Hot-Blooded Gluttons: Dependency, Coherence & Method in the Historical Sciences.

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Abstract

Our epistemic access to the past is infamously patchy: historical information degrades and disappears and bygone eras are often beyond the reach of repeatable experiments. However, historical scientists have been remarkably successful at uncovering and explaining the past. I argue that part of this success is explained by the exploitation of dependencies between historical events, entities and processes. For instance, if sauropod dinosaurs were hot blooded, they must have been gluttons; the high energy demands of endothermy restricts sauropod grazing strategies. Understanding such dependencies extends our reach into the past in spite of incomplete data. In addition, this serves as a counterexample to two accounts of method in the historical sciences. By one, historical science proceeds by identifying 'smoking guns': traces which discriminate between live hypotheses. By the other, historical hypotheses are supported by consilience: the convergence of independent lines of evidence. However, testing for 'coherency' between past hypotheses also plays a critical role in historical confirmation. Just as historical scientists exploit dependencies between past entities and present entities to infer what the past was like, they also exploit dependencies between past entities themselves. I do not suggest that archetypical historical science proceeds in this manner. Rather, the lesson I draw is that historical methodology cannot be characterized as archetypically relying on one method or another. Historical science is at base opportunistic, and is resistant to unitary analyses.

1. Introduction.

2. Snowballs & Explosions: the Basic Idea.

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1. Introduction

Our access to the past is fragmentary: geological processes like subduction ensure that mineral traces are destroyed; the probability of an organism fossilizing and its remains surfacing are miniscule; our picture of pre-Socratic philosophy is pieced together from passing mentions in incomplete texts. In the face of such destruction, some philosophers and scientists are pessimistic about uncovering past facts[1]; perhaps history's mysteries will remain so. And yet, historical scientists frequently produce firmly supported, well-founded and plausible narratives[2]. This paper investigates part of the explanation of this success: the exploitation of dependencies between past events, entities, mechanisms and processes (I will use the catchall term 'entity').

How the world is depends on how the world was: New Zealand's distinctive fjords, the Milford Sounds, were moulded by past geological events. During recent Pleistocene ice ages, glaciers carved Milford's valleys, eroding them to below sea level. The fjords formed when the glaciers receded and the valleys flooded. The glaciers also left the moraines which dot Milford's

[1] See, for example, Turner's ([2007]) arguments for anti-realism about historical science, Lewontin's ([1998]) pessimism about recovering hominid evolution, and Binford's ([1967]) epistemic deflation about discovering the behaviour and social structures of pre-literate societies.

[2] Historical scientists are not, of course, only in the business of providing narrative explanations of single cases, they are also interested in explaining large-scale patterns. Although my two cases studies are narratives (see Currie [2014a]), I assume the lessons will carry over to the investigation of historical regularities.

landscape. Had the ice ages not occurred, Milford would look different. Given that the Sounds are as they are, the ice ages must have occurred in certain ways. Our primary window into the past is granted by dependencies between contemporary form and past events, such as the Pleistocene ice ages and modern-day Milford. My central message is that such dependencies also exist between past entities, and that these are exploited by historical scientists. Support is not simply drawn from the relationship between a past hypothesis and contemporary traces, but from its coherence with other past hypotheses. How our picture of the past 'hangs together' is critical for historical science.

This matters for two reasons. First, if we overemphasize 'traces', such as the relationship between modern Milford's moraines and Pleistocene glaciation, how historical scientists construct sophisticated and plausible theories of the past looks mysterious. At least sometimes, such evidence is thin on the ground, yet rich hypotheses are produced, and investigation progresses. This mystery is party resolved when we see that historical scientists also exploit dependencies between past events themselves. Second, this undermines two attempts to characterize the methodology of historical science. Specifically, I target accounts which tie support primarily to common cause explanation, associated with Carol Cleland's 'smoking gun' view ([2002], [2011]), and accounts which emphasize the importance of independent lines of evidence, most clearly developed by Forber & Griffith ([2011]). These do not sufficiently emphasize the reliance on dependencies between past events, being overly focused on the analysis of 'traces', contemporary forms. I take this as reason to think that there is no simple model of archetypical historical methodology. Historical scientists are opportunistic and apply a plurality of methods.

I argue that testing for coherency between hypotheses about past entities is a common and important pattern of reasoning in historical science. This successfully generates knowledge by exploiting dependency relations which hold between entities located in the past. This matters because it explains the surprising epistemic reach of historical science. There is, then, a descriptive aspect to this paper: that coherency plays a role in historical reasoning. I also make normative claims about the nature of this reasoning. Although I will sometimes speak in terms of 'coherence', I don't see myself as committing to the epistemic power of coherence *per se.* My view is that our epistemic access to the past is extended in virtue of the dependencies between past events. This has an explanatory angle. Explanatory sufficiency, I will argue, demands that historical scientists take past events as embedded in the world's complex, interdependent structure. This demand, as well as our understanding of dependencies and the processes which produce them, underwrites 'coherence-tests' which generate rich knowledge of the past.

Having said this, I think in broad terms a similar story can be provided about both the evidence from traces, and the evidence I focus on. One way in which historical scientists generate evidence is by exploiting dependency relationships between the variables of contemporary states of affairs and past states of affairs. Milford's present-day geological features depend upon events in the Pleistocene, and are evidentially relevant in virtue of our knowledge of the relevant geological processes. Evidence is also generated by exploiting dependencies between entities contained in the past. As we'll see, if sauropods were endothermic (were hot blooded), they must have managed to consume large quantities of plant matter with high efficiency (they were gluttons). In virtue of this, having good reason to believe in sauropod endothermy also grants us reason to believe certain hypotheses about their grazing strategy. Just the same evidential story can be told for both the dependencies between present-day Milford and the Pleistocene, and between sauropod thermoregulation and browsing strategies. Dependencies of many types, then, gain evidential relevance in virtue of our knowledge of the various processes which produce them. In addition to describing the method of historical science, then, I also provide a story about its vindication[3].

[3] I'd like to thank an anonymous referee for pushing me on these points.

I introduce my argument by discussing Neoproterozoic and Cambrian events, before providing a more detailed case study: investigation of thermoregulative systems in sauropods. I then shift to a more abstract discussion. I define a very broad sense in which events, entities or processes might be dependent, show how these dependencies give rise to interdependent explanations, and how these relationships are evidential. Finally, I turn to attempts to characterize the methodology of historical science.

