Framing Causal Questions about the Past:

The Cambrian Explosion as Case Study

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Abstract. About 540 million years ago, a rapid radiation of animal phyla radically changed the Earth's biota in a geological eye-blink. What caused this "Cambrian explosion"? Over the years, paleontologists have pointed to a wide array of different physical mechanisms as the causal "trigger" for the explosion. More recently, some paleontologists have proposed complex causal pathways to which multiple physical mechanisms are said to have contributed. Despite their variety, these answers share an assumption that a single explanation can in principle be constructed that identifies some factor or confluence of factors as the cause of the Cambrian explosion. That assumption is unjustifiable. The Cambrian explosion had multiple causes, and different aspects of the event are best explained by different causes. These different causes cannot, even in principle, be integrated into a single causal explanation. We can learn much about the causes of the Cambrian explosion—or for that matter about any historical event—but only by attending more carefully to how we frame our causal questions about the past.

1. Introduction. Life on Earth before the Cambrian period was predominantly unicellular and homogeneous. The advent of the Cambrian was dramatic. In a geological blink of an eye, entirely new body plans appeared, many representing stem groups of modern forms of life. The "Cambrian explosion" was probably the single most significant radiation in evolutionary history. What caused it? In the past, most answers to this question have focused in on a single physical mechanism as the "trigger" primarily responsible for the radiation. More recently, some paleontologists have rejected the search for a single triggering cause, instead seeking to integrate an array of different physical processes into a single, complex causal explanation. Despite their differences, all these essayed explanations share a common assumption that a single explanation can in principle be constructed that identifies some factor or confluence of factors as the cause of the Cambrian explosion. That assumption is unjustifiable. Different aspects of the radiation are best explained by different causes. These different causes cannot, even in principle, be integrated into a single causal explanation. We can learn much about the causes of the Cambrian explosion. The search for a single, integrated causal explanation of the radiation, however, is chimerical. Pluralism in our explanations of the causes of historical events is ineliminable.[1] An approach that embraces

[1] My concern in this paper is causal explanations of historical events. I am not concerned with causal explanations of robust and repeating processes or with non-causal (e.g., statistical) explanations.

this fact offers the best prospect of knowledge of the causes of the Cambrian explosion, or indeed of any historical event.

2. The Search for a Primary Physical Mechanism. Most paleontologists who have analyzed the cause of the Cambrian explosion have searched for the single physical mechanism most directly responsible for the radiation. The candidate causes that scientists have proposed fall into three categories: environmental, developmental and ecological. Environmental explanations for the Cambrian explosion focus on developments in the earth's climate, chemistry or other similar factors. Developmental explanations point to changes affecting the ontogeny of individual animals. Ecological explanations privilege interactions among organisms, such as predation or parasitism.

Environmental mechanisms proposed as causes of the Cambrian explosion include: increased atmospheric oxygen made possible a range of new body types (Frei, et al., 2009); a "snowball earth" developed, with isolated ice-free refuges where new forms of life evolved (Runnegar, 2000); and tectonic movements released methane into the atmosphere, resulting in warming that enabled new forms to evolve (Kirschvink and Raub, 2003). Developmental mechanisms credited with setting off the Cambrian explosion include: key gene duplications allowed more complex animals to develop (Lundin, 1999); the evolution of neural cells enabled complex central nervous systems, driving the radiation (Stanley, 1992); and the increasing complexity of the "developmental toolkit" of regulatory genes opened up a much wider set of possibilities in ontogeny (Valentine, et al., 1999). Ecological mechanisms credited with setting off the Cambrian radiation include: increases in phytoplankton provided food for an array of new herbivores (Butterfield, 1997); new herbivores created ecological space for the development of a range of predators (Stanley, 1973); and the evolution of predators' ability to prey upon larger animals put pressure on prey, and in turn on predators, to evolve rapidly (Peterson, et al., 2005).

Despite their variety, the proponents of these alternative mechanisms share a similarity of approach. The scientists identifying developmental factors as primary do not deny the action of environmental factors (such as the presence of sufficient oxygen in the atmosphere to support large animals) or ecological factors (such as the availability of new ways of making a living that developmental mechanisms could seize on). And the same is true of the proponents of environmental and ecological explanations. Notwithstanding that a wide array of factors must have played a role in the causal sequence, however, they all identify one as primary. None of these scientists offer (nor, not being philosophers, should they be expected to offer) an explicit philosophical account of causation, and all are aware that a number of different forces cooperated in order to bring about the Cambrian explosion. Yet all, in one way or another, emphasize a single cause. Thus, Kirschvink and Raub (2003) identify methane as the "fuse" that set off the Cambrian explosion. And Peterson, et al. (2005) review an array of possible "triggers" and conclude that the evolution of predators that could prey on larger animals was "the ultimate cause" (50) of the Cambrian explosion.

We might best understand what these scientists have in mind by recourse to the concept of relative significance. A relative significance analysis conceives of each physical mechanism as a separable cause, responsible for some determinable part of the outcome. (For a fuller discussion of relative significance, see Beatty (1997).) The idea can be likened to vector addition of forces in physics. The analogy is not a perfect one: the relative contributions of environmental, developmental and ecological factors to the Cambrian explosion are not supposed to be ascertainable with mathematical precision, but in principle, the contributions are considered to be separable and additive. On this reading, a number of factors are understood to be operating, but one is identified as being of predominant significance relative to the other cooperating causes.

