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Critical Notice

MARGARET MORRISON, *Unifying Scientific Theories: Physical Concepts and Mathematical Structures*. Cambridge: Cambridge University Press 2000. Pp. viii + 272.

I Introduction

A central theme of Johannes Kepler's *Mysterium Cosmographicum* is that we gain knowledge and understanding of the celestial world when we have a unified account of it, for only a unified account reflects nature's ultimate simplicity. Kepler was not the first scientist to posit a connection between theory unification, understanding and truth, and he was certainly not the last. Kepler's theme is echoed, for example, in the Nobel addresses of the winners of the 1979 Nobel prize for Physics. All three winners emphasize how their achievement, the Standard Model in high-energy physics, brought about a unification of physical theory at a fundamental level, a unification that has been 'from time immemorial' a central goal of scientific understanding.[1] Although there is broad agreement that theory unification in science is a good thing, scientists are far from clear about just what theory unification consists in and why it should be an epistemic virtue. What does it mean to say that a theory is unified? How, if at all, do unified theories give us deeper under-

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[1] Abdus Salam, 'Gauge Unification of Fundamental Forces,' *Reviews of Modern Physics* **52** (1980) 525-38, at 526; cf. Sheldon Glashow, 'Towards a Unified Theory: Threads in a Tapestry,' *Reviews of Modern Physics* **52** (1980) 539-43; and Steven Weinberg, 'Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Interactions,' *Reviews of Modern Physics* **52** (1980) 512-23

standing of the natural world? Why should we believe that nature is ultimately simple and that unified theories are more likely to be true?

Philosophers of science have long been concerned with these questions. In the 1980s, influential work by Clark Glymour, Michael Friedman, John Watkins, and Philip Kitcher[2] articulated general accounts of theory unification that attempted to underwrite a connection between unification, truth, and understanding. According to the 'unifiers,' as we may call them, a theory is unified to the extent that it has a small theoretical structure relative to the domain of phenomena it covers, and there are general syntactic criteria that allow one to determine how unified a theory is. The explanatory power of a theory, and the understanding of nature it gives us, is a direct consequence of this unity. As well, the more unified a theory is, the better confirmed it will be (other things being equal), and under some conditions a theory's unity can justify realism about unobservable entities posited by it. In the 1990s disunity became the dominant theme, with books such as John Dupré's *The Disorder of Things*[3] and the Galison and Stump anthology[4] arguing that it is a mistake to view science as a unified practice and that rather than an epistemic virtue, unification in science is a metaphysical (perhaps even political) vice.

A great virtue of Margaret Morrison's *Unifying Scientific Theories* is that it does not attempt, as the unifiers do, to force a universal concept of unity onto a range of case histories and philosophical accounts of theory unification. Nor does it try, as the disunifiers do, to vilify (or simply throw away) the unity concept. Rather, Morrison is sensitive to the diversity of notions of unity at work in science, and her analysis is supported by detailed case histories of theory unification in nineteenth- and twentieth-century physics and biology.[5] One of Morrison's central

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[2] Clark Glymour, 'Explanations, Tests, Unity and Necessity,' *Nous* **14** (1980) 31-50; Michael Friedman, *Foundations of Space-Time Theories* (Princeton: Princeton University Press 1983); John Watkins, *Science and Scepticism* (Princeton: Princeton University Press 1984); Philip Kitcher, 'Explanatory Unification,' *Philosophy of Science* **48** (1981) 507-31 and 'Explanatory Unification and the Causal Structure of the World,' in *Minnesota Studies in the Philosophy of Science* Volume XIII, P. Kitcher and W.C. Salmon, eds. (Minneapolis: University of Minnesota Press 1989)

[3] *The Disorder of Things: Metaphysical Foundations of the Disunity of Science* (Cambridge, MA: Harvard University Press 1993)

[4] Peter Louis Galison and David J. Stump, eds., *The Disunity of Science: Boundaries, Contexts, and Power* (Stanford, CA: Stanford University Press 1996)

[5] This review focuses on the philosophical aspects of *Unifying Scientific Theories*, and space does not permit a discussion of many of the case studies and historical claims contained in the book.

aims is to navigate a course between the Scylla of contextualism and the Charybdis of general philosophical analysis. Against the unifiers she claims that theory unification is a local and complex process for which no general analysis can be offered: that unification does not underwrite, and is indeed sometimes not consistent with, explanation; and that unification does not contribute to theory confirmation nor provide the basis for realism about theoretical entities. Against the disunifiers Morrison claims that science has produced unified theories; that these theories share certain general features; and that unification is a theoretical virtue. In this paper I review and critically assess these claims, and in the final section I suggest an approach, avoiding both whirlpools and sea-monsters, that perhaps better realizes Morrison's goal of providing a new direction for fruitful philosophical work on theory unification in science.

II A Plethora Of Unities

By my count, Morrison discusses 13 types of unity: unity of science, unity of nature, reductive unity, material unity, metaphysical unity, ontological unity, theoretical unity, structural unity, synthetic unity, formal unity, heuristic (Kantian) unity, consilience, and 'true' unity. This plethora of unities is the result of Morrison's attempt, which she makes clear from the very first page of the book, to capture both the general features and the contextual nature of theory unification in science.

> What I hope my investigation will reveal are the ways in which theoretical unification takes on different dimensions in different contexts. What this means is that there is no ''unified'' account of unity — a trait that makes it immune from general analysis. Nevertheless, there are certain features that all unified theories possess, features that enable us to distinguish the process of unifying from that of simply explaining and conjoining hypotheses. (6)[6]

I am more optimistic than Morrison that theory unification in science is amenable to general analysis, despite its admittedly complex and diverse nature. Section VI of this paper will offer some grounds for this optimism by sketching how such an analysis might get started. For now, we can begin by grouping the unities into four kinds.

