The Collective Pursuit of Unification: The Role of Collective Epistemic Goals

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Abstract: This paper provides a simple game-theoretic analysis of *unification*. We argue that *ceteris paribus* a unified theory that promises greater cognitive benefits but also requires cooperation between scientists with different areas of specialization is no more rational to pursue than a less unified theory that promises lower cognitive benefits but requires no such cooperation. Further, pursuing unification becomes more rational when scientists adopt collective epistemic goals. Our analysis suggests a wide-ranging social epistemology that identifies conditions wherein different kinds of unification are rational to pursue.

Keywords: Unification, collective epistemic goals, game theory

1. Introduction

Unification is a hotly debated topic in the philosophy of science. Much of the debate concerns its status as a desideratum of inquiry: is unification a fruit that all of our scientific pursuits ought to bear? Such debates rarely countenance the *social interactions* between scientists required to produce a scientific theory. Using the tools of game theory, we provide a general social epistemology of unification that explains when it is rational to pursue unification, and also explains when it is rational to forego unification, even when it promises the greatest cognitive benefit.

After the perfunctory clarifications (§2), we argue that, ceteris paribus, a unified theory promising greater cognitive benefits but also requiring cooperation between scientists with different specializations is no more rational to pursue than a less unified theory promising lower cognitive benefits but requiring no such cooperation (§3). We then argue that pursuing unification becomes more rational when scientists adopt collective epistemic goals (§4). Finally, we highlight some of our model's implications for the current debates about unification, providing a wide-ranging social epistemology that identifies the conditions wherein different kinds of unification are rational to pursue (§5)[1].

2. Preliminaries

We begin by clarifying three central features of our account: pursuit (§2.1), unification (§2.2), and our game-theoretic assumptions (§2.3).

2.1. Theory Pursuit

We shall discuss why scientists *pursue* unified theories; not why they *believe* unified theories. Believing a theory means taking it as true; pursuing a theory means allocating resources towards its further development. Pursuit might take the form of testing the theory, refining its hypotheses, or applying for grants to undertake such tasks.

Belief and pursuit are distinct stances towards a theory. Scientists can believe theories without pursuing them, e.g. if they think the theory is true and requires no further development. Scientists can also pursue theories without believing them. This might happen simply because pursuit keeps them gainfully employed; less cynically, it may also occur if they are undecided about the veracity of a theory, and the pursuit promises to shed light on this issue. Our model is compatible with agents adopting any doxastic state or degree of belief while pursuing a theory.

Consequently, the rational standards for believing a theory differ from the rational standards for pursuing a theory. Roughly stated, the standards of rational belief concern *evidence*, while the standards of rational pursuit concern *utility*. Of course, scientists place high utility on evidence, so pursuit does not proceed entirely independently of epistemic considerations.

2.2. Unification

We will only discuss when scientists pursue theories exhibiting differing degrees and kinds of *unification*. We aim to use as *general* an account of unification as possible, primarily so that our social epistemology of unification will apply to most (if not all) accounts of unification currently in the philosophical marketplace of ideas.

Let a theory *h* *fit* a phenomenon or item of evidence *e* only if *h* stands in a scientifically significant and scientifically acceptable relationship to *e*. Candidates for fitting relationships include confirmation, deduction, explanation, prediction, retrodiction, analogy, manipulation, observation, providing understanding about, visualization, modeling, etc. Then the transition from one stage of scientific inquiry t_1 to another such stage t_2 marks an increase in unification if and only if:

(1) Fewer theories at t_2 are required to fit the same evidence than those required at t_1;

(2) The same theories fit more evidence at t_2 than at t_1; or

[1] Readers interested in the formal results underlying our discussion, especially in §§3-4, should consult the Appendix.

(3) Fewer theories fit more evidence at t_2 than at t_1.

For simplicity's sake, we restrict our attention to (1), by assuming that the set of phenomena to be fit is finite and fixed over time. We also assume that a unique theory fits any subset of phenomena. This omits the possibility of scientists pursuing different theories that fit the same collection of phenomena, but the variety of theories that can be pursued remains sufficiently rich to capture interesting ideas about unification.

As simplistic as this picture appears, it suffices for our purposes. In aiming to provide a social epistemology that is relatively invariant to the account of unification being endorsed, we thereby allow the reader to fill in the "fitting" relation and to count and define "theories" and "evidence" in whatever manner furnishes her favorite account of unification (Table 1).

Account of Unification	**Theory**	**Evidence**	**Fitting Relationship**
(Bartelborth 2002)	Theoretical Models	Pre-Theoretical Models	Embedding (Explanation)
(Kitcher 1989)	Argument Patterns	Explananda	Deduction (Explanation) [2]
(Morrison 1999)[3]	Theoretical Parameters	Phenomena	Necessity, Mathematical Structure
(Myrvold 2003)[4]	Hypotheses	Evidence	Conditional Probability, Informational Relevance
(Schurz and Lambert 1994; Schurz 1999)	Premises	Explananda	Inference
(Thagard 1978)	Hypotheses	Classes of Facts	Explanation

Table 1. A sketch of how the leading accounts of unification would be subsumed within our framework

Instead of fighting turf wars over the nature of unification, our primary focus concerns aspects of unification most relevant to scientists' decisions about theory pursuit. To that end, imagine a scientific community in which each member deliberates about pursuing one of many theories that differ in both the degree and kind of unification they

[2] Both Bartelborth and Kitcher provide unificationist theories of explanation. Consequently, if an explanandum can be embedded or deduced from a theoretical model/argument pattern that is a member of a unifying theory or "explanatory store," it is explained by an application of that model/pattern.

[3] While Morrison (1999: 6) states that "*there is no 'unified' account of unity—a trait that makes it immune from general analysis*," this entry captures one kind of unification that might not be subsumed under other entries, and springs from her discussion that "*true cases of unification… have a mechanism or parameter represented in the theory that fulfills the role of a necessary condition required for seeing the connection among the phenomena*" (32).

[4] See also (McGrew 2003; Schupbach 2005)

potentially offer. The first kind of theories fit only phenomena within her *field*, i.e. the set of phenomena in which the scientist specializes, owing to training and prior research. Alternatively, she can pursue theories fitting phenomena both within and outside of her field. If a scientist pursues the first of these strategies, she pursues a *local* theory; otherwise, a *cosmopolitan* theory. This is a sliding scale: maximally cosmopolitan theories fit at least one phenomenon from every field at a given time.

Unification has another dimension. Theories might be *grand*, and fit *all* of the phenomena within their purviews; or they might be *humble*, fitting only a subset of these phenomena. As with cosmopolitanism, grandeur comes in degrees. At one extreme, maximally humble or *parochial* theories fit only one phenomenon. At the other extreme, maximally grand or *global theories* fit all of the phenomena.

To complete our taxonomy, humble cosmopolitan theories (here after *bridge* theories) only fit a subset of phenomena spanning two or more fields. The extreme form of a bridge theory—maximally cosmopolitan and maximally humble—will thus fit exactly one phenomenon from every field. Conversely, a grand local (hereafter: *regional*) theory fits all of the phenomena within a scientist's field; a grand cosmopolitan theory fits all of these phenomena plus all of the phenomena of interest to the scientist but outside of her field.

