# Addressing Cognitive Hurdles to Interdisciplinarity in Natural and Engineering Science

Joining Forces of Philosophical Reflection and Semantic Networks

**By:** Ir. H. J. van den Brink

**Supervisor:** Dr. K. Karaca

**Examiner:** Dr. M. A. J. MacLeod

**Date:** *03-07-2024*

***MSc Thesis 201300088***

***Faculty of Behavioural, Management, and Social Sciences, Enschede, the Netherlands***

UNIVERSITY OF TWENTE.

***Department of Philosophy - Chair Philosophy of Science in Practice***

*In partial fulfilment of the requirements for the degree of MSc Philosophy of Science, Technology and Society – PSTS*

*Word count main text: 23.486 (Excluding table of contents, bibliography, acknowledgements and appendices)*

“Except under quite special conditions, the practitioner of a mature science does not pause to examine divergent modes of explanation or experimentation.”

Thomas S. Kuhn

The Essential Tension (1977, p. 233)

## Abstract

This thesis deals with cognitive hurdles to interdisciplinarity in the natural and engineering sciences. Due to the high degree of specialisation, interdisciplinary collaboration between scientists is very difficult. Specifically, scientists striving for interdisciplinarity face intellectual and technical cognitive, conceptual and methodological hurdles jointly referred to as 'cognitive hurdles'. The main research question is how philosophical reflection and semantic networks, also known as knowledge graphs, can aid natural and engineering scientists in overcoming cognitive hurdles to interdisciplinary research which arise due to their disciplinary perspective. This question is answered through a philosophy of science in practice approach which takes into consideration theory, practice and the world simultaneously. This approach is different from both the classical philosophy of science or social constructivist accounts of science which either neglect practice or the world respectively.

First of all, it is shown that cognitive hurdles can be traced back to differences in disciplinary perspectives between the interdisciplinary collaborators. This perspective pertains to more than just a particular subject-matter but methodologies, ontological and epistemic assumptions and preferences as well. If unfamiliar with the perspective of the collaborators, it is very difficult to understand their practices and achieve interdisciplinarity. In practice, this means that methodologies are hard to integrate and there are conceptual divides. Additionally, they might have conflicts over which values, both epistemic and pragmatic, carry more weight. Finally, there are no established procedures to approach the research as is the case in established disciplines, leading to unstructured problem-solving environments. It is shown that each of these cognitive hurdles is related to particular elements of the disciplinary perspectives of the scientists involved. After establishing this relation, the follow-up question is how such hurdles can be overcome.

In short, it is argued that a shared perspective needs to be developed. Developing this shared perspective is possible because disciplinary perspectives are not incommensurable like Kuhn suggested paradigms were. In order to develop such a perspective, the scientists should partake in an interdisciplinary workshop to discuss differences in their original disciplinary perspectives at the start of their collaboration. This requires philosophical reflection i.e. becoming aware of their disciplinary perspective. Here, the framework developed by Boon (2020b) is ideal for systematic analysis, articulation, and comparison of disciplinary perspectives. Of course, gaining insight into the disciplinary perspective of the other scientists can remain difficult while there is often not sufficient time to take a deep dive into relevant literature. This is where machine learning can help to make the relevant disciplinary corpus accessible.

Specifically, machine learning can be applied to largely automatically create semantic networks representing disciplinary corpuses. These networks visualise how methodologies, phenomena, measured parameters and epistemic and pragmatic values are related. Understanding such relationships would otherwise require a deep dive into the relevant corpus. Consequently, it is argued that such networks can aid interdisciplinary collaborations to gain insight into the disciplinary perspectives of their collaborators to then combine their perspectives in an *inter*disciplinary perspective enabling them to address the real-world problem.

The major conclusion from this philosophical thesis is that semantic networks – if combined with philosophical reflection – can contribute substantially to overcoming cognitive hurdles to interdisciplinarity. Specifically, three out of four cognitive hurdles identified in the literature, namely opacity of domain-specific practices to outsiders, conceptual and methodological divides, and conflicts over epistemic values. Unfortunately, problem-solving environments will always remain a bit unstructured because novel methodologies and approaches are being tested. Therefore, this fourth hurdle will not be overcome with philosophical reflection and semantic networks.

The primary limitation of this study is the lack of in-dept studies of cognitive hurdles to interdisciplinarity. Additional in-dept studies could have enriched the analysis and it is, therefore, recommended that philosophers of science engage more in empirical research. This would be beneficial for philosophy of science as well as scientists themselves. Despite this limitation, sufficient sources reporting cognitive hurdles have been cited throughout the thesis to warrant the conclusion that philosophical reflection and semantic networks can contribute substantially to overcoming cognitive hurdles to interdisciplinarity in the natural and engineering sciences so as to effectively collaborate to address a real-world problem.

# Acknowledgement

First and foremost, I would like to thank Koray Karaca for his supervision during this project. Thanks to you I finished the thesis after 20 weeks and on the date planned at the start. Especially during the final weeks of the thesis, you repeatedly provided feedback. The fact that you were remarkably busy, makes me even grateful for all the feedback you provided. Thanks to you, I improved my argumentation skills, learning to construct a rigorous argument which answers the main question. I tend to write down all I have read instead of focussing on the thing I am trying to argue. You repeatedly reminded me to think of line of argumentation, many thanks for that.

Then my second supervisor Miles MacLeod. Miles, you radiate calmness and a healthy relaxedness which I greatly appreciate. Like Koray, you are humble and never concerned with showing your academic achievements, focussing on the contents and how you could help me in my research instead. At the same time, you gave clear feedback during the green light meeting which enabled me to improve the thesis and pointed to an existing procedure to compare semantic networks with. Thanks for your valuable supervision.

Finally, I want to thank Mieke Boon who took the time to read and comment on my thesis at about two-thirds of the way. Your input enabled me to draft a coherent thesis and sharpen the discussion on Kuhn and disciplinary perspectives. Moreover, you pointed me to the NWO Call on Innovative Projects for which we submitted a proposal so that we can put the insights from this thesis into practice and do further research. Above all, you are always kind and approachable, thanks for your input.

# Contents

# 1 Introduction

## 1.1 Background

Contemporary science is characterised by a high degree of specialisation. One is quickly overwhelmed by the diversity and specialisation when reading the journal *Nature*. Due to the ever-growing specialised scientific knowledge, it has become practically impossible for a human scientist to thoroughly understand multiple specialised fields of science. As a consequence, understanding of the coherence of all of these different specialisations within the overall scientific endeavour is often lacking. Already in 1930, José Ortega y Gasset devoted one chapter of his *La rebelión de las masas* to the *Barbarism of 'Specialisation'* (1971 [1930], p. 151-158). In this chapter, Gasset sketches the scientist as someone with a lot of specialistic knowledge while, at the same time, lacking any general knowledge of the coherence of that specific knowledge within the larger scientific endeavour. This becomes especially problematic if the specialist simply overconfidently assumes that he can transgress into other areas of specialism without consulting the specialists in those other areas.

Moreover, he remarks that this 'specialist' is no longer knowledgeable about the overarching structure and methodology of the science that he is practising (Gasset, 1971 [1930], p. 158). About 3 decades later, the philosopher of science Thomas S. Kuhn refers to this in his book *The Structure of Scientific Revolutions*: "Though many scientists talk easily and well about the particular individual hypotheses that underlie a concrete piece of current research, they are little better than layman at characterizing the established bases of their field, its legitimate problems and methods." (Kuhn, 1996 [1962]: p. 47).

A similar observation is made for the engineering practice by engineer and philosopher Schuurman in his thesis titled *Philosophy and the Future* (1972). Already within their own discipline, engineers have to carry out their particular tasks without overseeing the whole (Schuurman, 1972, 1985). The technical knowledge of a single engineer cannot keep up with the pace of technological development. Specialization and teamwork have to compensate for this deficit, but it means that the individual engineer loses any idea of the coherence within the larger whole and of the diversity of specialistic possibilities and variations in technology. As a result, teamwork is necessary for technological development which adds another layer of complication to the engineering practice (Schuurman, 1972: p. 45-47). As these sources indicate, the problem of specialisation within science and engineering already became apparent decades ago. Since then, specialisation has only increased which means that scientists and engineers depend on other specialists when transgressing beyond their specialisation. However, this specialisation makes it very difficult to communicate and collaborate with other domains and results in a strong separation of (scientific) domains.

Particularly when these different disciplines and domains need to collaborate to address socio-technical problems in society, scientists run into the consequences of this specialisation.

It is precisely this kind of intensive collaboration what contemporary society expects. Scientific research is expected to address complex real-world problems like environmental problems, climate change, and illnesses (Aarts, 2024; Boon & van Baalen, 2019; Eigenbrode et al., 2007). Such problems are notoriously hard to tackle within a single discipline since this requires a thorough understanding of the systems that will be affected. In most cases, this requires insights from multiple scientific disciplines. The goal is that two or more disciplines address the problem together instead of from their individual disciplines. In case of interdisciplinarity, this means that these disciplines collaborate, not just as two (or more) divergent views on the same case which is referred to as multidisciplinary, but through cross-fertilisation, merging and developing an integrated view of the problem at hand (Eigenbrode et al., 2007; Mazzocchi, 2019). As such, real-world problems require specialists to collaborate intensively.

Historical examples of interdisciplinary research fields that have by now become established fields are chemical engineering and biotechnology. These emerged through the combination of mechanical engineering and industrial chemistry and the combination of chemical engineering and biology respectively (Foley, 2016). By now these fields have become established disciplines. Interdisciplinary research is one of the most promoted goals in policy. However, in practice it is difficult and research output is often of lower scientific quality than in the case of disciplinary research (Boon & van Baalen, 2019; MacLeod, 2018; Maglaughlin & Sonnenwald, 2005).

However, such integration is rather difficult. Recently, philosophers of science have shown that certain barriers are cognitive in nature. Here,

> "Cognitive obstacles" to interdisciplinarity are taken to refer to the more intellectual and technical cognitive, conceptual and methodological challenges researchers face coordinating and integrating background concepts, methods, epistemic standards, and technologies of their respective scientific domains—particularly in the context of collaboration—in order to achieve some benefit for solving specific problems or sets of problems." (MacLeod, 2018: p. 698)

As such, there is more to hurdles than just the high degree of specialisation alluded to by Schuurman (1972) and Gasset (1971 [1930]). It was the philosopher of science, Thomas S. Kuhn mentioned earlier who drew attention to these kinds of differences (Kuhn, 1996 [1962]). There are important differences between disciplines, they not only differ in terms of the aspect of nature – e.g. numerical, physical, biotic, technical, psychic – that is investigated, but also in terms of their methodologies, approaches, values, background assumptions, aims, and the role they attribute to technological artefacts and models. As such, there are not only methodological differences but, more importantly, more fundamental differences that are philosophical in nature as well, i.e. epistemological, ontological, and metaphysical differences.

Kuhn referred to this way of viewing the world as a scientist a 'paradigm'. He used this concept because scientists work within a particular paradigm when practising science. Broadly speaking, paradigm refers to the way in which scientists see the world. For example, in the Newtonian worldview in terms of particles with a certain mass with forces between them. According to Kuhn, a change in worldview, referred to as a paradigm shift was typically more of a conversion than a choice (Kuhn, 1977: p. 338), indicating the extra- or irrational nature of adherence to a certain paradigm. On such a view, cross-fertilization and the merging of multiple disciplinary perspectives is impossible since these are so radically different that they can be referred to as 'incommensurable'. On such a view, interdisciplinarity is impossible because scientists cannot meaningfully communicate, let alone collaborate across their disciplines. At the same time this adherence to such a way of looking at the world was extra-rational according to Kuhn, meaning that scientists would not be able to 'escape' this disagreement with other scientists.

These Kuhnian views on science have been criticised since then and largely abandoned. Nevertheless, it marked philosophy of science by drawing attention to broader context of scientific practice, in particular beliefs and assumptions about reality that guide scientific research. To be clear, this does not mean that philosophers of science are interested in the concept of 'scientific disciplines' as such[1]. In general, scientific disciplines have been interpreted from an institutional perspective in *Science and Technology Studies* research (Krishnan, 2009: p. 9-10). However, as we will see, drawing attention to the cognitive side of scientific disciplines is worthwhile to better understanding it dynamics. Despite this, a few philosophers of science have been further analysing scientific practices and what enables these practices. Specifically, they developed notions of 'perspectives in science'. Clearly, these are also important to understanding interdisciplinarity. However, in the philosophical literature, multiple concepts are being used, for example, 'systems of practice' (Chang, 2012), 'domain-specificity' (MacLeod, 2018), 'disciplinary perspectives' (Boon, 2020b) 'scientific perspectives' (Massimi, 2021). Why are these different concepts being used, what is their content, and can they be brought together?

The importance of understanding this thicker concept of disciplinarity is also supported by empirical research. Recent research has shown that difficulties in interdisciplinarity can in part

[1] Very recently, a paper appeared by Elgin (2024) defending the notion of scientific disciplines as levels of reality. Polanyi (1968) provides a different account referring to levels in reality.

be traced back to disagreements between disciplines that are epistemological, methodological and cognitive in nature (MacLeod, 2018). However, how to overcome and prevent such barriers is yet uncovered ground. One of the first relevant questions to answer is *whether* and *how* these hurdles can be related to diverging disciplinary perspectives. Although some researchers have taken the first steps to analyse and approach these hurdles more systematically (Boon & van Baalen, 2019), this topic has not been elaborately discussed in the philosophy of science literature yet. Although there is a relation between epistemological, methodological and cognitive hurdles and disciplinary perspectives, how to relate them precisely is unclear. Moreover, further research is required how these perspectives can come together in interdisciplinary collaboration.

This approach entails shifting the attention from theoretical philosophy to the relation between philosophical theory and scientific practice. The question is, what role can the philosophy of science play in overcoming hurdles which are the result of diverging disciplinary perspectives? This is an important question to answer if the philosophy of science is to be fruitful for actual scientific practices instead of floating into an abstract treatise about the nature of the scientific endeavour. Kuhn himself viewed paradigms as rigid and fixed; unless a significant event were to take place the scientists will adhere to it. Does the same apply to disciplinary perspectives or can these be moulded to a degree? If so, how can this be done, especially in the context of interdisciplinary collaborations?

There might be several objections against such an approach, especially by practicing scientists. First of all, they might doubt about 'perspectivism', is this term not too relativistic? Moreover, science as is does already take up enough time, how could philosophical reflection improve interdisciplinary collaboration? To address these questions, one particular framework will be argued for to show how it can help address hurdles to interdisciplinarity and engaging in fruitful interdisciplinary collaboration. Moreover, artificial intelligence can act as an aid in this reflection by giving insight into the discipline that the scientists are collaborating with, enabling them to understand the disciplinary perspective of the other scientists without having to read 30 papers from their field.

Next to philosophers of science, scientists themselves also experience the hight degree of specialisation. Despite this, only few set out to address these problems from within their own fields. Two good examples are Krenn & Zeilinger and Rzhetsky (2020; 2015). In their paper on semantic networks, Krenn and Zeilinger mention that "The vast and growing number of publications in all disciplines of science cannot be comprehended by a single human researcher. As a consequence, researchers have to specialize in narrow subdisciplines, which makes it challenging to uncover scientific connections beyond their own field of research. Thus, access to structured knowledge from a large corpus of publications could help push the frontiers of science." (2020: p. 1910). These semantic networks, which are created using machine learning and disciplinary publication corpuses, provide a representation knowledge within a particular subfield of science e.g. quantum physics. These are developed to aid scientists in exploring their own subdisciplines. They can be used to highlight underexplored area's and propose new experiments. Such networks sound promising for individual scientific disciplines.

Such application neatly fit the advice by *The Royal Society* in their May 2024, report. Th society underscores the importance of the interdisciplinary development of AI applications i.e. computer scientists working with natural scientists (Berman et al., 2023; The Royal Society, 2024). However, both the publications by Krenn & Zeilinger and Rzhetsky and the report of *The Royal Society* remain silent about the difficulties of integrating different fields of science. This brings up the question whether such networks could also play a role in interdisciplinarity. Specifically, to address cognitive hurdles to interdisciplinarity discussed earlier.

## 1.2 Research Questions

This thesis aims to answer the following main research question:

> How can philosophical reflection and semantic networks aid natural and engineering scientists in overcoming cognitive hurdles to interdisciplinary research which arise due to their disciplinary perspective?

This research question shows that first of all, this philosophical thesis is limited to the natural- and engineering sciences like physics, chemistry and biology, chemical engineering and biotechnology respectively. Social sciences lie outside the scope of this thesis. The reason is that these are quite different fields and hurdles are likely domain-specific. Secondly, this thesis concerns barriers resulting from diverging disciplinary perspectives. Interdisciplinarity can also be hindered by institutional barriers, however, such barriers lie outside the scope of philosophy of science. Moreover, this thesis deals with the role of AI in interdisciplinary practices, specifically semantic networks. The goal is to investigate the role that semantic networks can play in enabling interdisciplinary research. As such, the goal is not to investigate the role that AI can play in interdisciplinary research itself. To be perfectly clear, it is not argued that philosophical reflection and semantic networks will make all hurdles magically disappear. Instead, it is argued that, if combined, they can attribute substantially to overcoming cognitive barriers.

This leads to the following sub questions.

1. What does it mean to have a disciplinary perspective and how does it relate to scientific practices within disciplines?
    - What is a disciplinary perspective and how is it different from Kuhn's paradigms?
    - Seeing that different philosophers use different concepts for perspectives in science, which philosophical concept is most suitable to articulate and specify disciplinary perspectives?
    - Is the concept of disciplinary perspective tenable on a realist account of science? Can adherence to a disciplinary perspective be a rational matter on both accounts?
2. What is the role of a disciplinary perspective in cognitive hurdles to interdisciplinary research?
3. What role can philosophical reflection and semantic networks play in overcoming cognitive hurdles to interdisciplinarity?

## 1.3 Theoretical Framework and Approach

The Philosophy of Science in Practice forms the theoretical framework of this thesis. This philosophical approach has emerged through the work of a number of philosophers of science. For example, the philosophers of science in practice M. Boon. In her inaugural address as Professor of Philosophy of Science in Practice on the 10th of May 2012, she laid out her approach. As she puts it, her approach takes scientific practice to be broader than just the development of theories about reality as happens in the so-called 'fundamental sciences' (Boon, 2012). This is especially clear in the engineering sciences where, according to her, a different type of knowledge is produced. They do not 'merely apply' scientific knowledge of reality gained through fundamental science, instead, they have a unique approach, applying different kinds of laws to understand and construct knowledge about technical systems which require a unique combination of theoretical and empirical approaches (Boon, 2008).

In its mission statement, the *Society for Philosophy of Science in Practice* says that:

> "Philosophy of science has traditionally focused on the relation between scientific theories and the world, at the risk of disregarding scientific practice. In social studies of science and technology, the predominant tendency has been to pay attention to scientific practice and its relation to theories, sometimes wilfully disregarding the world except as a product of social construction. Both approaches have their merits, but they each offer only a limited view, neglecting some essential aspects of science. We advocate a philosophy of scientific practice, based on an analytic framework that takes into consideration theory, practice and the world simultaneously." (Society for Philosophy of Science in Practice, 2016)

This makes clear that the philosophy of science in practice aims to be fruitful for the practice of science in the broadest sense (Boon, 2012: p. 51). This philosophy is not just focussed on the acquisition and validation of knowledge but also its use. Moreover, instruments and models are taken seriously by researching how they shape scientific practices. As Hasok Chang puts it: “A serious study of scientific practice must be concerned with what it is that we actually do in scientific work. This requires a change of focus from propositions to actions.” (Chang, 2012: 17).

For a philosophy of science in practice methodology “it is crucial to have a productive interaction between philosophical reasoning and a study of actual scientific practices, past and present. This provides a strong rationale for history-and-philosophy of science as an integrated discipline, and also for inviting the participation of practicing scientists, engineers and policymakers.” (Society for Philosophy of Science in Practice, 2016). This neatly captures the methodology applied in this thesis. This methodology is also appropriate to studying the role that AI can play in the application domain of interdisciplinary research.

The first chapters on disciplinarity and interdisciplinarity will draw primarily from philosophical sources focussing on the broader practice of science. In chapter three, an empirical case is discussed to show that the philosophical insights arise in scientific practices and thinking about these practices on a philosophical level is relevant to the practice of science. Throughout the thesis, examples from practice, primarily chemical engineering, will be given to prevent an abstract philosophical treatise whose relevance and connection to practice are not clear.

## 1.4 Societal and Philosophical Relevance

Solving today’s real-world problems requires interdisciplinary collaboration. However, in practice, such research is difficult and research output is often not up to scientific standards. At the same time, AI technology has drawn a lot of attention from philosophers of science, however, these reflections often occur after the fact and at that point minor changes can (or are) made to the technology. Therefore, philosophers of science in practice should relate their insights scientific practices like interdisciplinarity and the potential role of AI technology in such a practice. In this way, contemporary developments of AI can be guided in a specific direction fruitful to scientific practice by, for example, in addressing problems with interdisciplinary collaboration and develop tools that support interdisciplinarity. Because of this, this thesis has technical and scientific relevance which translated into societal relevance because relevant problems can be solved. However, it also has philosophical relevance.

