1 Introduction

The title of this Element is likely to induce two common reactions. One is immediate scepticism, largely because the notion of the unity of science is often associated with reductionism, and nowadays (almost) no one likes reductionism. The other is one of historical interest, as for many, the idea of the unity of science brings to mind logical empiricism/positivism and perhaps the grandiose goal of completed science. But it is the *dis*unity of science that many authors are now interested in – pluralism is driving the contemporary philosophy of science. While this Element will touch on all these themes, its main target is elsewhere. The present author conceives of 'unity of science' as an *ontological* ideal – the thought that there is something that connects the various entities in reality, for instance, by way of one thing being composed of various other things. We can then ask a further question, for example, about whether the composed entities are reducible to their components or not. This way of thinking about unity of science clearly connects it with metaphysical themes about the structure of reality.

The concept of unity of science as an ontological ideal may be contrasted with unity of science as an *epistemic* ideal, focusing on the connections between the explanations and predicates of the scientific disciplines and scientific practice. This conception is at least partly motivated by the prospect of interdisciplinary research, for we do need to explain why it is useful to work across disciplinary boundaries. According to this line of thought, unity of science may have pragmatic or instrumental value, quite independently of reductionism. This reaction takes it that while the old reductionist connotations should be abandoned and pluralism is indeed thriving, there is nevertheless still something of value in the ideal of the unity of science.

This Element will start, in Section 2, by laying out a brief history of the unity of science and outlining the main reasons for the shift from unity to disunity and pluralism. Section 3 discusses the state-of-the-art regarding the unity of science, which is often driven by the epistemic/pragmatic model of unity. Two case studies will also be discussed, one from the biology-chemistry interface and one from the chemistry-physics interface. In Section 4, I will put forward my own conception of unity, following the ontological model.

We may ask: if the sciences are indeed disunified, then why is it possible to examine some higher-level phenomenon in terms of lower-level phenomena? Typically, the answer will have something to do with reduction – for example, we can explain some higher-level goings-on in terms of the behaviour of their *parts*. But what kind of reduction is this? Does it mean that there really is nothing going on at the higher level? Or does it merely mean that higher-level entities depend upon their parts? These are questions that will have an important bearing on unity of science.

A central claim of this Element is that there can be unity without *eliminative* reduction. In other words, even if we can give an ontological basis for the higher-level goings-on, say, in terms of their parts, this does not mean that we have to abandon the higher-level terminology – this is a form of *semantic anti-reductionism*. This still leaves open the question of the ontological basis of unity. My preferred answer to this question, to be developed primarily in Section 4, is that there is a singular ontological basis for unity in terms of *natural kinds*, which are ultimately what all the sciences are concerned with. The resulting view may be called *natural kind monism*: there is a single notion of 'natural kind' and anything falling under that notion can be defined in terms of the same general set of identity-criteria.[1] Natural kind monism may seem like a very controversial view, especially in the light of recent pluralistic accounts of kinds. The view concerns only the fundamental notion of 'natural kind', though: we need to postulate just one *fundamental* ontological category to account for natural kinds. This still allows us to accommodate plurality among higher-level kinds.

2 A Historical Overview of Unity

The notion of the unity of science is regularly connected to the notion of *reduction*. The initial thought is that the sciences can be unified into a theory of everything and that the theories within a single science, such as general relativity and quantum theory in physics, can also be unified. The goal would then be to ultimately reduce all higher-level phenomena to fundamental physics. According to this line of thought, unity of science just means that fundamental physics is what everything else is ultimately based on; the higher-level sciences are somehow *derivative*. The non-fundamental, higher-level sciences are typically called *special sciences*.

One way of understanding unity of science is in terms of the unity of the *entities* studied by the various sciences. The immediate challenge to this type of idea is the apparent plurality of higher-level entities such as molecules, biological organisms, and psychological states. How could such entities be accounted for solely in terms of entities studied in physics, such as fermions, bosons, and fields? This is where the notions of reduction and *bridge laws* come in, as the various levels of scientific discourse need to be somehow connected and one way to understand this connection is in terms of laws that 'bridge' the levels. A typical understanding of reduction is identity based.

[1] What is a criterion of identity? This question cannot be fully settled here, but in my view, the answer will involve giving an account of *sortal* terms such as 'cat' or 'mountain' (see Lowe 1989). So, in the present context, the thought is that natural kinds understood in the most general fashion will fall under a singular sortal term because they share their general identity criteria.

