View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Scholarship@Western

Western Graduate&PostdoctoralStudies

Western University
Scholarship@Western

Electronic Thesis and Dissertation Repository

5-25-2012 12:00 AM

Explanation in Science

James A. Overton
The University of Western Ontario

Supervisor
Robert W. Batterman
The University of Western Ontario

Graduate Program in Philosophy
A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy
© James A. Overton 2012

Follow this and additional works at: https://ir.lib.uwo.ca/etd

Part of the Philosophy of Science Commons

Recommended Citation

Overton, James A., "Explanation in Science" (2012). *Electronic Thesis and Dissertation Repository*. 594.
https://ir.lib.uwo.ca/etd/594

This Dissertation/Thesis is brought to you for free and open access by Scholarship@Western. It has been accepted for inclusion in Electronic Thesis and Dissertation Repository by an authorized administrator of Scholarship@Western. For more information, please contact wlswadmin@uwo.ca.

EXPLANATION IN *SCIENCE*

Monograph

by

James Alexander Overton

Graduate Program in Philosophy

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

© James Alexander Overton, 2012

THE UNIVERSITY OF WESTERN ONTARIO
School of Graduate and Postdoctoral Studies

CERTIFICATE OF EXAMINATION

Supervisor	Examiners
Robert W. Batterman	Paul Humphreys
	Christopher Smeenk
	Gillian Barker
	Steven Kerfoot

The thesis by

James Alexander Overton

entitled:

Explanation in *Science*

is accepted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

Date

Chair of the Thesis Examination Board

Abstract

Scientific explanation is an important goal of scientific practise. Philosophers have proposed a striking diversity of seemingly incompatible accounts of explanation, from deductive-nomological to statistical relevance, unification, pragmatic, causal-mechanical, mechanistic, causal intervention, asymptotic, and model-based accounts. In this dissertation I apply two novel methods to reexamine our evidence about scientific explanation in practise and thereby address the fragmentation of philosophical accounts.

I start by collecting a data set of 781 articles from one year of the journal *Science*. Using automated text mining techniques I measure the frequency and distribution of several groups of philosophically interesting words, such as “explain”, “cause”, “evidence”, “theory”, “law”, “mechanism”, and “model”. I show that “explain” words are much more common in scientific writing than in other genres, occurring in roughly half of all articles, and that their use is very often qualified or negated. These results about the use of words complement traditional conceptual analysis.

Next I use random samples from the data set to develop a large number of small case studies across a wide range of scientific disciplines. I use a sample of “explain” sentences to develop and defend a new general philosophical account of scientific explanation, and then test my account against a larger set of randomly sampled sentences and abstracts. Five coarse categories can classify the explanans and explananda of my cases: data, entities, kinds, models, and theories. The pair of the categories of the explanans and explanandum indicates the “form” of an explanation. The explain-relation supports counterfactual reasoning about the dependence of qualities of the explanandum on qualities of the explanans. But for each form there is a different “core relation” between explanans and explanandum that supports the explain-relation. Causation, modelling, and argument are the core relations for different forms of scientific explanation between different categories of explanans and explananda. This flexibility allows me to resolve some of the fragmentation in the philosophical literature. I provide empirical evidence to show that my general philosophical account successfully describes a wide range of scientific practise across a large number of scientific disciplines.

Keywords: philosophy of science, scientific explanation, natural kinds, scientific models, scientific theories, text mining, case study method, philosophical methodology

To Bob, for helping me find my own path.

To Judy, for helping me follow it.

To Lily and Andrew, whom we met along the way.

Acknowledgements

My doctoral research was made possible by a Canada Graduate Scholarships Doctoral Fellowship from the Social Sciences and Humanities Research Council of Canada. I gratefully acknowledge funding from Prof. Robert Batterman, the Joseph L. Rotman Institute of Philosophy, the London Health Sciences Centre Department of Medical Imaging, and the Canadian Institutes for Health Research Team in Image-Guided Prostate Cancer Management. I would like to thank the University of Pittsburgh for hosting me for two semesters, in 2009 and 2011, with the support of a CGS Michael Smith Foreign Study Supplement from SSHRC. I would also like to thank the Tilburg Center for Logic and Philosophy of Science for a very pleasant and productive visiting fellowship in 2011.

To the teachers, staff, colleagues, friends, and family who have supported me in so many ways, I continue to offer my most sincere thanks.

Contents

List of Tables

List of Figures

Chapter 1

Explanation

1.1 Explanation in Science

One of the goals of science is explanation. Scientists explain to other scientists how a particular gene regulates a phenotype, how patterns in the luminance of a particular star indicate the presence of planets, how the sizes of the populations of two particular linked species vary with environmental changes. Scientists explain to their students how genes are transcribed and code for proteins, how planets orbit and occlude stars, how the sizes of populations of organisms change and correlate. And scientists explain to the public and to policy makers how genes affect health and disease, the place of our planet and sun among the stars, and the effects of ecology on our lives and livelihoods.

Explanation is a practise that cuts across scientific disciplines and extends far beyond the sciences. We offer explanations to each other and to ourselves in our daily lives and in our various specialized fields. But the importance of science and the differences between scientific practises and other practises have led many to consider scientific explanation as a topic of study in its own right. By understanding scientific explanation we may shed light on other forms of explanation, or on the distinction between science and non-science. These goals are important, but the primary goal here is to understand what scientific explanation *is*. This is valuable to the extent that it leads to better scientific explanations and thus to better science.

But scientific explanation is not well understood. Scientists themselves seem to find the concept slippery. Textbook discussions of scientific method often tangle together hypothesis, prediction, and explanation without elucidating the latter.[1] Great

---

[1] For instance see `http://en.wikipedia.org/wiki/Scientific_method`. Hypothesis and prediction are distinct from explanation. Some hypotheses are merely predictions, and one can have both a prediction that does not explain and an explanation that does not predict.

scientists, famous for giving excellent explanations, are often unreflective or at best unclear about what makes a good explanation.[2] Psychologists have looked into what makes a proposed explanation satisfying – the “ah-ha!” moment – but there are too many examples where such a feeling is misleading (Trout 2007). Artificial intelligence researchers have built systems that can discover explanations of a sort, but only in a narrow range of highly restricted cases (J. R. Josephson and S. G. Josephson 1996). And all too often popular articles on scientific topics demonstrate confusion about what scientists have explained and have not explained. While scientific explanation is important, its nature and role are not as clear as they should be.

In this dissertation I take a philosophical approach toward scientific explanation. Philosophers have written extensively on the topic for 60 years, building on a tradition with ancient roots (Woodward 2011). Like most philosophers, I set aside questions of the psychology of explanation and the discovery of explanations, and ask instead what a scientific explanation *is*. I approach explanation as a topic in the *general* philosophy of science, cutting across scientific disciplines. And I combine traditional analysis and case studies with some new methods designed to keep the focus on scientific practise while covering a representative sample of cases. The result is a general account of scientific explanation that applies to a broad range of scientific practise, and that incorporates a number of insights from the philosophy of science literature. In this chapter I lay out my project and present an overview of my account.

1.2 Philosophy of Science

1.2.1 Background

Philosophy of science has roots in ancient philosophy. Pre-Socratic philosophers offered cosmological explanations of the nature of the world, its origins, its elements, and the order beneath its apparent diversity (Hankinson 2001). In this way they were precursors to modern scientists of many stripes. Aristotle not only took steps forward in science and scientific method but also in the philosophy of science and the understanding of explanation. His four causes are perhaps best understood as four forms of explanation, where his efficient causes are the best fit with the modern use of “cause”. Aristotle also elucidated natural kinds and developed a logic for reasoning

---

[2] Richard Feynman’s autobiographical *Surely You’re Joking, Mr. Feynman* is reflective but certainly not clear (Feynman, Leighton, and Hutchings 1985), and I would say the same for his interview on the BBC TV series “Fun to Imagine” (1983) available at `http://www.youtube.com/watch?v=wMFPe-DwULM` or transcribed at `http://lesswrong.com/r/discussion/lw/99c/`.

about them, both of which have an important role in explanation.

Between Aristotle and the 20th century, science and the philosophy of science both matured. Some philosophical topics discussed over this long period that remain important include causation, laws of nature, deduction and induction, and questions of realism and empiricism, among others. But explanation itself was not a central topic for philosophers concerned with science.

In the 20th century both science and philosophy of science became increasingly specialized. Philosophy of science as its own field of philosophy developed out of the Vienna Circle and strands of American pragmatism in the first half of the century (Woodward 2011; Reisch 2005; Richardson 2002). Carl Hempel made explanation an important topic in the emerging field (Woodward 2011; Hempel and Oppenheim 1948; Hempel 1965b). His empiricist commitments made him skeptical of appeals to causation, and his deductive-nomological (D-N) account of scientific explanation relies instead on deduction from natural laws and initial conditions. D-N was very influential on subsequent accounts of explanation, of which there are many, including: inductive-statistical (Hempel 1965a); statistical relevance (Salmon 1971); unification (Friedman 1974; Kitcher 1989); pragmatic (van Fraassen 1980); causal mechanical (Salmon 1984; Dowe 2000); mechanistic (Machamer, Darden, and Craver 2000; Bechtel and Abrahamsen 2005); causal intervention (Woodward 2003); asymptotic (Batterman 2002); model-based (Bokulich 2009); and more.

Philosophy of science as a field has often followed larger trends in science and the public perception of science. Until the 1970s, philosophy of science was almost exclusively focused on the science of physics. Physics was taken as the paradigm for other sciences by philosophers, by physicists, and often by scientists in other fields. And so philosophers of science working on explanation focused on explanation in physics, with its universal, exceptionless laws, various relations between them, their instantiation in differential equations, and so on. The so-called "special sciences" (sciences other than physics) were often taken to be reducible to physics (Oppenheim and Putnam 1958; Nagel 1961). But even within the science of physics, the focus was largely on two main areas: quantum mechanics and particle physics on the one hand, and gravitation and space-time on the other. Other important areas of physics, such as thermodynamics, statistical mechanics, fluid dynamics, and solid state physics, were excluded along with the special sciences. The result was a narrow view of science and scientific explanation, still heavily influenced by the Newtonian revolution. While appropriate for philosophical questions in fundamental physics, it was a poor fit for other scientific disciplines.

This narrow focus began to change with the increasing scope and power of the science of biology. The discovery of DNA was one triumph in a cascade of advances. A new generation of philosophers of biology began to examine thorny conceptual issues in genetics and evolution. On the subject of explanation they found that the existing accounts fell far short. Laws of biology may exist but they are few and far between, and do not play the central role given to them in physics. Rather than mathematical equations, biological explanations are often narrative or focus on systems that are stable by degrees. Biologists and physicists use “mechanism” to mean quite different things. And it is difficult to resist assigning purposes to biological organs and organisms because their behaviour appears so purposeful. Biologists appeal to causes, functions, models, and mechanisms in their explanations, and so philosophers of biology have appealed to these concepts to elucidate biological explanation.

The philosophy of physics and the philosophy of biology are the most prominent among a growing number of philosophies of specific sciences. Philosophy of cognitive science and philosophy of neuroscience are increasingly important and independent. In much of cognitive science the nature of the mind is explained in terms of functional modules. Those functional explanations build on the concept of biological function, but also on a computational sense of function. Mechanistic accounts of explanation for neuroscience build on biological mechanisms, but also on analogies to electronic circuits. So here too we see different approaches of explanation growing out of the specialized concerns of emerging philosophies of specific sciences.

As a final example, philosophies of the various social sciences have their own concerns that have implications for explanation. The social sciences must deal with individuals acting with intentions, who are communicating or concealing those intentions. Their explanations are sometimes singular and historical, sometimes general and probabilistic. Philosophers of science working in anthropology, archaeology, economics, and other fields must grapple with these differences. I only mention that there is growing interest in philosophy of chemistry, climatology, medicine, and more, as demonstrated by the proceedings of recent conferences.

The diversity of philosophies of specific sciences has been, and continues to be, productive and valuable for philosophy and for science. Many important questions can only be answered by means of such deep and specialized analysis. But the diversity has also led to fragmentation. In many of these areas there have been claims that existing philosophical accounts of scientific explanation are insufficient. As the long list of philosophical accounts of explanation given above suggests, the literature on scientific explanation is fragmented.

No doubt there is great diversity among the sciences. And no doubt it was a naïve vision that earlier philosophers of science had of physics as the model science to which all others would conform. But the failure of that vision need not lead us to accept its antithesis: that there is no common core to scientific explanation. I argue that there is a shared structure among the various forms of explanation. But before I put forward my argument we had best briefly survey some of the accounts of scientific explanation that philosophers have offered.

1.2.2 Philosophical Accounts of Scientific Explanation

Most histories of philosophical engagement with scientific explanation, including Woodward 2011, begin with Carl Hempel's D-N account. Here I do the same, and give short synopses of several other prominent accounts in rough chronological order.

Deductive-Nomological A D-N explanation is a sound argument in first-order predicate logic that essentially includes at least one natural law as a premise, and for which the explanandum (the statement of the thing being explained) is the conclusion (Hempel and Oppenheim 1948). If the natural laws are removed the deduction must fail. The other premises will often include boundary conditions and initial conditions. D-N explanations are usually taken to explain particular events, making predictions about the state of a system. However Hempel also intended D-N to apply to the deduction of special laws from more general ones.

D-N has been a very influential account. However it faces a large number of challenges and standard counterexamples (Salmon 1989, §2.3). Many subsequent accounts were designed specifically to addresses problems with D-N.

Statistical Relevance Wesley Salmon developed the statistical-relevance account to address failures of D-N to capture information about relevant causes (Salmon 1971). He appeals to a notion of statistical relevance, requiring that for C to be relevant to B it must the case that $P(B|A \wedge C) \neq P(B|A)$. This condition has intuitive appeal. However it requires the right partition of the space of possibilities, and it turns out to be very difficult to state necessary and sufficient criteria for the partition. Technical problems forced Salmon to abandon the statistical relevance account, but similar work has continued and found success in the form of structural equation models (Spirtes, Glymour, and Scheines 2000).

Unification This approach to explanation takes theoretical unification to be a condition for successful explanation. Michael Friedman presented an account based on this intuitive notion (Friedman 1974), and Philip Kitcher criticized (Kitcher 1976) and extended it (Kitcher 1989). On Kitcher's version we have an explanatory store of schemata for explaining the phenomena we observe, and the goal is to expand the scope of our explanations while reducing the size of the store. We do this by discovering increasingly powerful but stringent schemata. The intuitive appeal of this account is undermined by some of its consequences, such as its inability to distinguish between explanatory unifications and cases where the same formalism happens to apply in multiple cases, and its inability to allow for a shallow explanation to count as explanatory when a deeper explanation is available.

Pragmatic Bas van Fraassen argues that an explanation is simply an answer to a why-question (van Fraassen 1977). What answer should be accepted is a matter of pragmatics. Every question presupposes a contrast class of acceptable answers, and to answer the question is to pick out a member of that class. Alternatively, one can reject the question and its presuppositions. Depending on the context, almost anything one can think of could be an answer to some question, and so there is little more to say about the nature of a well-formed explanation. A consequence of van Fraassen's view is that there is no distinct category of *scientific* explanation – science does not explain, but merely provides facts and principles that are employed in our answers to why-questions (van Fraassen 1977, p. 149).

Causal-Mechanical After rejecting statistical relevance Salmon turned to an account of singular causal explanation. His concern was an analysis of causation compatible with our knowledge of physics, such that a "mark" can be transmitted by the causal interaction. Philip Dowe developed a related account (Dowe 2000). Both are suspicious of appeals to counterfactual conditions to spell out causation. Christopher Hitchcock has raised the criticism that causally relevant aspects of mark-transmission often pull apart from the explanatorily relevant aspects that Salmon was trying to distinguish (Hitchcock 1996). While perhaps successful as an account of explanation for photons in the void, it is difficult to see how the account can apply to the tangled causal webs studied in the special sciences.

Mechanisms Very much concerned with causal explanation in the special sciences are several accounts of "mechanisms". I will focus on Machamer, Darden, and Craver's (MDC) account (Machamer, Darden, and Craver 2000). An MDC mechanism is a system of entities and activities organized to be productive of changes from start conditions to termination conditions. To explain an event is to describe the mechanisms that generated it. Their use of "mechanism", as in much of contemporary scientific practise, goes far beyond mechanisms as machines and the science of mechanics (Craver and Darden 2005). Along with mechanisms they describe mechanism schemata and mechanism sketches to fill epistemic roles in their account. The MDC mechanism approach has been applied to a wide range of special science cases.

Causal Intervention James Woodward has developed a general account of causal explanation based in part on the structural equations literature (Woodward 2003). Woodward tries to capture very general features of causal explanation explicitly in terms of counterfactual dependencies. An explanation should answer "what if things had been different" questions about the explanans and the explanandum. The truth of the explanation depends upon truths about what would have been different if we had intervened at some point in the relevant causal chain. As with mechanisms, this approach is well suited to explanation in the special sciences.

Asymptotic Robert Batterman's account of asymptotic explanations handles an important set of cases in statistical mechanics and solid state physics where all other accounts fall short (Batterman 2002). Physicists' explanations in these examples revolve around the behaviour of a system in the limit as some quantity approaches infinity. In some cases the infinite quantity is the number of particles in the system, while in other cases it is the inverse of a wavelength. In each case the idealization contradicts our knowledge that the system is finite in the relevant respect, but the idealization cannot be relaxed or eliminated without abandoning the explanation. The idealization, which we know to be false, is essential to our best scientific explanation of the phenomenon.

Model Reflections on the pervasiveness of idealized models in science have led to other accounts of explanation, of which I take Alisa Bokulich's as one example (Bokulich 2009). Bokulich argues that a model explains its target when it exhibits a pattern of counterfactual dependencies about the target and meets an additional "justificatory step" that specifies its domain of application.

1.2.3 Too Many Explanations

The first thing to note about these philosophical accounts of explanation is their variety. Explanations are variously logical arguments, collections of statistical information, argument schemata, answers to why-questions, descriptions of mechanisms, descriptions of causal relations, mathematical arguments, or models. If we look at these accounts as each proposing an *explain*-relation, then the relata of the various explain-relations are quite different: laws of nature, predictions, theories, statements of probabilities, particular events, models, questions, sets of possible answers, etc.

Most of these accounts apply (or apply best) to a subset of the sciences. The D-N, statistical relevance, unification, and causal mechanical accounts apply best to fundamental physics. All of them rely on laws of nature, but it is far from clear that laws of nature play the same central role in biology that they do in physics (Smart 1959; Beatty 1995). The singular causal chains of the causal mechanical account are a poor fit for the complicated causal tangles present in a cell or organism. On the other hand, the mechanistic and causal intervention accounts apply very well in certain special sciences, but can be a poor fit for quantum mechanics or space-time theories. Their reliance on causation prevents them from capturing mathematical explanation, where acausal numbers and mathematical functions play an essential role. The asymptotic explanation account works very well for a set of cases where all the previous accounts fail. It provides wide-ranging lessons about idealization, but it is not general in scope.

On the other hand, Bokulich's model account is general and can probably be applied to cases in any science, if not to every case of scientific explanation. The pragmatic account of explanation is *very* general – it is designed to account for all forms of explanation.

It is also worth considering how these accounts are motivated and the evidence given to support them. In the original paper, the D-N account is presented using toy examples from physics. The statistical relevance account responds to D-N and some of the toy examples that were proposed as counterexamples. In his survey of scientific explanation Woodward notes how peculiar it is that philosophers discussing scientific explanation should so often appeal to homely examples of non-scientific explanations (Woodward 2011, §1, §2.4). The latter four accounts, however, are supported by case studies. The original MDC paper provides two cases: the discovery of DNA and a standard model of neurotransmission. It has been applied to a variety of cases in other publications. Woodward's book includes a range of cases, and Batterman develops several cases in great depth. Bokulich's paper discusses Bohr's model of the atom and cites a number of model explanations in the literature. I think that this shift in the evidence given as support is representative of a larger shift away from toy examples and toward detailed cases in the philosophy of science.

None of these accounts is universally accepted. The case studies provide evidence that scientists do in fact offer mechanistic explanations, causal intervention explanations, asymptotic explanations, and model explanations. Even this diversity is striking. Is scientific explanation really so heterogeneous, covering so many different relata? And if so, is it then fragmented by discipline or topic? Is there a general account of scientific explanation to be had amid this diversity?

To settle these questions I think we must reconsider our evidence about the practise of scientific explanation. How do scientists, in various disciplines, explain?

1.3 Evidence Base

While there are many sources of evidence about scientific practise, some are easier to make use of than others. I have chosen to consider scientific articles recently published in the journal *Science*. Several factors played a role in this decision.

First, the publication of an article is one of the main goals of most scientific research. This gives scientific articles a special status. Publication in *Science* is especially prestigious – these articles are held up as ideals toward which scientists should strive. This introduces a normative factor into my discussions of scientific explanation. If I can correctly describe the use of scientific explanation in these articles then I will have described some norms for scientific practise. In this way my project has both a descriptive and a normative aspect.

On a practical basis, published articles are easy to access and easy to collect in large numbers. It is a virtue of an evidence base that all sides in the debate have ready access to the data. It is also easy to draw a range of inferences about scientific practise from sets of published articles, given the right methods.

I also believe that, for the overwhelming majority of hypothesis-driven scientific articles, their central claim is some sort of explanation or the rejection of some explanation. If I am correct then scientific articles are an excellent source of evidence about scientific explanation. One of the goals of my analysis is to test whether this is in fact the case.

In choosing to apply novel methods to a large set of published articles from *Science* my goal has been to expand the range of evidence available in the philosophical debate over scientific explanation. But I recognize that this evidence base is still limited in many ways.

Scientific publications present only a fraction of scientific knowledge and practise. Years of painstaking work in the lab and in the field are neatly glossed in a few thousand words. Traditionally, philosophers of science have focused on the public face of science and ignored the myriad private details of scientific practise. But sociologists and historians have applied their own methods to the inner workings of science, and philosophers are increasingly engaged with such research.

I believe that the methods I develop in this dissertation could be successfully adapted and applied to, for instance, transcripts from laboratories and other ethnographic records. Without denying that there are many differences between public and private practise, I also believe that my general philosophical account of scientific explanation applies just as well to informal conversation as it does to the printed page. It would be fascinating to test these beliefs against an evidence base that reflects the private practise of science.

However, such a study would itself be limited without a supporting analysis of public practise. In order to sufficiently address my three questions about importance, generality, and goals, my methods also require a very large and diverse evidence base. Ethnographic research is laborious, and ethnographic records are relatively rare, but publications are plentiful and easy to collect in large numbers. In short, I think that an analysis of publications is the right place to start, and I hope that in the future this work will be extended to encompass a wider range of evidence.