Specifically, it has this relevance through its philosophy of science in practice approach. This approach focusses on, as the name suggests, philosophical problems arising from or in scientific practice particularly relating to the nature of reality, rationality, logic, assumptions, beliefs et cetera. However, interdisciplinarity has only recently started to draw the attention of philosophers of science (MacLeod, 2018). Although first philosophical insight has been gained into how these hurdles arise, how these can be overcome is yet uncovered ground (Science

Guide, 2024). Therefore, this thesis, in addressing hurdles to interdisciplinary collaboration and relating them to development in AI, has not only the potential to be fruitful scientific practices but will also lead to further development of philosophical frameworks for interdisciplinarity thus rendering this research philosophically relevant.

## 1.5 A Note for the Reader

This is a philosophical thesis which aims to address both philosophers and natural and engineering scientists. The aim is to elucidate what natural science and engineering science are about and how the philosophy of science can aid in overcoming problems related to interdisciplinarity. In other words, this thesis aims to shed light on the scientific practices of individual scientists as well a collaboration with other scientists. As such, it also tries to show that philosophy of science in practice has something valuable to bring to the table in scientific matters.

As such, this thesis primarily aims to innovate by bringing a variety of sources together and showing how these can contribute to the development of science and the philosophy of science. In doing so, the philosophy of science is fruitful for practicing scientists in interdisciplinary contexts and vice versa, philosophical theories about interdisciplinarity are find support in actual practices. Thet thesis will start of rather descriptive to develop shared basis to critically discuss the problems addressed in this thesis and enable the argumentative chapters. It is also only the last chapter that the notion of interdisciplinarity has been sufficiently discussed and the role that AI can play becomes clear. This might give the impression that there are two distinct, unrelated parts. However, this is not the case, chapter 2, 3 and 4 prepare the way for a fruitful discussion of semantic networks as well as make clear that there are several roles that semantic networks can play in interdisciplinary collaboration.

# 2 Disciplinary Perspectives

This chapter elucidate what it means to have a disciplinary perspective. First, the difference between natural and engineering sciences is discussed since these are central to the topic of this thesis. Then follows a philosophical discussion to better understand scientific disciplines and the resulting disciplinary perspective by dealing with the philosophical literature on this topic. Finally, one particular framework for disciplinary perspectives is defended to be used in the later chapters.

## 2.1 Natural and Engineering Science

### 2.1.1 Science and Technology: Distinct but Connected

This thesis is about interdisciplinarity in the natural and engineering sciences. In the introductory chapter, the differentiation between fundamental and engineering science was briefly touched upon. However, a clear differentiation is often lacking in philosophical discussions on science and technology leading to unnecessary confusion and lack of understanding. Therefore, this difference should be elucidated further before continuing.

Science and technology – Engineering sciences are focussed on the development of technology. This brings up another question concerning technology and how it differs from science. The difference between these if often forgotten but quite straightforward. Where the goal of science is gaining knowledge about reality, technology is about formation and changing that reality. So, science is about *knowing*, and technology is about *making* and *fabricating* (Schuurman, 1990).

Natural and engineering science – Both natural and engineering science concern physical reality. The established view is that technology is developed through the straightforward application of natural scientific knowledge i.e. about the laws of nature. In this traditional view, science concerns knowledge about nature (Kuhn, 1977: p. 31) and thus not about technology. This model, where the 'fundamental' sciences gain knowledge of reality and the 'applied' sciences merely apply this knowledge to develop technology, can be referred to as the traditional, linear model. However, such a linear model does not do justice to the distinct nature of the engineering sciences (Boon, 2008; Schuurman, 1990; Vlot, 2002). Throughout the previous age, the development of technology has been stamped by the scientific method[2]. However, it is different from the natural sciences since understanding and developing technology requires doing justice to the particular and individual nature of technological

[2] In chapter 3 of his (1949) dissertation electrical engineer and philosopher H. van Riessen was one of the first to systematically analyse and clarify how modern science stamped the development of technology (Vlot, 2002). Similarly, the rise of scientific laboratories for the development of technology during the start of the 20$^{th}$ century testifies for this (de Vries, 2005).

devices (Boon, 2008; Schuurman, 1990). Engineering science is a distinct type of knowledge creation that entails more than mere deduction from the theories in the natural sciences. As Boon (2008) puts it, these sciences combine theory and empirics to understand the tendencies and capacities of technical systems. The engineering sciences formulate general and universal knowledge about technical devices while doing justice to the individual, unique environment where the problem arises (Schuurman, 1990: p. 64).

The engineering sciences indeed draw from the natural sciences in the sense that a similar methodology is applied and fundamental principles and knowledge from the natural sciences are used to understand technical systems. However, the knowledge obtained in the natural sciences is often too ideal, i.e. about neatly isolated phenomena. Moreover, fundamental laws are mathematically intractable, meaning that idealisations are required, and it becomes unlikely that these laws can accurately describe the phenomenon or only in a very limited number of cases (Boon, 2008). As such, the theories and laws from the natural sciences cannot be applied directly to technological devices to gain knowledge about them. Boon (2008) uses the example of fluid flow through pipes in which classical fluid dynamics alone could not do justice to the technical phenomenon. In such cases, deduction from the general theories is insufficient and additional models are required to construct knowledge about the phenomenon. As such, engineering sciences form the bridge between the natural sciences and technologies by moving between abstract theories about phenomena in technological artefacts and the concrete technologies the engineering scientist investigates.

Finally, the following concepts: *technology* and *technics*, can respectively be used to distinguish between engineering science and technology itself. For example, chemical technology and chemical engineering science.

Fundamental and applied engineering science – This means that within engineering science another distinction can be made between fundamental and applied engineering science. In contrast to the former, the latter is focused on the development of concrete technological artefacts (Schuurman, 1990: p. 65). So, in the first case, the practical application in the development of technology is less context-dependent and thus the knowledge is more general and can be applied to understand and develop multiple technologies. For example, technical thermodynamics can be applied to understand multiple technical applications like reactor design and analysis of biochemical systems i.e. living cells.

In summary, the following sciences relevant to the engineer can be distinguished, basic sciences i.e. formal and natural science, fundamental engineering sciences and applied engineering sciences. Examples of the basic sciences are logic, mathematics, fluid dynamics, and thermodynamics. Fundamental engineering sciences are aimed at general knowledge of technological devices and materials, examples are technical thermodynamics, hydrodynamics, rheology, material science, technical mathematics, physical chemistry and molecular biology[3]. Applied engineering science is aimed at knowledge of particular technological devices, like bioreactor design and scale-up, membranes and distillation columns or materials like catalysts on solid surfaces, specific nanomaterials, polymers, cultured meat and genetic and tissue engineering, food physics et cetera. As discussed before, these sciences may be applied, but they are still scientific in nature, using the scientific method for analysis and abstraction and leading to a logically-coherent system of knowledge about these particular technical applications.

### 2.1.2 The Restricted Scope of Disciplines

As mentioned, a differentiation can be made between fundamental and applied engineering science. Next to specialistic knowledge of applied engineering science i.e. the development of concrete technology, the engineering scientist should also remain familiar with the fundamental engineering science in order to stay in touch with overall technological development (Schuurman, 1990: p. 65). Although Schuurman does not relate this to interdisciplinarity, it will become clear later in this thesis that a knowledge deficit about either fundamental engineering science or applied engineering science is in part responsible for hurdles to interdisciplinarity. This is also recognised in the context of interdisciplinary education in a biotechnology program; it is problematic when students miss the fundamental engineering science knowledge of technical mathematics (Foley, 2016). As such, fundamental engineering science bridges different applied engineering sciences. As the analysis of an interdisciplinary research project between systems biologists and molecular biologists will show, such a knowledge deficit is one of the reasons why interdisciplinary research can be difficult.

This clarifies Ortega y Gasset's general claim of a 'barbarism of specialisation' mentioned in the introduction. One of the elements of a disciplinary perspective is that it comes with a restricted scope. For example, in the natural sciences, scientists deal with the physical, chemical or biological aspects of reality. In that sense scientific research in natural science is always abstract in that it deals with certain aspects of reality, foregoing other aspects (Schuurman, 1980, 1997). This perspective also comes with a tendency to explain phenomena in terms of the aspect they are dealing with. Biologists give biological explanations, and physicists physical explanations. Similarly, in the engineering sciences, scientists also have a restricted scope due to a focus on particular branches of fundamental engineering science or

[3] It might seem that molecular biology should be part of biology i.e natural science. However, this depends on the type of knowledge the paradigm of aimed at (Element I. *Epistemic aim(s) of scientific research*) of the extended disciplinary matrix). In the engineering paradigm, biosystems are investigated with the aim of developing technical applications (Boon, 2017; MacLeod, 2018), making them engineering sciences.

particular technological applications like in the chemical, food or medical industries. This element of a disciplinary perspective is rather obvious. Scientists investigate certain things and not others, henceforth referred to as the restricted scope of scientific research. Such a view on scientific disciplines and the corresponding disciplinary perspectives also permeates into views on interdisciplinarity and what it entails. That is why a critical discussion of this notion is fundamental to understanding interdisciplinarity.

For example, Heijnsdijk (1970) considered the restricted scope or expertise of scientific disciplines to fully capture what a disciplinary perspective is about, a view shared by de Ridder (2019). On this view, interdisciplinarity entails the combining of insights gathered by different disciplines to combine them into a coherent understanding of reality. Through synthesis of the abstract knowledge from individual disciplines, a full description of reality can be acquired. However, such a view is blind to the context in which this knowledge was created assuming that once this knowledge has been justified in the individual disciplines, it can be transferred to other disciplines without difficulty (Boon, 2020b). As will be argued in this thesis, this context cannot be discarded if the difficulty of interdisciplinarity is to be understood, let alone overcome. Moreover, cross-fertilization of different disciplines requires understanding how methods and approaches are justified differently in different disciplines. This means that there is more to a disciplinary perspective than a restriction in scope. As will be show in the following sections, a disciplinary perspective pertains to more than just a restriction in subject-matter but methodologies, ontological and epistemic assumptions and preferences as well. To understand this thicker notion of disciplinary perspective, requires the development of a philosophical lens which is done in the coming paragraphs.

## 2.2 Disciplinary Perspectives

Natural and engineering scientists intuitively understand that they deal with some aspects of reality e.g. the physical, biological or technical, and research certain things and not others e.g. cultured meat or nuclear reactors. However, there is more to a disciplinary perspective than this restricted scope. Restricted scope alone is insufficient to capture what a disciplinary perspective is about and how it can lead to hurdles to interdisciplinarity. Understanding why interdisciplinarity is difficult requires insight into the epistemological, methodological and cognitive elements of disciplinary perspectives.

### 2.2.1 Kuhnian Paradigms

To understand the thicker notion of disciplinary perspective, the work of Thomas Samuel Kuhn (1922-1996) provides the chronological and philosophical starting point. The goal of this section is to show that his notion of ‘scientific paradigm’ enabled insight into the broader aspects of scientific practice which can make clear why interdisciplinarity can be difficult. At the same time, it will be shown that Kuhns account has some problematic aspects which, if directly applied to scientific disciplines, would render interdisciplinarity impossible.

In his renowned work *The Structure of Scientific Revolutions* published which was published in 1962, Kuhn introduced the concept of 'scientific paradigm'. Kuhn argues that science consists of periods of so-called normal science followed by revolutions. During normal science, the foundations of the scientific endeavour are not questioned and, according to Kuhn, science is focussed on puzzle solving within the established way of approaching problems i.e. a paradigm. For Kuhn, major theories, like Newtonian mechanics, are foundational for paradigms. Typically, more and more puzzles are being solved within the paradigm until the paradigm hits a barrier i.e. the scientists encounter puzzles which cannot be resolved within the paradigm – or rather major theory – of their discipline. If an alternative theory is available, a 'scientific revolution' ensues. This means that what was left unquestioned throughout the period of so-called normal science – the major theory, is now being questioned and, if refuted, a paradigm shift has occurred meaning that a new paradigm replaces the old one (Kuhn, 1996).

The notion of paradigm contains an important insight to understand problems with interdisciplinarity. If scientists have a particular perspective on reality that is incompatible with other perspectives, this explains why *inter*disciplinarity can be difficult. One of the ways Kuhn refers to such a paradigm is as a worldview (Ch. 10, p. 111-135). One example he uses to illustrate this comes from the context of chemistry, specifically the discovery of oxygen "Lavoisier […] saw oxygen where Priestley had seen dephlogisticated air and where others had seen nothing at all" (Kuhn, 1996: p. 118). This does not mean that a scientist can see anything he likes but rather that what is seen also depends on the disciplinary matrix or paradigm the scientist is part of. This also means that, according to Kuhn, scientists adhering to different paradigms have such a different way of approaching problems that fruitful collaboration will be impossible, a point discussed in more detail later on. What are these differences in approaches?

Importantly, Kuhn argues that different paradigms are *incommensurable* meaning that scientists from different paradigms "must fail to make complete contact with each other's viewpoints" (Kuhn, 1996: p. 148)[4]. Kuhn discussed three expressions of incommensurability namely in terms of standards, concepts and worldviews. With regard to the first two, the first instance of incommensurability is that scientists from different paradigms cannot communicate meaningfully because concepts have different meanings in their paradigms, meaning that they

---

[4] It must be noted that some philosophers of science argue that Kuhn did not adhere as extremely to incommensurability as put here (e.g. Godfrey-Smith, 2003). Although this might be correct, the point is to deal with the more extreme statements because, if these views are correct, this would undermine interdisciplinarity.

talk past one another. Secondly, there might exist different standards about, for example, what constitutes a good scientific theory e.g. whether it should include a causal mechanism or if a mathematical formalism suffices (Godfrey-Smith, 2003). Therefore, according to Kuhn, such conversations cannot be fruitful because scientists are locked in their paradigms.

In his 1969 postscript of *The Structure of Scientific Revolutions* Kuhn elaborated on the concept paradigm because it was considered unclear. Here, Kuhn uses the notion of a ‘disciplinary matrix’ (1996 [1962]: p. 181) as a substitute for a paradigm. Kuhn (1969) provided four elements in the matrix, acknowledging that this was not a definitive list. The elements included are symbolic generalisations, metaphysical paradigms, values, and exemplars. The symbolic generalisations are for formally generalisable expressions that everybody in the paradigm takes for granted e.g. $f = m \cdot a$ or ‘action equals reaction’. The second element, metaphysical paradigms, refers to shared commitments to metaphysical beliefs such as the entities the world consists of. For example, point particles in classical Newtonian mechanics or waves in electrodynamics. By the third element, values, Kuhn refers to what is considered important in a theory for example, should it predict or have explain? The last element, exemplars, refers to the typical problem-solutions a student is exposed to and learns to transpose onto unsolved problems within the paradigm. Especially the last element is important according to Kuhn since a paradigm can primarily be understood by looking at the exemplars of puzzle solving, whether with pen and paper or in a laboratory, novices are exposed to in order to learn the trade of the discipline.

According to Kuhn, the different elements in the disciplinary matrix constitute the paradigm and form a holistic whole the scientists in the discipline adhere to (Curd & Cover, 1998: p. 217). This means that a scientist either accepts or rejects the whole matrix and this matrix does not change during normal science. Therefore, reflection on and subsequent change of individual elements is not possible because the elements form an integrated whole. However, this claim implicitly rests on what Laudan refers to as *The Hierarchical Model of Scientific Rationality*. There are three levels of scientific rationality: factual, methodological and axiological. The factual concerns the entities and processes the world consists of the methodological concerns values liked simplicity, explanation or prediction sought for in theories and the role of instruments and experiments. Finally, the axiological concerns the goals and aims of science (Curd & Cover, 1998: p. 235). According to the hierarchical model, if scientists disagree at one level, they will argue about this disagreement from the level above to justify their position and a change in the lower level must lead to a change in the level above. However, there is no level above the axiological level which is about the overall aims and goals of science. On this view, debates can ultimately not be solved rationally, which is precisely Kuhn's position: “…there is no standard higher than the assent of the relevant community” (1996 [1962]: p. 94).

However, there is also *The Reticulational Model of Scientific Rationality* which 1) rejects the paradigmatic holism i.e. scientists can disagree over specific elements without disagreeing about the whole paradigm and 2) has a non-linear conception of justification i.e. scientist can retain their views of the goals and aims of sciences whilst changing views on lower levels. As such, the debates are not unidirectional, but reflection on the methodological level can lead to changes in the factual and vice versa. This means that, on the reticulational model of scientific rationality, rational debate is possible about separate elements of the paradigm and at different levels of scientific rationality (Curd & Cover, 1998: p. 235-239; Doppelt, 1986)[5].

As such, Kuhn's views have been heavily criticised. Although he did not deny empirical reality, he showed that the way scientists gain knowledge about reality is not self-evident but also influenced by things like metaphysical assumptions, preferences for certain epistemic values over others, and available scientific exemplars. Scientists have a certain perspective on reality which guides what they perceive. Despite all the critiques, this idea is now commonplace in the philosophy of science and any serious philosophy of science must somehow relate to it. However, at the same time, it was an enabling idea because it made awareness, further specification, and critical discussions about perspective possible.

### 2.2.2 Concepts of Perspectives in Science

As discussed in the previous section, Kuhn showed that the way scientists gain knowledge about reality is not self-evident but also influenced by things like metaphysical assumptions, preferences for certain epistemic values over others, and available scientific exemplars. However, at the same time Kuhn saw adherence to a paradigm as ultimately an extra-rational matter, a view that was subject to criticism. Moreover, the idea that scientists have a certain perspective on reality, explains why interdisciplinarity can be difficult. However, at the same time, there are several discrepancies. For example, paradigms seem to function predominantly at a high level in science, how does this translate to the lower levels i.e. the perspective of individual scientists? These scientists are part of a disciplines, certain subdisciplines, and specialisations within these subdisciplines. Although the notion that scientists have a certain perspective is applicable on all these levels, paradigms seem to primarily function at the higher level of disciplines. For this reason, and others, the notion of scientific perspective requires further specification than reference to paradigms in science. This section is meant to provide that specification.

In the philosophical literature, multiple notions of perspectives in science are used: 'systems of practice' (Chang, 2012), 'domain-specificity' (MacLeod, 2018), 'scientific perspectives'

[5] Further elaboration is beyond the goal of this thesis, but read Doppelt (1986) for a constructive critique of Laudan's who, according to Doppelt, provides insufficient support for his claim that reason for changes in aims and methods of science can be rational.

(Massimi, 2021), and ‘disciplinary perspectives’ (Boon, 2020b). In the case of MacLeod and Chang, their critique is that scientific disciplines, as generally understood e.g. physics, chemistry and biology, are way too broad categories. In practice, individual disciplinary matrices are much more likely found at the level of highly specialised fields within academic disciplines (MacLeod, 2018: p. 702). Therefore, the use of notions like ‘domain-specificity’ is considered a better fit to “capture the degree to which a cognitive system or cognitive domain is specialized for just specific tasks.” (MacLeod, 2018: p. 703). This specialisation is mainly in terms of the subject matter that is dealt with within that domain: “A system is domain-specific to the extent that it has a restricted subject matter, that is, the class of objects and properties that it processes information about is circumscribed in a relatively narrow way.” (Robbins, 2017). This concept of ‘domain-specificity’ seems too limited since a disciplinary perspective is about more than just a restriction in subject matter.

Similarly, Chang (2012) uses the notion of ‘systems of practice’. He acknowledges that Kuhns disciplinary matrix is very similar to his concept of systems of practice, however, he prefers the concept of ‘systems of practice’. The reason why he introduces this new concept is that he considers Kuhn’s disciplinary matrix unsatisfactory. He briefly explains why, and his critique is threefold. The first is very similar to MacLeod (2018). According to Chang (2012: p. 108) “A system of practice is formed by a coherent set of epistemic activities performed with a view to achieve certain aims.”. Here, epistemic activities refer to hypothesis testing, prediction and measurement. Importantly, such a system of practice need not coincide with a scientific discipline:

> “What we take as a whole system in a given situation may be seen as a constituent activity of a larger system, and what we see as a constituent activity in a given situation may in a different situation be analyzed as a whole system made up from other activities.” (Chang, 2012: p. 16)

As such, the notion ‘system of practice’ is meant to prevent remaining on the disciplinary level but spur analysis of ever finer-grained distinguishable levels of scientific practice. This critique is shared by Chang and MacLeod who both underscore that relevant differences in disciplinary perspectives are likely already applicable on the level of scientific specialisations rather than disciplines in the traditional sense as implied by Kuhn.

Chang’s second critique concerns the disorderly and indefinite nature of the Kuhnian concept of the disciplinary matrix (Chang, 2012: p. 18). This critique seems justified when considering Kuhn’s specification of the matrix which indeed required further specification. Chang’s third critique concerns the Kuhnian assumption accompanying the notion of the disciplinary matrix as something that strictly guides the practice of science during periods of normal science

(Chang, 2012: p. 18). According to him, “it may simply be that there is more of a continuum where Kuhn saw a rather sharp dichotomy, between normal science and extraordinary science.” (Chang, 2012: p. 107). With the notion of systems of practice, Chang aims to overcome this sharp dichotomy and leave behind the Kuhnian assumptions accompanying the notions of paradigm and disciplinary matrix.