According to strict *reductionism*, phenomena in the higher-level special sciences are *identical* to some complex lower-level (physical) phenomena. This is an understanding of reduction as identity, which is what makes it ‘strict’. Another traditional way of putting this is to say that the higher-level phenomena are nothing over and above the lower-level phenomena. In contrast, weaker forms of reductionism postulate relations that are weaker than identity to explain the connections between the sciences.

The origin of the reductionist conception of unity of science can be traced to the 1920s and 1930s, when the members of the Vienna Circle began writing about reduction. Rudolf Carnap paved the way for a new form of strong reduction, while Carl Hempel developed the deductive-nomological model of explanation. In addition, Otto Neurath pursued a somewhat more pragmatic approach to unity. Some of these different strands may be seen as culminating in Ernest Nagel’s work on reduction (see Nagel 1961 for his most influential contribution).[2] Much that followed was, in fact, direct commentary on *Nagelian reduction*, which emphasized the (logical) derivability of one theory from another, with the help of bridge laws (see van Riel 2011). This line of thought was further developed and systematised in a famous article by Oppenheim and Putnam (1958). But it was soon discovered that the logical empiricist approach was overly ambitious, and the extreme reductionist picture fell out of fashion. By the 1970s, Jerry Fodor (1974) countered the ideal of the unity of science with his own: the *disunity of science*. This has become a new normal: almost no one now believes that we can unify the sciences in the manner suggested by the strong reductionists. But to see why this is the case, it is worthwhile to briefly examine the idea of Nagelian reduction and the work by Oppenheim and Putnam that followed. This will be covered in Sections 2.1 and 2.2, before moving on to Fodor’s reaction and the debate with Jaegwon Kim that followed, in Sections 2.3 and 2.4. The phenomenon of *multiple realisability* has a key role in this debate, and the line of thought is finalised in Section 2.5 with a discussion of Louise Antony’s analysis.

Before we get started, a simple figure showing the varieties of unity (Figure 1) might be helpful. This is by no means the only way to distinguish different approaches to unity, and it should be noted that there are further distinctions to be made in the various subcategories. Simplified as it is, Figure 1 may give us a useful starting point. I will not provide detailed definitions of these varieties yet, as some historical context will be needed to

[2] See Cat (2017) for a more comprehensive discussion of the history of the unity of science, which does, of course, go back much further than the Vienna Circle. On Nagel’s view, see, for example, Needham (2010) and van Riel (2011), and on Neurath’s influence, see the articles in Symons, Pombo, and Torres (2011).

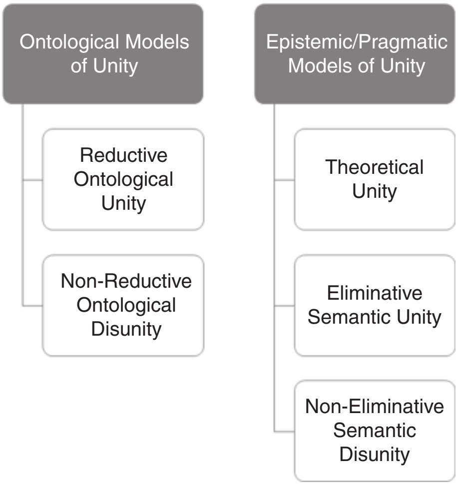

Figure 1 Varieties of unity and disunity (author's own work)

make sense of them. Accordingly, the following definitions should also be taken as tentative rather than final. Note also that the various versions of unity on the left-hand side and right-hand side are not necessarily mutually exclusive and indeed sometimes they are explicitly combined in various ways. Finally, while I have labelled two of the options as 'disunity', this does not mean that there could be no sense of unity involved – disunity merely entails a type of pluralism. The reader is invited to refer back to Figure 1 as needed.

Ontological models of unity, as the name suggests, concern the ontological structure of reality. They are intended to be objective models about how reality is structured, whether levelled or not.

Reductive ontological unity suggests that all entities reduce to some base class of entities, typically, those of fundamental physics.

Non-reductive ontological disunity suggests that reality may be structured into non-reductive levels that are connected, for instance, by compositional relations, where the composed entities are a genuine addition to reality.

Epistemic/pragmatic models of unity concern the structure of scientific theories and are hence guided by epistemic, explanatory, or pragmatic considerations relating to scientific practice.

Theoretical unity (or *unity of formalism*) suggests that a certain set of distinct phenomena may be (approximately) described in terms of a unified formal (mathematical) framework.