Intuitively, global theories unify the most; parochial theories the least. A global theory is a single theory that fits all of the evidence, so adopting it maximizes unification. Any shift from grander to humbler theories would require more theories to fit the same evidence, thereby decreasing unification. Our model permits a fine-grained taxonomy, in which these are two extremes (Figure 1).

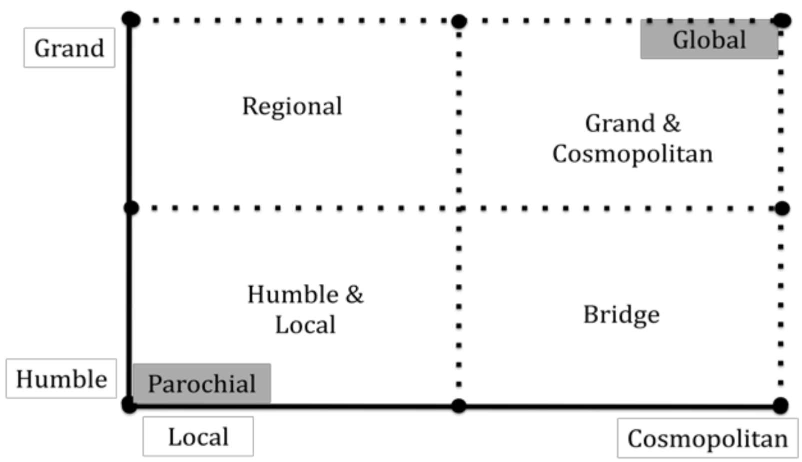


Figure 1. Varieties and Degrees of Unifying Theories

To illustrate these ideas, consider a simple scientific community in which there are only three phenomena e_1, e_2, and e_3, and two scientists *A* and *B*. *A*'s field consists of e_1 and e_2; *B*'s, of e_3. Then the possible theories would be: h_1, h_2, h_3, h_{12}, h_{13}, h_{23}, h_{123}. Here, the subscripts refer to the phenomena the theory fits, e.g. h_{23} fits e_2 and e_3. Using our earlier terminology, h_1, h_2, and h_3 are parochial theories; and h_{123} is a global theory. Given *A* and *B's* fields, h_{12} and h_3 are grand local theories, while h_{13} and h_{23} are bridge theories.

We do not assume cosmopolitan theories *inherently* increase unification. However, so long as there is more than one field in a scientific community, at least one cosmopolitan theory is always grander than any regional alternative. In this simple model, h_{123} is the only cosmopolitan theory grander than any regional alternative. Consequently, cosmopolitanism (via grandeur) is frequently a consequence of greater unification.

2.3. Assumptions

We are interested in the conditions under which it is rational to pursue unifying theories, yet we recognize that unification comes in many shapes and sizes. We now motivate the seven assumptions that will figure in our game-theoretic solution to this puzzle. These are not intended as decisive justifications, and we readily acknowledge that many of our assumptions are simplifying. Nevertheless, given the level of abstraction, all of these assumptions are plausible. We postpone added complexities for future research.

(A1) It is rational to pursue a theory h if and only if pursuing h maximizes expected payoff.

(A2) The expected payoff of pursuing h is a function of the costs of pursuing h, the benefits provided if the pursuit is successful, and the probability that pursuing h will succeed.

These two assumptions are basic tenets of "economic approaches to science" (Strevens 2011), and allow us to apply the tools of game theory. Here and throughout, "rational" means *subjectively* rational (likewise for "cost," "benefit," and "probability"). In other words, our answer only appeals to scientists' mental states (even if these states are objectively irrational or unjustified). Note further that the theory h is defined as a theory that fits some set of phenomena E; pursuing h means attempting to produce a theory that fits E. That pursuit is *successful* if and only if a theory is produced that actually fits E.

(A3) Ceteris paribus, the costs of pursuing a grander theory are greater than those of pursuing a humbler theory.

For each phenomenon e, ascertaining whether a theory fits e requires an expenditure of resources (time, effort, thought, equipment, etc.). Since grand theories require more of these expenditures, they cost more to pursue than humble theories.

(A4) Ceteris paribus, the costs of pursuing a cosmopolitan theory are greater than those of pursuing a local theory.

In pursuing a local theory, the scientist is familiar with the phenomena, leading hypotheses, etc. Since this is not the case with cosmopolitan theories, the scientist must allocate resources to familiarize herself in the adjacent field. Costs, then, increase monotonically along both the humble-grand axis and the local-cosmopolitan axis.

(A5) Ceteris paribus, the benefits of a successful grand theory are significantly greater than those of a successful humble theory.

Modulo one's theory of unification, a fit is a scientifically interesting and acceptable relationship between a theory and a phenomenon. Intuitively, more of these fits are better than fewer of them. For instance, theories that explain more or are supported by more evidence are ceteris paribus better than their counterparts. By definition, a grand theory fits with more phenomena than a humble theory. Thus, successful grand theories are more beneficial than their humbler counterparts. Moreover, science is about producing good theories; the benefits of grand theories grow faster than the costs.

(A6) Ceteris paribus, the probability that pursuit of a grand theory will result in success is lower than the probability that pursuit of a humble theory will result in success.

Ceteris paribus, fitting a theory to more evidence is harder than fitting it to less. Consequently, the scientist judges the pursuit of a humbler theory more likely to succeed than a grander one.

(A7) The probability that pursuit of a cosmopolitan theory will result in success depends on scientists in different fields cooperating; the probability that pursuit of a local theory will result in success does not.

A cosmopolitan theory h_C is more likely to succeed when scientists familiar with the different kinds of evidence with which h_C fits are working together[5]. Intuitively, if the pursuers are all in the same field, then any theory which fits evidence beyond that field is unlikely to succeed, since the scientists will be forced to speculate about evidence with which they are unfamiliar. Furthermore, because of the delicate division of labor between the specialists involved, a single specialist's failing to fill in his piece of the puzzle greatly undermines a cosmopolitan theory's chance of success.

By contrast, if everybody pursues a local theory, then cooperation is not needed: specialists are familiar with the relevant evidence and conceptual resources needed to develop local theories, and hence need not rely on the skill sets from specialists in other fields.

We do not assume that successful cosmopolitan theories yield greater benefits than their local counterparts. Some scientists may well prefer local theories to cosmopolitan theories if they are more interested in the phenomena within their field than that which falls outside of it. Other scientists may find the interdisciplinary work characteristic of cosmopolitan theory-pursuit to be intrinsically rewarding.

3. Stag Hunts and the Limits of Unification

These assumptions entail that unification is not rational to pursue always and everywhere. Because pursuing unified theories costs more and is less likely to succeed, these considerations will sometimes outweigh the corresponding benefits. We will focus on a more specific scenario: even when scientists take the costs and benefits to favor pursuing unification, the risks of specialists in other fields not contributing to a unified program may make the pursuit of less unifying theories more rational.