Finally, Massimi uses the notion of ‘scientific perspectives’ defined as “the actual—historically and intellectually situated—scientific practice of a real scientific community at a given historical time.” (Massimi, 2021: p. 6117). She divides this perspective into a first and second-order level. At the first-order level are the scientific knowledge claims, procedures, experiments, technological artefacts and such. At the second-order level are the justificatory, methodological-epistemic principles (Massimi, 2021). Massimi is quick to underscore that this notion is very different from Kuhnian paradigms. According to her, scientists are not captured in this paradigm like a fly in a spiderweb, unable to see the web itself. Instead, a paradigm provides justification for the knowledge claims about natural phenomena. This critique on Kuhn is similar to Chang’s third critique by claiming that adhering to a certain perspective is not an extra-rational matter like with paradigms.

As all of these authors acknowledge (directly or indirectly), these concepts are all inspired by Kuhn’s work which enabled philosophers of science to become aware of perspectives in science. Each of their concepts provide further specification. As such, each of these concepts seems to allude to something similar. However, in the context of this thesis, it is relevant to find a conceptual framework which can help actual scientists to articulate, specify and analyse their perspective. Therefore, the relevant question here is: ‘Which one is most suitable to analyse and articulate one’s perspective?’. Actually, none of these. The observant reader might have noticed that Boon’s concept of perspectives i.e. ‘disciplinary perspectives’ was not discussed in the preceding chapter. This concept, or rather its related framework is preferable over the other concepts for analysis, articulation and comparison of different scientific concepts.

### 2.2.3 Why Boon’s Framework of Disciplinary Perspectives is Preferable

Boon defines ‘disciplinary perspective’ as the fact that “researchers in specialized fields or disciplines have developed and internalized perspectives that give direction to how they approach research” (Boon, 2020b: p. 30). At first sight, this does not yet give any novel insights compared to the previous paragraph. However, she adds further specification by characterising the elements of such a perspective. As will become clear in a later chapter, the eleven elements she specifies mutually cohere and reinforce each other. These are:

1. Intrinsic aims and objectives – subject matter
2. Practical purposes
3. Research questions

4. Types of real-world phenomena (observable and non-observable)
5. Fundamental (ontological) principles, basic assumptions and beliefs
6. Mathematical frameworks and axiomatic systems
7. Theoretical (conceptual) frameworks and empirical (phenomenological) knowledge
8. Measurement instruments and procedures
9. Research methods and typical strategies
10. Epistemic and pragmatic criteria
11. Representational means

These elements characterise the discipline or specialisation (Boon, 2020b: p. 23-25)[6]. The choices scientists make are guided and constrained by their perspective even if they are unaware of it. As such, with this characterisation of disciplinary perspectives, Boon provides a Kuhnian framework to analyse scientific disciplines. This also makes her notion of 'disciplinary perspectives' pragmatically appealing because it includes a framework for formulation and specification of perspectives in science. Because this framework proposed here is meant to articulate and compare different perspectives in science, it is suitable for the purposes of this thesis where the goal is to elucidate the role disciplinary perspectives play in interdisciplinarity. As such it is not necessarily the concept i.e. the name 'disciplinary perspective' as such that is preferable but the framework it provides. However, at the same time, it does align with the other concepts in the sense that the critiques on Kuhn's paradigms as explicated in the previous paragraph are also incorporated in this concept.

Although 'disciplinary perspectives' is referred to as a Kuhnian framework, as it is worked out by Boon it aligns with the critiques on Kuhn's paradigm as expressed by MacLeod, Chang and Massimi[7]. First of all, it is more complete than 'domain-specificity' since it draws attention to the elements besides restricted subject matter. Moreover, Boon makes it adaptable to analyse any specialisation within science, thus moving beyond disciplines as traditionally conceived. In doing so, she dodges the critique of Chang and MacLeod that disciplinary perspectives might be specific to specialisations instead of being shared on the level of scientific disciplines like biology and chemistry. Of course, this seems to conflict with 'disciplinary' which might be

---

6 In an earlier paper, Boon provided similar elements to specify paradigms of science. These elements were I. Epistemic aim(s) of scientific research, II. (3.) Epistemic values & criteria for the acceptance of knowledge, III. Basic and 'regulative' principles, IV. (1.) Theoretical principles, V. (2.) Metaphysical pre-suppositions, VI. Ontology, VII. Knowledge, VIII. Epistemology, IX. Methodology, X. Exemplars of science (4.), XI. Role attributed to experiments and technological instruments, XII. Results/products of scientific research, XIII. Justification (Boon, 2017: p. 33-34). These are also show in Table 2 in the appendix. This extended disciplinary matrix is meant to articulate different views on science in general. The framework proposed here is meant to articulate and compare different perspectives in science. As such, it is suitable for the purposes in this thesis where the goal is to elucidate the role disciplinary perspectives play in interdisciplinarity.

7 A note for the philosophers of science. Massimi is known as a 'realist', therefore, she has been included in this discussion to show that perspectives are also tenable on a realist account of science. Because this point it is not central to the argument being made in the thesis and there is no room to deal with it in the main text, it is dealt with in detail Appendix II: Disciplinary Perspectives and the Realism Debate.

confusing, Nevertheless, it does draw attention to the fact that scientific perspectives are also heavily influenced by the general scientific discipline they are part of which is a pro.

Finally, the framework enables systematic analysis and evaluation of disciplinary perspectives, pointing to the possibility of critical reflection on one's scientific perspectives. This indicates that scientists can be aware of their perspective and articulate it instead of being caught in it like a fly in a spiderweb, unable to see the web itself. Thus, the shared critique by Massimi and Chang is subsumed in this concept as well.

One might question what holds these elements together, what makes them cohere into a disciplinary perspective. In short, the coherence is not first of all a logically-coherent one although that is not to say that they are logically incoherent. The coherence is primarily a practical one. In scientific practice, these elements form a coherent whole. Of course, this is an important question which requires further attention. However, it will be addressed in more detail in Chapter 5 concerning the role of semantic networks in dealing with hurdles to interdisciplinary.

In summary, due to its empirical applicability, and for the reasons stated above, Boon's framework will be used in this thesis and henceforth, when perspectives in science are mentioned, it will refer to 'disciplinary perspectives' by Boon (2020). In the next chapter the framework will be applied to analyse cognitive hurdles.

## 2.3 Summary

This chapter addressed the first main sub question: 'What does it mean to have a disciplinary perspective and how does it relate to scientific practices within disciplines?'. Because this thesis is restricted to natural and engineering science, these two were first defined to provide clarity. This analysis showed that one element of scientific disciplines is their restricted subject matter. However, it was argued that there is more to scientific disciplines than restricted subject matter by discussing Kuhn's work, particularly his notion of 'scientific paradigms'.

His work was used as a springboard towards further defining a disciplinary perspective. It was argued that disciplinary perspectives are key to understanding scientific practices. Such a perspective includes technical, methodological, epistemological, and ontological elements which enable the creation of new knowledge in that discipline. In response to Kuhn different philosophers of science have developed multiple concepts to talk about perspectives in science. Each of these conceptualisations include critiques of Kuhns views on science. It was argued that Boon's concept is preferable. First of all because it incorporates all the critiques included in the other concepts. Secondly, Boon also provides a framework for the analysis of disciplinary perspectives was most specific, fine-grained, defined and thus preferable to articulate and analyse disciplinary perspectives. This second pragmatic point carries weight in the context of this thesis because philosophical discussion of disciplinary perspectives, although worthwhile, is not a goal is itself.

The overall goal of this thesis to understand how cognitive hurdles to interdisciplinarity can be overcome. The question is how a notion like ‘disciplinary perspectives’ can help practicing scientists in overcoming hurdles to interdisciplinarity. To understand this, the relation between disciplinary perspectives and hurdles to interdisciplinary perspectives should first be elucidated. This is the topic of the next chapter.

# 3 Disciplinary Perspectives and Hurdles to Interdisciplinarity

In the introduction, it was mentioned that cognitive hurdles hinder interdisciplinarity. The preceding chapter clarified what a disciplinary perspective is and provided a framework for analysing such a perspective. In this chapter it is argued that cognitive hurdles can be traced back to the fact that the collaborating have different disciplinary perspectives. As was shown in the previous chapter, this perspective pertains to more than just a particular subject-matter but methodologies, ontological and epistemic assumptions and preferences as well. This chapter is meant to elucidate how disciplinary perspectives can lead to cognitive hurdles to *inter*disciplinarity. To do so, this chapter deals with a practical case that is simultaneously used to bring forth what makes interdisciplinarity difficult in practice and how it connects to disciplinary perspectives. This case study underscores that difficulties with interdisciplinarity are real and are not some abstract problems conjured up by philosophers. Moreover, such an empirical case helps better understand the nature of the problems interdisciplinary scientists face.

## 3.1 A case: Systems Biologists and Molecular Biologists

This section is intended to show how cognitive hurdles to interdisciplinarity are connected to the disciplinary matrix. This will be done by discussing insights from a 5-year long empirical study by MacLeod and Nersessian among systems biologists and molecular biologists (MacLeod, 2018; MacLeod & Nersessian, 2016). Why this case study? At the time of writing, this is the only in-depth academic source addressing interdisciplinarity in the natural or engineering sciences. Other papers reporting on empirical studies (e.g. Brister, 2016; Daniel et al., 2022; Maglaughlin & Sonnenwald, 2005), are not as structured or focused, making it more difficult to draw concrete examples and insights from them. Therefore, the insights gathered from the study by MacLeod and Nersessian, are highly valuable in understanding cognitive hurdles to interdisciplinarity. Here, the hurdles they identified are analysed from the disciplinary perspective framework by Boon (2020b), which was defended in §2.2.3.

In the 2018 paper, MacLeod discusses two examples of interdisciplinary research, one from social and one from the engineering sciences. MacLeod's example from the engineering sciences between molecular biologists and systems biologists is relevant to our argument. The case MacLeod refers to involves molecular biologists and systems biologists (2018: p. 705-706). The former have biological expertise along with experimentation experience i.e. wet lab experience but lack thorough mathematical training and are thus unfamiliar with modelling practices. Their expertise is experimental manipulation, and they are aimed at gaining insight via experimental data. The latter have engineering backgrounds, no biological training or wet lab experience. They are aimed at mathematically modelling biochemical systems to gain understanding and use this knowledge to potentially re-engineer them.

Based on five years of empirical study, MacLeod identified four consequences of domain-specificity:

1. The opacity of domain-specific practices to outsiders
2. Large conceptual and methodological divides
3. Conflicts over epistemic values
4. Unstructured problem-solving environments

The first entails that scientists from distinct disciplines might be unfamiliar with the practices in the discipline they collaborate with. For example, a systems biologist might request a molecular biologist to experimentally investigate a particular parameter relevant to their model. However, the molecular biologist might not understand what the systems biologist is asking for because they are unfamiliar with modelling. Despite efforts from both sides to get clarity, the molecular biologist is unable to grasp what is asked for because he is unfamiliar with the practice of mathematical modelling and the entities incorporated in such models. These do not translate directly to the entities he is familiar with from his experiments and thus bi-directional opacity of the practices in the other domain leads to frustrated efforts for collaboration.

The goal of the coming sections is to show that the hurdles identified by MacLeod (2018), are connected to several elements of the framework proposed by Boon (2020b). The analysis will show that this framework is very suitable to specify the nature of obstacles in interdisciplinary practices in the engineering sciences as also suggested by Boon & van Baalen (2019). This section starts off with Table 1 which provides an overview of the elements of the disciplinary perspectives that played a role in the hurdles to interdisciplinarity. These elements have been highlighted in a copper colour. In the follow-up sections, each of these hurdles and the elements that play an important role in them, are discussed in detail to show how these hurdles are linked with the disciplinary perspectives of the researchers.

*Table 1: An overview of the elements of the disciplinary perspectives related to hurdles to interdisciplinarity in the engineering sciences, specifically between molecular and systems biologists.*

<table>
<tr><th colspan="2">Element of the disciplinary perspective</th><th>Opacity of domain-specific practices</th><th>Large conceptual and methodological divides</th><th>Conflict over epistemic values</th><th>Unstructured problem-solving environments</th></tr>
<tr><td>I.</td><td>Intrinsic aims and objectives related to subject matter</td><td style="background-color:#f6cbab"></td><td></td><td></td><td></td></tr>
<tr><td>II.</td><td>Practical purposes</td><td></td><td style="background-color:#f6cbab"></td><td></td><td></td></tr>
<tr><td>III.</td><td>Research questions typical of discipline</td><td></td><td></td><td></td><td></td></tr>
<tr><td>IV.</td><td>Real-world phenomena</td><td></td><td></td><td></td><td></td></tr>
<tr><td>V.</td><td>Fundamental (ontological) principles, basic assumptions and beliefs</td><td></td><td style="background-color:#f6cbab"></td><td></td><td></td></tr>
<tr><td>VI.</td><td>Mathematical frameworks and axiomatic systems</td><td></td><td></td><td></td><td style="background-color:#f6cbab"></td></tr>
<tr><td>VII.</td><td>Theoretical (conceptual) frameworks and empirical (phenomenological) knowledge</td><td style="background-color:#f6cbab"></td><td style="background-color:#f6cbab"></td><td></td><td style="background-color:#f6cbab"></td></tr>
<tr><td>VIII.</td><td>Measurement instruments and procedures</td><td style="background-color:#f6cbab"></td><td style="background-color:#f6cbab"></td><td></td><td style="background-color:#f6cbab"></td></tr>
<tr><td>IX.</td><td>Research methods and typical strategies</td><td style="background-color:#f6cbab"></td><td style="background-color:#f6cbab"></td><td></td><td style="background-color:#f6cbab"></td></tr>
<tr><td>X.</td><td>Epistemic and pragmatic criteria</td><td></td><td></td><td style="background-color:#f6cbab"></td><td></td></tr>
<tr><td>XI.</td><td>Representational means</td><td></td><td style="background-color:#f6cbab"></td><td></td><td></td></tr>
</table>

In the first column of Table 1 the elements of Boon's framework are listed. In the second-fifth column each of the hurdles identified by MacLeod (2018) are listed and those elements related to this hurdle are highlighted in a copper colour. Why these elements are highlighted and not others, is discussed for each of the hurdles in the following sections.

### 3.1.1 Opacity of Domain-Specific Practices to Outsiders

As Table 1 shows, four elements are highlighted for the first hurdle, namely the opacity of domain-specific practices to outsiders. The opacity of domain-specific practices as described by MacLeod (2018) is indeed the result of a lack of training and practical experience: "the technical skills, understanding and experience required to operate within a domain can be opaque or intractable to non-specialists without adequate training." (2018: p. 707). Clearly this has to do with the subject matter of the discipline – element I. However, it is also related to other elements. For example, element VII empirical knowledge because technical terms are often related to particular methodologies and to understand these terms requires understanding the domain-specific practices like methodologies. Moreover, measurements and research methods are also related to this hurdle – elements VIII and IX. The molecular biologists were unfamiliar with problems of the most general scale, for example in technical mathematics: “In the current circumstances a collaboration usually starts with a biologist approaching a modeling lab and asking BI have some data can you model it, without any real understanding of the data demands for dynamic models.” (MacLeod & Nersessian, 2016: p. 408). Similarly, the systems biologists were unfamiliar with problems close to the actual biochemical systems being researched in the experiments.

So, this hurdle has to do with a lack of both understanding and practical experience. As such, it is not related to other elements like practical purposes for example. Instead, it is related to the methodologies used in the discipline. To be even more precise, with the practical skills and understanding of these methodologies. As such, this problem is not about the *justification* of these methodologies i.e. the philosophical assumptions accompanying them. This is different for the next problem.

### 3.1.2 Large Conceptual and Methodological Divides

The second consequence of domain-specificity MacLeod mentions is large conceptual and methodological divides (2018: p. 709-711). This has less to do with technical understanding and skills but more with the fact that methods do not align, e.g. the scale of experiments is incompatible. Although this cannot be fully separated from the opacity of domain-specific practices, this problem is less technical in nature. As MacLeod puts it:

> “In other cases the problems might be less directly due to a lack of technical insight into one another’s practices and more due to the fact that the conceptual and methodological distance between the cognitive domains is very large.” (2018: p. 709).

Clearly, this hurdle can also be explained in terms of mismatched disciplinary perspectives and related to several elements of this perspective. The systems biologists attribute a very different role to the experiments than the molecular biologists hindering integration of experiments and modelling. For the systems biologists, the experiments serve as input for the models which will provide understanding while the molecular biologists consider the experiment worthwhile in themselves. As such, there are different practical purposes with the research – element II. Moreover, a significantly different role is attributed to experiments, technological instruments and measurements – elements VIII and IX. Similarly, the molecular biologists aim to test a hypothesis about the biological systems under investigation whereas the systems biologists aim at a good working model which can be used to further understand and control the biological system. This has to do with representational means typical for the discipline – element XI.

With regard to the conceptual divides, these are related to element VII. It is good to realise that the concepts that are being used are laden with epistemological and ontological assumptions about reality – element V. Moreover, concepts are also related to established phenomena, measured parameters et cetera. Fort these two reasons, conceptual divides are not simply swept aside to start all over.

It is important to notice that in this case there is no disagreement about the other elements of the perspective. Take for example, element IV: Real-world phenomena. Both molecular and systems biologists are aimed at better understanding biological systems and agree that "biological systems are governed by their physical structure as well as by their higher order functions" (Boon, 2017: p. 33). Instead, they have doubts about what role an experiment or model can play in discovering these. This also has to do with epistemic values, which is a separate hurdle discussed in the next paragraph.

### 3.1.3 Conflict over Epistemic Values

The third hurdle, conflict over epistemic values is very clearly connected to the disciplinary perspectives, particularly epistemic values – element X. As MacLeod (2018: p. 712) puts it: "But divides like these are not just opacity problems, but reflect more basic hard-to-resolve disagreements, particularly when systems of practice flow from them.". In this case, there is fundamental disagreement about when certain claims are reliable. For example, there are differences in what types of explanations are deemed reliable, deductive-nomological in the case of systems biologists or detailed mechanistic in the case of molecular biologists[8]. Another example is the validation of models for which systems biologists view agreement between prediction and experimental output as sufficient whilst molecular biologists doubt whether this will suffice due to the simplicity of the models. These problems are clearly related to more fundamental, philosophical disagreements. As such, these are not just opacity problems, which might be resolved by gaining more technical insight into the other disciplines. No, these are more fundamental disagreements which are hard to resolve.

As Boon and van Baalen argue, such disagreements can also be the result of different views of what the goals of science are (Boon & van Baalen, 2019). On the realist view that science aims at truth, is likely that such disagreements arise and are very hard to overcome. Although this is interesting and relevant, for the sake of brevity and clarity of argumentation this problem is not discussed in the main text. Nevertheless, the interested reader is referred to Appendix II: Disciplinary Perspectives and the Realism Debate.

[8] See (Hempel & Oppenheim, 1948) for the deductive-nomological explanation, which includes general laws and is therefore also known as the covering law model of explanation. In contrast, the mechanistic type of explanation do not include such general laws but are *"descriptions of higher-level phenomena in terms of lower-level parts and their interactions."* (Fagan, 2016: p. 895).

### 3.1.4 Unstructured Problem-Solving Environments

The fourth consequence is the unstructured problem-solving environments (p. 714-716). This hurdle links to Kuhn's vision of a paradigm as uniting a problem-solving community. According to Kuhn (1996 [1962]: Ch. IV), normal science essentially is paradigmatic puzzle-solving which is successful precisely because it happens within a shared paradigm. However, in the case of interdisciplinary research, two different disciplines must cross-fertilise and merge. This means that the usual, implicit assumptions and rules no longer apply. As MacLeod puts it:

> "In principle any interdisciplinary project that tries to transplant domain-specific practices into a new domain these practices were not designed specifically for may put its researchers in the position of having to solve problems by inventing substantial new practices and methods on the spot for each individual problem." (2018: p. 715-716).

This is obviously cognitively highly intensive and thus not effective at all in the case of complex phenomena. It constitutes a significant hurdle to interdisciplinary research. In the case that two disciplines collaborate, the usual examples of how to solve the problems they are faced with, no longer apply. Kuhn placed extraordinary emphasis on these examples (Kuhn, 1996 [1969]: p. 187-191; Laudan, 1989 [1977]: p. 371). A student does not learn via verbal means alone but gains tacit knowledge by processing words and concrete examples together, highlighting the significant role of examples. However, in case of interdisciplinarity, these examples do not apply. This means that new structures need to be developed to create a structured problem-solving environment.

From the case of molecular and systems biologists it is clear that this hurdle particularly relates to mathematical frameworks and axiomatic systems as well as theoretical (conceptual) frameworks which are no longer shared – elements VI and VII. The fact that such frameworks are no longer shared, means that constant negotiation is required to create shared frameworks. Moreover, the fact that measurement procedures and research methods and typical strategies – elements VIII and IX are no longer shared, also attributes to unstructured problem-solving environments. Differences between disciplines with regards to these elements lead to unstructured problem-solving environments. Other elements are not that important, for example disagreements over epistemic values do not directly lead to unstructured problem-solving environments.

## 3.2 Incommensurability of Disciplinary Perspectives

In the case outlined above, the cognitive hurdles that make interdisciplinarity difficult can be understood as resulting from a mismatch in disciplinary perspectives. In interdisciplinary collaboration perspectives must somehow join to address the real-world problem at hand. However, there are significant cognitive hurdles which lead to the question of whether an interdisciplinary collaboration between scientists with diverging disciplinary perspectives is even possible? As discussed previously, Kuhn viewed paradigms in science as incommensurable, meaning paradigms "must fail to make complete contact with each other's viewpoints" (Kuhn, 1996: p. 148). As pointed out in the previous chapter, philosophers of science have criticised Kuhn's views on paradigms that also touch on incommensurability. For example, the extra-rational nature of holding on to a certain paradigm, rests on the hierarchical model of rationality which is subject to scrutiny as was discussed in §2.2.1.