The choice of publications from the journal *Science* also requires some justification. *Science* is an outstanding journal in several senses. Not only it is prestigious, it is especially competitive, and its mission is to publish highly influential papers. Such papers can also be high-risk, and more prone to retraction than those published in other journals. *Science* articles are especially short, compared to other journals, which may have a significant effect on the use of language. In short, by choosing *Science* as the source of my evidence I may be introducing bias into my analysis.

My methods can easily be adapted to publications in other scientific journals. The same methods could be applied to the top journals in various scientific disciplines (e.g. *Cell*, or more specifically *Annual Review of Immunology*), and the results compared to *Science*. However, an analysis of one or a few specialized journals would not allow me to sufficiently address my three main questions about importance, generality, and goals. The evidence base I have chosen is the right starting point, but by no means the end of the road.

Finally, by choosing publications from one recent year of *Science* I am open to other possible biases. Doubtless there are trends in the use of language by scientists, some of which may be significant to this analysis. My analysis will also be blind to changes in the nature of scientific explanation over time. A temporal analysis might be able to show trends in philosophy or philosophy of science reflected in science. I have thought it best to start with a snapshot contemporary science before trying to describe changes over time. I leave these interesting questions to future work.

My evidence base for this dissertation consists of 781 scientific articles from the journal *Science*. It includes all 72 of the long-form "research articles" and all 709 of the shorter-form "reports" published in regular issues between September 24, 2010 and September 23, 2011. I consider the abstracts and bodies of these articles, excluding their bibliographies and supplementary materials, for a total of approximately 1.6 million words and 11 million characters.

The set of articles covers a wide range of scientific disciplines, as shown in the following list. The number of articles marked with that keyword is given in parentheses. Figure 1.1 shows a plot of the number of articles by keyword. I have organized the keywords in order to draw out potential similarities between physical sciences, life sciences, and social sciences. I freely admit the shortcomings of this ordering but I believe it is slightly more informative than an alphabetical listing.

- (3) Computers, Mathematics
- (60) Physics
- (26) Physics, Applied
- (65) Chemistry
- (36) Materials Science
- (1) Engineering
- (27) Astronomy
- (29) Planetary Science
- (33) Geochemistry, Geophysics
- (19) Atmospheric Science
- (12) Oceanography
- (52) Biochemistry
- (35) Molecular Biology
- (25) Microbiology
- (50) Cell Biology
- (21) Genetics
- (26) Development
- (34) Evolution
- (27) Ecology
- (23) Botany
- (18) Paleontology
- (3) Anatomy, Morphology, Biomechanics
- (8) Physiology
- (6) Virology
- (19) Immunology
- (26) Medicine, Diseases
- (2) Epidemiology
- (54) Neuroscience
- (15) Psychology
- (3) Sociology
- (2) Economics
- (14) Anthropology
- (7) Education

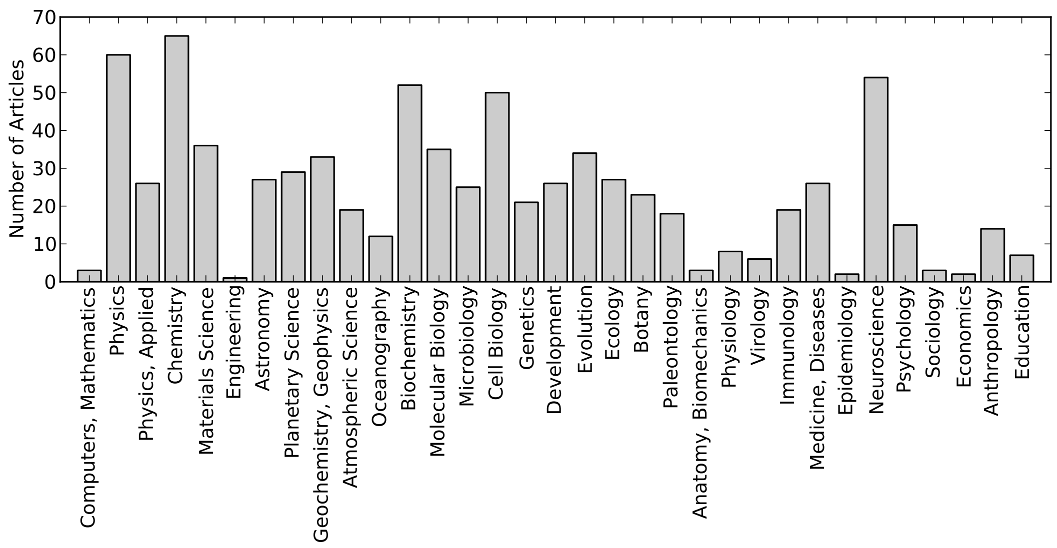

Figure 1.1: A plot of the number of articles in the data set by keyword.

1.4 Analysis

To address this broad and rich set of data I take two distinct approaches. The first is to use automated text mining techniques to search for words of interest such as “explain” and “cause”. Second, and more important, I take random samples from the data set and use them to develop a large number of small case studies across a wide range of scientific disciplines. From these cases I develop and test a general philosophical account of scientific explanation.

The first approach is a novel one in philosophy. Using computer programs I search through the millions of words in the data set for patterns in their usage. I measure the frequency and distribution of these words, look for the most common phrases that they occur in, and consider the positions at which they occur in the articles. The evidence I collect is no substitute for a conceptual analysis of the words of interest, but it provides some valuable new information.

My second approach is more traditional than the first. The case study is a method that philosophers of science rely upon. But by using random samples to collect a large number of cases I am able to support much stronger claims than a traditional case studies can. With a large number of cases I can show that the account I develop applies across a wide range of sciences. And by ensuring that my selection of cases is unbiased, I can show that my account of explanation applies to a large portion of the claims that scientists make in their papers.

There are three questions driving my analysis using these two different approaches. The first is whether scientific explanation is important for science. The second is whether scientific explanation is general, occurring across a wide range of scientific disciplines. The third is whether explanation is a goal of science. My ultimate conclusions are all affirmative: that explanation is important, that it is general with a general account to describe it, and that it is a goal toward which scientists strive. The general account I propose addresses the problem of fragmentation, and its broad applicability reaffirms the importance of scientific explanation for the philosophy of science.

To address these three questions I begin with the usage of "explain" words in *Science*. I use text mining to show that "explain" is a common word but not ubiquitous. It has strong connotations and so scientists tend to qualify their use of the word. I take a random sample of sentences that include "explain" and use them as the basis of case studies. I use these clear cases of scientific explanation to develop my account.

To address the question of the importance of scientific explanation I compare the use of "explain" words to other words of interest to philosophers such as "cause", "evidence", "theory", "model", and "law". "Explain" is about as common as "cause" and "evidence", more common than "theory" and "law", and less common than "model". But scientists explain without using the word "explain". Using a large random sample from the set of all the sentences in the 781 *Science* articles, I show that the account of scientific explanation I propose applies to at least a quarter of all the sentences. I also show that, if we include claims of inference to the best explanation, we can account for another quarter of the sentences. In sum, approximately half of all the sentences in the *Science* data set make some sort of explanatory or abductive claim on my general account of scientific explanation. A large portion of the *Science* data set cannot be understood without an account of scientific explanation.

To address the question whether explanation is a goal, I consider *where* "explain" words occur in scientific articles. They occur more frequently in the introduction and toward the end of the articles, suggesting that these words are used for setting and assessing the goals of the articles. But stronger evidence comes from a random sample of the abstracts from the *Science* data set. I consider the main claims being made in these abstracts and show that all of them have either explanatory or inference-to-the-best-explanation form on my account of scientific explanation.

Finally, to address the generality of scientific explanation, I show that "explain" words are used in all of the disciplines represented in the *Science* data set, and that my general account of scientific explanation applies to at least one case sampled from each of those disciplines, with a small number of exceptions that are most likely due to inadequate sample sizes.

1.5 A General Philosophical Account of Scientific Explanation

The two approaches I take to the data set are intended to provide empirical support for the general philosophical account of scientific explanation I develop here. But even without the support of text mining evidence and a broad range of cases, my account is intended to stand alone as a plausible philosophical account.

An explanation consists of an explain-relation, an explanans, and an explanandum. There is an ambiguity in the usage of "explanation", allowing the word to refer to a statement of the explanation, but I try to distinguish between the explanation itself and the statement of the explanation. Unlike Hempel, I do not restrict the explanans and explanandum to propositions, and I believe that my broader use of the terms is not unusual among philosophers of science.

The explain-relation holds between a quality of the explanans and a quality of the explanandum. In other words, it is always *something about* the explanans that explains *something about* the explanandum. While the explanandum quality always depends on the explanans quality, the basis for that dependence can take many forms. In every case the explain-relation between the qualities must be supported by a second relation that holds between the explanans and the explanandum themselves. I call this the "core relation" for the explanation. In some cases the core relation is *singular causation*: the explanandum quality depends on the explanans quality because the explanans causes the explanandum. In other cases the core relation is *modelling*: the explanandum quality depends on the explanans quality because the explanans is a model of the explanandum. While the explain-relation is essentially the same across a wide variety of scientific explanations, the core relation can differ widely.

In order to understand the differences between core relations we must consider the sorts of things that can be the explanans and the explanandum. I propose five coarse categories that allow us to classify the explanantia and explananda of a wide range of scientific explanations. The categories are: data, entities, kinds, models, and theories. Data are statements of measurements and observations of entities. Entities are concrete particular things in the world. Kinds are abstract universals that entities instantiate. Models are abstract descriptions that articulate the relationships among kinds and their qualities. Theories are the principles and systems of inference that are used to build models. Each category is widely recognized by philosophers, although the details of my usage sometimes differ from what is standard. In each case there are philosophical problems and disagreements over the nature and role of that category of thing in scientific explanations. I cannot address and resolve all of these issues, but I do locate my position for each category within the wider philosophical literature.

I call the pair of the category of the explanans and the category of the explanandum the "form" of the explanation. Given the five categories there are 25 possible forms of explanation. Differences in the form of explanation indicate differences in the core relation. Among these 25 forms there are four that I call "primary forms", because they are especially important for understanding explanation: theory-model, model-kind, kind-entity, and entity-data. Each of the four primary forms involves a shift from a more general explanans to a more specific explanandum. The four core relations for the four primary forms are justification, modelling, instantiation, and measurement, respectively. In a model-kind explanation it is something about the model (the explanans) that explains something about the kind (the explanandum), and the core relation that supports the explanation is *modelling.* The explanation will hold if and only if as the model is a model of the kind. This includes both the actual circumstances and the counterfactual ones that the core relation supports. Figure 1.2 shows the five categories, the four primary forms of explanation, and examples of the five "secondary forms" of explanation for which the explanans and explanandum fall into the same category. I call the other 16 "tertiary forms" of explanation because I consider them to be composites of the primary and secondary forms. Accordingly I focus my attention on the four primary and five secondary forms.

What makes these 25 forms count as forms of *explanation*? In what sense do the various core relations support a single *explain*-relation? The fragmentation of the philosophical literature on scientific explanation has meant a diversity of proposed conditions on what makes for an explanation. Despite the fragmentation, there are two proposed necessary conditions that philosophers have been widely accepted. The first is that explanations answer *why-questions.* The second is that explanations answer "what if things had been different" questions. These are, of course, closely related: I believe that the second condition is a more accurate expression of the key insight in the first condition.

James Woodward develops the second condition a part of the motivation for his appeal to causal counterfactuals. For my part, I see no reason to limit the counterfactuals to causal ones. All of the forms of explanation I propose involve a core relation that supports counterfactual reasoning, and thus allow us to answer “what if things had been different” questions. Those answers, given in counterfactual terms, are answers to the scientific why-questions that philosophers have been interested in.

This condition that all of the 25 forms of explanation meet is a broad one. There may well be other necessary conditions, or even sufficient conditions, to be found. Although broad, the condition is not toothless. It allows us to distinguish explanations from statements of fact, from descriptions, and from predictions. Each of the core relations articulates some more specific sort of of counterfactual relation, but all of them have at least this much in common.

The most complex form of explanation on my account is theory-data explanation because it spans the five categories from most general to most specific. Figure 1.3 shows the general structure for such a case. At the top are the explanans quality and the explanandum quality. At the bottom is the “base” of the explanation, which is shared between the explanans and explanandum. In the middle are the “cores” of the explanans and explanandum.

While this model was developed to capture the structure of explanatory claims, it also captures the structure of inferences to the best explanation. In these “evidential” cases the direction is reversed, and it is something about the more specific “explanandum” that gives evidence for something about the more general “explanans”. Figure 1.3 shows the “explain” and “evidence for” arrows pointing in opposite directions.

For each of the randomly sampled sentences or abstracts I develop a small case study and try to apply this structure. Often part of the structure is not apparent on the surface of the quotation, and so I take it to be implicit. Appendix A includes my analysis of all of the sampled cases. I distinguish clearly between the implicit and explicit items in each case analysis.

This general account addresses the problem of fragmentation in the philosophical literature that I raised above. Philosophers of science have often focused on one or a few of the many forms of explanation that scientists use. In giving detailed accounts of those forms for those sorts of explanantia and explananda they overlook the many other forms. There is room for a diversity of specific philosophical accounts because the practises of scientific explanation are in fact quite diverse.

Looking at figure 1.2 we can see that there is room for several of the existing philosophical accounts of scientific explanation. Mechanistic, causal intervention, and model explanation fit near the middle, among the categories of models, kinds, and entities. Unification and asymptotic explanation fit on the left, among theories and models. Causal mechanical explanation concerns singular causal relations among

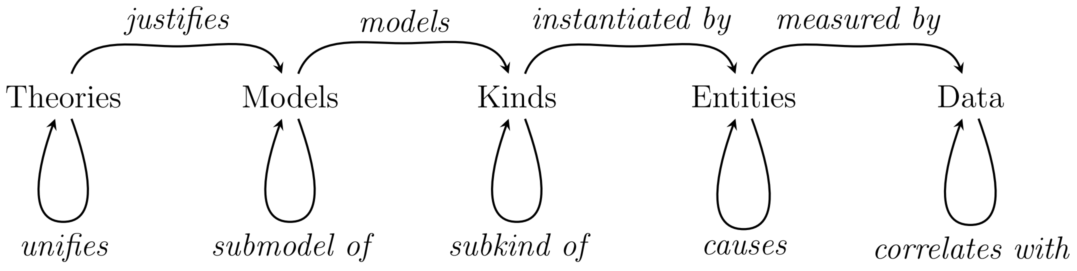

Figure 1.2: The five categories, four primary relations, and examples of five secondary relations.

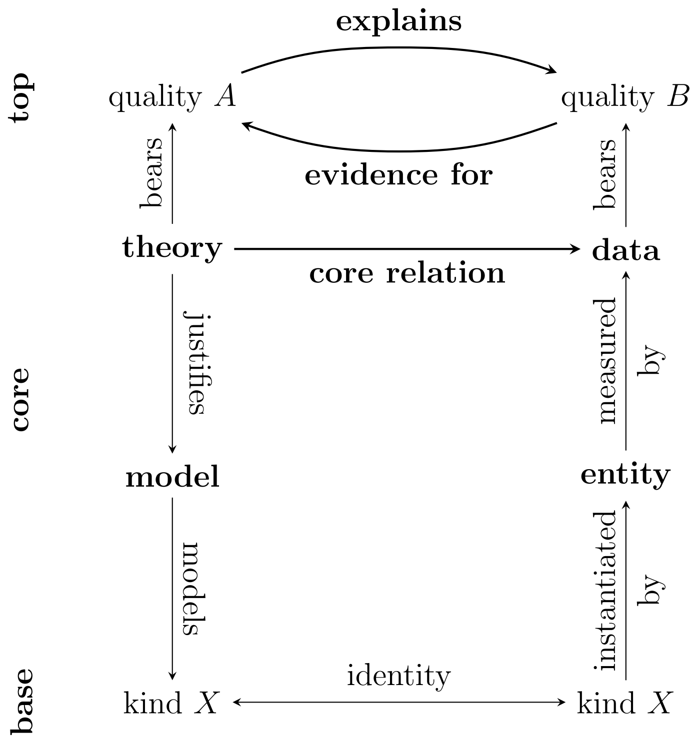

Figure 1.3: General structure of a theory-data explanation.

entities. D-N explanations are an interesting case, since they can span the full range from theory to data. My general account of the various forms of scientific explanation allows us to pull apart what D-N explanations run together.

This account may appear overly complex on first glance. Instead of one explain-relation we have both an explain-relation and a core relation to support it. Instead of one form of explanation there are 25 possibilities, each with a different core relation. But both of these complexities reflect the reality of scientific practise. Scientists use the word "explain" to express dependence relations between qualities in many different situations, but to understand the dependence in a particular case we must look to the relation that holds between the bearers of the qualities. While some of the forms of explanation are much more common than others, all 25 are used at least once in my sampled cases. By distinguishing the core relation from the explain-relation, and recognizing the variety among core relations, we gain a flexible and truly general account that can capture a wide range of cases of explanation across many sciences. The flexibility and generality are required in order to address the problem of fragmentation. On balance, the added complexity is a small price to pay.

1.6 Limitations

Scientific explanation is an important topic. I consider it to be central to the philosophy of science. Explanation touches on many other important topics, including causation, measurement, natural laws, natural kinds, modelling, idealization, confirmation, and theory change. By better understanding scientific explanation we gain insights into these other important areas.

But this comes at a cost. In order to fully understand scientific explanation we must be able to give accounts of causation, measurement, natural laws, natural kinds, modelling, idealization, confirmation, theory changes, etc. A complete account of this topic requires at least partial accounts of these others. And like scientific explanation itself, each of these other topics has its share of philosophical problems.

Faced with such a challenge, one response is specialization. By narrowing the scope to one branch of science we may be able to find questions that can be answered in full. This is often a good response, but it cannot be the only one. The general philosophical account of scientific explanation that I offer, and the novel methods that I use to support it, address important questions and provide useful answers, even if some of those answers are not complete.

Because I cannot hope to address all the philosophical topics that my account of explanation touches upon, I have tried to limit the scope of this work to the question: *what is a scientific explanation?* When I discuss data, entities, kinds, models, and theories, I try give an adequate characterization of each and to locate my position in the larger philosophical literature.

There are two questions in particular that are very close to my focus but remain outside the scope of this dissertation. The first is *what makes a good scientific explanation?* The second is *what is the nature and role of inferences to the best explanation?* Regarding the first, in analyzing the explanations in my sample cases I have not tried to evaluate whether they are good or bad ones. The main normative claim I make here is that these explanations are held up as exemplars by being published in *Science*, and I have given an account of their structure. Regarding the second, many of the cases I have sampled appear to be inferences to the best explanation. They have the same structure as explanations except that the direction of the inference is reversed. For some of the cases, if I merely substituted "suggests" with "might be explained by" the reader would not notice any tampering, because switching the direction of the inference makes no other difference to the structure. In my analysis I mark these cases as distinct, but I analyze them in the same way as the other explanations. A full analysis of inference to the best explanation on my general account is an important goal that I must leave to future work.

Despite the many connections between scientific explanation and other important philosophical topics, in this dissertation I aim to answer the question *what is a scientific explanation?* in such a way that I can resolve some of the fragmentation in the philosophical literature and show that scientific explanation is an important general goal of science.

1.7 Overview

This dissertation consists of nine chapters and two appendices. Following this introduction is the chapter on my text mining methods. I address the three questions about the nature and role of scientific explanation by means of various measurements of the frequency and distribution of words of interest in the *Science* data set. The results of this chapter provide insights into the use of "explain" words in science, and help to focus the analysis that follows.

The third chapter is the longest and most important. I discuss my methods for randomly sampling the *Science* data set to create a large set of small case studies. Sample A consists of 25 sentences containing at least one of the words "explain", “explains”, or “explained”. I use these cases to develop and discuss my general philosophical account of scientific explanation. Then I test the account against sample B, with 100 random sentences, and sample C, with 25 random abstracts. I close the chapter with a discussion of the evidence I have gathered from these samples and how it addresses the three questions about scientific explanation.

The following five chapters are each short. I present the five categories in turn: data, entities, kinds, models, and theories. The structure of each chapter is the same. I begin with some examples drawn from samples A, B, and C. I then provide a general philosophical discussion and characterization of the category. I describe each of the examples in this light. And I close with a discussion of the forms of explanation for which the explanans is in that category.

The body of the dissertation ends with a short conclusion. Following that are the two appendices. Appendix A is very long, including the full analysis of all 150 cases in samples A, B, and C. In appendix B I provide listings of the programs that I have used to collect my data set, perform the text mining, and sample and analyze my cases. The appendices are included for completeness, so that the reader can check the details of my analysis that interest them.

Chapter 2

Words

My goal is a philosophical answer to the question *what is a scientific explanation?* In pursuit of that goal I apply philosophical methods such as conceptual analysis and case studies. Because the claims I want to make are general, I need to appeal to a wide base of evidence. But I cannot analyze all 781 *Science* articles. Instead I apply some novel methods that allow me to draw inferences about practises of explanation across the large data set. In this chapter I discuss my text mining methods and apply them to several questions about the practise of scientific explanation.

2.1 Text Mining

Text mining is the analysis of large sets of textual data using automated methods. These methods usually involve some sort of natural language processing of the data. My uses of these techniques are humble, amounting to different forms of comprehensive search. The important thing for the current purpose is not the sophistication of the text processing but the inferences that we can draw about the data set. By using automated techniques we can consider much larger data sets, and with larger data sets we can ensure that we are representing the diversity of scientific practise more accurately.

In broad strokes what I have done is collect electronic copies of the text of the *Science* articles and used a set of computer programs to find patterns in that text. The programs are built using the Natural Language Tool Kit (NLTK, `http://nltk.org`), an open-source library of software tools for natural language processing. Code listings of the programs I have written are provided in appendix B.

Text mining is fundamentally about matching sequences of characters. However the relationships between sequences of characters and words is not straightforward.

The sequences “explain”, “Explain”, and “ex-plain” are distinct, although they are all tokens of the same word. A computer needs to be told that “explain”, “explains”, “explained”, and “explaining” are grammatical inflections of the same word. Even dividing sequences of characters into token words can be difficult. Although words are usually separated by spaces or line-breaks, there are also periods, commas, colons, hyphens, quotation marks, apostrophes, and other characters that sometimes separate words but are sometimes part of a word. For instance, periods terminate sentences, but they are also included in acronyms and abbreviations, making it difficult to automatically break a text into sentences.