To make this point vivid, we shall argue that the decision between pursuing a cosmopolitan theory and a humbler local theory exhibits a common game-theoretic structure known as a *stag hunt* (§3.1). We then illustrate how the Eclipse of Darwinism—when scientists disagreed about the evolutionary theories to be pursued immediately following *The Origin of Species*—is plausibly interpreted as a stag hunt in which the risks of cooperatively pursuing unifying theories were high, and the scientists consequently pursued less unifying theories (§3.2).

[5] This assumes that no scientist specializes in all of the available evidence.

3.1. Stag Hunt

A common decision problem in the pursuit of unification arises when a scientist is deciding between pursuing an arbitrary grander cosmopolitan theory h_{GC} and an arbitrary humbler local theory h_{HL} (and all else is held equal). In this context, our assumptions suggest that the scientists will face a decision problem known as a *stag hunt* (Skyrms 2004). In its canonical form, two hunters must individually choose to hunt a stag or a hare without knowing the choice of the other. If an individual hunts a stag, she succeeds only if her partner cooperates with her. While a hare is worth less than a stag, it requires no such cooperation.

We shall argue that pursuing h_{GC} is like hunting a stag; h_{HL}, a hare. Stag hunts are games in which there are two pure strategy Nash equilibria—one payoff dominant and the other risk dominant. A Nash equilibrium is payoff dominant if it is Pareto superior to all other Nash equilibria in the game, as would be the case if both individuals hunted a stag. A Nash equilibrium is risk dominant if players are most likely to choose the strategy corresponding to it in light of greater uncertainty about the actions of the other player(s). In the classic stag hunt example, hunting hares is risk dominant; if the players are uncertain about what the others are going to do, it is most rational for them to hunt hare.

(A3) and (A4) imply that the costs of pursuing h_{GC} will be greater than the costs of pursuing h_{HL}. (A6) implies that the probability of h_{GC} succeeding is less than that of h_{HL}. However, according to (A5), the benefits of h_{GC} outweigh these liabilities, so h_{GC} is payoff dominant. (A7) implies that only h_{GC}'s probability of success depends on scientists in different fields cooperating. If specialists in other fields fail to contribute to the pursuit of h_{GC}, then the scientist who pursues h_{GC} will incur heavier costs than she would have shouldered had she pursued h_{HL}, with no offsetting benefits. Thus, pursuing the humbler local theory is risk dominant.

To summarize, stag hunts require multiple equilibria; one of which is payoff dominant and another that is risk dominant. Some cosmopolitan theories are payoff-dominant, owing to their grandeur. However, this does not yet make them more rational to pursue, because the uncertainties in pursuing them may be too great. Because unification increases with grandeur, it is not always rational to pursue unification, even when its benefits are manifest.

3.2. The Eclipse of Darwinism

The "Eclipse of Darwinism," spanning from the 19th to the early 20th century, nicely illustrates the aforementioned hurdles to pursuing grander cosmopolitan theories. While a majority of biologists in the latter half of the 19th century accepted Darwin's hypothesis that species evolve, several offered hypotheses that competed with natural selection as an explanation of evolution. After presenting some historical details, we argue that scientists at this time adopted a risk dominant strategy in which they pursued only regional theories. Consequently, it is sometimes rational to pursue theories that are less grand (and hence less unifying) when uncertainties about how specialists in other fields will act are salient.

Four theories of evolution competed during the Eclipse: neo-Lamarckism, orthogenesis, saltationism, and neo-Darwinism. While advocates of all of these theories offered different answers to the question, "How do species evolve?", each also cited a characteristic kind of evidence as its support. In other words, each party to this debate found different kinds of evidence relevant, while failing to find every other party's evidence as relevant.

For instance, paleontologists and morphologists favored neo-Lamarckism, which held that the primary mechanism of evolutionary change was the inheritance of acquired characteristics (Cope 1867; Hyatt 1866), or orthogenesis, which held that evolution occurs by way of internally programmed forces or principles that generate structures unrelated to an organism's needs (Eimer 1898). Instead of morphological and paleontological evidence, saltationists—who held that the random genetic variations and mutations that propagated throughout a species via sexual reproduction explain evolutionary change, *sans* natural selection—primarily deployed evidence from genetics (Bateson 1902; De Vries 1903). By contrast, some neo-Darwinists relied on cytological evidence (Weismann 1896); others on evidence from field studies (Poulton 1890); and still others on biometric evidence (Pearson 1898; Weldon 1894-1895, 1901).

Advocates of these different theories had radically different methodological and metaphysical commitments. Methodologically, one of the biggest divides was between laboratory and field sciences. Laboratory scientists leaned on controlled experiments' exalted status in scientific practice; field scientists decried the artificial conditions of the laboratory. Similarly, there were also differences in whether quantitative and qualitative evidence was more relevant. These sorts of methodological differences made the evidence from other fields seem unlikely to fit within an individual scientist's preferred theory.

Metaphysically, the differences were even starker. While many Eclipse-era evolutionary theorists were materialists, some—particularly advocates of orthogenesis—were idealists. Those in the laboratory sciences tended to endorse causal-mechanical explanations and ontologies; biometricians were largely positivistic, eschewing explanation and ontology altogether; those in the other, less quantitative field sciences tended to endorse teleological explanations and ontologies. With such deep metaphysical divides running in tandem with specializations, specialists tended to think that other fields did not provide relevant evidence to a successful evolutionary theory.

As should be clear, Eclipse-era scientists were pursuing different theories, and each of these theories fit evidence that characterized a different field (paleontology, morphology, genetics, cytology, biometry, field studies). Consequently, they were pursuing local theories. On our model, this is because individual scientists harbored uncertainties about other scientists' willingness and ability to cooperate in the successful pursuit of grander cosmopolitan theories. Since the scientists of the Eclipse had radically different views about what constituted a successful theory, an individual scientist would assign low probability to other scientists in different fields contributing relevant evidence that would fit his preferred vision of a global theory.

For instance, if a geneticist sympathetic to saltationism sought to collaborate with a paleontologist during the Eclipse, he would have little confidence that the paleontologist would find the right kind of evidence to support saltationism, as few paleontologists were well versed in—or even sympathetic to—saltationism. Consequently, we see that it was rational to pursue regional (i.e. non-cosmopolitan) theories instead of a grander cosmopolitan theory that would unify paleontology, morphology, genetics, and the like.

To summarize, we have argued that even if a cosmopolitan theory fits more evidence, it may be more rational to pursue a local (i.e. less unifying) theory. This occurs when scientists fail to know if other scientists will cooperate by ascertaining if the cosmopolitan theory fits the evidence in the latter scientist's field.

4. Collective Epistemic Goals

Thus far, our arguments suggest that pursuing grander cosmopolitan theories is rational only if scientists have some way of eliminating particular uncertainties, but not *how* scientists manage this uncertainty. A wide variety of mechanisms have been proposed for getting agents to coordinate on one of multiple pure strategy Nash equilibria (Friedman 1993; Harsanyi and Selten 1988; Schelling 1960). Rather than providing a comprehensive survey of these solution-types and their bearing on scientific practice[6], we will show how one such mechanism provides a plausible account of how scientists pursue cosmopolitan theories.