This way of thinking about how physical processes interacted to bring about the Cambrian explosion is an error. In vector addition, if one force were to stop operating, the others would continue unaffected. In contrast, the various physical processes that cooperated to produce the Cambrian explosion are not separable causes. Each of these processes are aspects of a single explanation that cannot even in principle be disaggregated so that their respective contributions to the outcome can be compared. They are inextricably complementary in their explanatory role.

Consider the following thought experiment (borrowed from Keller, 2010, 7-9): Billy and Suzy want to fill a 100-liter bucket with water. Each holds a hose over the bucket, and each turns on their tap. The water flows from Suzy's hose more quickly—in the time it takes for 40 liters to flow from Billy's hose, 60 liters have flowed from Suzy's hose. This is an additive system, and it makes perfect sense to say that Suzy is "the cause" of 60 percent of the water in the bucket, and Billy is "the cause" of 40 percent. Now imagine that the children dump out the water and start over, but this time they use one hose; Suzy holds the hose over the bucket, and Billy turns on the tap. In this latter case, it is impossible to attribute any particular percentage of the water to either child. We no longer have a system with two independent variables the effects of which can simply be added together, and to the extent additivity has been lost, our ability to assess the relative significance of Suzy's and Billy's respective contributions has been compromised. To generalize, when an event has multiple causes, we can only apportion responsibility among the various causes if the causes are separable and additive. Keller (2010, 38). There is nothing particularly new about this insight. The basic intuition dates back to Mill (1843/2006, 327-28), who asked his readers to suppose that a man had eaten a particular food and died. The cause of his death included the eating of the food, but also his bodily constitution, state of health and other factors: we might reasonably suppose that he would not have died had he not eaten the food, but also if he had not been susceptible to the particular poison. There is no secure philosophical basis, argued Mill, for singling out one cause as most important, or for any determination of the relative significance among the network of cooperating causes.

Keller's and Mill's logic applies to the causes of the Cambrian explosion. Even if we could successfully identify all of the causes of the radiation, the various causes are not independent. Within any one category of causes (environmental, developmental and ecological), the interactions are bound to have been plentiful and significant. At least some changes in the environmental conditions facing a particular Cambrian predator species must also have affected its prey and/or its parasites, with those changes feeding back on the predator, and so on. Any gene duplication in a Cambrian herbivore must have interacted with other changes in the animal's genome in significant ways. And ecological changes by definition have interacting effects: the notion of predation presupposes interacting predator and prey species, just as parasitism presupposes interacting hosts and parasites.

The interactions *between* the environmental, developmental and ecological causes of the Cambrian explosion must have been even greater. Organisms do not just respond to their environments; they create them through what evolutionary biologists call "niche construction" (see, e.g., Odling-Smee, et al., 2003) and ecologists call "ecosystem engineering" (see, e.g., Jones, et al., 1994), with the resulting environmental changes feeding back on the niche constructing organisms, and also on other species. Moreover, how new toolkit genes affected the development of any particular lineage must have been strongly influenced by the ecological dynamics affecting that lineage.

In short, the interactions between the various environmental, developmental and ecological variables that constitute the physical mechanisms underlying the Cambrian explosion are themselves central to the causal story. Attempting to "disentangle" the causes entirely misses the point that their entanglement is central to their causal power. Environmental, developmental and ecological factors are not alternative explanations, but elements in a cooperating network of causes. As with Mill's poisoned man and Keller's children filling a bucket, we have no secure philosophical basis to determine the relative significance of the various causes of the Cambrian explosion. The causes cannot be disentangled.

When I argue that the causes of the Cambrian explosion are inextricably intertwined, I do not contend that no meaningful distinctions can be drawn among the event's causes. Different aspects of an event may have different causes, such that which cause strikes us as primary depends on what aspect of the event we are most interested in explaining. But these distinctions among causes are only meaningful in the context of the interests of the individual asking the causal questions. Consider an attempt to determine the primary cause of the United States' entry into World War II. Many causes undoubtedly contributed. Which we would consider primary depends on what aspect of the war we want to explain. If we ask why the United States declared war *on December 8, 1941*, we would almost certainly point to the Japanese attack on Pearl Harbor the previous day. If, however, we ask why the United States entered the war *at all*, we might say that geopolitics had by that date made eventual American entry into the war inevitable, with the only question being when and under what circumstances war would be declared. By choosing what aspect of an event to emphasize, we exert powerful influence on what factors seem most powerfully causal in the occurrence of that event.

Consider again the Cambrian explosion. If we ask why the explosion happened when it did rather than some millions of years earlier, we might identify whichever event came last temporally. If we were interested in explaining why the radiation generated such a wide array of completely new body plans, we might focus on gene duplications or toolkit genes. And if we wanted to explain why the Cambrian fauna came so quickly to dominate vast, and vastly different, ecosystems, we might point to the open field created by the mass extinction of major Precambrian taxa. In any case, the cause that strikes us as primary is at least as much a function of what we want to know about the event as it is about the facts of the event. There was no ontologically "primary" cause of the Cambrian explosion.

3. The Search for an Integrated Cause. Some recent studies of the Cambrian explosion have implicitly accepted this kind of argument. Marshall (2006), for example, considers a range of environmental, developmental and ecological mechanisms. He does not offer a definitive answer to the question "What caused the Cambrian explosion?" But he does state that we should seek a single explanation for the event that integrates all these different mechanisms into one complex cause:

> It is clear that environmental, developmental, and ecological factors must have played a role in the Cambrian radiation; however, the questions still stand as to which factors are most important, which variant(s) of each class of explanation is most likely correct, and how the various factors interact. (370-71.)

