline. Biglan (1973) ventures in his article to suggest that his work might provide a framework for studying different “cognitive styles” (p. 202) of academic fields.

In a paper that traces the historical roots of the current academic disciplines, Muller (2009) shows how the seeds of the hard/soft and pure/applied binaries were already present in the medieval university. He describes two “fault lines” (p. 206), which, although they fluctuated in prominence over the course of history, are still influential to this day. The first fault line that influenced the organisation of knowledge in the medieval university was the distinction between the “liberal” and the “mechanical” or “useful” arts (p. 206). As discussed in chapter one, the medieval university was strongly biased towards the seven “liberal arts” -- the seven “mechanical arts” were not taught in the university. We see here the early roots of the pure/applied distinction proposed by Biglan. The second fault line formed along a division within the “liberal arts”: the Trivium (grammar, logic and rhetoric) and the Quadrivium (arithmetic, astronomy, geometry and music), with the Trivium given unqualified primacy. The Trivium/Quadrivium division eventually gave rise to the distinction between the humanities and sciences, or Biglan’s soft/hard binary.

A number of sociologists (Becher, 1989, 1994; Becher & Trowler, 2001; Kolb, 1981) have built on the work done by Biglan in their studies on the significance of disciplinary difference. Kolb focuses on approaches to intellectual enquiry, and he uses different terminology to end up with similar binaries: abstract/concrete and reflective/active instead of hard/soft and pure/applied. In his elaboration on Biglan’s thinking, Becher (1994) includes work on what he calls the cognitive and cultural style of the disciplines. He describes the cognitive style of those that work in hard-applied disciplines like engineering as “purposive; pragmatic (know-how via hard knowledge); concerned with mastery of the physical environment; resulting in products/techniques” (p. 154). By contrast the cognitive style in the sciences (hard-pure disciplines) is described as “cumulative; atomistic (crystalline/tree-like); concerned with universals, quantities, simplification; resulting in discovery/explanation” (p. 154). Responding to this description, Trowler (2009) warns against an essentialist position that implies a static view of disciplines with a near causal link between the nature of the disciplines and the behaviour of the academic members of the ‘tribe’. Instead, in a later paper (2014), Trowler uses

the Wittgensteinian idea of family resemblance to make the case for a more nuanced moderate form of essentialism in order to still be able to comment meaningfully on substantive differences between disciplines.

From the discussion above, one can see that various attempts have been made to characterise differences between disciplines. It seems possible to make a preliminary argument for a distinction between the disciplinary fields of science and engineering. In the terms suggested by Biglan, the distinction would be between the hard-pure and hard-applied disciplinary fields. One difficulty here is that the concepts allow for little differentiation beyond the binary distinction of 'pure' and 'applied', or some variation of this. In addition, as discussed in this set of scholarly literature, there is no clear agreement on which aspects of the disciplines to consider – researchers have looked at a range of disciplinary traits. As the particular interest in this thesis is the epistemic properties of disciplinary knowledge, I next turn my attention to the specifics of the sociology of knowledge.

2.2 A sociology of knowledge

The thesis focuses on the valued disciplinary knowledge base that undergraduate students are inducted into. Before I take a look at the work of specific sociologists on knowledge, their understanding of disciplinarity at a general level, and how this speaks to the work done in this thesis, I need to situate the work in a broader conversation.

2.2.1 The knowledge-blindness argument and the social realist response

It may seem like stating the obvious, but knowledge is central to education as a social practice: the production of new knowledge, its recontextualising into curriculum, and the teaching and learning that takes place in classrooms, are what constitutes education. Knowledge 'matters', in particular theoretical knowledge, because, as Durkheim explains, it enables people to connect ideas that seem unrelated on the face of it, and also to "project beyond the present to possible futures" not yet experienced (Young, 2008, p. 42). For this reason, access to theoretical knowledge is an issue of distributional justice (Bernstein, 2000), as it allows students to participate in "society's conversation about itself" (Wheelahan, 2012, p. 2) .

Current dominant models of curriculum develop from particular theories of society and of knowledge. For more than a decade now, an increasing number of sociologists have argued that that there is a knowledge-blindness in many approaches to education (Maton & Moore, 2010a; Moore & Muller, 1999; Moore & Young, 2001; Muller, 2000, 2009; Shay, 2012; Wheelahan, 2012; Young, 2008). In essence, the argument is that social theories like social constructivism,

instrumentalism and conservatism, subordinate knowledge to different agendas of power, social practice and relevance (Muller, 2000; Wheelahan, 2012), and that this subordination has implications for policy and curriculum. Some of the consequences of a knowledge-blindness are curricula that emphasise competencies and skills or learning outcomes at the expense of knowledge (Allais, 2012; Muller & Young, 2014); integrated market-driven curricula at the expense of differentiation of knowledge, and vocational training⁷ that blocks student access to powerful knowledge to contribute to the important debates in society (Wheelahan, 2007). Social and critical realists have responded to the de-emphasis of knowledge in the curriculum by asserting that knowledge is *real* (knowledge is about something other than itself – *ontological realism*: an independently existing reality), emergent from, but not reducible to the context from whence it came (Young & Muller, 2010), that it is *fallible* and open to revision over time and contexts (*epistemological relativism*), and that it is possible to choose between competing theories for their correspondence to reality (*judgemental rationality*). It is a call for reclaiming and bringing knowledge back into curriculum (Muller, 2000, 2014; Young, 2008), and a reminder of why knowledge matters (Wheelahan, 2012).

It is in this context that the thesis takes as its focus differences in the nature of disciplinary knowledge as it appears in curricula: knowledge matters, and distinctions between disciplinary fields potentially affect curricula.

2.2.2 Bernstein and the sociology of knowledge

A crucial contribution to the sociology of education and the sociology of knowledge has been made in the work of British sociologist Basil Bernstein, described as “one of the most inventive modern thinkers in the social sciences and as amongst the most inventive in British sociology” (Moore, 2013, p. 1). During his life, Bernstein explored what Hasan (2005) describes as “*the fundamental theoretical question of classical sociology*” (p.22): “how does the outside become the inside and how does the inside reveal itself and shape the outside” (Bernstein, 1987, p. 563, as quoted by Hasan (2005), p. 22). Theorising the pedagogic process whereby powerful theoretical knowledge becomes accessible to the student (the ‘outside’ becoming the ‘inside’) was central in Bernstein’s thinking. According to Moore, one of Bernstein’s most important contributions is the way in which he understood and theorised pedagogy as having intrinsic power to interrupt the dominant reproduction of society, shaping and changing the ‘outside’. Bernstein developed a range of theoretical concepts that have been productively used by scholars in the fields of knowledge and the curriculum. Moore describes Bernstein’s theoretical

⁷ Scholars argue that much of vocational education is characterised by an emphasis on skills-based competency that displaces a strong disciplinary knowledge base, in effect stripping the vocational curriculum of powerful knowledge (Allais, 2014; Muller, 2000, 2014; Wheelahan, 2012; Young, 2008).

work and problem field as a “problematic” (p. 4): for Bernstein the problem came before the approach, and he rejected the possibility that any single theory could be comprehensive enough to deal with complex reality. In this section I will focus on concepts from the Bernsteinian problematic most relevant to this study.

One of the most fundamental distinctions Bernstein made was between two basic types of knowledge: horizontal discourse and vertical discourse. Horizontal discourse is everyday common-sense knowledge; it is often oral and context-dependent, and is acquired in informal settings. Bernstein also used the terms “profane” and “mundane” when referring to this type of knowledge. He described it as “segmentally organised”, with different parts varying in importance in different situations (2000, p. 157). More important for the current study, is vertical discourse (also variously called “sacred” or “esoteric” knowledge), which has “a coherent, explicit and systematically principled structure” (p.157). Vertical discourse is acquired in formal education situations and is the “powerful knowledge” (Young, 2013; Young & Muller, 2010) that allows students to form opinions about societal issues, judge competing claims in debates about contentious concerns (Wheelahan, 2012), and grow in ability to project beyond the immediately apparent. Muller (2012) describes horizontal and vertical discourses as respectively *functional* and *conceptual* in their integration: concepts in horizontal discourse are related at a practical, everyday level (“tied to empirical particulars” according to Muller (2007, p. 66)), whereas concepts in vertical discourse are integrated at the level of meaning.

Bernstein described two forms of vertical discourse. The first, horizontal knowledge structures, are sets of specialised ‘languages’ typical of the humanities and social sciences. The second, hierarchical knowledge structures, are typical of the sciences in the way knowledge grows: Bernstein used the symbol of a triangle to illustrate how multitudes of empirical instances (at the base of the triangle), general propositions and theories are integrated and subsumed in fewer, ever more abstract principles as the knowledge progresses. Bernstein saw physics as the ultimate hierarchical knowledge structure, but would describe both the science and engineering science knowledge under consideration in this thesis, as examples of vertical discourses with knowledge organised in a hierarchical way.

One of the most important concepts in understanding the work done by Bernstein, and one that has bearing on the work done in this thesis is that of *classification*. He explained that classification refers to relationships *between* categories, rather than to essential characteristics of categories. Bernstein could be called a sociologist of the boundary, and *classification* is a concept he developed to refer to the strength of boundary insulation between categories, and applied to the creation and maintenance of boundaries, and the relative strength of boundaries

(Bernstein, 1981, 2000). In the Bernsteinian context, boundaries can refer to a wide range of situations and relations, such as the boundary between everyday life and formal schooling, between different subject fields, between education and the world of work, between roles in society. As a sociologist Bernstein was interested in the way power functions in society, and “dominant power relations establish boundaries, that is, relationships between boundaries” (Bernstein, 2000, p. 6). He maintained that the true nature of something is understood in its separation from other things: “it is the insulation between the categories of discourse which maintains the principles of their social division of labour” (p. 6). For Bernstein, classification is the fundamental principle regulating the social division of labour (Bernstein, 1981), as well as the specialisation implied when recognising disciplines.

Classification plays an important role in understanding *regions* and *singulars*, two concepts Bernstein developed to distinguish between different types of disciplinary knowledge. *Singulars* are subject fields characterised by strong boundary maintenance and therefore strong classification. Singulars develop strong *introjected* identities (or, as Bernstein put it, their “discourses” (2000, p. 9) tend to only refer to themselves) and have strong “specialised rules of internal relations” (p.7). Kuhn would have described singulars as having a high paradigmaticity: they agree on what constitutes an appropriate problem in the discipline and ways to approach problem-solving. Bernstein called the singulars “narcissistic” (2000, p. 52). Consider this description by Kuhn, as quoted by Radder (2009b, p. 74) for another perspective on what is valued in the science singulars:

For a scientist, the solution of a difficult concept or instrumental puzzle is a principal goal. His success in that endeavour is rewarded through recognition by other members of his professional group and by them alone. The practical merit of his solution is at best a secondary value, and the approval outside the specialist group is a negative value or none at all. (Kuhn, 1970, p. 21)

Singulars’ identities therefore also impact on the development of a “specialised disposition” and conduct with regard to disciplinary matters (Muller & Young, 2014, p. 131). Bernstein mentioned physics and chemistry (also sociology and psychology) as examples. He described singulars as the disciplinary fields that create the field of production of knowledge (see the discussion of the pedagogic device later in this section).

Regions, on the other hand, are created by the ‘recontextualisation’ or transformation of knowledge from singulars, and also from other regions as pointed out by Young and Muller (2014). As a result, regions have weaker classification, because they are “the interface between the field of the production of knowledge and any field of practice” (Bernstein, 2000, p. 9).

Bernstein described the fields of engineering, medicine, architecture and information science as examples of fields where regionalisation has taken place⁸. He described regionalisation as “a very good index of the technologising of knowledge” (p.9), and regions as having two orientations: one towards the singulars, and another “towards external fields of practice” (p. 55). Bernstein believed that regions are formed when singulars are recontextualised into larger units, and he saw a proliferation of regions in what was offered by the newer universities. These regions are responsive to market forces to a greater degree than the singulars, and regions’ identities are formed by *projection* of the knowledge towards an external field of practice. Bernstein did not explore the notion of the field of practice in any detail, and it remains an area for investigation and theorisation. The process by which knowledge is regionalised has not been explained by Bernstein, and this too remains an area to be developed. It is not clear, for example, whether conceptualising degrees of variation in regionality and ‘singular-ness’ is sensible – are all regions of a kind? Is the classification strength of all singulars similar?

There is one more theoretical construct from Bernstein’s work that has direct bearing on the work done in this thesis, and this is his notion of the pedagogic device (Bernstein, 2000). An important question for Bernstein was how to explain how society goes about circulating its various forms of knowledge, and how this works to specialise a specific consciousness (Maton & Muller, 2007). The pedagogic device controls “who gets what and how” in pedagogic interactions (Moore, 2013, p. 154), and describes how the “discipline-specific expert knowledge” gets transformed into “school knowledge” (Singh, 2002, p. 572). Three sets of inter-related and hierarchical rules govern the ordering of the access, transmission and acquisition of knowledge: *distributive rules* govern the regulation and distribution of the valued store of society’s knowledge, *recontextualising rules* regulate the selection, delocation and relocation of knowledge from this canon of valuable knowledge for the purpose of curriculum development or pedagogic discourse, and *evaluative rules* clarify the criteria for successful acquisition of the knowledge or legitimate texts, and the specialised consciousness to be attained. Each of the sets of rules is associated with a field: first, the distributive rules with the *field of production* of new knowledge, the “unthinkable”, or the “yet-to-be-thought” (Bernstein, 2000, pp. 29,30), and the canon of tested and accepted disciplinary knowledge; second, the recontextualising rules with the *field of recontextualisation* where appropriate knowledge from the field of production is selected and recontextualised for the purposes of educational transmission to students, and third, the evaluative rules with the *field of reproduction* where the teaching, learning and

⁸ One difficulty posed by Bernstein’s examples of singulars and regions as they relate to this project, is that of category comparison: the subject fields of chemistry and physics as examples of singular disciplines are not at the same category level as his example of engineering as a region – engineering is a broad and diverse field, comprising many distinct disciplines like civil, chemical, electrical and mechanical engineering, to name but a few.

assessment of learning take place. Bernstein pointed out that the pedagogic device forms an “arena for struggle” (Bernstein, 1990, p. 206) and acts as “the ruler of consciousness” (Bernstein, 2000, p. 28) for the production and reproduction of culture (Bernstein, 1990). Ashwin (2009) emphasises the fact that the struggle takes place at all levels of the device: the rules for distribution of powerful knowledge are contested, the recontextualising rules for selecting, pacing and ordering of knowledge in curriculum depend on the dominant voices (institution, academics, professional bodies and government agencies) and, in the reproduction rules, a site for struggle can be discerned in what kind of knowledge is valued (legitimate text) as evidenced in the evaluation practices.

One important consequence flowing from the pedagogic device is that it makes it possible to distinguish between knowledge as it appears at different levels of the pedagogic device: physics knowledge in the curriculum is not the same as the knowledge produced by physics researchers. It has been recontextualised (appropriate knowledge has been selected from the canon, delocalised and relocalised in curricular form as it is presented at an appropriate level and pace, in a sensible sequence). Analytically this becomes an important distinction to make, and raises questions about the nature of the relationship between, for example, the field of production of knowledge and the field of recontextualised curriculum knowledge. Bernstein expresses a strong opinion: “As physics is appropriated by the recontextualising agents, the results cannot formally be derived from the logic of that discourse” (Bernstein, 2000, p. 34), and also that “[p]edagogic discourse can never be identified with any of the discourses it has recontextualised” (Bernstein, 2000, p. 33).

However, some scholars suggest that the connection between the fields of production and recontextualisation may be stronger than Bernstein allows for. A complete disconnect between the canon of disciplinary knowledge and the curriculum seems unlikely if curriculum is the means whereby students are inducted into the disciplines: “... if recontextualisation totally severs any relation, then how are specialised knowledges ever reproduced?” (Muller, 2007, p. 80). Muller asks the question whether the internal features of a knowledge structure place epistemological constraints on the type curriculum that can be developed from it. He suggests that there are (and should indeed be) limits on the form a curriculum can take as a result of the field of production it was recontextualised from. Muller points out that Bernstein’s comment above was made to illustrate a different point: that the regulative discourse of the local social order always takes priority over the instructional discourse of the particular pedagogic practice. A government (the regulative) can, for example, prescribe that all education (instructional) has to be ‘outcomes-based’, irrespective of the discipline. However, Muller believes that Bernstein changed his position in the course of his career to emphasise later a “specialization of

consciousness continuum" (2007, p. 80) across the fields of the pedagogic device. This specialisation of consciousness continuum (from the field of production to the field of reproduction via the field of recontextualisation) better reflects the coherence of Bernstein's theorisation of how the "outside becomes the inside". Muller points out that it would be hard to argue for any reproduction of a specialised discourse if the curriculum that would serve to induct students into the specialised discourse was completely disconnected from the logic of the disciplinary knowledge structure (see also Muller (2009), p.215, and the discussion below under conceptuality and contextuality). It is also important to keep in mind that much of Bernstein's thinking and theorising was done with the school curriculum in mind. The current study is situated at the level of an undergraduate university curriculum, which could be conceived of as considerably closer to the field of production than a school curriculum. In addition to this strong proximal relationship with the canonical disciplinary knowledge, in the tertiary education space the recontextualising agents (curriculum developers) are often the same people working as knowledge producers in the field of production.

However, much of this remains conjecture at present, and little empirical work has been done to investigate the link between the fields of production and recontextualisation at the level of higher education. The possibility and nature of a closer connection between the fields of production and recontextualisation than suggested by Bernstein is one of the aspects explored in the work described in this thesis.

So where does Bernstein's problematic intersect with the work done in this thesis on the nature of disciplinary difference between engineering science and science knowledge as presented in the curriculum? It locates the main focus of the thesis on hierarchical knowledge structures within vertical discourses. By itself, this does not assist the research done here, since both kinds of disciplinary knowledge fall in the same categories. Regions and singulars seem relevant concepts for the purposes of contrasting engineering and science knowledge. However, the constructs came late in the chronology of Bernstein's theory development, and as such are less developed. According to Beck and Young (2005), Bernstein's analysis of regionalisation is "partial and incomplete" (p. 189). The terms "are more suggestive than they are explanatory", as described by Muller (2007, p. 65) in a slightly different context. The role of classification of the boundaries separating disciplinary fields is potentially important, but just what weakened classification of a region would look like in empirical work is unclear, and needs elaboration. This is more pertinent when dealing with empirical data from disciplinary fields that are as closely related as science and engineering science.

Bernstein's notion of the pedagogic device analytically separates curriculum knowledge from disciplinary 'research' knowledge. The data for the project described in the thesis is curriculum data (see a more detailed discussion in the methodology chapter following here), and therefore part of the field of recontextualisation. By considering a research design that embeds disciplinary epistemic characteristics in the analytical framework, it becomes feasible to explore the possibility of traces of disciplinarity in the empirical data. Furthermore, the influence of the profession in Bernstein's notion of the field of practice seems potentially useful when considering engineering science knowledge, but again the notion is evocative rather than fully formed.

On the whole, Bernstein's problematic is therefore more suggestive than instrumental as an approach to the problem considered in this thesis. For this reason, I next turn my attention to the range of scholars who has been working in the Bernsteinian tradition, applying and developing his theoretical ideas further.

2.2.3 The work of scholars extending Bernstein's problematic

The work of Basil Bernstein has been applied in a large number of empirical studies over the past four decades – see for example empirical work discussed in Atkinson, Delamont & Davies (1995), Bernstein (2000), Morais, Neves, Davies & Daniels (2001), Muller, Davies & Morias (2004), Moore, Arnot, Beck & Daniels (2006), Christie & Martins (2007), Vitale & Exley (2016).

My focus in this section, however, will be on those Bernsteinian scholars who have been working at the theoretical edge, elaborating on and extending Bernstein's problematic. In this I will be concentrating on developments that come closest to the work done in this thesis, dealing with curriculum knowledge (in the field of recontextualisation), but also looking at the relation curriculum knowledge bears to disciplinary knowledge in the field of production as the origin of the recontextualised curriculum.

I consider first the field of knowledge production, where Bernstein used the notion of "grammar" (1999, 2000) to refer to the ability of horizontal knowledge structures to develop "relatively' precise empirical relations" (1999, p. 164) with the external world. However, this theoretical development was not done in a consistent way (O'Halloran, 2007). An example is Bernstein's description of mathematics as the horizontal knowledge structure with the strongest grammar, but with no empirical relations to the external world. Muller (2007) argues that Bernstein is using "grammar" to refer to an *internal* (rather than an external) feature of knowledge structures that constrains its tendency to proliferate languages or parallel theories.

Muller (2007) develops the notions of “*grammaticality*” and “*verticality*” to extend and refine Bernstein’s ideas of how a theory (or knowledge structure) grows. *Verticality* speaks to “the capacity of a theory or language to progress integratively through explanatory sophistication” (p.71). This is a further description of the typical way hierarchical knowledge develops in its ability to subsume and integrate knowledge at less general levels (See Bernstein’s (2000) metaphor of the triangle). Whereas horizontal knowledge structures will exhibit some verticality within segments, the overall verticality is weaker because of the tendency of these knowledge structures to proliferate languages rather than to subsume them. Horizontal knowledge structures therefore progress by introducing new incommensurate languages that give fresh perspectives on issues. *Grammaticality* of knowledge structures refers to “the capacity of a theory or a language to progress through worldly corroboration” (Muller, 2007, p. 71). It speaks to how theory engages with the world, with how emphatically it is able to identify empirical referents. Hierarchical knowledge structures deal with competing theories differently from horizontal knowledge structures, because their strong grammaticality makes it possible to settle disputes empirically. This is not an option for typical horizontal knowledge structures, where competing incommensurate theories tend to remain sitting next to each other, growing the structures primarily horizontally. Muller’s contribution here is to use grammaticality and verticality *together* to describe the ability of *both* hierarchical and horizontal knowledge structures to progress and develop in the field of production.

A large amount of scholarly work has been done at the level of the curriculum, or the field of recontextualisation, to use Bernstein’s term from the pedagogic device. One of the interests in this study is the relationship between knowledge practices in the fields of production and recontextualisation. Further to Muller’s conviction that the form of the knowledge structure constrains the type of curriculum that can and should be developed from it, he develops the notions of conceptual and contextual coherence of curricula (Muller, 2009). He argues that “*conceptuality*” describes a quality analogous to verticality for curriculum coherence, and “*contextuality*” a curriculum quality analogous to grammaticality. Muller broadly links conceptuality to verticality along Biglan’s hard / soft binary, and contextuality to the pure / applied binary, and so it becomes possible to identify a particular curriculum with an *overall logic* of either conceptual or contextual coherence. According to Muller, curricula in regions tend to favour *contextual coherence*, or “contextual adequacy” (2009, p. 216), and those in “hard” singulars *conceptual coherence*, or “adequacy to truth (logic)” (p. 216). Crucial here is the point that the fundamental features of the disciplinary knowledge structure constrain the type of curriculum recontextualisation. The curriculum logic has to reflect the integrity of the knowledge structure, and this is particularly important for curricula developed from disciplines

with a “vertical spine” (Muller, 2009, p. 219) if students are to avoid fundamental gaps in their knowledge, and master cumulative knowledge.

Muller visualises contextuality and conceptuality to apply along a continuum, and acknowledges that the continuum is complex. This is borne out by empirical work done by people like Suellen Shay and others (Shay, 2012; Shay, Oosthuizen, Paxton, & van der Merwe, 2011) which attempts to account for conceptual aspects present mostly in curricula with largely *contextual* coherence. This extends ways to think about curriculum: “Curricula are thus not *either* conceptually-coherent *or* contextually-coherent but they can be both or neither” (Shay, 2016, p. 773) .

A further attempt at capturing the complexity of the nature of curricula is made in the next ‘generation’ of the development of Bernsteinian concepts. These sets of concepts are useful for the description of a continuum (rather than binary) of curriculum expression, and results in topologies (rather than typologies) of curricula (Shay, 2012). This is found in the work done by Karl Maton (2013, 2014; 2010b) in his development of Legitimation Code Theory (LCT), which he calls “a conceptual toolkit and analytic methodology” (2014, p. 15). Maton developed a set of legitimation codes or dimensions to explore knowledge and curricula. In the context of this thesis, however, I will here refer to only one of these, namely Semantics, since it approaches aspects of the work explored in the thesis. Semantics consists of two sets of code modalities, semantic gravity (SG) and semantic density (SD). Each of these can vary in strength: SG+, SG-, SD+ and SD-. Semantic gravity refers to “the degree to which meaning relates to its context” (Maton, 2014, p. 110), and it varies along a continuum. Stronger semantic gravity (SG+) refers to a close relation between a concept and its “social or symbolic context of acquisition or use” (p.110). When semantic gravity is weaker (SG-), meaning depends less on context. Maton also uses the terms to talk about pedagogic processes: when there is a move from abstract ideas towards more concrete ones, semantic gravity is strengthened. Moving from concrete particulars to abstractions, is a process of weakening semantic gravity. Maton emphasises that the code modalities apply to all three fields of the pedagogic device, and goes on to explain that in the field of reproduction, conceptualising learning in terms of semantic gravity may mean that students need to develop “the capacity to *master* semantic gravity, in order for knowledge to be decontextualized, transferred and recontextualised into new contexts” (Maton, 2014, p. 110, emphasis added) as a condition for cumulative learning. The notion of semantic gravity is therefore also used in the context of critiquing skills-based, context-bound vocational knowledge to emphasise that powerful knowledge is knowledge that transcends context and can be abstracted to different settings. Here the argument is that stronger semantic gravity needs to be surmounted by weakening the semantic gravity in order to avoid segmented learning.

Maton re-conceptualises the notion of conceptuality as semantic density (SD) which “refers to the degree of condensation of meaning within socio-cultural practices (symbols, terms, concepts, phrases, expressions, gestures, clothing, etc.)” (Maton, 2014, p. 129). The stronger the semantic density (SD+), the more meaning is condensed within practices, and the opposite for weaker semantic density (SD-). Strengthening and weakening the semantic density involves processes of ‘condensing’ or ‘unpacking’ meaning, usually in the context of pedagogic practice.

Maton (2014) develops a “semantic plane” by combining semantic density and semantic gravity along perpendicular axes. As a result, four code quadrants are created that have been used productively by researchers to topologically investigate theoretical ideas, practices, curricula, resulting in semantic profiles and ranges that give insight into practices. Maton believes that semantics extends Bernstein’s theoretical ideas, since these can now be used to describe both internal and external relations.

There are two difficulties with using semantic gravity and density as the conceptual framework for the work done in this thesis. The first is the close proximity of the intellectual fields of science and engineering science. Both make extensive use of *the same technical terms* from thermodynamics, packed with meaning (stronger semantic density). In addition, mathematics (a language with high semantic density) is used in similar ways across the disciplines. It is therefore difficult to see how semantic density will allow for significant distinctions to be made between science and engineering science. Semantic gravity at first glance seems more promising: some will argue that engineering is the application of science, and therefore has stronger semantic gravity. However, the notion of engineering as applied science is not uncontested (see the discussion later in this chapter). Furthermore, ‘context’ as a concept has had to be interrogated in the theoretical work done in this thesis. Both science and engineering present knowledge in contexts, different contexts to be sure, but still rooted in contexts (the laboratory in the case of the sciences and the real-world problem context of the engineering sciences). There is a temptation to assign stronger semantic gravity to engineering science’s ‘real world’ context when compared to the controlled environment of the sciences. However, a counter argument can be made that *both* disciplinary fields have strong empirical referents in the ‘real’ world by which knowledge claims are validated (indeed, this is the hallmark of *all* hierarchical knowledge structures). The importance of empirical work in science ensures that knowledge in the sciences always has a contextual association, and technical knowledge in the professions will, by definition, have a contextual angle. The variation in strength of semantic gravity between science and engineering science may therefore be quite limited. Approaching semantic gravity from a different angle, it would be difficult to defend a claim that the professional environment of the scientist is less real or concrete than that of the engineer.

Secondly, the notion of semantic gravity has, in part at least, been developed to address a particular knowledge problem in education, the “spectre of segmentalism” (Maton, 2014, p. 106). Segmented learning results in an inability to transfer knowledge to contexts beyond the one in which the knowledge has been encountered. Maton (2014) describes this as an inability to decontextualize, transfer and recontextualise knowledge in a new context. Empirical studies using LCT often document how semantic gravity needs to be mastered in education to ensure cumulative learning (Blackie, 2014; Macnaught, Maton, Martin, & Matruglio, 2013; Matruglio, Maton, & Martin, 2013). Semantic gravity therefore presents a helpful way of conceiving of pedagogic practice where the teacher makes use of ‘semantic waves’ (Maton, 2013) to ‘unpack’ complex concepts by strengthening semantic gravity, followed by abstracting the knowledge to increase transferability across contexts (weakening semantic gravity). However, the focus of the thesis is not pedagogy, but the nature of the curriculum knowledge. Semantic density and gravity may therefore not be discriminative or granular enough to allow for distinction between engineering science and science knowledge structures in curricula.

2.2.4 Knowledge in the professions

As discussed in section 2.2.2, Bernstein pointed us in the direction of one of the differences between the disciplinary knowledge structures of interest in the thesis, namely the influence of the field of practice on the orientation of regional knowledge. While this concept was not developed further by Bernstein, there is a body of literature in the sociology of work in which the professions feature quite prominently (Abbott, 1993). In spite of this, Young and Muller (2014) call the sociology of the professions “a frustratingly under-specified area” (p.3). In particular, the (growing) range of professions and occupations makes it difficult to develop demarcation criteria to distinguish between professions and occupations. One important aspect of the difference between occupations and professions seems to be an awareness of the internal normative commitments and responsibilities displayed by professions (Grace, 2014; Sciulli, 2005), if they are to be more than mere “functional technical experts” (Grace, 2014, p. 27). Bernstein also seems to have had this in mind when he explained how inwardness and commitment shaped the way the outer world is engaged with. It is with this in mind that he remarked “we can find the origins of the professions” (Bernstein, 2000, p. 85, as argued in Beck & Young (2005)). Demarcation and definition of professions, however, are not the foci of this thesis, and although I return to the idea of normativity later, it is in the context of *knowledge* rather than professionalism.

Professional judgement, assessment of risk, specific skills and competencies, expertise – these are all aspects of what is understood to be professional practice. All of this takes place within

what has been called the 'knowledge economy', where there is a greater dependence in advanced economies on knowledge, information and knowledge-based skills than on production. In this economy, the role of the professional is crucial, because of the accelerated pace at which new technical and scientific advances are made, as well as the rapid rate of obsolescence of 'older' knowledge (Powell & Snellman, 2004). In spite of this, sociology has neglected "*knowledge itself*, and above all the sociological study of professional knowledge, goes virtually unremarked" (Young & Muller, 2014, p. 5, emphasis in the original). Young and Muller point out that this neglect has had an impact on discussions around the purposes of higher education and, especially on debates around what the focus of curricula should be at all levels of education. There is therefore a call for scholarly attention to all aspects of professional knowledge. Different contributions have been made to the conversations about what constitutes 'knowledge' and what 'expertise' (see chapters by Winch and Kotzee in Young & Muller (2014), also Winch (2010) and a seminal work by Ryle (1945) on 'knowing that' and 'knowing how'), but this falls outside the scope of this thesis, and no further attention will be paid to these aspects⁹.

Young and Muller (2014) suggest a case for considering two kinds of professional knowledge: theoretical knowledge "specialised to conceptual generality" and practical or for-purpose knowledge "specialised to a contextual purpose" (p.8), and that these speak to their respective "epistemic destinies" (p.9). However, they believe that the two types are embedded in professional knowledge making it problematic to conceive of distinctive components; they describe it as "the irreversible twist in the braid of contemporary specialised knowledges" (p.9). Not everyone would agree with the notion of specialisation to conceptual and contextual purposes as set out above: see the discussion later in this chapter on the truth-vs-usefulness debate.

2.2.5 Concluding remarks on the sociology of knowledge

The preceding sections give an overview of the analytical concepts from the sociology of Bernstein and the Bernsteinian scholars that have bearing on the project described in this thesis, namely a comparison of the epistemic properties of engineering science knowledge with science knowledge. This is approached from the field of recontextualisation with data gleaned from the curriculum used to induct students into specialised knowledge in the sciences and engineering sciences.

⁹ There is a case to be made for the argument that the *use* of professional knowledge requires a specialised 'knowing how' or procedural knowledge, as is perhaps the case in the use of property tables and graphs in engineering thermodynamics. See section 4.7 later.

The Bernsteinian concepts and those that have been developed adjacently by others working in the Bernsteinian tradition provide useful ways to orient the current project in the broader context of the sociology of knowledge. However, there are considerable difficulties with using the concepts as analytical tools for this research project, and these relate to the nature of the present project. The research discussed in the thesis requires the comparison of two closely related disciplinary fields. There can be little doubt about the reciprocal relationship between science and engineering: one (perhaps oversimplified) way to look at it is to refer to the way engineering draws upon scientific principles and laws, and in return the way in which scientific progress relies on the contribution of engineering in the development of equipment, but also in the cross-fertilization of parallel research fields. Knowledge in engineering has various components such as design knowledge (Cross, 1982), procedural knowledge and knowledge that recognises the societal responsibilities in the ethical, economical and legislative aspects of engineering (Meijers, 2009; Rogers, 1983). There are also technological explanations (Kroes, 2009), codified knowledge and rule-of-thumb heuristics that arguably represent different knowledge types (Figueiredo, 2008). However, nowhere does science and engineering knowledge exist in closer proximity than in the concepts of engineering science knowledge (Houkes, 2009). The study therefore requires a detailed fine-grained analysis of concepts from four closely related disciplinary fields. Early on in the research process, it became clear that there would be nuances and subtleties in the data that the binaries of the sociology theories would not extend to. Despite advancing propositions of continua, the notions of conceptuality, contextuality, semantic density and gravity are most compelling when applied to quite distinct empirical quantities. Attempts to use these concepts to apply to the data in this study resulted in the coding of the data collapsing into the binaries of 'weaker' and 'stronger', and once strength or weakness had been identified, the scope of the analytical process was exhausted.

Despite the contiguity of the science and engineering science knowledge structures, there was a richness of variation in the data that had to be accounted for, and therefore a need for an analytical instrument better able to capture a more nuanced view of the data.

It is important to point out that 'going outside' the Bernsteinian ambit for appropriate theoretical concepts is in keeping with the way Bernstein himself approached theory. Hasan & Webster (2005) describes Bernstein's problematic as an "exotropic theory... [that is] inherently relational: its problematic is at the centre of different kinds of processes and there thus exists a greater chance for reciprocal engagement amongst them" (p. 52). Rob Moore (2013), in his book *Basil Bernstein: the thinker and his field*, points out that Bernstein did not have a *comprehensive theory* in the conventional sense; Bernstein himself made it clear on several occasions that the problem, rather than a particular perspective, needed to take precedent: "...less an allegiance to

an approach, and more a dedication to a problem” (Bernstein, 1977, p. 171). According to Moore (2013), Bernstein’s concern was with how “a theory should be put to *work*. The concern is with where theory *goes to* in terms of explanations, not where it supposedly comes from in terms of its social base (standpoint)” (p. 90, emphasis in the original). Moore emphasises:

Theories, ‘isms’, are raided for resources that can be mobilized to tackle a problem and it is the problem that comes first. Bernstein always insisted (especially to his students) that having the right question was more important than having the right approach... Reality is always bigger than any theory. (p.95)

It is in this context that I had to turn elsewhere for discriminative theoretical concepts. Concepts that would be able to distinguish between knowledge in science and engineering science would have to be able to speak to the *nature and disposition* of the disciplines. It therefore made sense to look towards the philosophy of science and engineering science for this.

2.3 Applied philosophy of technology and engineering

The purpose of this section is to consider some of the contemporary issues in the philosophy of technology and engineering that have bearing on the project described in this thesis. I start the discussion with a clarification of some of the terms. This is followed by a consideration of teleological issues, and finally I review literature on two concepts, idealisation and normativity, that speak more directly to the problem investigated here.

The philosophy of engineering has been largely neglected in scholarly work: Meijers (2009) suggests a brief search of the Philosopher’s Index (described as the world’s most current and comprehensive database on scholarly philosophical articles) shows as much. A cursory word search, covering the database spanning 1940 – 2013, yields 54 588 entries for the keyword ‘science’. The keywords ‘engineering’ and ‘technology’ only produce 556 and 4862 entries respectively. Goldman (2004) argues that one of the reasons for this neglect can be found in the fact that engineering problem solving largely requires a contingency based form of reasoning (often involving context-sensitive value judgements) that has been largely neglected in favour of the necessity-based model of rationality employed in modern science that has dominated Western philosophy. Another reason can possibly be found in the historical development of science as discussed in the previous chapter: the empirical sciences developed from natural philosophy, and therefore can claim more of a philosophical tradition as part and parcel of the development of science from early on. Only relatively recently has related work been done in what can be called the philosophy of technology, often with reference to engineering. The

comprehensive 1453 page *Philosophy of Technology and Engineering Sciences* (Meijers, 2009) is therefore an important contribution to the field that I draw on in this discussion.

It is important to emphasise again that the focus of the current study is differences in disciplinary *knowledge* rather than general differences between disciplinary fields. However, in order to discuss these, it is important to get a general feel for broad differences. I return to the epistemological differences later in the chapter and in what follows in the study.

2.3.1 Terminology clarification: technology, engineering, engineering science

In order to be able to talk about differences between related ideas there has to be some agreement on the definitions of terms. This is not that easily achieved: Mitcham and Schatzberg (2009) point out that terms are contested, partly because the definitions have implications for relationships of the kind that are under consideration in the current study. Radder (2009a) does not believe that definitions of multidimensional concepts like science, engineering technology and engineering science can be a set of “necessary and sufficient conditions” (p.23), but should rather serve to identify “key features or typical patterns...[and] specify significant family resemblances”. This is the approach followed here.

The term ‘technology’ comes from the Greek word ‘*techne*’ which refers to craft or skill. According to Mitcham (1994), ancient Greek philosophers argued that every *techne* involved *logoi* (words or reason), and Aristotle saw it as a practice involving theoretical understanding (Parry, 2014). Later work links it more closely with physical activities of making or producing (as distinct from activities associated with politics and education). In the English-speaking world, the term ‘technology’ only became common after World War II. Mitcham and Schatzberg (2009) argue that term loosely referred to processes, objects and knowledge. They believe that both scientists and engineers at the time tended to regard technology as applied science. There were however differences in the hierarchy of the conceptualisations: scientists were more likely to see science as the ‘genus’ and application as the ‘species’ differentiation (in the Aristotelian use of the species-genus differentiation), whereas engineers thought about the mechanical or industrial arts as the ‘species’, and the science as the ‘genus’.

“Engineering” comes from the Latin word ‘*ingenera*’, which means to implant, generate or produce. During the Middle Ages this word was used to refer to the makers of military equipment and machines of war (Johnston, Gostelow & Jones, 1999; Meijers, 2009). From around the 17th century the term ‘civil engineering’ was used to describe non-military uses, such as bridges and roads. Meijers (2009) quotes Thomas Tredgold defining engineering for the

Royal Charter of Civil Engineers as early as 1828 as “the art of directing the great forces of power in nature for the use and convenience of man [*sic*]” (p.3). Johnston *et al.*(1999) endorse the (rather glowing) statement of intent proposed by the Institute of Professional Engineers of New Zealand (IPENZ): “Engineers will translate into action the dreams of humanity, traditional knowledge and the concepts of science to achieve sustainable management of the planet through the creative application of technology”(IPENZ, 1993, p. 9). Mitcham and Schatzberg (2009) call these types of descriptions “persuasive definitions” (p. 30). Common to these descriptions of engineering are the aspects of service to humankind, practice or application, and an understanding of context. I return to these claims in the discussion of purposefulness of engineering later in this chapter.

Most of those who distinguish between engineering and technology see engineering as a subset of technology. For instance, Radder (2009b) points out that the technological sciences include engineering science, information science, medical science and agricultural science. Rogers (1983) makes a further distinction. He believes that although engineering and technology intersect in terms of technical knowledge, there are areas where they do not overlap. In the case of technology, he suggests that some of the process industries such as food technology and paper-making cannot be considered true types of engineering knowledge. He typifies these as ‘know-how’ types of practical knowledge not yet disposed to theorising. In the case of engineering, he points out that engineers need knowledge of other disciplines like economics, accounting, law and organisational knowledge which lie outside the ambit of technology. He proceeds to focus on the technical knowledge of engineering that underpins technologies, claims that for these purposes there is very little difference between technology and engineering, and then uses the terms as synonyms in the rest of his book. The crucial point made is that engineering is a generative activity which produces not only artefacts, but also engineering science or technological knowledge. Mitcham and Schatzberg (2009) call engineering science the result of “a knowledge production activity internal to engineering” (p.42). For the rest of the work in this thesis I will be using the term ‘engineering science knowledge’ to refer to this particular type of knowledge.

2.3.2 Science vs engineering: primacy models

The rise of the engineering sciences after the industrial revolution (as discussed in the previous chapter) saw a shift towards a hierarchical view of the interaction between science and technology. Radder (2009b) describes how this led to a view of engineering science knowledge as “finalized science” (p. 74) with a temporal ordering where “science finds – industry applies” (p. 70). Radder (2009a) speaks of primacy models in which, initially, science dominated the

relationship, and technology (or engineering) was seen as merely applied science (See for instance the work of Bunge (1966)). Vannevar Bush's (1945) conviction that "basic science is the pacemaker of technological progress" (p.19) determined post-WWII science policy in the USA. His influential report to President Roosevelt resulted in the establishment of the National Science Foundation in 1950. This view of the science-technology relationship is also reflected in Biglan's (1973) classic characterisation of disciplines like engineering as 'applied' and others, like physics and chemistry as 'pure'.

The view of the primacy of scientific knowledge in the science-technology relation has lost ground since the late 1980s, and is no longer held seriously by philosophers of technology and engineering. Over the last 30 – 40 years, the previously-held hierarchical view of engineering knowledge as a derivation of science has been critiqued extensively, and most philosophers now insist that technology interacts with science on an equal footing (Adams, 1993; Barnes, 1982). See for instance also Staudenmaier's (1984) reference to "the unique and irreducible character of technological knowledge" (p. 716) and Koyré (1948) views technology as an independent system of thought, different from science, and the relationship between science and technology as a "subtle, indirect influence" (as described by Layton, 1974, p. 35). Layton himself (1971, 1974, 1976) argues from his position as historian of technology that there are numerous instances where it can be shown that engineering science knowledge developed independently from the sciences. This is supported by Vincenti (1990), who calls engineering "an autonomous body of knowledge, identifiably different from the scientific knowledge with which it interacts" (p.3).

There is also the secondary issue of 'cultural primacy', i.e. the status and significance assigned to the disciplinary fields in popular view. This too has changed over the past 30 years: "[t]o campaign today against ...[the primacy of science] is to throw oneself against a door that has been wide open for two decades ... technology has acquired, beginning about 1980, the cultural primacy that science had been enjoying" (Forman, 2007, p. 2). While there seems to be consensus that technology is no longer seen as applied science, not everyone agrees that technology now holds (cultural) primacy. Some, like Radder, (2009a) promote the notion of a two-way interactive approach where the disciplinary fields are seen as "independent, yet interacting entities" (p. 25). Channell (2009) goes even further with his suggestion of complete interdependence, whereby "the two areas form a symbiotic relationship so that the distinguishing characteristics of the two areas become blurred" in the notion of "technoscience", also promoted by scholars like Latour (1987) and Ihde (2004).

Ultimately the arguments around the primacy models or even the notion of technoscience are not productive as an approach to the research questions asked in this thesis. Primacy models keep the emphasis on relationships between broad disciplinary fields in these arguments, and leave the nature of the disciplinary knowledge largely unexplored. Houkes (2009), for example, critiques the STS (Science and Technology Studies) and technoscience scholars for not reflecting in a disciplined way on the nature of technical knowledge and developing “an empirically informed, up-to-date epistemology of technology” (p. 345). It is precisely into this gap that the work described in the thesis aims to make a contribution with its emphasis on the nature of similarities and differences in the disciplinary knowledge in science and engineering.

2.3.3 Engineering vs science: a conversation about goals

That there is a relation between science and engineering can hardly be questioned. It is the *nature* of this relationship that is of interest here. Historically, scholars have often limited the discussions to fairly naïve and obvious differences of how the aims of science and technology are perceived. The goals of science are said to be epistemic: the acquisition of knowledge. This is then contrasted with the goals of technology which are described broadly as the construction of things that society finds useful. Houkes (2009) calls this type of description of the aims of science and technology the “truth vs usefulness intuition” (p.312). An example of this can be seen in Roger’s (admittedly dichotomous) description of the difference: “A scientist looks at the world and tries to explain what he sees; and engineer looks at the world and tries to supply what he sees is missing” (Rogers, 1983, p. 3).

However, this oversimplified (and perhaps exaggerated) distinction does not do justice to the many rich and varied practices in science and engineering. There are, for example, problems with characterising science as an epistemic practice, or an “activity that systematically strives for theoretical and explanatory knowledge” (Radder, 2009b, p. 66), as this neglects the observational and experimental knowledge so often pursued in science. In addition there are philosophical concerns around the explanatory nature of the knowledge claims, since these would imply that science seeks “truth”. This is not uncontested: Bas Van Fraassen (1977, 2001), for example, argues for “empirical adequacy” rather than “truth” as the end of scientific inquiry, with explanation being a pragmatic outcome of science, rather than the primary aim. Similarly, the definition of engineering as the construction of artefacts (objects or processes) is too narrow: technology often generates new knowledge (Layton, 1974; Rogers, 1983; Vincenti, 1990) and design knowledge is seen as a much valued part of engineering (Kroes, 2009). Others argue that the experimental sciences are often also involved in design and manufacture of materials and processes to serve their purposes (Gooding, 1990). Then there are still others

(Ihde & Selinger, 2003; Latour, 1987) in the developing STS field, as discussed a little earlier in this chapter, who argue that modern science and technology are so interdependent that it makes more sense to speak of technoscience. Scientists use technology to do experiments, store and analyse data and communicate results.

All of this leads Radder (2009b) to suggest that simplistic references to the goals actually do not aid distinction between the fields. It is important to note that Radder is not saying that there are no differences worth investigating, but he cautions against sweeping claims that are easily refuted by not much more than a cursory consideration of common practices in science and engineering.

2.3.4 Epistemic emancipation

If the broad goals of the disciplinary fields of science and engineering are not that easily untangled, the question then remains whether there are other, more productive ways to approach differences between science and engineering science. At this point, I now return to a focus on the *knowledge* rather than the range of disciplinary activities and practices in science and engineering. This narrows the field of investigation from looking at all practices, products and behaviour of practitioners, to a consideration of a single aspect, namely the nature of the valued knowledge in the discipline. This approach is more likely to yield empirical objects with the potential for analytical distinction.

Houkes (2009) calls arguments about knowledge differentiation claims of “epistemic emancipation” (p. 310). He distinguishes between weak and strong epistemic emancipation. An example of weak emancipation is the difference between the epistemic values of chemistry and physics. Even though they address different subject matter, they follow the same approach to problems, share the same standards for truth-claim validation, and so on. Houkes points out that strong epistemic emancipation would imply that disciplinary fields do not share the same epistemic values, and operate by their own different epistemic rules. Conceivably the humanities and sciences would be examples of strong disciplinary emancipation; knowledge develops in different ways, relationships with the external world are different, and problems are tackled differently. In fact, there would likely be disagreement on what is considered an appropriate problem to solve in a particular disciplinary tradition. In Bernsteinian terms, the knowledge structures are different: horizontal and hierarchical knowledge structures could make claims of strong epistemic autonomy from each other.

But is this the case for the relationship between science and engineering science, or even between science and engineering, for that matter? Is engineering science a completely different

knowledge structure from science? People hold intuitions (as Houkes (2009) calls these) about the difference between engineering and science, but are these claims of strong, or perhaps rather weak, epistemic emancipation? If strong, then one should be able to point to conclusive evidence for this (in the same way that it is possible to argue convincingly for the difference between horizontal and hierarchical knowledge structures). If weak epistemic emancipation is what we are looking at, then how important (or interesting) is it to keep asserting it? There are seldom heated academic arguments about the independence of physics from chemistry as fields of study!

However, perhaps an argument can be made that the epistemic autonomy of engineering science is of a different order from the one between physics and chemistry. Perhaps different structuring factors are at play rather than merely different content. It is to this challenge that I next turn my attention.

2.3.5 The nature of difference – an empirical challenge

Houkes (2009) argues that those who hold the “truth vs usefulness” intuition as an argument for the unique nature of engineering science knowledge seldom move substantially beyond the intuition. Instead they discuss broad and general perceptions around the goals of the fields. He comes to the conclusion that to strive for strong epistemic emancipation of engineering science from science may not make much sense any more, but that there are several other interesting questions about the nature of engineering science knowledge to be answered. Houkes’ challenge is an empirical one: if ‘usefulness’ were to be an inherent characteristic of engineering science knowledge, what would this mean in practice? He proposes a number of possibilities for investigations; I will consider two here.

Firstly, he suggests that the way theories and models are used in the various disciplines might yield useful information. If “usefulness” is a central value, it should impact on the validation and use of modelling. He gives an example where a model that leads to a solution for a problem will be employed, even if the model is known to be incorrect. He describes an illustration from Laymon (1989a, p. 364) which he calls an “as-if” theory: to account for buoyancy effects experienced by a pendulum moving through air, it is treated as if air ‘sticks’ to the bob as it swings. The model is valued for its problem-solving ability, even though the model is known to be not strictly “true”.

Furthermore, where engineering science shares theories and models with science, it would be reasonable to expect that engineering science would adapt these to fit the purposes of engineering. These changed theories are unlikely to be re-absorbed in science, and Vincenti’s

(1990) description of the use of control volume analysis in thermodynamics is given as example of a theory absent from the sciences (see the discussion on this in section 5.2.1 of this thesis). Houkes' first suggestion therefore refers to *idealisation and modelling* in disciplines.