To move away from these Kuhnian assumptions about paradigms, philosophers of science further developed these ideas into perspectives in science (see §2.2). These perspectives are important to understand cognitive hurdles to interdisciplinarity as shown in the case of systems and molecular biologists (see §3.1). However, as was argued, unlike paradigms, disciplinary perspectives can be used to understand more fine-grained, lower levels of scientific disciplines. Individual scientists have a certain perspective they share with fellow specialists in their (sub)discipline. Although these disciplinary perspectives are distinct from Kuhn's paradigms, the question of incommensurability is also relevant on the level of disciplinary perspectives. If disciplinary perspectives are somehow incommensurable, how can *inter*disciplinarity be possible? It seems that interdisciplinary research would, by definition, be impossible because disciplines cannot cross-fertilise. Therefore, this question needs to be addressed before talking about interdisciplinarity.

According to Kuhn, scientists are more-or-less caught within their paradigm, unable to get out if no revolution occurs and unable to make contact with the viewpoints of scientists in other paradigms. This stance is critiqued by Boon, primarily in her 2017 paper on paradigms of science. In her 2017 paper, Boon aims to elucidate that different views of science are possible and that these views permeate into views on what scientific knowledge is, leading to distinct views on knowledge. She lays out two views of science referred to as the physics and engineering paradigms. The physics and engineering paradigms are distinct primarily because of their diverging epistemic aims of science and the types of knowledge produced. Where the physics paradigm is aimed at truth, the engineering paradigm is aimed at producing useful knowledge to solve problems[9]. This also leads to different types of knowledge, in one case the

[9] This differentiation between a physics and engineering paradigm, is not the same as the distinction between natural science and engineering science introduced in §2.1.1. What Boon (2017) is arguing, is that scientists, natural and engineering scientists alike, function in a certain paradigm that informs their practice and vice versa. As such, an engineering scientists, might adhere to the physics paradigm. As such, these paradigms are views on what constitute 'good science' broadly speaking. Very often, engineering scientists view physics as the real science and use it as a model for their work, however, in reality this does not fit the nature of engineering science leading to tensions and misunderstandings (Boon, 2008; Boon & van Baalen, 2019).

knowledge supposedly directly represents the world and in the other, it is an epistemic tool i.e. the relevance for the knowledge-user carries weight.

Although she builds on Kuhn, there are significant differences. According to Boon, a paradigm cannot be proven or dis-proven but rather, it is a self-fulfilling prophecy in the sense that it is guided by practice and at the same time is reinforced by the practice. This means that it can be articulated and reformulated to replace earlier ones (Boon, 2017). For example, Boon (2017) attributes the paradigm shift in the biomedical sciences not only to anomalies but also to "philosophical critique on the metaphysical and epistemological presuppositions of the physics paradigm" (Boon, 2017: p. 31) and new technological development. This is a significant deviation from Kuhn in the sense that in his view fundamental changes could only be the result of revolutions i.e. the response to a crisis in which case scientists discover an anomaly that indicates that something is fundamentally wrong which paradigm has not equipped them to deal with it (1996 [1962]: p. 86).

Although paradigms are distinct from disciplinary perspectives due to the reasons mentioned above, this background is important to understand since this also permeates into Boon's views on disciplinary perspectives (Boon, 2020b). According to her, scientists can be aware of their disciplinary perspective, and even critically articulate, analyse and change it through rational processes. This view enables her to develop the framework for the analysis and comparison of these perspectives, precisely because she believes that scientists can critically reflect on their perspective. In this sense, disciplinary perspectives are not incommensurable like Kuhn thought paradigms were. Scientists can be aware of their own perspective as well as the perspectives of other scientists.

Someone might object by saying that Kuhn never said that scientists could not be aware of their paradigm, how could they otherwise experience that their paradigms were incommensurable? This is certainly so, however, according to Kuhn, scientists indeed experience that no meaningful communication is possible with scientists from other paradigms. However, according to Kuhn they are not able to reflect on this fact from a higher level and come to agreement and, as a result, paradigms are incommensurable: scientists from different paradigms "must fail to make complete contact with each other's viewpoints" (Kuhn, 1996: p. 148)". Thus, for Kuhn incommensurability is something that just happens to scientists because they see the world so differently but at the same time, they cannot go beyond this disagreement leading to incommensurability. There is little to be done here in terms of philosophical reflection or rational engagement due to the extra-rational nature of adherence to a paradigm. In contrast, the point Boon argues is that scientists are not 'condemned' to this incommensurability but that they can become aware of their perspective, formulate it, compare it with other perspectives and even meaningfully engage with other perspectives. As such, disciplinary perspectives are not incommensurable in a Kuhnian sense.

However, commensurability does not entail reducibility. Disciplinary perspectives are not reducible to one another. For example, in the natural sciences, living systems cannot be adequately captured through research methods from the physical sciences. This does not mean that no inspiration can be drawn from other fields but that methods should suit the aspect of reality that is under investigation (Polanyi, 1968). As such, biology requires distinct methodologies which are not reducible to methods in physics[10]. It follows that disciplinary perspectives are also irreducible in this regard, if they were there would be a single discipline capable of capturing everything there is to know.

Similarly, in some cases, epistemic values are not reducible to one another. This was also the case in the interdisciplinary collaboration between molecular biologists and systems biologists. In such a case, collaborators will have to decide which values carry more weight in light of the particular real-world problem they aim to address. Because scientists can decide to adopt one value instead of another, or assign more weight to one, these values are irreducible but not incommensurable in the Kuhnian sense that there would be no standard to make a decision. In that sense, disciplinary perspectives are irreducible or at least have irreducible elements. These insights enable a thorough understanding of the particular nature of interdisciplinarity which will be worked out in the following paragraph.

## 3.3 Interdisciplinary Collaboration

The kinds of hurdles that plagued the systems and molecular biologists ranged from lack of insight into each other's practices to conflicts over epistemic values. As shown in in §3.1, these hurdles are the result of different disciplinary perspectives, which the researchers did not explicitly deal with in their interdisciplinary project. As argued in Chapter 2 and shown in the preceding paragraphs, a disciplinary perspective is best articulated with the framework developed by Boon. To reiterate, a disciplinary perspective consists of multiple distinct, interlocking elements. Among these elements are epistemic aims, epistemic values, metaphysical pre-suppositions, subject matter, methodology, the role attributed to experiments, and technological instruments and justification. These elements guide and inform practices (Boon, 2020b).

In the case of interdisciplinarity, researchers with different disciplinary perspectives will have to cooperate in an *inter-disciplinary* manner. To collaborate, researchers will have to deal with

[10] See (Polanyi, 1968) for example. Another example is the table 1 in Basden & Joneidy (2019) which provides examples of different methods in different sciences. Examples of methods are experiments in the physical sciences, taxonomic analysis in biology and surveys in social sciences.

the differences in disciplinary perspectives. The degree to which there will be differences will depend on the disciplines or subdisciplines involved in the research. The more they are akin, the less significant their differences will be. In practice, this means that every interdisciplinary research project is unique. In some cases, there might be agreement on several elements with disagreement on others, while in other cases there might be minor disagreements on all elements.

Seeing these differences in disciplinary perspectives, interdisciplinary researchers will have to navigate this 'space' between these perspectives. MacLeod's (2018) fourth hurdle to interdisciplinarity was unstructured problem-solving environments. Simply put, this means that scientists do not know how to go about answering their scientific questions, or do not even agree on the questions to be asked in the first place (think of element III of Boon's framework). Within their disciplines, their disciplinary perspective was shared with fellow researchers. As such, they did not have to defend their scientific questions, methodologies, use of experiments and general approaches if they aligned with the established disciplinary perspective. Of course, scientists critically evaluate methodologies to a certain extent, but how to evaluate them is, in part, also guided by their disciplinary perspective since this also involves criteria for the justification of these methodologies. This means that they do not need to defend their choices on a meta-level i.e. from beyond their disciplinary perspective.

The need to navigate this space between their disciplines is precisely what makes interdisciplinarity so difficult. As mentioned in the introduction, interdisciplinarity entails cross fertilisation of disciplines. This means that the disciplines involved in the research are 'substantially altered' in some way (Grüne-Yanoff, 2016: p. 343). In practice, this integration might lead to the creation of new disciplines like in the case of chemical engineering and biology into biotechnology. However, it might also be the case that both disciplines are 'substantially altered' without merging into a single, new discipline. As such, cross-fertilisation does not need to entail complete integration. As Grüne-Yanoff (2016) shows, it is also possible that disciplines are substantially altered through collaboration – which is a prerequisite for truly interdisciplinary research – but nevertheless remain distinct disciplines or fields of research. In either case, there is substantial change to the disciplines involved and there is cross-fertilization of disciplines, often to such a degree that a new discipline emerges afterwards.

As mentioned in the introduction, in the case of the natural and engineering sciences, the reason that disciplines start to collaborate is often a particular real-world problem. In order to solve this problem, a shared perspective is required. If this shared perspective is not developed, it is unlikely that the collaboration will lead to a solution to the problem. This is different from the cases that Grüne-Yanoff (2016) uses to show that interdisciplinarity does not need to entail integration of the disciplines. In the case of biotechnology, which emerged through the integration of chemical engineering and biology, a new scientific discipline emerged (Foley, 2016). Nevertheless, chemical engineering and biology still exist as separate disciplines. Biotechnology is able to address those technological problems related to large scale production using living organisms instead of chemicals as is the case in chemical engineering. The cases Grüne-Yanoff uses to argue that interdisciplinarity does not need to entail integration are *evolutionary game theory* and *hyperbolic discounting*. However, in both cases, there is no particular real-world problem to be solved. Take the case of *evolutionary game theory*. Here game theory was picked up by biologists, further developed into evolutionary game theory, and subsequently, 20 years later, picked up by economists again. Both fields were substantially changed due to these encounters, hence, Grüne-Yanoff classifies these as *interdisciplinary*. What is missing here is a particular real-world problem which requires a shared perspective to be addressed.

For example, in the case of the systems and molecular biologists, the models that were developed were to be used to predict and control biological disease phenomena like cancer (MacLeod, 2018). Success required the integration of their perspectives to successfully develop such models. This does not mean that molecular biology no longer exists or that technical mathematics no longer exists but that in this case these two fields need to be integrated for this particular research collaboration to produce these models. It is these kinds of interdisciplinary collaborations which are under consideration here. Such collaborations required the creation of an *inter*disciplinary perspective. This can be defined as follows:

> An interdisciplinary perspective is that shared perspective, defined by the 11 elements of the disciplinary perspective framework, which enables scientists to overcome cognitive hurdles to interdisciplinarity and address the real-world problem.

This definition excludes the possibility of sticking to one of the disciplinary perspectives i.e. what Brister (2016) refers to as 'disciplinary capture' or others as 'scientific subordination' (MacLeod, 2017). In that case, the interdisciplinary research would become monodisciplinary despite researchers from different disciplines being involved. As mentioned before, disciplines should be substantially altered through collaboration referred to as cross-fertilisation, often – though not always – leading to the integration of their disciplines. Therefore, it excludes scientists from staying within their own disciplinary perspective which would render the research *multi*disciplinary. Moreover, this definition points to the framework to specify the interlocking and mutually reinforcing elements of such a perspective (Boon, 2017; Boon & van Baalen, 2019). Although all of these elements are relevant to analyse and articulate this perspective, the researchers will have to find out for themselves which elements are most misaligned and come to an agreement in light of the real-world problem to be addressed. Particularly these elements where there is disagreement need to be discussed to formulate an interdisciplinary perspective, although always in relation to the other elements in the framework. This definition leaves open the option that (sub)disciplines collaborate in an interdisciplinary manner without integrating their disciplines into a new one. Nevertheless, addressing real world problem in an interdisciplinary manner requires the development of a shared perspective. This might mean that integration of the disciplines is only temporarily, specifically tailored to the problem at hand.

The notion of 'perspective' might suggest an emphasis on human cognitive faculties, without making explicit that tools like experimental apparatus and models play an important role in this perspective. This is what MacLeod (2018) tried to make explicit by referring to 'a shared problem-solving environment'. An interdisciplinary perspective includes more than theories and methodologies, epistemological values, criteria for the acceptance of knowledge, assumptions, ontological stances, metaphysical pre-suppositions and justification. It also includes the tools that scientists use like experimental procedure, experimental apparatus, the experiments themselves as well as different types of models. These tools enable them to reason, acquire understanding and discover. Fortunately, these are included in Boon's framework and, as we will see in Chapter 5, semantic networks can create awareness of this. As such, the definition underscores that interdisciplinarity is not adequately captured when just referring to the integration of existing knowledge from each other's disciplines or the integration of different concepts (Boon & van Baalen, 2019), which was suggested by Heijnsdijk (1970). Instead, formulating an interdisciplinary perspective means considering all the epistemic elements that enable the *creation* of new scientific knowledge.

As Eigenbrode et al. (2007) mention, the benefit of interdisciplinarity in comparison to transdisciplinarity and multidisciplinarity is that scientists are able to tackle questions in ways unforeseen in their own disciplinary perspective or to ask and formulate new questions altogether. At the same time, it will require significant effort to deal with the different disciplinary perspectives. However, scientists are not condemned to these hurdles if they recognise and take responsibility at the start of the project to formulate this interdisciplinary perspective. How they can do so and how semantic networks can aid, will be discussed in the following chapters.

Before discussing this, an objection must be dealt with. When reading this, some readers might agree that there is indeed such a thing as a perspective in science. They might also agree that scientist can become aware of their perspective and other perspectives but have doubts about the possibility of different perspectives integrating which is being suggested here. After all, the researcher might become aware of their disciplinary perspective as well as that of the other discipline but wish to adhere strictly to their own disciplinary perspective (Benz & Rossier, 2022; Brister, 2016). In this case, the purpose is that the other discipline will simply adopt methods and approaches of their own. This would be rather imperialistic (Brister, 2016: p. 23), but it is nevertheless possible. In the other case where both disciplines stick to their own disciplinary perspectives, the research would be multidisciplinary instead of interdisciplinary. Therefore, by nature, interdisciplinarity includes (a degree of) change and adaptation i.e. cross-fertilisation with the other disciplines (and their disciplinary perspectives) involved.

## 3.4 Summary

This chapter dealt with the second sub-question: 'What is the role of a disciplinary perspective in hurdles to interdisciplinary research?'. An empirical interdisciplinary case of system and molecular biologists was discussed to show that disciplinary perspectives are directly related to epistemic, methodological and cognitive hurdles to interdisciplinary collaborations. This analysis showed the applicability of Boon's disciplinary perspective framework to gain insight into the nature of the misalignment of disciplinary perspectives. In collaborations where (sub)disciplines need to address a real-world problem, integration is required. In this case, the disciplines have to develop a shared perspective to prevent hurdles like those identified between the system and molecular biologists. This *inter*disciplinary perspective was defined as:

> An interdisciplinary perspective is that shared perspective, defined by the 11 elements of the disciplinary perspective framework, which enables scientists to overcome cognitive hurdles to interdisciplinarity and address the real-world problem.

Developing this shared perspective is possible because disciplinary perspectives are not incommensurable like Kuhn suggested paradigms were. This *inter*disciplinary perspective can be articulated and developed using Boon's framework. When and how this is done, is the topic of the next chapter.

# 4 Development of an Interdisciplinary Perspective

The previous chapter already hinted at solutions for the hurdles to interdisciplinarity which are central to this thesis. It was argued that the formulation of an interdisciplinary perspective is paramount to successful interdisciplinary research. First of all, this chapter aims to answer the question of *how* scientists can formulate an interdisciplinary perspective in practice to specify this notion further. Secondly, this chapter is meant to provide further support to the thesis that if scientists explicitly recognise and take up this task at the start of the interdisciplinary collaboration, hurdles to interdisciplinarity like those identified by MacLeod (2018), will be taken away or at least significantly reduced.

## 4.1 When to Formulate an Interdisciplinary Perspective

To reiterate, in the previous chapter interdisciplinary perspective was defined as follows:

> An interdisciplinary perspective is that shared perspective, defined by the 11 elements of the disciplinary perspective framework, which enables scientists to overcome cognitive hurdles to interdisciplinarity and address the real-world problem.

To prevent hurdles to interdisciplinarity like those identified in the case of systems and molecular biologists, scientists should reflect at the start of their interdisciplinary collaboration. This has also been proposed by several philosophers of science (Boon & van Baalen, 2019; Brister, 2016; Looney et al., 2016). But, why at the start of the interdisciplinary collaboration, why not just initiate the research and see where problems arise? This approach might be appealing because it means that scientists can immediately start working instead of losing time reflecting and discussing things that might not seem directly relevant to their research. However, this is simply mistaken.

As Brister (2016) points out, discussion beforehand means that problems can be anticipated and discussed beforehand. This is important because it prevents going down a certain research track to later find out that this is not at all fruitful to the project because there is a total mismatch with the other discipline involved in terms of methodologies for example. Moreover, conflicts of epistemic values do not magically disappear if one just starts the research (MacLeod, 2018). Discussing these things beforehand prevents dealing with them ad hoc when important decisions or even investments have already been made. Moreover, dealing with them ad hoc is likely to create the kinds of confrontations described by MacLeod (2018) which are then interpreted as superficial communication failures between individual scientists instead of recognising that these conflicts have deeper roots. Therefore, reflection on disciplinary perspectives and the formulation of an interdisciplinary perspective should occur at the start of the collaborative process.

This proposal is very similar to van Baalen and Boon's approach described in a forthcoming paper. In this paper, they describe how they apply the framework in an interdisciplinary biomedical collaboration. Here, the principal investigator was the only person to use the framework to better understand the different disciplinary perspectives of the specialisations involved in the collaboration workshop (Van Baalen & Boon, forthcoming). Of course, the suggestion here is that all active researchers take part in the interdisciplinarity workshop. This approach in this paper neatly fits the approach described here. However, they mention that disciplinary perspectives are developed and internalised through practice. The section on interdisciplinary perspective might suggest that after one, or a few sessions at the start, this perspective is set in stone and fully developed. Of course, this is not the case in practice. Indeed, as van Baalen and Boon make clear, this perspective will primarily take form in actual practice. This is not contested here, but the point is that very important steps can and should already be taken at the start of the collaboration. Through analysis of disciplinary perspectives, certain areas of potential conflict will appear and discussing how to overcome these means taking the first step for integration of perspectives. Of course, like disciplinary perspectives, interdisciplinary perspectives will continue to develop through practice, for example through the emergence of new methodologies.

The benefit is that at the start of such collaborations, the goals of the project will be discussed. These goals concern the goals and aims of science in this particular project. This is the highest level of scientific rationality – axiological (Curd & Cover, 1998: p. 235). Often, choices will be made in light of these goals. As such, these goals can be critically discussed in light of the disciplines i.e. disciplinary perspectives involved, making sure that these goals are actually feasible in light of the disciplines involved. For example, in the case of systems and molecular biologists, the limitations of experiments and models should be clear when formulating the research goals to prevent wrong expectations about what kinds of questions models and experiments can answer. Of course, the development of this interdisciplinary perspective will continue throughout the collaboration. However, after the initiation at the start of the project, the scientists should be able to take a 'metacognitive' stance to issues that arise. However, the main outlines should be clear at the start to prevent the kinds of hurdles like those identified by MacLeod (2018). Seeing this, how should scientists go about formulating this interdisciplinary perspective?

## 4.2 How to Formulate an Interdisciplinary Perspective

As the definition shows, disciplinary perspectives can be made explicit with the disciplinary perspective framework developed by Boon (2020b). As argued in chapter 2, this framework is preferred because it is complete and prevents elements from being forgotten. Moreover, it prevents scientists from merely focussing on disagreements but will highlight where there is agreement as well. Moreover, something very similar, i.e. the *Toolbox Workshop*, has already been successfully applied in interdisciplinary collaborations pointing to the effectiveness of this kind of approach.

This *Toolbox Workshop* is a methodology that has been developed to enhance communication across disciplines (Eigenbrode et al., 2007; Looney et al., 2016; Schnapp et al., 2012). During such a workshop, collaborators reflect together to prepare for the research “by revealing and clarifying fundamental assumptions made by team members about the nature, conduct, and application of research.” (Looney et al., 2016: p. 222). Such a workshop is usually guided by a non-participant in the research, preferably a philosopher of science who can guide the conversation and sharpen the discussion (Brister, 2016; Looney et al., 2016). In order to do so, some scientific knowledge is preferable as well. However, this person is an ‘outsider’ who enables the conversation to take place in an orderly manner, makes sure that the right kinds of questions are being asked and the collaborators gain insight into each other’s practices. In that sense, this ‘non-participant’ can be considered a participant in the research when enabling interdisciplinary collaboration. However, what is meant here is that this person is not directly involved in the research and, therefore, can maintain some distance.