He therefore demands "a fully integrated explanation for the Cambrian 'Explosion'" (378). Marshall's project is a genuine departure from the studies that sought to identify a single physical mechanism as the primary cause of the Cambrian explosion. Yet his study is of a piece with those efforts in assuming that it is possible in principle to determine the one true causal history of the event. Marshall's demand for an explanation of the Cambrian explosion that arranges an array of different factors into a single integrated cause is not unique.

Recently, it has become something of the norm. Thus, Erwin and Valentine (2013, vii) purport to "bring all these [environmental, developmental and ecological] pieces together to integrate the patterns and processes involved." And Sperling, et al. (2013, 13450) proclaim their own "integrated causal hypothesis" for the Cambrian explosion.

None of these paleontologists have explicitly defended why they consider such a goal to be achievable. Mitchell (2003 and 2008) has, however, offered a philosophical defense of this kind of approach. Mitchell believes that many, perhaps most, biological systems are "integratively complex": they have subsystems which themselves are built up of parts. These subsystems and parts interact in highly complicated and non-additive ways, and there are important feedback loops and other interrelationships among different levels of the system (between the subsystems and their respective parts, the whole system and its subsystems and the whole system and its parts). Integratively complex systems are "minimally decomposable," in that fundamental aspects of the global behavior of the system are left unexplained even by a complete understanding of how its parts behave.

This complexity has consequences for how we must approach the task of identifying causes. As we have seen, if we have a system composed of parts where the behavior of the parts can be added together to determine the behavior of the whole, we can use "mechanical" or "combinatorial rules" to identify the causes of the system's behavior—like using vector addition to calculate net electromagnetic forces (2003, 192-193, 206-207). For integratively complex systems, however, the interactions among levels and feedback effects necessitate different models and abstractions targeted to different aspects of the system. We may be able to created models of subsegments of the overall network of causes that *do* behave in roughly additive ways—what Mitchell terms "local theoretical unification" (193-194)—but the overall causal nexus of these types of events will not be definitively specifiable.

For these integratively complex systems, Mitchell proposes a strategy she calls "integrative pluralism." "Pluralism" refers to Mitchell's stance on how we must treat *types* of events—for the reasons just stated, we simply cannot avoid "pluralism of models of causal processes that may describe contributing factors in any given explanatory situation" (189). "Integrative' comes in at the level of token events: while we require a plurality of models at the level of the type, when we come to analyze a token event of that type, we must integrate the various models into a single explanation. Mitchell conceives of integrative pluralism as an "account of how idealized models are to be integrated into explaining concrete, non-ideal cases" (189). For Mitchell, therefore, the need for integrative pluralism ends at the individual historical event: "However complex and however many contributing causes participated, there is only one causal history that, in fact, has generated the phenomenon to be explained" (217). Thus, "[P]luralism at the theoretical level does not entail pluralism with respect to the explanations of specific cases." (207.) For Mitchell, as for Marshall, Erwin and Valentine and Sperling, et al., to explain an individual historical event is to describe the single, particular "causal history" that in fact generated the event.

Mitchell's ideas have clear implications for evaluating the causes of the Cambrian explosion. Adaptive radiations involve ecosystems, composed of populations of different species, each made up of individuals, each with its own developmental system. These systems, subcomponents and parts interact in complex, non-additive ways. The population density of one species may affect the fate of other species, and the future fate of its own species. Changes in the ecosystem affect individual organisms, and activities of individual organisms can affect the whole ecosystem. When seeking to explain adaptive radiations in general, Mitchell would suggest that we therefore must employ a plurality of theoretical approaches: from ecology to developmental biology to genetics to geochemistry, and so on. But when we turn to a *particular* adaptive radiation like the Cambrian explosion, we must integrate these various approaches into a single explanation. In Mitchell's account of integrative pluralism, then, we have a philosophical defense of paleontologists' search for a single, integrated explanation of the causes of the Cambrian explosion.

4. Why There Can Be No Single Integrated Explanation of the Cambrian Explosion. Mitchell's notion of integrative pluralism, and the apparent application of something like it to the Cambrian explosion, presupposes that one can offer a single causal explanation of a token event, albeit an explanation grounded in a highly complex set of integrated causal factors. Thus, pluralism at the level of the type becomes monism at the level of the token. In this section, I argue that no one combination of factors can be integrated into a single explanation of the cause of the Cambrian explosion. Our explanations of particular events such as the Cambrian explosion must be as uncompromisingly plural as our explanations of adaptive radiations in general. Pluralism is ineliminable, even at the level of the token event.

The reasons that this is true interrelate and feed back on one another and are not strictly separable, but there is a heuristic value in considering them in three categories: a plurality of ways to define the event, a plurality of questions that we may ask about the event and a plurality of idealizations that we may deploy to analyze the event.

All the approaches to the Cambrian explosion that I have considered implicitly presuppose that we know what event it is we are seeking the cause of. When we ask the question "What caused the Cambrian explosion?" we assume that "the Cambrian explosion" means something fixed and determinate, such that it is possible to imagine a single correct answer to the question. But this assumption is not as unproblematic as it at first seems. As Danto (1965, 233-35) argued in the context of historical explanation in general, when we use the word "event" to describe what we want to explain, we mask something fundamental. We think of an event as singular, as an individual occurrence. But explanations of historical events are inherently explanations of *changes*. As Danto put it, when we ask for an explanation of the event of a car getting dented, we make implicit reference to the car in its previously undented state. Our explanation of the event is an explanation of how the car *changed* from being undented to being dented. See also O'Hara (1988, 147).