2. Snowballs & Explosions: the basic idea

Some entities' properties depend on the properties of other entities—and this provides empirical inroads to their investigation. As we saw in the introduction, there are dependencies between contemporary observations—'traces'—and the past, like Pleistocene ice ages and the Milford Sounds. There are also dependencies between different past events. Although I will explore sauropod thermoregulation in some detail, it is worth sketching another example to demonstrate that the phenomenon is not a quirk of my case study, and to introduce the main conceptual point.

Consider the relationship between two events in the deep past. According to the snowball earth hypothesis, at least twice during the late Neoproterozoic (say, 590 million years ago) the earth froze over. Relatively soon afterwards (a mere 50 or so million years) the earth's rocks record an unprecedented radiation of metazoan life known as the 'Cambrian explosion'. It is generally accepted that these events are linked: the ancestors of Cambrian fauna must have survived snowball earth. And this has consequences for our knowledge of both events. For instance, how could complex life survive a frozen planet? As Hoffman and Schrag ([2002]) put it,

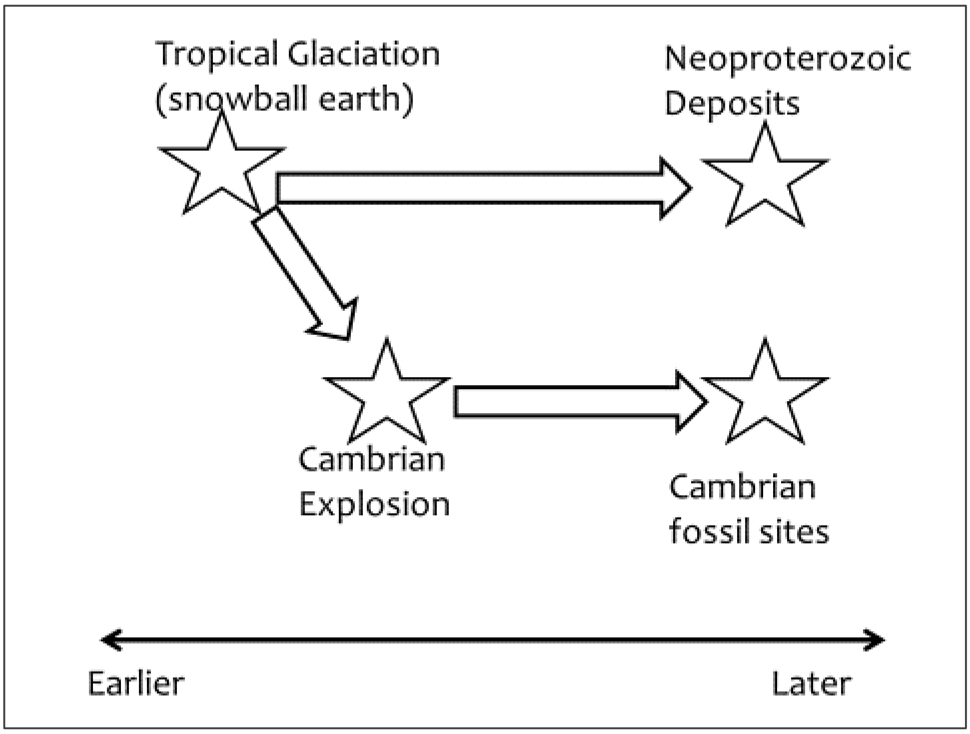
> Assuming snowball events occurred, what refugia ensured the survival of eukaryotic plankton, and early metazoans if they existed? How did the climate shocks entering and exiting snowball events impact their evolution? (147).

In response, scientists construct simulations testing between a complete freeze (a snowball) and something less extreme (a 'slushball') (see, for instance, Hyde et al [2000], Donnadieu et al [2004]). The occurrence of the Cambrian explosion gives reason to believe that the Neoproterozoic freeze was incomplete.

Moreover, Neoprotorozoic events are revelatory of the Cambrian. For the radiation to occur, pockets of life must have been isolated in order to diverge both phylogenetically and developmentally without evolving complex, novel traits. Snowballs could act as pelagic filters, ensuring life remained relatively simple due to the '… almost complete destruction of terrestrial biota and shallow-water, bottom-dwelling life…' (Runnegar [2000], 404). This could explain how early life was separated and evolved divergent resource pools for evolution to exploit once balmier Cambrian conditions arrived:

> ...some environmental filter was required to maintain early metazoans in 'larval mode' after they had invented set aside cells. This enabled them to diversify into well-separated lineages that ultimately became the independent sources of radically different body-plans (Ibid, 404).

Aspects of the Neoproterozoic glaciation and the Cambrian explosion, then, depend on each other. Given the explosion's occurrence, the glaciation must have occurred in certain ways. Had the glaciation been different, so too the explosion. Although the causal relations are asymmetric (as illustrated in figure 1), the relationships of dependence are more symmetrical.



1: Causal relations between entities in the Neoproterozoic, the Cambrian Explosion, and their present-day traces.

Not only did the Neoproterozoic glaciation leave traces in modern rocks, it also influenced how other events—such as the Cambrian explosion—occurred. Scientists utilize both traces from the Neoproterozoic and theories of the Cambrian explosion to test and support the snowball earth hypothesis. They also call on events from the Neoproterozoic to explain the Cambrian radiation. In short, the dependency between the two events is exploited to further investigate them. In what follows, I provide a detailed paleobiological case study, before turning to a more abstract discussion.

3. Were Sauropods Endothermic or Ectothermic?

Investigators of sauropod physiology exploit dependency relationships between the properties of extinct lineages. Sauropods, distinctively long necked, tiny-headed, barrel-bodied *saurischian* giants were, without doubt, one of the most successful terrestrial animals the earth has had the pleasure of hosting. Ranging in mass from 15 to 50 ton (Ganse et al [2011]), they dominated Mesozoic ecosystems from their late Triassic arrival through to being sent on their way at the Cretaceous' close. Sauropod gigantism is mysterious. No other terrestrial lineage comes close: the best mammals have managed is *Paracetherium*, at a middling maximum of 18 ton (Fortelious & Kappelman [1993]). A complex research program has developed which attempts to both reconstruct sauropod morphology and physiology, and to explain the lineage's evolution (see, for instance, Sander et al [2011], Klein et al [2011], Currie [2014]). Here, I focus on one aspect of sauropod physiology: thermoregulation.