Natural Language Processing (NLP) is the wider field that encompasses text mining techniques. NLP researchers have developed heuristics and algorithms for breaking sequences of characters into their lexicographical parts. These include methods for tokenizing (distinguishing word tokens from their surroundings), stemming (distinguishing the root of a word from its affixes), and lemmatising (grouping inflections of the same stem together). These tools are supported by enhanced dictionaries such as WordNet (`http://wordnet.princeton.edu`) that describe networks of relations between words.

Philosophers use language carefully and pay close attention to small variations in the usage of words. Dictionary definitions are often too crude to be helpful for philosophical analysis. But philosophers usually pay less attention to syntactic variations, and these are of primary importance for text mining. To perform an automated search for explanations in scientific literature we would need to build a list of all the syntactic representations of explanations that we want to match.

The relationship between sequences of characters and words is complex, but the relationship between words and concepts is even more so. Philosophers are interested in the concepts being expressed rather than the words that express them. When it comes to explanation, philosophers are not primarily interested in the words “explain” or “explanation”, but in explanations regardless of the details of the phrasing. I accept that concepts and not words are the proper targets of philosophical analysis.

However we must also offer evidence to support our philosophical analysis. Evidence is more convincing when it is publicly available, so that anyone can assess its value. Philosophical intuitions are a difficult sort of evidence to deal with. They are not public, and even when they are largely shared it is often hard to discern the differences between them. Philosophers have methods for doing so and I do not reject intuitions as a source of evidence for philosophy. But I do claim that we should also look to public forms of evidence, of which the use of language in published texts is one form. The task is then to transform public facts about language use into evidence about concept use.

In the following sections I make three main claims about the practise of scientific explanation and then use text mining methods to test them. While the focus is on the use of words, the goal is to learn about the concept of explanation.

2.2 Importance of Explanation

I have claimed several times already that explanation is an important scientific practise. Is there evidence to support this claim?

One of the simplest ways to assess the importance of a concept in a body of text is to measure the frequency with which associated words are used. If those words are used frequently then we have some reason to believe that the concept is important in that corpus. Conversely, if those words are used infrequently then we have some reason to believe that the concept is unimportant in that corpus. Relative frequencies can be more informative than absolute frequencies. If one set of words occurs more frequently than another then we have some reason to believe that the concept associated with the first set is more important for that corpus than the concept associated with the second set. However we must also be aware of word ambiguity. If one word can be associated with more than one of the concepts we are trying to investigate then this will undermine our inferences about importance based on frequency.

To measure the frequency of the words associated with a concept we must make a list of the strings of characters we are interested in. (Our tools can be designed to ignore certain differences, such as letter-case.) Here I have listed some words of interest, grouped by concept. Our primary target is the "explain" concept by means of variations on the word "explain". I have included groups for several concepts related to explanation, such as "because" and "understand". And I have included other important terms from the general philosophy of science such as "cause", "evidence", "theory", "law", "mechanism", and "model".

explain explain, explains, explained, explaining, explainable, explanation, explanations, unexplained, unexplainable, explicate, explicates, explicated, explicable, inexplicable

because because

reason reason, reasons, reasoning

account account, accounts, accounted, accounting

understand understand, understands, understood, understanding

evidence evidence, evident, evidential
show show, shows, showed, shown, showing
discover discover, discovers, discovered, discovering, discovery, discoveries
reveal reveal, reveals, revealed, revealing
suggest suggest, suggests, suggested, suggesting
implication imply, implies, implied, implying, implication, implications
indicate indicate, indicates, indicated, indicating
confirm confirm, confirms, confirmed, confirming
establish establish, establishes, established, establishing
cause cause, causes, caused, causing, causal, causation
theory theory, theories, theoretical
law law, laws, lawful
mechanism mechanism, mechanisms
model model, models, modelled, modelling
phenomena phenomena, phenomenon
effect effect, effects

The next step is to write a program to determine the word frequencies. NLTK provides a library of tools for this purpose. I have written a short program (see appendix B.4) that uses the NLTK tokenizers and frequency distribution tools to count the number of occurrences of words from each group in two different ways. First, we are interested in the number of articles in which the concepts of interest are deployed, so I have measured the number of articles for which at least one word in the group occurs. Second, we are interested in the number of times the concepts are deployed, so I have measured the total number of occurrences of words in each group.

Table 2.1 shows the results. Figure 2.1 plots the percentage of articles that include at least one token from each word group. Figure 2.2 plots the number of tokens for each word group.

These results show the "explain" group of words being used less frequently than we might have expected. The first conclusion we might draw is that scientific explanation is not as important as I have claimed. A closer look at the data tells a more complicated story. "Explain" is used about as often as "understand" and "cause". The "evidence" group has slightly more tokens and occurs in slightly more articles. "Explain" is used significantly more often than "theory", and much more often than "law". Even the "mechanism" and "model" groups of words are not used in too many more articles than "explain", although they both have markedly more tokens. If this evidence suggests that philosophers are wrong about explanation being important

	# Articles	% Articles	Tokens	Tokens per Article
explain	353	45.2	747	0.96
because	705	90.3	2516	3.22
reason	81	10.4	132	0.17
account	257	32.9	434	0.56
understand	366	46.9	620	0.79
evidence	410	52.5	843	1.08
show	737	94.4	4075	5.22
discover	135	17.3	226	0.29
reveal	485	62.1	1101	1.41
suggest	647	82.8	2497	3.20
implication	295	37.8	512	0.66
indicate	578	74.0	1636	2.09
confirm	346	44.3	654	0.84
establish	247	31.6	391	0.50
cause	404	51.7	938	1.20
theory	216	27.7	608	0.78
law	32	4.1	66	0.08
mechanism	460	58.9	1368	1.75
model	482	61.7	2084	2.67
phenomena	119	15.2	173	0.22
effect	534	68.4	2278	2.92

Table 2.1: For each word group we make four measurements: the number of articles containing at least one word in that group; the percentage of such articles among the 781 in the data set; the number of tokens matched from that group; and the number of tokens from that group averaged over all of the articles in the data set.

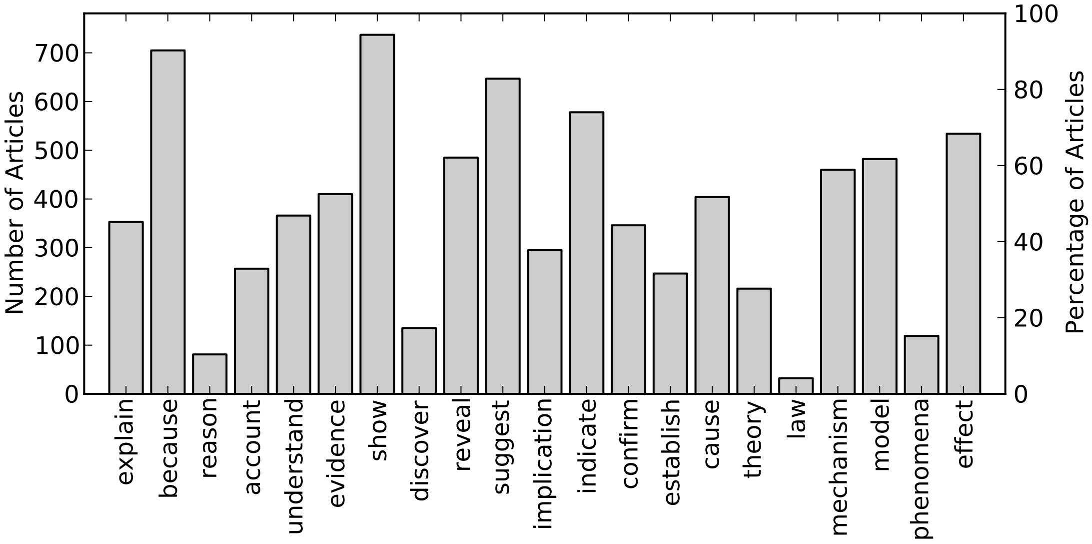

Figure 2.1: Plot of the percentage of articles that contain one or more tokens from each word group.

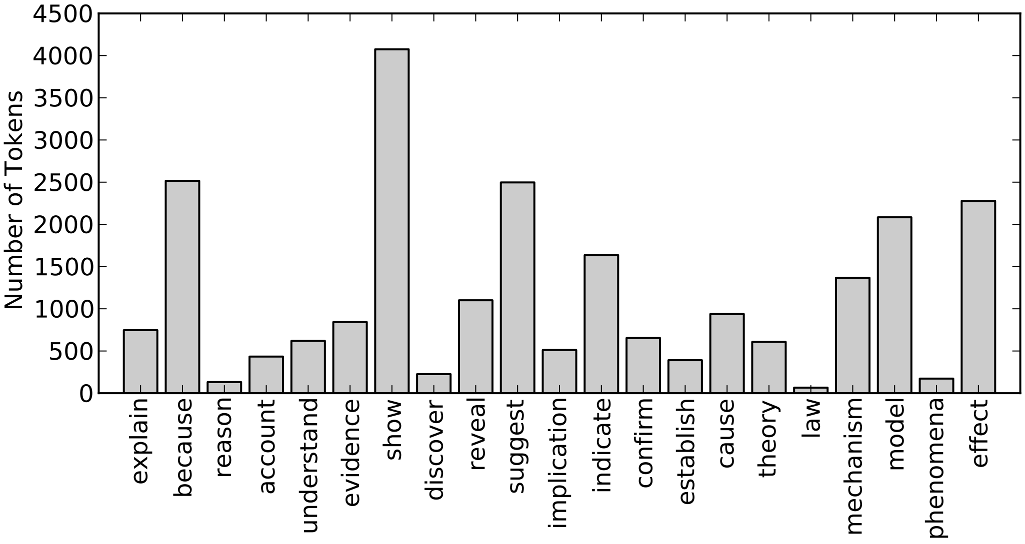

Figure 2.2: Plot of the number of tokens from each word group.

in science, then it also suggests that we are wrong about understanding, causation, theories, mechanisms, and models being important.

The word group that is used most frequently in the data set is “show”. Unfortunately “show” is ambiguous between an evidential sense that interests us and uses such as “figure 3 shows a decline” that are more difficult to connect to explanation. Just behind “show” is “because”, which is also used in multiple ways that may not all indicate explanations. The “suggest” group is almost as ubiquitous, and plays an important role in claims about evidence. The “indicate” group occurs in almost as many articles as “suggest” but has far fewer tokens.

The high frequency of these words suggests that they are more important in scientific writing than they are in other genres and thus that explanatory concepts are relatively more important in science. I have tested this hypothesis by comparing the frequency of the the words of interest in the *Science* data set to their frequency in two other genres, using bodies of text provided by NLTK. The first comparison corpus contains 18 long-form works of English literature selected from Project Gutenberg.[1] The second is the Reuters Corpus, containing 10 788 news articles. I used NLTK to count the number of occurrences of the word groups in the two comparison corpora and then compared the number of tokens per million words for each group. Table 2.2 and figure 2.3 show the results.

Here we see that for many of the words of interest the frequency in the *Science* corpus is significantly greater than in the comparison corpora. “Explain” words are used four times as often in *Science* as in the Gutenberg corpus and almost eight times as often as in the Reuters corpus. The results for “evidence”, “show”, “reveal”, “suggest”, and “indicate” are similarly dramatic, while “because” is used roughly twice as often in the science genre than the other genres. I take this to show that explanation, and related concepts for dealing with evidence, are more important in science than in fiction and news reporting.

Given that explanation is more important in science than in some other areas, why does “explain” only occur in less than half of all articles while “because” and “show” are ubiquitous? I propose that scientists think of “explain” as a strong word. While they may frequently be explaining, they only use the word “explain” and its

---

[1] See `http://www.gutenberg.org/`. The works are: Jane Austen’s *Emma*, *Persuasion*, and *Sense and Sensibility*; The King James Bible; William Blake’s *The Poems of William Blake*; Sara Cone Bryant’s *Stories to Tell to Children*; Thornton W. Burgess’ *The Adventures of Buster Bear*; Lewis Carroll’s *Alice in Wonderland*; Gilbert K. Chesteron’s *The Ball and the Cross*, *Father Brown*, and *The Man Who Was Thursday*; Maria Edgeworth’s *The Parent’s Assistant*; Herman Melville’s *Moby Dick*; John Milton’s *Paradise Lost*; William Shakespeare’s *Julius Caesar*, *Hamlet*, and *Macbeth*; and Walt Whitman’s *Leaves of Grass*.

	Science	Gutenberg	Reuters
explain	368	90	49
because	1241	723	625
reason	65	209	110
account	214	123	456
understand	305	315	49
evidence	415	32	41
show	2010	172	461
discover	111	78	49
reveal	543	37	14
suggest	1231	27	87
implication	252	9	31
indicate	806	11	119
confirm	322	25	87
establish	192	64	88
cause	462	252	211
theory	299	14	4
law	32	329	152
mechanism	674	0	18
model	1027	8	15
phenomena	85	2	5
effect	1123	61	218

Table 2.2: The number of tokens per million words for each word group in each of the three corpora.

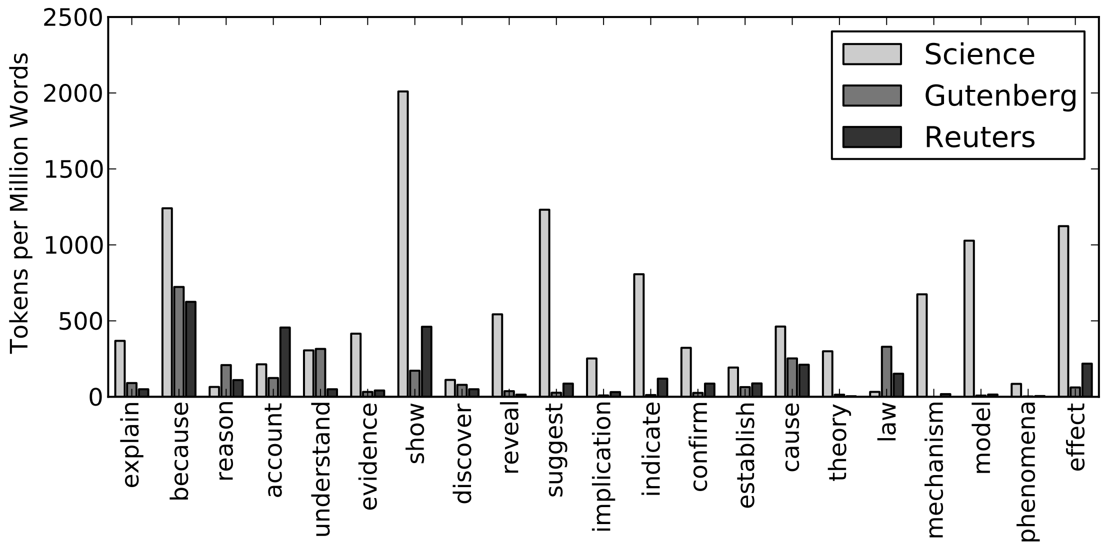

Figure 2.3: Plot of the number of tokens from each word group for the three corpora.

variants when they present or refute strong explanatory claims.

To test this hypothesis I have compiled a list of the phrases that the words "explain" and "be explained" occur in. Table 2.3 lists the most frequent short phrases. What is notable about these lists is how many of the phrases qualify or negate the word "explain" or "be explained". This provides some evidence that scientists treat "explain" as a strong word.

I then generated a list of qualified and negated phrases. The first part of each phrase is either "may", "can", or "could". The last part of the phrase is either "explain", "explained", or "show". I also added negations for each of these phrases (note that the contraction "cannot" is automatically separated into "can" and "not" by the NLTK word tokenizer). Then I counted the number of occurrences of these qualified phrases in the data set and calculated the percentage of qualified phrases among all the occurrences of "explain", "explained", and "show".

Table 2.4 lists the results. The differences are striking. More than a third of all uses of "explain" and "explained" are simple qualifications or negations. Of course, other uses may be qualified in more complicated ways not measured here. By comparison, only a handful of uses of "show" were so qualified.

In summary, I have shown how a number of different text mining techniques can be employed to answer questions about the use of "explain" and other words of interest in scientific articles. In considering whether explanation is important in science we have seen that words from the "explain" group are used in approximately

#	%	Top 2-Grams
144	30.57	explain the
114	24.20	to explain
98	20.81	explained by
94	19.96	be explained
36	7.64	may explain
34	7.22	explain why
24	5.10	can explain
22	4.67	could explain
21	4.46	not explain
20	4.25	explained in

#	%	Top 3-Grams
66	14.01	be explained by
58	12.31	to explain the
36	7.64	can be explained
34	7.22	explained by the
16	3.40	not be explained
15	3.18	explain the observed
13	2.76	may explain the
12	2.55	can explain the
12	2.55	can not explain
12	2.55	may explain why

#	%	Top 4-Grams
25	5.31	be explained by the
25	5.31	can be explained by
12	2.55	can not be explained
10	2.12	explained in terms of
10	2.12	not be explained by
9	1.91	be explained in terms
9	1.91	may be explained by
8	1.70	can not explain the
8	1.70	proposed to explain the
8	1.70	to explain the observed

#	%	Top 5-Grams
9	1.91	be explained in terms of
9	1.91	can be explained by the
7	1.49	can not be explained by
6	1.27	been proposed to explain the
6	1.27	can be explained in terms
6	1.27	have been proposed to explain
4	0.85	) , which may explain
4	0.85	can only be explained by
4	0.85	may be explained by the
3	0.64	could not be explained by

Table 2.3: The four lists show the ten most common "*n*-grams" – two-word, three-word, four-word, and five-word phrases – that include either "explain" or "be explained". For each phrase the number of occurrences is listed as well as its percentage among the 471 total occurrences of "explain" and "be explained" in the data set.

#	%	Phrases ("explain", "be explained")
36	7.64	can be explained
36	7.64	may explain
24	5.10	can explain
22	4.67	could explain
12	2.55	can not explain
12	2.55	can not be explained
10	2.12	could be explained
10	2.12	may be explained
3	0.64	could not be explained
1	0.21	may not explain
166	35.24	TOTAL (of 471 tokens)

#	%	Phrases ("show")
3	0.27	may show
2	0.18	could show
1	0.09	can show
1	0.09	may not show
7	0.62	TOTAL (of 1122 tokens)

Table 2.4: The two lists show the most common phrases from the list generated by a systematic combination of a *modal* ["may", "can", "could"] with a *base* ["explain", "be explained", "show"] and negations. For each phrase the number of occurrences is listed, as well as its percentage among the total occurrences of the base phrase(s) in the data set.

half of all articles in the data set. This is comparable to the “cause” group, more than the “theory” and “law” groups, and less than the “model”, and “mechanism” groups. Explanatory and evidential words are used much more often in the *Science* corpus than in two comparison corpora. But while “show” is hardly every used with qualifying words and negations in the *Science* corpus, “explain” is very often qualified.

Taken together, we have a variety of evidence to support the claim that explanation is important to science, but also that scientists consider “explain” words to be strong ones and use them sparingly.

2.3 Generality of Explanation

In addition to the importance of explanation I have also claimed that it is general – that explanations can be found in a wide range of sciences. The evidence to support this claim is more straightforward.

While table 2.1 provides totals across the data set, we can also measure the number of articles, percentage or articles, number of tokens, and average tokens within each keyword group. The disadvantage is that this breaks up our large data set into many pieces, some of which are too small to allow us to draw strong conclusions. Figure 2.4 is a plot of the percentage of articles that include at least one token of a word in the “explain” group, broken down by keyword. We see that “explain” words are used by one or more articles in every keyword group. The percentage within each keyword group varies, and some of the samples are small, but it is clear that “explain” is used with more-or-less the same frequency across most of the scientific disciplines considered. Figures 2.5 and 2.6 show the ubiquity of “because” and “show”.

This is not the case for all of the word groups. For instance, “law” is used infrequently overall but also confined to a limited number of fields as figure 2.7 shows. The “theory” group is used in most fields, but is only prevalent in a few, as seen in figure 2.8. Again, when broken down by keywords, some of the sample sizes are small, but each of the “cause”, “mechanism”, and “model” groups has at least one keyword for which no articles appear (see figures 2.9, 2.10, and 2.11).

In short, explanatory words are used across scientific fields, supporting the claim that explanation is a general practise found across the sciences.

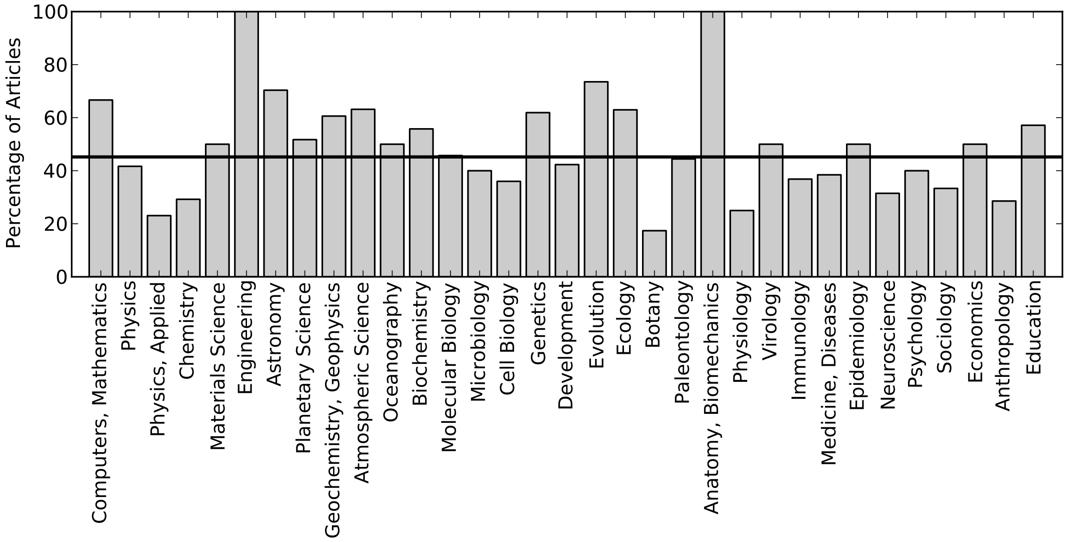

Figure 2.4: Plot of the percentage of articles that include at least one token from the "explain" word group, broken down by keyword, with a line indicating the overall percentage.