Of widest scope are unities associated with science or nature as a whole. Morrison's prime examples of these are the unity claims associ-

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[6] Page references are to Morrison, *Unifying Scientific Theories* unless otherwise indicated.

ated with the 'unity of science' program pursued by the logical empiricists. In his famous 1938 contribution to the *International Encyclopedia of Unified Science*, Rudolph Carnap advocated that the unity of science consists in a universal language for science: theories in different scientific fields are unified to the extent that their terms, or better their laws, are reduced to the terms or laws of a single field (indeed a single theory) (22). In his contribution to the *Encyclopedia*, John Dewey saw the unity of science in social and methodological terms, where science is unified to the extent that scientists in disparate fields followed a single scientific method and thereby participated in a united social effort (23). Otto Neurath's introduction to the first volume of the *Encyclopedia* articulates a third notion of unity, one on which the unity of science consists in a type of encyclopedic integration (23). This requires neither a universal language nor a common method, but rather a sort of harmony between diverse and mutually independent fields of inquiry. In all cases, the primary focus was on unification between scientific disciplines and fields of study. Claims about the unity of nature are material mode variants of the logical empiricist program. Here the claim is that nature as a whole has an ultimate simplicity or parsimony and that disparate scientific fields are unified to the extent that they reflect that simplicity. One of Morrison's central claims is that case histories of unification in science generally have few, if any, implications for inter-field unity of science or an ontological unity of nature (5). This is an important point, one on which many logical empiricist adherents to the unity of science program and all of their heirs (such as Friedman and Kitcher) will agree.[7]

A second cluster of unities make claims about nature limited in scope to a single scientific field or theory. William Whewell's consilience of inductions is a good example of this kind of unity.[8] Consilience occurs when a hypothesis is able to explain and predict facts of a different kind than those the theory was formulated to cover and thereby 'provide knowledge of the essential nature and real connection among things' (21). A consilient theory, such as Newton's Universal Gravitation, is unified because it shows that what were thought to be disparate phenomena are of the same kind. For Whewell, consilience occurs within an individual science or a specific domain of inquiry. Similarly, reductive unity occurs where two phenomena hitherto thought to be distinct are

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[7] Cf. Paul Oppenheim and Hilary Putnam, 'Unity of Science as a Working Hypothesis,' in *Minnesota Studies in the Philosophy of Science*, Volume II, H. Feigl, M. Scriven, and G. Maxwell, eds. (Minneapolis: University of Minnesota Press 1958).

[8] William Whewell, *Theory of Scientific Method*, R. Butts, ed. (Indianapolis, IN: Hackett 1968)

identified. Metaphysical (or ontological) and material unity seem to be closely related, covering cases in which a theory posits a small number of kinds of elementary entities or mechanisms. As Morrison is not concerned with general analysis, it isn't clear exactly how these various sorts of unity overlap and interrelate, but they do seem to form a group of related notions.

A third cluster of unities refers to the structure of a single scientific theory (rather than the domain of nature covered by the theory). Synthetic unity, for instance, involves the unification of many disparate phenomena under a small theoretical structure. For Morrison, this unification seems to be related to structural, theoretical, and formal unity, although it isn't clear from her discussion how, if at all, these unities differ. A structurally unified theory, for example, may make use of a small number of mathematical methods or structures. Morrison is clear that asserting a theory to be structurally or synthetically unified is not to make any ontological claim whatsoever. Moreover, a theory can be structurally unified at a high level, yet be quite diverse and disunified at the level of the low-level models used to account for the phenomena. Another of Morrison's central claims is that cases of unity of the reductive or ontological type are extremely rare. Almost all of the unified theories in science exhibit structural (or synthetic) unity only. At several points Morrison argues that cases in which one might be inclined to think that an ontological reduction has occurred within a domain of science ought not to be understood in that way. This is a welcome antidote to an all-too-common practice among some philosophers and historians of science, namely to jump to ontological conclusions based on structural properties of a theory (I examine one important case, that of electroweak unification, in Section V).

Morrison discusses one more kind of unification, which she intriguingly labels 'true' unification:

> In true cases of unification we have a mechanism or parameter represented in the theory that fulfills the role of a necessary condition required for seeing the connection among phenomena. (32)
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> A unified theoretical core *represented by a specific parameter* suggests that unification is the product of a specific theoretical construction that involves more than an enumeration of the argument patterns and models that the theory generates. In other words, there is something distinct about the structure of a truly unified theory that differentiates it from others. (200, emphasis added)

The displacement current, for example, is 'the parameter that represents, in some sense, the unification' (105). It is required for a unified account of electromagnetism and optics, and it is, as Morrison puts it, 'a necessary condition for formulating the Maxwell field equations' (106). Morrison's claim here is that the common feature of truly unified theories in science is the presence of a single parameter that is responsible for producing or representing the unity. This claim is at once essential to what Morrison wants to say about theory unification in science and deeply puzzling (I return to it in Section VI).