The second suggestion Houkes makes for investigating the substance of claims about "usefulness" of engineering knowledge comes from his discussion of prescriptive knowledge. His starting point is a quote from *The sciences of the artificial* (Simon, 1996): "the engineer ... is concerned with how things *ought* to be..." (p.4). Houkes describes the modal mood of science as largely "descriptive", and that of engineering as largely "prescriptive" (p. 337-338). He suggests that it should also be possible to track this empirically. It would not just simply be that there are more instances of the use of prescriptive language in engineering, but that the quality of it would be different. He gives an example from a physics text where the words "requires" and "desirable" (both prescriptive terms) are used, but when the context is studied, the words refer to qualities of empirical adequacy and generality. These are in line with the central values of physics as a discipline. However, it would be reasonable to expect to see instances of prescriptive language in engineering because of its value commitment to deliberate, intentional changes for practical purposes, and the design of artefacts that need to operate under specific conditions, and be actively manipulated, maintained and monitored. Here the emphasis is therefore on the prescriptive language or, more broadly, the *normativity* of the fields.

The concepts, idealisation and normativity, from the philosophy of science and engineering, will form the starting place in this thesis to develop an analytical framework for tracking differences and similarities in disciplinary knowledge.

2.3.6 A considered approach to the 'telos' of science and engineering

Before moving on to a more detailed review of the way idealisation and normativity are understood in science and engineering, I need to return to the issue of the goals and aims of science and engineering. As discussed above, the work done by Radder (2009) and Houkes (2009) shows that any attempt to reach 'essentialist' definitions of science and engineering (and engineering science), runs into difficulties (see also Mitcham, 1994; Mitcham & Schatzberg, 2009). The problem remains to find an empirical way to investigate aspects of the nature of engineering science knowledge. While the use of simplistic statements of goals and aims to enunciate differences between science and engineering is ineffectual beyond an initial immediate appeal, thinking carefully about the *implications* of disciplinary values for the way knowledge is used could be helpful.

A more profitable approach is therefore to start with an admittedly intuitive and even naïve proto-understanding of the aims of science and engineering, or what Tondl (1998) calls characteristic “complexes of goals” (p.261) of the disciplines. From this departure point, it then becomes possible to explore *implications* of these for different aspects of knowledge, and also for the relationships between them.

The Greek word ‘*telos*’ (τέλος) refers to an end or purpose, and a teleological orientation can be understood as a tendency towards purposefulness. In the light of the discussions above and the caution raised around essentialist claims about disciplinary aims, I will be referring to ‘fundamental values’ rather than to goals or purposes. In addition, in the context of this study the teleological orientation will be taken to refer to the fundamental values of the *disciplinary fields*, rather than the *knowledge* in the field. This is important because both disciplinary fields, both science and engineering, have purposes – both have *teloi*.

A basic presupposition for the work of science is the regularity of the world it attempts to investigate, understand and describe. Engineering, with its strong base in the sciences, also draws on this principle of regularity and orderliness. However, engineering starts from an even more foundational assumption, namely that the world is mutable, and capable of being manipulated and transformed to bring about change (Rogers, 1983). This value commitment of engineering to meet perceived human needs, places the design of artefacts at the heart of engineering. Artefacts have “a ‘*for-ness*’: it is *for* doing something or *for* being something” (Kroes, 2009, p. 534). The engineering science knowledge used to bring about this engagement with the human world and the perceived needs can therefore be expected to have an orientation towards *functionality* and *problem solving*.

The value placed upon usefulness, social relevance and action-orientation in engineering stands in contrast to what is generally perceived to be the values driving scientific activity. Science is concerned with understanding, describing and explaining the world and being able to make accurate predictions about the way things behave in the natural world as well as the world as changed by technology¹⁰. This is possible because of the regularity that exists in the natural world: science would simply not be possible in a random, capricious universe. Knowledge in science therefore can be expected to have a *theory focus* with concepts and their meaning being closely associated with explanatory theoretical frameworks. Valuable, powerful knowledge in science is often abstract (rather than contextual and concrete), and general in its application to

¹⁰ Note that the ability to make predictions is also highly valued in engineering; however, the predictive power of a model or theory is closely tied to function: problem-solving or the function of an artefact in engineering.

many instances (transferability and universality are valued aspects of scientific knowledge with its focus on explanatory power).

One way to articulate an initial exploratory way of thinking about the values of the disciplines and the impact of these on knowledge in the disciplines, is illustrated in Figure 2-1 below:

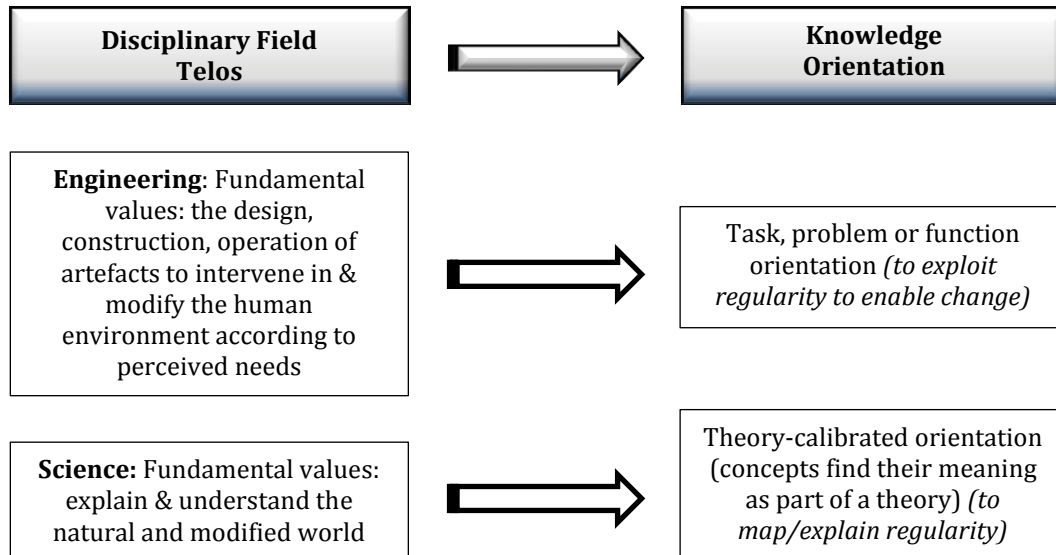


Figure 2-1: Implications of disciplinary field *telos* for knowledge orientation

The question now becomes *how to track* the knowledge orientations of the disciplines in empirical work. The process of operationalising these concepts for use in analytical framework will be discussed in detail in the methodology chapter following here. The concepts of idealisation and normativity, referred to by Houkes in section 2.3.5, will now be discussed.

2.3.7 Idealisation

Idealisation and modelling are important ways in which scientists and engineers engage with the world. Examples are the atomic model in physics and chemistry, harmonic oscillators in physics, modelling of transport patterns in civil engineering, scale models and mechanical prototypes in mechanical engineering, and computer simulations and modelling in virtually all branches of engineering and science. As a result, substantial attention has been paid to idealisation and modelling in the philosophy of science (Boon & Knuuttila, 2009; Cartwright, 1983, 1989; Frigg & Hartmann, 2012; Morgan & Morrison, 1999; Pirtle, 2010; Pitt, 2009; Weisberg, 2007a, 2007b). Philosophers describe idealisation in various ways: “a deliberate detour through fiction” (Godfrey-Smith, 2009, p. 103), a “selective distortion” (Van Fraassen, 2010, p. 511), and “the intentional introduction of distortion into scientific theories” (Weisberg, 2007a, p. 639). In idealisation, certain assumptions are made about phenomena that

are not 'true' in the strict sense of the word, in order to be able to explain the phenomena, make predictions or solve problems. Often a phenomenon is assumed to approximate an 'ideal case' and the model is then applied to make a prediction about the ideal case. Examples are the ideal gas model in chemistry, and the notion of a continuum, rigid bodies and particles in physics. Many of these are used in both the sciences and engineering sciences, but some believe that there are differences in the way idealisation and modelling are used in engineering. I return to these arguments a little later.

According to Boon and Knuuttila (2009), most philosophers of science agree that models are representations of an aspect of the world or "target system" (p. 694). Models specify structures that function as representations of observable phenomena, or even of the causal structures of phenomena. Van Fraassen (2010) describes representation as more than a physical or abstract replica of the target. It also involves a "selective distortion" (p. 511) of properties of the target, and even on occasion incorporating the representation in more complex systems apart from the target. There are generally two approaches to analysing the relationship of representation (Boon & Knuuttila, 2009; Giere, 2004), semantic and pragmatic accounts. Semantic accounts see representation as a two-part relationship between the model and the target, whereas pragmatic accounts recognise a third aspect in the relationship, that of the representation-users and their purposes. For the purposes of this thesis I will focus on the pragmatic accounts, rather than on semantic accounts, since the pragmatic accounts come closer to the fundamental values in engineering: Zwart reminds us that the knowledge gleaned from modelling in the engineering sciences always has the particular focus of "goal-oriented action based on that same knowledge" (Zwart, 2009, p. 633) – this suggests purposes of a model-user.

Pragmatic approaches to representation all have in common a focus on the intentionality of the representers and users of the model. Weisberg argues that it is important not only to look at the process and result of the deliberate distortion introduced in scientific theories, but also at the reasons or "representational ideals" (Weisberg, 2007a, p. 639) for the idealisation. He contends that there are at least three justifications for modelling activities, and that these result in different types of idealisation: Galilean, minimalist and multiple-model idealisation. Galilean idealisation is distortion in the form of simplification, introduced to gain a foothold in order to solve a difficult problem. The justification for this kind of idealisation is pragmatic, and the distortion is non-permanent; better understanding or greater computational ability usually leads to the re-introduction of detail and the removal of the distortion. Cartwright (1989) calls this type of modelling "(ur-)idealisation" (p. 354). A minimalist idealisation is a distortion whereby all extraneous properties of a phenomenon are removed, and only those characteristics crucial to the occurrence of the phenomenon and the fundamental properties of

the phenomenon are retained. The justification for this kind of idealisation is the explanatory power of causal factors. This type of idealisation does not typically lead to removal of the distortion. This is similar to Cartwright's notion of "abstraction" (Cartwright, 1989, p. 354), and the Aristotelian idealisation proposed by Frigg (2012). Multiple-model idealisation involves building several related but irreconcilable models, with each one explaining aspects of the nature and causal mechanisms of a phenomenon. This type of modelling is used with highly complex phenomena like weather patterns or ecological phenomena, and there are no expectations that a single model will be able to capture all of the complexity. Trade-off is a common feature of this type of modelling.

Boon and Knuuttila (2009) do not believe that even the pragmatic approach to representation takes us far enough. They believe that the representational account of modelling does not account for retrieving substantial new information about target systems from the model. They therefore propose that models should be viewed as *epistemic tools* with specific *epistemic purposes*. This approach keeps the focus on modelling as an activity by a user, but adds the view of models as independent objects (see also Godfrey-Smith, 2009; Morgan & Morrison, 1999; Weisberg, 2007b). Boon and Knuuttila (2009) believe that the most important aspect of viewing models as independent objects, is that this allows a focus on the functional properties of the models. This functional perspective sees models as "concrete objects that are constructed for certain epistemic purposes and whose cognitive value derives largely from our interaction with them" (Boon & Knuuttila, 2009, p. 700). They clarify the notion of concreteness as "a tangible dimension that can be worked on" (p.700). They argue that even 'abstract' mathematical models have this characteristic of 'concreteness' as modellers typically use external representations like diagrams or equations to construct and manipulate the model. The idea of interaction with the model by the model-user is also emphasised by others (Knuuttila, 2005; Morgan & Morrison, 1999). It is in this interaction with "self-contained artificial systems" (Boon & Knuuttila, 2009, p. 701) that new knowledge is gained from the model.

The diversity of types of models that can be developed (scale models, mathematical systems and equations, diagrams, etc.) strengthens the notion of models as epistemic tools; these various ways the model-user can think about phenomena allow for different kinds of inferences to be made. Furthermore, models aid thinking about a problem by constraining the problem at hand (similar to Weisberg's Galilean idealisation). In this way, modellers can turn constraints (such as simplifying assumptions) into enablers for problem-solving. It is also possible to use models to isolate important features of a phenomenon in forms that allow manipulation of these insulated properties. This potentially opens up novel approaches and new knowledge about phenomena (see the discussion above on Weisberg's notion of minimalist idealisation).

The question can now be raised whether there are any important differences in the way idealisation is used in engineering science. The literature is limited on this topic (see for example de Vries, 2010; Hansson, 2007; Pirtle, 2010). It is important firstly to acknowledge that ideal conditions are widely used in problem-solving in engineering science, often in very similar ways to the way the sciences use these. Galilean type idealisations, as described by Weisberg above, are often assumed when applying physics principles to practical problems. Solving these problems would not be feasible without the approximations, and engineers attempt to ensure that the approximations provide an acceptable result close to a desired optimum. In fact, engineers often use idealisation without even specifying it, such as assuming rigid bodies (only possible if a continuous distribution of matter (continuum) is assumed throughout a body), and treating objects as particles (when problems involve distances much larger than the object itself, eg. a bomber plane for a gunner operating on the ground). However, there is a tacit acknowledgment that these approximations affect the accuracy of results, and when design calculations are translated into construction calculations, engineers incorporate compensatory factors to account for inaccuracies. It is therefore the way engineers work with ideal conditions that sets apart their approach from idealisation as used by scientists.

However, a few scholars have expressed a belief that there are even more fundamental differences in the ways science and engineering science work with models and idealisation. As discussed earlier, the explanatory power of fundamental physical laws is highly regarded in science. So much so, that these laws are regarded as 'true'. A statement is regarded as true (or empirically adequate) if it explains a large enough number of different instances. However, in her influential essay, "How the laws of physics lie" (1983), Nancy Cartwright argues that *falsehood* is the consequence of the great explanatory power of laws and models. These only explain a highly idealised 'reality', and therefore has to settle for "descriptive adequacy" (p. 3), and cannot be 'true' in the strict sense of the word. The idealising assumptions that have to be made to make fundamental laws 'true' are different from the way the world presents itself in reality. Pirtle (2010) contrasts this with the use of models in engineering, and argues that the constraints of the 'real' world, for example demands of efficiency and safety of artefacts, "force [engineers] ... to do a better job of telling the truth" (p. 107) in their use of models and idealisation. This view is shared by Hansson (2007), who suggests that a more limited form of idealisation is employed in the engineering sciences. For the engineering science knowledge to be useful in real artefacts, the idealisation distortion has to be limited (de Vries, 2010)¹¹.

¹¹ De Vries uses 'idealisation' slightly differently: he sees idealisation (and abstraction) as aspects of generalisation, a property which he assigns to all sciences, including engineering science. He recognises that generalisation in engineering is constrained. Abstraction limits generalisability of knowledge because it omits aspects of reality; idealisation constrains generalisability because of simplification that

Idealisation involves the distortion of reality, for example in modelling, and Houkes (2009) speculates that there may be differences in the way it is used in engineering science and science. He suggests that there may be instances where engineering will take up a model because it yields results (is 'useful'), but the model will not be adopted in science as it does not allow answers to questions about detail, so valued in the sciences. Others (Hansson, 2007; Pirtle, 2010) have suggested a second possibility: that idealisation in engineering will in fact be more limited in engineering science than in science, as engineering knowledge is ultimately about the physical realisability of artefacts. Both possibilities were found to be present in the data, as discussed in chapter seven.

Boon and Knuuttila's (2009) notion of models as epistemic tools has a certain appeal in an engineering context with its concern for practical usefulness. However, what is of interest in my study is not the process of modelling *per se*, but how the product of idealisation is presented in a curriculum as the process of inducting students into the valued disciplinary knowledge. The purpose of introducing models into a curriculum may well be quite different from the purposes of the modellers. However, one would be justified in expecting that the nature of the model as an aid to think about a phenomenon might well be an important one in the curriculum. The data analysis will look specifically at how aspects and products of modelling and idealisation are used in the different thermodynamics courses in science and engineering science. This will include identifying instances of stripping of context and nonessential properties, selective distortion of properties and the use of approximation for epistemic purposes.

2.3.8 Normativity

The term normativity is often used in literature in a rather imprecise way along the lines of "issues having to do with norms" (Radder, 2009c, p. 893). There are some (Florman, 1976; Pitt, 2000) who claim that engineering and technology are value-neutral activities. The proponents of this view do not deny that technologies are 'useful', but see technology as merely means to an end. The usual motivation for the view is that technology and the products of technology are neutral, and that it is ultimately the *use* of technology that determines its value. The common example used is the American National Rifle Association slogan, 'Guns do not kill people; people kill people'. Franssen, Lokhorst and Van de Poel (2010) point out that the neutrality thesis is based on the assumption that instrumental value (being a means to an end) is ultimately no value at all. The neutrality thesis has been widely criticised (Feenberg, 1996; Peters, 2006;

comes with approximation. In the work done in the thesis, I wanted to separate generalisation and idealisation analytically to remain open to tracing them as separate concepts, and therefore the instrument developed in chapter three following here, treats the concepts differently in terms of modes and modalities.

Shrader-Frechette, 2000) as inadequate by philosophers of technology. Van de Poel (2009) points out that there are normative standards inherent in engineering practice as well as in artefacts. This is backed up in the work done by Radder (2009c) and Franssen (2009) as discussed below. Feenberg's (1996) paper reflects on the work of philosophers like Marcuse and Habermas and their critique of the neutrality thesis, and Peters (2006) discusses Heidegger amongst others. I do not propose to evaluate the merits of the arguments and counter-arguments in the debates, but will focus this discussion on the ways in which technology and engineering can be thought of as having a normative orientation.

Philosophers distinguish between different kinds of statements about the world. Firstly there are descriptive statements that are statements about how things are. These kinds of statements simply describe the properties of things in dispassionate terms, for example a screwdriver in terms of the shape, size and the materials it is made of. This type of statement or claim is frequently used in the sciences (and in engineering), since science tends to concern itself to a large extent with describing the way the world is. Another kind of statement is an evaluative statement. The evaluative domain of normativity refers to a value judgement: something is good (rather than right) or bad (rather than wrong). Evaluative statements assign value to something, such as 'This screwdriver is good for use with Phillips screws'. A third type of statement is a prescriptive statement. Prescriptive or deontic statements differ from evaluative statements in that they often carry some direction for action. The deontic domain refers to 'rightness' and 'wrongness', or to what one *ought to* or *ought not to* do, such as 'You should not use a Phillips screw driver for tightening a slotted screw'. Radder (2009c) points out that norms may be explicit or implicit, and that the notion of prescriptivity does not adequately account for implicit norms.

These statements or domains do not form watertight compartments. For example, it is possible that some descriptive statements can lead to evaluative statements: statements about the shape and size of a screwdriver enable an evaluation of the usefulness of the screwdriver.

Furthermore Franssen (2009) argues that the grounds for normative deontic statements can often be found in the relevance relation to a specific kind of descriptive statement he calls "normative facts" (p. 928). He typifies the normative as "being about the difference that facts about the world make to the question about what to do or believe or aim for" (p. 928). He therefore makes a case that all three types of statements can have normative significance. Deontic and evaluative statements are normative in a reasonably straightforward way, and descriptive statements or normative facts when they are used in a "reason-giving" relation relevant to reflections on actions, beliefs and goals of a person. In this view, normativity is then about the way action-oriented and belief-oriented concepts are linked.

Radder (2009c) approaches normativity slightly differently. He distinguishes between norms and values, and defines a norm as “a socially embedded directive concerning what people should (or should not) say or do” (p. 893). He points out that norms presuppose a value judgement of actions, goals or contentions. For example, ‘do not kill’ (norm) presupposes respect for human life (value). Therefore Radder conceives of the relationship between norms and values in a somewhat different way from Franssen’s approach. While it may be relatively simple to infer a value judgement from a particular norm, the reverse may be more complicated: a particular value judgement could lead to various normative suggestions for action. Furthermore, norms do not *determine* behaviour. Different norms (or values) that may be at odds could operate in a given situation, requiring a contextual judgement to determine action (in engineering design this is often the case, for example when economic concerns conflict with safety concerns).

Franssen (2009) approaches the discussion about normativity from the kind of statements that can be made about a technical artefact: that it is good (for its purpose), that it can malfunction, or that it ‘ought to’ perform in a certain way. He argues that these types of statements, together with the notion of the functionality of artefacts, are indications that artefacts must have a normative dimension. Both Franssen (2009) and Radder (2009c) focus their discussion of normativity on artefacts. Radder (2009c), however, furthermore argues that technologies are *inherently* normative. He arrives at this position by describing technologies as a “type of artifactual, functional system with a certain degree of stability and reproducibility” (p. 888) that can only be regarded as functional (realising its promise to fulfil some intended role) if it is embedded in a “suitable environment” (p.889). He defines *functionality* to include the potential of the system, the actual realisability (excluding purely fictitious potential) of the system, the relevant parts of the environment that impact on the successful use of the system, as well as the *intention* of the many human stakeholders. Radder’s argument for the inherent normativity of technologies therefore is both a theoretical claim (stemming from the characterisation of technologies as artefactual, functional and stable) and an empirical claim (requiring appropriate intentional human behaviour in the relevant part of the environment). Dancy (2006) also uses the notion of *intentionality* to argue for the normative nature of artefacts. He suggests that normative statements only make sense within an intentional conceptualisation of artefacts. Dancy endorses the view that artefacts have a dual nature: “artefacts are physical objects which are purposefully made and made for a purpose” (Dancy, 2006, p. 61).

Even though the philosophical discussions focus largely on the product of technology, the artefact, Radder argues that the inherent normativity also applies to engineering science concepts, since these are clearly required for the development and maintenance of technological

systems. This argument is important for my study with its focus on engineering science knowledge rather than engineering practice or the making and use of artefacts. In the data analysis, I will therefore look for indications of normative aspects in the pure science and engineering science knowledge concepts (expressions of functionality, intentionality), as well as statements or claims that signal evaluative and deontic or prescriptive use of concepts.

2.4 The research problem and some preliminary research questions

This chapter presented a survey of relevant literature for the study described in this thesis. I discussed various theoretical concepts from the sociology of knowledge and education, in particular, the work of Basil Bernstein and those who have been working on elaborating concepts from the Bernsteinian problematic. I demonstrated what the specific shortcomings of the theoretical ideas were for the particular study embarked on here. The limitations posed by the scope of the theoretical ideas from the sociology for the current research problem made it necessary to look towards the applied fields of the philosophy of science, engineering and technology to get insight into the nature of some of the more nuanced differences between closely related, but separate fields of knowledge. In this respect, the approach has been to start with a broad and relatively unsophisticated view of the fundamental values and concerns of the broader disciplinary fields of science and engineering, and explore two potentially productive notions, idealisation and normativity, to see how these find their meaning and application in the implications they have for disciplinary knowledge in the fields.

Radder (2009b) points out the need for *empirical studies* to be able to characterise the nature of the relationship between science and engineering: the specific “patterns that they share and... further patterns that are more typical of the one than of the other” (p. 87). The contribution the project described in this thesis hopes to make, lies in the empirical nature of the study as the theoretical ideas from the philosophy of science and engineering are applied to the data.

In the light of this study of the relevant literature from the sociology of knowledge and education on the one hand, and the philosophy of science, technology and engineering on the other, it is now possible to formulate a set of research questions to be addressed.

The main research problem can be phrased as follows:

What is the nature of disciplinary knowledge differences and similarities between the sciences and the engineering sciences as these present in curriculum texts?

This problem will be developed and expanded by considering further questions, for example, what methodological tools can be developed to differentiate the curriculum knowledge in each

of the closely related disciplinary fields of science and engineering science? What insight, if any, can the study of curriculum knowledge provide into the Bernsteinian concept of regionalisation of knowledge? Does the recontextualised knowledge from the science singulars share specific characteristics? Are there differences in the way the engineering sciences mobilise regional traits in the curriculum knowledge? What are the differences and similarities in the ways different regions relate to singulars? What is the nature and significance of the influence of what Bernstein calls “the field of practice” for the recontextualised knowledge of regions? What, if any, disciplinary imprint or ‘echo’ from the field of knowledge production is discernible in recontextualised curriculum knowledge? What is the nature of the relationships between different, but related disciplinary fields like science and engineering science? Are there any distinct disciplinary differences in how concepts like idealisation and normativity are employed and developed when curriculum knowledge in the engineering sciences is compared to that in the sciences?

The questions posed here will be used to inform the analysis of the data gathered from the curriculum texts. The next chapter discusses the methodological considerations for the research study: the justification of the method, the development of a research instrument, and a detailed description of the research design.

Chapter 3 Methodology

Knowledge cannot be prized apart from its form, and cut loose from assumptions about what the world must be like for it to have the form that in some theory of knowledge it is claimed to possess. From now on the boot is on the other foot: there is no escape from ontological commitment. (Bhaskar, 2008, p. 253, footnote)

...the sting is only removed from a system of thought when the particular conditions under which it makes sense are described. (Bhaskar, 2008, p. xxix)

In the previous chapter, I discussed the literature from the sociology of knowledge and from the philosophy of science and engineering that has had bearing on the study described in this thesis. At the end of the previous chapter, two philosophical concepts were identified that have potential for the analytical work needed in this research project.

This chapter sees the elaboration of these (and other) analytical categories in the section on the development of an external language of description, a detailed discussion of the research design, and justification of the methodological decisions made. I start off with locating the research within a particular ontological space. I move on to discuss the research design, before describing the development of an external language of description to arrive at an instrument for data analysis.

3.1 The epistemological and ontological positioning of the study

The fundamental philosophical position taken in this thesis is that of critical realism¹². Critical realism holds to three essential principles (see for instance Bhaskar, 2008; Sayer, 2010). Firstly, critical realism espouses a *realist ontology*. A realist ontology asserts that the world is real and exists independent of our experiences of and beliefs about it. Our knowledge about the world is not identical to the world that the knowledge is about. In the second place, critical realism distinguishes between ontology and epistemology, and combines a realist ontology with a form of *constructivist or relativist epistemology*. Espousing this kind of relativist epistemology means that we acknowledge that all knowledge is incomplete, partial and fallible, and therefore always subject to revision. It is also an acknowledgement that all knowledge is value-laden and theory-

¹² Social realism (SR), an aligned term, can be described (see for example Moore (2012)) as a translation of critical realist philosophy into a sociological framework, specifically speaking to knowledge and educational issues. However, since implications for education will only be considered as suggestions at the end of this study with its consistent focus on the content of the knowledge, I am using the term critical realism here.

laden. The third important characteristic of critical realism is the insistence that it is possible to evaluate competing knowledge claims, by the use of *judgemental rationality*. Since the (fallible) knowledge is about a real world, it is possible to evaluate different knowledge claims about the same real world phenomena, and arrive at a reasoned, but provisional, opinion about what reality is objectively like. This last characteristic guards against judgemental relativism, the claim that relativist (or constructivist) epistemology implies that all judgements of epistemic claims are equally valid. Critical realism holds that some judgements are objectively better than others, while at the same time recognising that judgements are socially and historically embedded, and therefore provisional. Moore (2012) argues that critical realism critiques both the absolutism of positivism and the relativism of constructionism.

By insisting on the distinction between ontology and epistemology, critical realism avoids the “epistemic fallacy” (Bhaskar, 2008, p. 5) which asserts that since no purely objective knowledge about the world is possible, there is also no objective world ontologically. Critical realists argue that even though we can only know the world epistemologically via concepts of our own making, it does not follow logically that the world in reality concurs with our concepts about it. The simple example of the revision of an earlier belief about the flatness of the earth should suffice: ontological reality did not change; people’s beliefs about reality changed.

What does this philosophical stance mean for the study described in this thesis? This is a study that considers epistemic differences and similarities between different, but closely related disciplinary fields of knowledge: science and engineering science. The relative durability of knowledge structures as objects in a real world, despite the longer-term affirmation of their provisionality, is in accord with the realist ontological and epistemological position of critical realism. The theory-rich nature of critical realism is also in keeping with the theorised approach followed in this study.

The critical realist question is always, “What must the world be like if we are to account for the differences and similarities we see?” Our knowledge may be limited by our experiences and viewpoints, but this is not to deny that a real world exists ontologically. For example, the models and idealisations employed and used in the sciences and engineering sciences are real ‘objects’. These often mental constructions are as real as any physical construct, and therefore open to investigation (Maxwell, 2012). The task of the critical realist researcher is to treat these constructs as real, and differences (or similarities) as fundamental, rather than superficial.

Furthermore, at an epistemological level, as a researcher, I will keep in mind that the theoretical lens I develop to look at reality is but one possible way to analyse data¹³:

Any system of classification or individuation of objects, any set of categories for describing the world, indeed, any system of representation at all is conventional, and to that extent arbitrary. The world divides up the way we divide it. And if we are ever inclined to think that our present way of dividing it is the right one, or is somehow inevitable, we can always imagine alternative systems of classification. (Searle, 1995, p. 160)

While acknowledging that the investigator is also the interpreter, and therefore the explanations or knowledge arrived at is necessarily interpretive and provisional, I also strive for a reasoned account (Maxwell, 2004; Sayer, 2010) to explain the data observations. It is important to be explicit about the theoretical frameworks used for data collection and analysis, and to report on dissonant and unexpected results, creating the space for exercising judgemental rationality.

3.2 Case study design

The concept of a research methodology suggests “a carefully considered way of approaching the world so that we may understand it better” (Sayer, 2010, p. 8). The ontological commitment of the researcher has implications not only for the kinds of knowledge claims that can be made, but also for the methods that can be employed in the research. Archer (1995) reminds us that ontology “acts both as gatekeeper and bouncer for methodology” (p.22).

The study described in this thesis uses a case study approach to investigate the nature of knowledge in the sciences and engineering science. A case study involves “the study of an issue explored through one or more cases within a bounded system” (Creswell, 2007, p. 73) in their real-world contexts (Yin, 2012). Some qualitative researchers (Simons, 2009; Stake, 2005; Thomas, 2011b) believe that the case study is a research design rather than a methodology, and that it allows the researcher to select from many different kinds of methods the one most suitable to the particular case. The case study approach is appropriate for use within a realist ontology, because case studies take reality seriously as they provide for nuanced, detailed descriptions of a complex world because of their strong relations to real-life situations (Flyvbjerg, 2001). Qualitative researchers rely heavily on what has been called “thick”

¹³ The notion of epistemology was complicated in this study by the fact that I had to be conscious not only of my own epistemological views, but also keep in mind that the research itself was about knowledge, and that the disciplinary knowledge fields under investigation each have their own (contested) ontological and concomitant epistemological positions.

descriptions. Ponterotto (2006) explains this commonly used term thus: "Thick description refers to the researcher's task of both describing and interpreting observed social action (or behavior) *within its particular context*" (p. 543, emphasis added). Ponterotto points out that 'thick description' needs to lead to 'thick interpretation', which in turn brings about 'thick meaning' of the research.

However, this rootedness in reality has a flip-side: one of the common critiques of the case study method is the limited opportunities for generalisation from a single study. The sometimes unexamined value placed on generalisability has been contested, seen for example in Flyvbjerg's (2001) conviction about research in the social sciences. He argues that the nature of social studies is such that general laws are highly unlikely to be arrived at, and that generalisability is therefore a misleading demand to be made of case studies: "Predictive theories and universals cannot be found in the study of human affairs. Concrete, context-dependent knowledge is therefore more valuable than the vain search for predictive theories and universals" (Flyvbjerg, 2001, p. 73). In a similar vein, Thomas (2011a) suggests that case studies provide (and should provide) exemplary knowledge rather than generalising knowledge.

This does not mean that qualitative research in general and the case study approach in particular yields nothing more than anecdotes about a particular situation. Yin (2011) argues for a broader way to approach generalisation (beyond statistical generalisation which relies on randomised sampling). He calls this "analytic generalization" (p. 99), whereby the researcher suggests a specific set of conceptual assertions or theoretical constructs that may be able to be applied to other situations. The purpose of an analytic generalisation is to situate propositions from the study at a conceptual level higher (or more abstract) than the immediate findings. Moore (2012) concurs: "Theory to be theory must have qualities that are translatable across situations otherwise we are limited to a collection of incommensurable standpoints that cannot 'talk' to each other – the postmodernist position" (p. 4). The theoretical framework of a study is used to establish a logic that can find wider application than the narrow case study under discussion (Yin, 2012).

The nature of case study design (as is the case with all qualitative research designs), has implications for the kinds of conclusions that can be drawn from a study. Since experimental closure with variable control is not an option, direct cause-and-effect conclusions are not possible, nor are they desirable. A critical realist ontology allows for the exploration of patterns and tendencies in data, and the purpose of research then becomes to develop explanations about observations and experiences.

As with other types of qualitative research, the case study approach makes use of purposive sampling (Patton, 1990; Yin, 2011). This is an intentional form of selecting data sources that are likely to yield the most relevant information for the purposes of the study. It also serves to extend the scope and usefulness of the information to be gleaned from case studies (Flyvbjerg, 2001; Lincoln & Guba, 1985).

In the section that follows, I deal with the specific research design decisions that were made for the study described in this thesis.

3.3 Details of the research design

As explained before, the purpose of this study is to consider the similarities and differences in the nature of the knowledge in science and engineering science. The first task was therefore a decision about which scientific and engineering science knowledge to select for the purposes of the study. The decision here had two components: I had to consider the 'site' of data collection as well as the types of data sources available.

3.3.1 Argument for the use of thermodynamics knowledge as the case study

The initial methodological decision to settle was the selection of the *case of disciplinary knowledge*; an appropriate area of particular conceptual content within the bodies of disciplinary knowledge had to be selected. It was important to select a body of theoretical content common to both engineering and science where there would be broad agreement on the principal content, concepts and laws. The research task would then be to compare these, and look for differences and similarities in the approaches of the disciplines to essentially the same content.

Scientists and engineers work in many common intellectual fields; examples are energy, electricity, mechanics, organic chemistry. After considering a number of options, I selected the field of thermodynamics knowledge. This is a fundamental topic in both the sciences and engineering as it deals with, amongst other things, the transformation of forms of energy. As mentioned in chapter one, Channell (2009) identifies thermodynamics as a "true engineering science" (p. 133) in the early historical emergence of the engineering sciences. Selecting thermodynamics as the body of theoretical knowledge also provided me with an opportunity to track the use of the knowledge concepts across different sciences (chemistry and physics) and different branches of engineering (chemical and mechanical engineering), thus strengthening

the research design. This would not have been the case had I selected electricity for example, as its scope would have been limited to electrical engineering and physics.

Thermodynamics is an established topic in the sciences and engineering, and a well-recognised research area at post-graduate higher education level. Some differences are to be expected across disciplinary fields. An example is the role of energy changes in solutions and chemical reactions, which feature in chemistry and chemical engineering, but would not be prominent in physics and mechanical engineering. However, even with these differences in emphasis, the conceptual content in thermodynamics is focused around a set of three well defined laws across disciplines. In the interest of limiting the scope of the data to be collected, a decision was made to focus on two major laws, the First and Second Laws of thermodynamics.

3.3.2 Locating the empirical work in the field of recontextualisation

As noted in chapter two, Bernstein (2000) makes a distinction between knowledge in the different fields of the pedagogic device, namely the field of production, the field of recontextualisation and the field of reproduction. Analytically, it is therefore important to distinguish between these in an empirical study. The *field of production* is the site of the comprehensive canon of disciplinary knowledge and also the site of generation of new disciplinary knowledge. Data sources here could, for example, include research practice and publication of new knowledge in research journals. At the other end of the pedagogic device, in the *field of reproduction*, pedagogic practice takes place: the teaching (transmission), learning (acquisition) and evaluation of valued recontextualised knowledge. Typical data sources for knowledge in the field of reproduction are examination papers and scripts, student understandings of disciplinary concepts, and lecturer practices. While data gathered from the field of reproduction gives invaluable insight into how teaching and learning takes place, these sources of data could perhaps be considered 'once-removed' from disciplinary knowledge, with some potential for distortion of the disciplinary characteristics by the external influences of idiosyncrasies in student and lecturer interaction.

The *field of recontextualisation* is the location of knowledge in the curriculum. Examples are textbooks and course notes, course descriptions, accounts of knowledge-in-transfer in the classroom situation (in either the intended or enacted curriculum), curriculum policy documents, etc. It could be argued that the recontextualised curriculum knowledge presents a reified collection of knowledge that is valued in the discipline at a particular time, prized for the induction of disciplinary novices. As such it offers a relatively robust and stable source of data. It was also a concern for curriculum structure and students' ability to navigate curriculum knowledge transitions that originally motivated this study, as described in chapter one of this

thesis. This contributed to the decision to focus on data from the field of recontextualisation for the current study.

The empirical objects in this study were therefore recontextualised objects: thermodynamics curriculum data was scrutinised for empirical evidence of recontextualised disciplinary knowledge differences and similarities in the broad fields of science and engineering science.

Thermodynamics is offered in six undergraduate courses at the University of Cape Town (UCT), in the disciplinary fields of chemistry, physics, chemical engineering and mechanical engineering. The decision to use six courses (rather than four) was made to ensure that a common breadth of thermodynamics topics would be covered in a particular field of study. Not all the courses were offered at the same academic year level; the level depended on various curriculum programme demands like sequencing of courses, workload, prerequisites for other courses, etc.¹⁴

Brief information about the courses:

CEM2007F: PHYSICAL CHEMISTRY AND SPECTROSCOPY. Thermodynamics is taught as a physical chemistry section of this second year chemistry semester course (around 15 lectures). Textbook: Engel, T., & Reid, P. (2010). *Physical Chemistry* (2nd ed.). Boston: Prentice Hall. (Only a section of the textbook covers thermodynamics)

PHY1004W: MATTER AND INTERACTIONS. Introductory thermodynamics concepts are taught as part of a 12 lecture thermal physics section in the standard first year physics offering during the first semester, introducing the basic notions of statistical mechanics. Textbook: Chabay, R., & Sherwood, B. (2011). *Matter & Interactions I: Modern Mechanics* (3rd ed.). Hoboken, NJ: Wiley & Sons Inc. (Only a section of the textbook covers thermodynamics)

PHY3021F: ADVANCED PHYSICS A. Thermodynamics and statistical mechanics is taught as half of this semester course at third year level, or one quarter of the final year physics courses (comprising two semester courses). Textbook: Schroeder, D. V. (2000). *An Introduction to Thermal Physics*. San Francisco: Addison Wesley Longman.

CHE2035S: THERMODYNAMICS I. This is a full semester course that focuses exclusively on thermodynamics at second year level in chemical engineering. Textbook: Sandler, S. I. (2006). *Chemical, Biochemical, and Engineering Thermodynamics* (4th ed.). Hoboken, NJ: John Wiley & Sons. (There is a third year level course entitled THERMODYNAMICS II, but this is a specialised course focusing on multi-component mixtures typical in the chemical engineering industry, and was not considered for this research study).

¹⁴ The courses described here are taken by different cohorts of students (except for chemical engineering students who take both CEM2007F and CHE2039S). The purpose of the study is not to follow the *particular* knowledge transitions students have to make in the field of thermodynamics, but rather the broad *disciplinary knowledge shifts* from science courses to engineering science courses in a typical engineering curriculum, as exemplified in Figure 1-1 in chapter one of the thesis.

MEC2022S: THERMOFLUIDS I. Thermodynamics is one half of this second year semester course in mechanical engineering, and the focus is on the First Law of thermodynamics only. Textbook: Cengel, Y., & Boles, M. (2011). *Thermodynamics: an engineering approach* (7th ed.). Boston: McGraw Hill. This course covers the first half of the textbook.

MEC3033F: THERMOFLUIDS II. Thermodynamics is one half of this third year semester course in mechanical engineering, and the focus is on the Second Law of thermodynamics only. Textbook: the second half of the same textbook as the one prescribed for MEC2022S.

One of the immediately striking features of the list of courses is that thermodynamics content in the science (physics and chemistry) courses is more limited: at most one half of a semester course is devoted to thermodynamics, and the thermodynamics is but one section in a more general science course. In chemical engineering the whole course's focus is thermodynamics, and in the case of mechanical engineering the thermodynamics content is spread across two halves of two semester courses in order to cover both of the two major thermodynamics laws. This is an early indication of a higher degree of specialisation in the engineering curricula.

The strength of the research design lies in the symmetry (two science disciplines and two engineering science ones), and also in the fact that more than one discipline in each of the bigger fields of science and engineering science is being considered. It was therefore possible to reflect on variance not only between science and engineering science, but also on dissimilitude within the sciences and engineering sciences.

3.3.3 Argument for the use of textbooks rather than classroom interactions

The next methodological issue to be addressed was which specific curriculum data sources to consider for inclusion in the study. As a starting place I attended all of the thermodynamics lectures in the six courses, took notes during lectures, recorded the lectures, and flagged anything that struck me as unusual or interesting. My goal was to focus on the way the *knowledge* content of the course was presented, and to filter out any pedagogic issues such as teaching style, course organisation, and incidental lecturer-student interactions outside the course content. The courses ran at different times of the year (four in the first semester and two in the second semester), and it was difficult to compare across courses as they were unfolding. After lectures, I listened to the recordings and started condensing the data in preliminary categories that were at that stage starting to surface in the data. I soon realised that this unstructured approach was unproductive, and more importantly, that it was almost impossible to separate the knowledge content from complex classroom and pedagogic interactions across

the six courses. There was a real danger that the data would include interesting, but ultimately arbitrary, peculiarities of a particular pedagogic practice, rather than only characteristics of the disciplinary knowledge. I needed a more stable and neutral data source, and at this stage made the decision to use the five prescribed textbooks as the primary source for data of the valued disciplinary knowledge (The time spent on lecture attendance was not wasted; it enabled me to familiarise myself again with the content of introductory thermodynamics which I last studied during my own undergraduate studies many years ago. I also used the lecture notes to aid navigation through the textbooks and was able to reduce the amount of content covered by excluding sections that were omitted in lectures).

Implied in this methodological decision is the assumption of a broadly common understanding of what constitutes a good undergraduate programme in the sciences and engineering sciences. The notion of expecting a fair amount of standardisation across undergraduate science and engineering science programmes, is primarily a Bernsteinian argument: scientific (including engineering science) knowledge is structured hierarchically by its nature. This kind of knowledge also grows and develops in a hierarchical way. A broad common knowledge base forms the foundation from which more abstract and complex concepts develop, and from which encompassing laws and theories evolve. Hierarchical knowledge structures imply a broadly agreed-upon starting point and sequencing of topics in curriculum texts like textbooks. One could argue that there would be stronger agreement on what to include in an introductory course in thermodynamics than, say, in an introductory history course in different parts of the world. It is therefore reasonable to regard the undergraduate textbooks under consideration in this study as standard texts in thermodynamics. They are internationally published (rather than locally produced) textbooks, and most (bar the one physics text) are second or later editions, indicating wide international use.

At this stage, some of the fundamental methodological issues have been settled, and the research design can therefore be summarised as an investigation into differences between and similarities across knowledge presented in undergraduate science and engineering science prescribed texts, making use of a case study design in which the approach to the same thermodynamics knowledge (the First and Second Laws of thermodynamics and their elaboration) is to be analysed. Four sub-cases were considered in parallel: thermodynamics in physics, chemistry, mechanical and chemical engineering. The data sources are five textbooks from the four disciplinary areas (one textbook each from chemistry, mechanical and chemical engineering, and two from physics). The focus of the study is the recontextualised engineering science knowledge, with the knowledge in science as a comparative backdrop.

At this point it is important to clarify the use of the term ‘discipline’ and ‘disciplinary’ in this thesis. To reiterate, as discussed in section 3.3.2, there is a difference between the field of production (site of new knowledge production and the full canon of disciplinary knowledge) and the field of recontextualisation (the selection of valued disciplinary knowledge for the purpose of developing a curriculum), and it is important to keep sight of the analytical difference between the two fields. As explained above, the data sources for the empirical study described here are curriculum texts, and as such contain curriculum knowledge from the field of recontextualisation. However, it is also possible to describe the sub-cases dealt with in this study, namely chemistry, physics, mechanical engineering and chemical engineering as different disciplinary fields in the university context of educating undergraduate students (speaking in Bernsteinian terms to the fields of recontextualisation and reproduction, rather than to the field of production of new knowledge). In the interest of clarity and brevity, I will therefore henceforth treat the textbooks as *empirical proxies* of disciplinary (curriculum) knowledge of this latter kind, with a clear understanding that it refers to *curriculum* disciplinary knowledge.

3.3.4 Consideration of ethics issues

In compliance with the university’s research ethics policy, ethics clearance was sought and granted from the Engineering and the Built Environment Faculty’s Ethics in Research Committee prior to commencing the research project. In the process the researcher had to demonstrate consideration of all potential ethics issues that the project could give rise to. As part of the initial planned data gathering consisted of lecture attendance, permission was obtained from all the course conveners to attend and record lectures. Lecturers informed students of the recordings and of the reasons for the researcher’s presence in lectures. In the end, lecture data was not directly used in the research project, although the lectures played an important role in orientating the researcher to the knowledge fields. No other ethical issues were encountered in the project.

3.4 Analytical framework

Basil Bernstein (2000) identifies two “languages of description” (p.132): an internal and an external language of description. The internal language of description is a conceptual description of the theory itself. This has to be ‘translated’ into an external language of description in order to be able to describe something other than itself, the empirical world. The task was to develop a ‘language’ that would allow me to talk about the differences and similarities in the data. In terms of the way this process was envisioned by Bernstein, I had to move from high level theoretical abstract ideas (such as ‘classification’, ‘regionalisation’,

‘normativity’ and ‘idealisation’), that are data-distant, to sets of concepts that could function as conceptual tools in a “data-near” (Moore & Muller, 2002, p. 634) framework for analysis of the data. This process of ‘operationalising’ the theoretical ideas is a crucial step before any theory can be brought to bear upon data.

3.4.1 An initial exploration

In the previous chapter (paragraph 2.3.6) I discussed the early stage of the development of an instrument that could potentially be used with empirical data that speaks to disciplinary knowledge differences. The process started with a focus on the teleological orientations of the broad *disciplinary fields* of science and engineering rather than the *knowledge* as a starting place: an inchoate articulation of the fundamental values of the broader disciplinary fields.

For science, this fundamental value is explanation: to “understand the way the world appears to us, and it accomplishes this aim by constructing and testing theories that appeal to features of the world which are not immediately obvious.” (Pitt, 2011, p. 168). Following from this, one can then expect that knowledge in science will have a *theory-calibrated orientation*: concepts find their meaning as part of theories that map the regularities in the world.

For engineering, on the other hand, the fundamental value lies in responding to a recognised human need by means of some intervention which could be the design, construction, and operation of artefacts that modify the human and social environment (Layton, 1987; Pitt, 2011; Rogers, 1983). This fundamental engineering value means that engineering knowledge will have an orientation that can be described as *task- or function-oriented*. The diagram below (first developed in chapter 2 as Figure 2-1, repeated here for ease of reference) illustrates the conception of a preliminary framework.

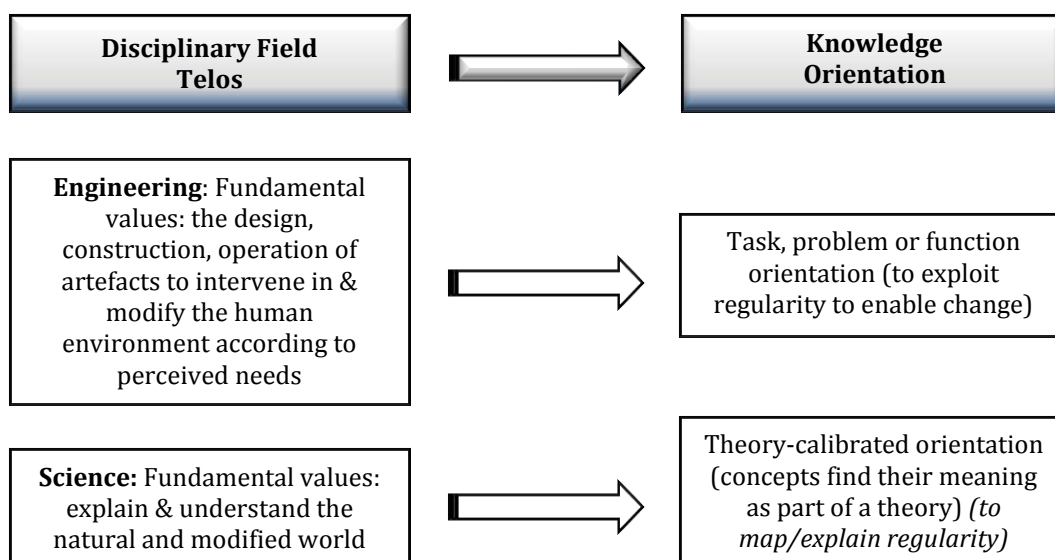


Figure 3-1: Implications of disciplinary field *telos* for knowledge orientation

The knowledge orientations arrived at in the diagram above are, however, still not data-near concepts, and it was at this point that literature from the philosophies of science, technology and engineering was called upon. As described in chapter two, the notions of idealisation and normativity were selected as potentially productive concepts, and with these in hand, I turned my attention to the data sources as found in the five text books.

3.4.2 The move to data

The purpose of this section is to describe some of the processes that led to the refining of the data instrument. Theorising in this way is a complex process that is iterative rather than linear. It is also non-reductive in the sense that it cannot be reduced to either inductive or deductive logic processes; it requires managing the tension in the dialectic between theory and data (Clegg, 2012). The process cannot be completely inductive: it is not a matter of 'finding' the appropriate theoretical framework hidden in the data. I will attempt to reconstruct here the meta-level processes involved in moving between the theory and data. In this there is a commitment to the ontological position described at the start of this chapter: the intent to treat the information from the textbooks as real and not constructed. This was done by attention to the detail of the data as demanded by the case study approach.

Starting off with the notions of 'idealisation' and 'normativity', the empirical task was always going to be alerted to certain theoretical possibilities (Clegg, 2012). Building on Figure 3-1 above, the concepts of idealisation and normativity were cast as knowledge *modalities*, and to activate these for use as analytical instruments I turned to the data from the textbooks. I used an iterative process of gradual data condensation to work through the texts. An *initial* attempt was to use content themes across all five textbooks (See Appendix B). This proved partially successful, as I was able to roughly code (green for idealisation, purple for normativity, and yellow for incidents that seemed significant, but were not instances of the normative or idealisation modalities).

Two things became clear at this stage: first, the categories were not discriminating enough. In addition there were some peculiarities flagged that were neither distortions of reality (idealisation), nor carried any evaluative connotations (normativity), but seemed to suggest a third qualitatively different category. It is important to remember that theory is always underdetermined by empirical data, and that there always needs to be an openness to recognise additional theoretical possibilities. At the same time though, this was the first round of data combing (a process which is not "innocent" (Clegg, 2012, p. 408), even with the best intentions), and it is quite likely that an excess of instances were flagged, simply because I was still in the

process of developing the categories. By the same measure it is quite possible that some instances were missed in this first round, hence the importance of iteration.