The primary goal of these toolbox meetings is to enhance cross-disciplinary communication. This also shows where this approach, although a step in the right direction, is not yet tailored to interdisciplinarity. The authors explicitly state that it is used in cross-disciplinary research in general which includes trans-, multi- and interdisciplinary research. This is problematic in the sense that it is not tailored to the unique nature of interdisciplinarity which was elaborated upon in the previous sections. As argued in Chapter 4, in contrast to trans- or multidisciplinarity, interdisciplinarity requires the development of an interdisciplinary perspective. Enhancing cross-disciplinary communication is an important element, but if that is all, it will be insufficient for interdisciplinarity. Knowing where perspectives do not match, does not yet remove the conflicts. Therefore, in the context of interdisciplinarity, this toolbox idea would require further development to meet the demands of interdisciplinarity.

For example, in the context of interdisciplinarity, it would also be beneficial if the non-participant guiding the workshop has experience with such research and is able to come up with historical examples to show how fields can cross-fertilise that might provide inspiration for the particular collaborators. In that sense, it is beneficial if the person is knowledgeable about subject matter as well. At the same time, the questions should be tailored to interdisciplinarity as well. Therefore, it is a good thing that there are different versions of these workshops. For example, there is a workshop tailored to the context of science, technology, engineering and mathematics (STEM) (Schnapp et al., 2012). For this context, the collaborators discuss epistemological and metaphysical questions like ‘What methods do you employ in your disciplinary research (e.g., experimental, case study, observational, modeling)?’ and ‘Can the world under investigation be reduced to independent elements for study?’ (Looney et al., 2016: p. 228). In general, such questions are important since it is known asking clarification questions stimulates reflection which means that people become aware of their assumptions and views (Boon, 2020a). As such, being asked questions about their approaches, assumptions et cetera, creates awareness of disciplinary perspectives (Looney et al., 2016).

However, the questions included in the STEM Toolbox Workshop do not yet reflect the breadth of elements articulated in Boon’s framework. For example, in element VII, the framework mentions *Theoretical (conceptual) frameworks and empirical (phenomenological) knowledge accepted in the discipline*. However, ‘concepts’ are not mentioned in the question while the scientists should engage over central concepts in their disciplines to gain insight into central concepts in other disciplines. Moreover, although there is a class of questions on confirmation in the STEM Toolbox Workshop, epistemic values and criteria like simplicity, explanation, prediction, coherence, and empirical adequacy are not made explicit while such concepts enable communication between the scientists. This is a lacuna in the *Toolbox Workshop*. Therefore, it would be completer and more specific to use Boon’s framework to articulate questions about each element.

It is beyond the goal of this thesis to fully develop the full list of questions based on Boon’s framework. However, the reader is referred to footnote 19 of Boon (2020b) which contains a reference to Boon and Knutila (2009) an provides a detailed list of ten questions particularly tailored to models to get an idea of the types of questions that could replace the existing STEM Toolbox Workshop questions. Similarly, in their forthcoming paper in the medical context, van Baalen and Boon provide suitable questions as well (Van Baalen & Boon, forthcoming). An example of such a general question from the STEM Toolbox Workshop is “Do values negatively influence scientific research?” (Looney et al., 2016: p. 228). The point is that this type of question as employed in the STEM Toolbox Workshop is not sufficient for interdisciplinary research collaborations. The questions should not be in general about science, but already tailored to the disciplines involved. An example of such a question would be ‘which epistemic criteria is more important, prediction or explanation in the justification of a model’. By making the questions more specific the answers will already give insights into the particular disciplinary perspectives under consideration instead of some general view.

It was argued before that interdisciplinarity requires the development of an interdisciplinary perspective. As such, awareness of their own perspective[11] as well as their collaborators does not yet constitute an interdisciplinary perspective. The following-up task is to discuss what the shared perspective could look like in light of their agreements and disagreements which they discovered when comparing their perspectives. Doing so means taking into account the existing expertise, available apparatuses and tools et cetera. The notion of 'perspective' might be suggestive and veil the importance of technical apparatuses and tools used in the research while these are key in natural and engineering science.

In short, the following three stages can be distinguished – but not disconnected – in interdisciplinary research. First of all, the scientist must be aware of their own disciplinary perspective. Secondly, they should become aware of the other disciplinary perspectives involved in the collaboration. And thirdly, they should develop a shared interdisciplinary perspective. Especially the first two can be achieved in a workshop, similar to the established STEM Toolbox Workshop, which instead takes Boon's framework to reveal alignment or misalignment between disciplinary perspectives. At this level of disciplinary perspectives, (mis)alignment is purposely used instead of (dis)agreement since disagreement suggests fundamental incommensurability while misalignment suggests that, if reconfigured, the (sub)disciplines could enter into fruitful collaborative research. After stages 1 and 2, the scientists can engage to discuss how to overcome these misalignments and bring their perspectives together to research the problem at hand.

In practice, in certain cases, this might mean that the best of both worlds can be combined. For example, in the case of systems biologists and molecular biologists, experiments and models could be combined to gain novel insights into the biochemical systems under investigation. However, in this case, a choice should have been made to overcome the conflict of epistemic values between these disciplines. Specifically, the molecular biologists had doubts about whether the models developed by the systems biologists could accurately describe the biochemical systems[12]. To resolve this problem, molecular biologists could recognise that the predictive power of the mathematical models used by systems biologists warrants their use in this particular project where the goal is to find out how biological systems can be influenced i.e. how they respond to certain inputs. Through such engagements, the collaborators are enabled to get a clear sight of what their research project is about, how their expertise and of the other (sub)discipline involved can be harnessed in such a way that the research questions

[11] L. Code developed the notion of 'epistemic responsibility' (Code, 1987) which points to the responsibility scientists have to be aware of and knowledgeable about their disciplinary perspective. Unlike moral responsibility, it is about how they create knowledge, hence 'epistemic' (Boon, 2012).
[12] Such a conflict also touches upon the realist – anti-realist debate.

can be answered in novel ways (Eigenbrode et al., 2007) and configure the research is such a way that resources can be spent efficiently from the start.

Of course, this does not yet make clear in what ways philosophical reflection can deal with each of the cognitive hurdles identified by MacLeod (2018). To argue how philosophical reflection and the creation of an interdisciplinary perspective will affect each of the hurdles, first semantic networks will be discussed. As will be argued, these can aid scientists in gaining insight into the disciplinary perspectives involved in the research thus aiding in philosophical reflection and as a consequence, in overcoming cognitive hurdles. By virtue of what they can do so, is discussed in Chapter 5.

## 4.3 Summary

This chapter partially answered the sub question ‘How can cognitive hurdles to interdisciplinary research be overcome?’. Partially, because it focussed on the role of the human scientist in overcoming hurdles to interdisciplinarity. After this chapter, it should be clear when and how scientists can develop and interdisciplinary perspective on a problem. First of all, it was argued that the collaborating scientists should start developing this perspective at the start of the collaboration to prevent hurdles from appearing later on in the project when significant choices have already been made (e.g. acquiring costly experimental equipment). Secondly, they can do so in an ‘interdisciplinary workshop’. This workshop can be modelled on the existing Toolbox Workshop Meeting with some adjustments. Primarily, the questions should be articulated using Boon’s framework because these are more specific and suitable for the interdisciplinary context. Moreover, in this way, their perspectives can be directly compared. These adjustments will render the workshop suitable for the development of an interdisciplinary perspective.

By discussing the when and how of an interdisciplinary perspective, this chapter also further elucidates what an interdisciplinary perspective is about. It is clear, that it is primarily up the human scientists to work on preventing hurdles to interdisciplinarity. However, as said scientists are specialists, meaning that it is hard to understand how other disciplines create knowledge. This requires philosophical reflection i.e. becoming aware of their disciplinary perspective and that this perspective pertains to more than just a particular subject-matter but methodologies, ontological and epistemic assumptions and preferences as well. Becoming knowledgeable about this would require reading publications from the other discipline and discussing these with the collaborators from that discipline. It will be argued that here AI can aid scientists. Specifically, Chapter 5 shows how semantic networks can aid scientists in addressing hurdles to interdisciplinarity. This chapter will also further elucidate how philosophical reflection can aid scientists in overcoming cognitive hurdles and how semantic networks can play a meaningful role in this.

# 5 Semantic Networks to Overcome Cognitive Hurdles to Interdisciplinarity

This preceding chapter highlighted the role of the human scientist in overcoming or rather preventing hurdles to interdisciplinarity. As mentioned in the introduction, semantic networks have already been applied to aid scientists in countering problems which arise due to the high degree of specialisation. This chapter explores the role that these networks can play in interdisciplinarity. Specifically, it is argued that if combined with philosophical reflection they can aid scientists in overcoming the cognitive hurdles scientists face during interdisciplinary collaboration.

As discussed in the introduction, Krenn and Zeilinger recognise and acknowledge the high degree of specialisation in science. They argue that semantic networks, also referred to as ‘knowledge graphs’, can play a role in countering particular problems which result from the high degree of specialisation. Specifically, they focus on the lack of connections with novel connections with other specialised fields of research. This is certainly a problem, however, as was argued in this thesis, knowledge from other disciplines or specialisation is often not as easily integrated as is assumed. It is very cognitively demanding for scientists to work with scientists from other subdisciplines. To prevent difficulties, an interdisciplinary perspective should be developed to address the particular real-world problem. To reiterate, this perspective can be articulated and analysed using Boon’s framework which consists of the following interlocking elements (Boon, 2020b):

1. Intrinsic aims and objectives – subject matter
2. Practical purposes
3. Research questions
4. Types of real-world phenomena (observable and non-observable)
5. Fundamental (ontological) principles, basic assumptions and beliefs
6. Mathematical frameworks and axiomatic systems
7. Theoretical (conceptual) frameworks and empirical (phenomenological) knowledge
8. Measurement instruments and procedures
9. Research methods and typical strategies
10. Epistemic and pragmatic criteria
11. Representational means

As argued in the previous chapter 4, it is paramount to develop an interdisciplinary perspective. To do so, scientists first become *aware* of their own disciplinary perspective, as well as the disciplinary perspective of the scientists they are collaborating with. In this section, it is argued that semantic networks can help scientists gain insight into disciplinary perspectives and thus also aid in the creation of an interdisciplinary perspective. Specifically, the strength of a semantic network is that it enables scientists to see and understand how distinct elements of the perspective relate and cohere into the overall disciplinary perspective. This is important, because addressing individual elements of the perspective is insufficient, precisely because a perspective forms a coherent whole. If semantic networks can indeed provide this insight, it follows that, based on the argumentation in chapter four, they can be used to address hurdles to interdisciplinarity.

For this argument to work, it must be shown that semantic networks help scientists better understand the coherence of particular elements of their disciplinary perspective within the overall disciplinary perspective. To do this, it should first be clear how semantic networks are constructed. Then, their functions and limitations with regard to addressing hurdles to interdisciplinarity need to be clear. So, first, how are they constructed?

## 5.1 Semantic Networks: The Basics

As the name suggests, a semantic network (SemNet henceforth) is a type of network that represents the semantic relations between concepts. These relations are referred to as 'edges'. For example, the concept of 'apple' is related to 'tree' and 'fruit' which in turn are related to other concepts. A SemNet can reveal relationships between different concepts and, in doing so, represent knowledge in a particular field (Lehmann, 1992). As will be discussed later, this particular knowledge representation has its limitations but in the context of interdisciplinary research, it can be used to address several cognitive hurdles. Before discussing how they can aid in overcoming hurdles, SemNets are first discussed in more detail. It is important to underscore that these SemNets can, in principle, be created by hand. However, seeing the number of scientific publications in particular fields, this is not practically feasible. Especially, if the number of publications is exponentially increasing (Milojević, 2015).

This is precisely one of those tasks in which ML is helpful. As explained, ML can process vast amounts of data so that humans can gain insight into them, academic publication in this case (Milojević, 2015). SemNets can be created using ML, thus effectively using available data. This has already been done in the context of quantum physics and biochemistry (Krenn & Zeilinger, 2020; Rzhetsky et al., 2015). These SemNets are based on the scientific concepts in these subdisciplines. How is such a network created?

The first step is to collect scientific literature that is part of the subdiscipline. These can be books, journal publications and data bases. The second step is to create a concept list. In principle this can be done in many ways. Here the procedure used by Krenn and Zeilinger (2020) is described. To create a concept list, first, a list is manually made by human scientists. This list is created by human scientists because they can judge which concepts are important. However, scientists might have missed key concepts. Therefore, to optimise the human-made list, it can be supplemented with an automatically generated list of concepts. Key concepts can be automatically identified from the literature using a natural language processing (NLP) tool.

In the case of Krenn & Zeilinger, this was the *Rapid Keyword Extraction* (RAKE) tool, but it could in principle be a different tool with the same function (Rose et al., 2010). This second list is thus created through an automatic query of scientific literature i.e. books, articles and databases which were collected in the first step. This AI-generated list is then scanned by humans to remove incorrectly identified concepts like the names of humans. Subsequently, both lists are combined into a single list (Krenn & Zeilinger, 2020).

So, by now there is a collection of scientific literature and a list of concepts. By themselves, these two are of little help and provide little insight. However, when these two are combined to create a SemNet, things change. In the third step, this network is created using machine learning technology. To understand how this happens, the necessary basics of machine learning (ML) are described. This subtype of AI consists of a network consisting of nodes that are connected. Which nodes are connected and to what degree they are connected, depends on the training data. This data is used to train the ML model, often for a specific task. Via the training data, the model learns how the different nodes are precisely connected and assign 'weights' to the connections between the nodes. In case the model is used for prediction, the arrangement of the network is based on a mathematical optimisation procedure to find the mathematical function which delivers the best performance i.e. most accurate prediction[13]. Nevertheless, in this case, the network itself is the product of interest, not the predictions that can be made based on the network.

In the case of SemNets, the concepts from the created list are the nodes in the network. This network is created by connecting the different concepts from the list. How when are concepts connected and what is the nature of this connection? Specifically, the concepts form the nodes, which need to be connected to create a network. If two concepts e.g. 'artificial photosynthesis' and 'electrical energy' are mentioned together in the title or abstract of a peer-reviewed paper i.e. 'co-appearance', they are connected in the network (Krenn & Zeilinger, 2020; Rzhetsky et al., 2015). Some concepts might not yet be connected which means that they have a low weight in the network. Others may have been connected very frequently already which means that they have a high weight in the network. So, by training on peer-reviewed papers, the SemNet is automatically built through the training process during which the machine 'learns'. The steps to create a SemNet using ML are summarised in Figure 1 below.

[13] The reader is referred to (Karaca, 2021) for a detailed description and overview of machine learning.

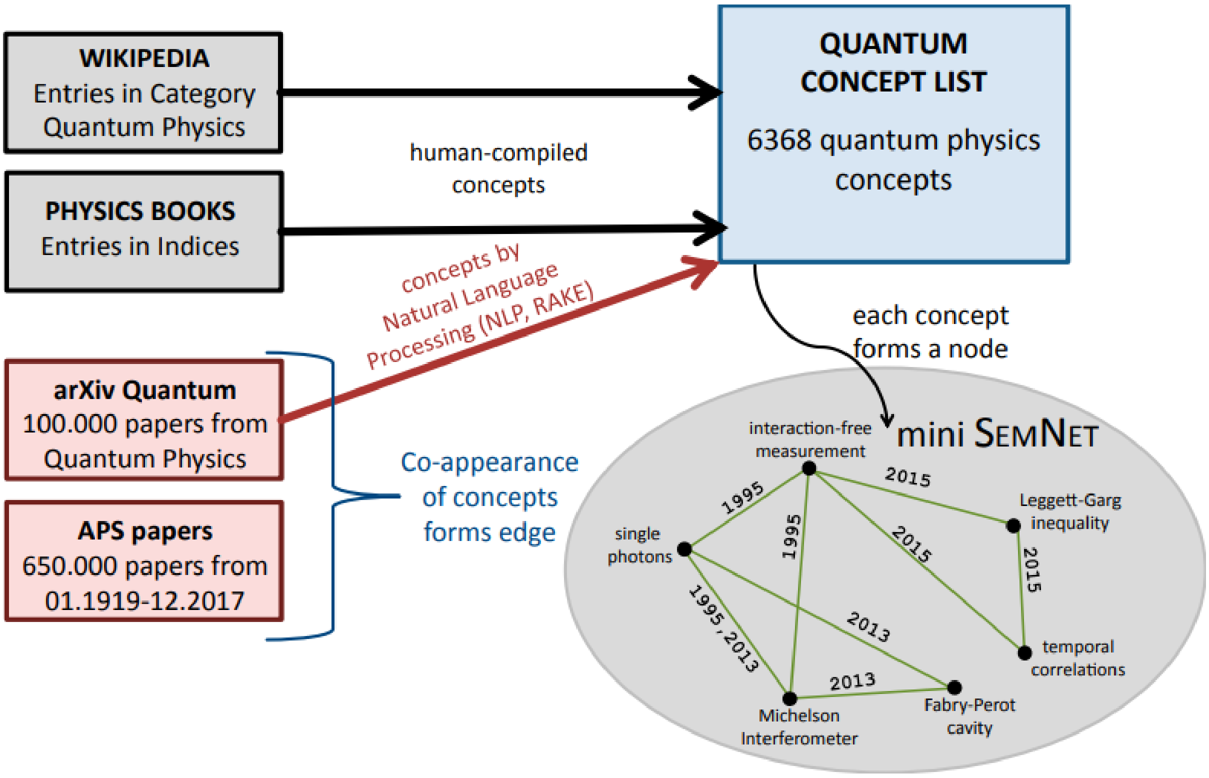


*Figure 1: Creation of the semantic network in the context of quantum physics copied from Krenn and Zeilinger (2020). RAKE stands for Rapid Keyword Extraction, which is a particular Natural Language Processing (NLP) tool. The numbers assigned to the connections between the nodes i.e. the edges, are the publication years of the peer-reviewed paper in which these two concepts were mentioned together.*

This network which has then been generated, consists of connected concepts and can be understood and interpreted by human scientists. Some might doubt how financially or practically achievable it would be to generate semantic networks. However, the fact is that the machine learning infrastructure for such semantic networks is already present[14]. Some wonder why ChatGPT or similar types of models are not used to generate knowledge graphs i.e. semantic networks. This would make it even more easy to generate them[15]. However, models like ChatGPT are trained on vast amount of data from unchecked sources. In that case, the data used to generate the semantic networks is not discipline-specific or peer-reviewed. In the approach laid out by Krenn and Zeilinger the network is created using peer-reviewed publications which ensures acts as a quality control mechanism and is, therefore, preferred.

What can semantic networks be used for? Of course, there are many ways of using semantic networks. For example, in the context of quantum physics, the network was used to analyse past physics trends as well as predict promising future research topics (Krenn & Zeilinger,

[14] For example, Krenn and Zeilinger (2020) provide the semantic network for quantum physics as well as the source code for deriving personalized predictions and suggestions. It is published at GitHub (https://github.com/ MarioKrenn6240/SEMNET).
[15] See for example this video by Nodus Labs: https://www.youtube.com/watch?v=XMwa9q6wWkw.

2020). Here, a new one is proposed, namely to provide insight into the disciplinary perspectives of collaborators. How can they fulfil this function?

## 5.2 Semantic Networks and Disciplinary Perspectives

In this case, the SemNet itself is the product that can aid scientists. Specifically, the SemNet can be used to provide insight into disciplinary perspectives. To understand *why* and *how* SemNets can provide insight into disciplinary perspectives, it is important to discuss the *kind* of knowledge they represent in more detail.

The concepts that are included in the SemNet, are of a broad variety. In the end, the variety depends on the concept list that is created. However, at the same time, the concepts need to be explicitly mentioned in the publications which are used to create the network to be linked in the network. If they are not explicitly mentioned in the set of publications, they will be unlinked and thus not part of the network. So the question is, what types of concepts are typically present in papers in the engineering and natural sciences? In this case, Boon's framework is used for a typology of concepts because the scientists will also use this framework for the analysis of disciplinary perspectives. Peer-reviewed papers in the natural and engineering sciences typically contain concepts directly related to the elements[16]:

- 1 Intrinsic aims and objectives e.g. 'chemical engineering', 'fluid mechanics'
- 2 & 9 Types of technologies e.g. 'photobioreactor', 'membranes', 'beam-splitter'
- 4 Phenomena e.g. 'photo respiration'
- 5 Assumptions e.g. 'conservation of mass and energy'
- 6 Mathematical frameworks and axiomatic systems e.g. 'thermodynamics'
- 7 Physio-chemical properties e.g. 'viscosity', 'hardness'
- 8 Measurement devices e.g. 'gas chromatography'
- 9 Methodological terms e.g. 'light-limited', 'plug flow reactor'
- 10 Epistemic and pragmatic criteria e.g. 'explanation', 'prediction', 'specificity', 'simplicity', 'applicability'
- 11 Representational means like certain types of simulations e.g. 'process simulation', 'ASPEN', 'SuperPro Designer', 'causal-mechanistic model'.

As such, peer-reviewed articles in the natural and engineering sciences contain a broad variety of concepts related to various elements of Boon's disciplinary framework i.e. the disciplinary perspective (Chapter 3). This means that entities in the network can be tagged as belonging to one of the elements of the framework. To be clear, it is not argued that Boon's framework is exhaustive, but that in the context of interdisciplinarity this classification helps enables the

[16] This statement is based on experience of the author i.e. reading dozens of papers from a natural and engineering science context. This means that no systematic literature review was conducted but this is not necessary to make the point. Anyone knowledgeable about natural and engineering sciences can acknowledge that such concepts are present. Moreover, other sources on semantic networks like Krenn and Zeilinger and Rzhetsky (Krenn & Zeilinger, 2020; Rzhetsky et al., 2015) mention these different types of concepts as well. The point here is that the framework can be used to tag the concepts in the network.

scientists to use the network to address cognitive hurdles. This method has its limitations since concepts directly related to element 3 *Research Questions Typical of Discipline* – are typically not present. Research questions are not captured in single concepts and are therefore not explicitly present in the network. However, the network indirectly reveals the typical research questions of a discipline. For example, it reveals the types of phenomena that are being researched and the mechanisms that are proposed i.e. in general 'What are the mechanisms for this phenomenon?'. As such, SemNets can provide insight into the relations between all elements of disciplinary perspective except three – typical research questions.