If explaining an event entails explaining a change, we must answer at least two questions before we can offer any such explanation: (1) what are the beginning and ending points of the change we wish to explain? and (2) what is the nature of the change we wish to explain? What, in other words, are the temporal and conceptual boundaries of the change that constitutes the "event" at issue? But the boundaries of events are not fixed and determinate.

In order to analyze an event, *we* must fix these boundaries. We must decide what we are going to treat as part of the event, and what we are going to exclude from the event. As Danto (1965, 167) put it, when we collect a number of historical incidents into a single "event," we are placing them into a temporal and causal structure, and there is "no a priori limit" on the different causal and temporal structures into which we can place any given historical incident.

Consider first, the temporal structure of the event. The beginning and ending of a historical event are not ontologically given; we determine them by reference to our interests. World War II is often treated as starting with the Germany's invasion of Poland, but we might set its beginning with the earlier annexation of the Sudetenland or with the Munich conference when Britain and France acquiesced in the annexation. Or we might contend that a full understanding of the war requires that we begin with the German humiliations at Versailles in 1919. Similar issues attend fixing the end of the war. These are not pedantic quibbles. When we fix the temporal boundaries of an event, we constrain what can count as a cause of the event. If we set the beginning of World War II at the annexation of the Sudetenland, the Allies' behavior at Munich becomes conceptually unavailable to us as a cause of the war—as part of the "event" we want to explain, Munich cannot simultaneously be a cause of that event.

What of the conceptual boundaries of the event? Just as we must choose when to set the beginning and ending of our event based on what we are most interested in understanding, so too must we choose the nature of the change that is of interest to us. One historian of World War II may be interested primarily in the military aspects of the conflict. His or her analysis of the Battle of Midway would likely focus on intelligence, tactics and materiel. A second historian more interested in strategic questions might take the view that the central question is not why the Allies won, but why the Japanese made the decision to initiate the fateful battle at all. Clearly, narrow military considerations affected the Japanese defeat; but the Japanese would never have suffered such a crippling blow had they never attacked in the first place. A focus on why Japan chose to attack will privilege different causal factors than a focus on why, Japan having attacked, it was defeated so decisively. Neither approach is the ontologically "right" one—different questions about the past require different answers.

The problem of fixing the temporal and conceptual boundaries of an "event" like the Cambrian explosion is far greater than with events in human history. Although there is debate about its duration, the event lasted at least ten million years, or something like 50 times as long as there have been anatomically modern humans on earth. We might plausibly set the beginning and ending of the Cambrian explosion at dates differing by millions of years. In part, this is a consequence of the imperfection of the geological record and our consequent inability to date events with even rudimentary precision. But even perfect knowledge of the facts would not allow us to fix the "right" dates for when the event began and ended. One researcher is interested primarily in the disappearance of the Precambrian fauna, which opened up ecological space for the radiation. Another focuses on the emergence of more complex multicellular forms represented by early trace fossils. A third attends primarily to the first hard-bodied organisms (the "small shellies") and a fourth on the first predators. None of these decisions can fairly be called "wrong." Different aspects of the Cambrian explosion strike different researchers as most requiring explanation. But these elements were separated by many millions of years. The researcher who starts the analysis with the extinction of the Precambrian fauna and ends it with the proliferation of new body plans is going to tell a different causal story than the researcher who focuses on the evolution of predation. Neither of these approaches is the ontologically "right" one—choosing between them is a matter of asking what aspects of the event we most want to understand, a question with an indefinitely large number of perfectly reasonable answers.

The conceptual boundaries of the Cambrian explosion are also unimaginably fluid. What exactly constitutes the "explosion" that needs explaining? Do we seek to explain the entirety of animal evolution over whatever period we select? Do we focus on only those evolutionary changes that we consider to be "major" innovations, however we might choose to define that term? Do we consider morphological or behavioral innovations as of greater theoretical interest? Or are we seeking to explain something else entirely?

Related to the question of how one defines the boundaries of an event is the problem of the inevitable plurality of the kinds of questions one might want to ask about an event. Different kinds of questions require different modes of analysis. Tinbergen (1963) built on Mayr (1961) by identifying four kinds of questions one can ask about the causes of phenotypic traits: evolutionary origins (what caused the trait to arise in the lineage?); functional consequences (what is the current adaptive function of the trait?); ontogenetic processes (how does the trait arise in individual organisms' development?); and mechanisms (what environmental, hormonal or other events trigger the expression of the trait in an individual organism). Different kinds of causal questions can be asked about the same biological phenomenon, and different categories of physical mechanisms and processes will be appropriate to answer the different kinds of causal questions. Moreover, these different answers will typically not be reducible to, or expressible in terms of, each other. Consider the Cambrian innovation that is hypothesized to have had a major role in the evolution of predation by enabling some organisms to crush the shells of others (see Zhang (2011)). What caused shell crushing to evolve in the first place, what function shell crushing came to perform, how the ability developed in ontogeny and what physiological mechanisms organisms used to crush shells are questions with radically different, and radically different kinds of, answers.