III Unification and Explanation

The explanatory power of a theory, it is often claimed, is intimately connected to its unity. Whewell, for example, claims that a consilient theory doesn't just unify hitherto disparate facts, it explains them. Morrison responds that the ability of a theory to uncover common patterns and make predictions in a new area isn't sufficient to underwrite explanation. She notes that Whewell's notion of consilience also involves an ontological claim, namely that a consilient theory tends to uncover the *vera causa*, the real causal connections in nature. However, even this causal knowledge may

> fail ... to function in a truly explanatory way. Hence, even though a *why* question may be answered by citing a cause, if there is no accompanying answer to the question of *how* the cause operates, or what it is in itself, we fail to have a complete explanation. (21)

Morrison seems to be setting the bar quite high when it comes to scientific explanation — explanation requires rather a lot, certainly a lot more than unification can deliver. Her argument is well laid out in Chapters 6 and 7 and can be summarized as follows. Many cases of theory unification in science involve only a structural unity. This kind of unification does not entail, and indeed is sometimes inconsistent with, an account of the specific, often complicated and messy, underlying physical mechanisms at work. A scientific explanation must consist in an account of, and impart an understanding of, these underlying mechanisms (236). Thus many cases of theory unification do not entail, and are sometimes even inconsistent with, explanation and understanding. Morrison's main target is Philip Kitcher's account of explanatory unification, along with his argument that for important cases in the history of evolutionary biology (Darwin's evolutionary theory and the neo-Darwinian syntheses of Ronald Fisher and Sewall Wright), structural unity within the theories is the source of the theories' explanatory power. Morrison's point here is an important one, and a useful antidote to the unifiers' tendency to identify unification and explanation. Her argument, however, is vitiated by too narrow a view of both scientific explanation and structural unification, as I'll now explain.

At many places Morrison repeats her claim that scientific explanation must consist in an account of underlying causal mechanisms, without ever developing or defending this view. Here are two representative passages:

> Explanation by derivation from quantitative laws very often doesn't provide what Richard Feynman calls the ''machinery'' of a particular system. The machinery is what gives us the mechanism that explains why, but more importantly *how*, a certain process takes place.... We want to know about the machinery, part of which involves knowledge of the causal behavior of the system. It is this feature that enables us to understand how certain processes take place. (3-4)
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> It is because we are interested in the how and why of natural processes that we must acknowledge the importance of and demand for explanations that go beyond deduction. Without that we have what [Elizabeth] Lloyd characterized as an ''accounting for,'' rather than an explanation. Thermodynamics was able to account for many phenomena, but one had to invoke kinetic theory in order to provide explanations. (202)

Morrison is clearly taking sides in what has been a long debate between those who favor a causal, mechanical account of explanation in science[9] and those who favor a structural, derivational account.[10] Her claim isn't just that adequate scientific explanations can appeal to underlying causal mechanisms, but that they *must* and that there are no other *bona fide* explanations in science.

Darwin's theory of evolution is an interesting case study of unification and explanation because of the dual roles played by its central postulate, the principle of natural selection. On the one hand, the selection principle gives rise to the structural unity of Darwin's theory, due to the fact that it plays an important structural role in the theory. That role is based on Malthus' principle that a population will grow at a geometrical rate while its food supply will increase only at an arithmetical rate (205). Natural selection is then a structural principle (although not the only one) that, by reducing the survival chances of poorly-adapted members of the population, both keeps the ratio of population to food stable and brings about an increase in fitness in a population. In this way, natural selection is the key to a structurally unified account of many facts about biogeography, comparative anatomy, cladistics, and the adaptation of organisms. On the other hand, natural selection acts as a *vera causa*, a

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[9] Wesley Salmon, *Scientific Explanation and the Causal Structure of the World* (Princeton: Princeton University Press 1984)

[10] Carl G. Hempel, *Aspects of Scientific Explanation* (New York: Free Press 1965); Philip Kitcher, 'Explanatory Unification & Causal Structure'

causal mechanism at work in a wide range of areas. In each particular case, however, the mechanism of selection needs to be supplemented with assumptions about other kinds of mechanisms at work, assumptions which vary widely from case to case. Morrison claims that the explanatory power of the principle of natural selection does not come from its unifying role but stems entirely from its causal role in specific applications: 'The unifying power of natural selection stands independently of the ways in which selection figures in explanation' (201). More precisely,

> The unifying power of selection arose from its association with a broadly based structural feature of populations that Darwin adopted from Malthus. Its explanatory power, on the other hand, is achieved at the level of models or specific applications. Here disunity and variety are required for success. Structural constraints are contextualized and coupled with additional assumptions necessary for understanding particular situations. (208)

My worry here is that Morrison is working with a rather narrow view of what constitutes the structural unity of a theory. Although she does not offer a general account of structural unity, she seems to be assuming that such unity exclusively consists in very high-level structure, such as the general principle of natural selection. However, it is true of all theories that, in order to explain specific phenomena, '[s]tructural constraints are contextualized and coupled with additional assumptions necessary for understanding particular situations.' Any account of structural unity must be able to handle these kinds of explanations, and Kitcher's account (which Morrison discusses at some length) is able to do so quite well. Kitcher's chief insight is that one important component of a scientific theory is a set of patterns of argumentation employed by scientists proficient in that theory; 'to know a theory involves the internalization of the argument patterns associated with it' (Kitcher, 'Explanatory Unification & Causal Structure,' 438). An argument that would be offered as an explanation or prediction by a scientist who accepts a certain theory Kitcher calls a *derivation*. Kitcher notes that distinct derivations may share a common *argument pattern* if they are similar in both logical structure and in the non-logical vocabulary they use. The degree of unification of a theory is determined by examining derivations and argument patterns associated with them. Roughly speaking, a structurally unified theory is one which uses few argument patterns to explain and predict a large range of results. Finally, explanation follows from unification. A derivation is explanatory simply when it is part of a theory that is itself structurally unified.