Eliminative semantic unity suggests that all predicates of higher-level sciences are identical to predicates of (fundamental) physics; hence all higher-level explanations are, in principle, replaceable by lower-level (physical) explanations.

Non-eliminative semantic disunity suggests that higher-level or special science predicates cannot be identified with predicates of physics (traditionally because of arguments from multiple realisation); hence higher-level explanations cannot be dispensed with and a type of pluralism is allowed. However, this view is typically combined with the idea that all higher-level predicates refer to entities that can be understood as being linked to lower-level entities (e.g., by using compositional or mechanistic explanations). This type of combination of *non-eliminative semantic disunity* and *non-reductive ontological disunity* is often called *non-reductive physicalism*.

2.1 From Logical Empiricism to Nagelian Reduction

Unity of science was a driving ideal in the logical empiricist tradition. It was closely tied to reductionism and an anti-metaphysical attitude, so the relevant sense of unity was primarily following the epistemic/pragmatic model of unity with a semantic focus on the language of science, but it may be considered to have had an implicit ontological element as well. The resulting picture is a combination of eliminative semantic unity and reductive ontological unity. We can see all these elements in Carnap's (e.g., 1928, 1934) work, and indeed in his formulation of unity in the book entitled *The Unity of Science*: 'all empirical statements can be expressed in a single language, all states of affairs are of one kind and are known by the same method' (Carnap 1934: 32).

While this formulation focuses on semantic and epistemic unity, it certainly suggests an ontological commitment to states of affairs of just one kind as well. However, I will omit an analysis of Carnap's metaphilosophical position (for a related discussion, see Tahko 2015a). The important feature here is the apparently anti-metaphysical background, which meant that unity of science was conceived as an epistemological and methodological project attempting to establish that all higher-level, special science statements, predicates, and explanations are reducible into those of physics. The implicit ontological import would then be that all *entities* also reduce to those of physics. These ideas were clearly present in Carnap's work. But instead of focusing on the well-reached history of the logical empiricist position and details of the work of its main architects, such as Carnap, we can directly jump to two of the core elements regarding the development of the logical empiricist tradition towards a systematic model of reduction and unity.

These two core elements are Hempel's (1942; Hempel and Oppenheim 1948; Hempel 1965) deductive-nomological (DN) model of explanation and Nagel's (1961) account of reduction. Both of these elements focus on explanatory connections. In brief, the DN model involves an *explanandum*, a sentence that describes the phenomenon we wish to explain, and an *explanans*, which is a class of sentences providing the explanation for the phenomenon. The deductive part of the model concerns the requirement that the explanandum must follow from the explanans by logical consequence. The nomological (i.e., 'law-like') part refers to the requirement that the explanans must contain at least one law of nature, and without it the deductive inference would not be valid. For example, take the universal generalisation that 'all gases expand when heated under constant pressure' (Hempel 1965: 338), which may be regarded as a law. According to the DN model, we can use this law and the fact that a given sample of gas has been heated under constant pressure to explain why the sample of gas has expanded.

Now let us connect the DN model with Nagelian reduction. Here is a representative passage from Nagel himself: 'A reduction is effected when the experimental laws of the secondary science. . .are shown to be the logical consequences of the theoretical assumptions (inclusive of the coordinating definitions) of the primary science' (Nagel 1961: 352). The basic form of a Nagelian reduction suggests that theory A reduces to theory B if and only if A is derivable from B with the help of any necessary 'coordinating definitions', which are more commonly known as *bridge laws* or bridge principles; these bridge laws can take the form of logical connections, conventions, or empirical hypotheses (1961: 354). It is not difficult to see that the DN model and Nagelian reduction are closely connected. In effect, the Nagelian model suggests that the reducing theory explains the reduced theory (with the help of bridge laws).

The DN model and Nagelian reduction dominated the philosophy of science for a time, but they did also come under heavy criticism (see, e.g., van Riel 2014). We will not need to provide these details here, but it is important that we understand the sense of unity that emerges from this background: the upshot is that all higher-level science explanations ultimately collapse into those of physics. But while the DN model and Nagelian reduction both operate at the epistemic level of explanation, there does seem to be an implicit ontological commitment to the idea that all entities reduce to (fundamental) physical entities. However, the difference between these two aspects needs to be clarified. In Oppenheim and Putnam (1958), which is the subject of the next section, we can find a clearer statement of the ontological view.