3.4.3 The process

I started off with initial rough descriptions of idealisation and normativity, in which idealisation was conceived of as distortions of reality. I was looking for instances in the data where context and complexity were deliberately being stripped. Normativity was approached by looking for instances where the knowledge carried specific evaluative connotations (the notion of 'efficiency' was an obvious one). This was done in a dialogical discourse with the data which involved constant and rigorous questioning of each instance:

- What is this an instance of?
- How is it different from the previous or next instance?
- What is the essence of the difference?
- How can X be seen to be of a similar type as Y?

Tentative refinement of each modality was followed by going back to the textbooks and scrutinising them for more or contrasting incidents of the refinements. At this stage of the close work with the data it became clear that a new category would be needed to code data that exhibited clear difference, but could not be coded as either 'normative' or idealised' knowledge. This data was coded as a third modality which I called 'specialisation' (see the discussion in 3.4.4 below, for a motivation and more detailed explanation).

It became clear that the modalities were still too data-distant to be useful: these concepts were still at a level of abstraction that constrained effective interpretation of the data. What was needed was a finer-grained approach that would allow for more circumscribed analytical distinctions.

3.4.4 Refining the instrument

By means of an analytical process involving constant comparison across instances in the different broad disciplinary fields, the concepts were refined and for each of the knowledge modalities two *modes* were developed. Refining the instrument in this way required a constant and active flow between literature, theory and data, employing "imagination" and "intellectual craftsmanship" (Clegg, 2012, p. 407, quoting Mills (1959)). These scholars use 'crafting' in the sense that the theoretical categories become conceptual 'tools' to think with. The literature, theory and data get assimilated in the researcher's 'life experience' and it is this that is drawn upon in pulling together what initially are tentative theoretical hunches or categories to 'try out'

on the data. The conceptual work done here does not take place in a theoretical vacuum, rather, literature from the field (the theory, philosophy and sociology of knowledge) is assimilated and drawn upon. It requires constant interpreting and re-examining of which aspects of the data are pulled in or left out as categories are delineated.

In this section I describe the development of the *modes* as further refinement of the knowledge *modalities*. In the development of the modes, the two broad disciplinary fields (engineering and science) were initially conceptualised as distinct analytical categories, but the modes generated the potential for a grading of intensity of strength across modalities (i.e. the modalities are conceptualised as continuous rather than discrete entities). This analytical approach made it possible to identify unanticipated deviations from 'typical' categorisation of science and engineering knowledge as polarities.

3.4.4.1 *The specialisation modality*

This category surfaced from the interaction with the data as described in 3.4.2-3.4.3.

The way I will be using specialisation¹⁵ is with reference to the way some of the knowledge appears to *engage with the fundamental values* of each of the disciplinary areas suggesting separate societal roles for the disciplines. The analytical task for data generation and analysis therefore involves identifying data instances where certain forms of knowledge are valued or prioritised over other forms. This implies that *both* engineering science knowledge as well as knowledge in science are specialised, but specialised in different ways.

The fundamental disciplinary values are respectively artefact operationalisation (for engineering) and explanation and description (for science). Visualising the specialisation modality as a continuous axis of variance, it is then reasonable to suggest the following modes of specialisation of the disciplinary thermodynamics knowledge:

- a. specialisation towards *particulars*: knowledge is directed towards deliberate intervention via particular devices, artefacts or systems
- b. specialisation towards *universals*: knowledge emphasises the generic form, and explanatory or predictive power brought about by generalisation (applying to more than one particular instance)

There clearly are aspects of specialisation present in normativity and idealisation (see the discussion in chapter seven later). However, the decision was made to separate the categories of

¹⁵ Specialisation is used elsewhere to refer to the division of cooperative labour in clearly defined societal tasks/roles (sociology), applying general knowledge to generate propositional knowledge (logic), or in instances where a less specialised object evolves towards greater specialisation (biology).

specialisation, idealisation and normativity at the stage of the data analysis, keeping an open mind for condensation of the categories at a later stage in the study. The reason for this is a concern about losing richness of detail in the data, should categories be collapsed too early (working with just the two 'lenses' of idealisation and normativity could potentially result in a blindness to other detail). The motivation for separation of the modalities was therefore a commitment to potential analytical and cognitive gain.

3.4.1.2 *The idealisation modality*

As discussed in chapter two, idealisation is the deliberate, selective distortion of reality for specific purposes of the modeller, in order to explain, predict or solve problems. It usually involves removing complexity (often also context), making simplifying assumptions and abstractions of real-life systems and objects. Models and idealisations are often used as epistemic tools for different purposes. In line with the fundamental values of the disciplinary fields the following modes were conceptualised for the continuum of variance in idealisation:

- a. idealisation towards *physical realisation*: this mode emphasises the task- or problem-directed nature of idealised knowledge where it is present. Zwart (2009), for example, comments: "...in engineering the ultimate purpose of modeling is to realize reliable artifacts or technical processes" (p.633). Idealisation is used to 'gain traction' for the solution of a difficult problem. This potentially involves the use of approximation, clarity about the simplifying assumptions made, and possibly involves removing or compensating for the abstraction as the problem solving progresses.
- b. idealisation towards *abstract-ideal theorisation*: here the idealised knowledge follows from or is employed in theory development. The knowledge often remains at an abstract level, and there is limited commitment to a return to a real-life context. In fact, the knowledge is often de-contextualised and general, in order to transfer across contexts.

3.4.4.3 *The normativity modality*

The discussion in chapter two indicated that different types of knowledge claims are made; some are simply descriptive statements about the way things are. These kinds of statements are obviously commonplace across all broad disciplinary fields as any disciplinary field of expertise will include bodies of declarative knowledge covering topics within its scope. Normativity, however, is associated with evaluative judgements being made. Radder (2009c) and others (Dancy, 2006; Franssen, 2009; Van de Poel, 2009) argue that the intentionality inherent in the production of technological artefacts brings a normative dimension to knowledge in these fields.

To allow for the possibility of a lesser degree of normativity¹⁶ prevalent in the knowledge in some of the other disciplinary fields under consideration, the following modes were developed along the normativity continuum:

- a. A normative knowledge orientation that is *constitutive*: here normativity plays a vital role in understanding the nature of the knowledge.
- b. A normative orientation that has at most an *incidental* role in describing the nature of the knowledge.

3.4.5 The analytical instrument

The external language of description as developed above now makes it possible to generate an analytical instrument for data analysis that finds its functionality in the modalities and modes. The instrument evolved from two ends: the *teloi* and knowledge orientations were developed from the literature, and applied to the disciplinary fields. There is increased complexification from left to right in the instrument as the modalities and modes were developed in conjunction with the data. The modes developed here make it possible to *operationalise* the modal continua, as the knowledge modalities are *actualised* or *effected* in the modes.

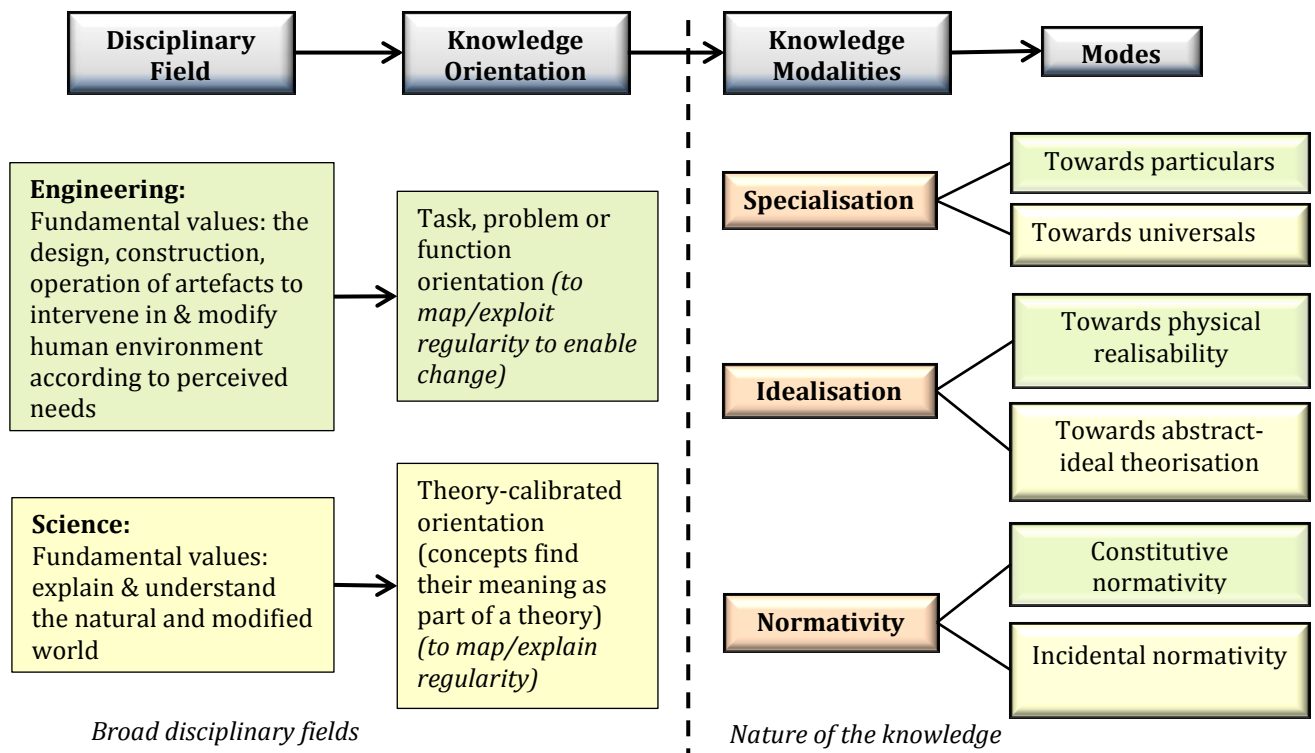


Figure 3-2: The full analytical instrument

¹⁶ See for example Simon's (1996, p. 5) opinion that "[n]atural science has found a way to exclude the normative and to concern itself solely with how things are".

3.5 Data generation and analysis

Qualitative research studies like the one described in this thesis make use of purposeful sampling procedures to generate data. The logic of purposive sampling lies in the selection of information-rich cases (Maxwell, 1996; McMillan & Schumacher, 1993; Patton, 1990; Yin, 2011) that inform the purposes of the study, "...cases worthy of in-depth study" (Patton, 1990, p. 181).

Purposive sampling took place at two levels in this study: firstly, at the level of selecting the cases for inclusion in the study. Four sub-cases or sites for data collection were selected: thermodynamics knowledge in prescribed textbooks in two engineering sciences (mechanical and chemical engineering) and two sciences (physics and chemistry). This strategy of purposive sampling is an example of what Patton (1990) calls *stratified purposeful* sampling. Here physics, chemistry, and mechanical and chemical engineering represent *strata* in the sciences or engineering sciences respectively. Stratified purposive sampling is particularly useful for comparative studies such as the one described in the thesis. As pointed out before, the sampling at sub-case level in this research project represents a strength of the research design. By including two sub-cases for each of the broad disciplinary fields (science and engineering), variations and similarities carry more weight than they would have otherwise. It also enables the investigation of variation within broad disciplinary fields, within the sciences and within the engineering sciences.

The second level of purposive sampling took place at the level of generating the data units of analysis. The units of analysis were themes in the thermodynamics knowledge (see the summary of the data analysis in Appendix A for the scope of theme analysis that took place). Patton (1990) describes this kind of sampling as *theory-based* or *operational construct* sampling. In effect the external language of description operationalised the theoretical constructs of specialisation, idealisation and normativity. Together with the thermodynamics knowledge themes, the theoretical constructs of specialisation, idealisation and normativity acted as 'filters' for data analysis, and instances of typical and information-rich illustrative examples were collected from the disciplinary curriculum knowledge represented in the textbooks.

The initial phase of data analysis took place in the application of the instrument to the data as described above. Creswell (2007) argues that data collection, analysis and even reporting are not distinct steps in qualitative research, but are "interrelated and often go on simultaneously in a research project" (p. 150). He proposes a "data analysis spiral" (p.150) to describe the analytical circles the researcher has to move in during the process of interpreting the data.

Each unit of analysis was considered, and then coded according to the descriptions of the modes developed in the external language of description, in at least two cycles of data condensation (see examples of the result of the data condensation in Appendix C and D. Note that these appendices represent an early stage of the data analysis as only one modality per unit is indicated). In the end, each unit of analysis was scrutinised three times (once for each of the modalities), and chapters four to six present the full analysis and coding. In each case a dominant or *principal modality* was identified, either specialisation, idealisation or normativity. Where present, other modalities were identified as secondary modalities. Each data unit was then coded with a *principal mode*, and, when present, with secondary modes. Coding decisions were motivated in all cases. The data generated in this way was grouped according to the *principal modalities*, and presented in the thesis in three chapters: chapter four presents data generated under the principal modality of specialisation, chapter five idealisation, and chapter six normativity. A summary of the results of the full coding process can be found in Appendix A. Shaded cells indicate departure from what would typically be expected for the broad knowledge fields. Similarities, differences across sub-cases and variations within them became themes for discussing the findings in chapter seven with regards to the research questions posed in chapter two.

This chapter described the ontological, epistemological and methodological concerns pertaining to the current research study. A series of arguments were presented to motivate the methodological decisions made. A detailed account was presented for the development of an external language of description and the generation of an analytical data-near instrument. The purposive sampling approach used in the study was discussed and a description of the data condensation and analysis process followed was given. The next three chapters give an account of the findings from the study, and is deliberately detailed in the account it gives of the data generated in the study, in keeping with the 'thick' descriptions characterising a case study approach.

Chapter 4 Findings and analysis of the data – Specialisation modality

A theory is the more impressive the greater the simplicity of its premises, the more different kinds of things it relates, and the more extended its area of applicability. Therefore the deep impression that classical thermodynamics made upon me. It is the only physical theory of universal content which I am convinced will never be overthrown, within the framework of applicability of its basic concepts. — Albert Einstein

The next three chapters present illustrative instances of the data generated by applying the analytical framework to the curriculum knowledge about the First and Second Laws of Thermodynamics, as presented in the five undergraduate textbooks from the six undergraduate courses: two mechanical engineering courses, both using the same prescribed textbook (Cengel & Boles, 2011), two physics courses: an introductory first year course (Chabay & Sherwood, 2011) and a third year course (Schroeder, 2000), a chemical engineering course (Sandler, 2006), and a chemistry course (Engel & Reid, 2010). In these next three chapters, the thermodynamics knowledge is discussed in terms of the three analytical categories, or modalities, that deal with the orientation of the disciplinary knowledge towards specialisation, idealisation and normativity.

Presented here are illustrative cases from each of the textbooks, rather than an exhaustive description of every important thermodynamics concept. For each unit of analysis all three modalities are considered for coding. A dominant or *principal* knowledge modality is identified in those instances where more than one modality is discernible. Each data unit is coded with one of the two *modes* of the modalities where present, and the coding decision is motivated on the basis of the modal descriptions given in chapter three. Where appropriate, secondary modes are identified and motivated. A summary of all coding decisions is presented in Appendix A.

The First Law of Thermodynamics articulates the fundamental empirical observation that energy cannot be created or destroyed, but that it is conserved during processes where one form of energy is transformed into another. A certain familiarity with the principle is assumed by the time students encounter the concept in university thermodynamics courses, since it is commonly introduced as the Conservation of Energy Principle in the secondary school science curriculum. The Second Law of Thermodynamics formalises another empirical observation, namely that natural processes proceed in a preferred direction; for example, heat will not flow spontaneously from a cold object to a warmer object. The Second Law of Thermodynamics is an

important addition to the body of thermodynamics knowledge, because, in principle, there is nothing in the First Law of Thermodynamics that would preclude the opposite flow of energy: energy of a system consisting of a hot object in contact with a cold object remains conserved if heat energy were to flow into the warmer object, provided that the cold object 'loses' the same heat energy.

The rest of chapter four is a description of the data that carries *specialisation* as the principal modality. This is followed by chapter five that presents data coded for the principal knowledge modality of *idealisation*, and chapter six that does the same for the principal modality of *normativity*.

4.1 Specialisation as principal modality

Thermodynamics knowledge in the textbooks displays a *specialisation* modality. This is evident in the way fundamental concerns of the disciplinary fields are prioritised. For science this involves keeping explanation and description as the main concern; for engineering the design, construction and operationalisation of artefacts in response to an identified human need are uppermost. In the empirical research, the analytical objective is therefore to identify units of data that speak to these valued disciplinary priorities. Two *modes of specialisation* were developed in chapter three in terms of the fundamental disciplinary concerns. Firstly, when specialisation is directed towards *particulars*, knowledge is focused towards particular devices, artefacts or systems. For the second mode, specialisation is directed towards *universals*, and knowledge emphasises the generic form, and the explanatory or predictive power brought about by generalisation.

The thermodynamics topics or themes discussed here are the same across all the disciplinary fields (and in this commonality of themes the organisation of the chapter differs from that of chapters five and six, following). The common themes provide the opportunity of a more direct comparison of the curriculum knowledge across the disciplinary fields. This is a consequence of themes that are, for the most part, of a more introductory or wide-ranging nature (eg. the meaning of 'thermodynamics', the overall approach to the field, etc.). The presentation of the findings below is therefore organised in the first place along common themes as units of analysis, and a short general description introduces each topic. Descriptions of illustrative data from the texts are interspersed with direct quotes from the textbooks.

4.2 The meaning of *thermodynamics*

In chapter one I described the emergence of thermodynamics as a body of systematic knowledge during the Industrial Revolution. The textbooks explain the origin of the term as an introduction to the topic.

4.2.1 Mechanical Engineering: the meaning of *thermodynamics*

In the introduction to the mechanical engineering textbook, the authors trace the etymology of the term ‘thermodynamics’, and in so doing give an indication of the emphasis of the textbook:

The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power), which is most descriptive of the early efforts to convert heat into power. Today the same name is broadly interpreted to include all aspects of energy and energy transformations including power generation, refrigeration, and relationships among the properties of matter. (Cengel & Boles, 2011, p. 2, emphasis in the original)

With this description of the term *thermodynamics*, the authors of the mechanical engineering textbook signal early on the interest of mechanical engineering in the *particulars* of the functional aspects of subject field rather than limiting the description to generalities: the importance of the conversion of energy into more ‘useful’ forms of energy in power generation and refrigeration. The phrase referring to “relationships among the properties of matter” is framed in a way that refers to *universals*. However, it is clear that the particulars are dominant in this description of what can be expected in thermodynamics. No secondary modality or mode is discernible.

Principal Mode: some universals,
particulars dominate

No secondary modality/mode

4.2.2 Physics: the meaning of *thermodynamics*

By contrast, the first year physics textbook does not introduce thermodynamics as a separate topic or discipline. The physics text is a mechanics textbook and therefore deals with much more than energy transformations. Interestingly, the term ‘thermodynamics’ appears in neither the index, nor contents pages of the textbook, but the energy principle (First Law) and entropy (closely aligned to the Second Law) are dealt with in two of the chapters. Thermodynamics is treated as simply one of the parts of the broader field of mechanics.

The third year Thermal Physics textbook author (Schroeder, 2000) deals with both classical thermodynamics and statistical mechanics. He gives a broad description of classical thermodynamics as

...the study of systems comprised of large numbers of particles, based on general laws that do not depend on the detailed microscopic behavior of those particles. The formulas that appear here apply to *any* large system whose macrostate is determined by the variables U, V, and N, and these formulas can be generalized with little difficulty to other large systems. (p. 120, emphasis in the original)

The description (or absence of a description) of what is meant by the term ‘thermodynamics’ seems to be an early indication of a more general approach to the topic. The mode of the specialisation of the knowledge in the case of both physics texts is therefore coded as an orientation towards *universals*, and no secondary modality is present.

Principal Mode: universals

No secondary modality/mode

4.2.3 Chemical engineering: the meaning of *thermodynamics*

In an approach similar to that of the mechanical engineering text, Sandler (2006), in his chemical engineering textbook, returns to the original language for the term, explains the two parts of the word *thermodynamics*, and places an emphasis on the steam engine origins of the topic:

... the prefix *thermo*, referring to heat and temperature, and *dynamics*, meaning motion. Initially thermodynamics had to do with the flow of heat to produce mechanical energy that could be used for industrial processes and locomotion. (p.1)

Sandler goes on to point out that thermodynamics was traditionally the domain of mechanical engineering. However, his intention is to develop a contemporary applied thermodynamics textbook that will also be relevant for chemical engineering topics, like separation processes, chemical reactor analysis and process design (Sandler, 2006, p. iv). Sandler’s explanation of the term ‘thermodynamics’, and his stated purpose with the textbook, strongly lean towards the mode of the *particulars*. The knowledge here carries no idealised or normative aspect; no secondary modality and mode is identifiable.

Principal Mode: particulars

No secondary modality/mode

4.2.4 Chemistry: the meaning of *thermodynamics*

The chemistry textbook authors explain that “...[t]hermodynamics is the branch of science that describes the behaviour of matter and the transformation between different forms of energy on a macroscopic scale” (Engel & Reid, 2010, p. 1).

This description of thermodynamics given by the chemistry authors is general and non-specific in its form; there is no reference to transforming heat energy into ‘useful’ forms and therefore, although the authors follow a macroscopic approach (rather than a statistical mechanical approach as was the case in physics), the specialisation orientation of the knowledge mode evidenced in the description leans towards *universals*, with no secondary modality present.

Principal Mode: universals

No secondary modality/mode

4.3 Overall approach to the subject field of thermodynamics

There are two possible ways of approaching an undergraduate course in thermodynamics. It can either be taught as classical thermodynamics, or else using a statistical mechanical approach. The classical approach is a macroscopic approach and the focus is on the ‘bulk’ properties of matter: pressure, temperature, volume, etc. Many of these properties of matter can be measured directly or calculated from simple relationships. The statistical mechanical approach, on the other hand, applies the laws of probability and statistics to large numbers of microscopic particles to predict and explain the macroscopic behaviour of matter.

4.3.1 Mechanical engineering: overall approach to thermodynamics

In the introduction to their textbook, the mechanical engineering authors, Cengel and Boles (2011), make it clear that the textbook is intended as both study material for undergraduate engineering students, as well as a reference book for engineers in practice. The objectives are to expose students to the basic principles of thermodynamics and to assist them “to develop an intuitive understanding of thermodynamics” (p. xvii) by exposing them to real-world engineering problems, like transportation vehicles, power generation systems and even household appliances. The priority given to problem-solving is signalled in the authors’ emphasis that the 7th edition of the textbook has over 400 new “real-world” (p. xx) problems.

Cengel & Boles (2011) justify the choice of the classical macroscopic approach to thermodynamics as more intuitive, and therefore more appealing to engineering students:

The traditional *classical*, or *macroscopic* approach is used throughout the text, with microscopic arguments serving in a supporting role as appropriate. This approach is more in line with students' intuition and makes learning the subject matter much easier. (Cengel & Boles, 2011, p. xviii, emphasis in the original).

It is the concern with engineering-type problems that drives the commitment to the macroscopic approach to thermodynamics. The authors acknowledge that properties of a substance depend on the behaviour of its microscopic particles, but even “[w]hen studying phases or phase changes in thermodynamics, *one does not need to be concerned with the molecular structure and behaviour of different phases*” (p.112, emphasis added). The macroscopic approach focuses on the bulk properties of matter (temperature, pressure, density, specific volume, etc.) that can be measured with ease and accuracy. Properties like enthalpy, entropy, internal energy cannot be measured directly, but these are calculated using simple mathematical relations. Therefore in the conceptualisation of properties like enthalpy and heat capacity, the emphasis in mechanical engineering is on the intersection with macroscopic properties of matter: enthalpy links macroscopic properties with the work done by gases, and specific heat is described in terms of “the energy storage capability of various substances” (p.174).

The statistical mechanical approach to thermodynamics is therefore less useful for the purposes of mechanical engineering, and the classical approach to thermodynamics signals the emphasis on *particulars*, rather than universals. There is no implicitly normative or idealised aspect present in the knowledge here, and thus no secondary modality.

Principal Mode: particulars

No secondary modality/mode

4.3.2 Physics: overall approach to thermodynamics

The first year textbook (Chabay & Sherwood, 2011) describes its focus as “learning how to model the nature of matter and its interactions in terms of ... the atomic structure of matter” (p.1).

According to its authors, this purpose allows for a consistent approach to mechanics and thermal physics, the two main subject fields covered in the textbook. Even at this early stage in the introduction to the textbook, the authors are signalling the value they place on using theoretical constructs and models across subject areas, and therefore unifying their approach to the fields of mechanics and thermal physics.

An example of how the microscopic approach to the subject matter is applied can be seen in the way the authors emphasise the particle model of matter when dealing with internal energy and thermal energy: "Thermal energy is random kinetic and potential energy of atoms and interatomic bonds within an object" (Chabay & Sherwood, 2011, p. 288), the so-called 'ball-and-spring model'— see also Fig. 7.23¹⁷ (Chabay & Sherwood, 2011, p. 297), where the authors explain that the model requires an account of the energy of every ball and every spring.

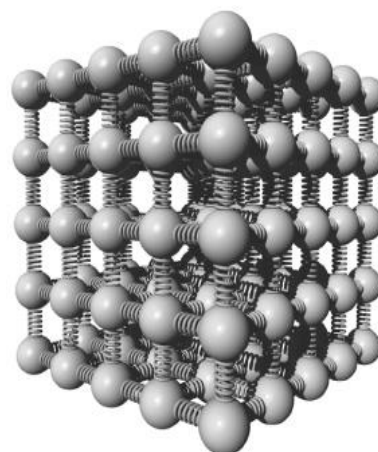


Fig. 7.23 In our model we must account for the kinetic energy of every ball and the spring energy of every spring (Chabay & Sherwood, 2011, p. 297)

Even when referring to large systems later in the text, the authors do so in terms of collections of microscopic entities: "Macroscopic systems are composed of many interacting particles" (Chabay & Sherwood, 2011, p. 288). Heat is energy transfer due to a temperature difference, and the authors explain that

[a]t the microscopic level there is actual work; when a hot block is placed in contact with a cold block, at the interface the atoms in the two blocks collide with each other, and do work on each other. The atoms in the hot block have greater average kinetic energy than the atoms in the cold block, so in an individual collision it is likely that a fast-moving atom in the hot block loses energy to a slow-moving atom in the cold block... On average there is energy flow (microscopic work) from the hot block to the cold block. (Chabay & Sherwood, 2011, p. 301)

First year students are introduced to the fundamentals of statistical mechanics in the chapter discussing entropy, where the starting point is the calculation of the probability of the distribution of quanta of energy across energy levels of atomic oscillators. This approach is discussed in more detail under the idealisation orientation in the next chapter, but my interest at this point is that it confirms the commitment to a microscopic explanation of macroscopic events: "Our criterion for understanding is whether the predictions of our microscopic model agree with measurements of macroscopic systems, such as measurements of heat capacity" (Chabay & Sherwood, 2011, p. 473).

¹⁷ All images used from Chabay, R., & Sherwood, B. *Matter & Interactions I: Modern Mechanics* (3rd ed.). Hoboken, NJ: Wiley & Sons Inc., © 2011, reproduced with permission from Wiley. All rights reserved by the publisher.

The other major concern in the physics textbook is the generalisability of the conclusions:

Which of our results are general? We have analysed simple models of solid matter. Nevertheless, the basic conclusions are quite general. For example, if our two model blocks were made of different materials, so that the energy quanta were of different size in the two blocks, this would complicate the procedures for evaluating the number of ways... to arrange the energy, but the basic conclusion would remain, that the entropy will increase to a maximum. (Chabay & Sherwood, 2011, p. 492)

The microscopic approach allows for an explanation across cases, which is prized in the physics text.

The third year textbook is titled “Thermal Physics” (Schroeder, 2000), and is divided into Thermodynamics and Statistical Mechanics. It is essentially a distinction between macroscopic (thermodynamics) and microscopic (statistical mechanics) behaviour of atoms. Schroeder points out that physics educators are not in agreement on which approach is best in an undergraduate physics course. Some prefer thermodynamics (the macro approach) which is “less mathematically demanding and more readily applied to the everyday world” (Schroeder, 2000, p. vii). Others prefer to focus on statistical mechanics because of the “detailed predictions and concrete foundation in atomic physics” (Schroeder, 2000, p. viii). Schroeder has attempted a middle ground by including both approaches.

... to understand matter in more detail, we must also take into account both the quantum behaviour of atoms and the laws of statistics that make the connection between one atom and 10^{23} . Then we can not only *predict* the properties of metals and other materials, but also explain *why* the principles of thermodynamics are what they are... (Schroeder, 2000, p. vii, emphasis in the original)

Schroeder explains how the two approaches (macroscopic and microscopic) work to generate knowledge via inference about objects. On the one hand, knowledge about microscopic detail does not contribute a great deal to principles governing changes in measurable bulk properties, such as temperature, conductivity, magnetic properties. The principles at work behind these general statements form the subject of *thermodynamics*. At another level though, since it is impossible to track the random movement of 10^{23} particles, the laws of *probability and statistical mechanics* are used to predict the macroscopic properties of the chunk of metal. He points out that in addition to the prediction of macroscopic properties, the quantum and statistical approaches have powerful *explanatory power* to refer to what lies behind the thermodynamic properties of substances:

... to understand matter in more detail, we must also take into account both the quantum behaviour of atoms and the laws of statistics that make the connections between one atom and 10^{23} . Then we can not only *predict* the properties of ... materials... but also explain why the principles of thermodynamics are what they are – why heat flows from hot to cold, for example. (p.vii)

For these reasons the Thermal Physics textbook author favours an approach that looks at both thermodynamics and statistical mechanics.

In practice though, even the macroscopic behaviour is referred to in terms of numbers of *particles* (as opposed to energy flow through engineering devices, for example): “[t]hermal physics deals with collections of *large* numbers of particles – typically 10^{23} or so” (p. vii, emphasis in the original). It is interesting to note that what Schroeder considers a “large” number of particles – 10^{23} particles – is one mole of matter, which in the macroscopic engineering thermodynamics context would be a tiny amount (9g of iron, for example).

Discussions on thermodynamic properties in the remainder of the textbook are often focused on a microscopic (atomic or molecular) level, even when statistical mechanical principles are not explicitly used. An example of this can be seen when changes in the internal energy of a substance is partly

explained by changes in the microscopic potential energy in the context of stretching or compressing interatomic springs in the model for solids

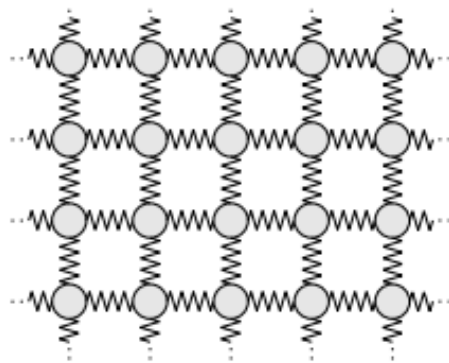


Fig 1.6. The “bed-spring” model of a crystalline solid. Each atom is like a ball, joined to its neighbors by springs. In three dimensions, there are six degrees of freedom per atom: three from kinetic energy and three from potential energy stored in the springs.

(Fig. 1.6¹⁸, Schroeder, 2000, p. 16).

The statistical mechanical approach, on the other hand, uses the laws of probability and statistical mechanics to emphasise the particle nature of matter. The microscopic statistical approach to thermodynamics emphasises the *universalities*: the particles that make up matter are generic atoms – it does not matter what kind of gas atoms or molecules are present. The strength of the approach lies in the *generality* of the model.

The choice of the statistical mechanical approach to thermodynamics in the physics textbooks is therefore an emphasis on specialisation of knowledge to *universals*, including the high value

¹⁸ All images used from Schroeder, Daniel V., An introduction to thermal physics, 1st, ©2000, reprinted by permission of Pearson Education, Inc., New York, New York.

placed on generalised knowledge that applies to numerous cases. The strong emphasis on the particulate nature of matter indicates a predisposition to idealisation of knowledge as a secondary modality, and here the emphasis is on abstract-ideal theorisation in the way the knowledge is developed to cohere with the atomic model of matter.

Principal Mode: universals

Secondary Modality: idealisation,
Mode: abstract-ideal theorisation

4.3.3 Chemical engineering: overall approach to thermodynamics

The chemical engineering textbook (Sandler, 2006) follows the classical macro-approach to thermodynamics, but the description of the classical approach is more general than the one given in the mechanical engineering textbook. There is, for example, no reference to specific engineering processes or devices:

Thermodynamics is a macroscopic science; it deals with the average changes that occur among large numbers of molecules rather than the detailed changes that occur in a single molecule. Consequently, this book will quantitatively relate the internal energy of a substance not to its molecular motions and interaction, but to other, macroscopic variables such as temperature... and density... (Sandler, 2006, p. 4)

Sandler makes a consistency argument to justify the use of the macroscopic approach: none of the other core undergraduate chemical engineering courses follow a molecular approach. He adds “that moving to the microscopic or statistical mechanics level adds little, except perhaps some confusion, and usually detracts from the flow of the course” (Sandler, 2006, p. iv). This does not mean that Sandler thinks that statistical and quantum mechanics are unimportant for chemical engineering students; they are important, “and that is why the physical chemistry course that deals with these should be retained” (p. v). It is, however, not the focus of the textbook under consideration.

Even though Sandler explicitly focuses on the classical approach to thermodynamics with its emphasis on macroscopic properties rather than on a statistical treatment of the behaviour of molecules, the microscopic understanding of matter is central in the discussions of macroscopic properties. In this respect the chemical engineering text is quite similar to the chemistry textbook (see 4.3.4 below). An example is Sandler’s explanation of how thermodynamics is approached differently in chemical engineering (compared to mechanics):

Thermodynamics is the study of the changes in the state... of a substance, when changes in its temperature, state of aggregation, or **internal energy** are important. By internal energy we mean the energy of a substance associated with the motions, interaction, and bonding of its constituent molecules, as opposed to the **external energy** associated with the velocity and location of its centre of mass, which is of primary interest in mechanics. (Sandler, 2006, p. 4, emphasis in bold in the original)

In spite of the macroscopic approach clearly being signalled in the introduction to the textbook, an awareness of the microscopic explanation of the macroscopic properties is evident elsewhere:

macroscopic variables such as temperature.... is primarily related to the extent of molecular motions, and density... is a measure of how closely the molecules are packed and thus largely determine the extent of molecular interactions. (Sandler, 2006, p. 4)

Another example of the prominence of molecular theory of interaction between atoms and molecules is the description of differences in the internal energy of gases, liquids and solids, explained in term of the interactional energy as a result of the separation distance between molecules (see Figure 3.3-5¹⁹ on p. 69): “in solids, the molecules generally are located very close to the minimum of the interactional energy function in an ordered lattice, so that a solid has even less internal energy than a liquid” (Sandler, 2006)

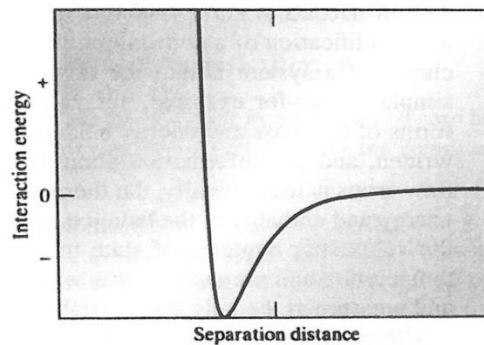


Figure 3.3-5 The interaction energy between two molecules as a function of their separation distance. Since the molecules cannot overlap, there is a strong repulsion (positive interaction energy) at small separation distances. At larger separation distances the interactions between the electrons result in an attraction between the molecules (negative interaction energy), which vanishes at very large separations.

Therefore, although the chemical engineering text follows the classical, macroscopic approach to thermodynamics, the strong commitment to a microscopic understanding of the macroscopic properties of matter is evidence of a stronger specialisation to *universals* in this particular theme.

¹⁹ All images used from Sandler, S. I. *Chemical, Biochemical, and Engineering Thermodynamics* (4th ed.). Hoboken, NJ: John Wiley & Sons., © 2006, reproduced with permission from Wiley. All rights reserved by the publisher.

For this reason, one could also argue that *idealisation* of the knowledge as a secondary modality is presented as a commitment to abstract-ideal theorisation in the prominence of the particulate model of matter in the chemical engineering text.

Principal Mode: universals

Secondary Modality: idealisation,
Mode: abstract-ideal theorisation

4.3.4 Chemistry: overall approach to thermodynamics

The preface and introductory chapter in the chemistry textbook (Engel & Reid, 2010) are more limited than those of the other textbooks used in this study. However, the authors are clear about their preference for the macroscopic approach to thermodynamics:

Thermodynamics is the branch of science that describes the behaviour of matter and the transformation between different forms of energy on a *macroscopic scale*, or the human scale and larger. Thermodynamics describes a system of interest in terms of its bulk properties. Only a few such variables are needed to describe the system, and the variables are generally directly accessible through measurements. A thermodynamic description of matter does not make reference to its structure and behaviour at the microscopic level. (Engel & Reid, 2010, p. 1 emphasis in the original)

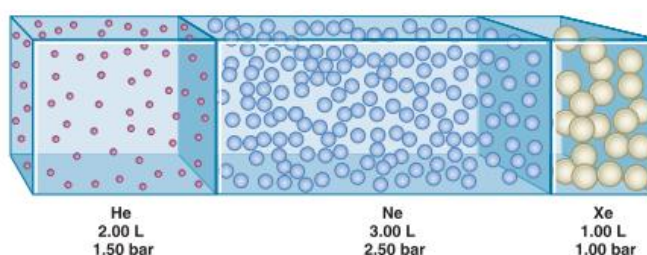
They argue that although the microscopic nature of matter forms the underlying ground for its macroscopic features, the macroscopic approach is more immediately relevant and useful.

In a way similar to the approach in chemical engineering, the chemistry textbook authors therefore express their intention to focus on the transformation of energy on a macroscopic

scale, and accessing the “bulk properties” (p.1) of matter through measurement of temperature, pressure, etc. However, diagrams consistently depict variations in properties using molecular or atomic structures. The diagram²⁰ for Example Problem 1.2 on p. 8 illustrates how chemistry students

EXAMPLE PROBLEM 1.2

Consider the composite system, which is held at 298 K, shown in the following figure. Assuming ideal gas behaviour, calculate the total pressure and the partial pressure of each component if the barriers separating the compartments are removed. Assume that the volume of the barriers is negligible.



²⁰All images used from Engel, Thomas; Reid, Philip, Physical chemistry: International Edition, 2nd, ©2010, reprinted with permission from Pearson Education, Inc., New York, New York.

are expected to develop a strong sense of the link between the microscopic behaviour of particles and the macroscopic properties of gases. When they see the diagram, they think of higher pressure as more (and more forceful) collisions on a particular area. The focus may be on the macroscopic property (pressure), but there is an implicit understanding of what it means in molecular terms.

Therefore, even though the chemistry textbook follows a macroscopic approach to thermodynamics, and the statistical approach is not explicitly used, the driving logic of the chemistry textbook is *not* an emphasis on particulars. It is therefore not the classical or statistical mechanical approach to thermodynamics *by itself* that determines an orientation towards particulars or universals. An understanding of the underlying molecular structure of matter in a generalised *universal* sense is communicated throughout the text and is fundamental to the orientation to *specialised* knowledge in chemistry. Therefore *idealisation* can be identified as a secondary modality in the knowledge presented here, and it functions in the mode of *abstract-ideal theorisation* in the use of the atomic theory of matter.

Principal Mode: universals

Secondary Modality: idealisation,
Mode: abstract-ideal theorisation

4.4 Systems, processes & devices

A fundamental concept in thermodynamics is the definition of a *system*, which simply is the space under consideration, defined by its boundaries. Everything outside the boundaries of the system is its surroundings. *Devices* in the context of the discussion that follows here, are objects or machines that fulfill a particular purpose, and *processes* bring about changes in the conditions that describe systems.

4.4.1 Mechanical engineering: systems, processes & devices

The mechanical engineering authors simply define a system as “a quantity of matter or a region in space chosen for study” (Cengel & Boles, 2011, p. 10), and distinguish between two types of systems: open and closed.

Closed systems are “control mass” systems (Cengel & Boles, 2011, p. 11). Closed systems consist of fixed amounts of matter, with no mass crossing the system boundary. Energy can cross the boundary of a closed system as heat or work (a special case of a control mass where not even energy can cross the boundary is called an isolated system). The volume of a closed system need not be fixed, and an important focus in the mechanical engineering textbook is

“*moving boundary work* or *PdV work* commonly encountered in reciprocating devices such as automotive engines and compressors” (p. 163, emphasis in the original). In a car engine, for example, the expansion of the combustion gases forces the piston to move in the cylinder resulting in the rotation of the crankshaft, with the moving boundary the inner face of the piston. Because of the proliferation of practical mechanical devices that use this process, moving boundary work is prominent in the mechanical engineering textbook.

The mechanical engineering text also deals with open systems, called “control volumes” (Cengel & Boles, 2011, p. 10). The control volume approach is typical of flow processes that are routine engineering processes. These systems will be discussed more comprehensively in chapter five, following here. The interest here is that control volumes are associated with the movement of mass (matter) through a space of interest, and are usually associated with typical engineering devices, such as pipes, radiators, nozzles, pumps, etc. Neither physics, nor chemistry use the term control volume, and open systems do not feature in the pure science textbooks (except for the irregular use of the term in Chabay and Sherwood (2011), see below).

From the discussion above it should be clear that the focus of the mechanical engineering knowledge in closed and open systems is closely linked to processes associated with engineering devices like automobile engines and compressors, pumps and radiators. This theme in the thermodynamics knowledge is therefore coded for the principal mode of *particulars*. The knowledge cannot be considered as idealised or normative, and therefore no secondary modality is associated with the knowledge described here.

Principal Mode: particulars

No secondary modality/mode

4.4.2 Physics: systems, processes & devices

Neither of the two Physics textbooks pays any significant attention to the flow of mass across system boundaries (there is a brief mention of “matter transfer” (Chabay & Sherwood, 2011, p. 302) as one of the “other” kinds of energy transfer, together with electricity, electromagnetic radiation and mechanical waves. The only forms of energy transfer to and from systems that receive any serious consideration in the physics texts are heat and work. This makes the systems considered in the science textbooks ‘closed’.

In the first year physics text, Chabay and Sherwood (2011) describe open and closed systems in a different way from the other textbooks: ‘closed’ systems are ones where no *energy* transfer to and from the system is possible (essentially an isolated system according to the definitions in

the mechanical engineering textbook), and 'open' systems are ones where the only energy transfer possible between the system and the surroundings is in the form of heat and work. Quotation marks are used in the original text (Chabay & Sherwood, 2011, p. 301) where the terms are introduced, possibly an acknowledgement by the authors that their terminology is non-standard.

Energy transfer in the physics textbooks is mainly discussed in general terms. An example of this can be seen in Chabay & Sherwood (2011) starting with "the simplest possible system ... consist[ing] of a single particle" (p. 221). The authors explain that in this discussion the single particle

could refer to a proton or electron, but it could also refer to a baseball or even a planet if during the process of interest there are no significant changes internal to the 'particle' such as changes of shape or rotation or vibration or temperature. (Chabay & Sherwood, 2011, p. 221)

The concern here is to start with the simplest and most general situation, and in many cases the knowledge remains at this most general of levels (see the discussion later about proving the general energy principle mathematically for a single particle).

Although Schroeder (2011) in the third year physics textbook does not make a distinction between open and closed systems, it is clear from the context (and from the absence of mass flow as energy transfer) that the systems under consideration are closed systems. He explicitly refers to the fact that different methodologies are required for solving flow processes and rates of flow: "In this book I will not say much about rates of processes, because these kinds of questions are often quite difficult and require somewhat different tools" (p. 37).

In terms of attention to thermodynamic devices, Schroeder allocates a chapter to the discussion of heat engines and refrigerators. This is done without any reference to the fact that these are flow devices (i.e. open systems) that operate with a working fluid. These are the only devices discussed in the textbook, and the context is the calculation of efficiency. Schroeder makes it very clear that his purpose is not to explain how heat engines and refrigerators function, but simply to quantify the efficiency (see chapter six on normativity).

My goal in this section is to make these ideas precise, and to determine exactly how much of the heat absorbed by an engine can be converted into work. Amazingly, we can say a great deal without knowing *anything* about how the engine actually works (p.122, emphasis in the original).

Precision calculations, rather than functional detail about heat engines, are what matter. The function and operation of the heat engine is not the concern in this textbook.

The chapter ends with a longer section on the principles at work in approaching temperatures near zero kelvin, and here the interest of the physicist to push the boundaries of new knowledge is evident, all at the atomic and even nucleic level:

... isn't 1K cold enough? Why bother trying to attain still lower temperatures? Perhaps surprisingly, there are a variety of fascinating phenomena that occur only in the millikelvin, microkelvin, and even nanokelvin ranges, including transformations of helium itself, magnetic behaviour of atoms and nuclei... To investigate these phenomena, experimenters have developed an equally fascinating array of techniques for reaching extremely low temperatures. (Schroeder, 2000, p. 144)

The emphasis of the physics textbooks on closed systems (in the standard definition of *closed*), the absence of any rate-of-flow considerations, and the scant attention given to working devices, suggest that the mode of the specialised knowledge orientation in physics is towards universals, and no secondary modality and mode is present here.

Principal Mode: universals

No secondary modality/mode

4.4.3 Chemical engineering: systems, processes & devices

Similar to the mechanical engineering textbook, the chemical engineering author (Sandler, 2006) addresses both open and closed systems (although the term *control volume* for open systems is not used by Sandler).

Sandler (2006) recognises the use of open systems as peculiar to engineering and one of the fundamental differences between thermodynamics as a subject in science and in engineering. He expresses a concern that engineering students are often exposed to thermodynamics in different disciplines (he mentions physics and chemistry) in undergraduate curricula. He believes the resulting redundancy is not beneficial, and that the different disciplinary emphases result in confusion for students. He is so concerned about this that he addresses engineering students specifically in the Preface to his textbook, and suggests that they should “forget what they have been taught about thermodynamics elsewhere” (p. ix), because the non-engineering courses only consider closed systems, whereas engineering applications need to also deal with open systems where mass flows into and out of systems. Typical examples in chemical

engineering are the work obtained from a fluid (steam) that flows across the large pressure drop in a hydroelectric power generation system, or a compressed-air tank being repressurised by connecting it to a high pressure air line.

Sandler points out that there are two broad types of problems of interest in chemical engineering. The first of these, *energy flow* type problems, are similar to problems in mechanical engineering: calculating the energy changes associated with the flow of heat, work or mass across system boundaries. Mechanical and chemical engineering specialise towards different particulars though, and this is evident in the textbook. As can be expected, chemical reactions, the production (and rate of production) of chemical species are more important in chemical engineering than in mechanical engineering. Mass balance equations are prominent in Sandler's chemical engineering textbook, also in the "rate-of-change" and "difference" forms of the equations. The rate at which mass changes in a system, and integration of these changes over a period of time to calculate the total change in mass (or preferably the change in the number of moles) of chemical entities is important in chemical engineering.

The second type of problem Sandler regards as important in chemical engineering is *equilibrium* type problems, and these are not emphasised in mechanical engineering. The equilibrium state is described as the inevitable result when "a system is not subjected to the continual forced flow of mass, heat or work" (Sandler, 2006, p. 5). Equilibrium is a "time-invariant state in which there are no internal or external flows of heat or mass and no change in composition as a result of chemical or biochemical reactions" (p.5). These fairly general definitions and descriptions are contextualised in the typical problems under consideration in chemical engineering practice: predicting the nature of the equilibrium conditions that a system evolves to from non-equilibrium (an example is predicting the final temperatures and pressures in gas cylinders if the valve between an empty and a filled cylinder is opened). Here the filling, mixing and leaking of gas in and from cylinders are examples of typical engineering processes and devices that chemical engineers use.

Another example of the kind of specialisation to particulars present in the chemical engineering textbook can be seen in Sandler's distinction between a state of equilibrium and a steady state. Sandler distinguishes between "natural flow" and "forced flow" (p. 8), or "pressure induced energy flow" (p.49). It is possible for an open system with spontaneous mass, heat or work flows to reach an equilibrium state. Equilibrium states are defined by the fact that the characteristics of the system do not vary with time, that there are no internal temperature, pressure, velocity or concentration gradients in the system, that there are no net transfers of heat, mass or work between the system and surroundings, and that the net rate of chemical

reactions is zero. However, if the surroundings impose a mass flow on the system by the action of a pump, or a temperature flow by exposing different parts of the system to different temperatures, it is still possible that the system could reach a time-invariant state. Since this results in a temperature or pressure gradient in the system (even one that remains constant over time), this would not be equilibrium, but a “steady state” (p.8). This differentiation in the chemical engineering text between equilibrium and steady state speaks very clearly to the particulars that are characteristic in chemical engineering practice.

The emphasis on open systems in addition to closed systems in the chemical engineering textbook, together with the type of processes and devices discussed in relation to the systems, indicate the commitment to the *particulars* of the field of practice in which chemical engineers work.

The knowledge is neither idealised nor normative, and therefore no secondary modality is present.

Principal Mode: particulars

No secondary modality/mode

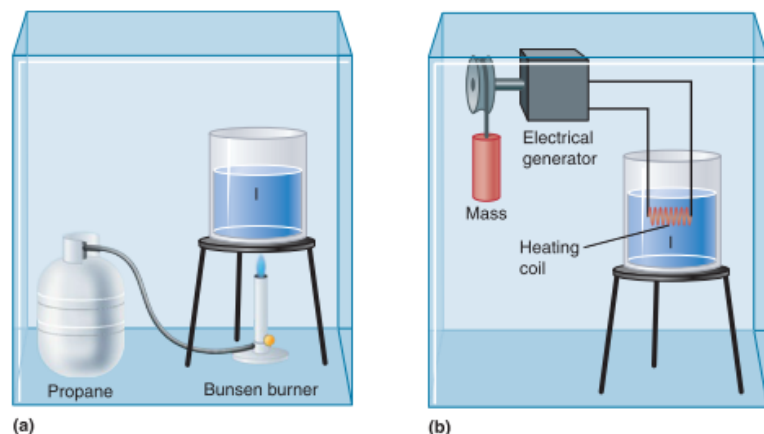
4.4.4 Chemistry: systems, processes & devices

The chemistry textbook authors (Engel & Reid, 2010) define both open and closed (as well as isolated) systems: “If a system can exchange matter with the surroundings, it is called an open system; if not, it is a closed system” (p. 2). Living cells are described as examples of open systems. However, the chemistry textbook pays very little attention to open systems; the isenthalpic Joule-Thomson expansion in an open system is dealt with briefly in the text (p. 59).