Darwin's theory is a paradigmatic case of a structurally unified and structurally explanatory theory, because a diverse range of phenomena can be derived and explained using a small number of argument patterns. The structural unity of Darwin's theory comes not only from 'broadly based structural feature of populations' but also from the fact derivations of an incredibly wide range of specific biological phenomena all fall under a small number of argument patterns. The fact that specific derivations make use of different local, contextual and varied assumptions, and even that some of these assumptions are about specific causal mechanisms, does not in itself vitiate the structural explanatory power of the theory. Morrison quotes one of these argument patterns at length, one under which fall derivations that answer the question, Why do almost all organisms in a population or species have a specific trait? (199) The pattern explicitly involves particular types of causal mechanisms, where the specific causal mechanism invoked will vary from case to case (derivation to derivation). My point is that these causal mechanisms may underwrite bottom-up type explanations about the emergence of a specific trait, but they also form part of top-down, structural explanations in this case.

Morrison aims to show how explanation and unification pull in opposite directions. To do this, she makes the strong assumptions that all explanations must be causal/mechanical and that structural unification is uniquely a high-level property of a theory. Morrison is very clear that she is not offering an account of scientific explanation, nor is she offering a general analysis of structural unity (or any other kind of unity, for that matter). I've suggested that in the absence of such analyses her assumptions are open to question. Where does that leave explanation and unification? It is always worthwhile to be reminded, as Wesley Salmon has emphasized, that the two concepts should not be identified and that bottom-up, causal/mechanical explanations play an important role in science.[11]

IV Unification and Confirmation

A virtue often claimed for theory unification is that, other things being equal, unified theories are better confirmed than their disunified competitors. Morrison demurs, contending that unification has no evidential import. She maintains that unification does not underwrite theory confirmation or realism about theoretical entities, and she claims her case

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[11] Wesley Salmon, *Scientific Explanation*; 'Conflicting Conceptions of Scientific Explanation,' *Journal of Philosophy* **82** (1985) 651-4; 'Four Decades of Scientific Explanation,' in *Minnesota Studies in the Philosophy of Science*, Volume XIII, P. Kitcher and W.C. Salmon, eds.

studies show that 'as a matter of historical fact unity seemed to provide little in the way of empirical support for theories' (57). Morrison's critical targets are Friedman's well-known argument connecting unification, confirmation and realism, and Whewell's account of unification, confirmation and the consilience of inductions. Her criticisms of Friedman's approach are well-founded but her worries about consilience miss the mark, I shall suggest, so Morrison has not given good reason to believe that unification can have no evidential import. I'll sketch a spectrum of positions *vis-à-vis* unification and confirmation, and show that Morrison occupies one extreme end of this spectrum.

Let's begin with Friedman's approach. Friedman cashes out the notion of unification as conjunction: a unified theory consists in a conjunction of previously unconnected theories, as when a basic molecular model of a gas (M_1) is conjoined with additional hypotheses from chemistry (M_2), statistical mechanics (M_3), electrodynamics (M_4), and so on, to produce the unified theory $M = M_1 \;\&\; M_2 \;\&\; M_3 \;\&\; M_4 \;\&\; \ldots$. Friedman goes on to claim that it is not just high-level theory M that benefits from unification, but the phenomenological description M*, consisting of the part of the theory couched in observational terms, itself may thereby be better confirmed:

> The hypotheses that collectively describe the molecular model of a gas [M] of course receive confirmation via their explanation of the behavior of gases, but they also receive confirmation from all the other areas in which they are applied: from chemical phenomena, thermal and electrical phenomena, and so on. By contrast, the purely phenomenological description of a gas [M*] ... receives confirmation from one area only: from the behavior of gases themselves....
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> The phenomenological description is better confirmed in the context of a total theory that includes the theoretical description than it is in the context of a total theory that excludes that description. This is because the theoretical description receives confirmation from indirect evidence — from chemical phenomena, thermal and electrical phenomena, and the like — which it then "transfers" to the phenomenological description. (Friedman, *Foundations*, 243-4)

Such a 'transfer' is simply a matter of basic logical coherence: the degree of confirmation of the theoretical description $c(M)$ may be driven higher than the degree of confirmation of the phenomenological description on its own $c(M^*)$. But since Friedman requires that the phenomenological description be a logical consequence of the theoretical one, it is logically incoherent to suppose that $c(M) > c(M^*)$, and we are forced to raise the degree of confirmation of the phenomenological description. Friedman requires here that the phenomenological description M* is a sub-model of M; that is, elements of M* can be identified with elements of M. In a final step, Friedman uses this connection between unification and confirmation to argue in favor of scientific realism (belief in M) as against anti-realism (belief only in M*). Friedman argues that only scientific realists, who believe in the literal truth of M, can unify high-level theories. In this way realists beat anti-realists at their own game: realists will be able to have better-confirmed phenomenological theories than anti-realists (Friedman, *Foundations*, 241-50). In sum, theory unification consists in the conjunction of high-level theories. This process can result in increased confirmation of the conjoined theory relative to its conjuncts and relative to the same evidential basis, as well as increased confirmation transferred to those low-level theories that are strict sub-models of the high-level theory.