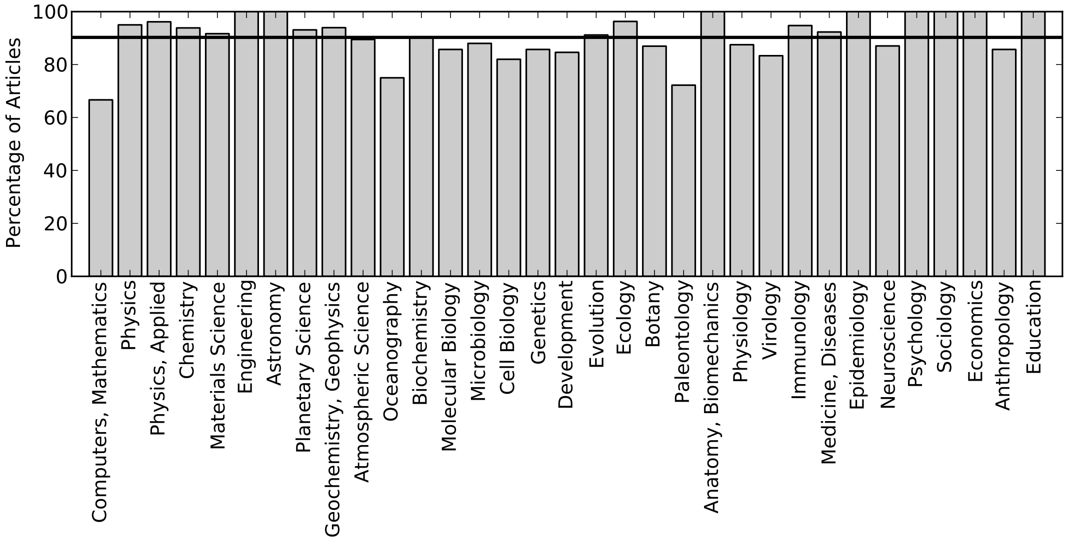

Figure 2.5: Plot of the percentage of articles that include at least one token of "because", broken down by keyword, with a line indicating the overall percentage.

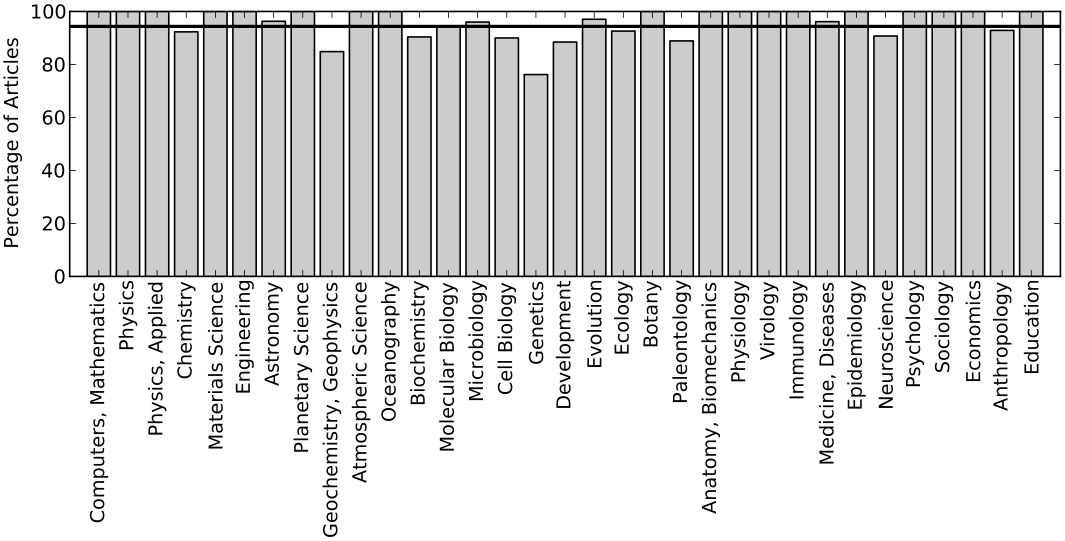

Figure 2.6: Plot of the percentage of articles that include at least one token from the “show” word group, broken down by keyword, with a line indicating the overall percentage.

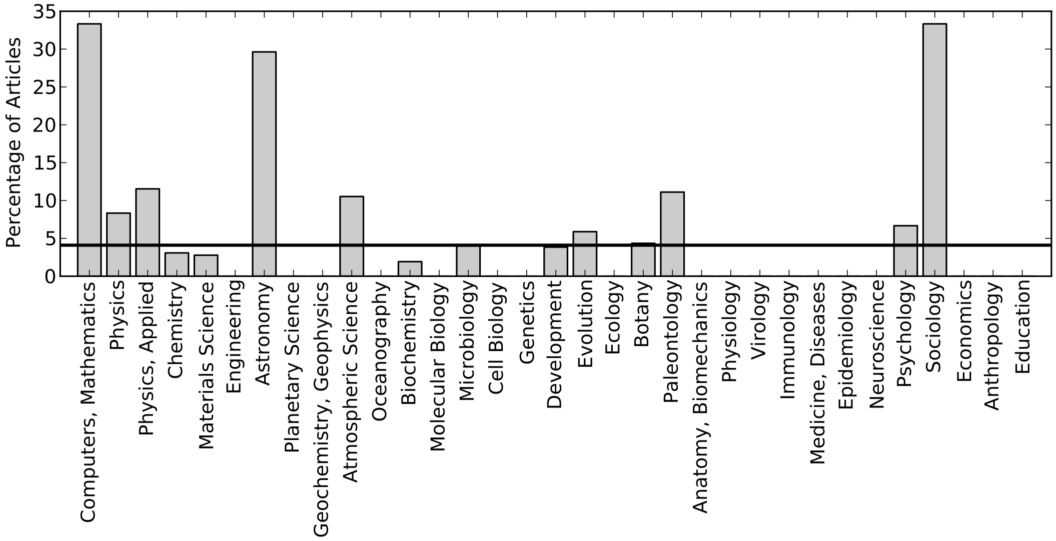

Figure 2.7: Plot of the percentage of articles that include at least one token from the “law” word group, broken down by keyword, with a line indicating the overall percentage.

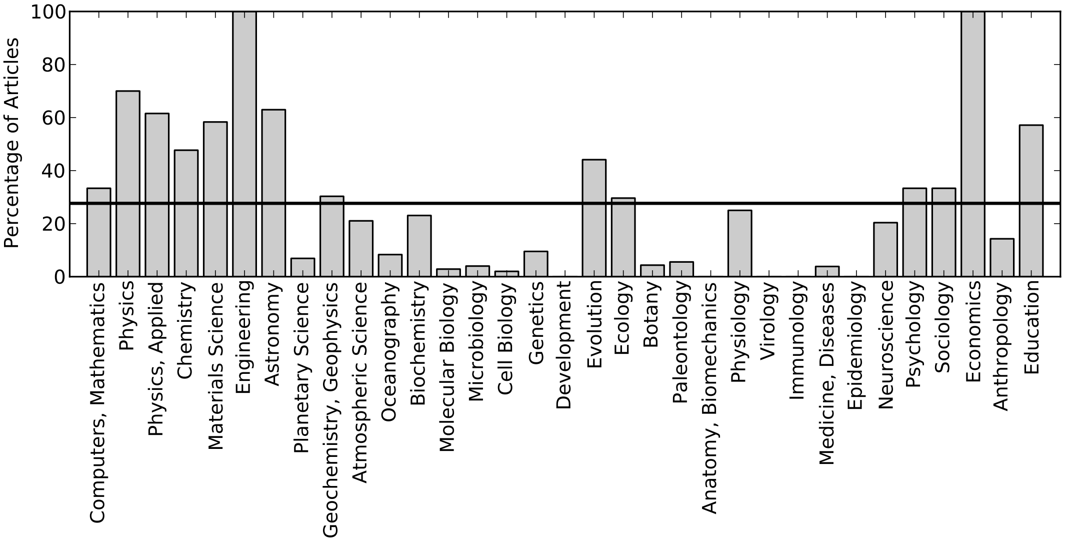

Figure 2.8: Plot of the percentage of articles that include at least one token from the "theory" word group, broken down by keyword, with a line indicating the overall percentage.

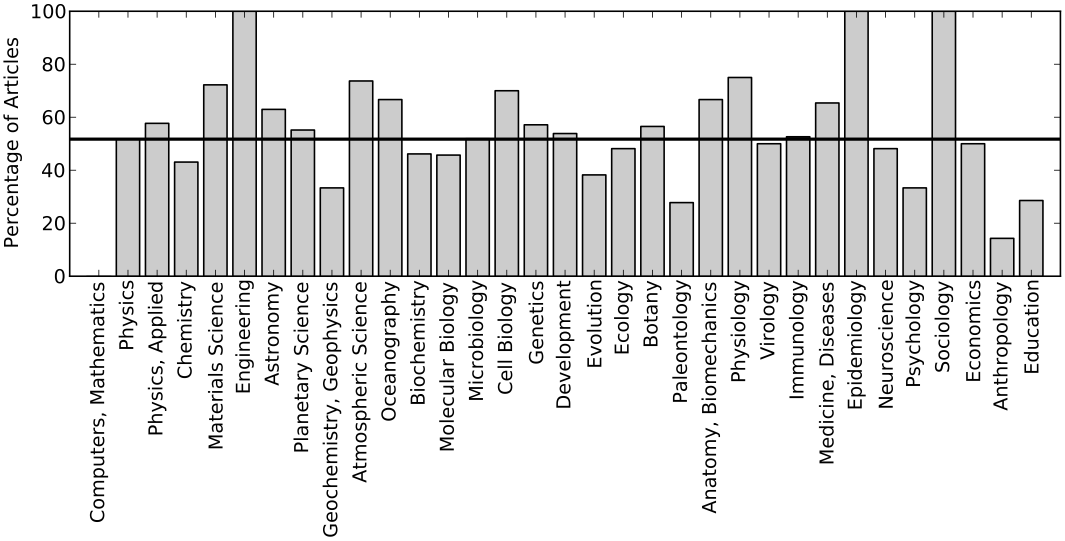

Figure 2.9: Plot of the percentage of articles that include at least one token from the "cause" word group, broken down by keyword, with a line indicating the overall percentage.

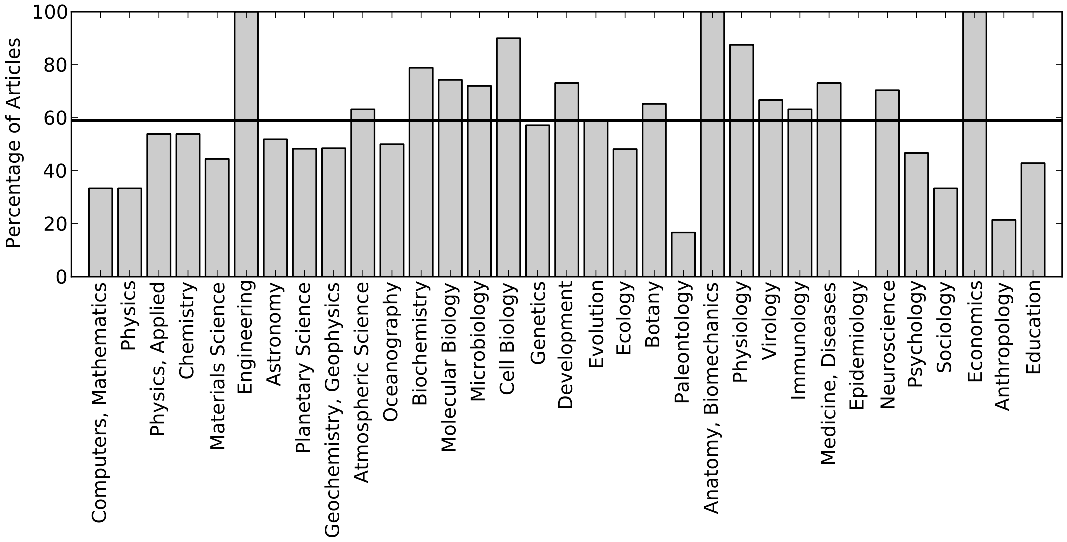

Figure 2.10: Plot of the percentage of articles that include at least one token from the "mechanism" word group, broken down by keyword, with a line indicating the overall percentage.

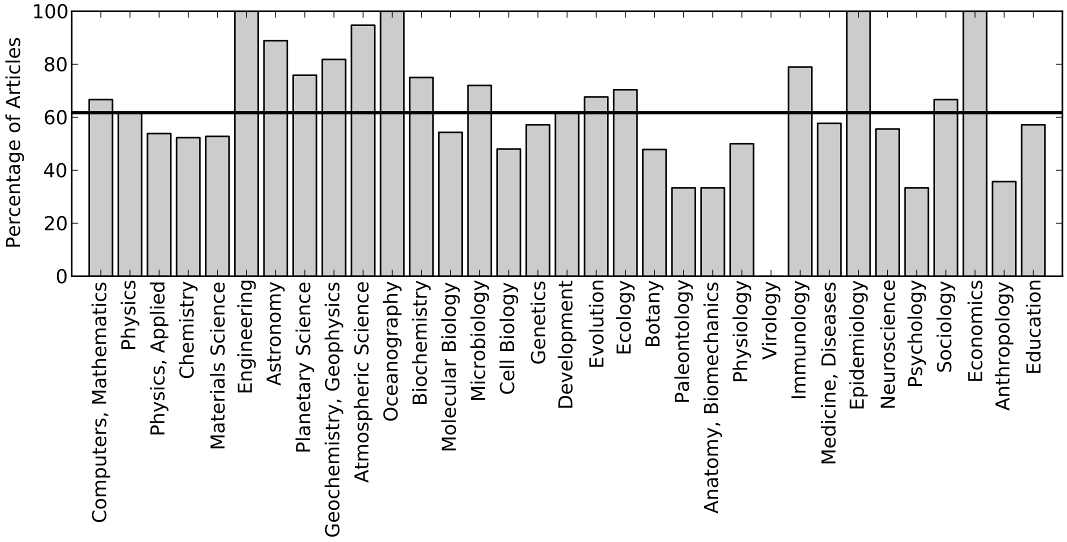

Figure 2.11: Plot of the percentage of articles that include at least one token from the "model" word group, broken down by keyword, with a line indicating the overall percentage.

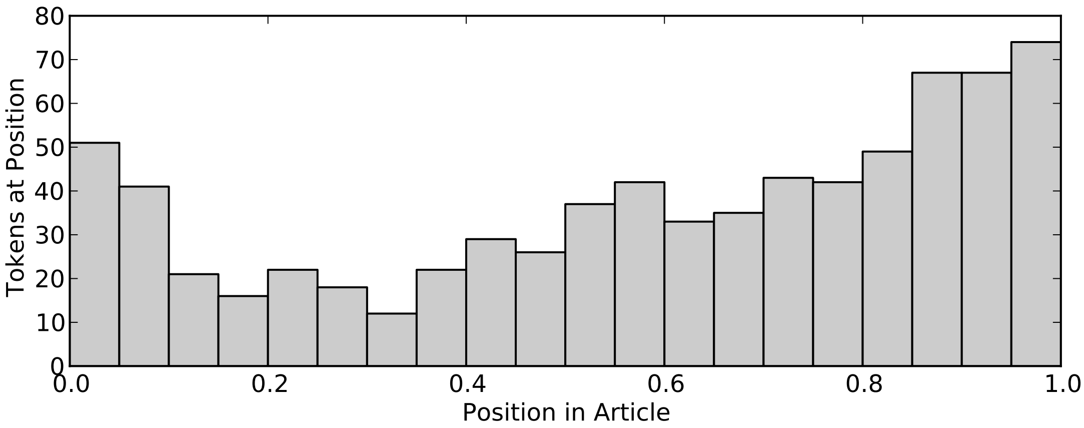

Figure 2.12: Histogram of the relative positions at which tokens of words in the "explain" group occur in articles.

2.4 Explanation as a Goal

I began this dissertation by claiming that explanation is a goal of science. Text mining techniques can provide some support here as well. In this case a relevant measurement is the position of the target words in the text. Since the abstract, introduction, and conclusion of a scientific paper lay out and evaluate the goals of the paper, words that are used more frequently near the beginning and end of the article than in the middle can be associated with the setting of goals.

Figure 2.12 shows a histogram of position data for the "explain" word group. After an initial peak the rate drops and then builds toward the end of the article. The "show" group has a somewhat similar pattern. The trend is clear but less dramatic than the plot for "understand" (figure 2.13), which has a strong "U" shape. Scientists tend to talk about understanding as they are setting out the plan of the article or reviewing what they have said. I take this as clear evidence that understanding is another goal of science, connected, of course, to explanation.

Other words of interest have relatively flat histograms, such as "because" and "cause" (figures 2.14 and 2.15). I believe that the differences between the histograms for the "explain", "because", and "show" can be accounted for in part by differences in the strength of the words.

The association between the use of "explain" words and the abstract, introduction, and conclusion provides weak evidence that explanation is a goal of science. The strong association for "understand" words is stronger evidence. In what follows I provide a stronger test by considering whether the central claims made in the abstracts

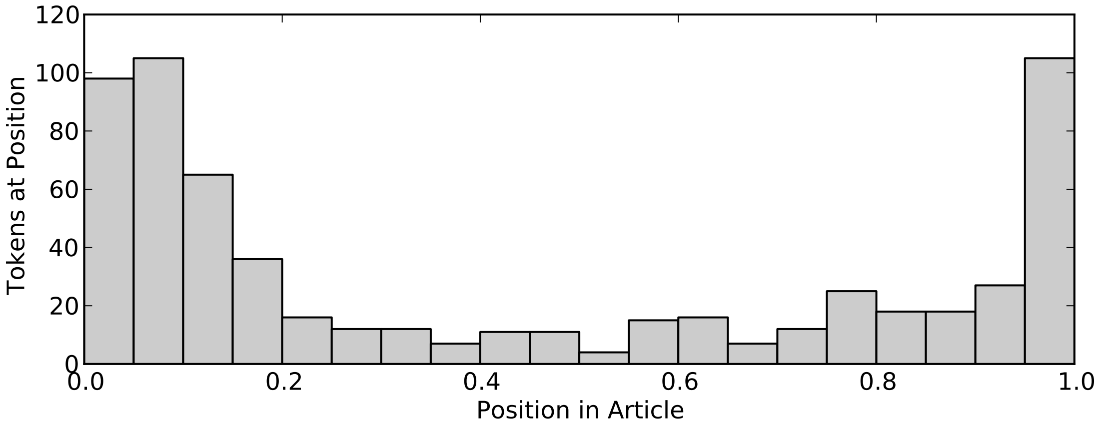

Figure 2.13: Histogram of the relative positions at which tokens of words in the "understand" group occur in articles.

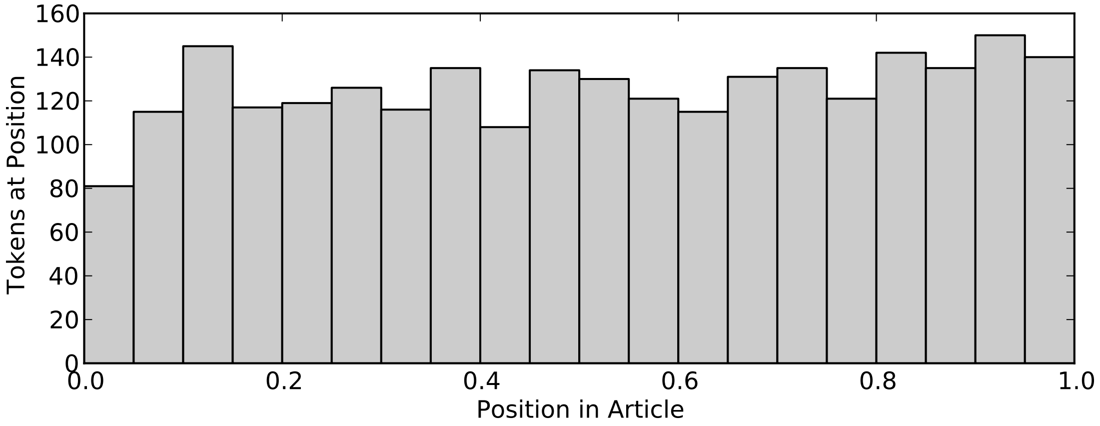

Figure 2.14: Histogram of the relative positions at which tokens of "because" occur in articles.

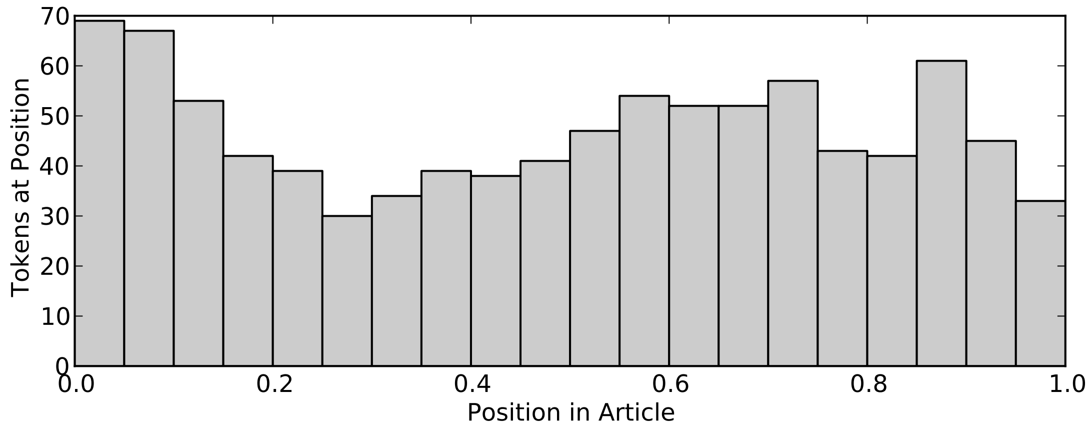

Figure 2.15: Histogram of the relative positions at which tokens of words in the "cause" group occur in articles.

of a representative sample of papers conform to my account of scientific explanation.

2.5 Evidence for Philosophical Accounts

In this chapter I have collected a range of evidence about the use of "explain" and other words of interest in the *Science* data set. This evidence supports my claims about the importance and generality of explanation and its role as a goal of science. The evidence is also telling for some of the philosophical accounts of explanation I surveyed in the first chapter.

One of the main divisions in the explanation literature is over the importance of causation. Is all explanation in science causal or is causal explanation just one type among others? My data shows that the usage of "explain" and "cause" is similar in many respects. They have approximately the same number of tokens, the same percentage of articles, and are both used across a range of scientific fields. One difference is in the position data.