In fact, the textbook authors go to some length to recontextualise an open system such as the heating of an open beaker containing a liquid (a typical chemistry laboratory setting) as a closed

FIGURE 2.4

Two subsystems, I and II, are enclosed in a rigid adiabatic enclosure. System I consists solely of the liquid in the beaker for each case. System II consists of everything else in the enclosure, and is the surroundings for system 1. (a) The liquid is heated using a flame. (b) The liquid is heated using a resistive coil, through which an electric current flows.



system. This is managed by imagining a closed adiabatic boundary around it that does not allow the transfer of heat to the outside. (See Fig. 2.4, Engel & Reid, 2010, p. 20).

Engel and Reid justify this by explaining that only the part of the surroundings closest to the system interacts with the system:

Defining the surroundings as the rest of the universe is impractical, because it is not realistic to search through the whole universe to see if a mass has been raised or lowered and if the temperature of a reservoir has been changed. (p. 19)

In order to show that limiting interest in the 'surroundings' of a system to the *immediate* surroundings is a generalisable assumption, Engel and Reid propose an imaginary isolated composite system consisting of a rigid sealed reaction vessel with diathermal walls immersed in an inner water bath which is in turn immersed in an outer water bath that separates it from the rest of the universe (see Fig 2.3 p. 19). The outer water bath is kept at the same temperature as the inner water bath, so no heat will flow from the inner to the outer water bath. In this way the composite system (reaction vessel + inner water bath) is isolated from the rest of the universe, which can be disregarded in any process.

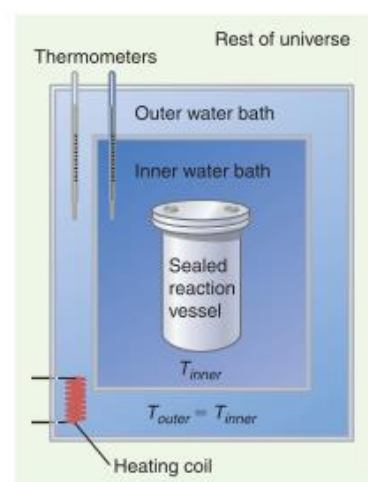


FIGURE 2.3
An isolated composite system is created in which the surroundings to the system of interest are limited in extent. The walls surrounding the inner water bath are rigid.

This fairly elaborate thought experiment is used to argue that only the immediate surroundings of a system are of interest. Effectively a 'new' closed system (system II) is created from the open system: system I is the beaker; system II is [system I + immediate surroundings]. This is an example of the high value placed on generalisability in the chemistry text, and the argument is based on plausible empirical conditions, even if they are virtual in this case.

In what at first glance looks like an interest in particulars, the chemistry authors briefly refer to examples of some real-life thermodynamics processes in the introduction to the textbook. The reason for this is explicitly stated as a motivation to demonstrate the usefulness and relevance of thermodynamics as a subject area. The examples could, interestingly enough, be considered typical (chemical) engineering examples: the first example refers to the yield from a plant built to synthesise ammonia gas from H_2 and N_2 being insufficient to make the process profitable. According to thermodynamics principles, the yield at equilibrium can be increased by increasing pressure and decreasing temperature. (The economic viability of a process is a typical engineering concern.) The second example describes a brief to use methanol to power a

car. An engineer designs an internal combustion engine that runs on the combustion of methanol. Another engineer designs a fuel cell. The claim is that the vehicle will travel further using the fuel cell. Thermodynamics makes it possible to compare the efficiencies of the two methods. (Improving the efficiency of a product is a classical engineering problem.) The third example refers to the need for a new battery to power a hybrid car. To provide the required voltage a significant number of electrochemical cells have to be connected in series, but because space is limited in the car, as few as possible need to be used. Lists of possible cell reactions and tabulated values of thermodynamic functions can be used to determine the number of cells needed. (This type of optimisation application is frequently used in engineering problems.)

It is important to note that apart from this brief mention in the introduction, the chemistry textbook authors *never* return to these types of problems anywhere in the textbook. The particulars present in the examples above are recruited in the service of the emphasis on universals. Problems in the textbook are always presented in a generalised, idealised laboratory setting.

The *specialisation* modality of the knowledge orientation in chemistry displayed here is therefore towards the *universals* or generalisations, rather than particular, specific instances. Any 'devices' (such as a piston and cylinder device) are presented as idealised conceptual tools for thinking about generalised conditions with no reference to real-life problem settings, and the secondary modality of idealisation is therefore directed towards the abstract-ideal theorisation of a laboratory setting.

Principal Mode: universals

Secondary Modality: idealisation,
Mode: abstract-ideal theorisation

Both mechanical engineering and chemical engineering distinguish between open and closed systems, which are dealt with extensively in the texts. In all instances the context is specific engineering devices and processes. The physics and chemistry textbooks, however, confine their discussions to closed systems, and although the chemistry text defines an open system, it is presented in idealised laboratory contexts, removed from the complexities of a real-world setting.

4.5 Enthalpy

4.5.1 Mechanical engineering: enthalpy

Cengel and Boles (2011) introduce enthalpy simply as one of the properties on the Property Tables (see the discussion under codified knowledge below).

The motivation for the introduction of this “combination property” (p. 124) is the recurring occurrence of the combination of flow energy and internal energy in important engineering applications in the context of the control volume: “[i]n the analysis of certain types of processes, particularly in power generation and refrigeration..., we frequently encounter the combination of properties $[U + PV]$. For the sake of *simplicity and convenience*, this combination is defined as a new property, enthalpy ... H ” (p.124, emphasis added).

The equation $H = U + PV$ is introduced without any further explanation, and its usefulness in control volume analyses “is the main reason for defining enthalpy” (p. 222), as it dispenses with the need to disaggregate flow work and flow energy. It is also important because it links energy to pressure and specific volume, two macroscopic properties of the vapour phase associated with the work done by gases, and which can be measured easily and directly. Enthalpy gives an indication of the total energy of a gas available as a result of its temperature and pressure. Enthalpy is discussed in more detail in the context of control volume analysis (see discussion in 5.2.1).

The context for enthalpy is therefore typical engineering applications, the singularly engineering notion of control volumes, and the convenience of a combination of frequently occurring energy types in engineering practice. Therefore, although the equation is general, I will code this mode instance as *particular*, with no secondary modality present for this knowledge content.

Principal Mode: particulars

No secondary modality/mode

4.5.2 Physics: enthalpy

The physics textbook author (Schroeder, 2000) starts his discussion of enthalpy H by pointing out that constant-pressure processes are common, both in the laboratory and in the natural world. He motivates the introduction of enthalpy to counter the tedium of keeping track of expansion-compression processes. Schroeder argues that instead of considering the energy

content (internal energy U) of a (closed) system, it makes sense to include “the work needed to make room for it” (p.33) at constant atmospheric pressure. This work is PV , the energy required “to push the atmosphere out of the way” (p.33).

Schroeder uses the same equation for the enthalpy as the mechanical engineering text: $H = U + PV$.

This is the *total* energy you would have to come up with, to create the system out of nothing and put it into this environment... Or, put another way, if you could somehow annihilate the system, the energy you could extract is not just U , but also the work (PV) done by the atmosphere as it collapses to fill the vacuum left behind. (p.33, emphasis in the original)

Even though the textbooks all agree on the equation that describes enthalpy ($H = U + PV$), this view of enthalpy is strikingly different from the way it was described in the mechanical engineering text, where the authors defined it as a concept of convenience, an often-encountered combination property that gives useful information in engineering control volume analyses. By contrast, the physics author interprets the property as work done against the atmosphere or by the atmosphere to ‘create’ or ‘annihilate’ a system.

This does not mean that that the concept is completely abstract in the physics text. Schroeder discusses practical examples, such as the small part of the energy needed to vaporise water (he quantifies it as about 8%) that is effectively the work needed to push the atmosphere away. Another example is given: when water forms from its constituent elements hydrogen gas and oxygen gas at constant pressure, energy (the heat of formation) is released. A small amount of this energy comes from work done by the atmosphere as it collapses to fill the space left behind by the O_2 and H_2 gas in the chemical reaction to form water.

The approach in the physics textbook, with its references to creating a generic system out of nothing or annihilating such a system, pushing the atmosphere out of the way to ‘make space’ for a system, or collapsing the atmosphere on obliteration of a generic system, is the reason for coding the knowledge about enthalpy as specialised towards *universals* in the physics textbook. This knowledge is neither idealised, nor normative.

Principal Mode: universals

No secondary modality/mode

4.5.3 Chemical engineering: enthalpy

In the chemical engineering textbook, Sandler introduces enthalpy as part of an energy balance (p. 49). Similar to what was done in the mechanical engineering textbook, Sandler proposes the convenience of simplifying an unwieldy equation: “This equation can be written in a more compact form by combining the first and last terms on the right side and introducing the notation $H = U + PV$ ” (p. 49-50). Enthalpy H is therefore a combination property, introduced without any derivation, and at this stage no physical meaning is attached to it.

Initially the approach to the knowledge about enthalpy here looks fairly general. However, soon specific engineering contexts are identified: “... some choices are especially convenient for solving certain types of problems. Thus, as we will see, an enthalpy-entropy Mollier diagram... is useful for problems involving turbines and compressors; enthalpy-pressure diagrams... are useful in solving refrigeration problems...” (p. 63). The author also points out that the equation is valid for real fluids (rather than only for an ideal gas), and for “solution of problems involving gases, liquids, solids, and mixtures thereof” (p.63). A so-called lever rule is introduced (without derivation) for calculations involving two-phase mixtures (typical of a chemical engineering context). The chemical engineering approach to enthalpy is clearly a functional, problem-centred approach rather than one concerned with theory-building and detailed explanation. The emphasis is on the use of the concepts to respond to empirical conditions presented by (chemical) engineering-type contexts, and for this reason the principal mode is coded as specialised towards *particulars*. No secondary modality is present.

Principal Mode: particulars

No secondary modality/mode

4.5.4 Chemistry: enthalpy

The chemistry textbook authors, Engel and Reid, derive an expression for enthalpy H in the context of wanting to determine the change in the internal energy of the system (p. 30-31). By limiting the conditions for the process to those during which no non-expansion work is possible (i.e. constant volume), they show that the change in internal energy (ΔU) is given by the heat flow (Q) at constant volume: $\Delta U = Q_v$. The argument is taken further for expansion-compression processes under reversible, constant pressure conditions, and it can be shown that $U + PV = Q_p$. A new state function H (enthalpy) is defined: $H = U + PV$, and at constant pressure the change in enthalpy ΔH is the heat flow Q_p between the system and surroundings. The textbook authors point out that chemical reactions are typically carried out at constant pressure rather than

constant volume (a reference to typical laboratory processes in open containers under atmospheric conditions, and expansion processes in piston cylinder devices). This means that when the energy change in a system is empirically monitored by measuring the heat flow between the system and surroundings, what is actually measured is the enthalpy change, rather than the change in internal energy. The importance attached to the empirical measurable property (and its physical meaning) is noteworthy. However, the discussion remains at a general abstract level: apart from the acknowledgement that most chemical reactions are carried out under constant pressure conditions, there is no specific discussion of the use of enthalpy in practical situations and devices. The careful derivation of the equation (as opposed to the simple introduction seen in both engineering texts), suggests a specialisation towards universals, rather than particulars in the case of chemistry here. No evidence of normative or idealised aspects can be seen here, and therefore no secondary modality has been coded.

Principal Mode: universals

No secondary modality/mode

4.6 Formulations of the First Law of Thermodynamics, sign conventions

4.6.1 Mechanical engineering: First Law of Thermodynamics, sign conventions

The nature of a physical law such as the First Law of Thermodynamics is explained by the authors of the mechanical engineering textbook:

[t]he first law cannot be proven mathematically, but no process in nature is known to have violated the first law, and this should be taken as sufficient proof. Note that if it were possible to prove the first law on the basis of other physical principles, the first law then would be a consequence of those other principles instead of being a fundamental physical law itself. (Cengel & Boles, 2011, p. 170)

The mechanical engineering textbook authors start with the general conservation of energy principle that “energy can neither be created nor destroyed during a process; it can only change forms” (p.70). This is used to develop an *energy balance* principle: “the net change (increase or decrease) in the total energy of a system during a process is equal to the difference between the total energy entering and the total energy leaving a system during a process” (p. 70), with the equation $E_{in} - E_{out} = \Delta E_{system}$. The quantity ΔE_{system} , the change in the total energy of the system, is comprehensive, and consists of changes in the internal energy ΔU , the change in kinetic

energy (ΔKE), and the change in the potential energy (ΔPE) of the system. If the system is stationary, there are no changes in KE or PE, and $\Delta E_{\text{system}} = \Delta U$.

Three mechanisms for energy transfers that can result in changes in the energy of the system are discussed: heat transfer Q , work transfer W , and mass flow m . This expands the energy equation:

$E_{\text{in}} - E_{\text{out}} = (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass,in}} - E_{\text{mass,out}}) = \Delta E_{\text{system}}$. Initially the discussion of the energy principle is kept at a fairly general level, and the way it changes for generic systems is discussed briefly: for adiabatic systems there are no heat transfers, so Q is zero; W falls away in systems where there is no work transfer, and in the case of closed systems the E_{mass} change is zero. Even though this discussion is general, the examples that follow explore implications of the First Law for a variety of devices and processes: cooling a hot fluid in a tank by stirring using a paddle wheel, the heating effect of a fan in a closed room, the rupture of a membrane between a pressurised air chamber and an evacuated one. For closed systems undergoing *cyclic work producing* processes, the final state is identical to the initial state, and ΔE is zero. This means that $E_{\text{in}} = E_{\text{out}}$, or that $Q_{\text{in}} = W_{\text{out}}$. The net work output during the cycle is equal to the net heat input in the cycle: $W_{\text{net out}} = Q_{\text{net in}}$. The emphasis on the work output is linked to the purposes of mechanical engineering devices where significant work output is the desired result. This notion will be expanded upon in chapter six.

As can be seen above, the textbook authors propose using a relaxed sign convention in the textbook:

the subscripts 'in' and 'out' denote quantities that enter and leave the system... All six quantities on the right side of the equation represent 'amounts', and thus they are positive quantities. The direction of any energy transfer is described by the subscripts 'in' and 'out'. (p. 73)

The authors believe that the equation then becomes more physically meaningful. However, the authors point out that this intuitive approach is easy to use when the magnitudes and directions of energy transfer are known, but less so for the times the energy transfer directions are unspecified. In this case, a direction for the energy transfers has to be assumed, and they choose to espouse the "classical thermodynamics sign convention" (p. 170) which assigns a positive sign to the heat flow *into* the system, Q_{in} , and the work done *by* the system, W_{out} . The equation associated with this sign convention for closed systems is $\Delta Q_{\text{in}} - \Delta W_{\text{out}} = \Delta E$. Here the notation " ΔE " is used rather than ΔU in recognition of the fact that some mechanical engineering systems are not stationary, but in motion, or involve an increase in PE.

What is interesting to note here is that the mechanical engineering textbook is the only one of the five texts considered in this project that uses this particular formulation of the basic equation, $\Delta Q_{in} - \Delta W_{out}$, of the First Law. Sign conventions are, by definition, an arbitrary choice (as long as the convention is used consistently, a physical system can be interpreted reliably). Even allowing for this arbitrary nature of sign conventions, the fact that mechanical engineering uses a different convention from the other three disciplines, is significant. The mechanical engineering textbook conceptualises the change in the internal energy of the system as the difference between the heat flowing into the system and the work done by the system. Implied in this conceptualisation is the assumption that the heat flowing into the system and the work done by the system is *positive*. This sign convention and equation used for the First Law in the mechanical engineering textbook speaks to the orientation of knowledge in mechanical engineering, namely the exploitation of the regularities in nature to solve problems or meet human needs. Heat engines have the purpose of changing heat energy into work energy. The emphasis in mechanical engineering is on work-producing devices. Intuitively it is more satisfying to get a positive answer, rather than a negative quantity, to the question, “How much work can be produced by this steam generator (or pump, etc.)?”

Interestingly, this argument is confirmed independently in the third year physics text, which uses the *opposite* sign convention. The author, Schroeder (2000), acknowledges in a footnote (p. 18) that some physics and engineering texts regard work (W) as positive when work-energy leaves the system, and that the First Law equation then becomes $\Delta E = Q - W$. He is of the opinion that this alternative convention might be “convenient when dealing with heat engines, but ... find[s] it confusing in other situations” (Schroeder, 2000, p. 18). Heat engines play an important role in mechanical engineering, therefore Schroeder’s observation endorses the way the mechanical engineering textbook authors state the First Law of thermodynamics as described in the thesis.

In the case of control volumes (open systems), the change in energy ΔE of a flowing fluid is given by the changes in the enthalpy, kinetic and potential energies of the fluid ($\Delta Q_{in} - \Delta W_{out} = \Delta H + \Delta PE + \Delta KE$). In the many cases where there is not appreciable change in the kinetic and potential energy of fluids, the First Law formulation simplifies to $\Delta Q_{in} - \Delta W_{out} = \Delta H$, and the change in enthalpy ΔH can easily be determined from the property tables. (Of course, in cases of high flow devices and pumps where fluids are pumped to different elevations, ΔPE and ΔKE cannot be neglected.) When the rate-form of the equation is used, the work W simply becomes the power-rating of the device, which further simplifies calculations. The energy balances for steady-flow systems (an application of the concept of a control volume) receive considerable attention in the mechanical engineering textbook (p. 224 – 240). This covers specific classes of

engineering devices, such as nozzles and diffusers, turbines and compressors, throttling valves, mixing chambers, heat exchangers, and pipe and duct flow.

Engineering artefacts are covered in some detail, demonstrating the commitment in the mechanical engineering textbook to apply the basic equations to practical working devices: nozzles increase the velocity and decrease the pressure of fluids; diffusers do the opposite; compressors, pumps and fans increase the pressure of the fluid and work is supplied from an external source (work *input*) to rotate the shaft. Turbines produce a work *output* as the fluid pushes against the blades to rotate the shaft, throttling valves (used in refrigeration) restrict the flow of fluids causing a significant pressure and temperature drop. There is also a (limited) discussion of unsteady flow of the kind encountered with charging and discharging of rigid tanks.

Even though the mechanical engineering discussion of the first law of thermodynamics and the sign convention is general, the comprehensive attention given to important and typical engineering devices signals the intent of the mechanical engineering textbook authors to induct students into the specifics of the discipline. The driving logic of the knowledge is towards *particulars*, rather than universals.

The knowledge is neither normative nor idealised, therefore no secondary modality has been identified here.

Principal Mode: Universals for the formulation of the law and its sign convention. Particulars in terms of the engineering devices considered. Particulars dominate.

No secondary modality/mode

4.6.2 Physics: First Law of Thermodynamics, sign conventions

As discussed earlier, the first year physics textbook does not deal with thermodynamics as a separate topic, and therefore does not refer to the laws of thermodynamics either, but uses the more general formulation of an energy principle:

The Energy Principle is a fundamental principle... The validity of the Energy Principle has been verified through a very wide variety of observations and experiments, involving large and small objects, moving slowly or at speeds near the speed of light, and even undergoing nuclear reactions that change the identity of objects. It is a summary of the way energy flows in the real world. (Chabay & Sherwood, 2011, p. 220)

Its statement of the Energy Principle is therefore broad and general, and the equation used reflects this: $\Delta E_{\text{system}} + \Delta E_{\text{surroundings}} = 0$. “The only way for a system to gain or lose energy, is if the surroundings lose or gain the same amount of energy” (Chabay & Sherwood, 2011, p. 221). *Generality* is the concern here. Chabay and Sherwood describe the Energy Principle as fundamental because

[i]t applies to every possible system, no matter how large or small... (from clusters of galaxies to subatomic particles)... [i]t is true for any kind of interaction (gravitational, electromagnetic, strong, weak)... it relates an effect (change in energy of a system) to a cause (an interaction with the surroundings) (Chabay & Sherwood, 2011, p. 221)

The mathematical argument for the Energy Principle is derived, considering the change in energy of a single particle as the result of work done by the surroundings on the particle. Chabay and Sherwood are concerned about potential confusion between the use of ‘heat’ as a scientific concept and the everyday use of the word. They therefore explain that they will avoid using ‘heat’ as a noun (in contrast to the mechanical engineering text), and prefer to speak of Q as the amount of energy that flows between a system and the surroundings as the result of a temperature difference between the system and surroundings. As discussed earlier in this chapter, the authors see Q as “microscopic work” (p. 301). The Energy Principle is updated to $\Delta E_{\text{system}} = Q + W$. This attention given by the physics authors to precise definitions and use of concepts signals their commitment to knowledge in the context of a theory.

The third year physics textbook (Schroeder, 2000) uses the equation $\Delta U = Q + W$, and describes it as simply a statement of the law of the conservation of energy: “the total change in the energy of a system is the sum of the heat added to it and the work done on it” (p. 19). Schroeder defines heat Q as any spontaneous flow of energy between objects as a result of a temperature difference between the objects. Work W is described as any other energy (other than heat) transfer into or out of a system. It is emphasised that both heat and work refer to energy in the process of transfer. The sign convention used in the physics textbook is to regard work done *on* a system as *positive*; the motivation for this is that it leads to an increase in the energy of the system. In a similar way, heat flow into a system is regarded as positive. Heat and work transfers *out* of the system will therefore be assigned a *negative* sign.

From the discussion above, it can be seen that the mode of the knowledge orientation is towards *universals*; the concerns are with general equations, and with derivation of equations for generalised instances. Since the knowledge is neither idealised nor normative, no secondary modality is assigned to the knowledge.

Principal Mode: universals

No secondary modality/mode

4.6.3 Chemical engineering: First Law of Thermodynamics, sign conventions

Sandler (2006) does not state the First Law of thermodynamics in any formal way. Although the chapter 3 heading is “Conservation of Energy” (p. 45), the exclusive focus of the chapter is on the implications of the First Law, i.e. in the derivation of energy balance equations for different (mostly general) scenarios. In fact, it is only in the following chapter, when entropy balances are introduced, that chapter 3 is referred to as dealing with the First Law of thermodynamics (the conservation of energy principle).

The data shows that *the rate of energy flow* is an important concept in chemical engineering. All of the energy balance equations are given in two forms: the differential form for rate-of-change in energy flow, and the difference form of the equations that calculate total changes. This is an indication of the concern in chemical engineering with industrial chemical processes where the overall yield, changes in concentrations, as well as the rate of change in the concentration of chemical species are important.

A generic ‘black-box’ balance equation is used as the starting point for derivations, as seen, for example, in the energy balances: rate of change in the total energy of the system = rate at which energy enters the system – rate at which energy leaves the system.

Similar to mechanical engineering, three different ways are recognised by which the energy flow into or out of a system takes place: work, heat and the energy accompanying mass flow (for closed systems only heat and work flows). The sign convention adopted in Sandler (2006) is to take energy flow *into* the system as *positive*, and out of the system as negative. The reasoning behind this sign convention and the accompanying balance equation is as follows: the total change in the internal energy of a closed system is the sum of the net changes in heat and work flow. Heat and work flow *into* the system *increases* the total internal energy of the system; if heat and work flow across the boundary out of the system, the total internal energy decreases. Therefore heat flow into the system is positive, but work done by the system is negative (different from the case in mechanical engineering where work done by the system was considered positive). For a closed system at rest at the reference position, the energy balance equation in chemical engineering is therefore given by $\Delta U = Q + W$.

Different kinds of work are discussed: flow work (in open systems) and two types of non-flow work (in closed systems). The notion of flow work is the same as that defined in mechanical engineering with the added description that it is “pressure induced energy flow” (p.49) in open systems. Non-flow work is either shaft work (with no distortion of boundaries) or boundary-

moving work (compression/expansion work, $W_{\text{compression}} = -P\Delta V$). By including these different kinds of work (as well as terms for moving systems with potential energy), and mass flow terms for open systems, Sandler is able to develop a much more general energy balance equation: “Since the mass and energy balances were formulated with great generality, they apply to any choice of system...” (Sandler, 2006, p. 70).

This can be given in the rate form (indicated by the ‘over-dot’ notation), i.e. indicating the speed at which the changes are occurring, for example:

$$\frac{d}{dt} \left\{ U + M \left(\frac{v^2}{2} + \varphi \right) \right\} = \sum_{k=1}^K \dot{M}_k \left(\hat{U} + \frac{v^2}{2} + \varphi \right) + \dot{Q} + W_s - P \frac{dV}{dt} + \sum_{k=1}^K \dot{M}_k (P\hat{V})_k$$
 (where U is internal, $\frac{v^2}{2}$ kinetic, and φ the potential energy per unit mass associated with the mass flow (Sandler, 2006, p. 49). Heat flow is denoted by $Q = \sum \dot{Q}_k$. Note that the subscript k refers to different streams of energy flow. This usage is peculiar to chemical engineering, and comes from the particular demands in chemical engineering industries where multiple reactant/product streams are common.

This rather unwieldy, but strikingly general equation is then applied to four types of systems: closed, adiabatic, open steady state and uniform (equilibrium) systems. This results in considerable simplification of the general equation in each case as certain terms fall away in the different systems. At this stage, the applications are still quite general, for example, a general closed or adiabatic system, rather than a specific one. A considerable part of the chapter is devoted to examples of applications: a compressor operating in a continuous, steady state manner, a frictionless piston and cylinder compressing a gas, the exhausting of a gas to the atmosphere via a pressure-reducing valve. These examples remain quite general, and the focus is on what the general equation simplifies to, rather than explicit specific examples. Some more distinctly engineering examples (with specific values for thermodynamic properties) are dealt with later in the chapter. These involve, for example, an adiabatic steady-state turbine with specific values for temperature and pressure at the inlet and outlet. Another example refers to a compressed-air tank to be repressurised under fairly idealised conditions.

Because the examples remain at a general level, with an interest in how the universal equation simplifies to under various general conditions, the knowledge here can be considered as primarily *specialised* towards *universals* in the formulation of the law and its sign convention. There is some evidence of particulars in terms of the engineering devices considered; however, universals dominate. The knowledge here displays neither normative nor idealised aspects, and therefore no secondary modality is assigned to the knowledge.

Principal Mode: Some particulars,
but universals dominate

No secondary modality/mode

4.6.4 Chemistry: First Law of Thermodynamics, sign conventions

Engel and Reid (2010) describe the First Law of thermodynamics in quite an abstract way as relating the change in the internal energy “ ΔU to the heat ...[Q] and work ... [W] that flows across the boundary between the system and surroundings” (p.15).

The internal energy is described at a molecular level consisting of the kinetic, potential, vibrational and rotational energy of the molecules that constitute the system. The chemistry textbook authors start their argument based on the empirical experience that energy cannot be created or destroyed and the internal energy of a system remains constant. This most general statement “looks uninteresting, because it suggests that nothing happens in an isolated system” (p.16). Engel and Reid extend the statement to a system in contact with its surroundings, and now the equation becomes $\Delta U_{\text{total}} = \Delta U_{\text{system}} + \Delta U_{\text{surroundings}} = 0$, or $\Delta U_{\text{system}} = -\Delta U_{\text{surroundings}}$, and, since the only way the internal energy of a system can change is by the flow of heat or work, $\Delta U = Q + W$ (note that the mass flow terms are absent, as the chemistry text does not consider open systems in any substantial way, as discussed under 4.4.4).

Work is described in the chemistry textbook in rather a mechanical (as opposed to a chemical) way: “... any quantity of energy that ‘flows’ across the boundary between the system and surroundings that can be used to change the height of a mass in the surroundings” (Engel & Reid, 2010, p. 16). Work done on the system is conceived of as the process of lowering or raising a weight on the piston of a frictionless cylinder (see Figure 2.1, p.16). The system here is the gas enclosed in an adiabatic cylinder and piston device. This piston and cylinder device is not in any way a ‘real’ device. It is an epistemic tool for thinking about a process quite removed from any empirical real apparatus. It is used to conceptualise the sign convention for the First Law employed in chemistry: if the weight is lowered, work is considered positive; if raised, work is negative. This sign convention implies that work done on the system by the surroundings is taken as positive (p.17). This is similar to the sign convention

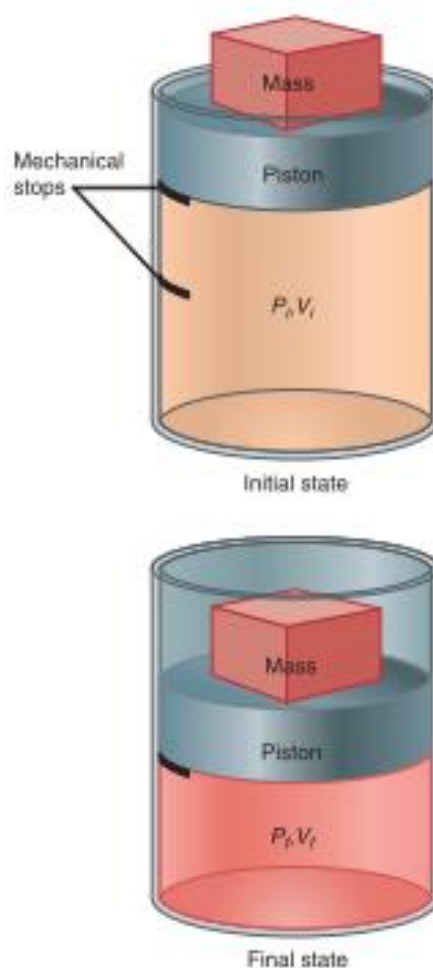


FIGURE 2.1
A system is shown in which compression work is being done on a gas. The walls are adiabatic.

used in chemical engineering and physics. Different types of work are briefly mentioned in the chemistry text. Some of these are similar to those addressed in the other textbooks (expansion work, electrical work), but also others that were not mentioned in the other textbooks: stretching of fibres, expansion of surfaces, reflecting some of the specialised chemistry interests.

Engel and Reid (2010) give an alternative formulation for the First Law by stating that the change in internal energy is independent of the path (the different steps of a process) between the initial and final state of the system, and only depends on the initial and final states. This is made plausible for kinetic energy and extended to other types of energy. The chemistry authors proceed to show that the same is not true for heat and work, where the process path determines the amounts of heat and work that flow. Internal energy is therefore a state function, and heat and work path functions. The discussion remains at a general level and is strengthened by a mathematical argument that uses an exact differential: the infinitesimal quantity, dU , only depends on the initial and final states when integrated $\Delta U = \int_i^f dU = U_f - U_i$. For any cyclic process the initial and final states are identical, and therefore there is no change in the internal energy of a system with a cyclic path: $\oint dU = 0$. The textbook authors mention that the cyclic integral for heat and work is not zero, but there is no discussion on the meaning of this.

The mode for the knowledge *specialisation* here is towards *universals* rather than specifics. There is no discussion beyond broad generalised principles that can be shown mathematically to be applicable to a range of generic systems. No secondary modality can be associated with the knowledge.

Principal Mode: universals

No secondary modality/mode

4.7 Codified knowledge (reference data)

There exist large amounts of reference data that are used in various kinds of scientific and engineering calculations. In the context of this study I will refer to this as codified knowledge. Among these are universal fundamental physical constants, physical properties of materials and elements, and conversion factors. International standardisation bodies, such as the Committee on Data for Science and Technology (CODATA) compiles, evaluate and disseminate reliable, multinational interdisciplinary data on a regular basis. Often numerical values are measured under standard conditions, and regular revision follows on advances in measuring techniques and instruments. This type of information is used as a matter of course in scientific and engineering work, and examples pertaining to thermodynamics can be found at the end of all of

the textbooks used in this project. These standard constants are used in equations linked to theories: the universal gas constant, R , is found in the Ideal Gas equation of state, $PV = NRT$, and the model or theory it refers to is the Ideal Gas model. The values of constants such as these can be considered generalised knowledge in their association with theoretical *universal* equations and theories.

A second type of reference data refers to tables of thermodynamic properties of water and specific refrigerants. This *particular* type of knowledge is often disseminated in graphs and diagrams, has an empirical origin and requires the user to make decisions about the appropriate selection of the data from the tables and diagrams. The data could be considered to have procedural aspects associated with it, and provides codified information across ranges of *particular* empirical contexts.

4.7.1 Mechanical engineering: codified knowledge (reference data)

The mechanical engineering textbook has a relatively short list of standardised constants (of the first type described above) at the end of the textbook, and includes standard gravitational acceleration, Boltzmann constant, the universal gas constant, given in no less than seven different units, standard atmospheric pressure (in six different units), etc. In keeping with the need for engineers to be able to convert between different metric and non-metric units, conversion factors for a variety of dimensions are given. This is indicative of the professional environment engineers have to operate in. In industry, devices manufactured in different parts of the world will have operating conditions specified in any number of non-standard units.

In addition to the standardised constants mentioned above, Cengel and Boles (2011) include a comprehensive appendix of 52 pages of thermodynamics reference data. Some of this is similar to what is found in the chemistry textbook discussed later (eg. ideal gas properties of selected gases, enthalpy and Gibbs function of formation of a very limited selection of elements and compounds). However, there are some notable exceptions, and my focus here will be on the comprehensive thermodynamics property tables and charts for water and refrigerant 134-a (see the excerpt of Table A-4, p. 911²¹), described as procedural data above.

²¹ All images used from Cengel, Y., & Boles, M. *Thermodynamics: an engineering approach* (7th ed.). Boston: McGraw-Hill, © 2011, reproduced with permission from McGraw-Hill Education (Asia).

TABLE A-4

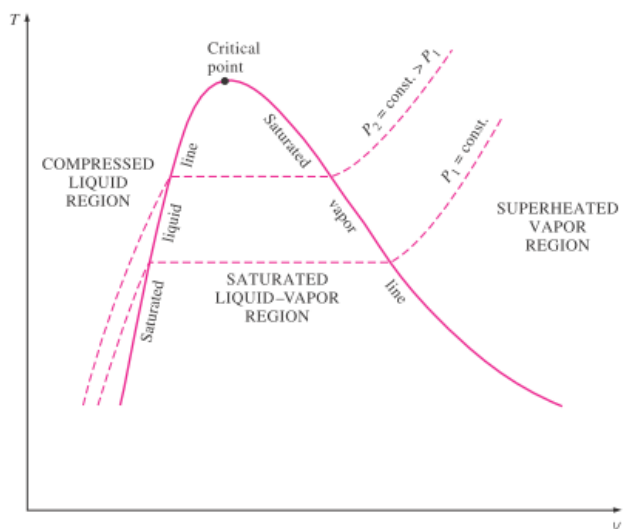
Saturated water—Temperature table (Continued)

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, $kJ/kg \cdot K$		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
205	1724.3	0.001164	0.11508	872.86	1723.5	2596.4	874.87	1920.0	2794.8	2.3776	4.0154	6.3930
210	1907.7	0.001173	0.10429	895.38	1702.9	2598.3	897.61	1899.7	2797.3	2.4245	3.9318	6.3563
215	2105.9	0.001181	0.094680	918.02	1681.9	2599.9	920.50	1878.8	2799.3	2.4712	3.8489	6.3200
220	2319.6	0.001190	0.086094	940.79	1660.5	2601.3	943.55	1857.4	2801.0	2.5176	3.7664	6.2840
225	2549.7	0.001199	0.078405	963.70	1638.6	2602.3	966.76	1835.4	2802.2	2.5639	3.6844	6.2483
230	2797.1	0.001209	0.071505	986.76	1616.1	2602.9	990.14	1812.8	2802.9	2.6100	3.6028	6.2128
235	3062.6	0.001219	0.065300	1010.0	1593.2	2603.2	1013.7	1789.5	2803.2	2.6560	3.5216	6.1775
240	3347.0	0.001229	0.059707	1033.4	1569.8	2603.1	1037.5	1765.5	2803.0	2.7018	3.4405	6.1424
245	3651.2	0.001240	0.054656	1056.9	1545.7	2602.7	1061.5	1740.8	2802.2	2.7476	3.3596	6.1072
250	3976.2	0.001252	0.050085	1080.7	1521.1	2601.8	1085.7	1715.3	2801.0	2.7933	3.2788	6.0721
255	4322.9	0.001263	0.045941	1104.7	1495.8	2600.5	1110.1	1689.0	2799.1	2.8390	3.1979	6.0369
260	4692.3	0.001276	0.042175	1128.8	1469.9	2598.7	1134.8	1661.8	2796.6	2.8847	3.1169	6.0017
265	5085.3	0.001289	0.038748	1153.3	1443.2	2596.5	1159.8	1633.7	2793.5	2.9304	3.0358	5.9662
270	5503.0	0.001303	0.035622	1177.9	1415.7	2593.7	1185.1	1604.6	2789.7	2.9762	2.9542	5.9305
275	5946.4	0.001317	0.032767	1202.9	1387.4	2590.3	1210.7	1574.5	2785.2	3.0221	2.8723	5.8944

This type of data does not appear in either the chemistry or the physics textbooks, and is therefore peculiar to engineering thermodynamics. Cengel and Boles identify the sources used for the standardised tables, as seen, for example, in the table issued by the International Association for the Properties of Water and Steam (Wagner *et al.*, 2000).

Thermodynamic property tables are indispensable for the problems engineers face in practice. Some engineering devices (like power generators and refrigerators) rely for their functioning on energy transformations associated with phase change of working fluids like water (steam) and refrigerants. During phase change, the relationships between properties like temperature, specific volume and pressure change. Plotting the changes gives rise to property diagrams, “great visual aids in the thermodynamic analysis of processes” (Cengel & Boles, 2011, p. 340). Different regions are identified on the property diagrams (see Fig. 3-18, p.120), and students need to familiarise themselves with each of these.

FIGURE 3-1
Property diagram of a pure substance.



The thermodynamic property tables in the appendix to the textbook are used in conjunction with property diagrams. The regions from the property diagrams are represented on different tables: saturated water (temperature table), saturated water (pressure table), superheated water, compressed liquid water, saturated ice-water vapour, similar tables for a commonly used refrigerant, “[f]or most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations” (Cengel & Boles, 2011, p. 124). Some of the properties on the tables can be measured, but others have to be calculated, and these measured and calculated quantities make up the thermodynamic tables which appear in the appendix to the textbook. The calculations are not simple; properties are interdependent, in some case on more than one variable.

Mechanical engineering students use the property diagrams and tables to solve problems. Students need to develop an almost physical orientation to the diagrams: the first task in solving a problem is to locate the problem in one of the regions on the diagrams. This determines which property table to consult for actual values. The process involves significantly more than simply reading off values in the table; some procedural knowledge is required for solving thermodynamic problems. The tables give discrete values for properties in small ‘steps’ of 5 °C or 5 kPa intervals. Students need to master the technique of *interpolation* to find values in between. Linear interpolation is an approximation where known data points are treated as if the properties fit a linear relation. Since the gaps are small with data points close together, any error arising from the approximation is small enough to be acceptable. *Interpolation* is a way to estimate a value that lies in between two *known or measured* values, within the measured range of data. *Extrapolation* (common in extending the predictive range of empirical work, but *not* used here), on the other hand, is predicting a value *beyond what is known or has been measured* (and therefore subject to greater uncertainty), on the basis of being part of a trend. It can therefore be argued that there is greater confidence about interpolated than about extrapolated data. This is important in engineering science where risk, safety and cost are concerns.

Although the mechanical engineering textbook uses the customary universal standardised constants, mastery of the codified knowledge in property diagrams and tables is a crucial element of the thermodynamics curriculum in mechanical engineering, and the principal mode of the specialisation modality is therefore coded as *particulars*. The knowledge considered here is neither idealised, nor normative; therefore no secondary modality is associated with the codified knowledge described here.

Principal Mode: particulars

No secondary modality/mode

4.7.2 Physics: codified knowledge (reference data)

The physics textbooks contain the usual fundamental physical constants such as the universal gravitation $G = 6.673 \times 10^{-11} \text{N.m}^2/\text{kg}^2$, Avogadro's number, Planck's constant, Boltzmann constant, the ideal gas constant R , amongst others. Since the first year textbook (Chabay & Sherwood, 2011) is a broad introduction to mechanics in general (rather than only thermodynamics), it also gives physical constants for use in electricity. These represent an emphasis on *universals*. These fundamental constants are common across disciplinary (science and engineering) fields, and associated with equations and theories.

Schroeder's (2000) third year thermodynamics textbook adds a few unit conversions to allow for calculations between different units, and some thermodynamic properties of selected substances. These properties are limited, both in the number of elements and compounds represented, and also in the conditions under which measurements and calculations of the values have been done: all values are given for 1 mole of substance at room temperature (298K) and atmospheric pressure (1 bar).

In the chapter on Engines and Refrigerators, Schroeder deals briefly with the steam engine as an example of a heat engine operating on the Rankine cycle. He introduces the idea of tabulated data in the context of efficiency calculations: "...you can look up the data needed to compute the efficiency in what are called 'steam tables'" (p. 134). Schroeder gives a brief extract from a rather dated standardised table (Keenan *et al.*, 1978) but it is for illustrative purposes: only 6 values are given on two tables (see for example Schroeder (2000), Table 4.1 on p. 136), compared to the more than 50 pages in the mechanical engineering text.

T (°C)	P (bar)	H_{water} (kJ)	H_{steam} (kJ)	S_{water} (kJ/K)	S_{steam} (kJ/K)
0	0.006	0	2501	0	9.156
10	0.012	42	2520	0.151	8.901
20	0.023	84	2538	0.297	8.667
30	0.042	126	2556	0.437	8.453
50	0.123	209	2592	0.704	8.076
100	1.013	419	2676	1.307	7.355

Table 4.1 Properties of saturated water/steam. Pressures are given in bars, where 1 bar = $10^5 \text{ Pa} \approx 1 \text{ atm}$. All values are for 1 kg of fluid, and are measured relative to liquid water at the triple point (0.01° C and 0.006 bar). Excerpted from Keenan *et al.* (1978).

Therefore, even though Schroeder acknowledges the *existence of steam* tables (no mention of phase diagrams or Mollier diagrams), there is no expectation that the physics students will need

(or be expected) to use these. There is simply not enough scope in the six values given for students to engage with the table in any procedural way.

Other than the brief reference to a few steam table values in the third year text, the physics textbooks focus on universals of the fundamental constants rather than on the particulars of the procedural codified knowledge of the thermodynamics tables and graphs. The predominant overall orientation of the physics disciplinary knowledge here is therefore coded as towards universals, with no secondary modality present.

Principal Mode: universals

No secondary modality/mode

4.7.3 Chemical engineering: codified knowledge (reference data)

In appendices to his chemical engineering textbook, Sandler(2006) provides similar fundamental physical constants that are used in standard scientific and engineering calculations. The textbook also contains lists of conversion factors between non-metric and SI units, similar to those in the mechanical engineering text. The standardised constants are further represented in the tables of molar heat capacities of selected groups of gases under standard ideal gas conditions (“Zero-Pressure State”, p. 914-916). A fairly comprehensive list of standard enthalpies and Gibbs energies of formation, as well as a table of heats of combustion are provided. This is similar to the tables in the physical chemistry textbook (Engel & Reid, 2010). This is to be expected, since chemical engineering and chemistry share a concern for the synthesis of chemical compounds that is less prominent in mechanical engineering and physics.

The chemical engineering textbook uses the balance equations for mass and energy to relate the mass, work and heat flows of systems to changes in their thermodynamic properties. However, some properties (like temperature and pressure) are much easier to measure directly empirically than others. Therefore it is more desirable to specify the state of a system by using temperature and pressure rather than specific volume, enthalpy or internal energy. Ideally, what is needed therefore, are interrelations that will allow for expressing some of the properties in terms of the more easily measured ones. As was the case in the mechanical engineering textbook, Sandler provides students with thermodynamic property data for water and steam (no tables for a refrigerant are provided, in line with the different concerns of chemical engineering compared to mechanical engineering). This *codified* knowledge is presented in either graphical or tabular forms, and can be considered to be *procedural*, as it requires more knowledge than merely substituting a standard constant value into an equation.

The graphical representations are detailed and dense, as seen, for instance, in the pressure-enthalpy diagram for methane, (Sandler (2006), Fig 3.3-2 p.66)

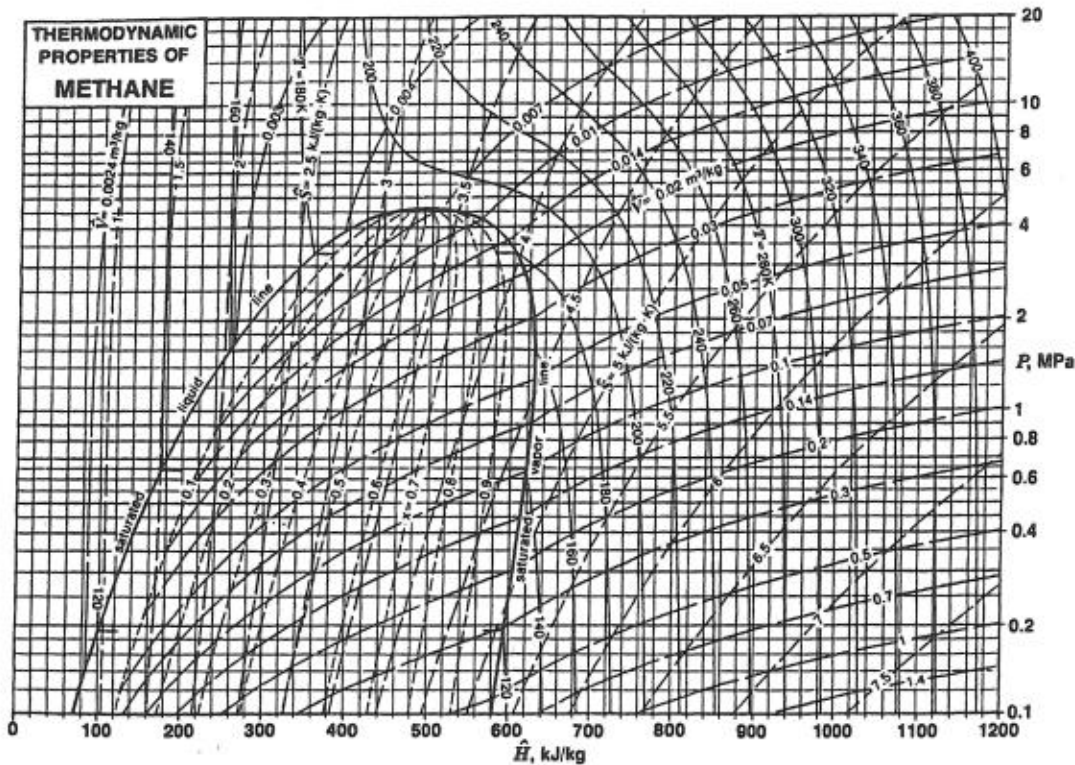


Figure 3.3-2 Pressure-enthalpy diagram for methane.

The variables are chosen because of their usefulness for certain types of problems: these can be H-S (turbines and compressors), H-P (refrigeration problems), T-S (for engines and power & refrigeration cycles). The graphs are less accurate for data that lie between graph lines and in parts of the diagram where the lines are close together. For this reason, Sandler proposes the use of tables of thermodynamic data, although interpolation will still be needed for data in between the discrete data points. Chemical engineering students are required to master similar *procedures* as the mechanical engineering students in order to use the diagrams and tables to solve typical chemical engineering problems. Therefore, although the typical scientific universal constants are present in the textbook, the codified knowledge leans towards *particulars*. The codified knowledge displays neither idealised, nor normative, properties and no secondary modality and mode can be identified.

Principal Mode: particulars

No secondary modality/mode

4.7.4 Chemistry: codified knowledge (reference data)

The focus of Engel and Reid's (2010) physical chemistry book is not exclusively on thermodynamics, and the fundamental physical constants in the appendix at the end of the book are therefore more comprehensive. They include physical properties (melting and boiling points, density and heat capacity) of a selection of common elements and compounds under standard conditions, thermodynamics data for selected organic and inorganic compounds, also under standard conditions, second virial coefficients and Van der Waals and Redlich-Kwong parameters for selected gases, etc. Standard reduction potentials and Gibbs function values are also provided as would be expected in a physical chemistry text. The authors list their sources for each table of data, examples are the Handbook of Chemistry and Physics (Lide, 2004), Thermochemical data of organic compounds (Pedley, Naylor, & Kirby, 1986).

There is a complete absence of codified *procedural* knowledge in the form of steam and refrigerant tables, Mollier diagrams and phase diagrams. There is therefore no procedural engagement with particular empirical conditions and problems of the kind seen in the engineering courses. The chemistry knowledge discussed here is kept at a general, universal level.

Principal Mode: universals

No secondary modality/mode

4.8 Concluding remarks

This chapter provides illustrative cases of the specialisation modality as evident in each of the textbooks. The data discussed here therefore displayed the specialisation modality as the principal modality. In each case the data was coded according to the dominant modal tendency (either towards universals or particulars).

The coding predominantly illustrates the prevailing tendency for the engineering sciences to specialise towards specific cases, or particulars²². This contrasts with the general tendency of knowledge in the sciences presented here to specialise towards universals. This overall tendency is not unqualified, though. In a few cases chemical engineering knowledge presented a

²² Describing the engineering sciences as specialised towards particulars, does not mean that there is *no evidence* of the use of universals in engineering science. Indeed, engineering sciences would not be 'scientific' (in the sense of following the scientific method in its investigation of phenomena) if they did not generalise or universalise (as pointed out by de Vries (2010)). Coding a data unit as specialised towards the particulars, indicates an added quality and that something other than the universality of the concept alone is valued. This 'something other' is the employment of knowledge towards specific problem solving or artefactual use.

specialisation that evidenced a concern for universals that were absent in the mechanical engineering knowledge. I return to this in the Discussion chapter.

It is interesting to note that very few secondary modalities were identified in the data presented, i.e. the data was seldom normative or idealised. Together with the fact that the data cut across similar themes in all four disciplines, this trend present an early indication that the orientation of the knowledge towards specialisation (either to universals or to particulars) may be of a different order to the other two modalities. This is expanded upon in the Discussion chapter. A summary of the data presented here is captured in Appendix A.

In chapter five following here, I present illustrative cases where the principal modality of the data is idealisation.