Morrison points out two problems with Friedman's account of unification and confirmation. First is Friedman's claim that theory unification is theory conjunction. Morrison argues that a unified theory is *not* a mere conjunction of previously-existing theories. Indeed, one of Morrison's central goals in the book is to find a way to distinguish truly unified theories from simply conjoined ones. This is a point well recognized in virtually all work on theory unification, including, surprisingly, Friedman's own earlier work on the topic.[12] As Morrison puts it, the evolution of unified theories typically includes a 'conceptual reshuffling' in which new concepts and hypotheses are introduced, old ontological commitments are abandoned, and so on. We need not go so far as to say that the new, unified theory is incommensurable with previous theories to admit that unifying theory change should involve much more than mere conjunction. Morrison's second worry is that the relation between high-level theory and phenomenological description is more complex than the identity relation (model to sub-model) that Friedman proposes. Typically there are many phenomenological models associated with a high-level theory, and as Morrison has convincingly argued elsewhere, the models have a diversity and a degree of autonomy that makes the model/sub-model approach inapplicable (47-51).[13]

A much stronger candidate for an account of the connection between unification and confirmation is furnished by Whewell's consilience model. Recall that consilience occurs when a hypothesis is able to explain and predict facts of a different kind than those the theory was formulated to cover. Typically the hypothesis is found correctly to predict facts hitherto accounted for only by a second, seemingly unconnected hy-

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[12] Michael Friedman, 'Explanation and Scientific Understanding,' *Journal of Philosophy* **71** (1974) 5-19; cf. Andre Kukla, 'Scientific Realism and Theoretical Unification,' *Analysis* **55** (1995) 230-8

[13] Cf. Margaret Morrison, 'Models as Autonomous Agents,' in *Models as Mediators: Perspectives on Natural and Social Science*, M.S. Morgan and M. Morrison, eds. (Cambridge: Cambridge University Press 1999).

pothesis. When these two hypotheses are thus connected, a new theory is created at a higher level, so to speak, since the new theory covers a broader range of phenomena using a more abstract conceptual structure. Consilience is, in this way, a sort of bootstrapping procedure: a consilience of inductions between two hypotheses creates a single new hypothesis at a higher level of breadth and generality. Typically, the higher-level hypothesis asserts an identity between the causes, mechanisms or other structures behind phenomena hitherto seen as distinct, as for example the structural identity of celestial and terrestrial gravitation in the case of Newton, or the identity of the cause of electromagnetic and optical phenomena in the case of Maxwell. According to Whewell, higher-level hypotheses that are the result of consilience can exhibit both an ontological unity, in that they typically assert the identity of entities hitherto thought to be distinct, and a simplicity or 'harmony' in their structure and expression.[14] Most importantly, consilience has great confirmational value. Independent measurements of a common cause — a *vera causa* — have greater evidential force relative to a unified theory than they do relative to multiple distinct (non-consilient) hypotheses.[15] Whewell himself puts it in forceful (if unfashionable) terms:

> The instances in which this [consilience of inductions] has occurred, indeed, impress us with a conviction that the truth of our hypothesis is certain. No accident could give rise to such an extraordinary coincidence. … That rules springing from remote and unconnected quarters should thus leap to the same point, can only arise from *that* being the point where truth resides. (Whewell, 153)

For Whewell, the consilience of inductions results both in a unified theory (ontologically and/or structurally) and in a theory that is better confirmed relative to non-consilient hypotheses and relative to the same evidential basis. Unification and confirmation are thus not directly connected but have a common source in the consilience of inductions.

Morrison worries that consilience in fact delivers far less than advertised. Maxwell's electromagnetic theory, for example, fits the consilience model, successfully unifying electromagnetic and optical phenomena. Yet the theory did not provide any epistemic support for belief in a specific *vera causa* underlying the phenomena. Early mechanical aether

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[14] William Harper, 'Consilience and Natural Kind Reasoning,' in *An Intimate Relation: Studies in the History and Philosophy of Science*, J.R. Brown and J. Mittelstrass, eds. (Dordrecht: Kluwer 1989) 125-31)

[15] Malcolm Forster, 'Unification, Explanation and the Composition of Causes in Newtonian Mechanics,' *Studies in History and Philosophy of Science* **19** (1988) 55-101

models gave way to more abstract field-theoretic formulations, yet throughout this development Maxwell rightly remained agnostic about ontological commitment to a specific hidden cause or mechanism producing the unification. This worry seems to miss the mark, since the consilience model, at least in its more recent interpretations by Forster ('Unification, Explanation') and Harper ('Consilience'), says only that a successful consilience of inductions gives us reason to believe there exists *some* common cause or mechanism producing the hitherto seemingly distinct phenomena. No one claims that consilience alone need license ontological commitment to a *particular* mechanism.

If Morrison is at one end of a spectrum, asserting that unification has no evidential import, then consilience approaches lie somewhere in the middle, claiming that unification and confirmation are indirectly connected and that unified theories may have a confirmational advantage relative to disunified ones, other things being equal. At the other end of the spectrum we find approaches that aim to eliminate the concept of theory unification in favor of purely evidential notions. For example, recent work that uses Akaike's Information Criterion (AIC) to explicate evidential concepts in science takes this approach. Here, the key notion is that confirmation should not focus on how likely a hypothesis is, relative to the evidence. Rather, the important facet of evidential support is to estimate how predictively accurate the hypothesis is likely to be, given the evidence.[16] Unification is a theoretical virtue, on this approach, just in case the more 'unified' theory has a greater estimated predictive accuracy than its rivals. 'At least for cases that can be analyzed in the way just described, it is gratuitous to invoke ''unification'' as a *sui generis* constraint on theorizing' (Forster and Sober, 14). For cases that cannot be so handled, 'the allure of unification [is] something of a mystery' (Forster and Sober, 12). I'm certainly not advocating eliminativism, but simply calling for a more wide-ranging examination of the evidential import of theory unification in science.