Specifically, we propose that when scientists adopt *collective epistemic goals,* certain action profiles—in this case, pursuing local theories—are removed from the decision problem. After briefly presenting the concept of collective goals (§4.1), we then discuss collective *epistemic* goals, and how they spur the pursuit of grand cosmopolitan theories (§4.2), with special attention to the unification that followed the Eclipse, the Modern Synthesis of genetics and natural selection.

4.1. Collective Goals

Before discussing collective *epistemic* goals, let us briefly discuss collective goals *writ large*. For our purposes, a goal is collective if it satisfies the following criteria:

> **Commitment**: Goals should not be easily changeable elements of the decision problem;
> **Constraint**: Goals should be inputs to deliberation and not (merely) outputs, such that agents should be constrained in their deliberation by the goals that they hold;
> **Identity**: The same goal should be shared among all the agents who are party to the collective action in order to count as a collective goal;
> **Distribution**: The collective goal should specify some contribution to be performed by every agent who is a party to the collective goal[7].

Informally, it suffices for a collective goal to be an exogenously specified element of the decision problem that removes certain act profiles from rational consideration by each agent who holds the collective goal. Collective goals thus alter the structure of the decision problem that agents face.

For instance, suppose that our hunters undertake a collective goal to hunt only big game. Then on the model we are proposing, this would prohibit certain actions—say

[6] Other solutions to coordination problems may also bear on the issues here; we leave this as an avenue for future research.

[7] There are many game-theoretic models which incorporate elements similar to what we call collective goals (Bacharach 1999, 2006; Bratman, Israel, and Pollack 1988; Cohen and Levesque 1990, 1991; Gold and Sugden 2007; Sugden 2000). Our model is broad enough to work with many of these variants.

hunting hares—from being viable individual options, as this would be incompatible with the collective goal.

An individual who holds an individual goal is constrained; she cannot rationally choose actions which conflict with her previously held goals. Similarly, an individual who holds a collective goal is likewise constrained; she cannot rationally choose actions believed to be outcome-incompatible with the collective goal. Every agent who holds the collective goal is so constrained. So, if the collective goal excludes act profiles required for one of the two equilibria (payoff or risk dominant), coordination problems—such as those found in the stag hunt—are resolved.

4.2. Collective Epistemic Goals and the Modern Synthesis

We shall assume that *epistemic* goals constrain agents with respect to the theories they can pursue, and do so on the basis of those theories' epistemic properties. *Collective epistemic goals* (CEGs) further satisfy the four conditions of Commitment, Constraint, Identity, and Distribution discussed in §4.1.

Strictly speaking, any CEG that prohibits the pursuit of either humble or local theories would suffice for our purposes, as these actions are required for the risk dominant equilibrium. However, this would oversimplify delicate issues involving the *content* of the CEG. For instance, consider the following (unpromising) candidate for a CEG:

> (Grand Cosmopolitanism CEG) Pursue only theories that are cosmopolitan and grander than any local alternatives.

This CEG inadequately explains why scientists choose to pursue grand cosmopolitan theories, because it is circular. In effect, it only says that it is more rational for scientists to pursue grander cosmopolitan theories when a goal rules out theories that are not grand and cosmopolitan. Thus, not all CEGs that prohibit the pursuit of local or humbler theories adequately explain why scientists pursue grander cosmopolitan theories.

Rather than provide a universal template for the content of *every* CEG that promotes the pursuit of grand cosmopolitan theories, we will simply use the aftermath of the Eclipse—the Modern Synthesis of genetics and natural selection theory—to illustrate that a CEG with nontrivial content can make it more rational to pursue these theories. In the transition to the Synthesis, pursuing certain theories that were viable during the Eclipse became goal-incompatible actions characteristic of the CEG model we endorse. Moreover, by its culmination in the 1940s, biologists were pursuing a theory that fit the totality of evidence in the field and laboratory sciences (Mayr 1942). Consequently, the Modern Synthesis heralded the grandest and most cosmopolitan of theories—i.e., a global theory.

In the 20th century, biologists sought to emulate "mature" sciences such as physics and chemistry. This led to an emphasis on controlled experimentation and statistical analysis. Since neo-Lamarckism and orthogenesis gained much of their empirical support from morphology and paleontology, and faced serious problems when subjected to the canons of the new experimental programs arising in 20th century biology, they lost credence as viable theories of evolutionary change. Indeed, even saltationism faced withering critiques based on experimental evidence[8].

Thus, we claim that scientists adopted a new collective epistemic goal in between the Eclipse and the Modern Synthesis:

(CEG_e) Pursue only those theories that exhibit no failure to fit *experimental* evidence[9].

CEG_e does *not* hold that *only* experimental evidence is relevant. Rather, it holds that theories failing to fit some experimental evidence should not be pursued. Consequently, paleontologists or morphologists should continue providing the non-experimental evidence characteristic of their fields, but must now fit that evidence to a theory that has no abject experimental failures.

CEG_e explains why pursuing a grander cosmopolitan theory would be more rational than not. In particular, theories such as neo-Lamarckism and orthogenesis do not fit experimental evidence. Consequently, the collective goal precludes the pursuit of these theories as a rationally viable option. Thus paleontologists or morphologists who held CEG_e stopped pursuing these theories and instead pursued theories that fit experimental evidence. But since only a limited number of theories do this, these field scientists pursued theories that promised to fit both their non-experimental evidence and that already fit experimental evidence. In short, they pursued *cosmopolitan* theories that unify field and laboratory evidence. Given that it was rational for field scientists to pursue theories of this sort, laboratory scientists knew that if they *also* pursued cosmopolitan theories, their chances of success would be higher than they had been during the Eclipse, as the field scientists were now pursuing a cosmopolitan theory.

Indeed, we can glean a more general argument from this example. Recall from §2.2 that unification increases when fewer theories fit the same evidence. By definition, CEGs exclude theories from being pursued. So, as long as the content of a CEG rules out local theories, then (ceteris paribus) a community with a CEG of this sort pursues fewer theories to fit the same evidence. Hence communities with CEGs are more likely to pursue unified theories than otherwise identical communities without CEGs.

Of course, that argument would also apply to the *Grand Cosmopolitan* CEG. However, unlike that CEG, CEG_e says nothing about *grand cosmopolitan* theories or *unification*, yet it nevertheless rules out the pursuit of certain local theories. This avoids the circularity that threatened the Grand Cosmopolitan CEG. Indeed, a CEG will mitigate uncertainty so long as it excludes theories that (i) possess epistemic properties that are present in one field but not another, and (ii) would have been pursued had the CEG been absent.

5. Implications for the Unification Debates

[8] Weismann's experiments on amputated mice tails was a famous disconfirmation of neo-Lamarckism; Morgan et al.'s (1915) fruit fly experiments, orthogenesis and to a lesser degree, saltationism.