Did sauropods regulate their temperature internally (endothermy) or externally (ectothermy)[4]? Answering this question is no walk in the paleobiological park. To support theories of thermoregulation in extinct lineages, scientists appeal to evolutionary speculation, physiological modelling, homologies, and bone histology. Although evidence points towards an endothermic system in sauropods, there is reason for caution. Our evidence is fragmentary and (so far) inconclusive. Let's run through some considerations from either camp. As Gillooly, Allen et al ([2006]) argue, heating can be less costly for larger ectothermic organisms. In planetary science, massive bodies conserve surface heat due to thermal inertia. A version of this effect, 'gigantothermy', may have operated in sauropods. This is supported by models which predict thermoregulation systems via reconstructions of body heat across different body masses. Moreover, models suggest that the challenges of heat dissipation could restrict maximal size in terrestrial endotherms.

The main argument for warm-bloodedness in sauropods is, as Ganse et al ([2011]) highlight:

> … the high growth rates recorded in the histology of their bones… There seems to be no way for giant sauropods to reach a body mass of >50 metric tons in a reasonable lifetime

[4] Thermoregulative systems are more complex than implied by my simplistic usage of 'endothermic' (maintaining a steady temperature through internal regulation) and 'ectothermic' (using external heat sources), but this is irrelevant for my purposes.

without having—at least partly during their life span—a high resting metabolic rate comparable to or even higher than that in mammals (108).

Ectotherms grow more slowly than endotherms, and bone histology sets sauropod growth at a blistering pace. They began life at 5kg and grew to 10,000 times that size in around 20 years, an infeasible feat for the cold-blooded. And so, an ectothermic sauropod would have advantages at larger sizes but would not grow with sufficient speed. An endothermic sauropod might grow fast enough, but respiration and heat dissipation would be problematic[5] as an adult. There is a further problem with endothermy which is the focus of my discussion: how could sauropods have eaten enough?

Ectothermic giants have comparatively low energy needs and so can afford to be (actually, must be) relatively sanguine in their pursuit of food. Endotherms need to be much more active: a 5 ton African Elephant spends 16 hours a day browsing. How could a 50 ton sauropod, then, manage to feed itself? They must have been gluttons: ingesting huge quantities of material with minimal energy expenditure.

Sander & Clauss ([2008]) answer this challenge by highlighting sauropod traits which would increase intake while minimizing outlay. They provide what Arno Wouters ([1995]) has called a 'viability explanation': the organism is explained in terms of needs which must be met if it is to survive and reproduce. Notions of 'function' in the explanation, then, are not evolutionary[6]. They are, rather, about the successful maintenance of an organism during its lifetime. As we shall see, their explanation relies on dependencies between aspects of sauropod morphology and physiology. I argue this leads to a mutually supporting explanation: the independent support we have for sauropod endothermy carries over to Sander & Clauss' account of sauropod feeding

[5] As Wedel ([2009]) and Ganse et al ([2011]) point out, sauropods' bird-like respiratory system, which included air-sacs and a pneumatised (hollow) skeleton, could have aided heat dissipation.

[6] Which is not to say that viability explanations do not have import for evolutionary theory: arguments that, for instance, sauropod neck length enabled them to ingest sufficient food typically carry with them the assumption that they also evolved for this purpose.

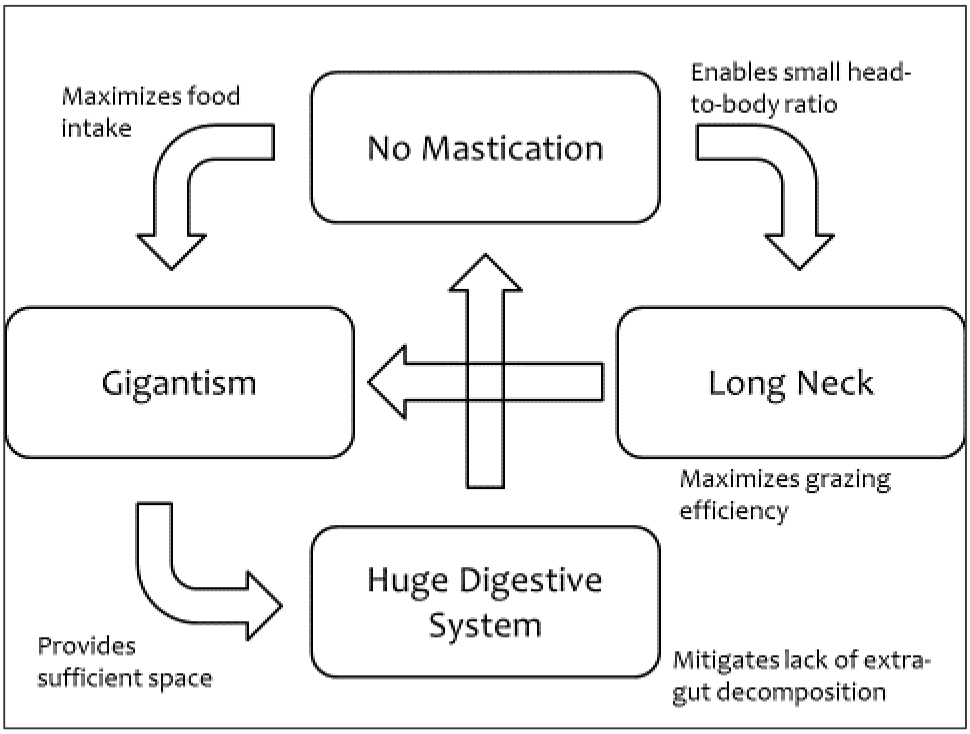
strategies, and vice-versa. As I make explicit in 4, the exploitation of such dependencies is a crucial part of the historical scientist's toolkit. Sander & Clauss emphasize two sauropod traits, not present in mammals, which both plausibly enable sufficient gluttony, and explain how other aspects of sauropod morphology could have supported those traits.