V The Case Of Electroweak Unification

We have seen that one of Morrison's central claims is that cases of ontological unity are extremely rare, and that most of the unified theories in science exhibit structural unity only. Morrison also claims that theory

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[16] Malcolm Forster and Elliott Sober, 'How to Tell When Simpler, More Unified, or Less ''Ad Hoc'' Theories Will Provide More Accurate Predictions,' *British Journal for the Philosophy of Science* **45** (1994) 1-35

unification does not, as a matter of historical fact, provide any confirmational support for theories. She supports these claims with detailed case histories from nineteenth- and twentieth-century physics: Maxwell's unification of electromagnetism and optics (which has both ontological and structural aspects); Einstein's unification of space and time in special relativity; and the Glashow-Weinberg-Salam unification of quantum electrodynamics with the weak nuclear force. Morrison's strongest case is electroweak unification, for here she claims that what was achieved was a purely structural (or synthetic) unification of hitherto disparate domains and that the theory had no confirmational advantage by virtue of its unity. Her argument is based on the unifying role that gauge symmetries played in the development of electroweak theory. My own reading of the electroweak case is slightly different. I believe that the structural unity Morrison describes, and indeed gauge arguments more generally, depend crucially on a prior assumption of ontological unity. Without the ontological assumption, as I shall argue, electroweak theory doesn't have structural unity at all. I'll also suggest that the electroweak model is, and was taken by physicists to be, more likely to be true because of its unity.

Gauge field theory, and the symmetries on which it is based, provide the mathematical framework in which the unification of weak and electromagnetic interactions is achieved. How? Morrison (e.g. 114-17) follows the usual textbook account quite closely. First, postulate the elementary non-interacting physical constituents of the subatomic domain. That is, make a guess at what the basic building blocks of matter are, without worrying about their detailed properties or their interactions. Write down a Lagrangian (generalized equation of motion) which simply lists quantum fields corresponding to the best guess (based on subatomic experiments) at the elementary particles which make up all matter. Second, require that this Lagrangian be invariant (remain unchanged) under a variety of symmetry transformations. These symmetries are both space-time, external symmetries such as Lorentz (relativistic) invariance and internal symmetries having to do with the conservation of quantities like energy, spin, charge, and their more esoteric variants. The demand that each Lagrangian satisfy its respective symmetries requires that we add certain terms to the free-field Lagrangian, and these terms describe quantum fields — called 'gauge fields' — carrying the electromagnetic, weak, and strong interactions as well as further matter fields. We seem to have 'derived' a description of the quantized electromagnetic field (and the photon) as well as other (strong and weak) interaction fields simply by demanding that the Lagrangians satisfy some symmetry principles.

As Morrison puts it for the case of electrodynamics, 'The structure of [the electromagnetic] field, which is dictated by the requirement of local symmetry, in turn dictates, almost uniquely, the form of the interaction, that is, the precise form of the forces on the charged particle' (116). Later work on gauge theories extended this to other forces of nature: 'gauge symmetry became a powerful tool that could determine the form of the matter-field interaction and could define much of the dynamical content of a theory of strong interactions. Its ability to generate that kind of dynamics was a role it continued to play in constituting the core of the electroweak theory' (117). Along with the additional mathematical techniques, such as spontaneous symmetry breaking and the Weinberg angle (a parameter describing the degree of mixing of the weak and electromagnetic forces), Glashow, Weinberg and Salam were able to construct the electroweak theory, a single gauge theory accounting for both weak and electromagnetic interactions.

What kind of unity was achieved here? Not a reductive unity, for as Morrison points out, it is not the case that weak and electromagnetic interactions were seen as one and the same thing (125). As well, the electroweak case does not underwrite any claims about the large-scale unity of nature as a whole (136, 139). Rather, Morrison argues, the unity is synthetic, where weak and electromagnetic interactions are subsumed under a single theoretical framework, that of gauge theory: 'the unity has been achieved not by simply conjoining the two theories ... but by introducing new components to the pre-existing theories of weak and electromagnetic interactions' (136). What is the difference between a theory which is simply the conjunction of a number of previous theories, and one which is genuinely unified? What counts as a single synthetic 'framework' covering a number of distinct processes as opposed to a patchwork of distinct frameworks? Morrison provides no general answer, but in the electroweak case it seems to be the role of gauge symmetry as the key bit of theoretical structure playing the unifying role. Of course, not just any bit of shared theoretical structure can play a unifying role. Theories in physics often share quite a bit of structure, yet we would not want to call them unified. For example, electroweak theory, quantum chromodynamics, and condensed matter physics all involve the same sorts of renormalization techniques, yet we would not want to say that these three theories are structurally unified for that reason. More intuitively, most physical theories share lots of basic mathematical structure (e.g. phase space structure), yet this isn't sufficient to count them unified. For Morrison, what makes gauge symmetry unifying in the electroweak case is its role in determining substantive facts about the form of the electromagnetic and weak interaction and generating much of the dynamical content of the theory.

The derivation of electromagnetic and weak gauge fields, as Morrison presents it, obscures the fundamental role played by *prior ontological commitment*. Principles of gauge invariance are best regarded as heuristics which allow one to construct a theory about the physical properties of forces in the subatomic domain. Not emphasized in Morrison's account is the fact that gauge invariance demands the Lagrangian to be invariant under the same symmetry transformations which leave the physical system of quantum fields invariant (modulo spontaneous symmetry breaking techniques). The existence of a quantum field describing a physical force (weak or electromagnetic) needs to be posited before the steps of the gauge invariance derivation can begin. As a heuristic principle, gauge invariance presupposes commitment to physical forces producing the dynamics of the subatomic domain.