Anscombe claims that the word "cause" acts as a placeholder, to be more fully determined by some more specific causal concept such as "*scrape*, *push*, *wet*, *carry*, *eat*, *burn*, *knock over*, *keep off*, *squash*, *make* (e.g. noises, paper boats), *hurt*" (original emphasis; Anscombe 1971, p. 9). This suggests that causal language is much more prevalent in the data set than a search for "cause" would show. I accept this point, but I believe that it is also true of explanation: "explain" acts a placeholder for more fully determined explanation concepts. This is an implication of the account of explanation I present in the next chapter.

The evidence about the use of “law” tends to undermine D-N as a general model of explanation in the sciences. This comes as no surprise, but the scarcity of uses of “law” is somewhat striking. “Theory” is more common and more general but the evidence does not provide much support for the unification account as the primary form of scientific explanation. The evidence supports the claim that mechanisms are important, particularly in certain sciences, and that description of mechanisms is a goal of science. It also supports the importance and generality of models and modelling. This set of evidence does not, I think, tell us much about the pragmatic account or asymptotic explanation.

2.6 Conclusions

Applying these text mining techniques to the *Science* data set reveals a range of information about “explanation” and related words. “Explain” words are common but not ubiquitous, used with a frequency comparable to other words of interest to philosophers of science. “Explain” is used much more in scientific writing than in other genres, and it is used across scientific disciplines. I think that these results provide confirmation of widely shared intuitions among philosophers about the generality and importance of scientific explanation. Perhaps surprising is the fact that such a large number of the uses of “explain” are qualified or negated. This indicates that “explain” is a strong word that scientists use sparingly, and perhaps accounts for the relatively low frequency with which these words are used by scientists in their articles, given the importance of explanatory practises.

This information is useful and it guides my further analysis, but text mining techniques can only tell us so much. They are no substitute for conceptual analysis, but rather a supplement. As philosophers analyzing a concept we consider the usage of words, often with a handful of examples in mind. With these methods we get a wider perspective on the usage. In the next chapter I turn to a more traditional philosophical analysis of explanation in light of what we have learned here.

Chapter 3

Analysis

I have offered evidence and arguments for the importance of explanation to a wide range of sciences. This makes it a good topic for general philosophy of science, at least *prima facie*. However it is still possible that scientists in each specific science mean something significantly different by “explain”. If so, then the analysis of these different senses of explanation is a task for philosophies of specific sciences, and the philosophical literature on explanation is justifiably fragmented.

To show that scientific explanation is general I need to provide an account of explanation that brings some unity to the concept and that applies to a wide range of sciences. Such an account must also allow for the diversity of scientific practises that we observe.

In this chapter I step beyond the limitations of text mining techniques and turn to case studies. In order to support the broad claims I wish to make I select my cases in a novel way. By choosing randomly from the *Science* data set I can avoid bias in my selection of cases, and by using a large number of small cases I can show that my account applies to a wide range of scientific practise.

I proceed in five stages. First I describe and defend my methods for selecting cases. Second, I draw on the clearest sampled cases of scientific explanation to begin building my account. I introduce several examples from sample A, which contains 25 cases where scientists explicitly use the word “explain”, “explains”, or “explained”. Then I present my methods for analyzing the cases and build toward a description of my general philosophical account of scientific explanation. Third, I test the account against sample B, which contains 100 random sentences from the *Science* data set. I also extend the account slightly to allow for cases of inference to the best explanation. Fourth, I present sample C, and argue that the main claims of all the abstracts in that random sample are either explanations or inferences to the best explanation.

Fifth and finally, I gather evidence from my analysis of sampled cases to support my answers to the three main questions: explanation is an important general goal of science.

3.1 The Case Study Method

Philosophers of science have long used the case study method for motivating and supporting philosophical claims. There are standard cases known to everyone in the field and there are new cases developed to test standing accounts or present new ones. Most papers that include a new case study include only one – they require significant effort to develop and present. The case studies that are used are carefully chosen.

A single case can be used as a counterexample to a general claim or as a demonstration of an existence claim. But philosophers usually want to do more than this. They want to use a small number of cases to support a general claim. This generalization step should be supported by some sort of argument.

However this step is usually left implicit in philosophy of science. I think that providing an explicit argument can be important, and is more important when the claim is more general. The claims I am making here are intended to apply to practises of explanation across a wide range of sciences, and so I have tried to justify them in their generality.

In this section I describe my methods for taking representative random samples of sentences from the data set and developing case studies from them. The nature of the data set, the sampling method, and the sample size provide support for the generality of my claims.

3.2 Selecting Cases

I have selected three sets of cases which I label samples A, B, and C. Each sample was collected to serve a different purpose but together they form a broad set of case studies in scientific explanation.

To support the generality of the claims I am making about explanation I need a large number of cases. By practical necessity, I cannot treat them all in great depth. My approach has been to select a single sentence as my target, fill in the necessary context, and use this as a small case study.

We have seen that uses of “explain” words are often qualified. I take this as evidence that “explain” is a strong word and that scientists use it carefully. So if we want to find cases where scientists are being careful about what is and is not being explained it makes sense to look for tokens of “explain”. I collected sample A by randomly sampling 25 tokens of the words “explain”, “explains”, and “explained” in the data set and developing each case from the sentence in which the token occurs. I use sample A to establish the core of my account of explanation.

Scientists often explain without using the word “explain”. With the core of my account of explanation and the list of associated phrases in hand, I move beyond “explain” and look for other instances of explanation that fit the structure. To collect sample B I selected 100 sentences at random from the *Science* data set.

I have also claimed that explanation is a goal of science. The text mining evidence for this claim was weak. I have collected stronger evidence by looking at the central claims made in the abstracts of papers in the data set, and checking that claim against my account of explanation. I collected sample C by randomly selecting 25 articles from the data set. I then looked for the central claim made in the abstract of each article and tested whether my account applies.

With the three samples combined, I have 150 cases of from which to build and test my general philosophical account of scientific explanation. Appendix A includes a full listing of all the samples with my analysis of each.

3.3 Sample A – Cases of “Explain”

Sample A consists of 25 quotations that contain at least one of the words “explain”, “explains”, or “explained”, selected at random from the *Science* data set. Of the 25 quotations in sample A, three did not seem to involve scientific explanations: cases A2, A16, and A25. Here is the text of case A2:

> For each value of T_c, we compute [equation 4] where the errors in the experimental and lattice QCD [quantum chromodynamics] quantities are obtained as explained above. (S. Gupta et al. 2011, p. 1527)

This use of “as explained above” seems to me to be synonymous with “as described above”. Since descriptions do not answer “what if things had been different” questions, I do not think this is a case of scientific explanation.

The remaining 22 sentences from sample A each seem to involve at least one scientific explanation of some sort. As expected, the range and variety of explanations is large. The following four examples demonstrate some of the diversity.

3.3.1 Case A12

> In summary, changes in water mass formation processes are not necessarily required to explain the high GNAIW [Glacial North Atlantic Intermediate Water] end-member δ^{13}C values. (Olsen and Ninnemann 2010, p. 695)

This sentence occurs in an article discussing the structure of the Atlantic Ocean in the context of the Earth's history of glaciation. Here the authors conclude their argument that the Industrial Revolution modified carbon isotope ratios in the North Atlantic. This accounts for some of the differences between the modern ocean and prehistoric glacial oceans, and so those differences no longer need be explained. The authors thereby solve an outstanding puzzle in the field. Note that the "Glacial North Atlantic Intermediate Water" is a proper noun – the name of a historical "formation" of water that scientists refer to in the same way as they refer to a particular formation of rock, e.g. the Canadian Shield.

3.3.2 Case A14

> Monoclonal conversion rules out a simple model of tissue maintenance that originates from a population of long-lived stem cells following a strict pattern of asymmetric division, and can be explained by two classes of behavior. First, crypts could be maintained by a hierarchy in which a single stem cell generates, through a sequence of asymmetric divisions, stem cells with a more limited proliferative potential. Second, tissue could be maintained by an equipotent stem cell population, in which stem cell loss is perfectly compensated by the multiplication of others. (Lopez-Garcia et al. 2010, p. 822)

(The first sentence was randomly selected, and the second and third are included as the referents of "two classes of behavior".) Intestinal epithelial tissues are maintained by populations of stem cells. This quotation comes from a paper that discusses the mechanism by which those stem cell populations coordinate their growth. Monoclonal conversion is the eventual complete domination of crypts by cells sharing a single (recent) common ancestor.[1] Here the authors mention three possible models for monoclonal conversion. They dismiss the first as too simple and give brief overviews of the other two.

---

[1] This simulation illustrates the process: `http://www.youtube.com/watch?v=Jw3mXwOUpPk`.

In the course of their paper the authors settle on a model in the third class, so I will focus on that explanatory claim. On this model it is the balance of the population, maintained by perfectly compensated multiplication of equipotent stem cells, that explains the eventual occurrence of monoclonal conversion in crypts of stem cells in intestinal epithelial tissues.

3.3.3 Case A4

> Physiological concentrations of ADP [adenosine diphosphate] inhibit kinase activity in the oscillator, and a mathematical model constrained by data shows that this effect is sufficient to quantitatively explain entrainment of the cyanobacterial circadian clock. (Rust, Golden, and O'Shea 2011, p. 220)

Circadian clocks are biological systems that oscillate with a regular frequency and allow organisms to regulate processes such as their day/night cycle, even when the original stimulus is not present. Such a clock becomes "entrained" when its oscillation synchronizes with the stimulus. The authors of this paper studied the biological clocks of cyanobacteria. They succeeded in their goal of creating a mathematical model that could account for their observations and make predictions about the rates at which the clocks become entrained to stimuli.

"Quantitatively explain" is a peculiar phrase, but I take it to mean that the mathematical model makes numeric predictions that match measured magnitudes such as the rate at which the oscillations synchronized. Here the authors state that the concentration of ADP is the key parameter for their model. In short, a parameterization of their model explains their data about entrainment of the cyanobacterial circadian clock.

3.3.4 Case A10

> No clear theoretical predictions for a star with parameters similar to those for HIP 13044 exist, hence it is possible that some high-order oscillations can explain the 1.4- or 3.5-day signal. (Setiawan et al. 2010, p. 1643)

A number of the *Science* articles report on the discovery of planets around distant stars. The method is usually to watch the star closely for periodic reductions in the brightness, possibly indicating that a planet has occluded the star. From the size, duration, and spacing of these reductions astronomers can infer the number, size, mass, and orbits of planets around the star. While the targets of these methods have usually been young stars, this paper reports on the discovery of a large planet around a star in the late stages of its evolution. Here the authors try to account for two unexplained signals in their data that are too frequent to indicate planetary occlusion but too slow to indicate the expected pulsations in the brightness of the star itself. They propose that something about higher-order oscillations in the brightness of the star itself may explain the length of the signals.

3.3.5 Phrases

In the 22 successful cases of explanation in sample A the following explanatory phrases occur at least once:

1. able to explain (2)
2. appears to explain, at least in part
3. are not necessarily required to explain
4. can also explain
5. can be explained by (7)
6. can possibly explain
7. cannot be explained by
8. could plausibly be explained by
9. explain why
10. explained
11. explained by
12. have been proposed to explain (2)
13. is explained in part
14. is not necessarily explained by
15. is sufficient to quantitatively explain
16. may be explained by
17. may best be explained in terms of
18. previously invoked to explain
19. this explains why
20. to explain
21. were not explained by

In every case, the "explain" word seems to indicate a binary relation: X explains Y. I take this binary explain-relation to be the target of my analysis.

What are the relata of the explain-relation? Following Hempel I label them the "explanans" and "explanandum" – the explanans explains the explanandum. I distinguish between statements of explanations and explanations themselves, and unlike Hempel I do not restrict the explanans and explanandum to propositions or parts of a statement.

3.3.6 Preliminary Glosses

In order to understand the structure of the explanations in the example cases, I isolate the statements of the explanations from the rest of the text and provide a gloss that expresses what I think the explanation is. This inevitably involves some degree of interpretation. I have *italicized* the portions of the glosses that do not appear on the surface of the text, and are thus the most open to interpretation, but there may still be room to dispute the remaining portions. I have tried to give the most natural reading I can of the cases in a self-contained sentence with "*X* explains *Y*" form. The phrase referring to the explain-relation is rendered in SMALL-CAPS.

A12 Changes in water mass formation processes ARE NOT NECESSARILY REQUIRED TO EXPLAIN the high GNAIW end-member δ^{13}C values.

A14 *The balance* of the population in a model of perfectly compensated multiplication of equipotent stem cells CAN EXPLAIN *the eventual occurrence* of monoclonal conversion in crypts of stem cells, in the maintenance of *intestinal epithelial* tissues.

A4 The physiological concentration of ADP in a mathematical model of kinase activity in circadian clocks of cyanobacteria IS SUFFICIENT TO QUANTITATIVELY EXPLAIN the rate of entrainment of the circadian clocks of cyanobacteria.

A10 High-order oscillations *in the luminance of stars* CAN POSSIBLY EXPLAIN the length of the signals *in the luminance* of HIP 13044.

The gloss of A12 is nearly identical to the original quotation. However in most of the cases it is more difficult to gloss the explanatory claim. This can be due to the order in which the claim is stated, because of implicit parts of the claim, for both reasons, or for some other complexity of English grammar.

In the gloss of A14 I emphasize the implicit claim that it is the balance of the population in the model that explains the eventual occurrence of monoclonal conversion. In both the explanans and the explanandum the context is the maintenance of intestinal epithelial tissues.

For case A4 I have reorganized and combined parts of the original to make the structure of the explanation clear. There is a parameter of the model, the concentration of ADP, that allows the model to predict the rate of entrainment.

Finally, for case A10 the context but not the quoted sentence makes clear that it is patterns in the *luminance* of the star HIP 13044 that are in need of explanation. What this gloss does not take fully into account is the language of "theoretical predictions" in the original.

These glosses are intended as starting points for my analysis. These glosses express well-formed explanations, but their structure is not yet entirely clear, and I believe that there is much that is still left implicit. What we need is a reliable method for bringing out the underlying structure.

3.3.7 Normal Form

English grammar is complex. In order to draw out the structure of the cases of explanation it would be good to simplify the glosses in some way. The main verb in these glosses is always "explain", which divides the statement of the explanans from the statement of the explanandum. Within the two parts, most of the significant words are either common nouns or adjectives modifying these nouns. In English it is often possible to switch between adjectival and noun forms. In order to clarify the explanatory structure of these cases I have *normalized* them by converting adjectives into noun form wherever possible. The effect is to create a "stack" of noun phrases connected by prepositions such as "of", "in", and "by".

This technique produces simple, ugly sentences. The advantage is that they make it much more clear just what things are involved in the explanation and what role they play. The normalized glosses show a number of robust patterns that were not visible in the originals. Without this step that structure remains hidden.

Here are the normalized forms of the four example cases:

A12 Changes in the processes of formation of water masses ARE NOT NECESSARILY REQUIRED TO EXPLAIN the large size of values of δ^{13}C in end-members of GNAIW.

are not necessarily required to explain

Changes
in the processes
of formation
of water masses

the large size
of values
of δ^{13}C
in end-members
of GNAIW.

A14 *The balance* of the population in a model of perfect compensation in the multiplication of equipotent stem cells by crypts of stem cells *in the maintenance of epithelial tissue of intestines* CAN EXPLAIN *the eventual occurrence* of monoclonal conversion in crypts of stem cells *in the maintenance of epithelial tissue of intestines.*

can explain

The balance
of the population
in a model
of perfect compensation
in the multiplication
of equipotent stem cells
in crypts
of stem cells
in the maintenance
of epithelial tissue
of intestines

the eventual occurrence
of monoclonal conversion
in crypts
of stem cells
in the maintenance
of epithelial tissue
of intestines.

A4 *The physiological concentration* of ADP of the mathematical model of the activity of kinase in circadian clocks of cyanobacteria IS SUFFICIENT TO QUANTITATIVELY EXPLAIN *the rate* of entrainment of circadian clocks of cyanobacteria.

is sufficient to quantitatively explain

The physiological concentration
of ADP
in the mathematical model
of the activity
of kinase
in circadian clocks
of cyanobacteria

the rate
of entrainment
of the circadian clocks
of cyanobacteria.

A10 The high-order of oscillations *in the luminance of stars* CAN POSSIBLY EXPLAIN the length of the signals *in the luminance* of HIP 13044.

can possibly explain

The high-order	the length
of oscillations	of the signals
in the luminance	*in the luminance*
of stars	of HIP 13044.

3.3.8 Patterns of Explanation

These example cases include a number of patterns that are representative of the other cases in sample A. In this section I describe some of the patterns in order to motivate my general account.

In case A4 we have ten distinct noun phrases: the physiological concentration, ADP, the mathematical model, the activity, kinase, circadian clocks, cyanobacteria, the rate, entrainment, the circadian clocks. Among these are nine types of things: physiological concentrations, ADP, mathematical models, activities, kinase, circadian clocks, cyanobacteria, rates, entrainment. Some of these types are good candidates for natural kinds: ADP, kinase, circadian clocks, and cyanobacteria. Natural kinds play an important explanatory role in philosophical accounts such as D-N. Mathematical models are another type of model that has been taken to play an important role in scientific explanations. The remaining types (physiological concentrations, activities, rates, entrainment) are also kinds of things, but perhaps not natural kinds. I propose a use of "kinds" that covers all these types – a more general sense than "natural kinds". I will develop this concept of a *kind* as we proceed.

In addition to these common nouns, two of the example cases include a proper noun: "HIP 13044" and "GNAIW". Each is clearly understood to be an instance of a kind in the explanation: a star and a water mass, respectively. We could add another implicit item below each of these proper names, specifying that HIP 13044 is a star and that GNAIW is a water mass.

If we add those items then a pattern emerges in these normalized examples: the bottom member or members of the explanans stack and the explanandum stack are identical kinds:

A12 water masses

A14 crypts of stem cells in the maintenance of intestinal tissue

A4 the circadian clocks of cyanobacteria

A10 stars

I call this kind the "base" of the explanation. It is something that the explanans and the explanandum share in common – the "topic" of the explanation.

A second pattern occurs at the top of the stacks. The top items are not natural kinds, but rather qualities of the next item. They pick out some quality of the explanans that is particularly salient for some quality of the explanandum, or conversely, some quality of the explanandum that depends on some quality of the explanans. This makes good sense – it is never *everything* about the explanans that explains *everything* about the explanandum, otherwise the two would (arguably) be identical. I call these the "explanans quality" and the "explanandum quality" respectively, or the "top qualities" of the explanation collectively.

If we take just those qualities from the explanans and from the explanandum, and join them with "explain(s)", then we get a well formed (though abbreviated and perhaps untrue) explanation:

A12 Changes explain the large size.

A14 The balance explains the eventual occurrence.

A4 The physiological concentration explains the rate.

A10 The high-order explains the length.

We can imagine a teacher making such a statement to drive home the key point at the end of a lesson. This suggests that the place to look for the explain-relation is at the top of the stacks.

Between the base and the top are the "cores" of the explanans and the explanandum. The cores bear the weight of the explain-relation. However they do not seem to be the relata of the explain-relation. Among the cores of the example cases we can see some other patterns. The word "model" occurs in the explanans. Words such as "values" and "signals" occur in the explanandum. The two proper nouns occur on the explanandum side of the core. Other kinds occur on both sides. These patterns hold for the rest of the cases of explanation in sample A. Words such as "rate" and "value" are qualities that modify other special kinds such as "measurement" and "observation". These always occur higher on the explanandum side than proper nouns do – they refer to data collected about particular things. Words such as "model" and "mechanism" always occur above some kind – they are models and mechanisms *of*

phrase	is sufficient to quantitatively explain	
top	*The physiological concentration*	*the rate*
core	of ADP in the mathematical **model** of the activity of kinase	of entrainment
base	in circadian clocks of cyanobacteria	in circadian clocks of cyanobacteria.

Table 3.1: Normalized structure of the explanation in case A4.

kinds. The occurrences of these "special types" shape the form of the explanation. Table 3.1 shows the structure just described for case A4: the top, core, and base for the explanans and explanandum, with some of the special types marked in the core.

After normalizing all of the cases in sample A there is enough evidence to motivate my general account. The sample A cases are core cases of explanation where the word "explain" is explicitly used. I develop my account from these core cases and then test it against samples B and C in the following sections.

3.3.9 Categories and Forms

At the centre of my account are five coarse categories that capture all of the noun phrases in sample A. We have already seen the "special types" that occur explicitly in the example cases, and there are many others in sample A:

models "model", "mechanism"

entities proper nouns, definite descriptions, "sample", "specimen"

data "measurement", "observation"

kinds all other kinds

There is one more category that does not occur on the surface of any of the cases in sample A, but is important to their structure. I label this fifth category "theories".

The five categories are then theories, models, kinds, entities, and data. Each demands a fuller analysis, and the following five chapters are dedicated to that task. But in very rough terms we can understand them as follows:

theories On my usage, a theory is a principle, set of principles, or a formal system that is a building block for models.

Types of theory: laws, empirical generalizations, mathematical formalisms.

Examples of theories: the theory of chromosomal supercoiling (B21), universal hydrodynamics (B2), the defensive function of sabre teeth (B54), the mathematical theory of differential equations (B45).

models A model is an abstract description of the relationships that hold between kinds and their qualities. A model *articulates* a kind.

Types of model: sets of differential equations, mechanisms, flow charts.

Examples of models: Brownian random walks modelling foraging behaviour (B49), reaction-diffusion equations modelling spatially periodic biological structures (B45), a hierarchical model of stem cell crypts (A14).

kinds A kind is an abstract universal class of entities that supports counterfactual reasoning.

Types of kinds: natural kinds, species, universals.

Examples of kinds: lithium (A1), *E. coli* (A8), Mn_4CaO_2 (B68), ADP (A4), circadian clocks (A4).

entities An entity is a concrete particular thing. I include both substances and processes under "entities". An arbitrary collection of entities can also count as an entity. References to entities often take the form of proper nouns or definite descriptions.

Types of entities: stars, samples, specimens.

Examples of entities: star HIP 13044 (A10), the Tagish Lake meteorite (A19), the sample of carbon monoxide extracted from ice core D47 in (A15).

data For our purposes, a datum is a statement about an entity. In *Science* articles they are usually referred to collectively as "data" and they come in several forms.

Types of data: measurements, observations, images.

Examples of data: the measurements of end-member δ^{13}C values in case A12, the measurements of rates of entrainment of circadian clocks in case A4, the observations of the severity of the Fog phenotype in *C. elegans* in case B58.