To facilitate understanding of these different concept types, an example from the context of bioprocess engineering is given below in Figure 2.

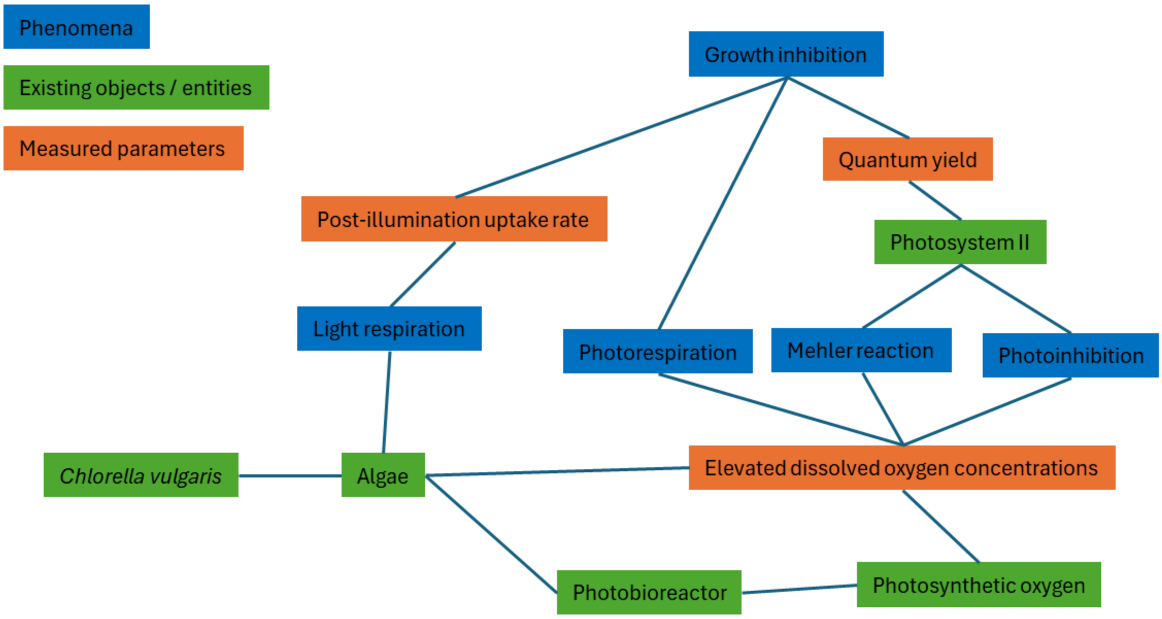


*Figure 2: Semantic Network in the context of bioprocess engineering – elevated dissolved oxygen concentrations and growth inhibition in algae. The different colour indicate the element of the disciplinary framework these concepts belong to. Created by the author himself.*

The example of a SemNet shown in Figure 2 shows the relationships between different concepts in the context of bioprocess engineering, specifically the relationship between elevated dissolved oxygen concentrations and observable phenomena growth inhibition in algae. In this example, the concepts have been divided into three categories: phenomena (in blue), existing objects/entities (in green) and measured parameters (in orange). As such, this SemNet contains several *types* of concepts e.g. experimental procedures and devices, measured parameters, and discipline-specific phenomena. This simple SemNet shows that these networks visualise knowledge in such a way that the *relatedness* of all elements of a disciplinary perspective becomes clear.

Two things are to be noted about this particular representation. First of all, in the semantic network that is used as an example here, the edges i.e. relations between the concepts, are not specified. In these networks, the relation is the 'co-appearance' of the concepts in a title or abstract. However, this does not yet specify the nature of the relationship. For example, an apple *is* a fruit, and gravity *causes* thing to fall down. Specifying relationships can done using 'relation extraction' NLP tools which range from rule-based to unsupervised approaches (Herman, 2019). Further specifying the nature of the relationship through relationship extraction adds further complication to the creation of semantic networks. Fortunately, relation extraction is not even necessary for these networks to be effective for their task envisioned here. If the entities in the network are assigned to a certain element (see start of this section) when making the concept lists, their relation is sufficiently specified. For example, in the case of a relation between a phenomenon and a measured parameter, it is clear that this measured value plays a role in the definition of this phenomenon, even to an outsider from another discipline. Therefore, relationship extraction is not even necessary for the purposes here.

The second thing to note, is that knowledge representation is not exhaustive. This means that the elements of Boon's framework are not fully captured by the concepts in the corpuses. Take for example element 10 *Epistemic and pragmatic criteria*. Although 'simplicity' might be an important value in both physics and chemical engineering, the notion of simplicity is still different. In the case of physics, it will be mathematically (or aesthetically) preferable for its own sake. In contrast, in chemical engineering, a mathematical model should remain tractable and mathematically solvable (Boon, 2017). This is a very important value in engineering sciences because they apply these models to understand and eventually design actual technical systems (Boon, 2008). So, although the same value plays a role and the same concept is used, semantic networks do not tell you everything about this element of the disciplinary perspective. In this sense, this representation is not exhaustive with regard to each element. However, despite this limitation, SemNets sufficiently capture the elements to highlight their relatedness and can, therefore, they can be applied to address cognitive hurdles to interdisciplinarity as is argued in the next section.

## 5.3 Semantic Networks and Overcoming Cognitive Hurdles

In the previous section, it was argued that SemNets can be used to visualise knowledge in such a way that the relatedness of the various elements of a disciplinary perspective is visualised. However, it is still unclear how this could help address hurdles to interdisciplinarity.

As was discussed in the earlier chapters on disciplinary perspectives, concepts that are used in particular (sub)disciplines are connected to all other elements of a disciplinary perspective. For example, the measured parameters in a scientific discipline determine what phenomena are part of the disciplinary perspective. In turn, these parameters need to be measurable and are thus connected to measurement devices. Similarly, the phenomena cannot be disconnected from the technological and methodological context e.g. experimental setups and technical devices (Boon, 2020b). This also means that these elements *together* form the disciplinary perspective and to understand the perspective means understanding all elements and how they form a coherent whole. If there is disagreement on one element of the perspective, for example, methodologies, these cannot be disconnected from the measured parameters, epistemic values, phenomena typically investigated in the discipline et cetera. Macleod refers to this as "the complex interdependencies between methods, technologies, epistemic values, stable lab environments, and cognitive structures on which functional scientific practice often depends." (MacLeod, 2018: p. 698). It are these 'interdependencies' that are visualised in a SemNet.

It is very time-consuming for a scientist to become knowledgeable about the other discipline through, for example, reading publications from that field. Often enough it already takes a lot of time to stay knowledgeable about the publications pertaining to their own specialisation. Here SemNets are a knowledge-tool helping scientists gain insight into the disciplinary perspective of the other scientists. Specifically, the interdependencies of different types of concepts in the disciplinary perspective, something which might otherwise be forgotten and, even if scientists are aware of it, would still require a lot of effort to 'see' how all these elements are related to one another. This means that SemNets can aid to address and overcome cognitive hurdles 1, 2 and 3 identified by MacLeod (2018) which were:

1. The opacity of domain-specific practices to outsiders
2. Large conceptual and methodological divides
3. Conflicts over epistemic values
4. Unstructured problem-solving environments

The argument here is that SemNets can aid scientists in philosophical reflection and the creation of an interdisciplinary perspective. Each of the hurdles will now be discussed to argue how semantic networks can aid scientists in addressing them.

### 5.3.1 Opacity of Domain-Specific Practices to Outsiders

The first hurdle is the opacity of domain-specific practices to outsiders which MacLeod defined as "the technical skills, understanding and experience required to operate within a domain can be opaque or intractable to non-specialists without adequate training" (2018: p. 707). Particularly in the understanding part can be addressed with SemNets because they provide insight into the coherence of a certain concept within the overall discipline. In this sense, SemNets give a birds-eye-view representation of a discipline. It is due to this birds-eye view that the SemNet is ideal to increase understanding of the practices in the other disciplines. In doing so it can, in part counter this first hurdle. Not because it can visualise particular concepts, but because it can show how concepts are embedded within the overall disciplinary perspective. Let's take the example of the system biologists who complained: "In the current circumstances a collaboration usually starts with a biologist approaching a modeling lab and asking BI have some data can you model it, without any real understanding of the data demands for dynamic models." (MacLeod & Nersessian, 2016: p. 408). A SemNet based on publications of systems biologists would help the molecular biologists to understand what the models that the systems biologists are making, are actually trying to achieve. Which phenomena are being modelled, which measured parameters are connected to this phenomenon, what type of model it is, and which type of data is required to build it and why? This birds-eye view of the disciplinary perspective of systems biologists would thus greatly increase the transparency of the practices in other domains. Of course, philosophical reflection and SemNets will not lead to practical skills, this is something that is only gained through actual practice. Nevertheless, SemNets can help address this hurdle by creating an understanding of the *why* and *how* of these practices.

### 5.3.2 Large Conceptual and Methodological Divides

This hurdle is divided into two parts: conceptual divides and methodological divides. First, the conceptual divides. Here, SemNets are compared to another procedure which has already been developed but not yet applied, namely *SenseDisclosure*. Specifically, this is a procedure to deal with 'problematically ambiguous terms' in cross-disciplinary contexts (Mennes, 2018; Mennes et al., 2019). What makes a term a 'problematically ambiguous term'? Well, "In order to be a problematically ambiguous term (henceforth 'PAT'), besides being ambiguous, a term should also play an important role, i.e. its interpretation should affect the course of action." (Mennes, 2018: p. 58). *SenseDisclosure* is a procedure to systematically discover *and* deal with these PATs.

This procedure was developed during a PhD project in which philosophy of science and computational linguistics were combined to facilitate cross-disciplinarity (Mennes, 2019). How does this procedure work? First, just like with SemNets, a corpus is compiled for both disciplines involved in cross-disciplinary collaboration. The second step is to collect terms from both corpora. In the third step, a shared jargon set is identified. Examples of shared terms that are ambiguous are 'matrix' and 'model'. In the fourth step, these shared terms are analysed with a language tool to automatically discover their meaning – this is the innovative part by Mennes. This meaning is constructed based on the context of the term i.e. the rest of the sentence. In doing so, the tool can then reveal the meaning of the concept. In step five, the human experts identify PATs based on the meanings discovered by the tool. In step six, a visual representation in the form of a world cloud is created for each PAT based on the neighbouring words in the sentences the term was used in. Specifically, this is a word cloud. Finally, in step seven, the collaborators decide how to deal with the PAT. It is then up to the collaborators themselves to resolve this difference in meaning. For example, they can adopt one of both meanings. Similarly, they can decide to give the word a new meaning. As such, PATs can be effectively discovered and addressed. This prevents PATs from hindering collaboration throughout the project (Mennes et al., 2019).

In terms of automatically discovering, *SenseDisclosure* is more suitable since in the case of SemNets scientists need to discover PATs themselves. Nevertheless, SemNets can help scientists deal with PATs as will become clear when discussing hurdle 3 of conflict over epistemic values.

Seondly, this hurdle is related to methodological divides. An example of a methodological divide is the fact that experiments or models are very different in terms of scale, hindering integration (MacLeod, 2018). Of course, SemNets will not make this problem disappear. However, they can help scientists make decisions *about* which methodologies to employ or help them find ways to integrate them. First of all, SemNets can help identify methodological divides already at the start of the project, for example, that experiments or models have a different scale, rest on different ontological assumptions or type of explanation. Once the scientists are familiar with 'disciplinary perspectives' they are also aware of their epistemological and metaphysical assumptions. As was shown in §5.2, the concepts in the SemNet can be classified according to the elements of the disciplinary perspective. Therefore, SemNets can aid scientists in discovering discrepancies between methodologies in this regard which can help them address these divides.

Secondly, and in conjunction, SemNets can aid in deciding which methodologies are necessary for the research problem because they help scientists understand the role that particular methodologies play in the other discipline (see hurdle one). If one understand the role that the methodology plays in the other discipline, decisions can be made *together*. This means that they will be able to decide beforehand which methodologies are best suited to understand or address the real-world problem they aim to address. If, for example, a particular methodology is related to a particular phenomenon and this phenomenon is key to understanding the real-world problem they are investigating, this methodology is necessary to be integrated into their overall approach. At the same time, other phenomena and their accompanying methodologies might not be necessary to understand the problem at hand. SemNets can help scientists make these decisions together because they enable scientists from one discipline to – at least generally – understand the role of this methodology in the other discipline. Thirdly, SemNets visualise to which phenomena, measured parameters, measurement devices and subject-matter methodologies are related. If scientists have an overview, it might help them find ways to integrate them. For example, they find out that certain parameters of phenomena are connected in ways they were not aware of because SemNets are based on an extensive literature corpus which the scientists cannot be fully knowledgeable about.

### 5.3.3 Conflict over Epistemic Values

The third value is the conflict over epistemic values. Take the example of the value 'simplicity' mentioned in the previous section. To reiterate, although 'simplicity' is an important value in both physics and chemical engineering, the definition is different. In the case of physics, it will be mathematically (or aesthetically) preferable for its own sake. In contrast, in chemical engineering, a mathematical model should remain tractable and mathematically solvable (Boon, 2017). This is a very important value in engineering sciences because they apply these models to understand and eventually design actual technical systems (Boon, 2008). This value can simply not be abandoned for these types of models and the SemNet draws attention to this pragmatic reason to adopt this value in the context of engineering science. As such, the definition of 'simplicity' is not something which can be changed because it is directly related to scientific practice. However, by just looking at the definition this might not be clear yet and the coherence with other elements of the disciplinary perspective is obscured in *Sensedisclosure* which focuses strictly on linguistics. SemNets can help address this problem which is likely hard to see if concepts are being discussed purely linguistically. In this case, a particular form of simplicity is valued by scientists, for a particular reason. SemNets visualise this and, in doing so, can help collaborators understand why certain values are so important and connected to other elements of the disciplinary perspective. Because of this, such a network can help them decide which definition of the value should adopted in light of the real-world problem under investigation.

This draws attention to the limitation of a purely linguistic approach as with *SenseDisclosure*. This procedure might be effective at discovering PATs but dealing with them is more difficult since concepts are not loosely floating around. Concepts are often intricately connected to practices, experimental and measurements devices et cetera. The procedure developed by Mennes foregoes the relatedness of concepts within the overall disciplinary perspective i.e. the methods, experimental setups, measured parameters, and observable and unobservable phenomena. Especially if collaborators want to resolve the PAT, they must have insight into the relatedness of this particular concept within the overall disciplinary perspective. Otherwise, they might adopt one definition of the concept which leads to further issues down the line as is the case for a value like 'simplicity'. Because the SemNet draws attention to experiments, measurement devices, experimental apparatuses and real-world phenomena, they draw attention to the real-world correlates of the concepts instead of just looking at their meaning disconnected from the real world. So, in contrast to *Sensedisclosure*, SemNets can provide insight into the coherence of a certain concept within the overall disciplinary perspective which can help scientists address PATs and thus conceptual divides.

### 5.3.4 Unstructured Problem-Solving Environments

The fourth hurdle is the unstructured problem-solving environments in interdisciplinary collaboration. As MacLeod puts it: “In principle any interdisciplinary project that tries to transplant domain-specific practices into a new domain these practices were not designed specifically for may put its researchers in the position of having to solve problems by inventing substantial new practices and methods on the spot for each individual problem.” (MacLeod, 2018: p. 716). As such, this hurdle has to do with a lack of established approaches and methods to go about addressing technical and research problems. The problem here is that scientists cannot simply approach their research the way they usually do. Here, philosophical reflection and SemNets only have a limited role to play. In a small number of cases, they might act as a source of inspiration by helping scientists discover a certain niche in the discipline where methods and approaches were combined to address a similar problem thus providing inspiration for structured approaches. Nevertheless, philosophical reflection and SemNets will not lead to structured problem-solving environments in and of themselves. These need to be actively developed and although developing an interdisciplinary perspective greatly increases the chance of success, it will still require effort by the collaborators. In that sense interdisciplinary collaboration will always remain intensive. As said, this is also an opportunity, to create novel methodologies, and integration of approaches which lead to a solution to the real-world problem (Eigenbrode et al., 2007). If successful it can even lead to novel (sub) disciplines.

The strength of this approach is that although ML is used to create the SemNet, this does not result in an opaque or black-boxed AI model. ML models are often ‘accused’ of being black-boxed, and rightly so. In short, this means that it is difficult or impossible for humans to track how the ML model arrives at its configuration. In practice, this means that it is unclear *how* exactly the ML arrives at its predictions (Babushkina & Votsis, 2022; Karaca, 2023; Sullivan, 2022). However, in the case of ML models for SemNets, it is perfectly clear what exactly constitutes the nodes in the network – these are the concepts from the concept list - and what determines the weight of the connections between the nodes in the network – this is directly dependant on the number of times the two concepts that are linked co-appear in the title or abstract of a paper. This means that, in principle, humans should arrive at exactly the same network if they have enough resources and time. However, the ML element means that humans do not have to do the practical work while being perfectly capable of understanding the model. Therefore, the model can be considered fully transparent which is an obvious advantage. Moreover, it needs to be transparent, otherwise the researcher could not learn from the model.

It is the very network itself that is created which is what is interesting for the interdisciplinary collaborators. This means that this type of ML model is not black-boxed i.e. it is tractable for human scientists. As such, it serves to make science less opaque instead of increasing opaqueness which could potentially become a hurdle in itself.

## 5.4 Summary

In Chapter 2, it was shown that a disciplinary perspective has many elements. In Chapter 3, it was shown that cognitive hurdles to interdisciplinarity are the result of different disciplinary perspectives. In Chapter 4, it was argued that philosophical reflection is important to develop an interdisciplinary perspective on real-world problems to overcome hurdles and work effectively. Like Chapter 4, this final chapter also addressed the third sub-question: 'How can disciplinary hurdles to interdisciplinary research be overcome?'. However, where Chapter 4 focussed on philosophical reflection, this chapter explored the potential of semantic networks in overcoming hurdles to interdisciplinarity.

The semantic networks, which are created through machine learning, offer a particular representation of knowledge within disciplines. It was shown that these semantic networks based on ML can help scientists gain insight into the disciplinary perspective of the scientists they are collaborating with, aiding in the creation of an interdisciplinary perspective. As such, semantic networks play a *limited, but meaningful* role in overcoming cognitive hurdles to interdisciplinarity. If combined with philosophical reflection they can aid scientists in addressing three out of four hurdles to interdisciplinarity identified by MacLeod (2018). Especially, the opacity of domain-specific practices to outsiders, large conceptual and methodological divides, and conflicts over epistemic values. In the case of the fourth hurdle identified by MacLeod – unstructured problem-solving environments – semantic networks might act as a source of inspiration but in general, this will always require substantial effort in interdisciplinary collaboration. As such, semantic networks will likely not be that helpful in addressing this hurdle. Finally, semantic networks have the added benefit that they are transparent and thus understandable by the human scientists making use of them. Therefore, they will not create further opaqueness which could be the case if they were black-boxed.

# 6 Limitations

In this thesis, it was argued that semantic networks have a meaningful role to play in addressing cognitive hurdles researchers face during interdisciplinary collaborations. It is particularly within the context of philosophical reflection that these can be effectively used to overcome cognitive hurdles to interdisciplinarity. However, the approach in this thesis has two limitations which need to be clear before discussing the conclusions and recommendations.

The first major limitation of this thesis is that semantic networks in themselves provide no guarantee that the opacity of domain-specific practices to outsiders, large conceptual and methodological divides, and conflicts over epistemic values will be overcome. In order for semantic networks to be effective in addressing cognitive hurdles, they should be combined with appropriate philosophical reflection. As such, adequate philosophical reflection is an important *condition* that needs to be met. However, this is something which scientists and engineers are generally not familiar with. This means that this approach is rather complex for the scientists involved and they might not immediately understand its relevance. Therefore, this approach rests quite heavily on the individuals – the scientists and the non-participants – guiding the scientists through the interdisciplinary workshop. As a result, its effectiveness quite uncertain beforehand since it requires an open mindset and good guidance. Nevertheless, if carried out successfully, semantic networks can contribute substantially to overcoming cognitive barriers.

The second limitation which needs to be mentioned is that the thesis is based on a single empirical case, the one with the systems and molecular biologists. As explained, this is due to the fact that there are no other systematic studies available. Additional empirical studies on cognitive hurdles between collaborating scientists could have provided a more thorough foundation that these problems occur more often in interdisciplinary collaborations in the natural and engineering sciences. Although this would have enriched the analysis, the case by MacLeod is sufficient to warrant the conclusions of the thesis since philosopher of science have run into similar problems in other projects although they did not report on these problems as systematically as MacLeod. Moreover, the fact that the *Toolbox Workshop* has been developed also shows that such problems are widely occurring and thus worthy of attention.