[9] For simplicity's sake, we abstract away broadly holist considerations that an experimental failure might not entail abandonment of a theory, but a revision to an auxiliary. If one likes, the failures we have in mind are ones that would counsel those with Duhemian "good sense" to abandon the theory.

Thus, pursuing unified theories, in the form of grand cosmopolitan theories, is only rational insofar as certain coordination problems in the scientific community are resolved. Furthermore, CEGs are one way that scientists resolve these problems. How does this bear on philosophical debates about unification? Our main lesson is that *different circumstances call for different degrees and kinds of unification to be pursued*.

Most parties in the debates about unification assume that certain inquiries, such as the Modern Synthesis (and many others in physics), have witnessed successful pursuits in unification, while several other inquiries (especially in the psychological and social sciences) have not witnessed the same kinds of successes. "Uniphiles" then claim that the latter inquiries should nevertheless treat unification as a desideratum, which would imply that it is always rational to pursue unification. "Disuniphiles" (e.g. non-reductionists and pluralists) deny this claim[10].

Given this taxonomy, we are disuniphiles. Absent some mechanism to mitigate the risks of pursuing cosmopolitan theories, it is sometimes rational to forego unification. It is worth repeating that Table 1 suggests that our simple framework of fitting more evidence to fewer theories subsumes many leading accounts of unification. Consequently, while remaining agnostic as to which (if any) of these authors has correctly characterized unification, our view entails that none of these accounts of unification will always be rational to pursue, because in communities where the risks of cooperatively pursuing unified theories is at least as great as the corresponding reward, it is at least as rational to pursue a local theory. Furthermore, so long as more than one field exists, a global theory will be a grand cosmopolitan theory, and hence amenable to the same arguments. Thus, unification is only rational to pursue when certain social conditions—such as a CEG—are in place.

As presented thus far, disuniphilia is a wholly negative position. Aside from its advocates' shared suspicions about global theories' indispensability in integrating different scientific projects, there is little consensus regarding the alternatives[11]:

(i) *Local unification* occurs when most unification is regional, save for a few bridge theories or "trading zones" that unify a small subset of fields (Galison 1997).

(ii) *Patchwork unification* (Figure 2) occurs when theories there are only (mostly) bridge theories, each of which is tied to only one other theory (or small number of other theories) by fitting evidence in a common field, but no theory fits evidence in every field (Cartwright 1999)[12].

[10] Compare: "Monists might admit that a plurality of approaches and models meet appropriate scientific standards (or satisfy the corresponding epistemic values) but insist that this is only because today's science is incomplete. But we do not believe that the plurality in today's science is necessarily a temporary state of affairs" (Kellert, Longino, and Waters 2006, xi.).

[11] Our discussion is not intended to be a close exegesis of these positions; only a rough approximation of their views given the simplifying assumptions of our model. Our choice of terms is not always felicitous: many of these authors might chafe at our labeling their views as kinds of "unification." We leave the fine-tuning of our model and its attendant terminology as a future exercise.

[12] See also Dupré's (1993) view of (dis)unification as a cluster of theories bearing only Wittgensteinian family resemblance.

(iii) *Field-driven unification* (Figure 3) occurs when one (or a small set of) field(s) unifies otherwise disparate theories (Darden and Maull 1977)[13].

(iv) *Integrative unification* occurs when several partial theories are used to achieve a more complete understanding of a phenomenon (Longino 2002; Mitchell 2002).

Undoubtedly, there are other kinds of pluralistic unification, but these suffice for our purposes.

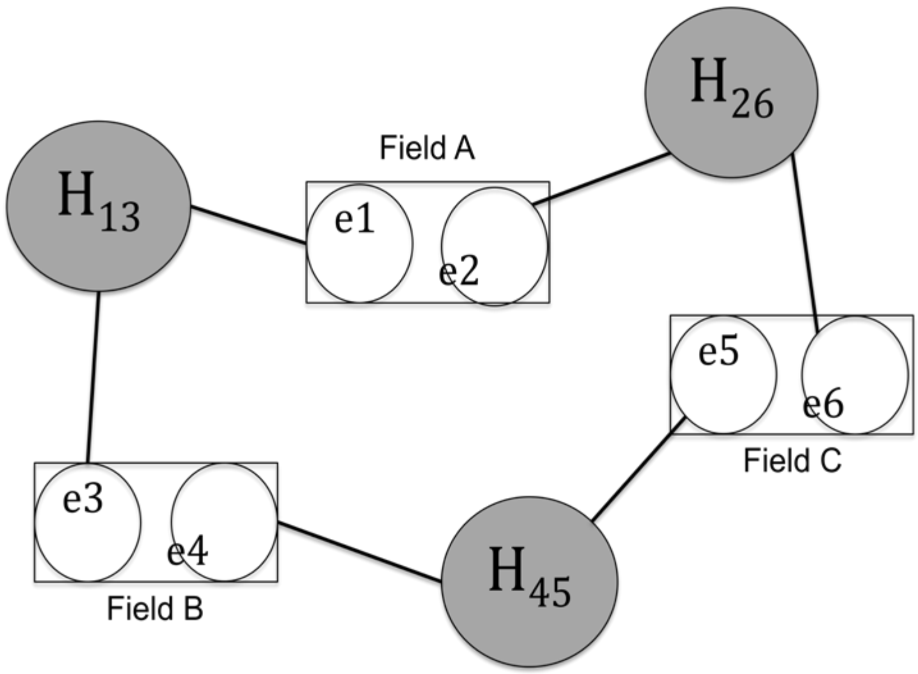


Figure 2. Example of Patchwork Unification.

[Grey circles denote theories; white circles, evidence; rectangles fields; and lines, fits.]

Our model sheds light on these "non-classical" brands of unification, as it suggests that they are rational to pursue under different circumstances. Thus, we urge *meta-disuniphilia* (a truly barbarous term!), i.e. disunity about the kinds of disunity that are rational to pursue.

Pursuing a bridge theory *à la* Galison is just a smaller scale coordination problem, and thus poses no special problem for our model. Local integration might be pursued if only a segment of a scientific community undertakes a CEG, while the rest remain uncoordinated or assign a very low probability to gaining cosmopolitan grandeur in their respective fields.

Pursuing patchwork unification will be rational when the pursuit of patchwork bridge theories is an equilibrium, and when there are no other equilibria that are more rational for scientists to pursue. Other possible equilibria include equilibria in which only

[13] Strictly speaking, Darden and Maull's "interfield" theories are bridge theories, modulo some differences in our definition of "fields." We focus on field-driven unification to illustrate the flexibility of our model.

local theories are pursued, and equilibria in which each scientist pursues a cosmopolitan theory grander than the patchwork bridge theory she would otherwise pursue.

If the patchwork bridge equilibrium is Pareto superior to the local equilibrium, and if no superior grand cosmopolitan equilibrium exists (e.g. because of high costs or low probability of success), then the same analysis of grand cosmopolitan unification applies to patchwork unification. This is possible if the patchwork theories are grander than the local theories for every scientist; or if the patchwork theories are equally grand as the local theories, but if each scientist values cosmopolitan theories more highly than local theories.