Why these five categories? Although this categorization is supported by the evidence I collect, I did not come to it through some process of induction from the data set. Instead I used my best judgement, informed by philosophical training. I began with the categories of "model" and "kind". Philosophers have long thought these two to be both significant and distinct. Kinds demand instances, my "entities". Data are important to science, and data about entities must be distinct from the entities themselves. Finally, philosophers have usually distinguished models from theories, and sought to account for both. Finer distinctions are certainly possible, but more categories would mean that my analysis would require even larger sample sizes than it already does. These five coarse categories allow me to distinguish many forms of scientific explanation, describe my samples in a rich way, and place many existing philosophical accounts of scientific explanation into a general structure.

Pairs of instances of adjacent categories on this scheme have standard relationships. Theories are the principles and systems used to *justify* a model. A model *models* a kind. Kinds are *instantiated by* entities. And entities have complex *measurement* relations to data. I call these the "primary" relations. Pairs of instances from the same category can have various "secondary" relations. Figure 3.1 shows this structure.

We can categorize explanantia and explananda according to this scheme. We do this by taking the highest item on the stack that is a theory, model, entity, or sort of data. If there is none, then we apply the default category of "kind". I call the pair of the category of the explanans and the category for the explanandum the "form" of the explanation. For instance, the form of example A4 is "model-data", because "model" occurs highest in the explanans and because "rate" (associated with the "data" category) occurs highest in the explanandum. In other words, in example A4 it is something about the model that explains something about the data.

3.3.10 The Structure of an Explanation

The most complex form of explanation on my account is a theory-data explanation. In a theory-data explanation we have at least one item from each of the categories: theory, model, kind, entity, and data. The relation between the theory and the data is the composite of the relations between the parts. Figure 3.2 depicts this form of explanation.

The theory-data form of explanation is the most complex. Other forms involve shorter chains of relationships. But while the chains may be shorter, they cannot skip any steps. If the form is theory-kind, then there must be a model somewhere in the explanation: the theory justifies part of the model and the model models the

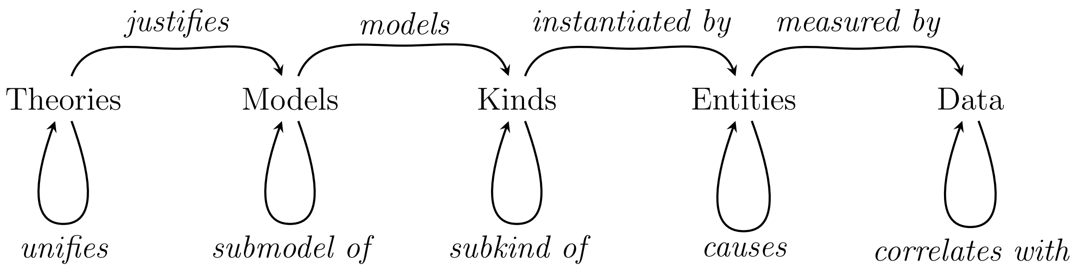

Figure 3.1: The five categories, four primary relations, and examples of five secondary relations.

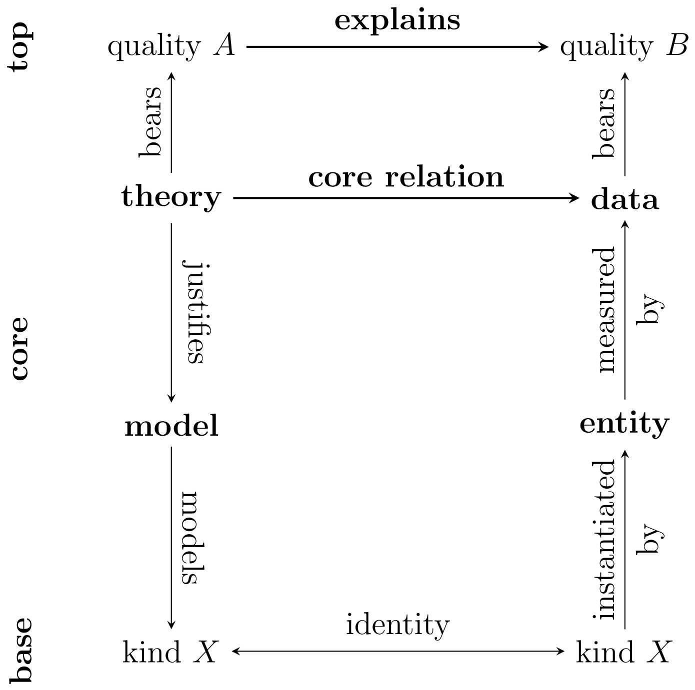

Figure 3.2: General structure of a theory-data explanation.

kind. The intervening step might be implicit because it is not one particular model that the authors have in mind, but rather just some model that involves the theory and models the kind. Likewise, a model-data explanation requires some kind and some entity: the model models the kind, which is instantiated by the entity, which is measured to result in some data. Again, some of these might be implicit.

Why not skip steps? The full answer requires a more detailed analysis of each of the categories, and that will come in the following chapters. But the question is important enough to address here in a preliminary way.

1. Why posit an implicit entity in an explanation of kind-data form? Because kinds are abstracta, lacking in causal powers. There are no measurements or observations or images of kinds, only the entities that are instances of them. For example, while all stars have mass, and we can measure the masses of stars, the kind *star* has no mass to measure. The trickier case is comparing kinds to those entities that are really collections. Data about collections of entities are really collections or summaries of data about particular entities, where each entity has causal powers while the collective itself does not.

2. Why posit an implicit kind in an explanation of model-entity form? Because the model will always apply not only to that particular entity, but to other entities (both actual and counterfactual) that are similar to it in the relevant respects – which is to say that the model applies to the kind. For example, a model of the brightness of star HIP 13044 over time will encode its mass and radius, but not other qualities, such as its position or momentum. The same model will apply to other stars that are similar in the relevant respects but differ in the irrelevant ones. Thus the model models the *kind* of star with that mass and radius.

3. Why posit an implicit model in an explanation of theory-kind form? This is perhaps the most difficult distinction to defend. In principle it is easy to distinguish between the law of gravitation and an equation that models the orbit of a planet. In practise, at least in sample A, there are no clear references to laws. Instead we see kind terms, such as “the luminance of stars”, but we know that there is a complex body of theory describing the dynamics of a star. In order to apply the theory to a class of entities we need to add additional assumptions and fix parameters. This is a process of model building, and the resulting model is distinct from the original theory.

For more thorough discussions of these points see the relevant chapters for kinds, models, and theories.

This general structure is powerful. All of the cases of explanation in sample A can be interpreted as explanations of this sort. However there are often implicit steps in the explanations. For instance, the statement of the explanation may mention a relationship between qualities of two kinds without using the word "model". Or it may say that some general principle does the explaining without mentioning either a "theory" or a "model". In order to express the structure of such explanations I insert implicit items, marked in italics, into the explanans and explanandum. Sometimes it is the implicit items that determine the form of the explanation.

3.3.11 Revised Glosses

While there is no algorithm for extracting the structure from a statement of an explanation, my method is designed to be easy to apply and reproducible. First, gloss the explanation. Then put it in normal form as a series of noun phrases. At the top, try to find the qualities of the explanans and explanandum, which may be implicit. At the base, try to match the bottom items of the explanans and explanandum. In the core, try to categorize the explanans and explanandum. This may require inserting implicit items to make clear that claims about theories, models, entities, or data are involved. The categories of the explanans and explanandum determine the form of the explanation.

Here are the final glosses and tables for the four example cases. Appendix A contains the quotations, notes, glosses, and tables for all of the cases in samples A, B, and C.

A12 Kind – data explanation

> Changes in the processes of formation of water masses ARE NOT NECESSARILY REQUIRED TO EXPLAIN the large size of **measurements** of δ^{13}C in end-members of **GNAIW** *which is a water mass.*

are not necessarily required to explain	
Changes	the large size
in the processes of formation	of **measurements** of δ^{13}C in end-members of **GNAIW**
of water masses	*which is a water mass.*

A14 Model – kind explanation

The balance of the population in a **model** of perfect compensation in the multiplication of equipotent stem cells by crypts of stem cells *in the maintenance of epithelial tissue of intestines* CAN EXPLAIN *the eventual occurrence* of monoclonal conversion in crypts of stem cells *in the maintenance of epithelial tissue of intestines.*

can explain	
The balance	*the eventual occurrence*
of the population	of monoclonal conversion
in a **model**	
of perfect compensation	
in the multiplication	
of equipotent stem cells	
by crypts	in crypts
of stem cells	of stem cells
in the maintenance	*in the maintenance*
of epithelial tissue	*of epithelial tissue*
of intestines	*of intestines.*

A4 Model – data explanation

The physiological concentration of ADP in the mathematical **model** of the activity of kinase in circadian clocks of cyanobacteria IS SUFFICIENT TO QUANTITATIVELY EXPLAIN *the rate* of entrainment *in the **measurements*** of the circadian clocks *in a **sample*** of cyanobacteria.

is sufficient to quantitatively explain	
The physiological concentration	*the rate*
of ADP	of entrainment
in the mathematical **model**	*in the **measurements***
of the activity	of the circadian clocks
of kinase	*in a **sample***
in circadian clocks	
of cyanobacteria	of cyanobacteria.

A10 Theory – data explanation

> The high-order of oscillations *of luminance in the* ***theory*** *of stellar dynamics in* ***models*** of stars CAN POSSIBLY EXPLAIN the length of the **measurements** of the oscillations *of luminance* of **HIP 13044** *which is a star.*

	can possibly explain
The high-order	the length
of oscillations *of luminance* *in the* ***theory*** *of stellar dynamics* *in* ***models***	of the **measurements** of the oscillations *of luminance* of **HIP 13044**
of stars	*which is a star.*

3.3.12 Preliminary Evidence for the Account

Having normalized all of the cases in sample A we can consider all the pairs of the types of the explanantia and explananda. While any of the 25 pairings is possible *prima facie*, we see that not all of them occur in the data set. Table 3.2 shows the results, and figure 3.3 presents a visualization.

In sample A all of the explanations fall on the left-lower half of the table. There are model-kind explanations, but no kind-model explanations. There are theory-data explanations but no data-theory explanations. There are also some kind-kind explanations. The two most common forms are model-kind and model-data.

Given the prevalence of model-kind and model-data explanations, we might be tempted to say that when scientists say “explain” they mean that they have a model that explains a kind or some data about entities of that kind. I allow that model-kind explanation is the prototypical use of “explain”. But while model-kind explanation is more common than the other forms, by focusing on models as the explanans we ignore half of the explanations in sample A. I have argued that there is a similar structure in each case, with the key difference being the core relation. In the next section I will defend the claim that the core relations for all the forms share a common thread: they all support the counterfactual reasoning that is required for explanation.

This evidence provides some preliminary support for my account: it is general enough to cover a wide range of cases, and any additional complexity is justified by the flexibility to cover many forms of explanation that occur in sample A. Since the account was designed specifically to handle the cases in sample A, this is no surprise. The account must be tested against a wider range of cases to see whether it stands up.

	data	entity	kind	model	theory
data	0	0	0	0	0
entity	2	3	0	0	0
kind	1	1	3	0	0
model	5	1	9	0	0
theory	2	1	1	0	0

Table 3.2: The number of cases in sample A for each of the 25 forms of explanation, where each form is the pair of an explanans type (row) and an explanandum type (column), and the five categories of data, entity, kind, model, and theory classify both explanans and explanandum.

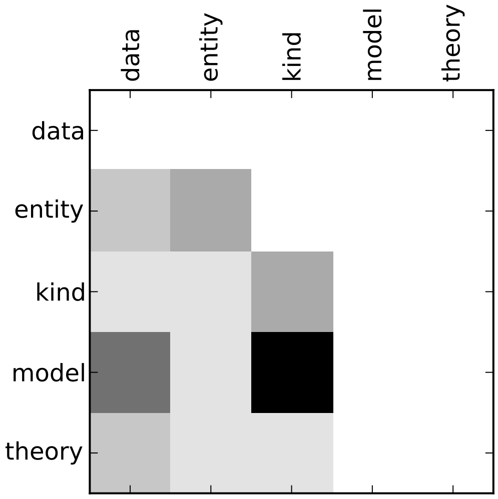

Figure 3.3: Visualization of table 3.2 in which darker colours indicate larger values.

3.4 A General Philosophical Account of Scientific Explanation

In scientific explanation the explain-relation holds between two qualities: the explanans quality and the explanandum quality. The explanandum quality depends on the explanans quality. If the explanans quality were different then the explanandum quality might also be different. Explanations allow us to reason counterfactually about the dependence of the explanandum on the explanans.

This much has been said before by philosophers of science. Woodward's influential account of explanation in terms of ideal interventions in causal processes is a counterfactual model of explanation (Woodward 2003). And the same insight can also be seen in other philosophical accounts, such as mechanistic, asymptotic, and model-based explanations. But the account I am proposing allows us to go further.

The explain-relation is always layered on top of some other relation between the explanans and the explanandum. I call this the "core relation". What I have called the "form" of the explanation determines, in a general way, the nature of the core relation. For example, in a model-kind explanation such as A14 the core relation is modelling. The counterfactual dependence of the eventual occurrence of monoclonal conversion on the balance of the population holds only to the extent that the model of the reproduction of the equipotent stem cells *models* crypts of stem cells in the maintenance of intestinal epithelial tissue. In a kind-data explanation such as example A12 the core relation is a composite of the instantiation of the kind by the entity (i.e. GNAIW is a water mass) and the measurement relation between the entity and the data (i.e. between GNAIW and the measurements of δ^{13}C in end-members). If GNAIW were not a water mass, the explain-relation would fail. If the measurements were not of GNAIW end-members, the explain-relation would fail to hold.

In general, the counterfactual supporting explain-relation between the explanans quality and the explanandum quality will hold as long and to the extent that the core relation holds between the explanans and the explanandum. We understand the details of the explain-relation in a given case by understanding the details of the counterfactual reasoning that the core relation supports.

Although the core relations can vary widely in different explanations across the range of scientific disciplines, the explain-relation is essentially the same. Scientists use "explain" in many different contexts, asserting an explain-relation between the qualities of various sorts of explanantia and explananda. The diversity of the uses of "explain" makes sense once we understand that there are diverse core relations supporting the explain-relation in different cases. Scientific disciplines may rely on some forms of explanation more than others. The five coarse categories I have proposed, and the forms of explanation based on them, are only a starting point, and there is room for more detailed analyses of specialized forms of explanation that may be unique to particular scientific disciplines.

3.4.1 Connections to Other Accounts

My account is designed to be a general one, covering explanatory practises across the sciences. I selected my evidence base and designed my methods with this in mind, keeping the focus firmly on scientific practise. My approach has not been to start with philosophical accounts of explanation and discover what they have in common. However, because various existing philosophical accounts do accurately describe practises of explanation, there are places for them within my general account.

If the deductive-nomological account had been completely wrong about scientific explanation then it would most likely have been rejected and forgotten. Instead it has lived on for decades as a spur and foil for new accounts. I think that D-N tangles together a number of insights that can be pulled apart using the distinctions I have developed. My view is that D-N describes theory-data explanation – a relatively rare form but a philosophically interesting one.

The nomological part of D-N explanation comes from the central role of laws of nature, which I classify under "theories". The conclusion of a prototypical D-N argument is a prediction or retrodiction of a measurement or observation about some entity, which I classify under "data". In the deductive form of a D-N explanation the data are statements about individuals, which I am calling "entities". The connection between laws and individuals is mediated by natural kinds, expressed by the predicates that apply to the individuals. These are included under my "kinds" category. And the role of models is apparent if one simply relaxes the D-N premises about initial conditions, leaving the rest of the laws, boundary conditions, and deductive structure intact. The result is a sort of argument schema with a free variable, which is a special case of what I am calling a "model" over a range of initial conditions.

Other existing accounts fit more easily into my general picture. Models have their own category, which I treat in chapter 7. I have argued elsewhere that mechanisms are best understood as a special class of abstract mathematical models (Overton 2011). Unification and asymptotic explanation have a place as forms of theory-theory explanation. Causal mechanical explanation fits as a form of singular causal entity-

entity explanation.

Among the philosophical accounts I surveyed in chapter 1, my account is closest to Woodward's causal intervention account. Both take counterfactual claims to be essential to explanation. While Woodward focuses on causal relations to support the counterfactuals, I generalize to a wider set of core relations.

Statistical relevance is an outlier – I do not have a place for it in my account. I share many of the doubts Woodward expresses about what statistical relevance actually explains (Woodward 2011, §3.3). In my cases I did not find any examples of a statistical explanans of a non-statistical explanandum.

In a following section I discuss the evidence I have collected in support of this account. That an account with this much structure can be so successful in describing practises of scientific explanation tends to count against van Fraassen's unstructured pragmatic account.

3.5 Sample B – Beyond "Explain"

My account of scientific explanation was designed around the cases in sample A, so it is no great surprise that those cases fit the account. Our confidence in the account will be much stronger if it can handle a wider range of fresh cases.

I collected sample B by taking a random sample of 100 sentences from the *Science* data set. Unlike sample A, I did not filter the selection for words of interest such as "explain". One of the limitations of the text-mining done in chapter 2 is the focus on particular words. In the analysis of sample B I have looked for explanations without restriction on the words used to express them.

After normalizing and structuring the explanations in sample B, I find 29 cases that fit my account of scientific explanation. A few of these use "explain" phrases but the majority use other language.

1. –
2. accounted for
3. because (3)
4. blocked
5. by showing that
6. can cause
7. could affect
8. could have served (3)
9. depended

10. did not significantly reduce
11. diminished
12. due to
13. induced (4)
14. inspired
15. is associated with
16. is best described by
17. is predicted to
18. is primarily set by
19. may be better understood … in terms of
20. may be better understood … not in terms of
21. might explain
22. one reasonable way to explain
23. owing to
24. protected
25. rescue
26. simulated
27. was proposed as a major source
28. we found a clear similarity between (2)
29. we reject the hypothesis (2)

Many of these phrases are much weaker than the "explain" phrases discussed above. The weaker phrases are not characterized in the same way by the use of qualifying words and negations. This much is no surprise.

The sentences in sample B also included phrases such as the following:

1. allow us to confirm that
2. as revealed by
3. demonstrated (3)
4. establishes experimentally
5. evince
6. imply that
7. it is highly probable that
8. it seemed likely
9. likely represent
10. might be evident in
11. most likely correspond
12. records (2)
13. reveal

14. revealed (3)
15. suggest that (2)
16. suggesting
17. suggesting that
18. suggests that
19. supports
20. were most likely due to
21. were most likely due to … rather than

These phrases do not express explanatory claims but rather some form of evidential claim. What is surprising is that the *structure* of these sentences matches the structure of the explanation sentences almost perfectly. If we normalize them and apply the same scheme we find top qualities, bases, and cores with items from the same five categories.

The key difference is that the direction is reversed. Whereas explanations have model-kind or theory-data form, these cases have kind-model or data-theory form. Instead of moving from the more abstract categories on the left of figure 3.1 to the more concrete categories on the right, in these cases we move from the right to the left. For each of these evidential claims, if we reverse the direction we get a well-formed explanatory claim.

3.5.1 Case B1

Consider an example:

> Surface-layer Mn, however, showed little if any shift (0.008 ± 0.008 V), again suggesting that such impurities do not respond to TIBB [tip-induced band bending]. (D. H. Lee and J. A. Gupta 2010, p. 1808)

This paper is about manipulation of electromagnetic fields of single atoms in doped semiconductors. TIBB is a change in the semiconductor bands caused by the tip of the scanning tunnelling microscope. I classify TIBB as a theory because it is only one factor in a model of semiconductor band behaviour. Here the authors state that TIBB does not change the magnetic field of Mn atoms, in contrast to Zn atoms where it plays a role.

I take the structure of this evidence claim to be as follows:

The small size or absence of a shift *in the **measurements*** of the voltage of the resonance peaks *in a **sample*** of the Mn atoms on the surface layer *of doped semiconductors* SUGGESTS *the lack* of a response *in the **theory*** of TIBB *in **models** of the semiconductor bands* of Mn atoms on the surface-layer *of doped semiconductors.*

suggests

The small size or absence	*the lack*
of a shift	of a response
*in the **measurements***	*in the **theory***
of the voltage	of TIBB
of the resonance peaks	*in **models***
*in a **sample***	*of the semiconductor bands*
of the Mn atoms	of Mn atoms
on the surface layer	on the surface-layer
of doped semiconductors	*of doped semiconductors.*

In an explanation we usually have a more general explanans on the left and a more specific explanandum on the right. (The exception is an explanation of secondary form, such as kind-kind or model-model, where there may not be a difference in generality.) In this case the left side is more specific, referring to data, and the right is more general, referring to theories. But as in an explanation we have the top qualities, the core, and the base, with the data above entities and theories above models. This evidence claim has the same structure as an explanation claim, except that the claim moves from the specific to the general rather than from the general to the specific. Simply switching the direction and substituting "explains" for the evidential phrase gives us a well formed scientific explanation. There are 23 cases like this in sample B. There are several cases where explanatory and evidential claims are mixed together. There are also several cases where it is difficult to determine from the structure of the sentence whether the claim is explanatory or evidential.

3.5.2 Evidence and Explanation

The standard high-level division of methods of inference is three-way: deduction, induction, and abduction. All three can be seen in scientific practise. Deduction is important when applying logical and mathematical theories, and when designing experiments to rule out alternatives. Various forms of induction are important in statistical methods. However the most characteristic form of inference in science is abduction, or inference to the best explanation.

The term "abduction" was coined by Charles Sanders Pierce in order to distinguish what he saw as a central scientific method from the more familiar methods of induction. Douven takes the key difference between the two to be the presence of explanatory considerations (Douven 2011, §1.1). Many philosophers recognize abduction as central to everyday reasoning, and many philosophers of science see it as central to scientific reasoning. Ernan McMullin's book on the topic is called *The Inference that Makes Science* (1992).

The striking similarity of structure in the explanatory and evidential cases strongly suggests that the latter are inferences to the best explanation. In sample B there are about the same number of cases of each type and there are several cases where both explanatory and evidential claims are being made. In many cases it seems somewhat arbitrary whether the authors phrased their claim in explanatory or evidential form. Were I to remove the linking phrase (e.g. "explains" or "suggests") and scramble the order, I doubt that a reader could tell which form the original took. Explanatory reasoning and these cases of evidential reasoning are tightly linked, and deserve to be analyzed together.