# 7 Conclusion and Recommendations

Since each chapter ended with a summary, these summaries will not be repeated here. Without further ado, the main conclusion of this thesis, as well as the recommendations based on the insights will be discussed. The major conclusion from this philosophical thesis is that semantic networks – if combined with philosophical reflection – can contribute substantially to overcoming cognitive hurdles to interdisciplinarity. Specifically, the hurdles of opacity of domain-specific practices to outsiders, large conceptual and methodological divides, conflicting epistemic values. Based on these insights, there are also a number of recommendations.

First of all, a more general recommendation. It is recommended that students in the natural and engineering sciences are educated in the philosophy of science, technology and culture. This is important for various reasons, but in general it will provide them with a sense of coherence of their discipline within science and ultimately society at large. This is important because technology affects society, and an engineer should be sensitive to this. As José Ortega y Gasset puts it: “To be an engineer and nothing but an engineer means to be potentially everything and actually nothing.” (Ortega y Gasset, 1961). To be a good scientist and engineer means to be aware that real-world problems are not adequately captured with a scientific-technological approach alone but have other relevant aspects as well. At the same time, some problems definitely require scientific-technological knowledge and skills to be solved, often from multiple disciplines. Here, philosophy of science can equip student with necessary basic knowledge and skills to deal with cognitive hurdles typically encountered in such collaborations. In short, by complementing their specialistic education with philosophy they can be specialists while at the same time being generalists.

Secondly, it would be beneficial for both science and the philosophy of science if philosophers of science start to actively collaborate with natural and engineering scientists in interdisciplinary research. As mentioned earlier, there are hardly any detailed accounts of the problems interdisciplinary researchers face. Such accounts can be expanded through collaborations where the philosophers of science are involved in the research. No just as observers, but also in an effort to apply existing frameworks and developing new ones to tackle hurdles to interdisciplinarity. It is here that philosophy of science can meaningfully impact scientific practices and deal. The philosophers can help scientists navigate the difficulties and philosophical problems that arise in their interdisciplinary practices. In doing so, philosophy of science can help scientists grow in wisdom. Vice versa, these interdisciplinary practices have the potential to bring up new ‘fundamental’ questions regarding the foundations of different scientific disciplines and their interaction. For example, the role that beliefs like realism play in hurdles to interdisciplinarity or the types of hurdles which are typical for certain interdisciplinary collaborations rather than others. This is especially important in a time of increasing specialisation on the one hand and the expectation of collaboration to address societal challenges on the other hand. In this sense, it is a call for scientists and philosophers to recognise and acknowledge their mutual dependency instead of living in supposedly isolated cultures.

Thirdly, it is recommended that philosophers of science engage with computer scientists to look for ways to effectively address hurdles which are then also tested in practice. Of course, this thesis already provides interesting insights and combines different philosophical accounts which is worthwhile in and of itself. These insights are the relationship between cognitive hurdles to interdisciplinarity and disciplinary perspectives and the role that semantic networks can play in overcoming these hurdles. This is relevant because AI applications for interdisciplinarity receive hardly any attention which is a missed opportunity. To address this deficit, this thesis prepares the way for the application semantic networks in interdisciplinary practices. However, if such applications are not developed and applied in actual research practices, this thesis will miss the desirable effect. Therefore, it is recommended that semantic networks should also be evaluated in practice to check whether they actually aid scientists in addressing cognitive hurdles. In doing so, philosophers of science, computer scientists, and natural and engineering scientists collaborate to develop *and* assess the effectiveness of these tools. This research can also shed light on the way the semantic networks can be tuned to address cognitive hurdles more effectively.

Moreover, the process of generating these networks for specific (sub)disciplines does not necessarily require a lot of effort if existing training data used to train other domain-specific AI tools like BioBERT, SciBERT and Med-PALM is used to generate semantic networks of various scientific disciplines. Of course, these domain-specific data can be updated with the most recent publications but still this would save a lot of time and effort and prevent people from unnecessarily collecting a discipline specific corpus while it already exists.

Additionally, there might be ways to enhance semantic networks to address hurdles. For example, through integration with other AI tools like the disambiguation tool. Moreover, it might be possible to build an AI tool that can systematically discover methodological divides between the disciplines, or conflicts over epistemic and pragmatic values. This would provide the scientists with a systematic way of discovering hurdles making the effectiveness of the approach less dependent on the human scientists which is one of the limitations of the current approach. Of course, the scientists will always remain responsible for the interdisciplinarity since science is a human activity. Nevertheless, the AI tool can be improved to further aid the scientists in overcoming hurdles to interdisciplinarity.

Finally, semantic networks can be used for more than overcoming cognitive hurdles, they might aid scientists in their interdisciplinary research. Semantic networks can be used to predict promising research directions for the interdisciplinary consortium, an option that was not explored in the thesis because the primary goal was to overcome cognitive hurdles. However, this is a promising venue to be explored. As discussed, semantic networks have been used to successfully predict promising research areas. This is based on the idea that concepts that are yet unlinked in the network, represent understudied research topics. The chance that scientists just wander through the literature to find relevant understudied research topics is becoming smaller and smaller as the amount of scientific literature in their fields continues to grow. As such, semantic networks can used to inspire combinations of ideas and technologies that others are unlikely to connect. This is especially promising in the context of interdisciplinarity where two (sub)disciplines are combined providing novel opportunities for research unforeseeable in a single discipline.

By combining the disciplinary corpuses of the respective disciplines, semantic networks can be used to predict research directions. For example, by highlighting concepts which are yet unlinked and are part of the expertise of the collaborating scientists. Of course, the problem here is that distinct disciplinary corpuses are combined. This method rests on the assumption that yet unlinked concepts, also present under researched areas of science. It has been shown that this approach is effective in disciplinary contexts. However, in the case of interdisciplinary research, multiple discipline-unique corpuses are combined meaning that this method might not be effective if applied straightforwardly. For example, does this method might lead to interesting insights which cannot be feasibly pursued by the scientists involved in the collaboration. To prevent this problem, it is worthwhile to research the unique problems that arise when predicting future research directions when combining multiple disciplines. Specifically, the question is whether combination of different corpuses can lead to good predictions for future research. This is worthwhile to investigate further.

# References


Aarts, D. (2024, June 20). Je krijgt betere wetenschap en oplossingen door interdisciplinair samen te werken. *Universiteit Leiden*. https://www.universiteitleiden.nl/nieuws/2024/06/je-krijgt-betere-wetenschap-en-oplossingen-door-trans--en-interdisciplinair-samen-te-werken

Babushkina, D., & Votsis, A. (2022). Epistemo-ethical constraints on AI-human decision making for diagnostic purposes. *Ethics and Information Technology*, *24*(2). https://doi.org/10.1007/s10676-022-09629-y

Basden, A., & Joneidy, S. (2019). Dooyeweerd's Understanding of Meaning (2): Some Implications. *Philosophia Reformata*, *84*(2), 141–170.

Benz, P., & Rossier, T. (2022). Is interdisciplinarity distinctive? Scientific collaborations through research projects in natural sciences. *Social Science Information*, *61*(1), 179–214. https://doi.org/10.1177/05390184221077787

Berman, G., Chubb, J., & Williams, K. (2023). *The Use of Artificial Intelligence in Science, Technology, Engineering, and Medicine*. https://www.ref.ac.uk/

Boon, M. (2008). Diagrammatic models in the engineering sciences. *Foundations of Science*, *13*(2), 127–142. https://doi.org/10.1007/s10699-008-9122-2

Boon, M. (2012). *Structureren en Interpreteren - Kennis Maken met Filosofie*. Universiteit Twente.

Boon, M. (2017). An engineering paradigm in the biomedical sciences: Knowledge as epistemic tool. In *Progress in Biophysics and Molecular Biology* (Vol. 129, pp. 25–39). Elsevier Ltd. https://doi.org/10.1016/j.pbiomolbio.2017.04.001

Boon, M. (2020a). *AI in society, and the issue of human dignity* (M. Boon, Ed.). https://research.utwente.nl/en/publications/ai-in-society-and-the-issue-of-human-dignity

Boon, M. (2020b). The role of disciplinary perspectives in an epistemology of scientific models. *European Journal for Philosophy of Science*, *10*(3). https://doi.org/10.1007/s13194-020-00295-9

Boon, M., & Knuuttila, T. (2009). Models as Epistemic Tools in Engineering Sciences: A pragmatic approach. In A. Meijers (Ed.), *Philosophy of Technology and Engineering Sciences* (Vol. 9, pp. 693–726). Elsevier. https://doi.org/10.1016/B978-0-444-51667-1.50030-6

Boon, M., & van Baalen, S. (2019). Epistemology for interdisciplinary research – shifting philosophical paradigms of science. *European Journal for Philosophy of Science*, *9*(1). https://doi.org/10.1007/s13194-018-0242-4

Brister, E. (2016). Disciplinary capture and epistemological obstacles to interdisciplinary research: Lessons from central African conservation disputes. *Studies in History and Philosophy of Science Part C :Studies in History and Philosophy of Biological and Biomedical Sciences*, *56*, 82–91. https://doi.org/10.1016/j.shpsc.2015.11.001

Chakravartty, A. (2017). Scientific Realism. In E. N. Zalta (Ed.), *Stanford Encyclopedia of Philosophy* (Summer 2017). https://plato.stanford.edu/entries/scientific-realism/#ThreDimeRealComm

Chang, H. (2012). *Is Water H2O? Evidence, Realism and Pluralism* (R. S. Cohen, J. Renn, & K. Gavroglu, Eds.). Springer. https://doi.org/10.1007/978-94-007-3932-1

Code, L. (1987). *Epistemic Responsibility*. University Press of New England.

Curd, M., & Cover, J. A. (1998). *Philosophy of Science: The Central Issues* (1st ed.). W.W. Norton & Company.

Daniel, K. L., McConnell, M., Schuchardt, A., & Peffer, M. E. (2022). Challenges facing interdisciplinary researchers: Findings from a professional development workshop. *PLoS ONE*, *17*(4 April). https://doi.org/10.1371/journal.pone.0267234

de Ridder, J. (2019). How many scientists does it take to have knowledge? In *What is Scientific Knowledge?: An Introduction to Contemporary Epistemology of Science* (pp. 3–17). Taylor and Francis. https://doi.org/10.4324/9780203703809-1

de Vries, M. J. (2005). *80 Years of Research at the Philips Natuurkundig Laboratorium 1914 - 1994*. Pallas Publications.

Doppelt, G. (1986). RELATIVISM AND THE RETICULATIONAL MODEL OF SCIENTIFIC RATIONALITY. *Synthese*, *69*(2), 225–252.

Eigenbrode, S. D., O’rourke, M., Wulfhorst, J. D., Althoff, D. M., Goldberg, C. S., Merrill, K., Morse, W., Nielsen-Pincus, M., Stephens, J., Winowiecki, L., & Bosque-Pérez, N. A. (2007). Employing Philosophical Dialogue in Collaborative Science. *BioScience*, *57*(1), 55–64. www.biosciencemag.org

Elgin, S. (2024). The Levels of Scientific Disciplines. *Topoi*. https://doi.org/10.1007/s11245-023-10007-6

Fagan, M. B. (2016). Stem cells and systems models: clashing views of explanation. *Synthese*, *193*(3), 873–907. https://doi.org/10.1007/s11229-015-0776-3

Foley, G. (2016). Reflections on interdisciplinarity and teaching chemical engineering on an interdisciplinary degree programme in biotechnology. *Education for Chemical Engineers*, *14*, 35–42. https://doi.org/10.1016/j.ece.2015.11.002

Godfrey-Smith, P. (2003). *Theory and Reality: An introduction to the philosophy of science*. The University of Chicago Press.

Grüne-Yanoff, T. (2016). Interdisciplinary success without integration. *European Journal for Philosophy of Science*, *6*(3), 343–360. https://doi.org/10.1007/s13194-016-0139-z

Heijnsdijk, J. (1970). *De interdisciplinaire benadering in wetenschapsbeoefening en wetenschapstoepassing*. Universitaire Pers Rotterdam Standaard Wetenschappelijke Uitgeverij.

Hempel, C. G., & Oppenheim, P. (1948). Studies in the Logic of Explanation. In *Philosophy of Science* (Vol. 15, Issue 2).

Herman, A. (2019, May 2). Different ways of doing Relation Extraction from text. *Medium*. https://medium.com/@andreasherman/different-ways-of-doing-relation-extraction-from-text-7362b4c3169e

Karaca, K. (2021). Values and inductive risk in machine learning modelling: the case of binary classification models. *European Journal for Philosophy of Science*, *11*(4). https://doi.org/10.1007/s13194-021-00405-1

Karaca, K. (2023). A Network Account of Models in High Energy Physics Experiments. *Philosophy of Science*, 1–31. https://doi.org/10.1017/psa.2023.73

Knutti, R. (2008). Should we believe model predictions of future climate change? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *366*(1885), 4647–4664. https://doi.org/10.1098/rsta.2008.0169

Krenn, M., & Zeilinger, A. (2020). Predicting research trends with semantic and neural networks with an application in quantum physics. *PNAS*, *117*(4), 1910–1916. https://doi.org/https://doi.org/10.1073/pnas.1914370116

Krishnan, A. (2009). *What are Academic Disciplines?* https://eprints.ncrm.ac.uk/id/eprint/783/1/what_are_academic_disciplines.pdf

Kuhn, T. S. (1977). *The Essential Tension: Selected Studies in Scientific Tradition and Change*. University of Chicago Press. https://doi.org/https://doi.org/10.7208/9780226217239

Kuhn, T. S. (1996). *The Structure of Scientific Revolutions* (3rd ed.). The University of Chicago Press.

Laudan, L. (1989). From Theories to Research traditions. *Readings in the Philosophy of Science*, 368–379.

Lehmann, F. (1992). SEMANTIC NETWORKS. *Computers Math. Applic.*, *23*(5), 1–50.

Looney, C., Donovan, S., O'Rourke, M., Crowley, S., Eigenbrode, S. D., Rotschy, L., Bosque-Pérez, N. A., & Wulfhorst, J. D. (2016). Seeing Through the Eyes of Collaborators: Using Toolbox Workshops to Enhance Cross-Disciplinary Communication. In *Enhancing Communication & Collaboration in Interdisciplinary Research* (pp. 220–243). SAGE Publications, Inc. https://doi.org/10.4135/9781483352947.n11

MacLeod, M. (2017). Scientific subordination, molecular biology, and systems biology. *Scientific Imperialism*, 186–204. https://doi.org/10.4324/9781315163673-10

MacLeod, M. (2018). What makes interdisciplinarity difficult? Some consequences of domain-specificity in interdisciplinary practice. *Synthese*, *195*(2), 697–720. https://doi.org/10.1007/s11229-016-1236-4

MacLeod, M., & Nersessian, N. J. (2016). Interdisciplinary problem- solving: emerging modes in integrative systems biology. *European Journal for Philosophy of Science*, *6*(3), 401–418. https://doi.org/10.1007/s13194-016-0157-x

Maglaughlin, K. L., & Sonnenwald, D. H. (2005). Factors that Impact Interdisciplinary Natural Science Research Collaboration in Academia. In P. Ingwersen & B. Larsen (Eds.), *dings of ISSI 2005 – The 10th International Conference of the International Society for Scientometrics and Informetrics* (pp. 499–508). Karolinska University Press.

Massimi, M. (2021). Realism, perspectivism, and disagreement in science. *Synthese*, *198*, 6115–6141. https://doi.org/10.1007/s11229-019-02500-6

Mazzocchi, F. (2019). Scientific research across and beyond disciplines. *EMBO Reports*, *20*(6). https://doi.org/10.15252/embr.201947682

Mennes, J. (2018). SenseDisclosure: A new procedure for dealing with problematically ambiguous terms in cross-disciplinary communication. *Language Sciences*, *69*, 57–67. https://doi.org/10.1016/j.langsci.2018.06.003

Mennes, J. (2019). *Facilitating Cross-Disciplinarity: Joining forces of philosophy of science and computational linguistics*. Universiteit Gent.

Mennes, J., Pedersen, T., & Lefever, E. (2019). Approaching terminological ambiguity in cross-disciplinary communication as a word sense induction task: a pilot study. *Language Resources and Evaluation*, *53*(4), 889–917. https://doi.org/10.1007/s10579-019-09455-7

Milojević, S. (2015). Quantifying the cognitive extent of science. *Journal of Informetrics*, *9*(4), 962–973. https://doi.org/10.1016/j.joi.2015.10.005

Ortega y Gasset, J. (1961). *History as a System and other essays toward a philosophy of history*.

Ortega y Gasset, J. (1971). *De Opstand der Horden* (J. Brouwer, Ed.; 14th ed.). Leopold N.V.

Polanyi, M. (1968). Life's Irreducible Structure. In *Source: Science, New Series* (Vol. 160, Issue 3834). http://www.jstor.orgURL:http://www.jstor.org/stable/1724152

Robbins, P. (2017). Modularity of Mind. In E. N. Zalta (Ed.), *Stanford Encyclopedia of Philosophy* (Winter 2017). https://plato.stanford.edu/entries/modularity-mind/

Rose, S., Engel, D., Cramer, N., & Cowley, W. (2010). Automatic Keyword Extraction from Individual Documents. In *Text Mining: Applications and Theory* (pp. 1–20). John Wiley and Sons. https://doi.org/10.1002/9780470689646.ch1

Rzhetsky, A., Foster, J. G., Foster, I. T., & Evans, J. A. (2015). Choosing experiments to accelerate collective discovery. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(47), 14569–14574. https://doi.org/10.1073/pnas.1509757112

Schnapp, L. M., Rotschy, L., Hall, T. E., Crowley, S., & O'Rourke, M. (2012). How to talk to strangers: Facilitating knowledge sharing within translational health teams with the Toolbox dialogue method. *Translational Behavioral Medicine*, *2*(4), 469–479. https://doi.org/10.1007/s13142-012-0171-2

Schuurman, E. (1972). *Techniek en Toekomst: Confrontatie met Wijsgerige Beschouwingen*. Van Gorcum & Comp. N.V.

Schuurman, E. (1980). *Techniek: middel of moloch? Een christelijk-wijsgerige benadering van de crisis in de technisch-wetenschappelijke cultuur*. J.H. Ko.

Schuurman, E. (1985). *Tussen technische overmacht en menselijke onmacht*. Uitgeversmaatschappij J. H. Kok.

Schuurman, E. (1990). *Filosofie van de technische wetenschappen*. Nijhoff.

Schuurman, E. (1997). Philosophical and Ethical Problems of Technicism and Genetic Engineering. *Society for Philosophy and Technology*, *3*, 27–44.

Science Guide. (2024, March 4). *'Interdisciplinair onderwijs populair, maar onderzoek ernaar staat nog in kinderschoenen.'* https://www.scienceguide.nl/2024/03/interdisciplinair-onderwijs-populair-maar-onderzoek-ernaar-staat-nog-in-kinderschoenen/

Society for Philosophy of Science in Practice. (2016). *Mission statement*. https://philosophy-science-practice.org/about/mission-statement

Sullivan, E. (2022). Understanding from machine learning models. *British Journal for the Philosophy of Science*, *73*(1), 109–133. https://doi.org/10.1093/bjps/axz035

The Royal Society. (2024). *Science in the age of AI: How artificial intelligence is changing the nature and method of scientific research*.

van Baalen, S., & Boon, M. (n.d.). *Understanding disciplinary perspectives: A framework to develop skills for interdisciplinary research collaborations of medical experts and engineers*.

van Riessen, H. (1949). *Filosofie en Techniek*. J. H. Kok N.V.

Vlot, A. (2002). *Tijd voor de eeuwigheid*. Uitgeverij de Vuurbaak.