If the patchwork bridge equilibrium is not the Pareto superior equilibrium, either because there exists a grand cosmopolitan equilibrium or because the patchwork bridge equilibrium is not superior to the local equilibrium, then the patchwork bridge equilibrium can still be rational for the agents to pursue, so long as each agent believes the others to pursue it. This might occur through the existence of a CEG, or through general salience concerns.

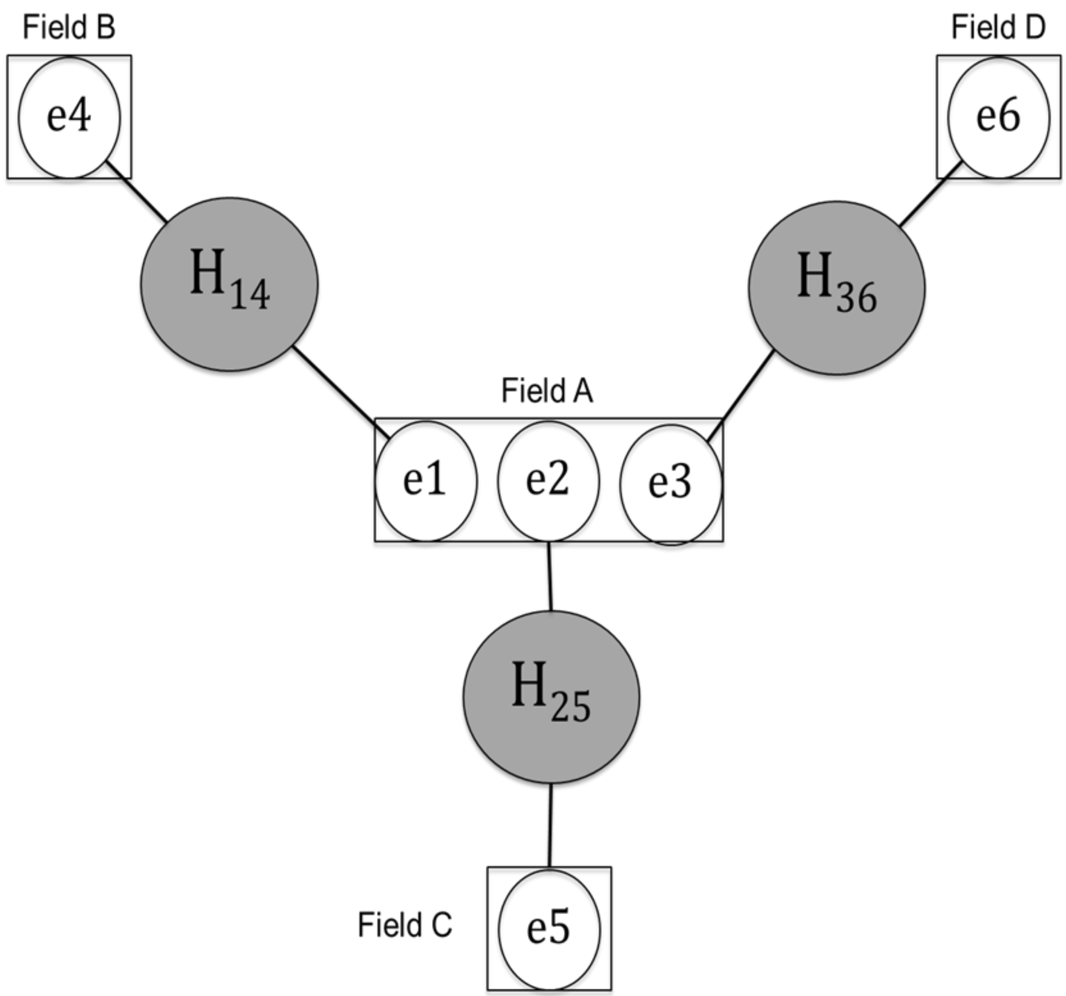


Figure 3. Example of Field-Driven Unification.

Similarly, field-driven unification is rational to pursue if the global equilibrium is not more salient than the field-driven equilibrium. (If different aspects of the same phenomenon are treated as distinct pieces of evidence in a single field, then this field-driven unification is also integrative, as we shall assume here.) Again, three equilibria are possible: local, field-driven, and grand cosmopolitan. The field-driven equilibrium is Pareto-superior to the local equilibrium; the disparate theories are unified with the common field, yielding a grander theory than they otherwise could produce. Moreover, in pursuing a number of cosmopolitan theories, the unifying field fits more evidence than a grand local theory would.

Thus, pursuing field-driven unification is rational so long as the field-driven equilibrium is more rational to pursue than the grand cosmopolitan equilibrium, which holds under varied conditions. First, pursuing grand cosmopolitan theories can be prohibitively risky, especially for scientists who specialize in disparate fields. For such a pursuit to be salient, scientists in these fields might be required to know how their work fits many other fields. By contrast, scientists pursuing field-driven unification might only need to know how their work fits with the unifying field. Depending on their content, CEGs can also promote field-driven equilibria over grand cosmopolitan equilibria.

6. Conclusion

Using the tools of game theory, we have provided a social epistemology that specifies the various conditions in which it is rational to pursue a wide variety of (dis)unified theories. We have shown that it can be rational, under certain circumstances, to pursue one of several limited kinds of unification. For virtually any conventional model of unification that has been offered, there are specific conditions where it is also rational to forego its pursuit. Consequently, even limited unification is not always a desideratum on theory pursuit. However, our model also specifies when the paradigmatic form of unification—a global theory—is rational to pursue; and also when more exotic forms of unification would be more rational to pursue.

Appendix

For simplicity, consider a scientific community consisting of two scientists A and B, and let $E = \{e_1, e_2, e_3, e_4\}$ be the set of phenomena confronting them, such that A specializes in $E_A = \{e_1, e_2\}$ and B specializes in $E_B = \{e_3, e_4\}$.[14] An action for a scientist consists of pursuing a theory intended to fit one or more phenomena. As defined above, a theory may be local or cosmopolitan, and within these categories, may differ in degree of grandeur.

In addition to the assumptions (A1)–(A7) stated in the text, we make the following additional assumptions for the sake of calculation:

[14] All results generalize to the case of N scientists, where N is finitely large.

(A8) A scientist will pursue a cosmopolitan theory iff he expects it to fit all phenomena within his area of expertise.

(A9) A scientist will not pursue a theory that seeks to fit all $e \in E$.

Note that (A9) prevents scientists from pursuing a "Theory of Everything", and shows how unification can be promoted even when there is no clear global theory to be pursued.

Given (A8) and (A9), the action sets of the scientists are given by $A_A = \{a_1, a_2, a_{12}, a_{123}, a_{124}\}$ and $A_B = \{a_3, a_4, a_{34}, a_{134}, a_{234}\}$, where a_{ijk} is the action of pursuing a theory that fits e_i, e_j, and e_k where $i, j, k \in \{1, 2, 3, 4\}$ and $i \neq j \neq k$.