A second source of plurality in the questions we ask about events is explanatory grain. Consider the "dot-com bubble" of the late 1990s. We might want to analyze the bubble as an instance of a type, eliding its particular details and seeking instead the commonalities that connect it to events such as the real estate bubble of the 2000s and 17^{th}-century tulip mania. Alternatively, we might want to examine that idiosyncratic event in all of its particularity. What factors led people to bid up the prices of certain technology stocks? What caused investors to conclude that the sector was overvalued? What events triggered the eventual crash? In such a case, we would want to understand what made the dot-com bubble different. When we investigate the dot-com bubble as a window into speculative bubbles generally, the causes that will strike us as most salient are those that are generally found in such asset bubbles. If we take the latter approach, however, the causal factors we will identify as critical might well be precisely those that are *not* features commonly associated with asset bubbles.[2] The same kinds of issues affect any analysis of the Cambrian explosion. The causes that will be most salient to understanding the event as a particular evolutionary event are different from those most relevant to understanding what the event can tell us about adaptive radiations in general.

The last of the three interrelated sources of inevitable plurality in how we talk about historical events is the different idealizations we use in analyzing the causes of historical events. Scientists seeking to explain the causal structure of robust, repeating processes frequently employ idealizations: representations of a natural phenomenon that omit or distort aspects of the phenomenon to make it more analytically tractable. In recent years, philosophers of science have begun to offer accounts of such uses of idealization. Giere (2004, 749-750), for example, discusses the fact that we model water as a collection of discrete molecules to understand diffusion and Brownian motion, but we model it as a continuous fluid if we are interested in how water flows through a pipe. An even more familiar example (not discussed by Giere) is that we model light as a wave to investigate interference but as a particle to investigate the photoelectric effect. For Giere, there is no problem with this kind of plurality of models—it is a function of the different questions we want to ask about the phenomena being modeled. Giere

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[2] Sober (1999) and Glennan (2009, 262-65) consider the issue of explanatory grain in more detail in different contexts.

(2010) generalizes the point, arguing that scientists use idealizations to model the world *always* "for some purpose, *P*." The right model of a phenomenon is thus a function not only of the phenomenon, but also of the particular purpose, *P*, of the particular scientist.[3]

But just as we use different idealizations to explore questions about types of events, so too do our explanations of the causes of token historical events inevitably employ idealizations. The use of idealizations in the analysis of tokens has not, as yet, been as carefully explored by philosophers of science. How do idealizations figure in our analyses of token historical events? The most fundamental of the idealizations we employ in historical explanations are our characterizations of events themselves. The

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[3] See also Weisberg (2007 and 2013). Weisberg offers a taxonomy of different uses of idealization. One use, which he identifies as "Multiple Model Idealization (MMI)," involves the use of "multiple related but incompatible models, each of which makes distinct claims about the nature and causal structure giving rise to the phenomenon" (2013, 103). Although there is an affinity between my analysis and Weisberg's, there are very real differences in approach, even beyond the fact that Weisberg is concerned with models of robust, repeating processes, where I am concerned with individual token events. Most notably, for Weisberg, MMI involves a single scientist creating multiple, incompatible idealizations. While I certainly believe that it is possible for a single researcher to deploy multiple, incompatible models, I am more interested here in situations in which different scientists deploy different idealizations. My approach is therefore more similar to Giere's.

past is a continuous spatio-temporal flow. When we extract certain incidents from that flow and attend to certain features of those incidents, we are creating representations of the past that omit or distort certain aspects of it to make it more analytically tractable—we are creating idealizations. But idealizations play a further role in our explanations. Having defined our event, we use simplifying or distorting analytical constructs to investigate it. We have already met several of the idealizations customarily employed in analyses of the Cambrian explosion: “environmental,” “developmental” and “ecological” factors. The world is not naturally cut at those joints. When we call a something an “environmental” factor, we are choosing to attend to certain of its features that we consider particularly salient for our present purposes. And there are other idealizations that we have not yet considered. If we are interested in the generation of evolutionary novelties, we must have some mechanism for describing and measuring that novelty, so we break the continuum of animal life up into species and genera and other taxa. If we are interested in the role of predation, we treat two kinds of organisms that interact in a variety of different ways as predator and prey, privileging these aspects of their interactions over others. To the extent that we focus on the importance of a relatively open field for new forms to radiate into, we emphasize the extinctions of Precambrian taxa. But “extinction” is an idealization that we give meaning to based on our particular purposes. We can define “extinction” as occurring immediately after the last surviving record of a particular type of organism, or when we deem that it ceased to be ecologically significant, even if some individuals may have survived, or at some other point that suits our investigations.

It might be objected that the inevitability of a *plurality* of delineations of events, questions about those events and idealizations employed in analyzing those events does not necessarily entail an *incompatibility* among those delineations, questions and idealizations. It is at least possible that the plurality could be integrated into a single, coherent explanation. Indeed, in some cases, it is not only possible, but reasonably clear how we might go about this. One historian might want to know why the Japanese attacked at Midway, and another why, the Japanese having attacked, they were defeated. One paleontologist might want to know why so much of the Precambrian fauna died off so quickly, and another why, the ecological field being so open, the new creatures that filled it had so varied an array of different body plans. There is no reason to believe, at least in principle, that those investigators could not reach common ground.