Chapter 5 Findings and Analysis of the data – Idealisation modality

With thermodynamics, one can calculate almost everything crudely; with kinetic theory, one can calculate fewer things, but more accurately; and with statistical mechanics, one can calculate almost nothing exactly. Eugene Wigner

This chapter continues the presentation of the data generated from the analytical framework. In the preceding chapter, the focus was on the specialisation modality as it presented in the data as the principal modality. The current chapter takes as its focus idealisation as the *principal* modality displayed in the disciplinary knowledge. The concept of idealisation functions as the primary analytical 'lens' for examining the thermodynamics knowledge presented in the texts, generating units of analysis for coding. The organisation of chapters five and six (following) differs from chapter four, in that chapters five and six present illustrative instances of the modalities present in the knowledge, in some cases across common topics, in others unique, solitary instances in a particular disciplinary field. It is about presences and absences, often (but not always) generating unique units of analysis in the sub-cases.

5.1 Idealisation as principal modality

In chapter two, idealisation is described as the intentional, selective introduction of distortion of reality for various purposes, for example, simplification in order to gain traction to solve difficult problems, stripping of non-essential features for the purpose of approximation, or modelling to explain behaviour across general cases. The current chapter tracks instances of idealisation found in the knowledge presented in the textbooks used in the four disciplinary fields.

As explained in chapter three, idealisation as a knowledge modality is operationalised in two modes developed to reflect the fundamental disciplinary values: does the idealisation ultimately move the thinking towards *physical realisability* (responding to a problem or need), or is it about *abstract-ideal theorisation* (assimilating ideas in theories about reality with explanatory power)? The data units were coded for one of the two modes of idealisation, either physical realisability or abstract-ideal theorisation. Each unit of data identified was subsequently also considered in terms of the other modalities (specialisation and normativity), and coded for these secondary modalities and modes where appropriate.

5.2 Mechanical engineering

5.2.1 Control Volume Analysis

Control volume analysis (CVA) is a systematic technique peculiar to the engineering sciences (Houkes, 2009; Pirtle, 2010; Vincenti, 1990). The mechanical engineering textbook authors, Cengel and Boles (2011), confirm CVA as a categorically engineering approach, developed for solving distinctive engineering problems of flow of fluids in *open* systems.

A large number of engineering problems involve mass flow in and out of a system and, therefore, are modeled as *control volumes*. A water heater, a car radiator, a turbine, and a compressor all involve mass flow and should be analysed as control volumes (open systems) instead of as control masses (closed systems). (Cengel & Boles, 2011, p. 11, emphasis in the original)

Control volume analysis is therefore a problem-solving approach or 'tool' that allows engineers to grapple with conditions typical in engineering (see also the tank-filling problem later in this chapter, discussed under chemical engineering).

Cengel and Boles (2011) even formulate the conservation of mass principle (one of the 'big' conservation laws in the natural sciences) explicitly in terms of the rate of flow through control volumes: "The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt " (p. 216).

A related idea that has relevance for open systems (rather than closed systems) is the notion of 'rate of flow'. In engineering, it is important to know, not only *how much* work a fluid can do as it moves through a control volume, or *how much* energy can be extracted from the moving fluid, but also *the rate* at which work is done and energy transferred. The faster the flow, the larger the amount of energy that can be transferred in a given time. The emphasis is often on mass flow rates rather than on the amount of fluid itself. The velocity of the flow influences normative aspects of engineering concerns: how long does it take to discharge the tank? How much fluid flows in a given time? Control volume analysis is therefore a valuable method for engineers to obtain crucial 'big-picture' information about issues like the temperature drop of steam across a turbine, the amount of heat that has to be supplied to incoming cold water in a water heater in order to supply a steady stream of hot water at the outlet, and energy flows associated with charging and discharging of vessels like tanks.

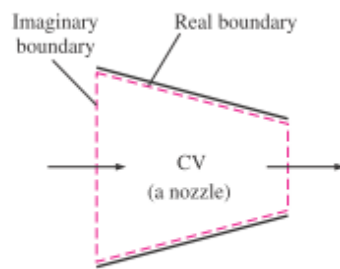
Control volume

boundaries (like any system boundary, closed systems included) can be real or imaginary, fixed or moveable. Often the inside of a device is selected as the control volume, for example, the inside of a nozzle through which a

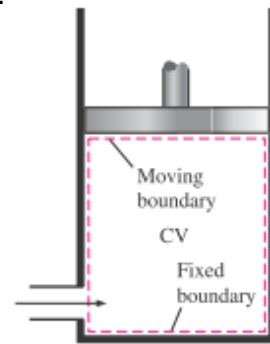
fluid flows. See for example Fig 1.22 p. 12 (inside of a nozzle or inside of a piston-cylinder device). Cengel and Boles point out that “[m]athematically speaking, the boundary has zero thickness, and thus it can neither contain any mass nor occupy any volume in space” (p. 10). Postulating the boundary in this way shifts the attention away from the boundary; the nature of the boundary itself is unimportant in control volume analysis. This is an example of the minimalist type of idealisation posited by Weisberg (2007a): non-essential features are removed from consideration. However, even though the *nature* of the boundary does not impact on the problem, the *position* of the boundary is of crucial importance in control volume analysis. The position of the boundary is discretionary (i.e. not prescribed), but a judicious choice simplifies the analysis of control volumes: “[t]here are no concrete rules for the selection of a control volume, but the proper choice certainly makes the analysis much easier” (Cengel & Boles, 2011, p. 11). Selecting the control volume boundaries in such a way that some of the conditions are known (or can be measured), makes it possible to calculate unknown parameters by using relatively simple balance equations. The reason for this is that the engineer’s interest is seldom in the detailed modelling of flow through a device; the locus of interest lies in the entrance and exit conditions and the overall results (Pirtle, 2010; Vincenti, 1990). The control volume itself is treated as a black box: what goes on inside the black box can be neglected; it is the boundary conditions that are of interest. It is in this sense that there is a simplification (or idealisation): detail of the fluid flow through the control volume is ignored, and boundary conditions are all that is considered.

The global or ‘big-picture’ nature of the control volume analysis approach does not imply that only approximate information can be gleaned from it; CVA has been theorised in engineering thermodynamics in some detail. An example of this theorisation can be seen in the discussion of flow work and the energy associated with a flowing mass of a fluid through a control volume (Cengel & Boles, 2011, p. 221).

FIGURE 1-22



(a) A control volume with real and imaginary boundaries



(b) A control volume with fixed and moving boundaries

Pushing mass into or out of the control volume requires work, and therefore a flowing fluid has an extra amount of energy associated with it, the flow energy. The fluid is imagined as consisting of fluid elements (small enough to treat as if their properties are uniform) that can be considered separately. For a fluid element about to enter the control volume, the fluid immediately upstream of it acts as an *imaginary piston* pushing the fluid element into the control volume (see Fig 5-11 p.

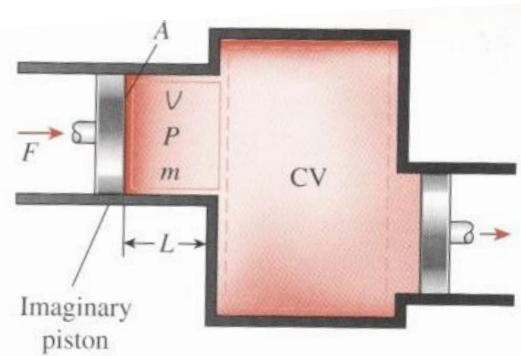


FIGURE 5–11
Schematic for flow work

221). The work done here by the imaginary piston is the flow work (or flow energy): $W_{\text{flow}} = PV$. Therefore the energy transported by the mass of a flowing fluid is given by $E_{\text{mass}} = PV + u + v^2/2 + gz$ (flow energy + internal energy + kinetic energy + potential energy).

At first glance the model described above seems quite theoretical: an imaginary piston performs work by pushing a fluid element into a control volume. Its main purpose seems to be to serve as an explanatory model for fluid movement through a control volume (the boundaries of which could themselves in principle be a theoretical construct). In some ways this is similar to the kind of idealisation one would expect to see in the sciences. However, by grouping together flow and internal energies to give enthalpy ($H = PV + U$), energy analysis of the control volume becomes relatively simple and practical. The energy due to the flowing mass of a fluid is given by adding enthalpy, kinetic and potential energy of the fluid, and there is no need to consider separately the extra energy required to push a fluid into or out of a control volume. Since enthalpy values can be found on Property Tables, it becomes a relatively straightforward matter to calculate the energy of a fluid in motion. The idealisation present in theorising the mechanism whereby fluids move through a control volume, ultimately allows for a direct and pragmatic calculation of boundary conditions of engineering devices.

The use of CVA is applied extensively to a number of steady-flow systems and devices. Cengel and Boles (2011) call steady-flow processes “somewhat idealized” (p. 224). It is assumed that even though fluid properties may vary in different places in the control volume, the properties remain constant at any particular point in the fluid for the duration of the steady-flow process. This is an example of an instance where the engineering science espouses a *limited* form of idealisation, and since the distortion so introduced remains within a tolerable range, it is acceptable. The authors point out that the approximation associated with the idealisation is reasonable in the context of engineering devices: “a large number of engineering devices such as turbines, compressors, and nozzles operate for long periods of time under the same conditions

once the transient start-up period is completed and steady operation is established” (Cengel & Boles, 2011, p. 224). The mechanical engineering textbook devotes considerable space (13 pages) to the discussion of each of these classes of engineering devices and approaches to calculations for each one: pumps and compressors transfer energy to fluids by increasing the pressure on the fluid; a turbine extracts energy from a fluid by decreasing its pressure; nozzles increase the velocity of fluids at the expense of pressure; fans mobilise gases by a slight increase in the pressure of the gas; throttling valves restrict the flow of fluids by decreasing the pressure on a fluid, causing a significant drop in the temperature of the fluid which makes them indispensable in refrigeration.

It is therefore clear that the notion of the control volume provides a conceptual tool for thinking about fluid flow through devices that rely on measurements and data readily available to the engineer in the Property Tables. The principal modality is idealisation (mode physical realisability) as a result of the idealised nature of the black box thinking employed.

Because of the peculiarly engineering nature of CVA, and its application to specialised engineering devices, the secondary modality is coded as specialisation (mode particulars).

Principal Mode: Physical
realisability

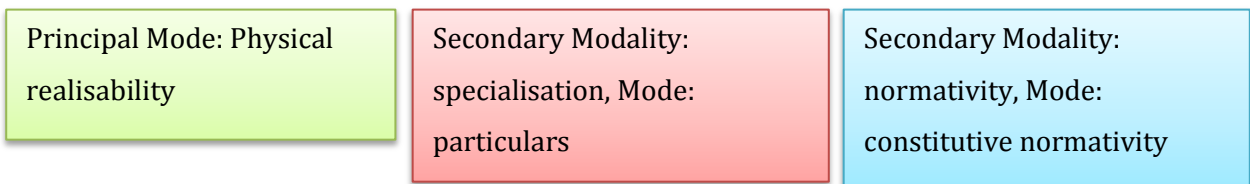
Secondary Modality:
specialisation, Mode: particulars

5.2.2 Quasi-equilibrium processes

“Moving boundary work or PdV work” (Cengel & Boles, 2011, p. 163) is common in reciprocating devices like car engines and compressors. However, because of the high speed piston movement of *real* engines and compressors, it is not possible for the gases inside the cylinder to maintain equilibrium. This means that the states through which the system passes cannot be determined analytically, and direct measurement is the only way such *real* systems can be analysed (plotting empirical measurements of P (pressure) against V (volume) and calculating the area under the PV curve for processes in real engines and compressors). However, thermodynamic analysis using equations *is* possible in the case of moving boundary work for *idealised* processes. A quasi-equilibrium process is one during which the system effectively remains in internal equilibrium at all times. This idealised process proceeds so slowly that it is possible for the system to return to the equilibrium position, and for properties to remain essentially constant. It is therefore possible to identify the states through which the system passes. The nett work W can be calculated from the integral $W = \int_1^2 P dV$ for a quasi-equilibrium process.

Why would the mechanical engineering textbook authors spend time on an ideal process that does not describe real engines and compressors? According to Cengel and Boles (2011) there is a twofold value in considering these idealised types of processes: firstly, some real engines approximate this type of process “with negligible error” (p.16) when the piston moves slowly. Secondly, and more importantly, under identical conditions during quasi-equilibrium processes the work output of an engine is found to be a maximum, and the work input into a compressor a minimum. The idealised quasi-equilibrium process²³ therefore presents a limiting case that can easily be analysed, and therefore be recruited for the purpose of giving insight into real processes. This comparison between ideal and real processes introduces a normative orientation in the sense that it invites a judgement call and potential action.

As a result, although an idealised process, the context in which quasi-equilibrium processes is discussed in the mechanical engineering text is the insight it gives into *real* processes, and the principal coding mode is therefore for *physical realisability*. Secondary coding for specialisation is towards the *particulars* of real engineering devices, and *constitutive normativity* for the comparison to a theoretical maximum of work that is possible to produce.



5.2.3 Carnot cycle

Another use of idealisation in mechanical engineering is seen in the way a particular type of quasi-equilibrium processes, namely reversible processes, are handled in the mechanical engineering textbook in the discussion of the Carnot cycle: “A reversible process is... a process that can be reversed without leaving any trace on the surroundings ... Reversible processes actually do not occur in nature. They are merely *idealizations* of actual processes” (p. 290, 291, emphasis in the original). Cengel and Boles give two reasons for “bothering with such fictitious processes ... First, they are easy to analyse... [and secondly,] they serve as idealized models to which actual processes can be compared” (p.191).

²³ Although quasi-equilibrium processes are considered across all of the disciplines, the mechanical engineering authors are the only ones who justify the consideration of the *idealised* process as useful for the information it gives as a limiting case in comparison to *real* processes (see the discussion on efficiency in the following chapter).

The Carnot cycle is a standard topic in any introductory thermodynamics course, and present in all the course textbooks under consideration. A Carnot heat engine is an *idealised* heat engine operating on the Carnot cycle. The cycle consists of four completely reversible processes, and gives the theoretical maximum efficiency of a heat engine that operates between two particular temperatures. These aspects are present in all discussions of the Carnot cycle in all of the texts. The mechanical engineering authors take this further.

A Carnot heat engine presents an example of Galilean idealisation as discussed by Weisberg (2007a) with ‘completeness’ as its goal. According to Weisberg ‘completeness’ has both an evaluative and regulative function as an idealisation, and both of these are present in the way the mechanical engineering authors use the Carnot cycle.

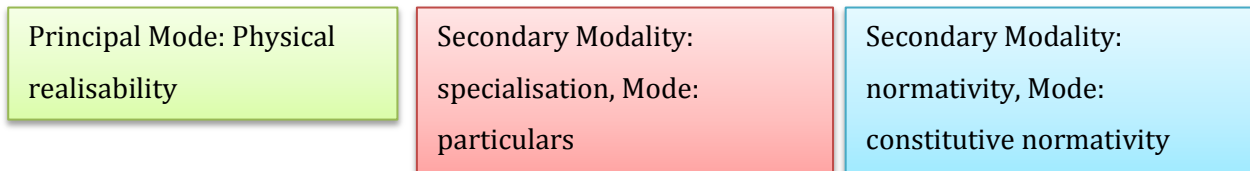
Firstly, by comparing real engines operating between the same two temperatures to the ideal Carnot heat engine, it becomes possible for the engineer to judge the performance of different *real* devices on the basis of how closely they correspond to the ideal. This is the *evaluative* function of the idealisation. Secondly, Galilean idealisation of this kind also has a *regulative* function. In the mechanical engineering textbook, the authors explain that knowledge of the maximum possible heat engine efficiency between two temperatures, is used by the engineer to direct the design of a real engine operating between the same temperatures towards lowering the irreversibilities in the device. The theoretical maximum efficiency is known and fixed, and any improvement of a real device has to be directed at improving the irreversibilities present in the real device.

As discussed in chapter two, with Galilean idealisation distortion is often temporary. This is not the case here: there is no attempt to re-introduce complexity of the irreversible processes at a later point. The ideal Carnot cycle is essentially a thinking tool for the engineer. The Carnot principles that follow from the Second Law of Thermodynamics give the engineer all she needs:

- Reversible (ideal) heat engines always have a higher efficiency than irreversible (real) ones operating between the same temperatures
- All reversible heat engines operating between the same two temperature reservoirs have the same efficiency

It is therefore possible to compare the performance of different devices designed to do the same task. The better device will be the one with fewer irreversibilities and with efficiencies closer to the theoretical limit set by the reversible processes. The purpose of considering the Carnot cycle here is to use it as a standard against which to compare real physical devices.

In the treatment of the Carnot cycle, the mechanical engineering textbook illustrates how the logic of the knowledge pushes the *idealisation* employed towards the *physical realisability* of engineering devices. Two secondary modalities are also present: the knowledge is *specialised* towards the *particulars* of specific engineering devices and processes, and the knowledge displays *constitutive normativity* in the decisions made possible for the design and comparison of different real devices to the upper limit of efficiency posed in the ideal Carnot cycle.



5.2.4 Approximation

The use of approximation is a form of idealisation: wittingly using an inexact or rough measure or estimate that introduces a form of distortion of reality. This is acceptable and even common in engineering, provided that the effect of the distortion is small enough not to compromise the functionality and safety of the device or process.

An instance of this can be seen in the mechanical engineering textbook when the authors caution students against using large numbers of significant figures in answers which implies greater empirical accuracy than instruments can measure. This is a common error that students are prone to make, and lecturers in science will give a similar caution. However, in a discussion on the use of significant digits in calculations, the mechanical engineering textbook authors extend the discussion, and point out that engineers will at times sacrifice accuracy (within reason) for ease of access to less accurate information. They give the example of using a value of 1000kg/m^3 for the density of pure water at 0°C when doing calculations of water with impurities at, say, 75°C . The error of around 2.5% is considered acceptable, and students are encouraged to round off answers in sensible ways. “Besides, having a few percent uncertainty in the results of engineering analysis is usually the norm, not the exception” (Cengel & Boles, 2011, p. 38).

Another example of the use of approximation in mechanical engineering can be found in so-called unsteady-flow devices, where the mass flow rate varies over time (for example, the decrease in flow rate as a tank is emptied) The authors point out that unsteady-flow processes are typically transient but common in engineering. Examples are the charging of rigid vessels from supply lines (such as filling an air tank for deep-sea diving) and discharging of tanks (eg.

driving a gas turbine with pressurised air from a tank). Cengel and Boles (2011) recognise that real-life unsteady-flow processes are difficult to analyse, but propose a way forward:

Most unsteady-flow processes... can be represented reasonably well by the **uniform-flow** process, which involves the following idealization: *The fluid flow at any inlet or exit is uniform and steady, and thus the fluid properties do not change with time or position over the cross section of an inlet or exit. If they do, they are averaged and treated as constants for the entire process.* (Cengel & Boles, 2011, pp. 241-242, emphasis in the original)

The averaging of fluid properties is an idealisation for the purpose of solving a practical problem, and the authors follow this up with an evaluative statement that speaks to the normative nature of the engineering science knowledge:

Although both the steady-flow and uniform-flow processes are somewhat idealized, many actual processes can be approximated reasonably well by one of these with satisfactory results. The degree of satisfaction depends on the desired accuracy and the degree of validity of the assumptions made. (p. 242)

Cengel and Boles (2011) acknowledge that idealisation delivers approximate results, and emphasise that *appropriate adequacy* rather than absolute *accuracy* drives the approach. There is a normative condition for approximation: idealisation is constrained by the requirements of the 'real' world. The distortion has to be quantified and be judged to yield 'acceptable' results for the problem that needs to be solved. Therefore knowledge claims produced by approximation are coded for the principal modality *idealisation*, mode *physical realisability*; the specific engineering setting of typical problems means that the secondary modality is *specialisation*, mode *particulars*, and the normative constraint on the idealisation gives another secondary coding, mode *constitutive normativity*.

Principal Mode: Physical
realisability

Secondary Modality:
specialisation, Mode:
particulars

Secondary Modality:
normativity, Mode:
constitutive normativity

5.3 Physics

5.3.1 Modelling

Modelling is explained in the Preface to the first year physics textbook. The textbook

places a major emphasis on constructing and using physical models. A central aspect of science is the modelling of complex real-world phenomena. A physical model is based on what we believe to be fundamental principles; its intent is to *predict or explain* the most important aspects of an actual situation. Modelling necessarily involves making approximations and simplifying assumptions in order that the model can be analysed in detail. (Chabay & Sherwood, 2011, p. v, emphasis added)

According to the authors of the first year physics textbook, idealisation is important in science, and its purpose is explanation of phenomena and prediction of behaviour, rather than physical realisability. Although 'approximation' is mentioned in the description above, it is clear that the purpose is to allow analysis of the *model*, rather than a quantified deviation from reality, as was the case with the mechanical engineering text discussed earlier. The authors describe idealisation as involving

simple, clean, stripped-down situations, free of messy complexities ... idealized models allow us to investigate simple patterns.... and learn what factors are important in determining these patterns. Once we understand these factors, we can revise and extend our models, including more interactions and complexities, to see what effects these have. (p. 82)

This description reminds us of the Galilean-type idealisation described by Weisberg (2007a): distortions in the form of simplifications are introduced in order to identify patterns as described above by Chabay and Sherwood. These distortions are revised only once understanding is gained. The re-introduction of complexities is for further understanding and theory-building rather than physical realisability. In this context the authors refer to the use of computational tools, and suggest that computational modelling has now become "as important as theory and experiment in contemporary science..." (p. v). The principal mode is therefore coded as abstract-ideal theorisation with the secondary modality specialisation, mode universals because of the commitment to investigate patterns, as described above.

Principal Mode: Abstract-ideal
theorisation

Secondary Modality:
specialisation, Mode: universals

5.3.2 The atomic model

Chabay and Sherwood (2011) introduce the particular focus of their textbook as “learning how to model the nature of matter and its interactions in terms of a small set of physical laws that govern all mechanical interactions, and in terms of the atomic structure of matter” (p.1).

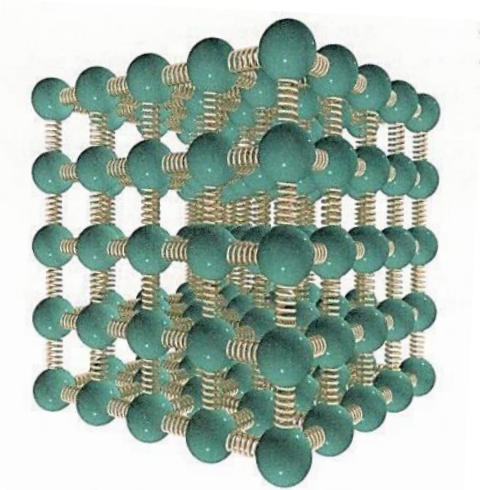


Figure 4.6 A simple model of a solid: tiny balls in constant motion, connected by springs. This figure shows only a small section of a solid object, which has many more atoms than are depicted here.

The starting point for the first year textbook is the atomic model, and a rather stripped-down version of it. A solid is conceived of balls connected by springs in order to explain the properties of macroscopic objects (see Fig 4.6 p. 140). An idealised spring is postulated between the atoms of solids, with zero mass, and no limitations on the spring constant. This model is then used to explore the internal and thermal energy of solids; the emphasis in the development of the model remains at the atomic level, which is in keeping with the textbook’s overall approach and consideration of statistical mechanics in thermodynamics.

The third year physics textbook author, Schroeder (2000), also employs the atomic model extensively in his derivation of thermodynamic equations. An example can be seen when the relationship between temperature and the energy exchange between systems is examined via a microscopic model of an ideal gas. Schroeder starts with a single particle:

The model will not be accurate in all respects, but I hope to preserve some of the most important aspects of the behaviour of real low-density gases. To start with, I’ll make the model as simple as possible: Imagine a cylinder containing just one gas molecule. (p. 10)

Schroeder then proceeds to use his model to develop an equation to link the ideal gas equation ($PV = NkT$) to the kinetic energy of the molecules of the ideal gas. He does this by expressing the pressure P in terms of the velocity of the molecule, and by extending that to a number N molecules, eventually arrives at $\frac{1}{2}mv^2 = \frac{1}{2}kT$, and taking into account that molecules can move in 3 dimensions, the translational kinetic energy $K = \frac{3}{2} kT$. The discussion that follows is makes clear that the strength of the modelling process in this example lies in the way the model allows for theorising the behaviour of ideal gases and even extends this, with constraints, to real gases (low density, with no interactions between molecules). Schroeder therefore employs the atomic model (principal modality idealisation, mode abstract-ideal theorisation) as a

fundamental theoretical starting point to argue via a generalised derivation for the microscopic understanding of a macroscopic property like temperature. Schroeder shows that “the temperature of a gas is a direct measure of the average translational kinetic energy of its molecules” (p.12). The secondary modality is *specialisation* with the mode *universals*, seen in the value placed on the *generalised* statement of the link between macroscopic and microscopic properties.

Principal Mode: Abstract-ideal
theorisation

Secondary Modality:
specialisation, Mode: universals

5.3.3 Statistical mechanics

The statistical mechanics approach is unique to the physics textbooks, and not followed in any of the other textbooks under consideration. For this reason, and because of the detail necessary to communicate the approach in terms of the knowledge modalities, the discussion is fairly dense.

The Second Law of thermodynamics and entropy are introduced in both physics textbooks (Chabay & Sherwood, 2011; Schroeder, 2000) by a look at time reversal invariance of macroscopic processes:

...why does heat flow spontaneously from a hotter object to a cooler object, never the other way? More generally, why do so many thermodynamic processes happen in one direction but never the reverse? This is the Big Question of thermal physics...

(Schroeder, 2000, p. 49)

Macroscopic processes are in general irreversible: ice cubes melt in a cup of hot water, a ball bounces lower off the ground with every bounce and heat energy flows from a hot object to a colder one. These processes take place in accordance with the First Law of thermodynamics, but the reverse processes would not *in principle* violate the conservation of energy law. As long as the water gets hotter while the ice cube gets colder, the total amount of energy in the ice cube + water system remains conserved. And yet experience shows us that these reverse processes do not take place. The physics textbooks use an approach that “deals with a statistical analysis of microscopic energy that puts limits on what is possible”(Chabay & Sherwood, 2011, p. 472). By contrast, the mechanical engineering text simply states irreversibility as a fact: “the presence of ... friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electrical resistance, inelastic deformation of solids, and chemical

reactions... renders a process irreversible” (Cengel & Boles, 2011, p. 291). The physics author, Schroeder (2000), on the other hand, argues that although the irreversibility of processes of the kind described above are not inevitable, they are exceedingly likely, and statistical methods are used to back this up.

Statistical mechanics uses probability theory to explain how microscopic behaviour of large numbers of particles determines the macroscopic properties and behaviour of matter. “... [W]e need to study *how* systems store energy, and learn to count all the ways that the energy might be arranged” (Schroeder, 2000, p. 49). The mathematical method that allows counting of ways of organising events is combinatorics, and students are introduced to this.

A quantum mechanical model of atoms in a solid is used as the starting point – the Einstein model of a solid (Chabay & Sherwood, 2011; Schroeder, 2000). The authors comment on the usefulness of the model:

[it] allows us to *understand in detail* the statistical nature of energy transfer between a hot object and a cold object, and why two objects come to ‘thermal equilibrium’... [and] *gain a more sophisticated and powerful understanding* of the meaning of temperature. (Chabay & Sherwood, 2011, p. 474, emphasis added)

Atoms are modelled as harmonic oscillators:

a solid...[is modelled] as a large number of tiny masses (the atoms) connected to their neighbors by springs (the interatomic bonds)... We would now like to use this model to ask detailed quantitative questions about the distribution of energy in a solid. (Chabay & Sherwood, 2011, p. 474)

The model is simplified even further when each atomic oscillator is pictured as moving independently of the atoms around it in three dimensions, as if it is connected to rigid walls instead of other oscillating atoms (see Fig 12.4, p.474).

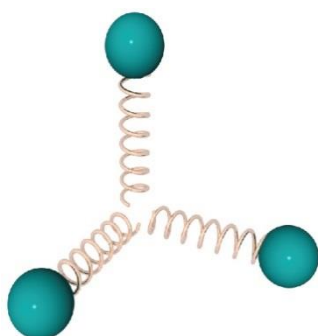
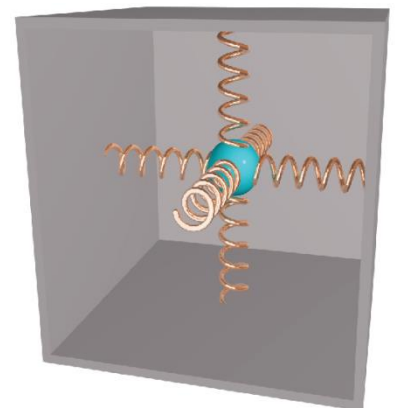


Figure 12.5, p. 475

Furthermore, since atoms are considered as independent, a single three-dimensional oscillator can now be replaced by three independent one-dimensional oscillators (see Fig. 12.5, p.475). This stripping of the model to the barest of detail allows the authors of the textbook to use simpler mathematical modelling of processes, and is an example of Weisberg’s minimalist idealisation, described in chapter

Figure 12.4 , p. 474



two: all extraneous properties of the phenomenon are removed, and only those crucial to the occurrence of the phenomenon are retained. This stripping results in a highly abstract and exceedingly generalised model. The motivation for this type of idealisation (distortion of reality) according to Weisberg (2007a) is the uncovering of the explanatory power of causal factors, as can be seen in what follows here.

The focus is on the sharing of energy, and Chabay and Sherwood start with a small Einstein solid consisting of three quantum oscillators (the equivalent of a single atom), sharing four quanta (units) of energy between them. There are four different general ways (called macrostates) to share 4 quanta of energy between 3 oscillators: either have 4 quanta in one oscillator with none in the other three, *or* 3 quanta in one, with one quantum in a second and no quanta in a third, *or* 2 quanta in each of two oscillators with none in the other one, *or* 2 quanta in one oscillator, and 1 quantum in each of the other two. For each macrostate, there are a number of different ways in which energy can be arranged, and these need to be counted. Each of these represents a microstate (to specify the microstate of a system, the state of every particle in the system has to be specified). Schroeder calls the number of possible microstates for each macrostate the multiplicity Ω of the macrostate:

Macrostate 1: all the energy could be given to one of the three oscillators and none to the other two; there are three ways (three microstates) in which this can be done, multiplicity $\Omega = 3$:

Oscillator 1	Oscillator 2	Oscillator 3
4	0	0
0	4	0
0	0	4

Macrostate 2: Alternatively, 3 quanta can be given to one of the oscillators, 1 quantum to another and no energy to the third; there are 6 ways (microstates) this can be done, multiplicity $\Omega = 6$:

Oscillator 1	Oscillator 2	Oscillator 3
3	1	0
3	0	1
0	3	1
1	3	0
1	0	3
0	1	3

Macrostate 3: Another possibility is for 2 quanta to be given to one of the oscillators, and 1 to each of the other two oscillators; there are 3 ways (microstates) this can be done, multiplicity $\Omega = 3$:

Oscillator 1	Oscillator 2	Oscillator 3
2	1	1
1	2	1
1	1	2

Macrostate 4: The last possible option is for 2 quanta to be given to two of the oscillators, and none to the third; there are three possible ways to do this, multiplicity $\Omega = 3$:

Oscillator 1	Oscillator 2	Oscillator 3
2	2	0
2	0	2
0	2	2

There is therefore a total of 15 possible ways (15 microstates) that 4 quanta of energy can be shared between 3 quantum oscillators. The total multiplicity of the system, $\Omega = 15$.

The fundamental assumption of statistical mechanics is that “over time, an isolated system in a given macrostate is equally likely to be found in any of its possible microstates” (Chabay & Sherwood, 2011, p. 476). Schroeder proves that for N oscillators and q energy units the multiplicity $= \frac{(q+N-1)!}{q!(N-1)!}$.

This is still a long way away from explaining why energy flows from a body at a higher temperature to one at a lower temperature. To explain how heat flows between two interacting systems, Schroeder describes how energy is shared between two Einstein solids, A and B, with three oscillators each, exchanging 6 units of energy between them. By applying the equation derived above, he shows that there are 462 microstates across 7 macrostates possible. Over a long time scale, all 462 microstates are equally likely since energy is passed randomly according to the fundamental assumption of statistical mechanics (see Figure 2.4, Schroeder, 2000, p. 57).

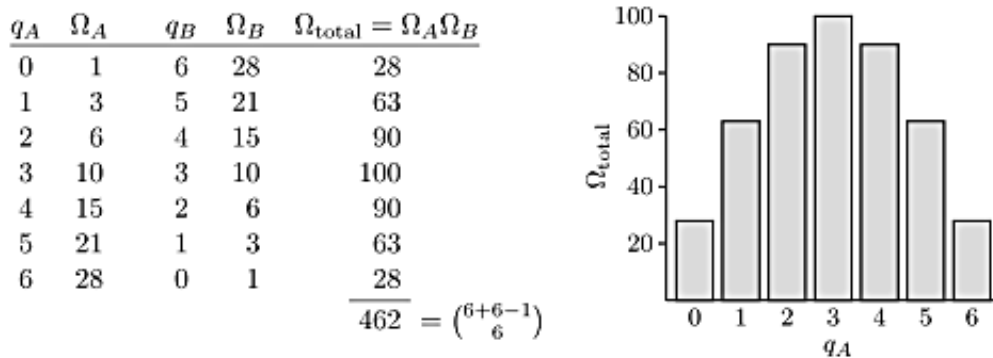


Figure 2.4
Macrostates and multiplicities of a system of two Einstein solids, each containing three oscillators, sharing a total of six units of energy

However, the summary shows that some macrostates are more probable than others. There are 100 ways in which the energy can be evenly shared between solid A and B, but only 28 ways in which all the energy can be found in solid B. The probability for even sharing of energy is therefore $100/462$, whereas for the extreme uneven distribution (all the energy in B) it is only $28/462$. This means that if the two solids A and B are in contact with all the energy initially in B and none in A, after some time it is much more likely to find an even distribution of the energy across A and B, and energy has flowed from B to A. When this is scaled up to hundreds of quantum oscillators, Schroeder points out that calculations need to be done by computer, and that the difference between finding the most likely and least likely distribution becomes enormous. For a system with two Einstein solids A and B consisting of 200 and 300 oscillators and 100 quanta energy to distribute, the most likely macrostate is around 10^{33} times more likely than the least likely macrostate. If solids A and B were brought into contact for some time, solid B starting out with all the energy initially and A with none, the likelihood that energy has flowed from B to A after some time is now simply astronomical. This implies that the system is effectively exhibiting irreversible behaviour – energy flows spontaneously from B to A, and never from A to B. This is illustrated in the peak width in the multiplicity graphs below: for

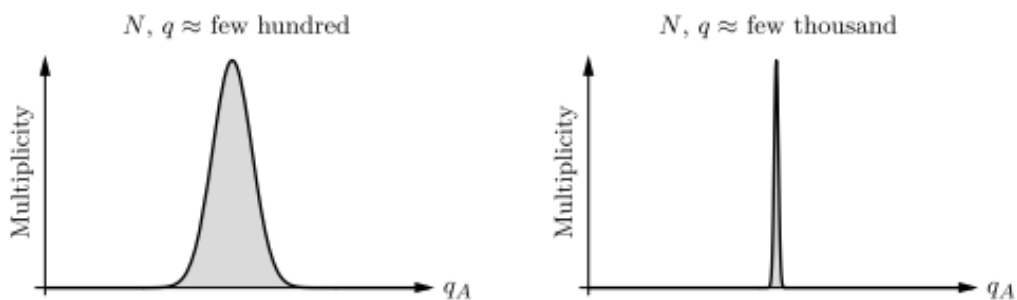


Figure 2.6
Typical multiplicity graphs for two interacting Einstein solids, containing a few hundred oscillators and energy units (left) and a few thousand (right). As the size of the system increases, the peak becomes very narrow relative to the full horizontal scale. For $N \approx q \approx 10^{20}$, the peak is much too sharp to draw.

systems consisting of large numbers of quantum oscillators and energy quanta, “... out of all the macrostates, only a tiny fraction are reasonably probable” (Schroeder, 2000, p. 60). Schroeder uses Stirling’s approximation to simplify the evaluation of the large factorials, and Gaussian functions to give an indication of the ‘narrowness’ of the multiplicity peak. (See Fig 2.6 Schroeder, p. 60).

He demonstrates that “when two large Einstein solids are in thermal equilibrium with each other, any random fluctuations away from the most likely macrostate will be *utterly unmeasurable*” (Schroeder, 2000, p. 66, emphasis in the original). With this the authors of the physics textbooks have now given a microscopic statistical argument to explain the so-called ‘arrow of time’, the fact that macroscopic thermodynamic processes are irreversible. “These considerations show that in the world of macroscopic objects such as ordinary-sized blocks, the most probably arrangement is essentially the *only* arrangement that is ever observed” (Chabay & Sherwood, 2011, p. 482). Schroeder explains that “[i]rreversible processes are not *inevitable*, they are just overwhelmingly *probable*” (2000, p. 49, emphasis in the original).

The description of the use of statistical mechanical methods demonstrates the use of minimalist idealisation in physics to develop *abstract-ideal theoretical* explanations for the irreversibility of macroscopic processes like the flow of heat. These explanations are powerful in their *universality* to apply across contexts. There is nothing specific or particular about the modelling of matter as one dimensional harmonic oscillators. The principal knowledge modality exhibited by the physics knowledge here is *idealisation*, mode *abstract-ideal theorisation*, with the secondary modality the *specialisation* of the knowledge towards the mode of *universals*.

Principal Mode: Abstract-ideal theorisation	Secondary Modality: specialisation, Mode: universals
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5.3.4 Entropy and temperature

Schroeder (2000) uses the argument developed from statistical mechanics concerning the likelihood of a particular distribution of energy in systems to give a version of the Second Law of Thermodynamics: “the spontaneous flow of energy *stops* when a system is at, or very near, its *most likely macrostate...*”, and a system in equilibrium will be found in its macrostate with the largest multiplicity. He calls this the “law of increase of multiplicity”. It is “... not a *fundamental* law at all – it’s just a very strong statement about probabilities” (p. 59, emphasis in the original). Another way to phrase the Second Law would be to say that “multiplicity [of a system] tends to increase” (p. 74). This stands in sharp contrast to the way the mechanical engineering authors

choose to formulate the Second Law of thermodynamics in terms of the irreversibility of processes associated with engineering devices like heat engines. For instance, the Clausius Statement of the Second Law in the mechanical engineering text reads: “It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body” (Cengel & Boles, 2011, p. 286). The fundamental concern of engineering to design artefacts that meet a perceived need contrasts with the fundamental concern in the sciences to explain and describe.

Schroeder (2000) introduces the concept of entropy S as a convenient way to work with the very large numbers introduced by the multiplicities of large systems, and defines it as the natural logarithm of the multiplicity multiplied by Boltzmann’s constant k : $S \equiv k \ln \Omega$. According to Schroeder the function of the Boltzmann constant is to introduce useful physical units for the concept of entropy. Another formulation of the Second Law of Thermodynamics is therefore “Any large system in equilibrium will be found in the macrostate with the largest entropy... or more briefly: Entropy tends to increase” (Schroeder, 2000, p. 76), or as stated by Chabay and Sherwood (2011): “... a closed system will tend towards maximum entropy” (p. 484). In addition, “[t]he entropy of a closed system never decreases. Only in a reversible process does the entropy of a closed system stay constant” (Chabay & Sherwood, 2011, p. 506)

Up till the introduction of entropy and multiplicity, the physics textbooks have used a more intuitive way to think about temperature: the property of objects that are the same when they are in thermal equilibrium (Schroeder, 2000), or the measure of the average kinetic energy of the particles of a substance (Chabay & Sherwood, 2011). Statistical mechanics and the concept of entropy that has been developed from it now make it possible to develop “a deeper connection between our macroscopic measurements of temperature and a fundamental atomic, statistical view of matter and energy. We... [have developed] a statistically based definition of temperature” (Chabay & Sherwood, 2011, p. 485).

When the entropy of systems is plotted against the energy of systems of Einstein solids that have been under consideration in the physics textbooks, a graph is obtained (Figure 3.1, Schroeder, 2000, p. 87):

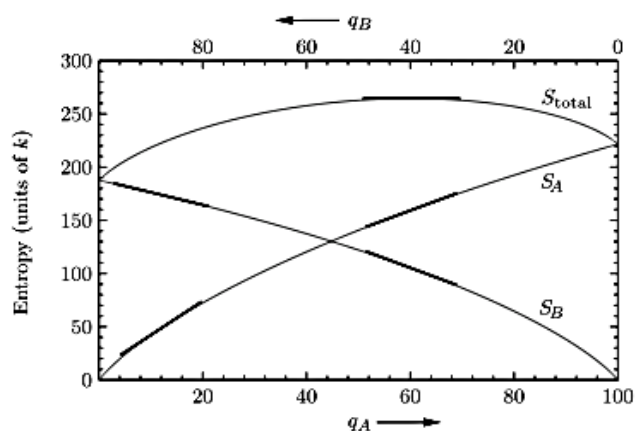


Figure 3.1

A plot of the entropies calculated in Table 3.1. At equilibrium ($q_A=60$), the total entropy is a maximum so its graph has a horizontal tangent; therefore the slopes of the tangents to the graphs of S_A and S_B are equal in magnitude.

At equilibrium the total entropy is a maximum and the horizontal tangent of the graph indicates that the slopes of the tangents to the graphs of S_B and S_A must be equal. Following on from Schroeder's observation that temperature is the thing that is the same when two objects are in thermal equilibrium, it follows that slope of the entropy vs energy graphs could be justifiably be linked to temperature. Both Schroeder (2000) and Chabay and Sherwood (2011) show that $\frac{1}{T} = \left(\frac{\partial S}{\partial U}\right)^{-1}$, and Chabay and Sherwood call this "a highly sophisticated and abstract way of defining temperature" (p. 487).

The statistical mechanics model presented in the physics textbooks and applied to large numbers of sub-atomic particles places forceful limitations on what is likely to take place in macrosystems: the unsymmetrical flow of time processes is explained in the overwhelming likelihood of irreversibilities. The principal mode of the idealisation modality, as shown in the statistical mechanical approach to explain entropy and define temperature in the physics textbooks, is therefore evidence of the *abstract-ideal theorisation mode* of the idealisation modality.

The secondary modality is specialisation, and the mode is universals; the model is valued for its explanatory power across many general instances.

Principal Mode: Abstract-ideal theorisation

Secondary Modality: specialisation, Mode: universals

5.4 Chemical engineering

5.4.1 Approximation

Similar to the approach in the mechanical engineering textbook, approximation and estimation are presented in the chemical engineering text as a common occurrence in engineering work. Sandler (2006) explains that there are good reasons why chemical engineering thermodynamics problems can give slightly different answers depending on the particular equation used to solve the problem:

... the properties of real substances are not completely known from experiment at all temperatures and pressures (and for mixtures at all compositions) and are approximately described by model equations.... Any one of several different equations may be use ... and each will result in a slightly different answer in solving a problem. However, *within the accuracy of the underlying equations, all the solutions are likely to be*

correct.... The situation here is the one continually faced by practicing engineers of needing to solve a problem even though the description of the properties is imperfect, and a choice of equation of state or activity coefficient model must be made. (Sandler, 2006, pp. ix-x, emphasis added)

Allied to this, an important engineering skill is the ability to make estimates when faced with incomplete information. A specific problem is stripped to a large extent of details by making simplifying assumptions. An example of this can be seen in Illustration 2.3-4, p. 42:

Water in a lake initially contains a pollutant at a parts-per-million concentration. This pollutant is no longer present in the water entering the lake. The rate of inflow of water to the lake from a creek is constant and equal to the rate of outflow, so the lake volume does not change. Assuming the water in the lake is well-mixed, so its composition is uniform and the pollutant concentration in the exit stream is the same as in the lake, *estimate* the number of lake volumes of water that must be added to the lake and then leave in order for the concentration of the pollutant in the water to decrease to ... one-tenth of its initial concentration... (Sandler, 2006, pp. 42-43, emphasis added)

In many ways this remains an idealised problem (the constant inflow and outflow of the lake over time, and the uniform concentration of the pollutant in the lake and outflow). However, the purpose of the idealisations is to get traction on the real-world problem, and to make an *estimation* of the answer. In many instances this is adequate for the type of physical problem posed here.

Another example of the need to use estimation is described by Sandler in the introductory chapter of the textbook. As a result of the proliferation of industrial chemicals, and therefore large numbers of potential multi-component mixtures available at different experimental conditions of temperature and pressure:

... many times engineers have to make estimates by extrapolating the limited data available to the conditions...of interest to them, or predict the behavior of multicomponent mixtures based only on sets of two-component mixture data... in these cases...approximations are made. (p. 2)

The pressure of the real world chemical industry requires that decisions be made on the basis of incomplete information:

...predictions may have to be made for mixtures in which the chemical identity of one or more of the components is not known. One example of this is petroleum ... many

components of different molecular weights are present that will not, and perhaps cannot, be identified by chemical analytic methods, and yet purification methods have to be designed, so approximations are made. (p. 2)

These are the realities faced as a result of real (as opposed to idealised) problems. Physical realisability of the thermodynamics knowledge in chemical engineering necessitates an ability to move beyond the idealisation presented by the theory and the equations that represent ideal conditions. In addition, the ability to estimate and approximate from incomplete information for the purposes of making design decisions in the real world to meet the demand of problem-solving for specific purposes in the chemical industry, is a common engineering practice. Idealisation of knowledge in chemical engineering science is therefore oriented towards physical realisability for the particularities of practice.

However, by contrast to the mechanical engineering text, the chemical engineering text does not emphasise a *quantification of the approximation* that was so prominent in the mechanical engineering textbook. For this reason, I will code the principal mode of idealisation in the chemical engineering knowledge in this instance as *weaker* physical realisability by comparison to the mechanical engineering text.

Principal Mode: weaker physical
realisability

Secondary Modality:
specialisation, Mode: particulars

5.4.2 Problem solving: tank-filling

Sandler (2006) explains the approach followed in the chemical engineering textbook to solve problems, and the importance of identifying the system boundaries in each case:

In many thermodynamics problems one is given information about the initial equilibrium state of a substance and asked to find the final state if the heat and work flows are specified.... Since we use thermodynamic balance equations to get the information needed to solve this sort of problem, the starting point is always the same: the identification of a convenient thermodynamic system... The seemingly most arbitrary step in thermodynamic problem solving is the choice of the system ... some system choices may result in less effort being required to obtain a solution. (p. 70)

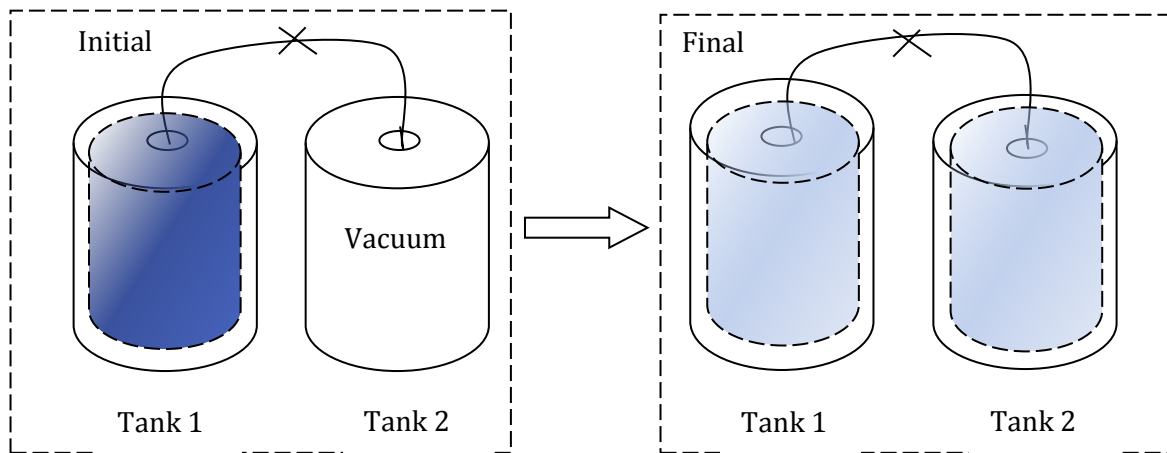
Tank-filling problems represent an important class of problems in the chemical engineering textbook. This example refers to two tanks joined by a valve, one with an ideal gas under

particular conditions, the other evacuated. The process is assumed to be adiabatic. The problem to be solved is to determine the final conditions in both tanks.

In order to solve the problem, a choice has to be made about what constitutes the “system”, i.e. where the boundaries are that distinguishes the system from the surroundings.

There are three possible approaches to the problem.

1. SYSTEM = Both Tanks (as enclosed by the dotted line below)

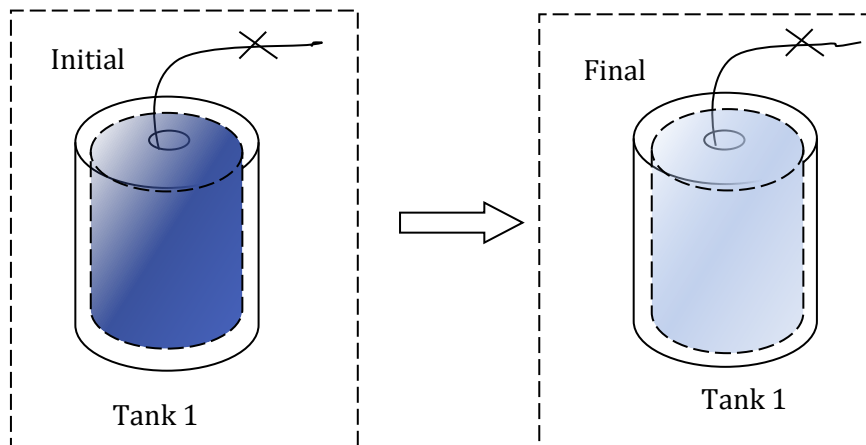


With the system as indicated, some implications follow:

- The system is CLOSED.
- No expansion work is done (on/by the system as a whole), so the total volume of the system remains constant.

The two balance equations (mass and energy) that can be developed from this are not enough to solve the problem, and a further set of equations needs to be developed, now considering a different system: the changes in tank 1, considered by itself.