Unfortunately, a full analysis of the evidential cases as instances of abduction, and of the relationship between explanations and abductions, is beyond the scope of this dissertation. I leave that fascinating topic to future work. In my analysis of cases (listed in appendix A) I have marked each as either explanatory or evidential based on the phrasing and whether the direction runs from general to specific or specific to general. In the following five chapters on data, entities, kinds, models, and theories I have included examples of both types for discussion. But my focus remains on the question *what is a scientific explanation?* In the tables and figures that summarize my results I have included both the explanatory and evidential cases in order to show the full scope of this account of scientific explanation, but I have also pulled apart the two types in order to show the differences.

3.5.3 The Importance of Explanation

In chapter 2 the text mining results showed that "explain" words are used in just less than half of the articles in the *Science* data set. I noted that this was surprising if explanation is as central to science as many philosophers of science have thought. Other methods showed that "explain" is a strong word that scientists do not use lightly, but did not shed much light on the actual frequency of explanation within *Science* articles.

My analysis of sample B answers these questions about the importance of explanation in a much more direct way. Although the sample size does not compare to the comprehensive searches in chapter 2, this method is not restricted to predetermined lists of words of interest and it avoids many problems of word ambiguity.

The results from sample B show that 29 of all the randomly sampled sentences contain scientific explanations and that 23 of all the randomly sampled sentences include some evidential claim with a similar structure. Because the sentences were sampled randomly, we have reason to believe that a similar portion of all the sentences in the abstracts and bodies of the all the recent articles in *Science* are explanations or evidential claims with that structure. Once we step beyond the word "explain" we see that explanations are ubiquitous in science.

Finally, it is worth noting that the distribution of the forms of explanation across the cases is more uniform in sample B than in sample A. More forms are represented but for each there is a relatively small number of cases. I summarize this data below.

3.6 Sample C – Aiming to Explain

To create sample C I randomly selected 25 abstracts from the *Science* data set. In each case I looked for the main claim being made in the abstract. Most of the sampled abstracts follow a very similar form: establish the problem area, describe the approach, summarize the results, and perhaps point to an application. The main claim for these cases is usually contained in the final or second-to-last sentence of the abstract, but sometimes it spans several sentences.

3.6.1 Case C4

Consider the following abstract from a paper about the structure of ribosomes.

> During protein synthesis, the ribosome controls the movement of tRNA [transfar RNA] and mRNA [messenger RNA] by means of large-scale structural rearrangements. We describe structures of the intact bacterial ribosome from *Escherichia coli* that reveal how the ribosome binds tRNA in two functionally distinct states, determined to a resolution of ∼3.2 angstroms by means of x-ray crystallography. One state positions tRNA in the peptidyl-tRNA binding site. The second, a fully rotated state, is stabilized by ribosome recycling factor and binds tRNA in a highly bent conformation in a hybrid peptidyl/exit site. The structures

> help to explain how the ratchet-like motion of the two ribosomal subunits contributes to the mechanisms of translocation, termination, and ribosome recycling. (Dunkle et al. 2011, p. 981)

This abstract summarizes a complex argument for which the conclusion (and the main claim of the abstract) is the final sentence. I believe it to be an explanation with the following structure:

The ratchet-like quality of the motion *in **models*** of the structures of the subunits of the ribosome explains in part *multiple qualities* of the translocation, termination, and recycling of the ribosome.

explains in part

The ratchet-like quality	*multiple qualities*
of the motion *in **models*** of the structures of the subunits	of the translocation, termination, and recycling
of the ribosome	of the ribosome.

3.6.2 Explanation as a Goal

In all 25 of the sample C cases it appears to me that the main claim being made is either an explanatory or an evidential claim matching the structure I have described. I count 14 explanatory and 11 evidential cases. But even more than in sample B, the distinction between evidence and explanation seems to be fuzzy. I did not discern a clear pattern that would distinguish cases where an explanatory claim is made from the cases where an evidential claim is made. The abstracts always include claims about the specific data or results, and general claims about the kind, models, or theories that account for them.

In chapter 2 I claimed that explanation is a goal of science and used text mining techniques to test that claim. My methods included measurements of the relative location of the words of interest. A pattern that emphasizes the beginning and end of the article provides weak evidence that the words of interest are used in setting and assessing the goals for the paper. I concluded that there was some weak evidence to support the claim that explanation is a goal of science.

With sample C we have much stronger evidence for this claim. In all 25 of the sampled abstracts an explanatory structure is clear in the authors' main claim. In half of the cases the main claim is explanatory while in the other half it is evidential. Without a full analysis of these evidential claims as abductions, my conclusion is not as strong as it could be. But on the basis of the structure alone I am confident in saying that explanation is a goal of the large majority of articles in *Science*.

3.7 Evidence for This Account

My account of scientific explanation is intended to stand alone as a plausible philosophical account. The explain-relation between the qualities of the explanans and explanandum depends upon a core relation that holds between the explanans and explanandum. The explanans and explanandum fall into five coarse categories of increasing generality: data, entities, kinds, models, and theories. Although explanation is essentially the same across a wide range of uses, there are many forms of explanation that differ in the details of the core relations. And although I have not provided a full analysis of abduction, there seem to be many cases of inference to the best explanation that match this structure.

In developing and testing this account I have collected a set of data about its successes and failures and the various forms of explanation in the *Science* data set. I take this evidence to show that my account is not only plausible, but successfully accounts for a wide range of scientific practise.

Table 3.3 summarizes the results. Of the 25 cases of “explain” sentences in sample A, nearly all fit my account. Of the 100 random sentences in sample B, half are either explanatory or evidential. Of the main claims of the 25 abstracts in sample C, every one is either explanatory or evidential.

3.7.1 The Generality of Explanation

I take the results of sample B to have established that explanations are ubiquitous in scientific articles and thus important for understanding scientific practise. Sample C was designed to show that explanation is a goal of science. The last of the three main questions I asked in chapter 2 is whether explanation is general, applying across a wide range of scientific disciplines.

The 150 cases in samples A, B, and C are large enough to draw conclusions about scientific explanation in general. When those 150 are divided among the 33 disciplines in the *Science* data set, which are unevenly distributed, we do not have large enough samples to draw strong conclusions for each area. But a preliminary

Sample	Sample Size	Explanation Cases	Evidence Cases	Successful Cases	% Explanation Cases	% Evidence Cases	% Successful Cases	Explanation Instances	Evidence Instances	Successful Instances
A	25	22	0	22	88.0	0.0	88.0	29	0	29
B	100	29	23	51	29.0	23.0	51.0	38	27	65
C	25	14	11	25	56.0	44.0	100.0	18	12	30
ABC	150	65	34	98	43.3	22.7	65.3	85	39	124

Table 3.3: Summary of results by sample and in total, showing: 1. the number of cases sampled; 2. the number of cases for which at least one explanation on my account was found; 3. the number of cases for which at least one evidential claim on my account was found; 4. the number of cases for which at least one explanation *or* evidential claim on my account was found; 5. the percentage of cases containing at least one explanation on my account; 6. the percentage of cases containing at least one evidential claim on my account; 7. the percentage of cases containing at least one explanation *or* evidential claim on my account; 8. the number of explanations on my account found across all cases; 9. the number of evidential claims on my account found across all cases; 10. the sum of the number of explanations *and* evidential claims on my account found across all cases.

analysis is worthwhile with the data that we have.

Table 3.4 shows the results of my analysis of the three samples broken down by keyword. Five disciplines were not sampled at all: economics, engineering, epidemiology, sociology, and virology. The small number of articles in each area makes this no surprise. There are two disciplines that were sampled but for which there were no successful explanations: computer science and mathematics (which *Science* groups together), and genetics. For every other area there is at least one successful case of explanation. In short, I have collected evidence that my account of scientific explanation applies to 26 of the 28 sampled disciplines. While it is possible that my account does not apply to explanations in computer science, mathematics, economics, and engineering, I believe that we can easily find cases of explanation fitting my account in genetics, epidemiology, sociology, and virology.

In chapter 2 we saw that "explain" words occur in all the disciplines in the *Science* data set. These results show that not just the words but the practises of scientific explanation occur across scientific disciplines. Although the forms of explanation may differ, explanation is a general practise in science.

3.7.2 Forms of Explanation

It is the diversity of forms of explanation that allows my account to be as general and flexible as the previous results show it to be. But this flexibility raises the question as to whether we are talking about the meaning of "explanation" any more, or something more general. And perhaps this complexity is unnecessary – perhaps scientists only use some of the possible forms of explanation and not others.

Table 3.5 and figure 3.4 show the distribution of forms of explanation by sample, both in the explanatory and evidential cases and when the two are combined. The sample A cases were selected for the presence of "explain" words, and the distribution of forms of explanation shows that model-kind and model-data are the most common. (There are no evidential cases in sample A.) In sample C the model-kind form also dominates. And in the combined results there are more than double the number of model-kind explanations as any other form. I take this to show that the prototypical form of explanation in contemporary science is model-kind explanation. When scientists use the strong word "explanation" in their publications they tend to be proposing or refuting a model-kind explanation, and in the main claims of their papers they tend to be proposing a model-kind explanation.

Sample B has much more variety in the forms of explanation than the other two

	# of Articles	% of Articles	# of Articles Sampled	% of Articles Sampled	Sampled Cases	Explanation Cases	IBE Cases	Successful Cases	% of Successful Cases
Computers, Mathematics	3	0.38	1	33.3	1	0	0	0	0.0
Physics	60	7.68	9	15.0	9	3	3	6	66.7
Physics, Applied	26	3.33	4	15.4	4	0	1	1	25.0
Chemistry	65	8.32	10	15.4	10	4	1	5	50.0
Materials Science	36	4.61	7	19.4	7	4	0	4	57.1
Engineering	1	0.13	0	0.0	0	0	0	0	–
Astronomy	27	3.46	6	22.2	8	2	2	4	50.0
Planetary Science	29	3.71	4	13.8	4	1	1	2	50.0
Geochemistry, Geophysics	33	4.23	10	30.3	11	4	5	9	81.8
Atmospheric Science	19	2.43	5	26.3	6	3	1	4	66.7
Oceanography	12	1.54	5	41.7	5	2	2	4	80.0
Biochemistry	52	6.66	9	17.3	11	2	3	5	45.5
Molecular Biology	35	4.48	6	17.1	6	3	2	5	83.3
Microbiology	25	3.20	6	24.0	6	4	0	4	66.7
Cell Biology	50	6.40	7	14.0	8	5	1	6	75.0
Genetics	21	2.69	1	4.8	1	0	0	0	0.0
Development	26	3.33	1	3.8	1	1	0	1	100.0
Evolution	34	4.35	4	11.8	6	5	2	6	100.0
Ecology	27	3.46	6	22.2	6	2	1	3	50.0
Botany	23	2.94	6	26.1	7	2	2	4	57.1
Paleontology	18	2.30	3	16.7	3	1	2	3	100.0
Anatomy, Morphology, Biomechanics	3	0.38	1	33.3	1	1	0	1	100.0
Physiology	8	1.02	3	37.5	3	3	0	3	100.0
Virology	6	0.77	0	0.0	0	0	0	0	–
Immunology	19	2.43	2	10.5	2	1	0	1	50.0
Medicine, Diseases	26	3.33	4	15.4	4	1	2	3	75.0
Epidemiology	2	0.26	0	0.0	0	0	0	0	–
Neuroscience	54	6.91	8	14.8	10	7	1	8	80.0
Psychology	15	1.92	2	13.3	2	1	0	1	50.0
Sociology	3	0.38	0	0.0	0	0	0	0	–
Economics	2	0.26	0	0.0	0	0	0	0	–
Anthropology	14	1.79	5	35.7	6	1	2	3	50.0
Education	7	0.90	2	28.6	2	2	0	2	100.0

Table 3.4: Breakdown of results by article keyword, showing: 1. the number of articles with that keyword; 2. the percentage of articles with that keyword among all the articles; 3. the number of articles from which at least one case was sampled; 4. the percentage of the articles with that keyword from which at least one case was sampled; 5. the number of cases sampled from articles with that keyword; 6. the number of cases sampled from articles with that keyword that include at least one explanation on my account; 7. the number of cases sampled from articles with that keyword that include at least one evidence claim on my account; 8. the number of cases sampled from articles with that keyword that include at least one explanation *or* evidence claim on my account; 9. the percentage (if any) of cases sampled from articles with that keyword that include at least one explanation *or* evidence claim on my account.

samples. There is also a large variety in the phrases used to express the explanation, including everything from "could affect" to "induced". But these various forms are no less scientific explanations. They have the same structure as model-kind explanations, differing mainly in their core relation. If we take model-kind explanation to be, not the prototype, but the *only* legitimate form of scientific explanation, then we eliminate at a stroke the large majority of the cases sampled. While there are more model-kind explanations than any other form, there are four times as many explanations that have some other form.

In the combined results for all three samples we see that there is at least one case for each of the 25 forms of explanation. Some forms are only used once or a few times in the sampled cases, with the right half of the table being particularly sparse. Here we have another situation where the large number of cases becomes diluted by the large number of available forms and our ability to draw strong inferences is diminished. Nevertheless, the samples from the *Science* data set show a wide variety of forms of scientific explanation, touching on each of the possibilities.

3.7.3 Evidence for Other Accounts

In my samples from the *Science* data set there are many references to mechanisms and models and many causal claims. This tends to support the mechanistic, model-based, and causal intervention accounts of scientific explanation. As I have argued elsewhere, I think that the prominent MDC account of mechanisms should be recast as a sort of causal modelling, but the importance of mechanisms particularly in biology and neuroscience is not in doubt (Overton 2011). Both my account and Bokulich's model-based account build on Woodward's counterfactual approach, and to that extent my analysis of core relations in cases of modelling and causation tends to support their respective accounts.

I did not find evidence supporting the other philosophical accounts of scientific explanation in my samples. Regarding asymptotic explanation this is no surprise, since the cases it was developed to support are discipline-specific and the focus is on broad theoretical methods rather than the narrower topics that appear in *Science* articles. For the unification account I expected to find some cases but did not. There were few probabilistic explananda, and so few cases for which to apply the statistical relevance account. Likewise, nothing quite like a D-N explanation appears in the sampled cases. While there are cases of causal explanation, there are few that fit Salmon and Dowe's accounts of causal-mechanical explanation (one possible case is

		Explanation					Combined					Evidence				
		data	entity	kind	model	theory	data	entity	kind	model	theory	data	entity	kind	model	theory
Sample A	data	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	entity	2	3	0	0	0	2	3	0	0	0	0	0	0	0	0
	kind	1	1	3	0	0	1	1	3	0	0	0	0	0	0	0
	model	5	1	9	0	0	5	1	9	0	0	0	0	0	0	0
	theory	2	1	1	0	0	2	1	1	0	0	0	0	0	0	0
Sample B	data	2	0	0	0	0	2	7	2	1	2	0	7	2	1	2
	entity	5	5	0	0	0	5	7	3	1	0	0	2	3	1	0
	kind	4	1	2	0	0	4	1	4	3	2	0	0	2	3	2
	model	1	1	5	1	0	1	1	5	1	1	0	0	0	0	1
	theory	1	1	7	2	0	1	1	7	2	1	0	0	0	0	1
Sample C	data	0	0	0	0	0	0	4	0	0	5	0	4	0	0	5
	entity	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	kind	1	1	4	0	0	1	1	4	1	1	0	0	0	1	1
	model	0	0	10	0	0	0	0	10	0	0	0	0	0	0	0
	theory	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0
Samples ABC	data	2	0	0	0	0	2	11	2	1	7	0	11	2	1	7
	entity	7	8	0	0	0	7	10	3	1	1	0	2	3	1	1
	kind	6	3	9	0	0	6	3	11	4	3	0	0	2	4	3
	model	6	2	24	1	0	6	2	24	1	1	0	0	0	0	1
	theory	3	3	9	2	0	3	3	9	2	1	0	0	0	0	1

Table 3.5: The number of explanations and evidence claims on my account among the sampled cases, broken down by form of explanation. The results are given by sample and in total (major rows), and by type (major columns): explanations alone, combined (explanations *and* evidence claims), and evidence claims alone. Within each minor table the row provides the category of the explanans and the column provides the category of the explanandum.

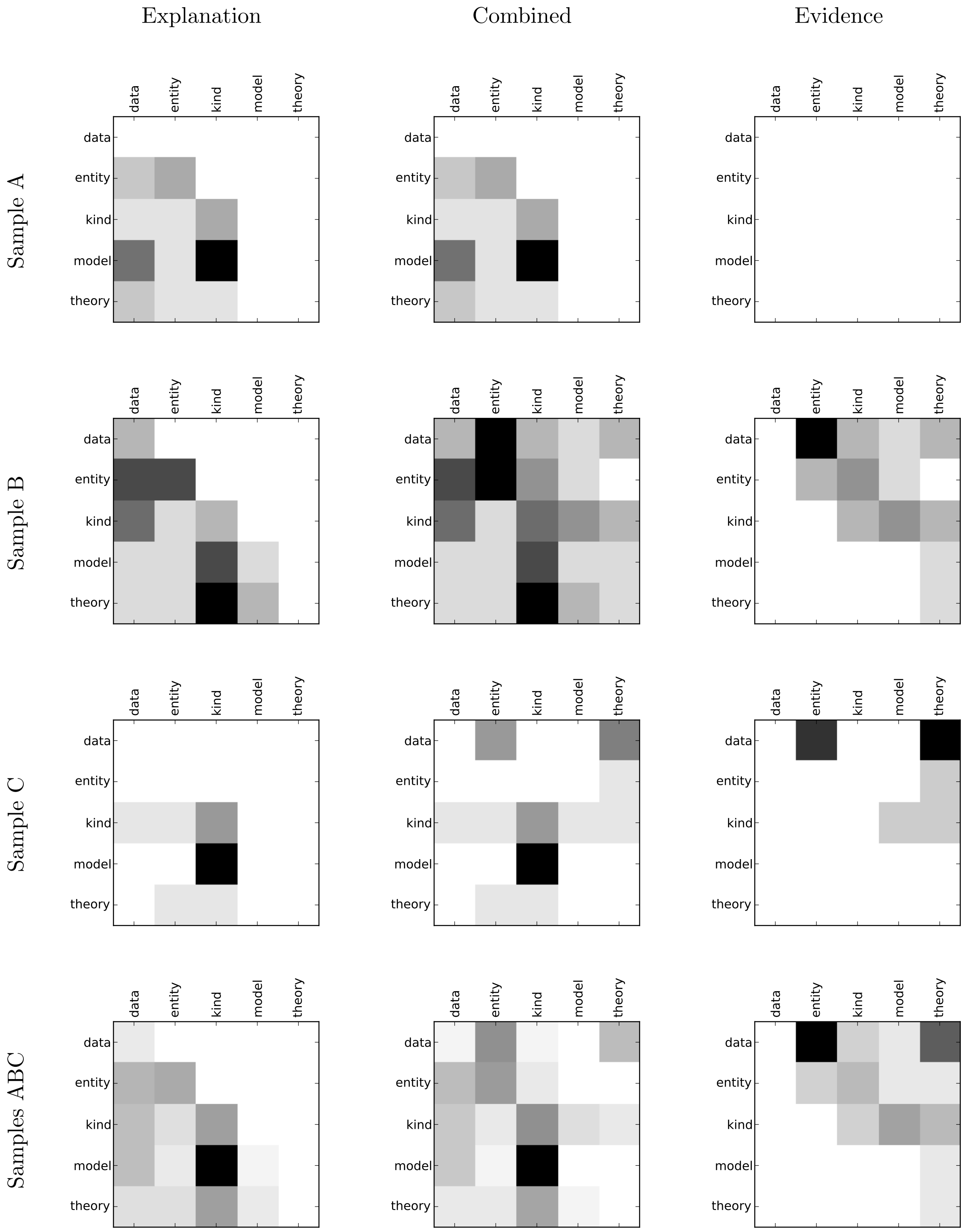

Figure 3.4: Visualization of table 3.5 in which darker colours indicate larger values.

B60).

I recognize that my methods may not be sensitive to explanations of these sorts. It is possible that they work above the level of sentences and paragraphs that I am analyzing, or that they mainly involve theoretical forms of explanation that are not prevalent in *Science* papers. However I think that the onus is on the proponents of those views to show us particular cases where explanations of those sorts occur.

Arguably, each of the cases for which my account succeeds could be accounted for as a pragmatic explanation. Perhaps even some for which my account fails would count as successes of pragmatic explanation. However I take this to be a weakness rather than a strength of the pragmatic account. The structure of my account, the distinction of the five categories, and the forms of explanation all provide valuable resources for analyzing particular cases. We do not learn nearly as much when we discover that some claim is a pragmatic explanation.

3.8 Summary

In this chapter I have used a number of cases drawn from random samples of the *Science* data set to develop and defend a general philosophical account of scientific explanation. On my account an explanation consists of an explain-relation, an explanans, and an explanandum. The explain-relation holds between qualities of the explanans and the explanandum and allows for counterfactual reasoning about the dependencies between the qualities. While this explain-relation remains essentially the same, it always requires some core relation between the explanans and explanandum for support. In order to understand the details of the dependencies between qualities we must look to the core relation between the bearers of the qualities and the counterfactual reasoning that it supports. Five coarse categories for the explanans and explanandum help to distinguish a broad range of core relations, and there is evidence that scientists do in fact use this full range of forms of explanation.

The application of my general account to the three samples allows me to address the three main questions I introduced in chapter 1. Sample B shows that a large portion of the claims in scientific articles are explanatory and thus that explanation is important to science. Sample C shows that explanation is a goal of science, since the main claim in every abstract considered is some sort of explanation or inference to the best explanation. And there is strong evidence that my account applies across a wide range of scientific disciplines.

The account also allows me to address the problem of fragmentation in the philosophical literature on scientific explanation. Philosophers have tended to focus on one or a few forms of explanation, overlooking the others. This accounts for the striking differences in relata for their explanations, from data to entities to kinds, models, and theories. Several of the philosophical accounts in the literature fit as specific cases of my general approach. But my account is not overly permissive. D-N explanation is ultimately a poor fit, as is statistical relevance, and I see my highly-structured proposal as at odds with pragmatic explanation.

This chapter comprises the core of the dissertation. In the following five chapters I provide details and examples of the five categories and the various forms of explanation. I also locate my categories within the larger philosophical literature. In the process I raise many philosophical problems that I cannot fully address. The five chapters are meant to supplement this one by helping to specify just what a scientific explanation is on my general philosophical account.

Chapter 4

Data

Much of the practise of science concerns the careful collection of data. In this chapter I consider some examples of the role of data in explanations from the *Science* data set and use these examples to chacterize the "data" category in my account of explanation.