My point is not that *all* delineations, questions and idealizations are incommensurable, but that *some* are, and where that is the case, no integration is possible. Temporal or conceptual delineations of events will sometimes not be integrable. If the temporal boundaries of two alternative delineations of an event overlap rather than falling into sequence, those two delineations cannot be simply stitched together. Questions may be posed about an event that are not just different, but incompatible. Perhaps most vividly, our idealizations may conflict. One cannot simultaneously see water as a fluid and as a collection of discrete molecules, or light as a wave and a particle. The two idealizations are incompatible. The experience of the alternatives is more in the nature of a gestalt switch. At any given moment, we can see the particle *or* we can see the wave, just as, at any given moment, we can see the duck *or* we can see the rabbit. Similarly, at any given moment, we can see a particular Cambrian organism as its genotype *or* we can see it in its ecological relations to some other organism. But we cannot simultaneously see it in both these aspects, to say nothing of the indefinitely large number of other aspects in which different researchers might reasonably choose to render it.

In a significant sense, then, the attempts to offer complex, integrated causal explanations for the Cambrian explosion represent an advance over explanations focused on a single "triggering" cause. Some causal influences *can* be intertranslated. And even where they cannot, integrated explanations are more consistent with a reality characterized by causal multiplicity and complexity than single-factor explanations. Yet, if there is no definitively correct answer to the question of how to set the temporal and conceptual boundaries of the Cambrian explosion, if it is desirable that paleontologists should ask different questions—and different *kinds of* questions—about the Cambrian explosion, and if paleontologists' different goals, questions, training and institutional context should lead them to deploy different, and sometimes incompatible, idealizations, then we will never be able to identify *the* cause of the Cambrian explosion, however much our knowledge advances.

5. Is a Chronicle of the Incidents Involved in the Cambrian Explosion Possible?

Assume for the moment that I am correct that a single, definitive causal history of the Cambrian explosion is unachievable. Different paleontologists will set the boundaries of the event differently, will ask different questions about it, and will employ different, and sometimes incompatible, idealizations, all of which together will warrant different causal histories of the Cambrian explosion.

Danto (1965) believed he had at least a partial solution to the problem; let us now consider it. As we have seen, Danto pointed out that explaining events entails explaining change, and that explaining change entails determining the temporal boundaries of the change to be explained—determining when we are going to start and end our event. And he understood that these are *choices*, choices that each investigator must make for him or herself, based on what he or she wants to know. Danto was (uncomfortably) aware that all this might suggest that all history is fiction, that historians construct the past rather than revealing it. He addressed this concern by inviting us to imagine a perfect witness, a witness who knows everything that happens the moment it happens and transcribes it all precisely and instantaneously, exactly when and how it happens. Danto called the account of such a witness an "Ideal Chronicle" (1965, 149). The Ideal Chronicle is not, of course, a real possibility, but Danto proposed it as a kind of regulatory ideal. Historians may individuate events differently, ask different questions and deploy incompatible idealizations, but Danto suggested that all legitimate histories would need to be consistent with the Ideal Chronicle, to the extent that that Chronicle could be known. The Ideal Chronicle would thus serve as a generally-accepted common ground from which all histories would be built. See also O'Hara (1992, 139).

Perhaps this offers us a way out of anything-goes relativism about statements about the past—a limitation of the epistemic consequences of the inevitable plurality of causal explanations for historical events. Perhaps we could construct a chronicle of each incident that was part of the Cambrian explosion, identifying to the best of our knowledge and ability what happened exactly when and how it happened, without any interpretive or subjective elements. It would be imperfect and subject to change as new facts emerged, but it would, perhaps, be an objective foundation on which to build our causal reasonings. We might at least hope to agree on what Danto (1965, 148) called "a full description of an event *E,"* by which he meant "a set of sentences which, taken together, state absolutely everything that happened in *E*…." Such a full description, Danto continued, "bears some analogy to a map: there is an isomorphism between the full description and the event of which it is true…. Such a [full] description then will be definitive…."

There is clearly something to Danto's intuition. It would be perverse to deny that there are facts about the Cambrian explosion on which we can expect at least general, if perhaps not universal, agreement. And any causal history of the Cambrian explosion that denied or failed to account for those facts would be, to that extent, suspect. Paleontologists generally accept, for example, that around 540 million years ago, there was a significant extinction event in which very many species and higher taxa disappeared, that atmospheric oxygen increased substantially around this time and that a much larger variety of hard-bodied organisms existed 20 million years after the period we are concerned about than did 20 million years before. These facts are far from exhaustive; the list could easily be multiplied many times over.

Yet these facts do not form anything like the kind of chronicle Danto envisioned. Danto was concerned with human history: by definition, written records by human witnesses existed and, to a greater or lesser extent, still exist. For human history, we have witnesses (albeit imperfect) and their chronicles (albeit incomplete). We have no witnesses to, and no full description or chronicle of, the Cambrian explosion. We have evidence about that event, but the evidence is much further removed from an Ideal Chronicle than is the case with even the most poorly attested events in human history. There is a deeper problem, however. By the very act of locating a particular incident in the temporal and causal sequence of the event that we call "the Cambrian explosion," we are leaving the realm of chronicle. Take any incident that we might want to say was an important cause of the Cambrian explosion. By definition, as and when that incident occurred, the Cambrian explosion did not yet exist, so no chronicle limited to instantaneous descriptions of incidents as and how they happened could include any reference to "the Cambrian explosion." We have, rather, left the realm of chronicle and are individuating events, deciding what questions to ask about them and employing idealizations to help us get a purchase on them.