2. SYSTEM: Only Tank 1

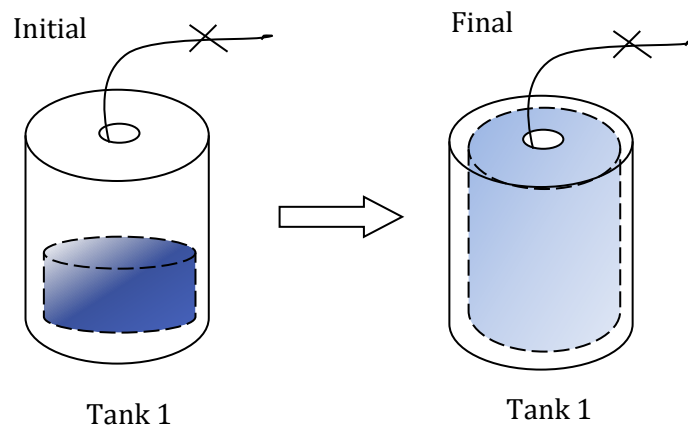


This system is now no longer closed, but open, and the differential forms of the equations have to be used, since the amount of gas between the initial and final states changes. After a considerable amount of mathematical manipulation (p. 77-79), an answer is reached.

Once the Second Law of thermodynamics has been introduced and entropy is developed as a third type of balance equation for problem solving, Sandler returns to the same problem. The approach to the system definition is different: again the focus is on Tank 1, but now a different part of Tank 1:

3. SYSTEM = the portion of the gas in tank 1 that remains behind when the pressures in the two tanks have been equalised.

To draw the *initial* system, the student has to imagine “only that portion of the contents of the first cylinder that remains in the cylinder when the pressures have equalized” (Sandler, 2006, p. 128).



In this case the system is closed, but the volume changes. By introducing the entropy balance as a third balance, the problem now becomes simple to solve.

The interest here lies in the idealisation as a distortion that is introduced in the approach to solving this problem; the ideal gas model does not allow for the conceptualisation of the gas in this way. For this approach to the problem to be effective, the portion of the contents of the gas (a fraction of the actual gas molecules) that does not move into tank 2 has to be imagined as occupying a fraction of the volume of tank 1 in the initial state. This conceptualisation of the system is a completely virtual construct, but essential to the solution, because without this the expansion of the gas portion in the closed system cannot be accounted for. This flies in the face of the ideal gas model that insists that a gas will fill the volume it occupies as a result of the continuous motion of its particles.

The objective of the idealisation (distortion) employed here is the solution of the problem:

Although the system choice is an unusual one, it is one that leads quickly to a useful result. This demonstrates that sometimes a clever choice for the thermodynamic system can be the key to solving a thermodynamic problem with minimum effort. (Sandler, 2006, p. 129)

In terms of Weisberg's categorisation, this is an example of the pragmatic Galilean idealisation where problem solving is the central concern. The orientation to knowledge demonstrated in this example is the physical realisability of the solution rather than allegiance to the abstract theory of the ideal gas model. In fact, it can be seen as another instance (see Approximation under mechanical engineering in paragraph 5.2.4 earlier in this chapter) where the physical realisability of the solution constrains the amount of idealisation the engineering scientist is willing to entertain in the use of the Ideal Gas model.

The approach to the problem in the chemical engineering text effectively suspends the tenets of the ideal gas model for the purpose of solving the problem. The ideal gas model is implied in the mathematical equations employed, but the model's requirements are suspended when the amount of gas left behind in the original tank is conceived of as an identifiable (virtual) amount of gas at the start of the problem. This speaks to the suggestion made by Houkes (2009) as he explores what empirical evidence could possibly account for a (weak) "epistemic emancipation" of engineering science. Houkes proposes that if scientific theories are valued in engineering science not only for their explanatory value, but also for their "usefulness", one might expect to see instances where changes to the theory will be made in the engineering science for practical "usefulness" purposes. The problem-solving approach described here is an example of what Laymon (1989a) calls a "fictional-as-if theory" (p.364): the gas in tank 1 is taken to behave *as if* it is possible to isolate the portion of the gas that remains behind in the tank. This is acceptable (and even desirable) in the engineering science text because it allows for a simple way to solve the problem at hand. The 'adjustment' made to the Ideal Gas theory in this example reflects a shift away from the fundamental value in the sciences as discussed in chapter two (explanation and description of phenomena) towards the fundamental value in engineering (responding to needs and problems identified). I argue that this represents an example of empirical evidence for Houkes' construct of weak emancipation of engineering science knowledge.

The principal modality for this aspect of the thermodynamics knowledge in the chemical engineering text is therefore idealisation (mode physical realisability as the driver), with the secondary modality specialisation (mode particulars) because of the typical engineering environment, and the strong association with the fundamental engineering values of problem-solving present in this example.

Principal Mode: Physical
realisability

Secondary Modality:
specialisation, Mode: particulars

5.5 Chemistry

5.5.1 The Ideal Gas model

The ideal gas model is used ubiquitously throughout the chemistry text, in spite of the classical macroscopic approach followed for thermodynamics. Here I will discuss the way the chemistry authors, Engel and Reid (2010), deal with deviations from ideal behaviour.

The ideal gas law provides a first look at the usefulness of describing a system in terms of macroscopic parameters. However, we should also emphasise *the downside of not taking the microscopic nature of the system into account*. For example, the ideal gas law only holds for gases at low densities. Experiments show that Equation (1.8) [the ideal gas equation of state] is accurate to higher values of pressure and lower values of temperature for He than for NH₃. Why is this the case? (Engel & Reid, 2010, p. 9, emphasis added)

Engel and Reid recognise that the idealisation implied in the use of the ideal gas law does not hold for real gases at higher densities. Their commitment to the *explanatory power* of the microscopic model manifests here as a discomfort with the macroscopic approach of classical thermodynamics followed in the textbook, and they give a detailed description of the way in which the atomic model of matter explains deviations from the ideal gas behaviour. The idealisation inherent in ideal gas behaviour is premised on two assumptions: that the atoms or molecules of an ideal gas have no volume themselves (and can therefore be treated as point masses), and that there are no interactions between the atoms or molecules. Engel and Reid use the potential energy of the interaction between two molecules or atoms of a typical real gas as a function of the separation between them to explain deviation from ideal behaviour.

The graph (see Engel & Reid (2010), Fig 1.7, p. 9) indicates three regions with different potential energy between two particles: at $r > r_{\text{transitional}}$, the potential energy is essentially zero; between $r_{\text{transitional}}$ and $r_{V=0}$ there is attraction (negative potential), and for $r < r_{V=0}$ there is repulsion (positive potential). $r_{\text{transitional}}$ depends on the energy of the gas particle. Gas density increases as

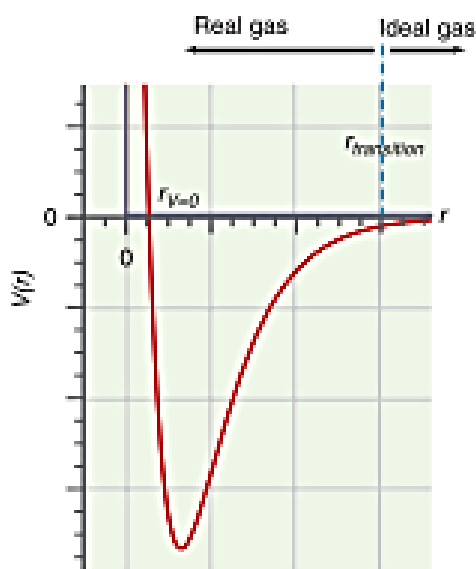


FIGURE 1-7

The potential energy of interaction of two molecules or atoms is shown as a function of their separation, r . The red curve shows the potential energy function for an ideal gas. The dashed blue line indicates an approximate r value below which a more nearly exact equation of state than the ideal gas law should be used. $V(r) = 0$ at $r = r_{V=0}$ and as $r \rightarrow 0$

molecules or atoms approach one another because of weak Van der Waals interaction between them. These depend on the fluctuating dipole moments in each molecule, which is determined by the polarisability of the electron charge typical for the type of molecule. This interaction between molecules leads to a higher value for the gas pressure and volume than predicted by the ideal gas law. The Van der Waals equation of state is introduced to take into account the limited nature of the two main assumptions made in the ideal gas model:

$$P = \frac{nRT}{V-nb} - \frac{n^2a}{V^2}, \text{ with values for } a \text{ and } b$$

characteristic for different gases and determined empirically.

The chemistry textbook authors value the ability to give an *explanation* for the behaviour (and deviation from ideal behaviour) of real gases. This

explanation remains grounded in the main theoretical model accepted by the scientific community, and therefore carries credibility. The Ideal Gas model is indeed validated by the explanation of deviation in terms of the theory, since it supports empirical observation.

The primary mode of abstract-ideal theorisation is prominent in the effort to explain deviations from ideal behaviour in terms of the theory. The secondary modality is specialisation, mode universals, because of the emphasis on wide applicability of the theory.

Principal Mode: Abstract-ideal
theorisation

Secondary Modality:
specialisation, Mode: universals

5.5.2 The equivalence of energy and work

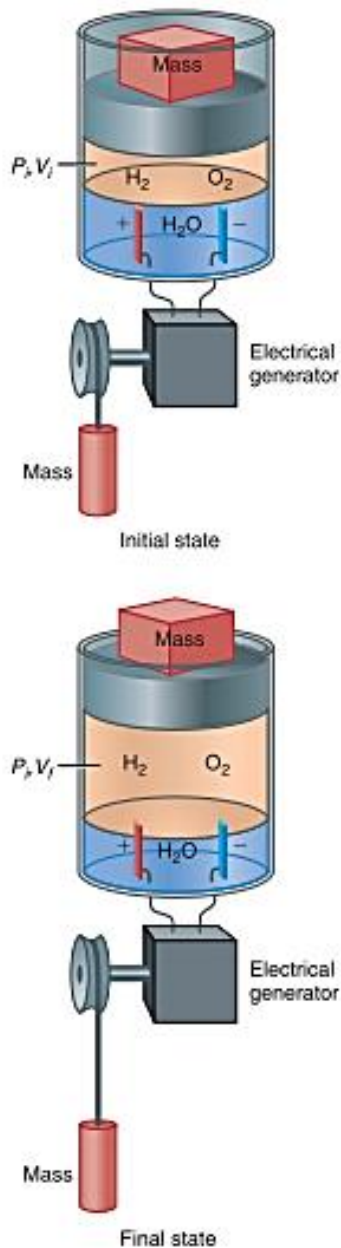


FIGURE 2.2
Current produced by a generator is used to electrolyze water and thereby do work on the system as shown by the lowered mass linked to the generator.

An important principle, first demonstrated by Joule, is the equivalence of heat and work. The extension of this principle to cover the equivalence of *all* forms of energy is demonstrated by the chemistry authors, Engel and Reid, in the way they relate typical chemical reactions to mechanical work as a force acting on a body over a specific distance. Chemical reactions (heating a reaction mixture, compressing a gas, and sending an electric current through an electrolyte) are presented as part of a chain of energy transformation events, confirming, even if presented at an intuitive rather than explicit level, the First Law of thermodynamics that energy cannot be created or destroyed, but transformed from one form into another. Fig. 2.2 (Sandler (2010), p. 17) illustrates this: a falling mass changes potential energy into mechanical energy, spinning a generator that converts the energy into electrical energy, used to effect electrolysis of water, a chemical reaction resulting in gaseous products, leading to flow work on the piston, lifting a mass.

Two features are striking in these examples: the context of the discussion, and the effort to move from the particulars to the more general. The discussion takes place in the context of an idealised controlled laboratory setup. It is stripped of confounding factors like friction on the generator shaft and between the piston and the cylinder walls, and the heating of the electrolyte. The 'device' considered here is not real; it would be an inefficient way of lifting a mass (the end result of the chain of

transformations) with energy losses all along the way in the form of friction, heat flow, etc. The 'device' is recruited to support the theory, and the empirical environment is the laboratory, generalised and idealised with no comment on or reference to real-world conditions.

The logic of the knowledge orientation in chemistry in this example is towards *abstract-ideal theorisation* in the principal idealisation mode, and the controlled laboratory environment emphasises the *universals* mode of the specialisation modality.

Principal Mode: Abstract-ideal
theorisation

Secondary Modality:
specialisation, Mode: universals

5.6 Concluding remarks

In this chapter, illustrative cases of idealisation of knowledge as the principal modality from each of the textbooks were presented. The data was coded in terms of two possible modes of idealisation, depending on whether the logic drove the idealisation towards physical realisability, or towards abstract-ideal theorisation. The general tendency was for the engineering science knowledge to display a concern for physical realisability of systems and devices. In some cases this meant that the idealisation was constrained because of the demands of the real-world devices, or, in one instance, led to an infraction of a widely accepted scientific model in the interest of solving a problem. A few instances where knowledge in chemical engineering displayed a weaker commitment to physical realisability were identified. Idealised knowledge in the sciences in each case confirmed a commitment to abstract theory-building.

Every data instance was also considered in terms of secondary knowledge modalities (always specialisation and occasionally normativity), and coded for these. On the whole, the pattern of mechanical engineering followed an 'engineering-like' configuration towards particulars and normative (where present), with chemical engineering occasionally presenting a concern for universals. Knowledge in the two science texts consistently displayed tendencies towards universals in the secondary modal coding. This is explored further in chapter seven. A summary of the coding decisions made in this chapter is captured in Appendix A.

Chapter 6 Findings and Analysis of the data – Normativity modality

“Entropy scares the hell out of an engineer...”

– Mechanical engineering lecturer, introductory lecture on entropy

This chapter concludes the presentation of the data generated from applying the analytical framework to the thermodynamics knowledge in the textbooks. Here the focus is on normativity as it presents as the principal modality in the data. The data generation involved viewing the textbook knowledge through a normative ‘lens’, and identifying instances (strong and weak) of this in the knowledge²⁴. The topics covered by the data units are not all the same across all the textbooks, as the data generation effectively involved uncovering ‘presences’ and ‘absences’. Each unit of analysis was also considered in terms of the other two modalities as potential secondary modalities, and coded accordingly.

6.1 Normativity as principal modality

As discussed in chapter two, a number of philosophers of technology advocate a view that technologies are inherently normative. It has been suggested (Dancy, 2006; Radder, 2009c) that the normativity relates to the intentionality and functionality of artefacts in engineering and technology and that these may be discernible in engineering science knowledge. In developing the external language of description in the methodology chapter of the thesis, two modes were developed for the normative knowledge modality, namely *constitutive* and *incidental* normativity. Constitutive normativity is about the presence of evaluative or axiological aspects of the knowledge discernible in the data, for example the strongly normative use of the concept of ‘efficiency’ in mechanical engineering. Incidental normativity is about a de-emphasis of evaluative aspects in the knowledge, or at best a weak normative orientation.

6.2 Mechanical engineering

Already in the introduction to the mechanical engineering textbook, Cengel and Boles (2011) explain that that they will include in the text examples to foster an understanding of aspects of

²⁴ Identifying certain data units as displaying constitutive normativity, does not deny that many of the knowledge units do not present any normativity at all: most disciplinary knowledge is declarative and value-neutral. However, the presence of constitutive normativity is a striking aspect of knowledge displayed in some of the data.

economics associated with energy use, references to renewable energy and the efficient use of existing resources. The authors also signal that they will attempt to raise awareness of safety concerns in the examples and problems set. This is an early indication of a normative stance.

6.2.1 Aspects of cost in problems

It is important to note that there are seldom *explicit* normative statements in the textbook. The authors make use of what Radder (2009c) calls *implicit* normativity: students are led through examples and asked to solve certain types of problems that have normative implications.

Example 2-13 is a case in point.

The lighting needs of a classroom are met by 30 fluorescent lamps, each consuming 80W of electricity. The lights in the classroom are kept on for 12 hours a day and 250 days a year. For a unit of electricity cost of 7 cents per kWh, determine the annual energy cost of lighting for this classroom. Also, discuss the effect of lighting on the heating and air-conditioning requirements of the room. (Cengel & Boles, 2011, p. 76)

In the example students are made aware of the cost of lighting. They are required to think of the impact on other energy needs: the heating effect of the lighting reduces the heating requirements by a small amount, but increases the demand on air-conditioning. In a more explicit statement in the discussion of the example, the authors point out that energy conservation measures are important, since the annual energy cost of lighting this one classroom is around \$500, and that if incandescent bulbs had been used instead of fluorescent tubes, the energy cost would have been four times as much.

Examples like the one discussed here are plentiful in the mechanical engineering text, hence the principal modality is normativity, with a modal coding of *constitutive normativity*. The peculiarly engineering setting of the problems is the motivation for a secondary modality of specialisation, coding towards *particulars*.

Principal Mode: Constitutive
normativity

Secondary Modality:
specialisation, Mode: particulars

6.2.2 First Law Efficiency

The normative aspects of the mechanical engineering science knowledge is perhaps most visible when dealing with the topic of efficiency of energy transformations that has been developed into a highly sophisticated topic in the mechanical engineering text. In some instances efficiency

is dealt with in an explicit quantitative way, as evidenced in the formal definition and equations for calculations: “Efficiency is one of the most frequently used terms in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished” (Cengel & Boles, 2011, p. 78). Efficiency is also described as “performance”, and the normative connotation here is quite clear: $\text{Performance} = \frac{\text{Desired Output}}{\text{Required Input}}$.

At other times the normativity is more implicit, as can be seen in a worked example on renewable wind energy. Students have to calculate the wind energy available from steady wind blowing at a particular speed for a specific flow rate. The authors point out that real wind turbines are currently only able to convert about one third of the wind energy into electrical power. This is an example of an implicit normative orientation to the knowledge. Students are constantly reminded that efficiency of energy transformation has real effects, and that technological development in the future will change current efficiency levels (with an implied follow-on for take-up rates of renewable energy).

The authors raise cost implications in the examples provided. For example, although the efficiency of an electric household geyser may be in the region of 90%, a consumer with access to low cost natural gas may spend less on water heating using a gas geyser with an efficiency of only 55%. The idea of ‘trade-off’ is present here in an implicit manner and students are expected to consider the economic implications of a low cost- low efficiency energy source compared to a higher-cost-higher-efficiency source.

The performance equation at the start of this section is applied to different devices and implications are discussed. An important application is the efficiency of different fuel types in combustion processes where the heating value (HV) of fuel is the amount of heat released when a unit of fuel is burned completely and the products of the combustion are cooled to room temperature. Water is usually one of the products of combustion, and a lower heating value (LHV) is given if the water leaves the combustion vessel as a vapour in the exhaust gases. This is the case in car and jet engines, where it is not practical to cool the exhaust gases. In furnaces, however, the water in the combustion gases is often completely condensed, the heat of vaporisation is recuperated, and therefore the fuel efficiency of furnaces is based on a higher heating value (HHV). The engineering concern with efficiency of processes is clear here, even though the normativity is implicit. To make decisions based on the ‘true’ efficiency of processes it is necessary to know whether the heat of the flue gases is being utilised.

For more complex systems the overall efficiency is distinguished from the efficiency of the different parts. An example is the overall efficiency of a power station which is composed of the

generation efficiency (the ratio of the electrical power output to the mechanical power input), and the thermal efficiency of the plant (the ratio of the net shaft work output of the turbine to the heating value of the fuel input). This allows the engineer to improve systems by focusing on how to improve efficiencies of the different processes in a complex system.

Students are given an approximate indication of the general efficiencies of engineering devices: “The overall efficiencies are about 26-30 percent for gasoline automotive engines, 34-40 percent for diesel engines, and up to 60 percent for large power plants” (Cengel & Boles, 2011, p. 80).

More explicit is the discussion on lighting efficacy which relates the amount of light produced to the electricity consumed by the bulb. Students are made aware of the fact that compact fluorescent light bulbs produce around four times as much light per watt electrical power as an incandescent light bulb. Incandescent bulbs only use around 5% of the electrical energy to produce light; the rest is radiated as heat and therefore adds to the cooling load of air conditioners. The authors point out that the life span of a compact fluorescent bulb is 10 000 hours (ten times the life span of an incandescent bulb), that compact fluorescents plug into the same electrical sockets (therefore requiring no extra installation costs), and that the higher initial cost of fluorescents is therefore off-set by their considerably greater electrical efficiency.

The performance equation is also adapted for fluid systems like pumps (pumps, fans and compressors all fall under this general description) where the pump efficiency is defined as the ratio of the increase in the pressure, velocity or elevation of a fluid to the mechanical energy supplied by the device. In the case of a turbine the interest is in the reverse process of extracting mechanical energy from a fluid by a turbine and the turbine efficiency is the ratio of the mechanical output of the turbine to the mechanical energy decrease of the fluid. The authors point out that the ideal of 100% conversion cannot ever be attained (see the discussion below on Second Law efficiency), but that there are always efforts in engineering to approach this value by minimising frictional effects.

Another example in this section asks student to calculate the amount of energy and money saved if a worn-out standard motor is replaced by a high-efficiency motor. Students are also given the price difference between a standard and high-efficiency motor, and asked to calculate the simple pay-back period. In this way engineering students are sensitised to the practical and real tangible implications of efficiencies, and implicitly on the effect of these on the business bottom line.

The strong emphasis on normative considerations is the motivation for the principal modality, with a modal coding as *constitutive normativity*. The specialised engineering setting in the typical problems sets up specialisation as a secondary modality, with a coding of *particulars*.

Principal Mode: Constitutive
normativity

Secondary Modality:
specialisation, Mode: particulars

6.2.3 Steam 'quality'

A more subtle example of normativity at work can be found in the section dealing with the phase change of pure substances. During the vaporisation of a liquid there is a period of time when the substance is a saturated mixture of liquid and vapour phases. The relative amounts of liquid and vapour phases vary with temperature, and a new property of the mixture is defined: the *quality* x of the saturated mixture = $\frac{m_{vapour}}{m_{total}}$, has a value between 0 and 1. The name given to the property already carries a normative connotation, and one of the important applications of the use of quality is in steam turbines. The quality x gives an indication of the "wetness" of the steam: a low value for x indicates a "wetter" steam which causes damage to turbine blades as the moisture in the steam causes pitting (a form of corrosion) on the blades. For this reason the steam is often moved through a dryer which removes some of the liquid moisture in the steam and increases the quality of the steam (with obvious concomitant extra cost).

Steam quality in mechanical engineering is an example of normativity functioning as the primary mode (mode *constitutive normativity*), and the specialised context of steam-driven turbines is the reason why the knowledge is also coded with the secondary mode of *particulars*.

Principal Mode: Constitutive
normativity

Secondary Modality:
specialisation, Mode: particulars

6.2.4 Quantifying error

Another example of the normative orientation to knowledge can be found in the way Cengel and Boles (2011) deal with the use of the ideal gas equation for real gases like water vapour.

It has been well established that real gas behaviour closely approximates ideal gas behaviour under certain limited circumstances. The ideal gas equation of state is a convenient way to predict the behaviour of gases in specific phase regions. Outside these regions, real gases deviate from ideal behaviour predicted by the ideal gas equation. In the previous chapter on

idealisation I described the use of the van der Waals equations of state used in chemistry to account for the deviation from ideal behaviour. The authors of the mechanical engineering textbook have a different approach to the problem of real gas deviation: they quantify the percentage error that results from using the ideal gas equation to calculate real gas behaviour. Fig 3-47 (Cengel & Boles, 2011, p. 137) indicates regions (mainly at low pressure) where the error that results from treating water vapour as a real gas is regarded as negligible.

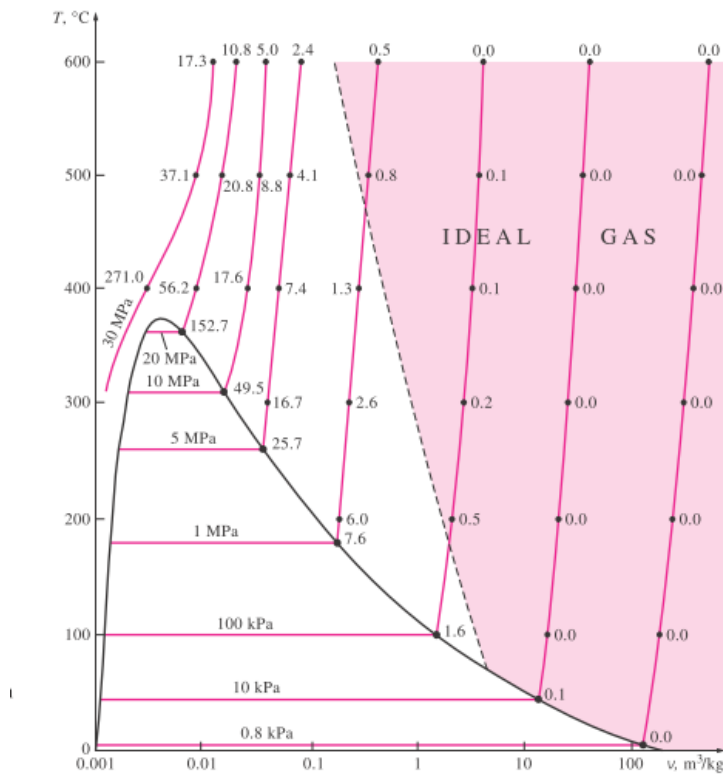
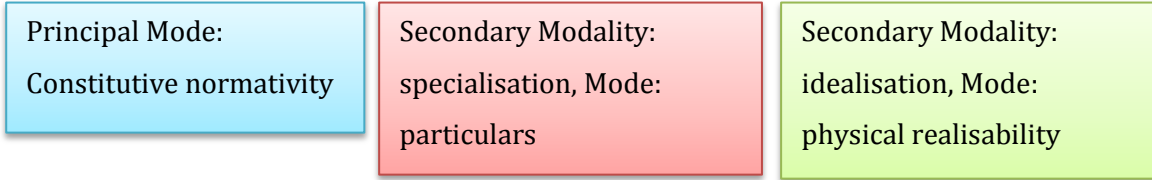


FIGURE 3—47
Percentage of error
($[|V_{table} - V_{ideal}|/V_{table}] \times 100$) involved in
assuming steam to be an ideal gas, and
the region where steam can be treated as
an ideal gas with less than 1 percent
error.

There is a trade-off between the effort required to get an exact answer from a van der Waals equation, and the ease of using a simple relationship which gives a solution adequate for a particular purpose. The water vapour present in air-conditioning units can be treated as an ideal gas (very low pressure) with an acceptable error level. However, applying the ideal gas equation to the high pressure conditions present in steam power plants results in unacceptable high error margins.

The quantification of error margins, and the judgement call on the *adequacy* of an approximation for a particular purpose results in a principal coding of this example of knowledge in mechanical engineering as constitutive normativity.

Two secondary modalities (and modes) are identified: the *specialisation* of the knowledge is towards the *particulars* of specific engineering systems and devices (acceptable for refrigeration; unacceptable for steam power stations), and the requirement of *physical realisability* as a knowledge mode places a limitation on the extent of *idealisation* tolerated.



6.2.5 Regulatory requirements

A more explicit example of the normative at work can be seen in problems that refer to regulatory requirements of statutory and standard-setting bodies such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE): See for example the problem on p.251-252:

The minimum fresh air requirement of a residential building is specified to be 0.35 air change per hour (ASHRAE, Standard 62, 1989). That is, 35 percent of the entire air contained in a residence should be replaced by fresh outdoor air every hour. If the ventilation requirement of a 3.0-m-high, 200m² residence is to be met entirely by a fan, determine the flow capacity in L/min of the fan that needs to be installed. Also determine the diameter of the duct if the air velocity is not to exceed 4 m/s. (Cengel & Boles, 2011, pp. 251-252)

Students are made aware of official safety standards that govern minimum acceptable and legal requirements for the design of a system (ventilation system in this instance). This is an example of *constitutive normativity* as a principal mode, with the statutory standards a motivation to code the secondary *specialisation* modality as oriented to the *particulars* of the engineering profession.



6.2.6 The 'value' of energy

In a discussion of various forms of energy, Cengel and Boles explain that certain types of energy are more 'valuable' than others; kinetic and potential energy of *objects* (like the kinetic energy of

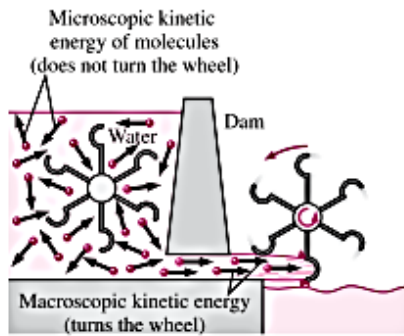


FIGURE 2-7
The microscopic kinetic energy is an organized form of energy and is much more useful than the disorganized microscopic kinetic energies of the molecules

turbine blades) are more valuable than that of *microscopic particles*. The kinetic energy of the object or device is characterised as an “organized form of energy”, which the authors describe as much more valuable (“useful”) than the disorganised kinetic energy of the molecules of the object as a result of their random motion (Cengel & Boles, 2011, Fig 2-7, p.56). This notion of “valuable” energy, and the normative orientation associated with knowledge that accompanies it, is expanded upon in the Second Law of thermodynamics.

Cengel and Boles (2011) introduce students to the Second Law of thermodynamics in a brief overview of the topic. They explain that the Second Law of thermodynamics is used for three main purposes: firstly, to explain why certain processes, like a cup of coffee cooling down, will always run in a particular direction (in principle the First Law of thermodynamics does not prohibit a cup of coffee getting hotter by absorbing energy from its environment).

Secondly, the Second Law

asserts that energy has *quality* as well as quantity ... [p]reserving the quality of energy is a major concern to engineers, and the Second Law provides the necessary means to determine ... the degree of degradation of energy during a process. (p. 274, emphasis in the original)

In the third place, it allows a determination of the *theoretical limits* of the performance of engineering devices like heat engines and refrigerators. It is

closely associated with the concept of *perfection*. In fact, the second law *defines* perfection for thermodynamic processes. It can be used to quantify the level of perfection of a process, and point the direction to eliminate imperfections effectively. (p. 275, emphasis in the original)

The last two of these uses of the Second Law of thermodynamics carry with them normative implications central to engineering, and I discuss the idea of *theoretical limits* and *perfection* in the following section under Second Law efficiency.

The notion of *quality* of energy mentioned in the quotation above refers to the fact that some forms of energy can be completely transformed into other forms of energy. Energy

transformations are fundamental in engineering processes. An example is the complete transformation of electrical energy from the heating element of a kettle into heat energy. However, not all forms of energy transform completely into different forms of energy; heat energy, for example, cannot completely be transformed into work. For this reason electrical energy is a more 'valuable' form of energy than heat energy. This is an intrinsic characteristic of forms of energy and does not refer to energy losses like friction along the way in transformation processes. It is also this concept that explains why a relatively small amount of high temperature thermal energy (such as that released in the process of nuclear fission) is more valuable than the vast amounts of low temperature thermal energy (such as that stored in the upper layers of the world's oceans). More of the high-temperature heat energy can be converted into work, and is therefore more 'useful' for the purposes of typical engineering processes. The "degradation of energy during a process" (p. 274) referred to above is another way in which Cengel and Boles (2011) describe the inevitable way in which energy transformation processes result in less valuable energy during transformation processes. The science textbooks briefly refer to the same process, but use the more value-neutral term of energy "dissipation" (see for example Chabay and Sherwood (2011), p. 310) instead of the normative energy "degradation" in the mechanical engineering text.

The principal knowledge modality displayed here is *normativity*, and the prominence of the modality is captured in the mode, *constitutive normativity*. The specificity of the engineering setting pushes the *specialisation* modality towards *particulars*.

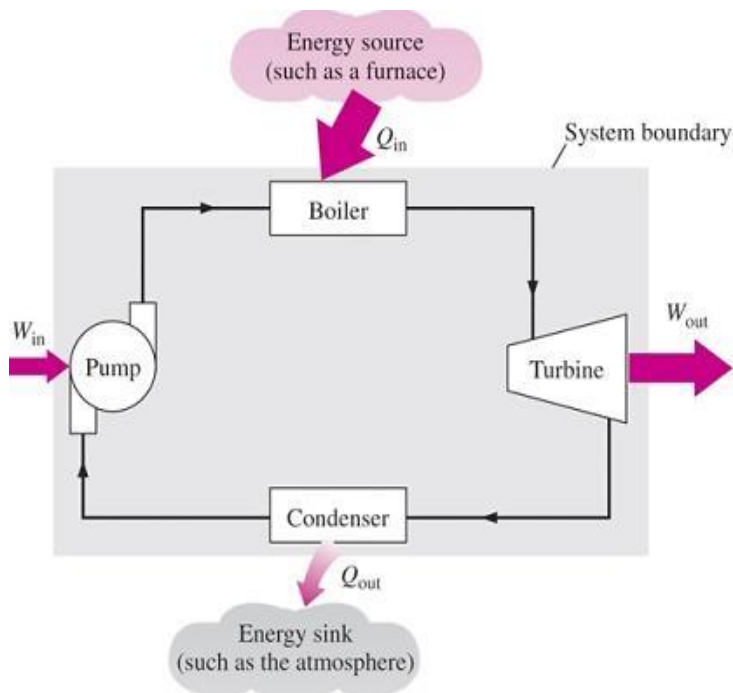
Principal Mode: Constitutive
normativity

Secondary Modality:
specialisation, Mode: particulars

6.2.7 Second Law efficiency

The Second Law of thermodynamics also addresses a concern with efficiency, namely theoretical limits for the performance of engineering devices like heat engines (the third main purpose for considering the Second Law of thermodynamics, as mentioned above). An example is the functioning of a steam power plant for generating electricity (see Cengel & Boles, (2011), Fig 6-10 on p. 277).

Fig.6-10, Cengel & Boles (2011),



Heat engines are not idealisations²⁵, but a category of *actual* engineering devices with specific properties: "[t]hey receive heat from a high-temperature source (solar energy, oil furnace...); they convert part of this heat to work (usually in the form of a rotating shaft); they reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.)" (p. 276). They operate on a thermodynamic cycle and use a working fluid (eg. water) to and from which heat energy is transferred. At the end of the cycle

the working fluid is returned to its initial state. A portion of the work output is consumed internally to complete the cycle (in the case of the power generation cycle, work is required to pump the condensed water from the condenser back to the boiler to complete the cycle).

The normative nature of concepts is signalled to the engineering students in the terminology used to discuss heat engines: "dumping" and "rejection" (p. 276) of a portion of the energy results in lower efficiency. This dumping of energy is a fundamental consequence of the cyclic nature of heat engines and is unavoidable. It is not the result of dissipative effects of the heat engine, and applies to both actual and idealised heat engines. The terminology indicates the undesirable (if unavoidable) aspects of the process.

The thermal efficiency of a heat engine is a central focus in the chapter on the Second Law, since it measures how efficiently a heat engine can convert the heat it receives to work. Cengel and Boles (2011) demonstrate that the efficiency is given by $\eta_{th} = 1 - \frac{Q_L}{Q_H}$, with Q_L and Q_H the amount of heat transferred between the heat engine and the high temperature (H) and low temperature (L) reservoirs. This means that the thermal efficiency of *any* heat engine is less than unity, which places a theoretical limit on the performance of commonly used real engineering systems. The authors point out that even under the most ideal conditions it is a consequence of the fundamental nature of heat engines that some heat has to be 'wasted' by

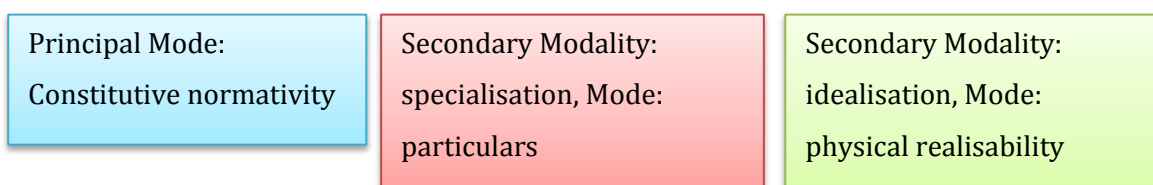
²⁵ The Carnot cycle (discussed in 5.2.3) is special case of a heat engine, and is an *idealised* heat engine.

transferring it to a low temperature reservoir in order to complete the cycle. This is formalised in the Kelvin-Planck statement of the Second Law of thermodynamics:

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work... [or] also expressed as *no heat engine can have a thermal efficiency of 100 percent* (p. 281, emphasis in the original).

In engineering this fundamental statement has practical implications; the notion of a theoretical limit for a heat engine acts as a standard against which the efficiencies of various real devices can be measured. The maximum efficiency possible depends only on the temperature difference between the sink and source. Furthermore, knowledge of the theoretical limit has the function of directing the design of a particular real system towards identifying inefficiencies. The theoretical limit of a heat engine can be used “to quantify the level of perfection of a process, and point the direction to eliminate imperfections effectively” (Cengel & Boles, 2011, p. 275). Note that “perfection” here refers to an efficiency of less than 100%, in effect an acknowledgement that the physical reality of Second Law efficiency constrains the ‘ideal’ possible.

The idea of the theoretical limit as a measure of perfection functioning as a comparative standard for evaluating different heat engines is the motivation for coding the principal modality and mode of the knowledge here as *constitutive normativity*, and the use of this knowledge to guide design of particular practical heat engines towards better efficiency justifies the coding of the secondary modality of *specialisation* (mode *particulars*). Idealisation as another secondary modality is constrained and directed towards physical realisability.



The arguments made in 6.2.1 – 6.2.7 indicate that the strongly normative nature (implicit and explicit) of knowledge in the mechanical engineering textbook authors’ emphasis on efficiency, quality of processes, acceptable approximations and in the types of problems students have to solve. Although engineering devices are quite prominent in the data units considered here, the normativity in mechanical engineering is clearly broader than a merely a function of the artefact relation, as suggested by Franssen (2009) – the notion of quality of energy is an instance.

6.3 Physics

6.3.1 'Real-life' context of problems

There is very little in the physics textbook (Schroeder, 2000) that can be described as normative. This does not mean that the examples or the problems set at the end of chapters have no relation to the everyday world or that they are completely limited to the laboratory environment.

An example can be seen in Problem 1.21:

During a hailstorm, hail stones with an average mass of 2 g and a speed of 15 m/s strike a window pane at a 45° angle. The area of the window is 0.5m² and the hail stones hit it at a rate of 30 per second. What average pressure do they exert on the window? How does this compare to the pressure of the atmosphere? (Schroeder, 2000, p. 14)

However, the way the problem is framed does not engage the student in a normative orientation to the knowledge to recruit for solving the problem.

Even where a cost comparison is set as part of a problem, the 'context' is artificial: in one of the problems students are asked to compare the per-calorie cost of gasoline and cornflakes (Schroeder, 2000, p. 36). Since there is no evaluative decision implied in the problem, a normative orientation to the knowledge cannot reasonably be attributed to the problem.

I found one example of what could arguably be constructed as an *implicit* normative orientation to a problem: students are asked to estimate the total rate of conductive heat loss through walls, floor, windows and roof of a typical house, and the cost of replacing the heat lost in a month by electric heating of the house. However, this type of problem was extremely rare in the physics texts, and the primary knowledge mode is therefore coded as *incidental normativity*.

Although the secondary specialisation modality in normative knowledge would usually imply specificity (i.e. particulars implied in the evaluative aspect of the normative), the infrequency of examples in the physics texts justifies the logic of a coding of the secondary *specialisation* modality with a *universals* mode.

Principal Mode: Incidental
normativity

Secondary Modality:
specialisation, Mode: Universals

6.3.2 Second Law efficiency

Schroeder (2000) devotes one chapter of his textbook to heat engines and refrigerators that operate at maximum theoretical efficiency, and acknowledges that this is useful because of the information it gives about the link between operating temperatures and efficiency. His interest in the topic is in an accurate calculation of the work that can be produced, not in the physical artefact and its function

Schroeder briefly deals with the fact that the efficiency of a heat engine cannot be greater than unity. He points out that “[i]n general, for the greatest maximum efficiency you should make the cold reservoir *very* cold, or the hot reservoir *very* hot, or both. The smaller the ratio T_c / T_h , the more efficient your engine can be” (Schroeder, 2000, p. 124, emphasis in the original).

However, Schroeder then loses sight of the *purpose* of efficiency in engines (namely to construct an efficient real artefact that converts as much energy as possible from one form into another), and gets side-tracked in the abstract mathematical meaning of the equation:

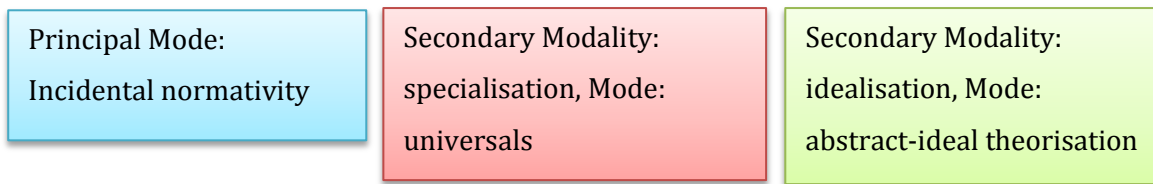
It’s easy to make an engine that’s *less* efficient than the limit $1 - T_c/T_h$, simply by producing additional entropy during the operation. Then to dispose of this entropy you must dump extra heat into the cold reservoir, leaving less energy to convert to work. (p. 124, emphasis in the original)

There is very little sense here that Schroeder is interested in the physical realisability of real heat engines, and certainly does not attend to the drive towards *better* efficiency which is so marked in the engineering texts.

Two brief sections in the textbook deal with real heat engines and refrigerators, but these are almost incidental in the physics text: “This [real heat engines] is a vast subject, but in this section... I’ll describe a few examples of real engines and refrigerators, *to alleviate the abstraction of the preceding sections*” (p. 131, emphasis added). There is no sense that the examples of real engines are an integral aspect of the knowledge Schroeder wants to communicate. In addition, discussions remain at a general descriptive level: a generic Otto cycle, steam engine and refrigeration cycle are briefly considered.

For this reason the principal mode of the knowledge in the physics text dealing with Second Law efficiency is coded as *incidental normativity*. The coding of the secondary *specialisation* modality of the knowledge is therefore focused towards the mode of *universals*. The secondary *idealisation* modality of the knowledge is towards the mode of *abstract-ideal theorisation*, as can be seen in the treatment of the theoretical limit of efficiency: the formula is treated as

decontextual mathematical equation with an artificial physical meaning, in the emphasis on how to *lower* efficiency.



6.4 Chemical engineering

As was the case in the mechanical engineering textbook, Sandler (2006) signals some normative considerations in the introduction of the textbook: "...other applications of thermodynamics considered in this book include how chemicals distribute when released to the environment, determining safety by estimating the possible impact (or energy release) of mechanical and chemical explosions..." (p. 2).

6.4.1 Problem solving

On the whole, however, a normative orientation to the knowledge is much more implicit in the chemical engineering textbook than was the case in the mechanical engineering text. It can be inferred from the types of problems set for students to solve, and the worked example problems offered. For example, a tank in a chemical plant that is used as an energy conservation measure (with implied cost savings) is described. The tank is used as a temporary storage space for steam from exhaust processes, and students are required to calculate the amount of steam that can be stored at a given pressure. In another problem a rigid chamber with two compartments is described: one containing a gas at high pressure and temperature, the other evacuated. Students have to calculate the final temperature in the chamber if the division between the two compartments ruptures. Implicit here is the danger posed by rupturing of tank compartments in an industrial setting.

A slightly more explicit example of a normative orientation in the knowledge is offered in a problem which involves a cost calculation:

It is thought that people develop respiratory infections during air travel because much of the airplane cabin air is recirculated. Airlines claim that using only fresh air in the cabins is too costly since at an altitude of 30 000 feet the outside conditions are -50°C and 0.1 bar, so that the air would have to be compressed and heated before being introduced into the cabin. The airplane cabin has a volume of 100 m³ with air at the in-

flight conditions of 25°C and 0.8 bar. What would be the cost of completely refreshing the air every minute if air has a heat capacity of $C_p^* = 30 \text{ J}/(\text{mol K})$ and energy costs \$0.2 per kWh? (p. 97)

Although a principal *normative* modality can be discerned in the typical problems set in the chemical engineering textbook, these tend to be less explicitly normative than was the case in the mechanical engineering text. In keeping with the flexibility provided by the gradation provided in the modal continuum, I therefore code the mode as *weaker constitutive normativity* for this aspect of the chemical engineering knowledge.

The specificity of the engineering problem setting indicates a coding of a secondary *specialisation* modality as towards *particulars*.

Principal Mode: weaker constitutive normativity

Secondary Modality: specialisation, Mode: Particulars

6.4.2 The 'value' of energy

In respect of the Second Law of thermodynamics, Sandler (2006) pays much less attention to heat engines than was the case in the mechanical engineering textbook. There is a brief reference to what was called the quality of energy in mechanical engineering:

...there is a real distinction between them [heat and work] in that work or mechanical energy can spontaneously (naturally) be converted completely to heat or thermal energy, but thermal energy can, with some effort, be only partially converted to mechanical energy. It is in this sense that mechanical energy is regarded as a higher form of energy than thermal energy. (p. 115)

Sandler also refers to a "degraded" (p.106) form of energy when mechanical energy is converted to heat. However, there is no further exploration of this idea in the chemical engineering text, and Sandler does not give any specific engineering examples for this general observation of the principle of grading types of energy in transformation processes. For this reason the knowledge in this example is coded as *weaker constitutive normativity*, and the lack of specific engineering examples pushes the secondary *specialisation* modality towards *universals*, rather than particulars.

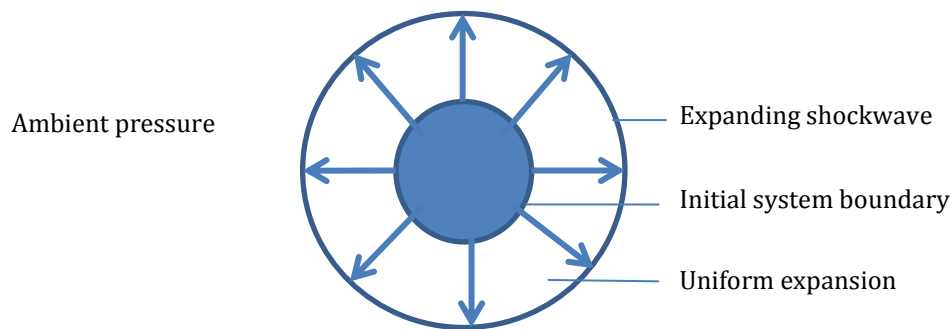
Principal Mode: weaker constitutive normativity

Secondary Modality: specialisation, Mode: Universals

6.4.3 Mechanical explosion problem

A clearer example of a normative orientation to knowledge can be seen in the section on the thermodynamics of mechanical explosions (Sandler, 2006, pp. 173-182). An example of a mechanical explosion is the result of the failure of an over-pressurised container of a given volume of air at room temperature and high pressure. The problem requires an estimate of the damage done by the explosion.

Figure 5.3.1. (Sandler, 2006, p. 174)



A crucial step in solving the problem is to define the 'system' and the 'surroundings', since there is an exchange in the energy between system and surroundings in the form of 'work' that the system performs on the surroundings in the explosion. This 'work' is the damage that needs to be calculated to solve the problem. In this case the expanding shock wave is defined as the system. The characteristics of an explosion allow the engineer to justify certain assumptions or idealisations made in order to solve the problem: firstly, explosions are so rapid that a reasonable assumption is that there is insufficient time for heat or mass to transfer to or from the initial exploding body across its boundary. This means that the system can be treated as closed. The exploding matter expands extremely fast, creating a shock wave as the surrounding air is thrust away. The pressure outside the shockwave is ambient, but inside the shockwave the pressure is much higher than ambient pressure. This pressure differential is the cause of damage during an explosion.

The shockwave front continues to travel outwards as a result of the rapid expansion of the gases inside the front. The rapidity of the expansion also allows the engineer to assume that the expansion occurs uniformly. As the volume expands, the pressure inside the shock front falls as predicted by gas laws. This process continues until the pressure inside the shockwave eventually becomes equal to the ambient pressure and the final temperature of the gas is lower than the initial temperature.

The description above with the associated idealising assumptions allows the engineering student to treat the problem as a closed (no mass transfer to the surroundings), adiabatic (no heat transfer to the surroundings) system with a uniformly expanding boundary. It is then possible to derive a set of relatively simple equations, using the mass, energy and entropy balances from the First and Second Law of thermodynamics. Without going into detail on the mathematics, the following equations are derived:

Mass balance equation: No change in the mass: $m_{\text{final}} - m_{\text{initial}} = 0$ (closed system)

Entropy balance: $S_{\text{final}} - S_{\text{initial}} = S_{\text{gen}}$ where S_{gen} is the entropy generated across the shock wave.

Energy balance equation: The change in internal energy of the system is equal to the work done on the surroundings by the expanding boundary: $U_{\text{final}} - U_{\text{initial}} = W$. This equation allows the calculation of the work W done by the shockwave on the surroundings, which is the damage done in the explosion.

With the exception of S_{gen} , all of the thermodynamic properties of the system can be calculated or read off detailed thermodynamics property tables. The amount of entropy generated across a shock wave, S_{gen} , is almost impossible to quantify, and so, to solve the problem, S_{gen} is neglected (S_{gen} is set to zero):

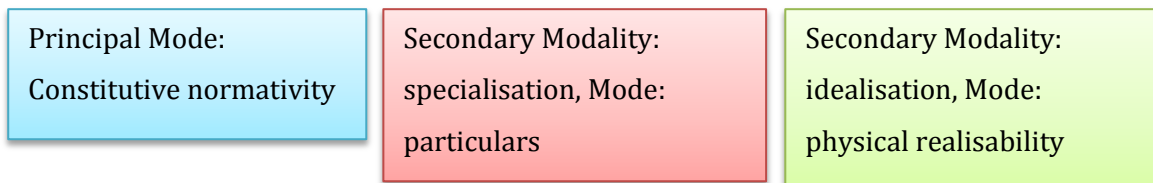
...the only generation of entropy occurs across the shock wave. If we neglect this entropy generation, the work we compute will be somewhat too high. However, in safety problems we prefer to be conservative and err on the side of overpredicting and energy release resulting from an explosion, since we are usually interested in estimating the maximum energy release and the maximum damage that could result. Further, we do not really have a good way of computing the amount of entropy generated during an explosion. Consequently, we will set the $S_{\text{gen}} = 0$... (Sandler, 2006, p. 175)

Sandler here uses a simplifying approximation to solve the problem. The calculation results in a somewhat inaccurate answer, but because the result *overestimates* the damage from the explosion, it is an acceptable and cautious approach.