2.2 Oppenheim and Putnam on the Unity of Science

Oppenheim and Putnam (1958) distinguish three different unity theses:

- Unity of language (epistemological reduction)
- Unity of laws (implies the unity of language)
- Unity of science (in the strongest sense, implies unity of laws and unity within a science)

Unity of language is described as the idea that all *terms of science* are reduced to one discipline, such as physics, whereby 'reduction' would most plausibly be understood definitionally. This would result in a type of *epistemological reduction*, where all the claims of the special sciences could, at least in principle, be translated into claims of some more fundamental science. It is worth taking a moment to pause and think what this would mean, if true. It would mean that the vocabulary used in the special sciences – terms such as *covalent bond*, *cell wall*, *neuron*, *memory*, and so on, could ultimately be replaced by ones of a unified science. The idea could be understood as semantically *eliminative*, in that all this higher-order vocabulary could be eliminated in favour of the language of, say, fundamental physics. But even if we *could* eliminate all higher-level language, it is a rather radical claim to say that we *would* do so. There are individual cases where this has happened, though. To provide just one example, the now thoroughly abandoned idea of *vitalism* suggested that there is something fundamentally different about living organisms – namely, they are non-mechanical, containing an 'élan vital' or vital force that gives life to inanimate material bodies. The theory of vitalism involved a sophisticated theory, but the notions employed by that theory, such as that of a vital force, have been completely eliminated by contemporary science. By the late nineteenth century, the experimental progress of developmental biology and emerging modern biochemistry, combined with the lack of any experimental support for vitalism, made it clear that vitalism has no future (see Gatherer 2010 for a short history of vitalism). However, it should be noted that a plausible understanding of the unity of language should not entail full elimination of all higher-order vocabulary. Even if it were possible in principle to eliminate such vocabulary, it would surely be difficult – for instance, we do still talk about 'life' in a rather abstract fashion. Hence, there is room for non-eliminative semantic disunity.

Unity of laws, as defined by Oppenheim and Putnam, is a stronger thesis than unity of language. The thought is that all the scientific laws could be reduced to the laws of one unified science. On the face of it, unity of laws seems to be a more interesting thesis, as it does not focus on the individual terms used in science (albeit Oppenheim and Putnam do take it to imply unity of language). The precise meaning of 'reduction' is left open by Oppenheim and Putnam and I will do the same for the time being, but it appears that here we are moving towards an ontological model of unity. I will shortly discuss an example, but it may be helpful to do so in the context of the strongest sense of unity of science that Oppenheim and Putnam entertain, as it explicitly mentions also the connections within a discipline: 'Unity of Science in the strongest sense is realized if the laws of science are not only reduced to the laws of some one discipline, but the laws of that discipline are in some intuitive sense "unified" or "connected"' (Oppenheim and Putnam 1958: 4).

They specify immediately that the required 'connection' between the laws should be something stronger than the mere conjunction of these laws. What might qualify as this type of unification? A plausible candidate is provided by *electroweak unification* – the successful effort to unify two of the fundamental forces (and hence the laws concerning them), the *weak force* and the *electromagnetic force*. In fact, the electromagnetic force itself already unifies two apparently distinct forces – namely, the electric force between charges which is governed by *Coulomb's law* and the magnetic force. The *Lorentz force law* summarises both of these forces.

The unification of the weak and electromagnetic interaction is rather more complicated, as it involves further exchange particles, namely the W and Z bosons that are involved in weak interaction. Indeed, it was the prediction and discovery of the W and Z particles and the resulting unification of the weak and electromagnetic interaction that led to the 1979 Nobel Prize in physics being awarded to Weinberg, Salam, and Glashow. The press release announcing the award serves to highlight just how deeply ingrained the search for unity in science is:

> Physics, like other sciences, aspires to find common causes for apparently unrelated natural or experimental observations. A classical example is the force of gravitation introduced by Newton to explain such disparate phenomena as the apple falling to the ground and the moon moving around the earth.
>
> Another example occurred in the 19th century when it was realized, mainly through the work of Oersted in Denmark and Faraday in England, that electricity and magnetism are closely related, and are really different aspects of the electromagnetic force or interaction between charges. The final synthesis was presented in the 1860's by Maxwell in England. His work predicted the existence of electromagnetic waves and interpreted light as an electromagnetic wave phenomenon. . . .
>
> An important consequence of the theory is that the weak interaction is carried by particles having some properties in common – with the photon, which carries the electromagnetic interaction between charged particles.