First, consider the sauropod neck. There is debate about the evolutionary purpose, morphology and physiology of this distinctive trait[7]—too much to summarize here (see Christian & Dzemski [2011]). Needless to say, on most accounts the neck either differentiates feeding heights (the neck operates like a 'crane', allowing higher foliage to be reached), or increases browsing range while minimizing movement (the neck operates like a vacuum cleaner, allowing the sauropod to consume large quantities of food without having to shift its bulk, see Ruxton and Wilkinson [2011]). In both cases, a long neck increases food consumption at minimal cost. Why, then, do mammalian giants not have long, serpentine necks? The answer is dentition. Mammalian teeth are extraordinarily specialized, and this sets a lower limit on the ratio between head and body size. Mammals need large heads to accommodate their fancy teeth, and so long necks are infeasible without significant bracing and support. Sauropod teeth were not as specialized, which freed them to have a lower head-to-body-size ratio, and thus a long neck.

Second, sauropods did not chew. Although they had diverse dentition, reflecting diverse life-ways, all sauropods swallowed unmasticated plant matter. Mammals outsource much of their digestion (in the extreme case of ruminants, repeatedly through cud chewing), but this decreases ingestion volume. Sauropods didn't stop to chew, and so maximized food intake. Of course, this comes with a cost: without chewing or gizzard-stones, sauropod digestion was carried out entirely 'in-house'. And this is one reason why, viability speaking, sauropods may have

[7] The main point of contention, besides the 'purpose' of the neck, is on morphological reconstruction: could sauropods raise their necks?

needed to be gigantic: to house their extensive digestive 'vats'. We can think of Sander & Clauss' viability explanation, then, as a four node network represented by figure 2:



2: Viability explanation of sauropod endothermy

Viability explanations identify a need, and posit the conditions under which that need holds. Endotherms need significant quantities of food, and this limits maximal viable size. For sauropods to be both gigantic and hot-blooded, then, they must have been gluttons. Ruxton & Wilkinson ([2011]) estimate that larger sauropods required 237kg of fern, conifer and gymnosperm per day: this calls for features enabling the ingestion of prodigious amounts of food. Sander & Clauss identify two such features: not chewing and a long neck. But the viability of these features also needs explanation: an enormous gut is required to digest all of that unmasticated food, and this needs a lot of space.

We have independent reason to think that sauropods were gluttons, and to think they were hot-blooded. In addition to this, the two hypotheses are evidentially linked: if they were hot-blooded they were surely gluttons, and their gluttonous feeding strategy grants reason to think they were hot-blooded. Understanding the dependence between sauropod traits extends our knowledge. I will summarize some independent evidence, before illustrating their dependence.

We have reason to believe that sauropod physiology was true to Sander & Clauss' work independently of concerns about thermoregulation. Paleobiologists exploit an impressive array of evidential sources. Ruxton & Wilkinson undertake a geometric investigation to demonstrate the energetic benefits of increased neck length. Hummel, Gee et al experiment on the descendants of Jurassic plants (ferns, gymnosperms and so on), fermenting them in vats and taking heat as a proxy of nutritional value. This is used to suggest that Mesozoic flora could support sauropods. Analysis of sauropod fossils, trackways and coprolites are used to reconstruct their morphology and physiology.

We also have independent reason to believe in sauropod endothermy: it is infeasible for an ectotherm to grow at sauropod rates. First, high growth rates are expected based on sauropod life-spans: sauropods only live for so long, and must get from 5kg to 50,000kg. Second, there is evidence from evolutionary theory. Assuming that sauropod gigantism is at least in part a response to predation, we should expect fast growth; if you seek safety in bulk, get bulky quickly. Third, there is more direct evidence of high growth rates from bone histology. Moreover, the charge of ectothermic infeasibility is supported by physiological theories, tested against contemporary ectotherms and endotherms.

In addition to these independent reasons, Sander & Clauss link the physiological picture in figure 2 to endothermy. As we saw with theories of Neoproterozoic glaciation and the Cambrian explosion, each provides insight into, and supports, the other. If sauropods are endothermic, then they must have been capable of ingesting much more food, at much less outlay, than mammals; hot-blooded sauropods had better be gluttons. So, if we think sauropods were endothermic, then something along the lines of figure 2 must be right. And, of course, this is true in reverse: figure 2 represents a viability explanation of sauropod endothermy. The confirmation of sauropod endothermy and Sander & Clauss' physiological picture is coupled.

As we saw with snowball earth and the Cambrian metazoan radiation, exploring dependencies between possible sauropod feeding strategies and thermoregulative systems also generates new hypotheses. For instance, even if Sander & Clauss are right, how did such large terrestrial endotherms solve problems of heat dispersal? Farlow ([1990]) suggests that sauropods led dual metabolic lives. Beginning as endotherms, their metabolic rates dropped off as they approached adulthood, thus avoiding the danger of overheating and taking advantage of gigantothermy. I have no idea how plausible this hypothesis is, but further research will no doubt shed light.

And so, by considering dependencies between different aspects of sauropod morphology and physiology, Sander & Clauss reach into the past in spite of apparently fragmentary evidence. Let's draw some lessons.

4. Dependent Entities & Interdependent Explanations

In this section I analyze, in abstract terms, the phenomenon illustrated in 2 and 3. I start by characterizing a notion of dependence and from that, interdependency between explanations, and their mutual support. This will form the basis of my claim that coherency between past hypotheses plays an important role in the method of historical science, and explains why considerations of coherence work. Note that I will shift from speaking ontically of dependencies between events, processes and entities (and their elements, which I will call 'variables') to discussion of explanations as representations. This is for convenience, and I doubt anything turns on it.

How the Cambrian explosion occurred was in part dependent on events in the Neoproterozoic. It may be that, had the world snowballed completely, life would not have survived, or the metazoans may not have radiated when they did, if at all. Moreover, if snowball events kept a cap on biological activity, allowing phylogenetic divergence without phenotypic novelty, then the radiation having occurred as it did, depended on the periodicity and length of snowball events. Although the causal relation is asymmetric, the dependence is (more) symmetrical. If one variable, say the extent of Neoproterozoic icepack cover, is set too high, then another variable, maybe the timing of the metazoan radiation, changes. And conversely, if the metazoan radiation occurred differently, then there may be differences in the Neoproterozoic. I capture such dependencies via a notion of 'minimal dependence':

> Some variable, v_1, is *minimally dependent* on another variable, v_2, just when v_2 taking a particular value, or range of values, effects the probability of v_1 taking a particular value, or range of values[8].