This problem could, in principle, be addressed by not referring to the Cambrian explosion or any other causal and temporal sequence in our chronicle, but the chronicle would then need to be not a chronicle of all of the incidents that were part of the Cambrian explosion, but of literally all of the incidents that occurred on earth around 540 million years ago. Obviously, such a chronicle is impossible. More fundamentally, even if we had such a chronicle, it would not assist us in understanding what caused the Cambrian explosion. It would be quite literally unusable. It may be helpful to revert to Danto's suggestion that a chronicle could be made to be isomorphic with the past and that it is in that respect like a map. In his short story/essay "On Exactitude in Science," Jorge Luis Borges (1946/1998, 345) used a parable to explore the problems posed by a map that is isomorphic with the territory it depicts. Borges imagined an empire in which cartography was the king of the sciences. Maps got better and better, until the map of a province was the size of an entire city. Eventually, the cartographers of the empire struck a map "whose size was that of the Empire, and which coincided point for point with it." It soon became clear to all that "the vast Map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters." Eventually, all that remained were "Tattered Ruins of that Map, inhabited by Animals and Beggars."[4] Borges's point is that maps are useful precisely because they are *not* isomorphic with the territory they represent—the "perfect" map is useless precisely because of its perfection. The map that coincides point-for-point with the region it represents cannot convey any understanding about that region that we do not already have.

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[4] A similar idea was expressed even earlier by Lewis Carroll (1893, 169). A perfect map with a scale of a mile to the mile was made, but it could not be used because the farmers objected that, if it were spread out, it would cover the entire country and shut out the sunlight.

Danto was right that the analogy between maps and histories is a fruitful one, but he drew the wrong lessons. Maps are useful in navigating a landscape as much because of what they omit as because of what they depict. A street map helps us get where we want to go by showing roads, intersections and freeway entrances, but also by *not* showing what might interfere with the task of route-finding—such as county lines and elevations. Indeed, the practices that I have described as fundamental to causal explanations of historical events—delineating their temporal and conceptual boundaries, determining what questions we want to ask about them and creating idealizations that will assist us in getting purchase on them—have direct analogies in the cartographic context. Spatial boundaries are to cartography as temporal boundaries are to history: any map shows only the territory that is necessary to its function. As we set conceptual boundaries to our histories, so we do too with maps: topographic maps depict different kinds of features than do maps of political boundaries or demographic data. A geological map is designed to help us answer questions about earth forms and processes, while a road map is intended to help us reach a physical destination. And all maps employ idealizations suited to their functions: a political map may represent an entire metropolis spanning many miles and many millions of people by a single point, while a street map may use one graphical symbol to represent a footpath, a second to represent a city street and a third to represent a highway.

And just as these delineations of boundaries, clarifications of questions and creation of idealizations are the very features that make maps useful to us as representations of objects in space, so are these the same features that make histories useful to us as representations of objects in time. We can only gain understanding of the past by artificially breaking the uninterrupted spatio-temporal flow into "events." These events, constitute simplified representations of a part of the past so that we may tell ourselves an intelligible story about it. We *must* simplify the past by turning it into discrete events in order for us to get any purchase on it. A faithful representation of a segment of the past in all its particularity would not be an explanation at all. It would be *the past*, or rather a simulacrum of the past, a doppelgänger. It would be akin to Borges's Map.

6. What *Can* We Know about the Causes of the Cambrian Explosion? If even a true chronicle of the Cambrian explosion is unintelligible or useless, are we led inexorably to agnosticism or relativism? Perhaps the cause of any given state of the universe is the immediately preceding state of the universe, and it is impossible to say anything more precise than this about causes. Or perhaps there are no standards for adjudicating between different causal explanations for an event, and every explanation is as good as any other. Does my approach require me to accede to either of these conclusions? Is it possible for us to talk intelligibly about the causes of the Cambrian explosion, and what kinds of things are we able to say? I contend that, if we delineate clearly the boundaries that we are setting around the events we seek to explain and characterize precisely the questions we want to ask and the idealizations we want to use to investigate those events, we can make intersubjectively evaluable causal claims *given our delineation of our event, the precise causal questions we ask and the idealizations we employ.*

Mackie (1965) was getting at something very like this idea when he referred to delineating our “causal field.” He (249) considered the question “What causes influenza?” We may mean by that question to ask about the particular virus that carries the disease, or we may mean to ask what causes some people exposed to the virus to get influenza while others do not. “What causes influenza?” is a poorly formulated question, and it is pointless to argue about whether a particular virus or a weakened immune system is the right answer. But the pointlessness of the exercise derives from the framing of the causal field, not from any inability on our part to understand influenza and its causes. Longino (2013) is after essentially the same quarry when she emphasizes that different accounts of the causes of human behavior “parse” the interacting variables differently, and that each alternative parsing of the variables generates “partial knowledge,” which must remain partial as it is not integrable into a single, coherent account.

Although his terminology is different, Waters's (2007) analysis of geneticists' particular focus on differences in DNA sequences as “the causes” of various phenotypic changes gives a clear picture in a concrete case of what kinds of causal statements we can make even if we conceive of explanatory pluralism as ineliminable. Waters (556-57) takes as a paradigm case Morgan's early-20th-century experiments on fruit flies. In one experiment, Morgan mated females with red eyes with males with purple eyes. He knew that the females were homozygous with respect to a particular gene suspected to influence eye color, with two copies of the wild-type allele. He also knew that the males were homozygous for a mutant allele of the same gene, which he suspected to be responsible for their purple eyes. Previous experiments had established that the mutant allele is recessive to the wild-type. When the flies were mated, the offspring would be heterozygous at the locus, getting one wild-type allele from the mother and one mutant allele from the father. When the offspring all turned out to have red eyes, Morgan concluded that he had shown that the presence of at least one wild-type allele at the relevant locus is the cause of a fly having red eyes.