> These so-called weak vector bosons differ from the massless photon primarily by having a large mass; this corresponds to the short range of the weak interaction.[3]

As the press release makes clear, a key part of the unification of the weak and electromagnetic forces are the shared properties of the exchange particles. The next step is to explain the primary difference, which has to do with mass. The story continues with *electroweak symmetry breaking*, and the more recent discovery of the *Higgs boson*, but we need not enter these complications. What should already be clear is that the search for unity is one of the key values of scientific inquiry, and indeed of the Nobel Committee, and there are many celebrated examples of this in the history of science. No wonder, then, that Oppenheim and Putnam attempted to systematise this idea.

We have so far omitted one important detail: when we speak of unification in science or discuss cases such as the unification of the weak and electromagnetic forces, it is not obvious that we are talking about 'unity' in the same sense that Oppenheim and Putnam or contemporary philosophers always intend. There is clearly something in common with these cases, which is why I have used electroweak unification as an example of how the laws of physics might be 'connected' in the sense that Oppenheim and Putnam require. But we should keep in mind the distinction between ontological models of unity and epistemic/pragmatic models of unity. In particular, the case I have just described could be understood in the sense of theoretical unity (or unity of formalism), so we should consider this form of unity in more detail.

The idea behind theoretical unity is simply that we may discover a formal (mathematical) framework, which manages to approximately model a certain set of distinct phenomena. For a given purpose, it may be sufficient to use a simple unified formalism. To continue our previous example, consider the role of the electromagnetic force in holding together atoms and molecules. The electromagnetic force is by far the most significant force in determining atomic and molecular structure. It has an infinite range, just like gravity, but given the extremely small masses of particles in the atomic scale, gravity is negligible. The strong force, by contrast, is very strong indeed, but its range is very short – it holds the nucleus together. The weak force has an even shorter range, 0.1% of the diameter of a proton. If we are interested in the molecular range, it is really just the electromagnetic force that matters. So, for most calculations that we might wish to make concerning the molecular scale, it is entirely unnecessary to consider gravity, *even though* gravity is in effect at all scales. Thus theoretical

[3] Press release, NobelPrize.org, accessed 27 June 2019. www.nobelprize.org/prizes/physics/1979/press-release.

unity has an element of interest relativeness, which is useful and even necessary for science, but it is not the type of ontological unity that some philosophers may be interested in.[4]

In contrast, ontological models of unity concern the structure of reality rather than the structure of theories. Yet, so far, we have not specified a properly *ontological* as opposed to *epistemological* sense of reduction that might underlie such unity. Let us turn back to Oppenheim and Putnam, who also state that they wish to set aside epistemological versions of the unity thesis (cf. Oppenheim and Putnam 1958: 5). Relying on previous work by Kemeny and Oppenheim (1956), they take reduction to be a relation between *theories*. This may not quite capture the sense of ontological unity that I have just been alluding to, but we should not be misled by this, for Oppenheim and Putnam do specify that a key part of reduction is that a set of observational data *explainable* by one theory is explainable by the reducing theory. This explanatory connection, we may assume, is supposed to track the ontological relation between the phenomena that the theories describe. What is that relation? Oppenheim and Putnam call it *micro-reduction*. As they specify, this relation concerns the *objects* or entities that theories deal with, so it is ontological rather than epistemological in the intended sense.

The idea of micro-reduction is something that survives in contemporary philosophy (under different labels), so it is useful to consider it in some detail (cf. *microstructural essentialism*, which we will return to later; see also Tahko 2015b). Micro-reduction is transitive, irreflexive, and asymmetric. As Putnam and Oppenheim (1958: 7) observe, the transitivity of the relation is of particular importance since it establishes a hierarchy of *reductive levels*. The thought is that there must be more than one such level (rather than a ‘flat’ one-level reality), there is a unique lowest level (such as fundamental physics), and a common denominator for each level (any thing on one level, except for the fundamental one, must be composed of parts on the level immediately below it). In practice, this means that if psychology reduces to neuroscience and neuroscience to biochemistry, then in virtue of transitivity, psychology will also reduce to biochemistry. This strict hierarchical structure may seem controversial because sometimes it does seem that we have to consider two levels at more extreme ends. For instance, the field of *quantum biology* applies results from

[4] Indeed, it is ontological unity that I am most interested in, instead of theoretical unity, which is primarily epistemic. For a thorough discussion of theoretical unity (in physics), see Morrison (2000). It is worth keeping this distinction in mind, because the pursuit of theoretical unity has such an important role in science. It may often also point to ontological unity, but it does not entail it. Note also that one may of course be interested in *both* theoretical and ontological unity, as many philosophers of science surely are.