This notion of dependence captures both constitutive and causal relationships. Most causal relationships are *inter*-entity, process or event; they hold between variables in different systems. Constitutive relationships are *intra*-entity, process or event; holding between variables in the same system. The dependency between snowball earth and the Cambrian explosion is inter-entity, while some dependencies appealed to in reconstructing sauropods are intra-entity; sauropods need small teeth to allow for the small heads required for their long necks. Although I

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[8] This is clearly inspired by recent work on 'manipubility' accounts of causation and explanation, in particular Woodward ([2001], [2010]) and Waters ([2007)]. Some philosophers might worry about the apparently ontic but non-chancy notion of probability I appear to be appealing to—see Lyon ([2010]) for an excellent discussion of the kind of thing I have in mind. It is worth comparing this notion with that of supervenience. Supervenience relations typically hold between properties at different ontological 'hierarchies', and are intended to articulate metaphysical views about reduction. For instance, one might explicate the notion that 'beauty' is a natural property using supervenience: the 'beauty' of an entity is determined by that entity's physical properties. One of many ways of capturing supervenience is modally: one property supervenes on another just in case any changes to the first property necessitate changes to the second property (see Stalnaker [1996] for other versions). Minimal dependence is weaker than supervenience as changes in the dependent entity do not necessitate changes in the other entity. It is also broader, as it includes causal relations and is indifferent to ontological hierarchies.

characterize dependence in terms of 'variables', elements in a system, a derivative sense between entities is readily available. Two entities are dependent just when there is dependency between at least one of each's variables. I want minimal dependence to be as broad as possible: mere statistical dependence is all that is needed—although typically historical scientists will represent dependence in causal terms. As we shall see, by building on this notion we can characterize how such dependencies grant access to the deep past.

Consider the events in figure 1. Not only are the 'traces' of the Neoproterozoic and the Cambrian minimally dependent on those events, but they are minimally dependent on each other. It is plausible that, if one event was different, the other would be too. In virtue of this, if we have either theories representing those dependencies, or empirical evidence of their correlation, they will be evidentially relevant to one another. Typically, historical scientists do not rely on mere empirical correlations to bring out dependencies: rather, they posit causal models which connect past entities. For traces such as Cambrian fossils and Neoproterozoic rocks, background theories of geology and taphonomy grant evidential relevance by connecting them to the past[9]. Similarly, theories of the conditions needed for life grant evidential relevance between snowball events and the Cambrian explosion. In virtue of such theories, we can draw on these dependencies to support and constrain hypotheses. If sauropod thermoregulation is set to 'endotherm', then resource needs will be higher than otherwise. This makes other viability claims, such as neck length functioning to maximize volume while minimizing energy expenditure, more likely. Again, theories which explain the dependencies between variables grant evidential relevance.

Prima facie, There is no important difference, evidentially speaking, between exploiting what I am calling 'traces'—dependencies between contemporary phenomena and past targets, and

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[9] Peter Kosso ([2001]), following Binford, calls this 'middle range theory'.

the phenomena I am interested in here[10]. In both cases, evidential relevance is granted by theories representing the relevant dependencies and the processes which produce them. Having said this, I will soon argue that coherency considerations—exploiting dependencies between past entities—is driven by explanatory considerations. Such dependencies cannot be ignored for fear of explanatory insufficiency. Before making that argument, I will briefly cash out some different kinds of dependency.

Presumably, the more dependency there is between or within entities, the more potential there is for exploitation. There are three senses in which the level of dependence could increase. First, more variables might be dependent. If Sander & Clauss are right, endothermy in sauropods depends not only on neck length, but on a lack of mastication, extensive digestion, and gigantism. Entities which are 'enmeshed', with large numbers of dependent variables, are easier accessed than more isolated entities. This is because new information about any particular variable is more likely to carry over to others. Knowledge of sauropod endothermy will probably affect knowledge of neck length, digestion and masticatory habit. Moreover, enmeshed entities are more likely to generate independent lines of evidence which, as we shall see, can boost a hypothesis' overall support.

Second, variables can be linked more determinately: instead of restricting values to a range, they can be restricted to a particular value, or to a more conservative range. Woodward's ([2010]) notion of 'causal specificity' can be applied to this phenomenon. A causal relation between two variables is maximally specific if there is a one-one mapping function between the value taken by one variable and the value taken by another. For instance, the relationship between my stereo's volume dial and its decibel output is more specific than the relationship between the power button on my stereo and its decibel output. This is because changes to the

[10] Carol Cleland ([2011]) argues against the importance of coherent narratives in historical method on the basis of their being too speculative. I take it that the story I provide here responds to this complaint.

volume dial affect decibel output gradually and systematically, while hitting the power button cuts output to zero. Understanding the specificity of dependencies is important. For instance, by experimenting on modern flora thought to be representative of the Jurassic, and estimating their nutritional content, Hummel, Gee et al potentially provide a more determinate idea of how much sauropods needed to ingest. This depends on how specific the relationship between nutritional content and ingestion volume is. If it is highly specific, then fine-grained information about Jurassic flora will make a difference to sauropod ingestion capacities (and matter for hypotheses about the relationship between gigantism and endothermy). However, if the relationship is low in specificity, detailed information will not have that effect. Background theories about the specificity of the relationship between intake volume, nutritional content, and digestion, then, are essential for understanding sauropod gigantism.

Third, the probability of the dependent variable falling within a specific range can increase. Some evidence for sauropod endothermy, such as the implausibility of high growth rates in ectothermic systems, does not change the specific values of, say, how much sauropods needed to eat. However, they do make it more likely that sauropod necks functioned to maximize intake. Call this a dependency's 'strength'. Low-specificity dependencies can still be important if they are 'strong'. Imagine that the relationship between snowball earth and the Cambrian explosion is similar to the power switch on my stereo. If there is a snowball event, the explosion will likely occur, but how the snowball plays out does not affect how the explosion plays out. However, the snowball is necessary for there to be an explosion. If that were the case, then there being a Cambrian explosion grants extremely good reason to think that there was a snowball event in the Neoproterozoic, but it does not tell us much about the extent, nature or timing of the snowball.

An important determinant of our access to a past entity, then, is not simply how many traces it has left us, but how dependent it was on other entities in the past. We can understand dependencies between and within entities in terms of how enmeshed they are (how many variables are dependent), their specificity (how informative) and their strength (how much they constrain possibility).