Furthermore, Sandler encourages students to compare the amount of work done by the system (i.e. the damage produced by the explosion) to the blast energy released in the (chemical) explosion of a mass of TNT. Sandler also points out that if the pressurised tank above contained a combustible substance (rather than air), there is a real danger that a secondary chemical explosion could occur when the expanding vapour-containing shock front comes into contact

with enough oxygen to ignite. This would obviously add to the devastation caused by the explosion.

The normative concern that drives the problem-solving approach gives the knowledge mode as *constitutive normativity*, and the approximation made in order to arrive at the answer means that a secondary knowledge modality, *idealisation*, is present. The resulting approximation is justified by the safety concern for the physical circumstances under which the explosion takes place (mode *physical realisability*), and the typical industrial context of an overpressurised tank, identifies another secondary modality, *specialisation*, mode *particulars*.



Overall, the normative orientation of the knowledge in the chemical engineering textbook is less prominent and also more implicit than in the mechanical engineering text. In addition, no attention is paid to what could be called First Law efficiency of devices (there are some examples of Carnot efficiency and coefficients of performance of refrigeration cycles). Even in the explosion example discussed above a normative orientation is muted, apart from the injunction to over-predict (rather than under-predict) the damage from an explosion: the safety concern is implicit, rather than explicit.

6.5 Chemistry

6.5.1 Uses for thermodynamics

Under a heading at the start of chapter one, "What is thermodynamics and what is it used for?" (p. 2), Engel and Reid (2010) mention four applications of thermodynamics. They refer to improving the yield in an ammonia reactor, comparing the efficiency of methanol as fuel for an internal combustion engine and an electrochemical fuel cell, balancing space constraints with the requirements of voltage generation by a battery, and making operating decisions about the cost of synthesising a catalyst for a specific reaction. All four of these examples have normative implications. However, they are mentioned in passing in an introductory paragraph to indicate that thermodynamics has practical uses. *No further mention* is made of anything similar to this in the chemistry textbook: no examples and none of the end-of-chapter questions have any normative orientation whatsoever. For this reason the driving primary mode of this knowledge

is *incidental normativity*, and the secondary modality of *specialisation* is towards *universals*, rather than the particulars which a normative orientation usually results in.

Principal Mode: Incidental
normativity

Secondary Modality:
specialisation, Mode: Universals

6.5.2 Second Law efficiency

In the section dealing with heat engines, Engel & Reid refer to the important consequence of the Second Law of thermodynamics, namely that “the maximum theoretical efficiency [of a heat engine]... is less than 100%, which limits the efficiency of an automobile engine” (p. 81). However, there is no sense of the implications of this, and certainly no indication that this could be used as a standard to improve efficiencies of real devices. The knowledge therefore remains at a general, universalised level, which explains the primary coding decision of *incidental normativity*, with a secondary coding of *specialisation* towards *universals*.

Principal Mode: Incidental
normativity

Secondary Modality:
specialisation, Mode: Universals

6.6 Concluding remarks

This chapter describes illustrative instances of normativity as the principal knowledge modality in the five text books. The coding reflects the prominence of normativity in the data units: either constitutive or incidental normativity. If present at all in the sciences, instances of normativity are incidental. By contrast, the engineering science textbooks displayed a variety of instances of normative knowledge, especially in the case of mechanical engineering. Normativity was more muted, and less explicit in the case of knowledge in chemical engineering.

Each unit of data was also considered in terms of the other two modalities (specialisation and idealisation) as potential secondary knowledge modalities. Typically the engineering science knowledge displayed specialisation towards particulars, and an idealisation modality influenced by the physical realisability mode. On occasion knowledge in chemical engineering displayed a tendency towards universals in the specialisation modality. Knowledge in the sciences tended to specialise towards universals, and where the idealisation modality was present as a secondary modality, the tendency was towards abstract-ideal theorisation.

A summary of all the coding decisions made in chapters four to six is presented in Appendix A.

Chapter 7 Discussion of results

"Begin at the beginning," the King said, very gravely, "and go on till you come to the end: then stop."

– Lewis Carroll, *Alice in Wonderland*

The preceding chapters four to six contain an analysis of the data gathered from the curriculum texts for two engineering science and two (pure) science disciplines, using the analytic framework developed in the methodology chapter (chapter three). Appendix A provides a summary of the main coding decisions made during the analysis set out in chapters four to six. The current chapter is an interpretation of the analysis in the light of the research questions framed in chapter two. It presents a discussion of the findings of the research in terms of insight into the nature of the specialisation of knowledge in the professions in general (in particular Bernstein's notion of regionality), a better understanding of the disciplinary differences presented in curriculum knowledge in the natural and engineering sciences, and an empirical engagement with selected concepts from the philosophy of engineering.

I start the chapter with a reminder of the journey this far: a brief contextual re-statement of the research problem located in the relevant literature, and a motivation for the research design used and analytical instrument developed in this study. This is followed by a closer discussion of the analysis, keeping in mind the research questions: first a look across the disciplinary knowledge modalities, then a discussion of the implications of this for an understanding of the differences and similarities between science and engineering science disciplinary knowledge. This is followed by a discussion of a refinement of the analytical tool in the light of the findings with a clarification of relationships within and between elements of the analytical framework. After this, the discussion moves to a more abstract level, as implications of the study for the sociology of educational knowledge and the philosophy of engineering science are raised. Lastly, limitations of the study are discussed.

7.1 Locating the study

The initial interest for the study grew from a concern around the success (or lack thereof) of engineering students as they negotiate their way through an engineering curriculum, in particular the transition required of students from the pure science courses at the start of their curricula into the engineering science courses later in their academic career. As pointed out in chapter one of the thesis, this transition has not received much attention in engineering

education literature, in particular when framed in terms of epistemic differences and similarities between knowledge in the sciences and the engineering sciences.

Distinctions between science and engineering are often drawn in intuitive ways; society acknowledges engineering as a distinct profession, even while recognising that there is a close relationship between science and engineering. The distinction is visible in the way higher education is organised in universities and colleges, with science and engineering students educated in separate faculties and departments. There is a general, perhaps vague, understanding that disciplinary differences do exist, and that these are significant enough to rationalise distinct fields of study. However, what lies at the heart of the distinction between engineering and science is less clear, and most will be hard-pressed to define the differences in unambiguous terms.

The disciplines as we find them today in the modern university are the result of a historical process of refining and defining valued knowledge. In chapter one of the thesis some of the history of the disciplinary fields was traced, with a specific focus on the relationship between the fields, from the early fore-runners of craft knowledge and natural philosophy to the rigorous science and engineering disciplines we see today. The history demonstrated that the relationship between the broad disciplinary fields of science and engineering is complex and varied: at times independent of each other, at other times functioning in hierarchical relationships, and sometimes entirely intertwined. Scholarly work exploring of the nature of the relationship between the broad fields is seldom supported by empirical work, and theorisation usually refers to the broad disciplinary fields, leaving issues around disciplinary epistemology largely unexplored.

Focusing on *knowledge*, rather than on the range of disciplinary activities and behaviour in science and engineering makes it possible to identify analytically distinct empirical objects for a research study. In particular in this project, *curriculum knowledge* functions as a relatively enduring empirical proxy for valued knowledge used to educate and induct students into the disciplines (see the argument made in chapter two about the likelihood that the curriculum knowledge displays a measure of the disciplinary characteristics).

The work described in this thesis therefore contributes an empirical study of epistemological characteristics of engineering science knowledge against a backdrop of those in science, as these are presented in curriculum.

7.2 The research design

The research design used a case study approach in which nominally the same curriculum knowledge (two foundational laws in thermodynamics) was compared across four sub-cases, two in engineering and two in the sciences. This symmetry of design also afforded an opportunity to explore potential variation within the broad fields of engineering and science. As explained in chapter three, a methodological decision was made to focus on knowledge as presented in the five textbooks prescribed for six undergraduate courses at the University of Cape Town, rather than attempting to extract disciplinary content knowledge from lectures. This ensured more stable empirical data less influenced by the caprices of individual lecturer decisions. In all cases the introductory undergraduate textbooks were published by international publishers, and most of the texts (except the one physics textbook) are later editions of the texts. This is an indication of their dissemination and acceptance as international academic texts suitable for undergraduate instruction (see also the Bernsteinian argument developed in section 3.3.3, explaining reasons for expecting significant agreement on the breadth of topics in typical undergraduate technical textbooks).

7.3 Analytical framework

An important part of the work done in the thesis was the development of an analytical framework that would allow for the selection and analysis of the empirical objects identified in the textbook disciplinary knowledge. Investigating the nature of *engineering science* knowledge, and comparing this to knowledge in *science*, set a challenging analytical problem because of the close adjacency of the knowledge fields. It required a diagnostic instrument capable of fine-grained distinction, and developing this tool was the initial research task.

7.3.1 Considering possibilities from the sociology of educational knowledge

The theoretical work of British sociologist Basil Bernstein provided a valuable starting point. Bernstein theorised the educational process in his development of the pedagogic device as a description of the way the “outside becomes the inside...” (Bernstein, 1987, p. 563). In the process, he developed a sociology of knowledge that allowed for a differentiation between new knowledge becoming part of the canon of a discipline in the field of production, the delocation and relocation of this knowledge into curriculum knowledge in the field of recontextualisation, and finally the acquisition of knowledge through pedagogic practices in the classroom in the field of reproduction. It was therefore important to clarify the position of the study in terms of these

three levels. The empirical data described in this thesis was collected from curriculum texts, and was therefore recontextualised disciplinary knowledge.

Bernstein's notions of singulars and regions were relevant for the study described here: the science disciplines of chemistry and physics are considered typical singulars in the Bernsteinian tradition, with strong classification and boundary maintenance. Bernstein described regions as disciplinary fields with weaker boundary maintenance, and an outward orientation towards what he called the field of practice of typical professions and occupations. The engineering sciences (mechanical and chemical engineering) would therefore be considered regions. In many ways the notions of singulars and regions were underdeveloped in the Bernsteinian framework. The terms came late in the chronology of Bernstein's theoretical development, and "are more suggestive than they are explanatory", (Muller, 2007, p. 65) in a slightly different context. The concepts are therefore challenging to operationalise directly, and lack definition as analytical tools. By themselves they do not suggest variation *within* the categories, and while Bernstein's distinction between regions and singulars is useful as a first pass at differentiating between knowledge in science and engineering, it remains at best a fairly blunt instrument for use with detailed empirical data.

Bernstein's work has been extended by various scholars (see the references to the work of Johan Muller, Karl Maton, Suellen Shay and others in more detail in chapter two). Maton's work on Legitimation Code Theory, in particular semantics, has been used in educational research to refer to the relationships between knowledge and context (in semantic gravity) and between knowledge and the condensation of meaning in symbols (in semantic density). These concepts have been productively used in research of pedagogic practice, and their appeal is apparent for describing differences between contrasting disciplinary fields. However, semantics could not provide enough granularity for distinctions between the contiguous fields considered in this study, as both the sciences and the engineering sciences generally have strong semantic density because of the importance of mathematics, graphs and equations in both broad fields. Furthermore, the empirical work in the thesis addresses *the same knowledge concepts* in thermodynamics, with comparable semantic density across all sub-cases. A similar argument could be made for broadly corresponding strength in the semantic gravity of the larger disciplinary fields of science and engineering: both disciplinary fields have strong empirical referents in the 'real' world, and both present knowledge within contexts, even if the contexts are different for the broad fields.

7.3.2 Considering the philosophy of engineering science and science

None of the theoretical tools considered from the sociology of knowledge were therefore exhaustively able to meet the requirements of this research study to investigate differences and similarities in the knowledge of the closely related fields. The applied philosophies of science and engineering concern themselves with the nature and approach of the disciplines, and these were considered next as potential sources of theoretical concepts that would facilitate analysis of the data.

Various philosophers counsel against essentialist delineation of the disciplines, and Houkes (2009) cautions against an oversimplified polarisation of the goals of science and engineering as “truth vs usefulness” (p.312). A more nuanced approach is needed to proceed beyond a superficial distinction between disciplinary goals. A commitment to consider *knowledge* rather than all disciplinary practices means that the focus in the thesis is therefore on epistemic differences and similarities, or the degree of “epistemic emancipation” (Houkes, 2009, p. 309). Houkes distinguishes between strong and weak epistemic emancipation²⁶, and intriguingly suggests that it should be possible to probe weaker epistemic emancipation empirically if differences could be found in the way the disciplines approach certain epistemic practices. Two of these, idealisation and normativity, were explored further in this thesis. A third analytical category, specialisation, was developed in interaction with the data, as described in chapter three.

Specialisation is used in this thesis to describe the way the fundamental values of the broad disciplinary fields are enlisted in aspects of the knowledge, alluding to the potentially different social functions (description and explanation for the sciences, and artefact realisation in engineering) of the disciplines.

Idealisation is an important epistemic approach in both science and engineering science. This involves the intentional (Weisberg, 2007a) and selective (Van Fraassen, 2010) distortion of knowledge for specific purposes. One of the questions explored in the research described in this project, is whether there is any evidence in the data for differences in the way idealisation is employed in the sciences and engineering sciences.

Normativity, a concept from the philosophy of technology, is often centred on the artefactual nature of technology (Dancy, 2006; Franssen, 2009), such as the evaluative consideration of the functionality of artefacts and the intentionality in the construction of artefacts. In chapter two I

²⁶ As discussed in chapter two, Houkes suggests that at best a weak epistemic emancipation is likely for engineering science knowledge (strong epistemic emancipation would suggest *no* intersection of epistemic values and criteria between science and engineering science).

describe how Radder (2009c) proceeds beyond the artefact in his view that technology, and therefore engineering, is inherently normative. Evidence of qualitative differences in normative emphases in the knowledge in science and engineering knowledge was explored in the data.

7.3.3 The analytical instrument and data analysis

These three concepts, specialisation, idealisation and normativity, became the starting point of developing a potentially productive analytical framework. Chapter three describes the way the concepts were operationalised for application to the empirical data. Starting from a proto-understanding of the *teloi* of the broader disciplinary fields, strong function and theory orientations were suggested for the knowledge in engineering and science disciplines respectively (see Figure 3.1).

From this beginning, it became possible to conceptualise specialisation, idealisation and normativity as knowledge *modalities*, elaborating on the knowledge orientation. Nevertheless, the modalities remained data-distant (Moore & Muller, 2002), and needed mobilisation before they could be brought to bear upon the units of data. This involved viewing the modalities as axes of variance and developing sets of *modes* as the ends of a continuum along which the modalities varied (see the visualisations described in paragraph 7.4 below). For the modality of specialisation the modes are *particulars* and *universals*; for the idealisation modality, the knowledge either idealises towards *physical realisability* or *abstract-ideal theorisation*. In the case of the normative modality, the knowledge modes vary from *constitutive* normativity to *incidental* normativity. The analytical instrument as a whole is described in Figure 3.2 of the methodology chapter, and shows the full progression from disciplinary *telos* to knowledge modes. The modes are conceived of as continua, rather than binaries. The model therefore suggests the possibility of variations in modal strength.

The units of analysis were thermodynamics knowledge themes. Once identified, data units were considered in terms of each of the three modalities, and coded for the modes. In multi-modal instances, a principal mode was identified. Appendix A summarises the coding results.

7.4 Discussion of the modalities across the disciplines

I next discuss an overview of each of the three modalities, taking into account how they varied across the four disciplinary knowledge fields as observed in the data gathered from the textbooks. Here the focus will be on the coding of *principal* modalities (see Appendix A); later in this chapter the secondary modalities and the relationships between modalities will be considered.

7.4.1 The knowledge modality of specialisation

Chapter four dealt with the data analysis around the modality of specialisation as a principal knowledge modality. Three immediate observations come to mind: firstly, the data presented was more voluminous than was the case for the data presented in the other principal modalities. Secondly, the thermodynamics knowledge themes in data units described in chapter four are shared across all the disciplinary areas, and, with one exception (enthalpy), were of a meta-theoretical nature: the meaning attached to the term 'thermodynamics', the overall approach to the topic followed by textbook authors, the way systems and devices are conceptualised in the textbooks, the formulation of the First Law and the sign convention associated with this, and the use of codified or condensed knowledge across the disciplinary areas. Furthermore, specialisation is the knowledge modality that refers most directly to the fundamental concerns of the disciplinary fields: for the sciences the descriptions and explanations of phenomena, and for the engineering sciences the interventions that modify and change the human world according to a need. The *modes* that operationalise the specialisation modality are specialisation towards *universals*, expressing the intention to explain across phenomena, and specialisation towards *particulars* at the other end, progressing beyond abstract notions to the specifics required in a particular situation. The implication of these three observations is a possibility that the specialisation modality may be of a different order from the other two modalities (idealisation and normativity). This is elaborated upon in 7.5.1 below where the relationships between modalities are considered. However, treating specialisation as an independent equal modality at the initial stage of the analysis, made methodological sense, and allowed for cognitive gain by providing more options for coding of the richly textured data.

For much of the data, the coding confirmed the links to the fundamental disciplinary concerns as envisaged in the design of the analysis instrument: the physics and chemistry data in all cases specialised towards universals. This is in line with the sciences' fundamental concern for explanation (see Figure 3-1). Even when the chemistry textbook followed the classical macroscopic approach to thermodynamics (similar to both engineering sciences), microscopic atomic explanations were constantly called upon to explain macroscopic thermodynamic properties. Whereas the engineering science data mostly specialised towards particulars, there were some exceptions. It is perhaps not unexpected that mechanical engineering would display some specialisation to universals in the formulation of the First Law of thermodynamics; it is after all a general statement of a fundamental natural law. In spite of this, the distinct sign convention adopted in the mechanical engineering textbook under consideration (possibly signalling the engineering concern for the work output of devices, as suggested in 4.6.1), and the

strong emphasis on its application in devices, meant that the categorising of this data unit was coded as still strongly specialised towards particulars.

The chemical engineering text presented some knowledge related to engineering devices. However, there was less that could be coded as “particulars” in the formulation of the First Law. Also, the use of a markedly general formulation of the First Law consisting of the summation of terms that cover a wide range of physical systems confirmed the coding of the chemical engineering data as predominantly specialised towards universals in this case. Furthermore, the chemical engineering textbook knowledge often relied on referencing microscopic detail in spite of the broadly macroscopic approach to thermodynamics. This is one Important difference between the two engineering science disciplines under consideration, and can probably be attributed to the nature of the basic science (chemistry) that chemical engineering fundamentally draws from: the prominence of the atomic model to explain chemical reactions finds its way into the chemical engineering science more markedly than was the case for the mechanical engineering text.

As discussed in the methodology chapter (in 3.4.4), the modalities are conceived of as continua rather than dipoles. Keeping this in mind, it then becomes possible to conceptualise the disciplinary fields along a specialisation continuum.



Figure 7-1: The specialisation continuum

Figure 7-1 illustrates a few important ideas. Firstly, it is clear that there is a difference in the way the sciences and the engineering sciences specialise: the data from the thermodynamics textbooks confirms that the science knowledge specialises towards more universal, general ideas that would align with the theory-committed orientation of knowledge suggested in the theoretical framework (Figures 3-1 and 3-2). This supports the fundamental value of the science disciplines to describe and explain phenomena across many instances. Knowledge in the engineering sciences, on the other hand, specialises towards particulars, in keeping with the specifics demanded by the task- or problem orientation of knowledge in engineering.

Secondly, there are differences in the way the disciplines specialise: Figure 7-1 suggests that the mechanical engineering (MEng) knowledge specialises to a larger degree towards particulars than chemical engineering science (CEng) knowledge.

The importance of engineering devices like compressors, nozzles, turbines, refrigerators, water heaters, pumps, throttling devices in the engineering science textbooks is an important difference between the science and engineering texts²⁷. Devices were largely absent from the three science texts, or else were dealt with in a cursory manner. Similarly, although all textbooks used codified knowledge in the form of fundamental physical constants, the absence of the codified procedural knowledge in property tables, and Mollier and phase diagrams was striking in the science textbooks (there was a brief acknowledgement of the existence of property tables in the third year physics text, but no procedural attention given to it). The thermodynamic property tables and Mollier diagrams in the engineering texts are detailed empirical data highly valued in the engineering science for the comprehensive knowledge of macro properties given under different operational conditions. The prominence of the engineering devices and the condensed procedural knowledge in the tables and graphs are important references to what Bernstein called the field of practice of the engineering sciences, and they provide empirical evidence for an important orientation towards the field of practice for the technical professional knowledge. I return to this observation later in the chapter (see 7.6).

7.4.2 The knowledge modality of idealisation

As discussed in chapters two and three, idealisation and modelling are extensively used in the sciences and engineering sciences as they engage with the world. Idealisation is described in the literature as intentional and sometimes selective distortion of reality for various purposes. It involves the deliberate employment of assumptions about phenomena (for example simplification or approximation) that may not be accurate in a strict understanding of the real-world phenomena, in order to be able to explain phenomena, make predictions or solve problems (including the design of artefacts). A view of models (in both the sciences and the engineering sciences) as epistemic tools and independent 'concrete' objects (Boon & Knuuttila, 2009) that have been constructed for a particular epistemic purpose, could be substantiated in some of the examples of the data discussed in chapter five (see for example control volume

²⁷ The notion of coding the engineering sciences' emphasis on devices as towards 'particulars' has to be qualified: the level at which the devices are discussed in the engineering science texts is less specific than what would be required in a design task. For example, engineering science covers thermodynamic processes in *generic* power stations and turbines rather than a specific turbine or a particular generation or fleet of power stations. Nevertheless, in the context of comparing engineering science knowledge with knowledge in the sciences (rather than with engineering design), coding engineering science as knowledge of *particulars* is reasonable (see also de Vries (2010))

analysis in mechanical engineering, and harmonic oscillators in physics). Models as epistemic tools emphasise the functional properties of the models, and the way the modeller can manipulate and interact with the model as demanded by the particular requirements of a problem. The cognitive value of the model lies in the fact that this kind of interaction with the model is possible. Models do more than merely represent a target system.

In the data considered here, idealisation includes entities that are clearly identifiable models, such as the ideal gas model, but also simplifications or approximations of real processes and phenomena, such as treating real processes as quasi-equilibrium processes.

The modes developed for the idealisation orientation refer to the different purposes with the idealisation activity, and ultimately to the fundamental aims of the broader disciplinary fields of science and engineering: the idealisation enables thinking about the knowledge to be either towards *abstract-ideal theorisation* or towards *physical realisability*. The data analysis in chapter five demonstrates that in all cases considered for physics and chemistry the idealisation remained at the abstract-theoretical level. This is seen most clearly in the use of the ideal gas in chemistry, and in the development of the statistical mechanical model in physics to describe the behaviour of matter. The models developed are detailed and able to explain and predict the macroscopic properties of matter.

One of the differences between the engineering sciences and the natural sciences is that knowledge production in the engineering sciences has the particular focus of “goal-oriented action based on that same knowledge” (Zwart, 2009, p. 633). This emphasis on action shapes the kind of modelling that takes place in engineering science, and therefore idealisation tends towards physical realisability. This is clear for mechanical engineering knowledge in the textbook: the summary of coding decisions in Appendix A indicates that for mechanical engineering, the idealisation orientation of all the data units discussed is towards physical realisability. The notion of the control volume is an example of a thinking tool exclusively used in engineering science (Pirtle, 2010; Vincenti, 1990). It is a virtual construct, conceived of purely for the purpose of solving open system flow problems, typical in engineering. In control volume analysis, the control volume is treated as black box with all extraneous properties removed. The focus is on fluid flow through an open, defined volume, conceived of in terms of inputs and outputs, with no concern given to the inner detail. Control volume analysis is clearly an example of a case where idealisation is used as an epistemic tool for solving problems of a particular kind.

Other examples of the use of idealisation in mechanical engineering include various cases of approximation, for example treating unsteady flow as steady flow and real gases as ideal gases.

The complexities of the 'real' world cannot be completely ignored in engineering problems even though full knowledge of a multitude of variables is often not possible. Approximation, when simplifying assumptions are made, then provides a way into ill-defined problems. The measure of satisfaction with the answer obtained by approximation is determined by the margin of error of uncertainty introduced by the approximation, which is therefore often stated explicitly in the mechanical engineering text. Physical realisability of a problem solution requires tolerance for approximation, provided the distortion so introduced does not compromise functionality and safety. Appropriate adequacy for functionality is therefore the practical outworking of physical realisability. This is seen in the mechanical engineering science data in the insistence on quantifying the error introduced by the use of approximation. Approximation is acceptable as long as it produces a solution that is fit-for-purpose required by the physical reality.

Another example of idealisation in the mechanical engineering textbook can be seen in the way the ideal Carnot cycle is used. Although the Carnot engine is covered in all the thermodynamics texts under consideration, in the mechanical engineering text there is an emphasis on using the ideal Carnot engine as a standard against which the efficiency of real heat engines is measured. The demands of the 'real' world and the need for physical realisability are therefore always present when idealisations are used in the mechanical engineering textbook.

Chemical engineering displays a weaker tendency towards physical realisability than mechanical engineering in all the cases discussed in chapter five, with one exception. Open systems are also treated as black boxes, but here a general non-specific balance equation is developed that is adapted across different generic types of systems. Although the chemical engineering textbook author emphasises the complexity of the physical world, he mostly deals with the needs of physical realisability via simplification by the use of specific assumptions, estimates and approximation in the face of incomplete information – a weaker commitment to physical realisability than was the case in mechanical engineering.

In spite of the weaker emphasis on physical realisability, it is also in the chemical engineering textbook that attention is drawn quite explicitly to the constraints of idealisation. The ideal gas model is a powerful idealisation used across all of the texts investigated in the study. However, for those fluids commonly used in (chemical engineering) industrial applications, the author points students to the detailed tables of empirical data available for calculations. The demands of physical realisability here overshadow the power of explanation offered by the model under ideal conditions.

There is one other interesting exception where the chemical engineering text displays a strong commitment to physical realisability. The idealisation employed in the tank-filling problem (see

5.4.2) is a completely utilitarian distortion of reality, engaged solely in the service of solving the problem at hand. The simplest way to solve the problem requires an approach using a distortion that not only violates *reality*, but also the theoretical *model* of ideal gas behaviour. The ideal gas model does not allow for identifying, at the start of the problem-solving process, the proportion of gas molecules *left behind* at the end of the process. It is therefore diametrically at odds with the type of theory building that idealisation is often used for in the sciences, and is employed here to find a way to solve a complex physical problem. The concept of idealisation as an epistemic tool (Boon & Knuuttila, 2009), here employed towards physical realisability (solving the real-world problem of tank-filling), is quite prominent. In a sense this is an example that illustrates that “physical realisability” is not the same as correspondence to “physical reality”. It is less a commitment to the “truth” Pirtle (2010) refers to, than a commitment to solving a problem, and in that sense dedication to *physical realisability*.

By contrast, the data from the chemistry textbook shows how the ideal gas model is infused throughout the textbook. Even though a macroscopic classical approach to thermodynamics is followed throughout, diagrams often show molecular detail to relate to macroscopic properties of pressure, temperature, volume and amount of matter. It is the underlying explanatory power of the model that is important in the chemistry text. This becomes abundantly clear when the chemistry authors discuss deviation from ideal behaviour exhibited by real gases. A very different approach from that of the two engineering texts follows. Whereas the engineering textbooks move swiftly to empirical data for real gases to facilitate the insistence on physical realisability, the chemistry text’s chief concern is to be able to *explain* the deviation from ideal behaviour under various circumstances. The authors express their uneasiness with following *only* the classic macroscopic approach, as it does not get to the bottom of the *reasons* for the deviations from ideal behaviour. They use changes in the potential energy between two interacting molecules that depend on the polarisability of the electron cloud of the two molecules as they approach each other to explain the deviation. For the chemistry authors, it is most important to be able to give an explanation in terms of the ideal gas: real gas behaviour deviates from ideal behaviour, but the atomic/molecular model that encapsulates the ideal gas model is able to explain the deviations. This theoretical explanation in terms of the main theory accounts for the empirical observation of real gas behaviour, and the theory is in fact corroborated because of the evidence that it can deal with empirical behaviour. The idealisation most prized here is one that leads to building and affirming abstract-ideal theorisation.

The two physics textbooks follow a very different approach from the other three textbooks: instead of the classical macroscopic approach, a statistical mechanical approach is followed. The first year textbook authors describe the role of modelling as a central aspect of science for the

purpose of predicting and explaining behaviour. Their description of modelling mirrors Weisberg's (2007a) Galilean idealisation: phenomena are stripped of "messy complexities" (Chabay & Sherwood, 2011, p. 82) to enable patterns to become visible and understand factors that impact on these. These patterns lead to revision and elaboration of the model. The third year textbook author demonstrates this in his discussion of the ideal gas model that starts off with just a single gas molecule. He builds an explanation of the behaviour of the molecule that links the kinetic energy of the particles with the ideal gas equation.

However, it is ultimately the way the statistical mechanical approach allows the physics texts to deal with *explaining* fundamental aspects of the Second Law of thermodynamics that demonstrates the commitment to the abstract-ideal theorisation mode of idealisation. (By contrast the engineering texts' starting point is the *fact* of the irreversibility of some macroscopic processes: heat flows from a hotter to a colder object, a ball dropped to the ground bounces lower each time it hits the ground, etc.). Using combinatorics and factorials to calculate the likelihood of a particular distribution of energy for large numbers of particles, the physics authors use arguments from statistical mechanics to explain *why* macroscopic thermodynamics processes are irreversible. The physics texts apply probability theory to large numbers of particles to demonstrate how energy is distributed amongst particles in large systems, why objects reach thermal equilibrium, and ultimately develop a theorised understanding of the meaning of temperature. Particles are modelled as idealised harmonic quantum oscillators that store energy in different macrostates corresponding to different numbers of microstates (ways of distributing quanta of energy across oscillators). Although all microstates are all equally likely, some macrostates are more probable than others: the macrostates with the largest number of corresponding microstates. The ability to *predict and explain* the macroscopic behaviour of matter is highly valued in the physics texts, and their orientation to idealisation is therefore towards the abstract-ideal theorisation.

The empirical data from the textbooks illustrates quite vividly how idealisation is approached in different ways in the disciplines for distinct purposes. The scientific concern for generalisable theoretical explanations places no constraints on the amount of idealisation employed, hence Cartwright's (1983) reference to the "lying laws of physics" (Laymon, 1989b, p. 353). Cartwright's argument is that the fundamental physical laws (which involve idealisation in order to apply broadly) are powerful explanatory tools, but that these come at the cost of a loss in "descriptive adequacy" (p. 3). On the other hand, the demand for physical realisability in the engineering science knowledge implies that the distortion brought about by idealisation cannot stray too far from the complex demands of the real world (presented in the data, for example in the quantification of error introduced by approximation). This confirms Hansson's (2007)

suggestion that the engineering sciences make use of “less far-reaching idealizations” (p. 526), and Pirtle’s (2010) argument that models in engineering ultimately have to “tell the truth” (p. 95), with ‘truth’ here referring to a closer correspondence with reality.

Houkes (2009) suggests something slightly different (but still illustrating engineering science knowledge’s strong allegiance to solving ‘real’ problems), namely that the engineering sciences might employ idealisation for pragmatic purposes of finding a solution to a problem. In principle, it is therefore possible to use a method or an approach that is not strictly speaking ‘true’ or accurate, but gives an acceptable answer to a complex problem. Houkes suggests that this method or approach will not be taken up in the sciences, as it counters the kind of detailed explanatory knowledge valued in the sciences. The data discussed in chapter five offered two instances of this kind of idealisation: the control volume analysis prominent in mechanical engineering is not taken up in the sciences (see paragraph 5.2.1), and the tank-filling problem in chemical engineering offers a simple solution involving a ‘model’ that contradicts the ideal gas laws and theory (see paragraph 5.4.2).

In all of these examples, the influence of engineering’s field of practice (to use Bernstein’s term) in engaging with physical realisability required for problem solving is evident. See the further discussion under 7.6 later in this chapter.

In view of the fact that the modalities are conceptualised as continua, it becomes possible to represent the idealisation modality in Figure 7-2.



Figure 7-2: The idealisation continuum

The diagram indicates strong inclination towards abstract-ideal theorisation of the science disciplines in the physics (PHY) and chemistry (CHE) idealisations, as well as the tendency towards physical realisability in the engineering science knowledge. The weaker engagement with physical realisability evident in the chemical engineering text (CEng) when compared to the mechanical engineering (MEng) knowledge is also evident on the idealisation continuum.

7.4.3 The knowledge modality of normativity

In the context of the study normativity refers to evaluative and deontic aspects of the use of concepts. As discussed in chapter two, various philosophers of technology argue for a strong normative aspect of engineering science knowledge. The functionality and intentionality of engineering systems play an important role to explain this, and were evident in the data. Considering the typical fundamental values in the sciences (explanation and description), it would be reasonable to expect more value-neutral and descriptive knowledge in the sciences. In the light of the anticipated importance of normativity in engineering, the mode ends developed for the normative modality continuum of the knowledge were '*constitutive*' and '*incidental*'. This was done to reflect that at the one end normativity is an intrinsic quality of the knowledge, whereas at the other end normativity, when present, it seems almost peripheral.

The normative knowledge modality is unmistakable in the engineering sciences, and is especially well-developed in the mechanical engineering textbook. There were numerous and varied examples of normativity in the mechanical engineering textbook data, and as a consequence knowledge is coded '*constitutive*'. Normativity is an intrinsic quality of thermodynamics knowledge in the mechanical engineering text. Some of the instances of normativity found in the data were more implicit, as in the cost calculations in the problems set, and in the choice of terminology employed, like '*steam quality*' to refer to the moisture content of steam in power generation, and the '*dumping*' and '*wasting*' of energy in heat engine cycles. In other cases the normativity is more explicit: there is an extended discussion on the *quality* of energy, with some forms of energy (eg. electrical energy) more valuable than other forms of energy (eg. heat energy). Efficiency is an important topic, and both First Law efficiencies (the performance of a machine or process) and Second Law (thermal) efficiencies are covered in detail. Second Law efficiency (the formulation that thermal efficiency is intrinsically lower than unity), expressed in the equation $\eta = 1 - \frac{Q_L}{Q_H}$, is dealt with across all disciplines, as would be expected in textbooks that cover the Second Law. However, the normative aspect of this concept is particularly strong in the mechanical engineering textbook where it is emphasised as the fixed theoretical upper limit for the efficiency of a heat engine. In the mechanical engineering text this limit provides a standard against which actual devices can be compared and improved. A starkly different emphasis is particularly evident in the physics textbook where the author talks about the equation as a purely mathematical construct, and considers how to produce a *less efficient* engine (as though this could be conceived of as equally desirable) by generating extra entropy in a process, dumping more energy to leave less energy to convert to work (see the discussion under 6.3.2). The mechanical engineering textbook also carries examples where the authors quantify the error margin introduced by approximation. Although approximation is a simplification (and therefore refers to idealisation), the focus here is on

quantifying the inaccuracy introduced by this type of idealisation. This is an instance where an idealised deliberation (the approximation) is given a normative inclination.

Normativity is also evident in the chemical engineering text, but to a lesser degree, and more implicit (this could perhaps partly be explained by Alexander’s (2009, p. 1008) observation that that the notion of efficiency has been historically more prominent in mechanical engineering than in other engineering professions). An interesting example of normativity at work in the chemical engineering textbook is found in the discussion of the mechanical explosion of an over-pressurised vessel (high pressure vessels are typical in the chemical engineering industrial environment). Here the simplifying assumption made (neglecting the generation of entropy in the explosion) is justified by the over-riding safety concerns of engineers. The approximation gives an over-estimate of the damage rather than simply a less accurate solution. Therefore the motivation for coding the normative modality as principal (rather than the idealisation modality) with a mode of constitutive normativity is found in the abiding engineering concern for safety.

Normative aspects are virtually absent in the thermodynamics knowledge in the sciences: there is no discussion of First Law efficiency in either the chemistry or the physics text. The theoretical limit on Second Law efficiency is briefly mentioned as a consequence of entropy generation in both cases, but the implications in real-life applications are not explored. The chemistry textbook briefly mentions some efficiency issues in the introduction to the textbook, but this is not taken up anywhere beyond the introduction to thermodynamics. The way the physics text deals with Second Law efficiency has already been discussed above, and therefore the absence of normativity in both chemistry and physics results in a coding of the normative modality as *incidental*.

Figure 7.3 illustrates clearly that the engineering science knowledge as displayed in the engineering textbooks has a much stronger normative orientation than the science knowledge

Knowledge Modality	MODE	
Normativity	incidental	constitutive
	PHY CHE	CEng MEng

Figure 7-3: The normativity continuum

in the physics and chemistry textbooks. Furthermore, the normative mode of the knowledge in mechanical engineering is noticeably stronger and more explicit than is the case in the chemical engineering text.

7.4.4 Implications for an understanding of disciplinary knowledge

Taken together, the information summarised in Figures 7-1 to 7-3 gives us insight into some of the characteristics of disciplinary knowledge. As the knowledge under consideration in the five undergraduate university textbooks nominally covers the same epistemic content, it would be reasonable to expect quite significant overlap between such closely related fields as science and engineering science. This is indeed the case, but the analysis of the data from the textbooks also illustrates some important differences between knowledge in the different disciplinary fields.

Broadly speaking, Figures 7-1 to 7-3 demonstrate that knowledge in the sciences tend to be positioned at the opposite end of the modality continua compared to the knowledge in the engineering sciences. This is illustrated in the overall general tendency for knowledge in the sciences to specialise towards universals, idealise in a way that contributes to abstract-ideal theorisation for the purpose of building theory, and present a normative inclination that was either absent or at best incidental. The engineering science knowledge, on the other hand, mostly specialises towards particulars, idealisation is strongly influenced by a demand for physical realisability of the knowledge, and a significant disposition towards normativity in the knowledge is evident. This is not to say that the engineering sciences ignore the need for explanations and predictions; rather, the valued engineering science knowledge is focused on explaining and predicting the behaviour of the artefact under the different conditions that impact on the functional and problem context. It is interesting to note that the differences are not necessarily a function of the particular conceptual content. An example is the overall approach to thermodynamics where it is not the classical or statistical mechanical approach *per se* that predisposes specialisation towards particulars or universals. Although the chemistry text follows the same classical approach to thermodynamics as both engineering science texts (as opposed to the statistical mechanical approach in physics), chemistry knowledge is still clearly specialised towards universals rather than the particulars preferred in the engineering sciences.

The continuum (rather than binary) nature of the modalities suggests the possibility of variations in modal strength across and within broad disciplines. This is indeed confirmed in the engineering science data: the knowledge in the chemical engineering text is markedly less specialised towards particulars, less concerned with physical realisability in idealisation and less explicitly normative than the mechanical engineering knowledge. This is emphasised in Appendix A by the darker shading of the cells in the table where the chemical engineering knowledge differs from the expected coding for engineering science. There are different ways to interpret this difference between mechanical and chemical engineering science knowledge: firstly, considering the fundamental roots of chemical engineering as a discipline ('chemical'

rather than 'physical'), it could be an indication that chemical engineering curriculum knowledge is closer to chemistry than mechanical engineering is to physics knowledge. From a historical perspective, the separation between physics and mechanical engineering applications and the development of mechanical engineering as a clearly identifiable field of study predates a similar move for chemical engineering (see the discussion in the historical section of chapter one of this thesis). This is not to suggest that there is an inevitable trajectory of increased separation between the sciences and engineering sciences over time though; factors other than merely the passage of time could play a role in this (see the rest of the discussion below).

Secondly, the position of chemical engineering along the knowledge modality continua could be interpreted as referring to a stronger similarity between chemical engineering knowledge and the thermodynamics knowledge in *both* chemistry and physics. One possible explanation for this is the prominence of the influence of the atomic model of matter in all of these disciplines, specifically here with reference to thermodynamics. (More empirical work would be needed to establish whether the same could be said about other shared fields of knowledge between the disciplines.) In chemistry, chemical engineering and physics, atoms and molecules and underlying molecular behaviour in the atomic model are significantly more prominent in the data, and are valued for explaining the macroscopic behaviour. In this chemical engineering knowledge may be more 'science-like' than knowledge in mechanical engineering, which relies less on microscopic underpinnings of macroscopic behaviour of engineering devices and such.

Lastly (and perhaps not quite independent of the previous two suggestions), the difference in modal positions of mechanical and chemical engineering could suggest that mechanical engineering has developed a greater degree of specialisation in the Durkheimian sense (in terms of societal roles of the disciplines) from its closest root discipline (physics). There seems to be a greater epistemic emancipation evident in the mechanical engineering text. This impression is strengthened in the greater emphasis in the mechanical engineering text on typical engineering devices; an explanation for this could possibly be found in a stronger 'pull' exerted by the field of practice on professional knowledge.

It is possible that empirical studies similar to the current one on content topics other than thermodynamics could illustrate similar variation within the sciences. This would have to be explored purposefully in follow-on studies²⁸.

²⁸ In an article in the influential journal, *Nature*, Ball (2006) asks the provocative question whether the problem orientation of industrial chemistry, a branch of chemistry, in fact turns it into a form of engineering, in its focus on "a quest for particular solutions to particular problems" (p.501) as it seeks to synthesise chemical compounds for specific needs. See also Bensaude-Vincent's (2012) description of

7.5 Relationships between and within modalities

One of the contributions of the thesis lies in the theory development work that has been done, and I now turn my attention to the theoretical instrument generated in the work.

7.5.1 Relations between modalities: configuring the macro-structure

Up till this point I have treated the different parts of the theoretical framework used in this thesis as autonomous elements: each modality was considered individually in its interaction with the units of analysis. One of the questions left unanswered till this point in the thesis is whether relationships exist between the three modalities, and if so, what the nature of these is.

During the data analysis process each data unit was considered in terms of all three knowledge modalities of specialisation, idealisation and normativity, and principal (and secondary where present) modes were assigned to each (refer to Appendix A). A number of observations can be made on the basis of this (note that the discussion follows here is done at the level of the *modalities*, rather than the *modes*).

Firstly, the data units coded with the specialisation modality as principal modality display (largely) mono-modal coding: very few secondary modes were identified. The reason for this is that the knowledge considered is largely declarative, and does not display any normative inclination; no explicit or implicit evaluative considerations can reasonably be associated with it. Neither does the data display any idealisation or distortion of reality as such. Accordingly the knowledge concerned is coded largely mono-modally as principally oriented either towards particulars, or towards universals.

Secondly, the data units identified in the specialisation chapter are common across all disciplines, and can therefore possibly be considered to be more 'fundamental' or 'elemental' than some of the data units in the other modalities that are more emblematic of specific disciplines. Closer scrutiny of the specific themes covered by the units of data in the specialisation modality chapter strengthens this impression: the data units tend to deal with meta-level information. Examples are the meaning of the term 'thermodynamics', overall approach (either classical or statistical-mechanical), prominence of microscopic vs macroscopic detail, prominence of systems and devices in the knowledge, approach to the introduction of the First Law and the accompanying sign convention, and the use of codified information across the topics. The one exception to this is the approach to enthalpy, but even here an argument could

chemistry as an 'impure' science. This line of thinking was not pursued in this thesis, but would be an interesting further piece of work to explore.

be made for the more elemental nature of the concept in the bigger field of thermodynamics. Lastly, all of the data with a principal modality code of either idealisation or normativity, *also* carries a specialisation code.

All of this seems to suggest that specialisation is somehow a larger, perhaps more fundamental modality, possibly at a different level, and encompassing the other two modalities.

The outcome of the coding described above and summarised in Appendix A, suggests that the coding patterns in the data could be presented as a Venn diagram displaying the logical relationships between sets. Note that the Venn diagram is a representation at the level of the *modalities*, rather than at the level of the modes:

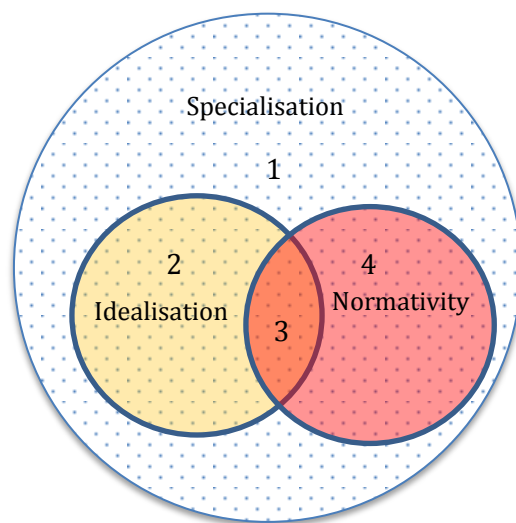


Figure 7-4: The structural configuration of disciplinary knowledge modalities

The diagram represents all of the data under consideration, i.e. all of the thermodynamics knowledge in the textbooks. Specialisation is presented here as the all-encompassing modality, enveloping the other two modalities.

Area 1 represents the principal modality of specialisation of the knowledge; the disciplinary curriculum knowledge here carries a mono-modal coding (either particular or universal). This is most of the knowledge discussed in chapter four, where the knowledge has neither normative nor idealised aspects, and therefore carries no secondary coding. Examples of Area 1 knowledge include broad descriptions of the subject content, the overall approach to the fundamental (First) Law followed in each discipline, and the value placed on either microscopic or macroscopic detail.

Data in area 2 and 4 is coded for two of the three modalities: either idealisation or normativity as principal modality, *and also* for specialisation as a secondary modality. Area 2 represents the knowledge that takes one of the idealisation modes (physical realisability or abstract-ideal theorisation) as the principal mode, with a secondary specialisation modality. The knowledge here results from some form of distortion or approximation of reality, but is largely value-neutral and is therefore not coded for normativity as a principal modality. Examples include control volume analysis (mechanical engineering), statistical mechanics (physics) and the ideal gas (chemistry). Area 4 circumscribes the normative modality as the principal modality, but with a secondary specialisation mode. In this case the knowledge is both normative and specialised, but distortion of reality is largely absent in the textbooks. Examples are the notions of the theoretical limit of efficiency, and the value of energy in the mechanical and chemical engineering textbooks.

There are cases where some of the knowledge is given *two* secondary mode codes in addition to the principal mode. Area 3 therefore has all three modalities present: either normativity or idealisation as the principal modality, with both a specialisation modality and another secondary modality of either idealisation or normativity (depending on which principal mode it took). This is the case, for example, with quantifying the error (normative modality) that results from using an ideal gas to approximate a real gas (idealisation modality) under specific empirical conditions (specialisation modality). Other examples here are the efficiency of the Carnot heat engine, an idealisation, which is the theoretical maximum possible efficiency against which to compare (a normative concern) real heat engine conditions (specialisation), and also the calculation of the damage done in a mechanical explosion (specialisation) where an approximation (idealisation) is acceptable because it results in an over-estimation of damage, meeting the safety concerns in engineering (normative modality).

The discussion above recounts the way the knowledge modalities relate in terms of the organisation and structuring of the analytical tool developed in this research project. Specialisation is therefore found to be the main configuring modality in its reference to universalising or particularising knowledge in the first instance. Within the specialisation of knowledge, idealisation and normativity are further significant modalities found in the disciplinary knowledge, and there is potential for these modalities to intersect. In addition to the structuring aspects and relations to each other, there is a further capacity for the modalities and modes to mutually influence and shape the actualisation of the modalities. This is discussed in the next section below.

7.5.2 Relations within: making sense of the relationships between modalities

The Venn diagram developed in the previous section suggests a particular *organisation* of the knowledge modalities in terms of overlaps and containment of modalities. In addition, the data suggests further complexities in the relationships between the knowledge modalities and the forms of the modalities taken in the modes. There seem to be ways in which some modalities influence the *effect* of other modalities, in the operationalising of the modes. This will be discussed below in terms of internal relations of the modalities and modes. Two instances of some form of interaction between modalities are discussed in this section: firstly, that between idealisation and specialisation, and secondly, the relationship between normativity and idealisation.

As discussed before, the idealisation modality of the knowledge refers to elements of distortion of reality introduced into the representation of the knowledge. This is operationalised in modes that either speaks to an orientation to physical realisability in the knowledge, or else to an orientation towards abstract-ideal theorisation. It should be self-evident that *more idealised* knowledge will also be *more universal*; as particularisations of specific conditions are removed in the process of idealisation, the knowledge becomes more general. This means that abstract-ideal theorisation (idealisation modality) will lead to knowledge that is specialised towards universals. Conversely, more specific knowledge will be *less idealised*, and the demand of physical realisability of actual, real artefacts will require knowledge to be specialised towards *particulars*. In this case it becomes clear that the two idealisation modes (abstract-ideal theorisation and physical realisability) are indeed instances of greater and less idealisation that impact on the specialisation of knowledge either towards universals or towards particulars. For the engineering sciences, the more limited form of idealisation observed, is also specialisation towards physical realisability. In the end, the constraints of the operational context of the artefact limit the extent of idealisation that is appropriate. In the case of the sciences with a tendency to specialise towards universal knowledge, it makes sense that there would be fewer constraints on the idealisation that can be employed towards abstract theory elaboration.

Furthermore, I suggest that there is also a relationship between normativity and idealisation. As argued above, the idealisation modality can be conceived of as an axis of variance with the modes of abstract-ideal theorisation and physical realisability as modes of greater and lesser idealisation. Furthermore, normativity in the context of this study refers to a modality of knowledge that implies some form of evaluation or value judgement. This too varies in strength

across the data in this research study: from strong (or *constitutive*) normativity to weaker (or *incidental*) normativity.

Two clear examples of what appears to be a relationship between normativity and idealisation were seen in the data of the mechanical and chemical engineering textbooks, and both involved the use of approximation. As discussed earlier, approximation is an example of idealisation that involves the use of simplifying assumptions made in order to progress in situations where complete information about a problem is either unavailable or difficult to obtain. The engineering science textbooks displayed a use of approximation that was less noticeable or absent in the science texts. This tolerance for approximation in the engineering science knowledge does not imply a predilection for less accurate solutions in engineering science. It is rather an acknowledgement that there are instances where adequacy, rather than accuracy, provides 'good-enough' information for an approach to a problem. I called this *appropriate adequacy* in 5.2.4 of chapter five. This was seen in the chemical engineering textbook's approach to the problem of quantifying the effect of an explosion. Neglecting the term in the equation that is difficult or impossible to quantify, makes it possible to get an approximate answer which is justified by that fact that it gives an over-estimation of the force of the explosion. The approximation (an idealisation) is acceptable because the resulting overestimation errs on the side of concerns about safety (a normative consideration). Similarly, the mechanical engineering text quantifies the percentage error introduced in calculations that comes with the use of the ideal gas equation (idealisation) under real, everyday conditions. A judgement call has to be made whether a particular error margin is acceptable in a specific real situation (a normative concern). As Layton (1971, p. 575) points out, engineers use approximation in the interest of saving time and money, but they develop methods with a hierarchy of adjustable rigour as demanded by a problem setting. This is an example of the normative at work *within* idealisation.