The pursuit of a theory will not inevitably lead to its development. Thus, let p_l (or q_l) be the probability with which scientist A (or B) succeeds in developing a theory which fits exactly l phenomena, where $l \in \{1, 2, 3\}$. By (A6), we have $p_1 > p_2 > p_3$ and $q_1 > q_2 > q_3$. Without loss of generality, we assume that $p_1 > q_1$[15].

The pursuit of a theory imposes a cost on a scientist and yields a benefit if the pursuit is successful. For notational simplicity, we assume:

(A10) The gross benefit and cost of a theory that fits exactly l phenomena is invariant over the precise phenomena being addressed by the theory for all $l \in \{1, 2, 3\}$.

The cost of pursuing a theory that fits l phenomena is denoted by c_l and the gross benefit received from the successful development of such a theory is V_l for scientist A and W_l for scientist B. By (A3) and (A4) we have $c_1 < c_2 < c_3$. By (A5), we have $V_1 < V_2 < V_3$ and $W_1 < W_2 < W_3$.

In accordance with (A3)–(A7), the structure of payoffs for scientist A is specified as follows and that of scientist B is defined analogously (substituting W_l for V_l throughout). Let $U_N(a_m, a_n)$ be the net payoff for scientist N from the act profile (a_m, a_n). Then[16]:

$$U_A(a_1, a_3) = U_A(a_1, a_4) = U_A(a_1, a_{34}) = U_A(a_1, a_{234}) = U_A(a_2, a_3) = U_A(a_2, a_4) = U_A(a_2, a_{34}) = U_A(a_2, a_{134}) = \boldsymbol{p_1 V_1 - c_1}$$

$$U_A(a_{12}, a_3) = U_{A(a_{12}, a_4)} = U_A(a_{12}, a_{34}) = \boldsymbol{p_2 V_2 - c_2}$$

$$U_A(a_{123}, a_4) = U_A(a_{124}, a_3) = \boldsymbol{p_3 V_3 - c_3}$$

$$U_A(a_1, a_{134}) = U_A(a_2, a_{234}) = (\boldsymbol{p_1 + q_3})\boldsymbol{V_1 - c_1}$$

$$U_A(a_{12}, a_{134}) = U_A(a_{12}, a_{234}) = \boldsymbol{p_2 V_2 + q_3 V_1 - c_2}$$

[15] Apart from a purely technical restriction, this also introduces a desirable heterogeneity into the model, either with respect to the relative complexity of the two sets of phenomena the scientists are interested in or with respect to their relative competence.

[16] In pursuing a theory that seeks to fit e_1, scientist A obtains a net expected payoff $(p_1 V_1 - c_1)$ from her own efforts. Additionally, the effort of scientist B gives her an expected payoff of $q_3 V_1$ by way of greater corroboration of her research interest e_1.

$U_A(a_{123}, a_3) = U_A(a_{124}, a_4) = \boldsymbol{p_3 V_3 + q_1 V_1 - c_3}$

$U_A(a_{123}, a_{34}) = U_A(a_{124}, a_{34}) = \boldsymbol{p_3 V_3 + q_2 V_1 - c_3}$

$U_A(a_{123}, a_{134}) = U_A(a_{123}, a_{234}) = U_A(a_{124}, a_{134}) = U_A(a_{124}, a_{234})$
$= \boldsymbol{p_3 V_3 + q_3 V_2 - c_3}$

The game can now be represented by the following payoff bimatrix:

$A\backslash B$	a_3	a_4	a_{34}	a_{134}	a_{234}
a_1	$p_1V_1 - c_1$, $q_1W_1 - c_1$	$p_1V_1 - c_1$, $q_1W_1 - c_1$	$p_1V_1 - c_1$, $q_2W_2 - c_2$	$(p_1 + q_3)V_1 - c_1$, $q_3W_3 + p_1W_1 - c_3$	$p_1V_1 - c_1$, $q_3W_3 - c_3$
a_2	$p_1V_1 - c_1$, $q_1W_1 - c_1$	$p_1V_1 - c_1$, $q_1W_1 - c_1$	$p_1V_1 - c_1$, $q_2W_2 - c_2$	$p_1V_1 - c_1$, $q_3W_3 - c_3$	$(p_1 + q_3)V_1 - c_1$, $q_3W_3 + p_1W_1 - c_3$
a_{12}	$p_2V_2 - c_2$, $q_1W_1 - c_1$	$p_2V_2 - c_2$, $q_1W_1 - c_1$	$p_2V_2 - c_2$, $q_2W_2 - c_2$	$p_2V_2 + q_3V_1 - c_2$, $q_3W_3 + p_2W_1 - c_3$	$p_2V_2 + q_3V_1 - c_2$, $q_3W_3 + p_2W_1 - c_3$
a_{123}	$p_3V_3 + q_1V_1 - c_3$, $(q_1 + p_3)W_1 - c_1$	$p_3V_3 - c_3$, $q_1W_1 - c_1$	$p_3V_3 + q_2V_1 - c_3$, $q_2W_2 + p_3W_1 - c_2$	$p_3V_3 + q_3V_2 - c_3$, $q_3W_3 + p_3W_2 - c_3$	$p_3V_3 + q_3V_2 - c_3$, $q_3W_3 + p_3W_2 - c_3$
a_{124}	$p_3V_3 - c_3$, $q_1W_1 - c_1$	$p_3V_3 + q_1V_1 - c_3$, $(q_1 + p_3)W_1 - c_1$	$p_3V_3 + q_2V_1 - c_3$, $q_2W_2 + p_3W_1 - c_2$	$p_3V_3 + q_3V_2 - c_3$, $q_3W_3 + p_3W_2 - c_3$	$p_3V_3 + q_3V_2 - c_3$, $q_3W_3 + p_3W_2 - c_3$

Figure 4. Payoff matrix of game.

We solve the game under the following assumptions:

(A11) The (marginal) increase in expected benefit from pursuing a theory that fits two phenomena over one that fits a single phenomenon is less than the (marginal) increase in cost. Formally,

$p_2V_2 - p_1V_1 \leq c_2 - c_1$ and $p_2W_2 - p_1W_1 \leq c_2 - c_1$.[17]

(A12) The cost of pursuing a theory which fits three phenomena is sufficiently higher than one which fits a single phenomenon. Formally,

$c_3 - c_1 \geq p_3V_3 - (p_1 - q_1)V_1$ and $c_3 - c_1 \geq p_3W_3 - (p_1 - q_1)W_1$[18]

(A13) The gross benefit from pursuing a theory which fits two phenomena is sufficiently greater than that from a theory which fits a single phenomenon. Formally,

[17] (A11) stipulates that humbler local theories are preferred over grander local theories. The overall proof would still hold if (A11) stipulated the reverse.
[18] This assumption makes (A5) precise.

$$V_2 \geq \left(1 + \frac{q_1}{q_3}\right) V_1 \quad \text{and } W_2 \geq \left(1 + \frac{q_1}{q_3}\right) W_1$$[19]

Proposition 1: Under (A11)–(A13), the set of pure strategy Nash equilibria of the game is $NE = \{(a_1, a_3), (a_1, a_4), (a_2, a_3), (a_2, a_4), (a_{123}, a_{134}), (a_{123}, a_{234}), (a_{124}, a_{134}), (a_{124}, a_{234})\}$