The nature of dependencies turns crucially on the ‘contingency’, or path dependence and sensitivity of the system in question. Contingency is a central issue in paleobiology, and this is not the place for a discussion of the conceptual intricacies (see Desjardins [2011]; Turner [2011], [2014] and Beatty [2007], for instance). Suffice to say, some entities are highly sensitive to initial conditions and stochastic effects. Dependency relationships pertaining to such entities will be highly local and specific. It is plausible, for instance, that the evolution of sauropod gigantism was highly contingent: their size is unique in a terrestrial animal, and its explanation points to a cluster of local events in the history of that phylogeny (see Currie [2014] for discussion of the explanation’s form). These dependency relationships, then, only hold under very specific conditions. This means that many dependencies must be captured by localized models, rather than general theories.

Contingency has led me to shift from discussion of ontic dependence, holding between variables, events and so on, to discussion of explanation, hypotheses and models. I will continue in this vein, arguing that the reliance on dependencies between past entities has an explanatory flavor. This forms the basis of my argument that explanatory sufficiency underlies the exploitation of such dependencies.

I have stated that I see the story of evidential relevance for dependencies between past entities to be similar as that for dependencies between contemporary traces and the past. Both count as evidence in virtue of background theory which captures the relevant dependencies. However, it is worth delving into how historical scientists exploit such dependencies in more detail. This will matter in section 5 when I compare various models of the method of historical science. When past entities are highly dependent in the ways discussed above, and we have models which grant evidential relevance by illuminating that dependency, we can construct what I call 'interdependent' explanations which are 'mutually supporting'.

'Interdependence' is a relation between two explanations or hypotheses[11]. Recall Sander & Clauss' network. Sauropods are gigantic in order to mitigate their lack of mastication, they do not masticate because specialized dentition would make their small heads infeasible, and they need small heads in order to have long necks. Such explanations overlap. The explanation represented in figure 2 is a group of related explanations stitched together into a larger narrative. This larger narrative consists of various hypotheses which are explanatorily interdependent insofar as removing one part of the explanation would undermine it. Explanation of sauropod dentition which does not mention their long necks misses important, perhaps essential, detail.

> Two explanations, *a* and *b*, are *interdependent* just in case *a* must include *b* for explanatory sufficiency, and vice-versa.

Explanatory interdependence leans heavily on a notion of explanatory sufficiency. The thought is that successful explanation requires for some details to be included and others omitted. How to account for and justify specific claims about sufficiency—what to include and what to omit—is, to say the least, a vexing philosophical issue[12] and I don't want to commit to a particular view here. I can provide an illustration, however. Interdependence concerns the inclusion of details in an explanation: for instance, an explanation of sauropod feeding strategies which fails to mention the dependency between long necks and tooth specialization is defective. One can capture this by appealing to explanation's contrastive character: that is, a good explanation picks out the factors which differentiate the target from relevant contrasts (Lipton

[11] Potochnik ([2010]) discusses cases of explanatory independence and epistemic interdependence. Explanations of sauropod physiology and evolution might be like this. Although in explaining sauropod physiology I can black-box their evolutionary story (and so they are independent in terms of explanation), the justification of that story nonetheless turns in part on facts about sauropod evolution.

[12] For some versions, see Strevens ([2008], chapter 8), Weisberg ([2007]), Craver ([2007], chapter 7).

[1990]). An essential contrast for sauropods is with mammals: if having a long, supple neck is such an effective way of maximizing browsing efficiency, why is this not seen in mammals? The answer is in mammalian tooth specialization. Our fancy teeth need to be housed in heads of a sufficient ratio to body size, and a low ratio is required for sauropod-like necks. Small heads, and thus long necks, are denied to mammals—and this explains the contrast with sauropods.

And so, because *a* and *b* are targeting dependent events whose dependencies play an essential role in dividing the relevant contrasts, an explanation of *a* ought to capture that dependency and vice-versa. A viability explanation of sauropod endothermy which does not account for sauropod grazing is deficient, as an endothermic giant would have to consume large quantities of food, and it is this capacity which makes the difference between sauropods and other endotherms. Note that appeals to contrasts are just one way of understanding explanatory sufficiency: other machinery may be more or less amenable to my purpose here. The important point is that the requirements of explanatory sufficiency plausibly force dependence between past entities into the picture. This feature explains the importance of coherence in historical science, as our understanding of the dependencies themselves grants epistemic relevance.

Explanatory interdependence frequently (perhaps always) goes hand-in-hand with *mutual support,* a kind of evidential interdependence.

> Two explanations, *a* and *b*, are *mutually supporting* just in case they have coupled confirmation: *a* is more likely if *b* is true, and vice-versa.

First, consider the relationships between the nodes in figure 2. Taken together, they explain how sauropods were more efficient consuming machines than mammals. This explanation can be divided into smaller parts which constitute answers to different questions. For instance, because sauropods did not masticate they required extensive gut systems. This is explanatory interdependence: the whole network consists of smaller explanations elegantly fitted together, and those smaller explanations must mention each other, at pains of insufficiency. For example, the explanation that sauropods have large bodies to accommodate large digestion vats is insufficient without reference to their lack of mastication, as animals which chew partly out-source their digestion, and so do not need to be as enormous.

Now consider the relationship between that network and the hypothesis that sauropods were endothermic. We have independent grounds for thinking sauropods are warm-blooded: growth rates, physiology and ecology all suggest this. Because the network makes endothermy more plausible, our credence in the network's explanation should be tied to our credence in endothermy. If we think endothermy likely, we should think the network likely. And, if we think the network likely, then we should also think endothermy likely. After all, if sauropods were endothermic, something like that network must be true. The two are mutually supporting: they do not merely constrain one another but actively boost each other's likelihood. The dependencies between events, then, can act as a kind of evidential conduit: evidence for one hypothesis becomes evidence for another. This picture underwrites a normative claim about method in historical science. Explanatory sufficiency often demands that historical entities be investigated in terms of the dependencies they hold with other entities in the past. When such dependencies are well understood, and have some of the qualities I mentioned earlier (are enmeshed, informative and strong), robust, rich reconstructions of the past are the result.