Figure 7-5 suggests that there is a negative correlation between idealisation and normativity: the stronger the normative demand of the knowledge, the less idealisation of knowledge is acceptable.

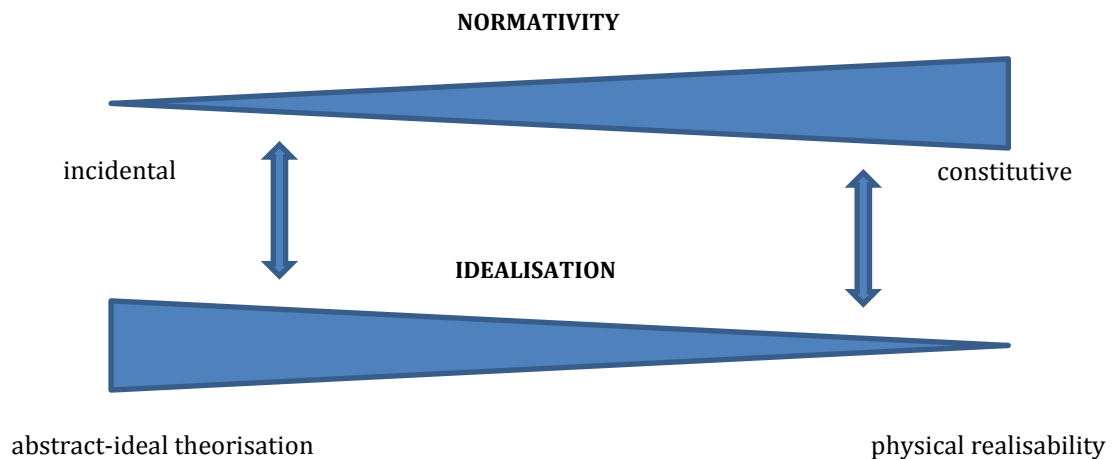


Figure 7-5: Internal relations between degrees of normativity and idealisation

There is therefore a sense in which it is actually normative demands of the knowledge that limit idealisation; the *normative* aspects of engineering science knowledge provide the resistance or ‘push-back’ on *idealisation* of knowledge.

The fact that normativity was virtually absent in the knowledge in physics and chemistry, implies that there is very little check on the idealisation of knowledge in the sciences. This strengthens the ability of abstract-ideal theorisation and explanation in the sciences. This argument therefore supports Pirtle’s (2010) contention that the engineering sciences have a commitment to ‘truth’ as opposed to Cartwright’s (1983) provocative reminder that physical laws in science are often formulated in terms of ideal rather than ‘real’ conditions. The engineering sciences are concerned with “the world as it presents itself to us” rather than “describing a world that we can track” (Pirtle, 2010, p. 107). For the engineering science knowledge as presented in the curriculum texts, a normative condition operates: the requirements of the real world constrain the idealisation of knowledge that is appropriate.

7.5.3 The analytical framework and causal tendencies

While it is not possible (nor desirable) to draw strong deterministic lines between the theoretical ideas explored in this thesis and the detail observed in the data from the textbooks, it is possible to identify certain tendencies that can go some way towards explaining the differences and similarities found in the data units selected from the textbook knowledge. Sayer (2000, p. 15) reminds us that “[t]here is more to the world, then, than patterns of events: events arise from the workings of mechanisms which derive from the structure of objects, and they take place within... contexts” .

The task of the researcher is to identify and ‘unpack’ trends with the capacity to shape the outcomes observed in the data, and this I will now attempt to do in a more general way. In this research project, the similarities and differences in the disciplinary curriculum knowledge observed in the empirical data are the eventual outcomes arising from the very different fundamental purposes of the general disciplines of science and engineering. These purposes, although initially somewhat artlessly framed, are also relatively stable or persistent, as demonstrated in the literature chapter. The causal tendencies traced out in the project arise from the *teloi* of the disciplinary fields: for science the fundamental value is to explain and understand the natural world; for engineering it is to respond to a perceived need by designing, constructing and operating artefacts that modify the human environment. In the case of engineering, the broad disciplinary field is therefore also effectively the field of practice in engineering (see the discussion a little later, under 7.6, on the influence of engineering professional bodies on the kind of knowledge valued in engineering).

These *teloi* (of the sciences and engineering sciences) present persistent structures with the potential to effect a particular knowledge orientation (see Figure 7-6): in the sciences the knowledge orientation tends to be theory-bound (or theory-calibrated as suggested in chapter three), whereas engineering science knowledge tends to have a function or task orientation. The knowledge orientations are actualised in several knowledge modalities: specialisation of the knowledge, the degree of idealisation tolerated in the disciplinary knowledge, and the propensity for normativity in the knowledge. These give rise to sets of modal continua that are used to describe the outcomes observed in the data.

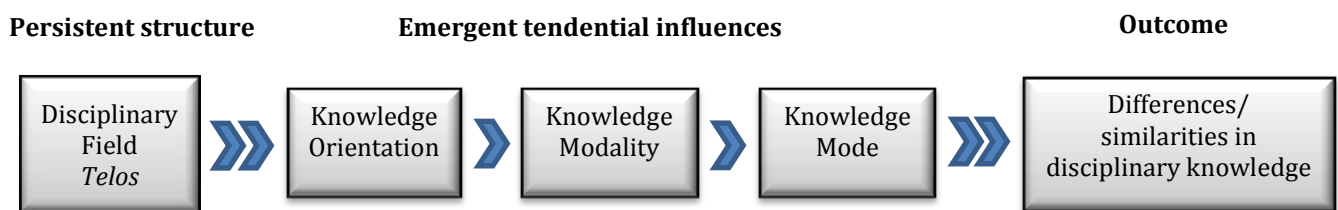


Figure 7.6: Persistent disciplinary structures’ influence on knowledge

Whether a particular modality is activated depends on the conditions or context: modalities have the *potential* to be exercised and influence particular outcomes, but they are not always activated. Examples of these different ways in which modalities operate are noticeable in the data. Normativity is, for example, seemingly not activated (or activated in a severely restricted way), in the science (physics and chemistry) knowledge. It is, however, quite prominent in the mechanical engineering knowledge and less so in chemical engineering. Idealisation is activated in all of the different disciplinary knowledges, but the different conditions created by the

presence of normativity in engineering science knowledge influence the way the idealisation was activated; the demands of physical realisability from the professional field of practice in engineering science constrain the amount of simplification of the real world complexity that can be tolerated. In the sciences, however, idealisation of the curriculum knowledge is less restricted in the absence of the influence of a normative modality (see the discussion earlier under 7.5.2, and Figure 7.5). This is an example where the influence of a particular modality (here idealisation) is modified because of the interaction with another modality (normativity), resulting in different outcomes as reflected in the modes.

Note that the argument here is not for regularity, but rather for necessity (Sayer, 2000). The constitutive normative orientation of engineering science knowledge influences the shape of the knowledge, and the knowledge therefore *has to be* specialised towards particulars, and any idealisation of the knowledge *has to* take cognisance of the push towards physical realisability. In a similar way, the absence (or incidental) normativity of knowledge in the sciences makes possible the high degree of abstract-ideal idealisation observed in the knowledge, and implies that knowledge *will be* specialised towards universals, rather than to particulars. This in itself is a realist view of sharpening conceptualisation of the relations between modes. It involves “counterfactual, rather than associational thinking: that is ...[the thinking is] concerned not merely with what happens to be associated with what, for that may be accident, but with *whether the associations could be otherwise...*” (Sayer, 2000, p. 16, emphasis added).

Approaching the tendential influences from the opposite end (i.e. starting with the outcomes, and modes) and asking questions about what they imply for the nature of the disciplinary knowledge also gives the potential for new insights.

For example (see Figure 7-7), asking questions about the *meaning* of the prominence of devices in mechanical engineering, or the *implication* for the use of approximation in the explosion problem in chemical engineering, or the *meaning* of the emphasis on molecules in the otherwise macroscopic approach to thermodynamics in chemistry, or the *purpose* of the high level of abstraction in the statistical mechanical model used in physics, serve as a consistency control of the qualities described in the knowledge orientations as these arise from the disciplinary *telo*. The disciplinary *telo* are encompassing disciplinary aspirations, and the knowledge, although emergent from these, is not reducible to them.

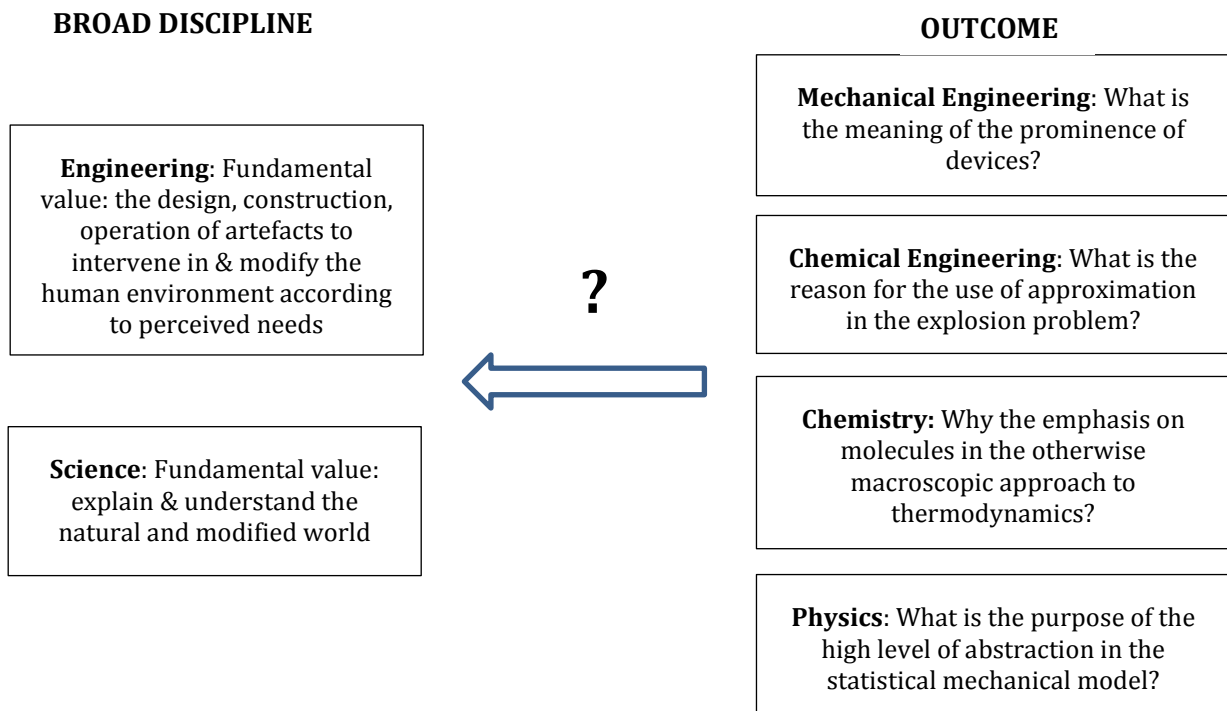


Figure 7-7: Tracing outcomes back to fundamental disciplinary values

This tracing back process allows an exploration of the causal influences: given the nature of the emphases of the disciplinary *telos*, could the particular outworking of the influence have resulted in a different outcome?

7.6 Regionality and the Field of Practice

As discussed in the literature review of the work on the sociology of knowledge (see section 2.2.2 in chapter two), Bernstein left a number of concepts under-developed in his problematic, and the purpose of this section is to discuss how the work done in the thesis contributes to conversations around these notions.

One Bernsteinian concept worth returning to here is the distinction made in the pedagogic device between the fields of (knowledge) production and recontextualisation. The results of the current study indicate that although curriculum knowledge is undoubtedly a recontextualisation of knowledge in the field of production (i.e. there is a process of selection and transformation of disciplinary knowledge to a pedagogic context amenable for transmission to disciplinary inductees), curriculum knowledge carries a discernible impression of the field of production it has been selected from. The de-location and re-location of disciplinary knowledge from the field of production to the curriculum do not dislodge the underlying logic of the structure and priorities of the disciplinary knowledge. Curriculum knowledge in mechanical and

chemical engineering display specialisation towards particulars, prominent normativity and constrained idealisation. Physics and chemistry curriculum knowledge, on the other hand display the priorities of scientific knowledge in its specialisation towards universals, broad use of idealisation resulting in positioning concepts within theories and an absence of normativity. The curriculum therefore provides a relatively stable reification of disciplinary knowledge, and a fruitful site for empirical study.

The work described in the thesis speaks to a deeper understanding of the Bernsteinian concepts of regions and singulars, classification and the influence of the so-called field of practice. The study highlights complexities in the concepts of singulars and regions in a number of ways. An impression that all engineering sciences are clear regions and all of the sciences are unambiguous in their singular-ness is misleading. As discussed earlier in 7.4.4, the work in this thesis clearly shows that not all engineering sciences are alike, and that there exists at least the potential for variations in the sciences. The analytical instrument developed shows that the knowledge modalities vary along a continuum, and that mechanical and chemical engineering sciences were different in the ways modalities were appropriated.

The results from the study therefore trouble the notions of singulars and regions as they are considerably more complex and diverse than suggested before. Bernstein described singulars as disciplines with an ‘inwardness’ and with strong maintenance of the boundaries around the valued disciplinary knowledge. In Bernstein’s terms, it is this otherness of the singulars that is responsible for distinguishing their specifically different role in the division of labour in society, and their “specialised disposition” (Muller & Young, 2014, p. 131). The analytical framework used in the project enabled a more textured description of what singular-ness looks like in curriculum knowledge. Because of the tendential chain to the broad fundamental disciplinary purposes, one can now speculate that knowledge in the sciences will tend to specialise towards universals since the intent with the knowledge is to describe and explain broadly. For the same reason, idealisation tends to be employed generously in the development of theories to explain general behaviour at an abstract level. The search for descriptions that will apply across broad contexts brings with it almost necessary distortions to ‘smooth out’ differences that are treated as incidental rather than significant. Furthermore, normative influences on valued knowledge tend to be carefully constrained (beyond the view that a theory is ‘good’ when it ‘holds’ across many instances, of course) – there is no substantive call for evaluative judgements of knowledge claims beyond the correspondence with theory (a reminder of Kuhn’s (1970, p. 21) opinion that “...the approval outside the specialist group [of scientists] is a negative value or none at all”).

Regions, on the other hand, are described by Bernstein (2000) as having weaker boundary maintenance (classification) and are the result of a recontextualisation of singulars and other regions. He also described regions as facing both inward towards singulars and outward towards external fields of practice (Bernstein, 2000). The results from the current study give insight into how this second orientation towards the field of practice plays out in the knowledge in engineering science. It tells us what the process of regionalisation possibly entails. In the first place, knowledge in the engineering sciences for a large part tends to specialise towards the particulars; this can be understood in the context of the fundamental value in engineering placed on responding to a perceived societal need, and on modifying the human environment in interventions that respond to these *specific* needs. Secondly, and related to this, the tendency of scientific knowledge to idealise (in order to generalise) is curtailed in the engineering science knowledge that has to be applied in specific circumstances in the field of practice²⁹. Therefore, engineering science knowledge tolerates markedly less distortion of reality in idealisation than was evident in the science knowledge. Lastly, normativity plays a significant role in structuring aspects of engineering science knowledge. Again, this can be ascribed to the influence of the field of practice that engineering science knowledge is for. Engineering practitioners encounter various normative influences like efficiency and effectiveness, economic considerations, sustainability issues, safety, risk and ethical concerns. Echoes of these can be seen in the engineering science knowledge. There are also *intersections* of some of these in the engineering science knowledge. Approximation, a form of idealisation, is important in engineering practice, but at the same time quantification of the error introduced by approximation becomes a normative evaluation of what makes for appropriate approximation in a particular situation. The normative notion of *adequacy* as a measure of rigour required in the idealised approximation is introduced, albeit in an implicit, rather than explicit way in the data from the study.

The study thus gives some insight into influences of the field of practice, and consequently into some aspects of the nature of knowledge in the (engineering) profession. There are different aspects of professional knowledge, with the work done here limited to the technical engineering science knowledge. The data gives a glimpse of how “the outside become[s] the inside” and how “the inside ... shape[s] the outside” (Bernstein, 1987, p. 563, quoted by Hasan (2005), p. 22). The field of (engineering) practice (outside) strongly influences the form technical knowledge in the engineering sciences takes. The pedagogic process inducts disciplinary neophytes into the

²⁹ *Engineering design knowledge* specialises even further than engineering science knowledge: in design the distinctive characteristics and specification demands of a unique practice context has to be taken into account – a particular rather than a generic turbine, for instance. Also see the argument made in footnote 27 in this chapter.

valued knowledge, which in turn shapes the thinking and disciplinary orientation of students (inside) as part of the pedagogic process, with the potential to eventually shape their interaction with the field of practice (outside). The focus on particulars (rather than universals) is a consequence of the requirements of the field of practice in the form of the regulatory professional bodies, to engage “complex engineering problems” that require “specialized engineering knowledge”, are often ill-defined, “under- or overspecified”, and “require identification and refinement...” (Engineering Council of South Africa, 2014, p. 4). Solutions to these kinds of problems are often “not obvious, require originality....and information from variety of sources that is complex, abstract or incomplete” (Engineering Council of South Africa, 2014, p. 5). Highly generalised universal knowledge is therefore not “powerful knowledge” in the context of the complexities brought by reality. This explains, in part, the tendency of the engineering science knowledge to specialise towards particulars, and also to limit the extent of idealisation present in the engineering science knowledge. Furthermore, as pointed out in chapter two, the professions have strong normative orientations: professional judgement based on expert knowledge results in normative decisions to be made at various levels. It is the influence of the professional field of practice that was evident in the normative elements observed in the engineering science knowledge. I therefore suggest that it is the frame of reference provided by the profession that functions as the driver of regionality of the knowledge, an external influence that insists on weakening the boundaries around disciplinary knowledge for real-world influences of the profession to permeate the knowledge.

The theoretical instrument developed for the analysis of the empirical data in this study therefore provided a nuanced way to explore the field of practice and its influence on knowledge structuration. It may be plausible to attribute differences in the outcomes such as differences between mechanical and chemical engineering knowledge, ultimately to differences in the fields of practice of mechanical and chemical engineering. The notion of ‘context’ becomes effectively more textured as a function of the different modalities. Specialisation engages with the fundamental values of the disciplines, idealisation varies with juxtaposition to artefacts, and normativity adds an evaluative aspect to the notion of context.

The discussion above raises another interesting distinction: in Bernstein’s terms regions like the engineering sciences have their existence ascribed to the weakening of classification or the weaker boundary maintenance around knowledge as it opens up to influences from the external field of practice (and varieties of singulars and other regions). Furthermore, problem solving in engineering certainly requires engagement across disciplinary boundaries; engineering will turn to mathematics, the sciences and even the social sciences. However (and in some sense perhaps paradoxically), the results of the study indicate a quite strong (projected) identity

reflected in the engineering science knowledge. It is clearly possible to differentiate between science and engineering science knowledge. It therefore seems not inappropriate to argue for fairly *strong* boundary attention (i.e. a form of stronger subsequent, ultimate classification) to account for the clear 'engineering-ness' of engineering science knowledge. The orientation to the field of practice results in recognisably different knowledge, or, in the words of Bernstein himself: "...it is the insulation between the categories of discourse which maintains the principles of their social division of labour... it is the full stop between one category of discourse and another...which is crucial to the specialisation of any category" (Bernstein, 2000, p. 6). The issue of boundary maintenance around knowledge is therefore more complex than perhaps indicated in the Bernstein theorisation, and the research described in the thesis suggests that the influence of the so-called field of practice is fundamental in this boundary development. The true nature of engineering science knowledge is understood only in the *separation* from other forms of knowledge, brought about by its responsiveness to the demands of complex fields of practice.

7.7 Limitations of the study

The research described in this thesis uses a case study design. Flyvbjerg (2001), amongst others, points out that generalised laws are unlikely to emerge from social studies research because of the complexities and the multiplicity of contexts in the social world. While the case study design facilitated a nuanced, in-depth exploration of a circumscribed dataset, the scope of the 'thick' descriptions and interpretation was necessarily limited. Firstly, only undergraduate thermodynamics knowledge was considered, and one would have to consider whether there are inherent peculiarities in the conceptual content of the field. The prominence of the concept of efficiency, for example, is a central one in thermodynamics knowledge, especially in engineering. One would have to explore normativity in conceptual fields other than thermodynamics to see whether the normative modality remains as powerfully present in engineering, as was observed in thermodynamics.

Secondly, the study focused on four disciplinary fields (chemistry, physics, mechanical engineering and chemical engineering). The work done here needs to be extended to other sciences and engineering disciplines to determine whether the findings hold wider applicability. This would especially be the case for the theoretical framework developed in the research described here. Further work is needed to establish whether one could claim a level of analytic generalisation where the logic of the theory work could be applied beyond the current study (Yin, 2011, 2012).

Furthermore, the data collected for the study came from five particular undergraduate textbooks prescribed at a single university. While these texts were from respected international publishers, it is clear that they represent particular recontextualising decisions in the choice of textbooks, and are therefore limitations to the scope of the study. Furthermore, the physics textbooks prescribed in the particular undergraduate courses took a statistical mechanical approach to thermodynamics. Although an increasingly common approach to teaching undergraduate thermodynamics in physics, the classical approach (a macro-approach) is another option in use at some universities. It is possible that with a classical approach to thermodynamics in physics, differences between the physics and mechanical engineering knowledge would be less stark than those that were evident and described in this thesis.

In addition, the focus of the study was on the engineering sciences, with the knowledge in the science disciplines acting as a comparative foil. In the process the science discipline possibly received less attention than the engineering science knowledge. For example, while the research clearly indicated differences between the two engineering sciences (mechanical and chemical engineering), no such variation was observed in the science disciplines, even though the potential for distinction existed in the analytical instrument. It is not clear whether this discrepancy was a methodological limitation or a function of the instrument, the conceptual content, or the particular disciplines examined.

7.8 Concluding remarks

Chapter seven presents an overview of specialisation, idealisation and normativity as knowledge modalities in relation to the data. Thermodynamics curriculum knowledge from various disciplinary fields was plotted against continua of variance in the modalities. In the process the structure of the analytical instrument was refined. Specialisation was revealed as an encompassing modality, with knowledge specialised either towards universals or particulars in the first instance. The knowledge modalities of idealisation and normativity provided additional texture for understanding particular aspects of the knowledge.

Knowledge in the sciences (chemistry and physics) located at the opposite end of the modal continua from the engineering sciences: scientific knowledge presented a tendency to universals, idealisation was used extensively to build and integrate into theoretical bodies of knowledge, and normative concerns were largely absent from the knowledge.

At the other end of the modal continua the field of (engineering) practice strongly influenced the regional nature of the knowledge in mechanical and chemical engineering sciences, although not uniformly for the two disciplines. The specificity of a need or problem that engineering science

knowledge is applied to brought about a specialisation towards particulars, and constrained the amount of idealisation appropriate for the knowledge. Furthermore, the ethical, economical, and productivity demands originating from its field of practice resulted in a normative slant to the engineering science knowledge.

Chapter 8 Conclusion

“I am, and ever will be, a white-socks, pocket-protector, nerdy engineer—born under the second law of thermodynamics, steeped in the steam tables, in love with free-body diagrams, transformed by Laplace, and propelled by compressible flow. As an engineer, I take a substantial amount of pride in the accomplishments of my profession.”

— Neil Armstrong, comment at the National Press Club (USA), 2000

The research study described in this thesis set out to investigate the nature of disciplinary knowledge differences and similarities between the sciences and the engineering sciences. The initial concern that gave rise to the study was the structure and shape of a typical undergraduate engineering curriculum. The early part of the curriculum has a focus on the basic sciences, but this emphasis relocates as students transition to senior years when the engineering science content becomes the greater part of the curriculum. Students therefore progress as they continue through their engineering curriculum, from working mainly in the basic sciences, towards a competence in managing knowledge from the engineering sciences. The point of departure for this study was to grapple with the nature of fundamental epistemic differences between the sciences and engineering sciences that underpin this curriculum progression.

8.1 Positioning the study

The research is theoretically informed by two fields of scholarly work, the sociology of educational knowledge (in particular the work of Basil Bernstein) and the applied philosophies of science and engineering science.

According to Bernstein, the two broad disciplinary fields of science and engineering under consideration in the study are both systematically principled discipline structures with hierarchical developmental trajectories. These cognate disciplines therefore have much in common, posing a challenge for empirical analytical distinction. Although under-theorised, Bernstein distinguished in his theoretical work between regions and singulars, with knowledge in the sciences functioning as singulars. The engineering sciences are described as regions in Bernstein’s terms, Janus-faced in their orientation towards singulars as well as towards their (indeterminate) fields of practice. The research described here attempted to complexify the singular-region distinction to account for the variation observed in the epistemic properties of the curriculum knowledge.

For this purpose concepts from the applied philosophies of science and engineering (technology) were enlisted to assist in developing an analytical framework for exploring the nature of the disciplinary knowledge differences and similarities. The research described in the thesis therefore contributes a case study to the sparse use of empirical work in the fields of applied philosophy. Starting from a broad understanding of disciplinary values (tentatively followed in the selective historical tracing of relations between the broad disciplinary fields in chapter one), epistemic orientations were suggested. In the process, three knowledge modalities (specialisation, idealisation and normativity) were developed, each conceived of as changing in quality along a continuum between a set of modes designed to describe different expressions of the modalities. Specialisation in the context of the thesis was explored as the modality closest in its connection with the fundamental values of the broad disciplinary fields: description and explanation for the sciences on the one hand, and problem solving and artefact development on the other hand for the engineering sciences. The knowledge modes here were specialisation towards either universals or particulars. The idealisation modality refers to the effect on disciplinary knowledge of a deliberate distortion of reality for various purposes. The modal ends explored for the idealisation continuum were abstract-ideal theorisation as an epistemic property, and physical realisability as a feature of the disciplinary knowledge. The last modality, normativity, was conceived of as either constitutive or incidental as a distinctive quality of disciplinary knowledge.

The modalities and modes served to operationalise the epistemic properties as differences and similarities that were explored in the data, in a theoretical framework developed as described.

8.2 Research study design

The work is presented as a case study of curriculum knowledge in thermodynamics, essentially covering the same conceptual content of the first two laws of thermodynamics in all of the disciplinary fields. The epistemic properties were investigated in four sub-cases, in mechanical engineering, chemical engineering, physics and chemistry.

Data was collected from prescribed undergraduate textbooks in the four disciplinary fields. This situates the research study in the curriculum, or the field of recontextualisation, to use the Bernsteinian term. Curriculum knowledge is re-located, recontextualised disciplinary knowledge. The study is therefore also an exploration of disciplinary epistemic traits as they present in curriculum knowledge.

The data was analysed using the analytical framework developed as described above, with the units of analysis consisting of thermodynamics knowledge themes. These were considered in

terms of each of the knowledge modalities and modes, and coded accordingly. The nature of the research design allowed for the possibility of considering variations not only between science and engineering science, but also variations within the two broad fields, as was indeed borne out in the differences observed in the data between mechanical and chemical engineering science.

8.3 Contributions made by the study

The research done in the study contributes to various conversations in the sociology of educational knowledge, to epistemology in the sciences and engineering sciences, and to the applied philosophy of engineering. There is also a methodological contribution.

The principal difficulty with applying existing theoretical ideas from the sociology of educational knowledge to the data collected in the project was the lack of nuance of the concepts for empirical purposes. To apply the highly abstract theory to the complexities of contiguous knowledge fields, the textured instrument described in the thesis had to be developed. The three different knowledge modalities made it possible to explore various aspects of the differences. The knowledge in the engineering sciences was found to be remarkably different from the knowledge in the sciences: both mechanical and chemical engineering knowledge emphasised particulars, rather than universals, had stronger normative aspects, and employed a limited form of idealisation in their commitment to physical realisability. Knowledge in the sciences was more universal, normativity was incidental, and idealisation was used expansively. The study therefore contributes to an “empirical turn” in the philosophy of technology and engineering (Achterhuis, 2001; Kroes & Meijers, 2001), and speaks specifically into the scarcity of applied practical (as opposed to theoretical) work done in the applied philosophy of the disciplines of science and engineering science. It provides empirical evidence of what a weak ‘epistemic emancipation’ of engineering science knowledge might comprise (Houkes, 2009).

Applying the instrument to the data revealed additional complexities in the analytical instrument, with implications for methodology and theory. Firstly, the specialisation modality operated at a more fundamental level than the others, indicating that the most elemental disciplinary variance is along the universals – particulars knowledge modes. Furthermore, the more idealised the knowledge, the more universal the knowledge becomes for application across instances; knowledge specialised towards particulars constrains the amount of idealisation possible. Lastly, the normativity and idealisation modalities vary in strength, with a negative correlation between them: stronger normativity results in a weaker idealisation, and vice versa. The constitutive normative demands on engineering science knowledge mean that

particular epistemic claims should be evaluated for suitability in a particular situation. I argue that this constrains the idealisation that is appropriate, resulting in a commitment to physical realisability of the knowledge. Conversely, the weaker or incidental normativity of knowledge in the sciences places no limits on the idealisation in the sciences, resulting in stronger idealisation in the science knowledge. My argument in the thesis is that the near absence of (or at most incidental) normative judgements in the science knowledge facilitates a more single-minded focus on abstract-ideal theorisation in the sciences. Knowledge is valued for contributing to elaboration (or challenge) of theoretical bodies of knowledge; there is no resolve to achieve practical implementation of the knowledge.

The research described here contributes to a more complex theorising of the singular-region distinction in the work of Bernstein. Firstly, the empirical textbook data confirms that the curriculum, as valued knowledge important for inducting students into the disciplines, carries an imprint of the discipline. The recontextualisation of knowledge, from the field of production and re-location in curriculum, retains recognisable disciplinary characteristics of the knowledge. Secondly, according to Bernstein, regionalisation of knowledge involves a weakening of knowledge boundaries brought about by exposure to the field of practice. The research results expound what this means for engineering science curriculum knowledge: regionalisation of knowledge, with its weakening of disciplinary boundaries, increases specialisation towards the particulars of the professions. The detail of a specific engineering problem is valued, rather than universalised theoretical knowledge for generalisation purposes. This inclination will, by implication, decrease tolerance for a distortion of reality in idealisation, as a result of an accompanying commitment to a physical realisable artefact or system. Furthermore, there is a tendency to evaluate the knowledge produced for its suitability for a specific real-world purpose.

In addition, even though these characteristics were shared by the knowledge from the two regions (chemical engineering and mechanical engineering) examined in the study, there were also subtle disciplinary differences in terms of the extent to which regional traits were displayed: there was a more muted normative orientation and weaker commitment to physical realisability in the case of chemical engineering. The research described here also indicates interesting variations *within* the regions (and therefore also potentially within singulars, although the study did not specifically focus on this): regions are not homogeneously similar in their characteristics.

Finally, the study elaborates on what Bernstein refers to as the field of practice, and in this, it contributes specifically to a more detailed conceptualisation of professional knowledge. The

work done in the thesis confirms the impact of the field of practice: the engineering profession influences the nature and structure of professional technical knowledge (this argument was made in 7.6 with reference to the requirements of engineering professional bodies). The impact of the professional field of practice is developed in the thesis with the tracing of patterns of influence from the fundamental disciplinary values (Figure 7.6). The disciplinary values are, in effect, also professional values in the engineering field of practice: a commitment to intervention in the human environment in response to a perceived need or problem. This *telos* acts in effect as a persistent structural influence on the form the knowledge takes: disciplinary knowledge in engineering science therefore has a task- or problem-orientation. In the thermodynamics data this was expressed as a tendency to particularise to the specific engineering setting rather than to universalise in the knowledge across contexts. The marked normative dimension of the knowledge was a constant reminder to evaluate in terms of the 'fitness' for the purpose for which the knowledge was being employed. Furthermore, these normative aspects of the knowledge limited the extent to which distortion of the knowledge was appropriate in engineering science, and a resolute insistence on physical realisability of solutions to problems ensured that the practical demands of the field of practice were never lost sight of. In all of these ways it was to a large extent the prominent influence of the field of engineering practice that shaped the nature of knowledge in engineering science.

8.4 Future directions

The work done in the thesis could be extended by investigating the applicability of the theoretical framework to other engineering disciplines and to different conceptual content other than thermodynamics.

The theoretical framework developed for the purposes of the research done here explored three knowledge modalities, with specialisation as the more fundamental, and normativity and idealisation as potentially different secondary modalities. There were aspects of specialisation not covered by the normative and idealisation modalities, and it is conceivable that further work in other engineering disciplines and conceptual content may reveal additional knowledge modalities.

Although the analytical framework tracked modal variations between the engineering sciences (chemical and mechanical engineering), the study did not identify significant epistemic differences between physics and chemistry. However, there is nothing about the theoretical framework that prohibits diversity across the sciences, and in principle it should be possible to find differences. It would therefore be interesting to pursue purposefully a closer study to focus on the nature of potential structural differences between chemistry and physics knowledge.

The work done in the thesis was largely exploratory and oriented towards theory development. There is therefore scope for studies that would apply the findings of the research in the study of professional knowledge, and in the education of students for the professions. There are many worthwhile questions to pursue: for example, what are the implications of differences in disciplinary knowledge as set out in this research project for student learning? What insight does the study provide into the difficulties experienced by engineering students as they negotiate the transition from basic science in the early part of their academic career into engineering science in their senior years? How could the research results inform engineering curriculum planning and pedagogy?

There are also potential implications for the understanding of the way scientists and engineers function and for their roles in modern society. Cross- and inter-disciplinary collaboration between scientists and engineers is commonplace in the global workplace. An understanding of the different fundamental disciplinary values and the ways in which these affect knowledge orientation could contribute to the interaction and communication between discipline experts.

The field of philosophy of engineering science can be described as “a field in transition” (Meijers, 2009, p. 15). There are many questions that are beginning to receive attention in the philosophy of engineering, and the work done in the thesis provides an example of an empirical investigation into a few of those. Much more needs to be done, though, and some of this has been identified in the comprehensive *Philosophy of technology and engineering sciences* (Meijers, 2009), and *Philosophy of engineering: an emerging agenda* (Van de Poel & Goldberg, 2010). One of the issues that links with the work done in this thesis is the role of practical ‘usefulness’ in validating theories in engineering science (rather than ‘truth-likeness’) Although the empirical work done in the thesis contributed examples, this aspect needs further exploration. Linked to it is a question about the role of intentionality and volition in developing engineering science knowledge (see for example Mitcham (1994)). Other examples of philosophical issues related to the research done here that need to be explored in more detail are the role of idealisation in engineering science, and the role and nature of engineering theories and how these differ from scientific theory. I argue for an association between increased normativity and constrained idealisation in engineering science. This has to be investigated purposefully. Other issues associated with normativity and values in engineering include philosophical accounts of the role of trade-offs and optimisation in design: just how are competing values, for example efficiency, safety and cost, weighed in engineering decisions?

8.5 Concluding remarks

The research described in the thesis gives insight into the nature of epistemic differences between knowledge in the sciences and engineering sciences, and proposes an analytical instrument that could potentially find wider application beyond the current study. It elaborates on Bernstein's notions of regions and singulars, challenges a hierarchical view of the pure and applied disciplines, and contributes empirical work to the applied philosophy of engineering science. The work suggests implications for thinking about the nature of professional knowledge, the education of engineering students, and for communication between scientists and engineers.

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Appendices

Appendix A: Summary of coding decisions made in chapters four to six

Issue/Theme	Disciplinary Field	Principal Modalities		Secondary Modalities			Fig 7.4 Area	
		Principal Modality of knowledge	Principal Mode	Specialisation	Normativity	Idealisation		
				Secondary Mode	Secondary Mode	Secondary Mode		
Meaning of "thermodynamics"	Mechanical Engineering	Specialisation (Chapter 4)	Particulars (some universals)	Specialisation	–	–	1	
	Physics		Universals		–	–	1	
	Chemical Engineering		Particulars		–	–	1	
	Chemistry		Universals		–	–	1	
Overall approach to thermodynamics	Mechanical Engineering		Particulars		–	–	1	
	Physics		Universals		–	Abstract-ideal	2	
	Chemical Engineering		Universals		–	Abstract-ideal	2	
	Chemistry		Universals		–	Abstract-ideal	2	
Systems, processes & devices	Mechanical Engineering		Particulars		–	–	1	
	Physics		Universals		–	–	1	
	Chemical Engineering		Particulars		–	–	1	
	Chemistry		Universals		–	Abstract-ideal	2	
Enthalpy	Mechanical Engineering		Particulars		–	–	1	
	Physics		Universals		–	–	1	
	Chemical Engineering		Particulars		–	–	1	
	Chemistry		Universals		–	–	1	
Formulation of 1st Law, sign convention	Mechanical Engineering	Particulars (some universals)	–	–	1			
	Physics	Universals	–	–	1			
	Chemical Engineering	Universals (some particulars)	–	–	1			
	Chemistry	Universals	–	–	1			
Codified knowledge	Mechanical engineering	Particulars	–	–	1			
	Physics	Universals	–	–	1			
	Chemical engineering	Particulars	–	–	1			
	Chemistry	Universals	–	–	1			
Control Volume Analysis	Mechanical engineering	Idealisation (Chapter 5)	Physical realisability	Particulars	–	Idealisation	2	
Quasi-equilibrium processes			Physical realisability	Particulars	Constitutive		3	
Carnot			Physical realisability	Particulars	Constitutive		3	
Approximation			Physical realisability	Particulars	Constitutive		3	
Modelling	Physics		Abstract-ideal theorisation	Universals	–		2	
Atomic model			Abstract-ideal theorisation	Universals	–		2	
Statistical mechanics			Abstract-ideal theorisation	Universals	–		2	
Entropy & temperature			Abstract-ideal theorisation	Universals	–		2	
Approximation	Chemical Engineering		Weaker physical realisability	Particulars	–		2	
Problem solving: tank-filling			Physical realisability	Particulars	–		2	
Ideal gas model	Chemistry		Abstract-ideal theorisation	Universals	–		2	
Equivalence of heat & work			Abstract-ideal theorisation	Universals	–		2	
Aspects of cost in problems	Mechanical Engineering	Normativity (Chapter 6)	Constitutive	Particulars	Normativity	–	4	
(First Law) Efficiency			Constitutive	Particulars		–	4	
Steam 'quality'			Constitutive	Particulars		–	4	
Quantifying error			Constitutive	Particulars		Physical realisability	3	
Regulatory requirements			Constitutive	Particulars		–	4	
The 'value' of energy			Constitutive	Particulars		–	4	
Second Law efficiency			Constitutive	Particulars		Physical realisability	3	
Real-life' context of problems			Physics	Incidental		Universals	–	4
Second Law efficiency				Incidental		Universals	Abstract-ideal theorisation	3
Problem solving			Chemical Engineering	Weaker constitutive		Particulars	–	4
The 'value' of energy	Weaker constitutive			Universals		–	4	
Explosion problem	Constitutive			Particulars		Physical realisability	3	
Uses for thermodynamics	Chemistry		Incidental	Universals		–	4	
Second Law efficiency			Incidental	Universals		–	4	

Appendix C: Early iteration of data condensation

Elaboration of Knowledge Orientations	Issue/Theme	Specific Example	Course	Inlined / lean / disposed to (MODE)	Code
Specialised: towards particulars, towards universals	micro-macro issues	macro (classical) approach (discussed in Intros)	MechEng	Particulars	MeP
		macro (classical) approach (discussed in Intros)	ChemEng	Particulars	CeP
		macro (classical) approach (discussed in Intros)	CHEM	Particulars / Universals	CHPU
		P,V,T measurable properties	MechEng	Particulars	MeP
		P,V,T measurable properties; link between internal E and macro properties	ChemEng	Particulars / Universals	CePU
		Bulk properties accessed via measurement; however microscopic explanation for behaviour	CHEM	Particulars / Universals	CHPU
		Diagrams use molecular/atomic structure to show compression, heating of gas	CHEM	Universals	CHU
		micro approach (discussed in intros)	PHY	Universals	PHU
		large numbers of particles	PHY	Universals	PHU
		PE associated with stretching/compressing interatomic spring	PHY	Universals	PHU
	Stat. quantum behaviour of atoms provide underlying explanation for behaviour	PHY	Universals	PHU	
	open/closed systems, flow systems (discuss together with "Devices")	closed systems: moving boundary work	MechEng	Particulars / Universals	MePU
		closed systems: moving boundary work	ChemEng	Particulars / Universals	CePU
		closed systems compression & expansion work	CHEM	Universals	CHU
		closed systems compression work	PHY	Universals	PHU
		Open & closed systems	MechEng	Particulars / Universals	MePU
		Open & closed systems	ChemEng	Particulars / Universals	CePU
		Open systems: control-volumes, flow work, flow energy	MechEng	Particulars	MeP
		Steady flow systems	MechEng	Particulars	MeP
	steady state	ChemEng	Universals	CeU	
	Equilibrium	Equilibrium	ChemEng	Universals	CeU
		System boundaries determine possibility for eq: conc eq: boundaries permeable for all species, thermal eq: diathermal boundaries	CHEM	Universals	CHU
	balance equations	mass, energy & entropy balances	ChemEng	Particulars	CeP
		mass a form of energy transfer in control volumes	MechEng	Particulars	MeP
	enthalpy (possibly group together with Heat capacity)	different streams, subscript k	ChemEng	Particulars	CeP
		enthalpy: a combination property	MechEng	Particulars	MeP
		enthalpy: a combination property	ChemEng	Particulars	CeP
		enthalpy: a combination property	CHEM	Particulars / Universals	CHPU
	heat capacity	creating space for the system	PHY	Universals	PHU
		intuitive introduction	MechEng	Particulars	MeP
		Explanation i.t.o. molecular model	CHEM	Universals	CHU
		C_p bigger than C_v because of work against surroundings to expand	PHY	Universals	PHU
	Reference to equipartition theorem, degrees of freedom	PHY	Universals	PHU	
	devices	Work-producing devices.			
		Turbines, compressors, nozzles, water heaters, car radiators	MechEng	Particulars	MeP
		Work-producing devices.			
		Turbines, compressors, nozzles, water heaters, car radiators	ChemEng	Particulars	CeP
		Tanks: filling & leaking	ChemEng	Particulars	CeP
	Derivations, relationships from empirical data (possibly group together with definitions)	Examples of usefulness in intro to CHEM: eng devices	CHEM	Particulars	CHP
		Equation of state like IG Law	CHEM	Universals	CHU
		Derivation of energy balance eq for diff systems	ChemEng	Particulars / Universals	CePU
		Derivation of heat capacity eq's via empirical relationships	ChemEng	Universals	CeU
		Derivation of heat capacity eq's via empirical relationships	PHY	Universals	PHU
		See also IG in PHY: argue from single particle to large numbers	PHY	Universals	PHU
		Statements of the 1st law, quite general. Introduced as conserv of energy principle. Adiabatic system considered. work implications of this	MechEng	Particulars / Universals	MePU
		Statements of the 1st law, quite general. Introduced as conserv of energy principle. Adiabatic system considered.	ChemEng	Particulars / Universals	CePU
		Statements of the 1st Law, quite general. Introduced as conserv of energy principle. ΔU only depends on initial & final states. independent of path; proven for KE in CHEM for single molecule	CHEM	Universals	CHU
		Statements of the 1st Law, quite general. Introduced as conserv of energy principle. proven from 1st principles for a particle at subatomic level. PHY also emphasises generality: applies to every possible system, true for any kind of interaction, relates an effect to a cause.	PHY	Universals	PHU
		Sign convention same for ChemEng, CHEM, PHY	ChemEng	Universals	CeU
		Sign convention same for ChemEng, CHEM, PHY. CHEM explains the reasoning behind sign convention when work is defined.	CHEM	Universals	CHU
Sign convention same for ChemEng, CHEM, PHY. PHY author explains that opposite sign convention may make sense when dealing w heat engines in engineering.		PHY	Universals	PHU	
Sign convention different: Work done by the system is positive		MechEng	Particulars	MeP	
Definitions/descriptions of heat, work and temperature		Fairly general across the board	MechEng	Universals	MeU
		Fairly general across the board	ChemEng	Universals	CeU
		Fairly general across the board	PHY	Universals	PHU
		Fairly general across the board, small differences when types of work is discussed	CHEM	Particulars / Universals	CHPU
Other	Description of hierarchical knowledge	PHY	Universals	PHU	
	Description of hierarchical knowledge	ChemEng	Universals	CeU	

Appendix C (continued)

Normative: Evaluative/axiological: better/worse, value-neutral Value-neutral is difficult: it may not work as a separate category. Perhaps it will rather have to be normative: presence and absence, and dealt with in the discussions?	Efficiency, cost safety, (environmental & sustainability issues)	Performance = (Desired output)/(Required input)	MechEng	Normative	MeN
	"quality" of energy	Macroscopic organised KE of object more valuable than microscopic disorganised KE of molecules	MechEng	Normative	MeN
	Quantification of error/approximation	Ignore KE, PE in energy balance eq	ChemEng	Normative	CeN
		Quantifies % error in graph (p. 137) that comes with treating a real gas as an IG	MechEng	Normative	MeN
	Mixture quality	Quality of mixture in the PV-T graphs: degree of 'wetness' of steam (link w device)	MechEng	Normative	MeN
Efficiency (deontic, prescriptive: right/wrong)	oil heaters, rather than radiation heaters	MechEng	Normative	MeN	
Idealised: towards physical realisation, towards abstract ideal	control volumes	imaginary / real boundaries	MechEng	Physical realisation	MePr
		Imaginary piston to explain flow through control volume	MechEng	Physical realisation	MePr
	Approximations, assumptions	steady-flow devices (somewhat idealised, but good approximations)	MechEng	Physical realisation	MePr
		steady-flow devices (somewhat idealised, but good approximations)	ChemEng	Physical realisation	CePr
		J-T expansion, throttling valve assumed adiabatic	ChemEng	Physical realisation	CePr
		J-T expansion, throttling valve assumed adiabatic	MechEng	Physical realisation	MePr
	Modeling	PHY	Abstract ideal	PHYAi	
	Quasi-static equilibrium	Quasi-static equilibrium processes, but good approximation for real processes	ChemEng	Physical realisation	CePr
		Quasi-static equilibrium processes, but good approximation for real processes	CHEM	Abstract ideal	CHAI
		Quasi-static equilibrium processes, but good approximation for real processes. Reasons for use: -ease of analysis -Serves as a standard, since max work is done under these conditions	MechEng	Physical realisation	MePr
	Ideal Gas model	Described as giving relationships between properties that is "sufficiently general and accurate" (in the properly selected region). Identifies it as an imaginary substance, good for use at low P, high T: air, N ₂ , etc. but NOT steam in powerstation or refrigeration gases. Limited applicability. Quantifies error (see elsewhere)	MechEng	Physical realisation	MePr
		IG model discussed in detail in CHEM at molecular level	CHEM	Abstract ideal	CHAI
		introduction of real gas eq of state (vd Waals) Coefficients in empirical tables	CHEM	Abstract ideal	CHAI
		Derivation of values for W,Q,ΔH, ΔU for 4 generic reversible processes by Ideal Gases	CHEM	Abstract ideal	CHAI
		IG model one of 3 models to analyse thermo system behaviour in PHY (others Einstein solid, 2 state paramagnetic model). Only 2 assumptions (ergodic hypothesis & Equal a Priori Probability Principle). Invoke IG as experimental fact, further generalisations: degrees of freedom, equipartition theorem, etc.	PHY	Abstract ideal	PHAI
	Reversible processes	Reversible & irreversible processes	MechEng	Physical realisation	MePr
		Reversible & irreversible processes	ChemEng	Physical realisation	CePr
		Reversible & irreversible processes	CHEM	Abstract ideal	CHAI
		Reversible & irreversible processes	PHY	Abstract ideal	PHAI

Appendix D: second iteration of data condensation (one modality only)

Elaboration of Knowledge Orientations	Disciplinary Field	Issue/Theme	Mode
Specialised: towards particulars, towards universals	Mechanical engineering	Meaning of "thermodynamics"	Particulars
		Approach	Particulars
		Systems & Devices	Particulars
		Enthalpy	Particulars
		Formulation of 1st Law, sign convention	Particulars, some universals
	Physics	Meaning of "thermodynamics"	Universals
		Approach	Universals
		Systems & Devices	Universals
		Enthalpy	Universals
		Formulation of 1st Law, sign convention	Universals
	Chemical Engineering	Meaning of "thermodynamics"	Particulars
		Approach	Particulars, some universals
		Systems & Devices	Particulars
		Enthalpy	Particulars
		Formulation of 1st Law, sign convention	Universals, some particulars
	Chemistry	Meaning of "thermodynamics"	Universals
Approach		Universals	
Systems & Devices		Universals	
Enthalpy		Universals	
Formulation of 1st Law, sign convention		Universals	
Normativity	Mechanical engineering	Aspects of Economics in problems	Constitutive, implicit and explicit
		Efficiency	
		"quality" of steam	
		acceptable error	
		Aspects regulatory requirements (problems)	
		quality of energy	
		theoretical limit ("perfection")	
	Chemical Engineering	Heat engines: efficiency	Constitutive, less noticeable, more implicit than in ME
		Implicit problems	
		value of energy	
	Chemistry	Explosion problem	Illustrative
		4 examples of usefulness of thermo	
Physics	theoretical limit	Illustrative	
	weak problems		
Idealisation	Mechanical engineering	efficiency of heat engine	Towards physical realisability
		CV	
		steady & unsteady flow	
		approximation	
	Physics	Carnot	Towards abstract-ideal theorisation
		Modelling	
		Atomic model	
		Statistical mechanics	
	Chemical Engineering	Entropy & temperature	weaker physical realisation
		microscopic less useful	
		black-box thinking	
		simplifying assumptions	
Chemistry	Ideal gas	physical realisation	
	tank-filling example	Towards abstract-ideal theorisation	
Codification (essentially a form of specialisation: consider incorporating under Specialisation)	Physics	Ideal gas	standardised constant dominates
		physical constants	
	Chemistry	very limited steam tables	standardised constant only
		physical constants	
	Mechanical engineering	physical constants	both present, but condensed procedural mode prominent
		Steam tables	
		Property diagrams	
	Chemical engineering	physical constants	both present, but condensed procedural mode prominent
		Steam tables	
Mollier diagrams			