The postulate of gauge invariance seems to unify electroweak theory while other bits of shared formalism do not because the postulate of gauge invariance presupposes a small ontology of elementary quantum fields. It is not the postulate of gauge invariance but rather a prior ontological commitment to a small number of elementary quantum fields which functions to unify the electroweak theory. If I am right, shared structure in electroweak theory is 'unifying' when it refers to a small number of elementary entities. Electroweak theory is an ontologically unified (in the sense of ontologically parsimonious) theory: a small number of elementary entities — quantum fields — produce a diverse range of subatomic interactions.[17]

Where does that leave unification and confirmation in the electroweak case? Morrison points out, quite rightly, that an additional theoretical hurdle had to be overcome before the electroweak theory was even considered to be a candidate for empirical confirmation (132-3). When first proposed, the electroweak theory had not been shown to be renormalizable. What this means is that the theory didn't make predictions that could be directly tested by experiment; more precisely, the trustworthiness of the mathematical techniques used to derive predictions from the theory had not been established. The proof of renormalizability, which came a few years after the theory was first proposed, was a necessary condition for physicists to commit to doing experimental or theoretical work on it. The proof of renormalizability turned electroweak theory into a candidate for a fundamental theory of the subatomic

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[17] Of course, nothing said so far justifies such an ontological commitment. There are well-known worries that this kind of ontological commitment might be incompatible with quantum theories in general (Arthur Fine, *The Shaky Game: Einstein, Realism and the Quantum Theory* [Chicago: University of Chicago Press 1986]) as well as more specific arguments that quantum fields themselves might not have a coherent physical interpretation (Paul Teller, *An Interpretive Introduction to Quantum Field Theory* [Princeton: Princeton University Press 1995]).

domain. Morrison concludes that unity has no confirmational import, since prior to renormalization electroweak theory was considered very unlikely to be correct even though it had a high degree of unity (134).

However, the electroweak case does not support Morrison's position with respect to unification and confirmation. Renormalization is a precondition for deriving reliable predictions from the theory, and hence a necessary condition for experimental test and confirmation. This is consistent with the fact that the high degree of unity of the theory could, once the renormalization problem was solved, play a positive confirmational role. It is also consistent with possibility that for theories that do not face problems like renormalization, the unity of a theory may have confirmational import. In fact there is some historical evidence, for example in the Nobel addresses of Salam, Weinberg, and Glashow discussed previously,[18] that the physics community took the unity of the electroweak theory to bear in favor of the truth of the theory. Whether they were right to do this is a question that cannot be settled here, and as we have seen there is a spectrum of positions on this issue.

VI Unification, True or False

Let us return to what is perhaps Morrison's main theme, that theory unification is a local and complex process for which no general philosophical account can be offered; as she puts it, unity in science is 'immune from general analysis' (6). In the remainder of this paper I would like to suggest that this claim ought to be resisted. It is certainly not the case (as Morrison seems to imply) that *just because* unification is a local and complex process it is thereby not amenable to general philosophical investigation of the sort common in philosophy of science. I believe general analyses *can* accommodate the contextual nature of theory unification, and I believe there is much more to be said about what theory unification consists in. I would now like to sketch one way in which such an analysis may begin.

Morrison does want some grounds for distinguishing cases of true unification from those of spurious or false unification, and she maintains that truly unified theories share certain general features. The simple conjunction of two disparate hypotheses does not, in general, count as a

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[18] Salam, 'Gauge Unification'; Weinberg, 'Conceptual Foundations'; Glashow, 'Towards a Unified Theory'; cf. Lillian Hoddeson, Michael Riordan, Max Dresden, and Laurie Brown, *The Rise of the Standard Model: Particle Physics in the 1960s and 1970s* (Cambridge: Cambridge University Press 1997)

true unification, nor does unification result from the fact that distinct hypotheses share certain bits of structure, such as an inverse square law or a Lagrangian formulation. As we have seen, the common feature of truly unified theories, for Morrison, is the presence of a single parameter that is responsible for producing or representing the unity. This feature enables us to distinguish truly unified theories, and Morrison's case histories provide examples of such a unifying parameter: the displacement current in Maxwell's electrodynamics, the Weinberg angle in electroweak theory, the relativistic parameter γ (or β) in the special theory of relativity, and the Malthusian parameter m in the neo-Darwinian synthesis. True unity isn't a form of ontological (or material) unity since it does not involve ontological commitment. As Morrison says, the unifying role of the displacement current does not underwrite its 'acceptance as a real physical quantity or process' (106). Nor is true unity merely a form of synthetic or structural unity, since for Morrison, the mechanism or parameter required for true unity goes beyond a merely formal or structural account (32, 106).