This picture is suggestive of coherentist accounts of justification, but is not wedded to them. Coherentists, roughly speaking, hold that we are justified in believing the truth of some proposition if it coheres with the other propositions we believe to be true. For the coherentist, justification is holistic: it depends upon how a particular belief fits in our 'web' of belief. The view is typically contrasted with foundationalist accounts of justification, where most propositions are justified via some form of entailment from known fundamental principles. Although the importance of dependency relations to historical science fits nicely within a coherentist account, it is not necessary to take that view on justification to understand historical science—my analysis surely doesn't turn on the ultimate nature of justification. Indeed, there is nothing that I can see to stop a foundationalist from accommodating what I have said. Insofar as various epistemic views agree that evidential relevance is set by background theories which represent dependency relations, I do not need to commit to one or the other. However, I have argued that in some cases support for historical hypotheses comes in large part from their coherence with our picture of the past. That is, the links between the ways things are now and the ways things were, is not sufficient to understand the rich knowledge historical science produces. We must also concern ourselves with links between entities in the past.

And so, dependencies between past variables, as well as dependencies between the past and the present, provide inroads to the past. Scientists exploit these by constructing interdependent explanations with coupled confirmation—call these 'coherency tests'. Despite incomplete, fragmentary traces, understanding the relationship between events in the past allows us to extend our reach into it. This is one part of the story of how historical scientists achieve so much with so little material remains. In the final section, I use this discussion to tackle philosophical accounts of the methodology of historical science.

5. Smoking Guns & Consilience

I have argued that coherency-tests between past hypotheses is a critical part of the method of historical science. These tests are underwritten by dependencies between and within past entities and driven by the demands of explanatory sufficiency. In this section, I criticize two further views. By one, historical science follows a distinct methodology—in particular, progress is made by explaining puzzling correlations between traces, and hypotheses are empirically discriminated by hunting out new traces, or 'smoking guns'. By the other, historical methodology is continuous with other sciences, and primary support is provided by 'consilience', that is, the independent convergence of evidence. I lay out and compare the two views, before arguing that they underemphasize coherency-tests: the exploitation of dependency between past entities. I will resist taking coherency-tests as a rival to these views, but rather suggest that the historical sciences use a plurality of methods.

A popular way of understanding the methodology of historical science is the practice of inferring 'common causes': that is, historical hypotheses are supported in virtue of unifying a group of apparently disparate traces. Take Aviezar Tucker ([2004], [2011]), for instance:

> The historical sciences are concerned with inferring common causes or origins: contemporary phylogeny and evolutionary biology infer the origins of species from homologies, DNA, and fossils; Comparative Historical Linguistics infers the origins of languages from information preserving aspects of existing languages and theories about the mutation and preservation of languages over time (Tucker [2011], 20).

On this kind of view, a surprising correlation between traces is resolved by postulating a past event which explains both. In addition to Tucker, Sober ([1988]) and Kleinhans et al ([2005], [2010]) could be read in this light. The most developed of these views, and my focus, is Carol Cleland's:

> Hypotheses concerning long-past, token events are typically evaluated in terms of their capacities to *explain* puzzling associations among traces discovered through fieldwork (Cleland [2011], 552).

By Cleland's lights, the methodology of historical science proceeds by identifying puzzling traces, postulating a series of hypotheses which could account for them, and then hunting for 'smoking guns': further trace evidence which discriminates between those hypotheses (Cleland [2002], [2011], [2013])[13]. Hummel, Gee et al's study of Jurassic flora was motivated by the hypothesis that sauropod gigantism was driven by low nutritional content in Mesozoic plants.

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[13] Particularly in her [2002], Cleland present this method in contrast with 'experimental science', see Turner ([2009]) and Jeffares ([2008]) for pressure on this distinction.

Midgley et al ([2002]) claim that sauropod gigantism is an adaptation to the Jurassic's low-nutritional flora. Because nutritional content is low, high quantities of food must be ingested. A solution is to increase digestive capacity (and thus overall size). Assuming there is a positive relation between the nutritional costs of size increase and digestive payoff, low nutrient content could drive selection for gigantism. If this hypothesis is true, the descendants of Mesozoic plants are likely to have less nutritional content than more modern arrivals. This can act as a smoking gun which discriminates between Midgley et al and other's hypotheses.

And so, for Cleland, historical methodology is primarily abductive, and progresses by discriminating between competing hypotheses on the basis of the discovery and analysis of further traces. The central concept of her account is the 'smoking gun', a piece of trace evidence which, given the set of hypotheses currently on the table and the evidence so far, speaks in favour of one hypothesis over another. In addition to her claim's plausibility when matched to the practice of historical science, she also appeals to both metaphysical principles ([2002]), and physical theories ([2011]) to underwrite this methodology.

Other philosophers emphasize the importance of multiple streams of evidence (Wylie [2010], [2011]; Currie [2013]; Forber & Griffith [2011]). Here's an example of such 'consilience'. Hummel, Gee et al speculate that sauropods preferentially dieted on the more nutrient-rich plants of the Mesozoic: particularly gymnosperms, but also some conifers and ferns. They suggest this hypothesis could be corroborated by analysis of sauropod coprolites. Let's imagine that we discover some coprolites and from these infer that, indeed, sauropods primarily ate gymnosperms. We now have two pieces of evidence. The first is based on Hummel, Gee et al's study combined with gigantism in sauropods: given the high demands of gigantism, it is plausible that sauropods ate high-nutrient plants. The second is based on coprolite analysis. These two evidence streams are, in Alison Wylie's terms, 'vertically independent': they rely on different auxiliary hypotheses, but converge on the same result.

> Of necessity, evidential reasoning depends on multiple strands of arguments: it emanates from disparate elements of the archaeological record, draws on background knowledge that originates in diverse source fields, and bears on an array of conditions and events that constitute the complicated lives of the material things that make up the archaeological record (Wylie [2011] pp386-387).

When two independent lines of evidence converge on the same result, the amount of support generated is more than the sum of their individual contribution. Imagine that the hypothesis that sauropods had a high nutrient diet was false even though it is indicated by Hummel, Gee et al's study, and the (imaginary) analysis of coprolites. If that were the case, then the two studies would have (1) got the wrong answer, but nonetheless (2) independently converged on that mistake. This is much less likely than the hypothesis being true. The independent convergence of evidence, then, can dramatically boost a hypothesis' support (see Fitelson [2001] for a Bayesian proof).