Proof: Let $BR_A(x)$ be the best response set of player A to the action x of player B. Let $x = a_3$. Then $V_A(a_{123}, a_3) > V_A(a_{124}, a_3)$, so $a_{124} \notin BR_A(a_3)$. By (A11), $V_A(a_{12}, a_3) \leq V_A(a_1, a_3) = V_A(a_2, a_3)$. Further, by (A12), $V_A(a_1, a_3) = V_A(a_2, a_3) \geq V_A(a_{123}, a_3)$. Hence, $BR_A(a_3) = \{a_1, a_2\}$. By analogy, $BR_A(a_4) = BR_A(a_{34}) = \{a_1, a_2\}$. Finally, note that (A12) and (A13) imply:

(i) $\quad c_3 - c_1 \leq p_3V_3 - p_1V_1 + q_3(V_2 - V_1)$

By (A11), (A12) and (i), $BR_A(a_{134}) = BR_A(a_{234}) = \{a_{123}, a_{124}\}$. The characterization of the best response set for scientist B follows analogously and the following BR diagram establishes the proposition.

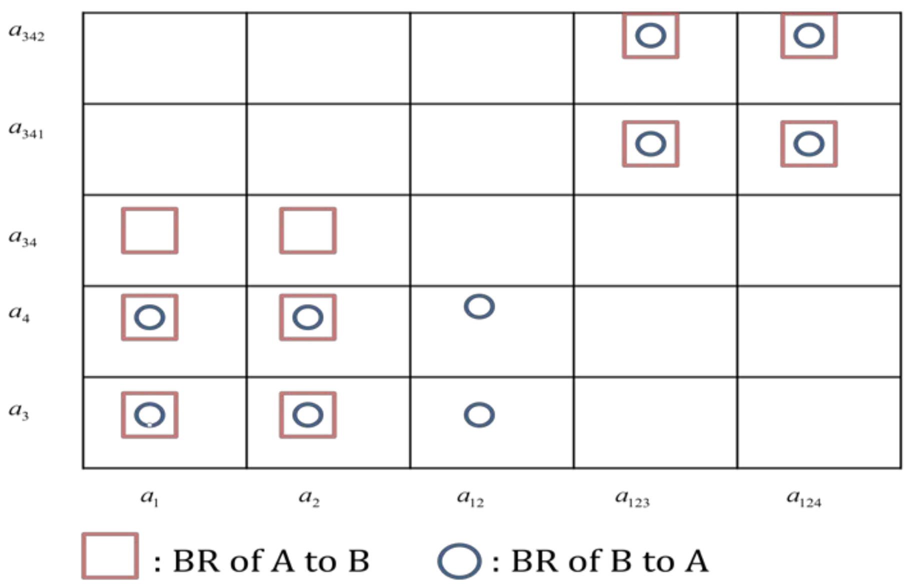


Figure 5. Best response diagram from Stag Hunt Game.

Proposition 2: The game described above is a Stag Hunt Game.

Proof: It suffices to note that the following inequalities should hold for the game to be a Stag Hunt:

$(p_3V_3 + q_3V_2 - c_3) \geq (p_1V_1 - c_1) \geq 0$ and $(q_3W_3 + p_3W_2 - c_3) \geq (q_1V_1 - c_1) \geq 0$

These follow directly from the assumptions listed above.

[19] This assumption makes (A6) precise.

Before we investigate the impact of a collective epistemic goal (CEG) on the basic game, note that (A12) implies the following:

$$\text{(ii)} \qquad W_1 \geq \frac{p_3}{p_1 - q_1} W_3 - \frac{1}{p_1 - q_1}(c_3 - c_1)$$

As noted above, the functional effect of a CEG on a game is to remove certain actions from rational consideration. For simplicity of presentation, we model CEGs as altering the payoffs of outcomes proscribed by the CEG such that they do not become equilibrium choices[20]. Assuming that scientist A specializes in experimental evidence and B in non-experimental evidence, the experimental CEG (CEG_e) has the effect of reducing the benefit that scientist B receives from his local theories a_3, a_4, and a_{34}. As such, assume that:

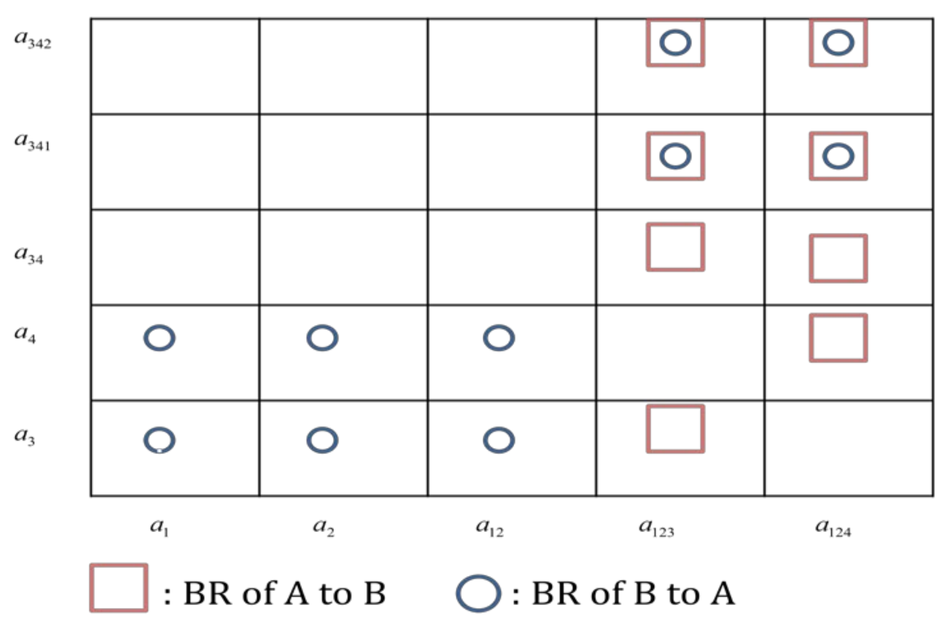
(A14) CEG_e reduces W_1 such that $W_1 \leq \frac{p_3}{p_1 - q_1} W_3 - \frac{1}{p_1 - q_1}(c_3 - c_1)$.

Note that since $W_2 = W_1 + \frac{q_1}{q_3} W_1$ (by (A13)), this reduces W_2 as well.

Proposition 3: Under (A11), (A13) and (A14), the set of pure strategy NE of the game with CEG_e is given by $NE = \{(a_{123}, a_{134}), (a_{123}, a_{234}), (a_{124}, a_{134}), (a_{124}, a_{234})\}$.

Proof: Noting that (A14) is essentially reversing the inequality in (A12), the proof follows along similar lines to that of Proposition 1.

The best response diagram is as follows:



[20] This captures the functional effect of CEGs on deliberation; we do not make the further claim that this is an exhaustive definition of CEGs.

Figure 6. Best response diagram for Stag Hunt Game with CEG.

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