Morrison's discussion of true unity raises many questions. It is not at all clear what links the heterogeneous group of theoretical concepts she labels 'unifying parameters,' how a unifying parameter enables us to distinguish true from false unity, nor how true unification is distinct from ontological or structural unity. Consider the displacement current. Morrison traces the development of the displacement concept, from its early interpretation as a distortion of vortex cells in a mechanical ether through its more abstract definition as the quantity of charge crossing a surface of matter or the ether in Maxwell's later theory. By the late nineteenth century, the displacement current referred to the motion of charges in matter or in the ether. This suggests that 'true' unity, in this case, is in fact ontological, where the specific mechanism of charge displacement produces a range of electromagnetic phenomena. In the twentieth century the displacement current was freed of any ontological interpretation since it is nothing other than the rate of change of the electric field,

$$\mathbf{J}_{\mathrm{displ}} \equiv 1/4\pi \cdot \partial \mathbf{E}/\partial t.$$

The displacement current here is a theoretical concept, one that arguably does unify electromagnetics since it enables Maxwell's second equation to reveal the dependence of the magnetic field on current densities (displacement and conduction),

$$\mathrm{curl}\ \mathbf{B} = 1/c \cdot \partial \mathbf{E}/\partial t + 4\pi/c \cdot \mathbf{J}.$$

This unification, however, is purely structural and better regarded as being achieved by the concept of a *current density* rather than the displacement current itself. The unifying roles of the Weinberg angle in electroweak theory, the relativistic parameter γ in the special theory of relativity, and the Malthusian parameter m in the neo-Darwinian synthesis seem equally puzzling (space does not permit an examination of these cases here).

A more systematic analysis of the unity concept is both possible and useful. Such an analysis may begin by recognizing that claims about the unity of a theory mean one of two sorts of things. In one sense, a theory might be said to be unified because it posits a small number of kinds of elementary entities or mechanisms, or at least a smaller number relative to competing theories; call this *ontological unity*. Ontological unity is a fact about the ontology of the theory, not a structural fact about the theory. For example, Maxwell's electrodynamics is ontologically unified because it shows that optical and electromagnetic phenomena are of the same kind. Ontological unity may be a consequence of the theory's reduction of one domain of phenomena or mechanisms to another. It may be because the theory is the product of a consilience of inductions in which the common cause or structure of two seemingly distinct phenomena is posited. Or it may simply be because the theory is ontologically parsimonious, positing a small number of basic kinds of elementary entities or mechanisms. It is worthwhile to emphasize that in the latter two cases no theoretical reduction is required for ontological unity; indeed, a theory with a small basic ontology may contain several levels of emergent phenomena with their attendant autonomous models or hypotheses. As we have seen, the unity of the electroweak theory is precisely this sort of non-reductive ontological unity.

Ontological unification is a multiply contextual notion. Theories typically admit a range of interpretations, and these interpretations may posit widely divergent ontologies. Under some interpretations a theory may have a very large elementary ontology (for example, an ontology closely tied to the phenomena), while under other interpretations the ontology may consist of a very small number of elementary entities out of which the plethora of observable entities is constituted. As a rule, one can only say that a theory has an ontology, *a fortiori* ontological unity, when there is some consensus within a relevant scientific (or perhaps philosophical) community about the interpretation of the theory. The overused notion of a scientific paradigm may be useful here to characterize, in an approximate way, the context relevant to judgments of ontological unity.[19] As well, ontological unity typically makes sense only

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[19] Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press 1970)

as a comparative notion between theories within a scientific field — another way ontological unity is a local, contextual matter. Finally, once an interpretation is fixed there remains the problem of counting the number of kinds basic entities or processes it posits. Such an enumeration depends crucially on local judgments about natural kinds, and this too is plausibly regarded as a thoroughly contextual matter.

In a second sense, a theory might be said to be unified because it covers a broad range of phenomena using a small theoretical structure, again relative to competitors; call this *structural unity*. Structural unity is a difficult notion to make precise, in large part because of the thorny question of how to judge the size of a theoretical structure. Intuitively, a smaller theoretical structure is one that contains fewer independent laws (brute facts) about how the world works (Friedman, 'Explanation'; Watkins, *Science and Scepticism*). However, structural unity cannot be measured simply by counting the number of laws or the number of free parameters in a theory. For one thing, there is the vexed question of how to individuate laws in any principled way.[20] For another, one would prefer an approach that does not require theories to be formulated in axiomatic terms. More promising is the intuition that structural unity has to do with the fact that the derivations or models used by scientists are relevantly similar. We have already seen one way to make this intuition more precise, namely Kitcher's account on which a structurally unified theory is one that uses few argument patterns to explain and predict a large range of results.

As with ontological unity, the notion of structural unity is essentially tied to a local context or paradigm in a multitude of ways. How to count the number of argument patterns or model types in a principled way? As I have argued elsewhere, the notion of an argument pattern only makes sense when very closely tied to scientific practice, and in particular how scientists learn and apply their theories.[21] How to judge the range of phenomena covered by a theory? Again, this depends on judgments about natural kinds, among others, that are inextricably contextual.

To sum up, my preliminary suggestion is that all unified theories in science are either ontologically unified or structurally unified (or both). One consequence is that 'true' unity does not exist as an independent kind; while a parameter, physical variable, or other theoretical concept

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[20] Philip Kitcher, 'Explanation, Conjunction, and Unification,' *Journal of Philosophy* **73** (1976) 207-12

[21] Andrew Wayne, 'Theoretical Unity: The Case of the Standard Model,' *Perspectives on Science* **4** (1996) 391-407

often plays a key role in theory unification, this is best understood as a structural or ontological role. We have seen that the displacement current provides an example of a theoretical concept playing first an ontological, then later a structural unifying role in the context of two very different paradigms. My hope is that this account will also help to clarify the explanatory and confirmational implications of theory unification.

Notions of unity have played important roles in the development of science, roles which neither the unifiers of the 1980s nor the disunifiers of the 1990s were able fully to appreciate. Morrison's book should help philosophers do better in the 2000s. *Unifying Scientific Theories* offers an exemplar of the historical and philosophical breadth that are important and badly needed in philosophical attempts to understand the many faces of unity in science.[22]

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