One response to Morgan would be to argue that there are a lot of other causes of flies' red eyes. An eyeless fly with the wild-type allele will not have red eyes even though it has the allele, so in a sense it is not strictly correct to identify the allele as "the cause" of red eyes. Waters understands this, but he nevertheless identifies the wild-type allele is "the cause that makes a difference" in eye color. Eyelessness would have an effect on fruit flies, but it would not cause a difference in eye color.

Morgan can be seen as having delineated his causal field by defining the boundaries of what we want to explain as a population of red-eyed offspring of mothers homozygous with the wild-type allele and fathers homozygous with the mutant allele, all other features of the system being held constant. Given that delineation, he was able to show that having one copy of the wild-type allele caused flies to have red eyes rather than purple ones. This is precisely the kind of causal statement I have in mind when I contend that notwithstanding a commitment to ineliminable pluralism, one can make intelligible and evaluable causal statements if one carefully defines one's field of inquiry and delineates precise causal questions.[5]

I should clarify one potential source of confusion. I have defended the argument that, in the context of a question such as "What caused the Cambrian explosion?", causal factors can only be determined in the epistemic context of a particular delineation of the

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[5] Morgan's experiment offers an opportunity to explore the relationship between the explanatory pluralism that I am defending and the notion of "contrastive explanation." The literature on contrastive explanation ranges widely (see, e.g., von Fraasen (1980), Hitchcock (1996) and Schaffer (2005)), but the central premise is that causal statements are best understood in terms of contrasts. We should not ask why Morgan's fruit flies had red eyes, but why they had red eyes *rather than purple ones*. This notion does indeed identify an often-useful strategy for delineating a causal field (indeed Schaffer (2005) begins his essay with an epigram from Mackie on the role of fixing the causal field). There is, however, more to the proper delineation of a causal field as I am defining it than a contrast with an alternative state of the world. The notion of contrast does not, for example, capture the differences I have described in the kinds of questions we put about an historical event, or in the idealizations we employ to analyze such an event. Contrastivity also only captures one way (albeit a powerful way) of what I (following Mackie) have described as fixing the causal field.

boundaries of the event, and a set of questions beings asked and idealizations being deployed. I would make the same case with respect to the question "What causes eye color in fruit flies?" Waters (2007, 555) sometimes seems to deny this, contending that "some causes are actual difference makers while others are not (regardless of epistemic context)." The apparent conflict in our positions is not, I think, real. Despite this statement and others to like effect, Waters (569) acknowledges that the selection of a difference-making cause presupposes some particular population within which the cause operates and that our interests factor into the identification of that population. Fixing the population plays the same role in Waters's analysis of types of events as the delineation of the causal field plays in my analysis of token events. In both cases, our interests inexorably enter into the process. But *given the population thus fixed or the causal field thus delineated*, we can make ontologically meaningful distinctions among causes. When we come to consider causal questions that are not framed with sufficient specificity (like "What caused the Cambrian explosion?" or "What causes eye color in fruit flies?"), we cannot draw ontological distinctions among causes: the failure clearly to define our causal field renders the causal claims meaningless.

Waters was analyzing a stable process in a population of organisms. What does partial knowledge look like in the context of a particular event in evolutionary history? We can see how these ideas could apply to the Cambrian explosion by returning to Marshall (2006). Although his ultimate object is the single integrated causal story of the Cambrian explosion, some of Marshall's preliminary suggestions (which he hoped would be superseded by our ultimate discovery of an integrated cause) are instructive. He (361) begins by describing five aspects of the Cambrian explosion that demand explanation. Why did the number of animal species increase so explosively? Why did the morphological differences between species expand so dramatically? Why did the explosion happen when it did, rather than earlier or later? Why did the radiation take some tens of millions of years to occur, instead of being of some shorter or longer duration? And why have such "explosions" not recurred? He then constructs a table (372) summarizing the environmental, developmental and ecological variables, noting which have the most explanatory power with respect to each of his five questions. Marshall's preliminary conclusion is: "I suspect that roughening [of the organisms' fitness landscapes] was the primary driver of the Cambrian 'explosion,' *given that the environment was conducive and the bilaterian developmental system was in place*." (377, emphasis added.)

These passages are, I contend, steps toward the kind of knowledge that we *can* attain of the causes of the Cambrian explosion. Note, in particular, the italicized portion of the tentative conclusion. If we delineate our causal field by holding constant environmental and developmental factors, we can pick out ecological dynamics that might have been important parts of the causal nexus. And by thinking about his five critical questions, we can posit different delineations of the causal field that allow us to explore other key questions about the radiation. I am not competent to evaluate the specific preliminary answers that Marshall offers, but these passages illustrate in embryo how we can make meaningful and evaluable statements that can in principle pick out genuinely ontological aspects of the causal background of the Cambrian explosion. That we can never hope to integrate them into a single explanation does not detract from the real contribution that they can make to our knowledge of the evolutionary past.

Acknowledgments

I would like to thank Helen Longino, Jessica Riskin, John Beatty and two anonymous referees, all of whom read earlier versions of this paper and offered valuable suggestions on how it could be improved. I would also like to thank the participants in the Pizza Munch at the California Academy of Sciences, particularly Michael Ghiselin, Elihu Gerson, Jim Griesemer and Roberta Millstein, to whom I first presented the idea for this paper and who generously offered advice and direction. This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

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