# Appendices

## Appendix I: The Extended Disciplinary Matrix

*Table 2: The extended disciplinary matrix proposed by M. Boon (2017) p. 33 & 34. Taken with consent by M. Boon.*

This schema presents the proposed elements of the disciplinary matrix (first column), and their substantiation for the two paradigms of science, using biological and biomedical sciences as example.

| Elements constituting the paradigm | A. Physics paradigm (e.g. as reconstructed from Schrödinger) | B. Engineering paradigm (as reconstructed from current authors) |
|---|---|---|
| **I. Epistemic aim(s) of scientific research** | 1. *Discovery* of basic physical entities (basic 'building-blocks' of nature), fundamental principles and general laws that govern nature.<br>2. *Explanation and prediction* of observed phenomena in terms of theories (fundamental principles and general laws).<br>3. *Unification* of theories. | 1. *Construction of epistemic tools*: Knowledge production (e.g., concepts, laws and models) for practical uses, including epistemic uses that aim to discover *how* to generate and manipulate (biological or technological) functions for practical uses (e.g., as in medicine, agriculture and biotechnology).<br>2. *Explanation and prediction* of natural and technologically generated phenomena and functions in terms of concepts, laws and theories, thereby generating models that enable actual design, production and manipulation of these phenomena and functions.<br>3. *Interdisciplinarity* (rather than unification), which concerns the epistemic aim of generating scientific models in view of specific epistemic purposes (for practical uses). |
| **II. Epistemic values & criteria for the acceptance of knowledge** (Kuhn's third element) | 1. truth (and empirical adequacy)<br>2. simplicity in the sense of generality<br>3. universality,<br>4. explanatory & predictive power,<br>5. logical consistency,<br>6. coherency with accepted knowledge,<br>7. derivability of knowledge at higher levels from knowledge at lower levels,<br>8. testability. | 1. empirical adequacy, reliability and relevance in view of epistemic purposes (for practical uses),<br>2. simplicity in the sense of manageability & tractability,<br>3. balance between generality & specificity in view of epistemic aims,<br>4. explanatory & predictive reliability,<br>5. logical consistency,<br>6. coherence with accepted knowledge relevant to epistemic uses,<br>7. integration of knowledge from different fields and levels,<br>8. validation in view of epistemic uses. |
| **III. Basic and 'regulative' principles** (i.e., basic assumptions and rules guiding scientific research). | 1. *Unification*: 'aim at unity of knowledge.'<br>2. *Reductive explanation* i.e., 'aim at explanation of phenomena in terms of general laws and basic physical entities' (e.g., as in Human Genome project).<br>3. *Generalization* (inductive inference) based on reproducibility and the *ceteris paribus* principle, which involve, e.g., *testing* generalizability through reproducibility in a carefully controlled and stable (non-dynamic) environment (e.g., Robert, 2004).<br>4. *Invariance*: i.e., 'search for physical phenomena that are stable at a variety of relevant physical conditions' (also see Woodward, 2001). | 1. *Integrative pluralism & pragmatism* (e.g., Mitchell, 2009)<br>2. Construction of models for diverse epistemic purposes (e.g., explanation, prediction, building experimental models and computer simulations)<br>3. *Generalization* based on reproducibility and the regulative principle of *same conditions – same effects* (Boon, 2012b), which involves, e.g. testing generalizability of knowledge in relevant, new, physical conditions, thus taking into account un-foreseen interactions.<br>4. *Invariance* (next to reproducibility): 'search for physical phenomena that are stable at a variety of relevant physical conditions' (also see Woodward, 2001). |
| **IV. Theoretical principles of a discipline** (Kuhn's symbolic generalizations) | 1. Basic laws of a discipline, especially physics, such as Newton's laws of motion, Maxwell's laws of electricity and magnetism, the fundamental laws of thermodynamics, and the Schrödinger equation in quantum mechanics.<br>2. Laws such as $PV(T) = c(T)$; $V = I.R$. | 1. Basic laws are employed in model building (for specific types of target systems).<br>2. Phenomenological concepts and laws (derived from specific experimental set-ups, Feest, 2010; Boon, 2012a) are employed in model building.<br>3. Fundamental law-like presuppositions, such as, the conservation of mass, energy and atoms, or, as in thermodynamics 'heat cannot spontaneously flow from cold to hot,' are employed in (mathematical) model building.<br>4. Typical engineering principles in modelling a specific system in order to reduce complexity, for example, distinguishing between dynamic, semi-steady state and steady state within a certain 'time-window' (cf. Kremling and Saez-Rodriguez, 2007). |
| **V. Metaphysical pre-suppositions** (Kuhn's second element) | 1. The world has a simple, hierarchical structure and is well ordered.<br>2. The world consists of a hierarchy of basic entities and general laws at lower levels that 'govern' objects & phenomena at higher levels.<br>3. *Physicalism*: each particular physical system (including biological systems) is constituted by nothing but physical and chemical entities and their interactions | 1. The world has a complex, non-hierarchical structure: "large numbers of functionally diverse, and frequently multifunctional, sets of elements interact selectively and nonlinearly to produce coherent rather than complex behaviours" (Kitano, 2002a).<br>2. Physical phenomena are composed of physical and chemical entities and governed by laws of nature. However, phenomena do not exist nor emerge independently, but in an interaction with their environment.<br>3. Biological systems are governed by their physical structure as well as by their higher-order functions. |
| **VI. Ontology** (i.e., how the subject-matter of research is conceptualized) | 1. The physical world is conceptualized in term of objects, their properties and their causal workings.<br>2. *Ontological reductionism* (agrees with metaphysical presuppositions): Higher-level objects, their properties and their causal behaviour supervene on lower-level physical objects and properties (i.e., no difference in a biological property without a difference in some underlying physical property), and each particular biological process is metaphysically identical to some particular physico-chemical process (Brigandt and Love, 2015). | 1. In current systems biology and synthetic biology, *phenomena* (objects, properties, and processes) are usually conceptualized in terms of their function (see examples in Fig. 1).<br>2. Biological structures are seen through an engineering perspective, calling them complex 'biological *systems*,' which are conceptualized in terms of their function using engineering analogies (e.g., Fig. 1), such as 'mechanisms,' 'modules,' 'informational systems' (Ideker et al., 2001), 'modular circuits' (Kitano, 2002a), and different kinds of networks such as 'cybernetic networks' (Kauffman, 1971), 'gene/ |

(*continued*)

This schema presents the proposed elements of the disciplinary matrix (first column), and their substantiation for the two paradigms of science, using biological and biomedical sciences as example.

| Elements constituting the paradigm | A. Physics paradigm (e.g. as reconstructed from Schrödinger) | B. Engineering paradigm (as reconstructed from current authors) |
|---|---|---|
| | | metabolic/signal transduction networks' (Kitano, 2002b), 'molecular networks' (Boogerd et al., 2013), and 'biological networks' (Somvanshi and Venkatesh, 2014). |
| **VII. Subject-matter** (i.e., types of 'things' studied in scientific research) | 1. Biological phenomena in nature. Focus is on fundamental, 'causally explanatory' basic entities: (e.g., genes and their molecular structure),<br>2. Basic entities are considered as independently existing. They are studied in isolation, at controlled, static environmental conditions (Robert, 2004). | 1. Biological phenomena and systems, both in nature and those generated in (material) synthetic models. Focus is on different kinds of entities (e.g., basic genetic and non-genetic molecules, mechanisms, pathways, biological circuits and different kinds of networks).<br>2. Dynamics of biological phenomena and systems.<br>3. Biological functions and functioning.<br>4. Technological production and manipulation of (artificial) biological phenomena and functions by means of interlocking modelling techniques (using experimental, theoretical, mathematical and computer models, e.g. Nersessian, 2009). |
| **VIII. Epistemology** | 1. Scientific research aims at 'truth'.<br>2. Scientific research aims at theories and explanations. *Theoretical* and *explanatory reductionism* (Sarkar, 1991; also see Brigandt and Love, 2015): Strict laws (universal, exceptionless, spatio-temporally unrestricted) are required for explanation, and *why-necessary* explanations are better than *how-possible* explanations (Rosenberg, 2006). Higher-level theories must be reduced to – and deduced from lower-level theories, and explanations of higher-level phenomena are in terms of at lower levels.<br>3. *Hierarchy* of knowledge. Knowledge of basic constituents and their properties, which is a-temporal. Higher-level theories must be reduced to – and deduced from lower-level theories, and explanations of higher-level phenomena are in terms of lower-levels.<br>4. Theories and models aim to be '*true*' *representations* of the real world (e.g., as in Boogerd et al., 2013: "a successful causal model is a mechanism responsible for the systemic behaviour articulated in terms of 'real' processes and parts."). | 1. Scientific research aims at 'use': *How* and *How possible*<br>2. Scientific research aims at *epistemic tools*: Epistemic results (theories, models, laws, concepts) are epistemic tools constructed for epistemic uses such as construction of explanations and predictions, model-building (e.g., mechanistic, mathematical, experimental and synthetic models), creative thinking, problem-solving, computer simulations, and design of experimental equipment (Boon and Knuuttila, 2009; Knuuttila and Boon, 2011; Boon, 2012a; Green, 2013).<br>3. *Integration* of knowledge: Knowledge of dynamics, which involves spatial and temporal relations. This also allows for reductive causal explanations of lower-level phenomena in terms of higher-level properties (Hüttemann and Love, 2011). Furthermore, biological phenomena are conceptualized in terms of their structure and their function (cf. concept of dual nature, Kroes, 1998, 2010).<br>4. Scientific knowledge is not necessarily 'true' representations – it does not necessarily refer to real parts and processes. It could resemble a control diagram an engineer would draw to study general properties of feedback (e.g., Boogerd et al., 2013; also see Isaac, 2012). |
| **IX. Methodology** | 1. *Methodological reduction* is the idea that biological systems are most fruitfully investigated at the lowest possible level, and that experimental studies should be aimed at uncovering molecular and biochemical causes. A common example of this type of strategy is the decomposition of a complex system into parts (e.g. Bechtel and Richardson, 1993). | 1. *Methodological reduction* is a pragmatic strategy in which a phenomenon is studied at controlled conditions. Many other strategies are used to study the complexity of biological systems (MacLeod and Nersessian, 2013, 2015; also see Humphreys, 2004 on the use of mathematical templates). |
| **X. Exemplars of *science*** (rather than exemplars of *theories*, as in Kuhn's fourth element) | 1. Physics (Schrödinger, 1944).<br>2. Analytical and physical chemistry. | 1. Synthetic chemistry (e.g., Bensaude-Vincent, 2015).<br>2. Engineering sciences such as chemical engineering, mechanical engineering, electrical engineering, computer sciences, biotechnology, and nanotechnology. |
| **XI. Role attributed to experiments and technological instruments** | 1. Experiments to discover and test theories.<br>2. (Development of) instruments to generate novel phenomena, to study phenomena, and to measure phenomena of nature (Boon, 2004 calls these roles of instruments: *Manufacture, Model, Measure*). | 1. Experiments to test models and quantify specific parameters, but also to simulate and manipulate in order to generate or control (functional and artificial) phenomena.<br>2. (Development and understanding of) technological instruments that produce specific (artificial and functional) phenomena (Boon, 2017a). |
| **XII. Results/products of scientific research** | 1. *Epistemic*: Theories and laws.<br>2. *Physical*: Discovery of physical phenomena. | 1. *Epistemic*: data-sets, phenomenological laws, scientific concepts, mechanistic and mathematical models, as well as scientific models of (the workings of) technological instruments and experimental set-ups.<br>2. *Physical*: Physical phenomena that may be of functional interest.<br>3. Material: Technological instruments and experimental model-systems.<br>4. *Virtual*: Mathematical tools and models, and computer models. |
| **XIII. Justification** | 1. Aim is to *test* (confirm or falsify) a hypothesis,<br>2. basically, through the hypothetical-deductive method (as in Fig. 2), which tests predictions deduced from the hypothesis by means of experiments, often also using computer simulations. | 1. Aim is to *validate* epistemic results such as scientific models but also computer models (of complex multi-level systems), that is, to assess whether they meet the intended epistemic uses (also see Mitchell, 2009 and Section 4.3 above).<br>2. How to *validate* computer models for biomedical applications, for instance, is the topic of this special issue. Knuuttila and Boon (2011) argue that much of the justification of a scientific model takes place when building it (rather than by experimental tests only). |

## Appendix II: Disciplinary Perspectives and the Realism Debate

At this point, some philosophers of science might wonder whether this ‘perspectivism’ necessitates an anti-realist account of science. Moreover, most scientists themselves will intuitively tend to adhere to the realist side. Anti-realism is part of a debate central in the philosophy of science which concerns the question about the realness of theoretical postulates. The goal here is not to settle this debate or give an extensive overview of the different possible variations in realist and anti-realist views. The modest goal of this paragraph is to deal with the potential objection against perspectivism that would require an anti-realist view of science since the aim is to develop a theory which is neutral with regard to this debate[17].

Although there are different variations possible, the general claim of scientific realism is that “our best scientific theories give true or approximately true descriptions of observable and unobservable aspects of a mind-independent world.” (Chakravartty, 2017). Observable entities are those that can be observed directly by the senses i.e. chairs or fellow humans. Unobservable entities are those that are not directly visible via the senses like electrons or genes. To specify the definition further, scientific realism has three dimensions; metaphysical (or ontological), semantic and epistemological. First of all, scientific realism holds that we, humans, can know the world as it is i.e., we can know the things that exist in and of themselves. This is also referred to as mind independence because our knowledge of the things that exist is not determined by how our mind works, or the ideas we bring into scientific investigation. The semantic dimension is that scientific entities, both observable and unobservable, have truth value. In this case, scientific claims are interpreted literally. Finally, its epistemological dimension is that theoretical claims constitute knowledge of the world (Chakravartty, 2017).

Importantly, scientific realists do not claim that all current scientific theories are true since better theories might replace previous ones. However, they underscore that science is about getting to know what the world is truly like. As such, science aims at truth. One important consequence is that theories and models are perceived as direct representations of the target system. If correct, is difficult to understand how there can be significant differences among scientists (and paradigms in science). If science aims at truth, it seems unlikely that there can be two fields in biology with different epistemic standards or conflicting models and that *both have valid ways* of investigating reality. As such, the notion of disciplinary perspective seems to presuppose an anti-realist perspective on science. However, is this the case? To answer this question requires spelling out anti-realism.

[17] Although Boon holds an anti-realist view of science (see Boon, 2017, 2020b), the framework she developed can still be used to analyse any perspective in science regardless of one holds a realist or anti-realist account of science because it alludes to elements inherent (although often implicitly) to any specialistic science.

Scientific anti-realism entails that we, humans, cannot know the world as it is in itself, that is, our knowledge of the world is mind-dependant. Like with scientific realism, because there are different variations the discussion will be limited to Bas van Fraassen's (1941) views. His disagreement with the realist position is primarily related to its third, epistemological dimension. According to him, the goal of science is not truth, but empirical adequacy. This means that a distinction is made between observables, regarding which statements can have truth value, and unobservable, regarding which statements can only be empirically adequate. As such, empirical adequacy entails that what a theory postulates about observable entities, is true. On this view, theories, as far as they include unobservable, like Newton's law of gravity for example, are not considered a direct representation of how the world is. Instead, such a law is empirically adequate because its predictions coincide with observable phenomena.

This anti-realist position allows for various disciplinary perspectives to be valid even though they might disagree concerning unobservable entities. On the other hand, it is much more difficult to see how multiple disciplinary perspectives can be valid from a realist perspective. However, the notion of disciplinary perspective is also relevant and tenable from a realist perspective. As Massimi (2021) shows, scientific realism i.e. scientists agreeing *that* something is and *what* something is, does not rule out perspectivism. This means that scientists can reach epistemic agreement about *that* something exists and *what* it is while their scientific perspectives can be different. Here, 'scientific perspective' refers to the first and second-order levels mentioned before. At the first-order level lie the scientific knowledge claims, procedures, experiments, technological artefacts and such. At the second-order level are the justificatory, methodological-epistemic principles (Massimi, 2021).

For a realist like Massimi, both these levels are required to understand how knowledge comes about. Of course, the aim in the end is to get at the true knowledge claim. However, in the process of getting there might be what Massimi refers to as 'perspectival disagreement'. This entails that there might be disagreements among epistemic agents at the first or second-order levels. In the first case, there is disagreement about what counts as a reliable procedure whereas at the second-order level, the disagreement is about the justification of procedures to generate scientific knowledge claims (Massimi, 2021: p. 6123). Even though for realists, truth – i.e. providing a description of how things really are – is the primary aim of science, the historical fact that scientists can disagree on multiple levels of scientific practice means that perspectives must be taken seriously if the scientific practice is to be understood.

In short, the potential objection against perspectivism that is would require an anti-realist view of science is refuted. According to scientific realists, different scientists can rationally hold on to different scientific perspectives. As such, taking 'perspectivism' seriously does not require an anti-realist account of science. This does not mean that there are no forms of perspectivism which do presuppose an anti-realist view of science but discussing that is beyond the goal of this thesis.

## Appendix III: Realism as a Hurdle to Interdisciplinarity

Someone might object that all this talk about perspectives seems to suggest that anything goes, are there no more overarching principles to decide what makes science good science? As such this talk about perspectives might suggest a kind of relativism. If science aims at truth, how can conflicting representations of reality, as brought forth in different disciplinary perspectives, co-exist? Moreover, does anti-realism which no longer takes truth as the primary criteria not entail a loss of any overarching standards to assess the quality of science?

The acknowledgement of perspectives in science presupposes something which is perceived. If there are diverging disciplinary perspectives, it is that which is perceived that connects them. Of course, this must be something perceivable independent of the disciplinary perspective the scientist is engaged in. In Appendix II: Disciplinary Perspectives and the Realism Debate, it was argued that realists do not need to view scientists with different perspectives as irrational. As such the mere presence of multiple perspectives is not be problematic. However, when scientists with different perspectives engage in interdisciplinary, problems arise when (some of) these scientists hold realist accounts of science.

For a realist like Massimi, what connects perspectives are 'phenomena'. Disciplinary perspectives provide different perspective on these phenomena. An example of such a phenomenon is *electric charge*. According to her the scientists use "data to provide evidence for the phenomenon at stake within the technological, experimental, and theoretical resources available to each. Thus, the ensuing data-to-phenomena inferences are thoroughly perspectival." (Massimi, 2021: p. 6117). As pointed out before, realist also have a truth-stance towards unobservable phenomena. Thus, for a realist like Massimi, unobservable phenomena exist independently of the disciplinary perspective. This also means that disagreeing models or theories about the same unobservable phenomena must necessarily lead to metaphysical inconsistency for a realist. However, for an anti-realist, there is no such consequence, unless there is empirical disagreement e.g. disagreement with experimental data or observable facts. This means that scientists who, consciously or not, hold a realist view of science will have difficulty taking another disciplinary perspective seriously if there is disagreement with regard to unobservable phenomena between their perspectives. On the realist view, only some disciplinary perspectives can be considered 'truth-conducive' i.e. leading to a true description of reality (Massimi, 2021: p. 6121). This view thus hinders fruitful interdisciplinary research.

This constitutes a kind of pragmatic approach to adopt anti-realism in light of interdisciplinarity. However, there is also a more fundamental objection. For a realist like Massimi, unobservable phenomena exist independently of the disciplinary perspective. However, the question is whether this is really the case. In contrast to Massimi, Boon (2020b) points out that phenomena do not exist independently of the disciplinary perspective. In a sense, these phenomena are *created*. Take for example element IV which is about phenomena. This element includes measurement instruments, procedures that produce data and observable phenomena, experimental setups used to investigate the phenomenon (Boon, 2020b: p. 24). The point is that by virtue of these measurements instruments and experimental setups, certain phenomena are *created*. This does not mean that these phenomena are not real, but that the phenomena themselves are part of the disciplinary perspective. As such, unobservable phenomena might exist, but not independently of the disciplinary perspective they are conceived in.

This also explains why interdisciplinarity can be so difficult because phenomena cannot be straightforwardly incorporated in other disciplinary perspectives. However, if unobservable phenomena depend on disciplinary perspectives, what then connect different disciplinary perspectives? Here the anti-realist position would point to real-world problems. For example, certain illnesses, climate change, or the need for energy transition. More specific examples are genetic research to increase drought resistance of crops and research into functionalities of proteins for cultured meat. This is also in line with today's funding policies where even 'fundamental' research justified with reference to these societal problems. In general, science is expected to be useful for society (Boon & van Baalen, 2019). Similarly, the case of molecular and systems biologists, the goal was to understand the biochemical systems in order to control or even re-engineer them. Often, it are these kinds of problems which bring together multiple disciplines because the monodisciplinary approaches are insufficient to address these challenges. A good example are models to understand the effects of climate change. These require input from heterogeneous data sources and a range of disciplines and specialisations like physics, chemistry, biology, geosciences et cetera (Knutti, 2008).

Placing an emphasis on the importance of practical usability of scientific knowledge is what Boon (2017) refers to as the 'engineering paradigm'. It a certain view of science which reflects a significantly different understanding of scientific knowledge than realists which Boon (2017) refers to as the 'physics paradigm'. On the anti-realist view knowledge is viewed as an 'epistemic tool', this means that its usefulness to solve problems is an important value. On the realist view, knowledge is a direct representation of truth. As argued, this view can prevent fruitful interdisciplinary collaboration with other scientists. This anti-realist view of science does more justice to the actual practice of engineering scientists – in the sense explained in §2.1.1 – which always have to keep the practical context in mind.

Of course, critics might respond that engineering science is simply wrong and if primarily focussed on the empirical adequacy maybe even unscientific. However, such a response fails to acknowledge the point made. As pointed out, even realists like Massimi must acknowledge that different disciplinary perspectives are (or at least can be) rationally pursued. This also means that an anti-realist account of science does not result in an anything goes mentality, far from it. There are clear epistemic criteria that need to be met (see element X of the disciplinary perspective). Engineering scientists cannot just conjure up anything they like, things are thoroughly tested and validated. Often first on laboratory and then on pilot scale in the case of biochemical engineering. However, the fact of the matter is, there is no need to resort to truth or direct description of physical phenomena to responsibly use of this knowledge in the later development of technology by technologists. As is argued doing so even prevents understanding how different disciplinary perspectives might provide valuable knowledge for the problem at hand.

A similar critique is that, if the engineering sciences are so focussed on empirical adequacy, why are there theories involved in the first place, why not pursue purely empirical data in a Baconian fashion? Just gather empirical data and draw conclusions directly from the data. However, as Boon (2008) points out, the drawback of a purely empirical method, is that it lacks an underlying theory to connect different problems. As such, the knowledge is too specifically tailored to particular technological devices which prevents the unification of knowledge. This is not fruitful since it would require experimental apparatus to be built for every individual case. The theory that connects the cases will refer to underlying (invisible) phenomena e.g. the Newtons law of gravity. As such, unobservable phenomena a present and relevant to engineering science as well. This is why an engineering scientist must be knowledgeable about both fundamental and applied engineering science as was mentioned in chapter 2.