Forber & Griffith ([2011]) argue that convergence '…provides the primary source of support for such historical reconstructions' (1). Their argument is based on the need to overcome problems of testing holism: failures of some tests (even smoking guns!) can be blamed on failures in auxiliaries, rather than the tests' putative target. Hummel, Gee et al's study relied on several auxiliary hypotheses. For instance, that contemporary gymnosperms have similar nutritional content to Mesozoic gymnosperms, and that heat produced during fermentation is a proxy of nutritional content. Midgley et al could respond to Hummel, Gee et al's study by undermining either of those auxiliaries. As Forber & Griffith discuss, because independent lines of evidence rely on different auxiliaries, '… they provide epistemic support that is less sensitive to testing holism' (3).

And so, we have two views about the primary method of historical science. Each highlights a pattern of reasoning which is taken to play an important role in how they generate knowledge. On the one hand, historical scientists seek smoking guns, on the other, they seek convergences between independent lines of evidence. Note that both Cleland and Forber & Griffith are clear that these positions are not definitions of historical science, but are competing archetypes. However, I suspect these archetypes are not as incompatible as it first appears.

Forber & Griffith (to an extent following Jeffares [2008]) read smoking guns as '… a naturally occurring *experimentum crucis*' (3). That is, a smoking gun is a single piece of evidence which discriminates decisively between two hypotheses. If this is what Cleland thinks, her view is extremely implausible. First, in practice much evidence from the past is incomplete and ambiguous, and so critical tests are few and far between. Second, in light of testing holism it is unclear whether there are any *experimentum crucis* in an epistemic sense: a faulty auxiliary premise can undermine what looks like the most critical of tests. This is particularly pressing in historical contexts, where the connection between evidence and hypothesis is often extremely indirect. In recent writing ([2013]), however, Cleland more clearly distances herself from this kind of view:

> Considered in isolation, independently of the other lines of evidence, few traces would unambiguously count as a smoking gun for a hypothesis. A smoking gun for a hypothesis is a capstone piece of evidence; it can only be judged as a smoking gun when combined with the rest of the evidence available (Cleland [2013], 4).

What counts as a smoking gun depends upon the context of investigation; it is only against the backdrop of what evidence is currently available that a smoking gun counts as such. Indeed, Cleland embraces a wide conception of 'smoking gun'. These are not critical tests which unambiguously differentiate between theories. Rather, they are collections of new trace evidence which can be bought to bear on past hypotheses. Cleland discusses evidence from field studies of ammonite fossils, morphological changes across preserved shellfish, shifts in pollen deposits, and their collective role in supporting reconstructions of the late Mesozoic. '… [A] smoking gun may consist of a large and diverse body of new evidence' (Cleland 2013, 5). In short, the hunt for ‘smoking guns’ just is the hunt for common causes, specifically the hunt for *new* traces to be so unified.

What, then, is different about the two views? Cleland argues that hunting for further traces is justified on the grounds that we should expect them to be bountiful and diverse. Her argument for this expectation appeals to the nature of the relationship between the present and the past. Roughly, because causal relations spread and multiply over time, events in the past should have many downstream effects. If so, past events will have more than sufficient available traces for us to empirically discriminate between relevant hypotheses. The central difference in opinion, then, concerns how historical scientists go about generating evidence, and why this works. By one, the main business of historical science is the hunt for smoking guns, which is underwritten by the nature of the relationship between the present and the past. By the other, it is the hunt for consilience, which is underwritten by the need to overcome testing holism. The two models of method have differing justifications.

Regardless of their relationship, the two archetypes have an important commonality: they both focus on a particular kind of dependency relation, that between entities in the past and contemporary ‘traces’. Cleland explicitly appeals to the capacity of past hypotheses to explain ‘puzzling associations’ of traces. Forber & Griffith also discuss historical reconstruction as providing ‘…the resources to successfully explain puzzling extant traces, from fossils to radiation signatures…’ (1). The main source of evidence by both accounts, then, are dependency relationships between a past entity and its downstream traces. Coprolites are evidence of sauropod dietary preferences in virtue of there being dependencies between what sauropods ate, and features of coprolites.

However, I have argued that in some contexts historical support is licensed by dependencies between past entities. If sauropods were hot-blooded, then, given their gigantism, it is likely they sought out flora of high nutritional content. Because if a giant is to be viable, she needs sufficient food. Hypotheses of gigantism and grazing strategies are, in virtue of these dependencies, interdependent. In addition to providing explanations of traces, then, historical scientists strive for a coherent picture of the past. By linking past entities—developing models of their dependency—historical scientists further explore and test hypotheses. Emphasizing traces is not sufficient to explain the rich and plausible hypotheses historical scientists produce.

One might object by pointing out that Forber & Griffith or Cleland's account can accommodate dependencies between past entities. Surely the dependency between gigantism and thermoregulation just is a smoking gun on Cleland's account, and just is one of the streams of evidence on Forber & Griffiths' account. Indeed, I could also point out that their case studies can be understood in terms of aiming at a maximally coherent pictures of the past. However, this objection misses the point. Accounts like Cleland's are supposed to be explanatory: they give us some traction on how historical scientists do their work, and what justifies it. My claim is that it is often the dependencies between past entities (driven by the requirements of explanatory sufficiency), rather than consilience or identifying smoking guns, which is doing the work in supporting hypotheses about the past.

And so, do I want to forward the hypothesis that historical scientists hunt for coherency between past entities, and the construction of interdependent explanations, as opposed to smoking guns or consilience? No, I don't think so. The lesson is that historical science is too disunified to admit of an 'archetypical' characterization; there is no methodological 'essence' to be had. And this is not surprising: historical scientists are nothing if not opportunistic. As they frequently lack experimental access to their targets, and sometimes face incomplete and biased evidence, historical scientists apply whichever methods maximize their epistemic reach. And indeed identifying smoking guns, drawing together independent streams of evidence, and discovering dependencies between past entities, are all important parts of this story. The point is this: the success of historical science is not due to some unified method, but due to a plurality of methods.

The attention historical scientists pay to coherence between past hypotheses goes some way to explaining their success. Despite an apparent paucity of data, ensuring that their picture of the past is consistent by uncovering dependency relationships between past entities, sometimes allows them to overcome epistemic challenges. Historical scientists, then, have more resources at their disposal than it may first appear. This is not, by any means, the full story: a complete explanation of historical method must point to their opportunism and their methodological pluralism, rather than to any one approach (see Currie [2015]). The philosopher's task from here is, I think, to investigate whether we can say anything systematic about that plurality: it could be that different methods are more effective in different epistemic contexts, and that understanding those relationships could help explain both scientific practices and their varying successes.

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