4.1 Examples

A12 In summary, changes in water mass formation processes are not necessarily required to explain the high GNAIW [Glacial North Atlantic Intermediate Water] end-member δ^{13}C values. (Olsen and Ninnemann 2010, p. 659)

As we saw in the previous chapter, the explanandum of this explanation is a set of carbon isotope ratios of end-member chemical compounds sampled from a prehistoric formation of water.

B71 Using 10-min sliding window calculations, we found a clear similarity in the time course between theta power and gridness . . . and a consistent relationship between the power of theta and the gridness score . . . . (Brandon et al. 2011, p. 597)

The authors investigated the association between theta oscillations in the brains of rats and the activation of neurons believed to track spatial location.

A9 The exact origin of the size dependence activity is not yet known, and our measurements cannot be explained by the change in coordination

> number based on the Benfield geometric model. (Tedsree et al. 2011, pp. 226-227)

Here the authors refer in a general way to the set of their measurements of the adsorption energy of catalysts, ruling out one possible explanation of the data.

B58 The severity of the Fog phenotype in +/*fem-1*(*Df*) heterozygotes depended not only on the identity of the deficiency but also on the history of the *fem-1*(+) allele. (C. L. Johnson and Spence 2011, p. 1314)

The Fog phenotype is a "feminization" of heterozygotes of *C. elegans*, which is caused not only by the presence of a particular gene, but also by the history of the presence of that gene in ancestors (i.e. its epigenetics).

B23 Cryo-electron microscopy (cryo-EM) images of these crystals revealed notable ring-shaped (or, less likely, spiral-shaped) assemblies. (van Breugel et al. 2011, p. 1198)

The images are of crystals of the SAS-9 protein, an important component of cilia and flagella.

4.2 Discussion

The nature and role of data in scientific and non-scientific reasoning has been an important philosophical topic. Much of the discussion has been part of the empiricist tradition, or in response to it. Those questions have involved the nature of sense data, the foundational status of sense data, the extension of the senses with instruments, reliable forms of inference from data, etc. My goal here is certainly not to settle these debates. Instead I want to characterize the nature and role of data in the explanatory claims that appear in the *Science* data set.

I find it useful to start with the distinction between data and phenomena presented in Bogen and Woodward 1988. The core of the distinction is between the data that result from complex causal chains, and are thus tightly tied to the details of a given experiment, and the general, repeatable phenomena that the data can tell us about.

> Data are, as we shall say, idiosyncratic to particular experimental contexts, and typically cannot occur outside of those contexts. Indeed, the factors involved in the production of data will often be so disparate and numerous, and the details of their interactions so complex, that it will not be possible

> to construct a theory that would allow us to predict their occurrence or trace in detail how they combine to produce particular items of data. Phenomena, by contrast, are not idiosyncratic to specific experimental contexts. We expect phenomena to have stable, repeatable characteristics which will be detectable by means of a variety of different procedures, which may yield quite different kinds of data. (Bogen and Woodward 1988, p. 317)

On the one hand, phenomena are general things that can be investigated in multiple ways and are the proper targets of systematic explanations. On the other hand, data are idiosyncratic and tightly tied to the particular circumstances of a given experiment. Data are connected to phenomena in particular cases by long and complex chains of singular causation. The chains of causation are often so complex that we have no hope of offering an explanation of them. Instead we design our experimental methods to block confounding influences, we empirically assess the reliability of our instruments, we repeat our experiments, and we then apply statistical methods to the results. The goal is to step beyond the circumstantial limitations of the data and establish a more general claim about the phenomenon.

In most cases I believe that what Bogen and Woodward intend by "phenomena" is a close match for what I mean by "kind". In their example of the melting point of lead we collect data about many different specimens of lead in order to draw a general conclusion about all lead. However this is not always clear in their paper, and sometimes the better match seems to be my "entity" category. We might measure the Sun in many different ways but the data are always about the Sun. In either case, kinds and entities are proper targets for systematic explanations, and I agree that it is often futile to try to explain the complex chains of singular causation that link an entity to the data about it.

The distinction between data and phenomena helps to make clear how *specific* data are, in contrast with the more general categories of kinds, models, and theories. But what are data? I think it is clear that they are statements of measurements and observations about their targets. This is at odds with what Bogen and Woodward say at one point: "Data, which play the role of evidence for the existence of phenomena, for the most part can be straightforwardly observed" (Bogen and Woodward 1988, p. 305). Data certainly play the role of evidence, but to my understanding data are not themselves observed – they are statements of observations. (Concrete records of such statements can be observed, e.g. written on a page, but that is not the point under discussion.) I think that my usage conforms to the standard usage in science.

Because they are statements, data can be made concrete in various sorts of records.

There can be multiple copies of a set of data, in computer files, in print, or perhaps stored in the minds of people. The recording and transmission of data can involve long and complex chains of singular causation, but this is rarely the subject of scientific explanation. In the following chapter I say more about the processes of measurement and observation that link data to entities and the complex chains of singular causation those processes require. For the purposes of this account my main interest is in the shift from entities to statements about entities. I leave aside any further discussion of how data are recorded and focus on the data themselves as statements.

Data are statements of measurements and observations. Measurements and observations are about concrete particular things. As Bogen and Woodward point out, data are idiosyncratic in the sense that they are tied to the details of particular experiments. Particular chains of singular causation link the targets to the observers and measurement devices, and the details of those chains are rarely the subject of scientific explanation. Instead, scientists design their experiments and empirically test the reliability of their instruments to ensure that the details of those causal chains do not matter. In this way they can move beyond the specificity of the data to make general claims about entities and kinds of entities.

4.3 Data in *Science*

It is worth noting that explanations involving data are not the most prevalent group in the data set. For all the effort scientists put into carefully collecting the right data to support their claims, the majority of the sentences in *Science* articles, judging by my samples, are about the nature of the claims and not the data itself. Large sets of data are usually summarized in a small number of figures.[1] Additional discussion of the details of the methods and the results may be left to the supplemental material and not published in the article itself. In many cases the data themselves are not published at all. This may be the result of the short form of *Science* articles, and articles in other journals may differ. Nevertheless, the data category is an important one, and many of my sampled cases include explanatory claims involving data.

In the examples above we have several different forms of data. The most straightforward is A12. Samples of ocean sediments deposited during the Holocene era (∼12

---

[1] I recognize that a shortcoming that my approach, shared with most other philosophical discussions of explanation, is that I do not address the role of plots, figures, and other images in scientific explanation. However I think there is room for them on my account. Plots, for instance, are a good way to communicate certain sorts of complex counterfactual relationships. I leave this topic to future work.

000 years ago) were taken and analyzed using a mass spectrometer or other related device in order to determine the ratio of carbon 13 to carbon 12. Measuring the δ^{13}C is a standard method for discovering the isotopic “fingerprint” of a material and establishing its age and origin. But the causal chain by which we go from the GNAIW water mass that deposited the sediments to a numerical δ^{13}C value is daunting. As Bogen and Woodward note, most of the details of the singular causal chains do not make a difference to the end result. The key is that the right kind of singular causal chain holds between GNAIW and the numerical values. When the right kind of causal chain holds, the numerical values will depend on the nature of GNAIW in the right way, and we will have learnt something about GNAIW. If the causal chain is broken the dependency will fail, and inferences about GNAIW will be undermined.

In case B71 we have more detail about how a set of data is analyzed. Here the data are about the activation of neurons in the brains of rats and the goal is to determine whether these particular neurons track spatial location. The authors describe a correlation within the data set that they later take to reflect a general causal relation between the power of theta oscillations and the activation of the neurons. Again the causal chain between the brains of particular rats and the data is long and complex. Here the goal is not to draw conclusions about the brain of a particular rat but instead about the brains of all rats, and in turn the brains of similar organisms. Not only is the right kind of causal link between entity and data required in each of these cases, but the right kind of inference between kind and entities as well. This is discussed in chapter 6.

Case A9 is typical of many references to data among the sampled cases. Rather than referring to the data in detail, the authors refer in a general way to the data they have collected about the size of the catalysts and their adsorption energy. As in B71 it is correlations in the data that are of immediate interest. The dependence of the adsorption energy on the size of the molecule demands an explanation, and the authors assert that one standard model cannot account for this important correlation in the data.

In case B58 we do not have measurements in a traditional sense. The Fog phenotype is a bundle of qualities that are used to classify specimens of the *C. elegans* nematode worm. Rather than measuring the length or weight of the worm, biologists make judgements about phenotypes using a set of criteria. While some phenotypes are binary, e.g. present or not present, in this case the authors distinguish between different degrees and make claims about the “severity” of the phenotype. I include this example to show that data need not be numerical measurements made with some instrument, but can be standardized classifications of entities as judged by human observers.

Case B23 is interestingly different. Instead of measurements or values we have "images". Images are not usually understood to be statements, but the image from a modern digital camera is quite clearly a 2-dimensional grid of measurements of the intensity of light in three or four ranges of wavelengths. For analogue photography, instead of pixels we have crystals of silver iodide or other photosensitive chemicals, and "measurement" is the transformation of the chemical in response to light. Often it is not the image itself but judgements about the image that are really the data being considered. In all these cases the causal chain between the entity and the data is long and complex, but if the chain holds in the right way then the result is a measurement of some quality of the target entity at that time.

These five examples show how references to data in the sampled cases are usually but not always marked by keywords such as "measurement", "observation", "values", or "images". Some cases can be problematic. For instance, "observation" is sometimes used to refer to the conclusion of some previous line of argument, as in case A3 where sea temperatures from the Hirnantian era are not observed in any direct sense. Similarly, the word "results" can refer to data, but often refers instead to the conclusion of previous arguments. "Results" is used in many of the sample C cases to refer to all the smaller arguments of the article and state how they support some more general conclusion.

In summary, data are statements *about* entities collected in the course of scientific practise in order to draw conclusions about those entities. The two main sorts of data are measurements (e.g. δ^{13}C values, intensities of electron streams) and classifications (e.g. severe Fog phenotype). In my samples from the *Science* data set nearly all of the references to data were collective. In every case the data are linked to the target entity by a measurement or observation process involving a complex causal chain. The details of those causal chains are not explained. Instead, as Bogen and Woodward describe, the integrity of the causal chain is checked empirically, and experiments are designed to avoid confounding influences and ensure that the details of the causal chain can safely be ignored. The data are *about* the target entity only if the causal chain holds.

4.4 Forms of Explanation

In each of these chapters on the five categories I conclude with a discussion of the primary and secondary forms of explanation for which the explanans is in that category. The primary forms hold between items in adjacent categories in figure 3.1, while the secondary forms hold between items in the same category. Because the "data" category is the least general of the five, there is no primary form of explanation for this chapter. The next chapter discusses the primary form of entity-data explanations. The secondary form of explanation *between* data is the only form discussed in this chapter.

4.4.1 Secondary: Data-Data

A data-data explanation is one for which both the explanans and the explanandum fall into the "data" category. The core relation must relate data to data in a way that supports counterfactual reasoning. There are several relations that can play this role. If the explanandum data are a subset of the explanans data then they depend on the explanans data in the appropriate way, but it might be a stretch to call this "explanation". More interesting would be cases of mathematical or statistical transformations of the explanans data, simplifying, summarizing, or drawing out patterns that are stated in the explanandum. While there are many such possible transformations, the minimum requirement is that the explanandum data depend on the explanans data in a counterfactual-supporting way.

There is only one case of data-data explanation among my samples of the *Science* data set: B71. The authors describe the results of "10-minute sliding window calculations" on their data set, which show "a clear similarity in the time course" between two of their variables. Although it is possible that they are referring to entities or kinds, their language focuses on patterns in the data. It can then be a quick jump from these correlations in the data to the conclusions they later draw about medial cortex neurons in general. Another possibility is to consider this a "data model" (Frigg and Hartmann 2006, §1.2). But in this case there is not much of a model to be seen – the authors merely state a correlation and do not go into significant detail about the relationships between the variables.

The core relation for an explain-relation must support counterfactual dependencies between the explanandum and the explanans. In the following chapters we will see examples of causal and modelling relations that do exactly this. Causes and modelling are more familiar cases of counterfactual-supporting relations, but there are many others. The key is Woodward's observation that explanations must be able to answer "what if things had been different" questions. While mere coincidences do not meet this standard, most claims about *correlations* in science seem to me to be intended to do just this. In B71 the authors are claiming that the gridness time course and score depend on the theta power. Other relations, such as subset part-hood and various mathematical and statistical transformations, can have the same properties. While this is not a prototypical case of explanation, the structure is essentially the same, and we can understand the details of the explain-relation in a particular case by understanding the details of the core relation in that case.

Data are the foundation of empirical methods. But the immediate goal of collecting the right sorts of data is to learn something about the *entities* that the data are about.

Chapter 5

Entities

The data that scientists collect are about things in the world. The collective label I use for these things is "entities". In this chapter I consider a range of examples of entities in order to characterize this category and distinguish entities from the data about them.

5.1 Examples

We have seen several examples in the previous two chapters where a particular entity is involved in an explanation. In case A12 we have GNAIW, a large formation of water, and in case A10 we have the star HIP 13044. In both of these cases it is something about the data that is explained. In the following examples it is something about the entity itself that is the explanans or explanandum.

A19 The differences in MCAs [monocarboxylic acids] among the Tagish Lake specimens may be explained by differing degrees of parent body modification. (Herd et al. 2011, p. 1305)

The Tagish Lake specimens are fragments from a meteorite recovered from Tagish Lake in Canada's Yukon Territory.

B63 The concurrent decreases in larval supply and mass flux were most likely due to hydrodynamic transport away from the ridge rather than changes in source production. (Adams et al. 2011, p. 580)

This paper describes how large-scale ocean eddies, caused by atmospheric events such as El Niño, can change deep-ocean currents and affect the ecologies of hydrothermal vents. Here the authors propose that these transporting currents better explain the changes they observed than would changes at the source.

B100

> This Hirnantian-aged unit [a sample of carbonate] records a major drop in sea level and a large positive carbon isotope excursion; both are recognized globally in other sedimentary successions. (Finnegan et al. 2011, p. 904)

The Hirnantian is the final stage of the Ordovician period, occurring approximately 445 million years ago and lasting approximately 1.9 million years. It was a period of glacial melting and rising sea levels, and corresponds with a major extinction event. As such it is of great interest for climate scientists. Here we have a sample from that period that provides evidence of some of these changes in climate.

B60

> Although the absolute delay τ, corresponding to a group velocity of $v = 1600$ m/s, is small in the present system because of the relatively small optical depth $\mathcal{N}$, the observation nonetheless establishes experimentally that a vacuum input control field can delay a probe pulse. (Tanji-Suzuki et al. 2011, p. 1268)

Here we have a use of "observation" referring to an event rather than data. The authors developed techniques for controlling the rate of interactions among photons in an optical cavity.

B13

> Seismic analysis of the Sun has already shown that merely reproducing the luminosity and temperature of a star will not guarantee that the internal structure, and hence the underlying physics, is correct. This inspired the inclusion of additional physics, such as the settling over time of chemical elements because of gravity, in stellar models. (Chaplin et al. 2011, p. 215)

In this quotation the authors discuss the history of models of the structure and dynamics of the Sun.

5.2 Discussion

The nature and role of entities in science is the point of contention in one of the central debates in the philosophy of science. The realist position, in broad strokes, is that scientists discover truths about things in the world in the course of their work. The claim does not sound radical, and the majority of scientists and philosophers would likely accept it. However problems arise on several counts. One is unobservable entities, where our knowledge is quite indirect and subject to doubts. Key examples include subatomic particles, stars too faint for the naked eye, or the inside of the Sun. Another is the problem of the pessimistic meta-induction about theory change: if all the scientific theories that have been replaced by our present theories made claims that were not true, then we seem to have some reason to doubt that the "truths" we hold today will stand the test of time. Other problems with strong realism arise in the reduction/emergence debate, where objects at multiple levels of description seem to have equal claims to causal powers, leading to problems of causal over-determination. Adherents of various forms of empiricism, instrumentalism, and anti-realism oppose realist claims in order to avoid or solve problems such as these.

In characterizing the "entity" category on my account, I wish to avoid taking sides in the realism debate as much as possible. However the language used by the scientists writing in *Science* is most consonant with a realist position: scientists seem to refer to entities in the world, even quite strange entities, much as we do in our everyday language. This fact about language use is one that any opposing view must face. I have aimed for the most straightforward reading of the cases and so my language largely matches that of the scientists. Ultimately I believe that proponents and opponents of realism alike will be able to recast my account and my arguments in their own terms, without undue distortion.

The starting point for my analysis of the "entity" category is that entities are concrete particulars. First, they are concrete as opposed to abstract, which means that they participate in the causal nexus "inside of" space and time. The data discussed in the previous chapter are statements, which may be recorded and transmitted in various ways, but their content is timeless, has no location, and is not itself causal. The kinds, models, and theories discussed in the next three chapters are also abstract. But entities are things that begin or come into existence at some time, endure for some period of time, and then end or are destroyed or transformed into something else. While they exist, most entities are capable of interacting in causal chains, but there are some marginal cases that I will discuss below. Second, entities are particular as opposed to universal. While there are many men, there is only one Socrates. There cannot be multiple instances of Socrates simply because entities are not such things as to have instances. The following chapter on kinds contains a longer discussion of universals and instantiation.

None of the members of the other four categories of my account are concrete particulars and so in this sense entities are easy to distinguish. However we must still consider how references to entities occur in the *Science* articles. I also present a few of the more difficult references to entities that are important for understanding the cases.

In the *Science* data set references to entities come in several forms. The simplest form is the proper name. HIP 13044 is a concrete particular star that formed at some point in the past and will be destroyed at some point in the future. It was discovered by the Hipparcos mission and given the proper name "HIP 13044" in the Hipparcos Catalogue of stars. "Glacial North Atlantic Intermediate Water" (GNAIW) is the name of a formation of water in the North Atlantic that is believed to have existed during the Holocene era, circa 12 000 years ago, but no longer exists. GNAIW is unobservable in the sense that it no longer exists and we rely on various natural records to infer its existence. HIP 13044 has an apparent magnitude of 9.4, meaning that it is invisible to the unaided human eye. But in both cases the use of proper names here appears to be the same as the use of proper names in everyday language.

Other forms of reference to entities include definite descriptions and indexicals. In the examples above we have "the Tagish Lake specimens" in case A19 and "This Hirnantian-aged unit" in case B100. Tagish Lake is a particular place and the Hirnantian age is a particular period of time – more on places and times below. Often the definite descriptions are more complex and do not involve proper names at all, relying instead on kind-terms and qualities to form the description. The definite article "the" can indicate a reference to an entity, but this is not conclusive since there are many examples where the reference may be to a kind: e.g. "the black bear is an omnivore".

Finally, many references to entities are implicit in the cases I sampled from *Science*. Case B60 is an example. While there is no direct reference to a particular pulse of light, it is clear from the meaning of the sentence that the authors must have observed a delay of a certain sort in a particular pulse of light in the course of their experiments, and are drawing conclusions about the possibility that vacuum input control fields can delay pulses in general. In cases where there is a clear reference to data I have inferred that there must be at least one entity involved, since the data must be about *something* with causal powers and not just an abstract kind or model or theory.

The minority of references to entities in the sampled cases are singular. GNAIW is a single water mass, HIP 13044 is a single star, Tagish Lake is a single place, and the Hirnantian age is a single period of time. Singular entities are the most common targets of proper names and ultimately it is single entities that participate in causal chains that generate data. However the majority of references are to collections of entities. The individual members of these collections are not named in the *Science* articles, although they may very well have names or serial numbers that are used in the course of experiments. Ultimately it is the members of the collection that have causal powers and not the collection itself.

The differences between the use of single entities and samples of kinds marks in a general way the difference between historical sciences and experimental sciences. It is in historical sciences such as astronomy, oceanography, climate science, geology, paleontology, anthropology, etc. that proper names and explicit references to entities occur. In chemistry, biology, genetics, physics, neuroscience, immunology, etc. samples of a kind are used to stand in for the kind itself.

Of the five categories that my account of explanation depends upon, entities are perhaps the easiest to characterize and to distinguish in the samples from *Science*. However there are some marginal cases that I wish to include under "entities" that require some justification: processes, periods of time, regions of space, and collections.

The examples of entities given so far have been things that philosophers would traditionally have classified as substances. The word "entity" also implies that we are talking about static substances. However I also wish to include concrete particular processes under the category of "entity". There are many examples of processes in samples from the *Science* data set, for instance A12 refers indirectly to the water mass formation processes that created GNAIW. However none of these processes are given proper names and so the references are either by definite description or implicit.

Other difficult cases include particular periods of time and particular locations in space. The Hirnantian age and Tagish Lake are both particulars that came into existence, endured, and will pass out of existence. However it is less clear that the Hirnantian age is concrete or has causal powers. There is a difference between Tagish Lake and the location in space that the Tagish Lake specimens were found, and one can insist that spatial regions are not concrete or causal. While it is not clear that periods of time or regions of space are concrete, neither are they abstract in the way that data, kinds, models, or theories are. They are certainly particular. Despite these difficulties, locations and periods of time are particular, and cannot have their own instances. My considered opinion is that they best fit into the "entity" category, and that is the approach I have taken in my analysis.

The final difficult case to consider is the most important. As mentioned above, while the historical sciences often mention singular entities by proper name, the experimental sciences usually refer to unnamed collections of entities. I include these collections in my “entities” category and distinguish them from kinds.

Consider case A4 where the explanandum is data about the circadian clocks of a sample of cyanobacteria. In that paper the authors discuss an experiment with two branches, the first where they experimented on biological oscillators that they had synthesized, and the second where they experimented on whole bacteria. In the latter case it is clear that they did not experiment on all the cyanobacteria that exist, have ever existed, or could ever exist, and so we are not discussing the *kind* of cyanobacteria. Instead the authors experimented on a sample of cyanobacteria and drew their conclusions about the kind on that basis.

The sample of cyanobacteria was a collection of some number of concrete particular cyanobacteria. The collection came into existence at some point in time, endured and presumably underwent some changes, and then ended (or will end at some time in the future) when all the members died or were scattered. The collection was particular – it was not such a thing as to have multiple instances. It could have been (and perhaps was) given a proper name.

When we say that data were gathered about the collection we can rephrase this claim as saying that a set of data was gathered about the members of the collection. The collection does not have a circadian clock, but each of its members does. (There are of course some measurements that can be made of the collection itself, such the number of its members.) The collection has no causal powers above and beyond the causal powers of its members. In the literature on reduction and emergence we find philosophers such as J.S. Mill distinguishing such composites (mere sums of their parts) from more interesting structures supporting emergent behaviours (McLaughlin 1992).

I use “collection” rather than “set” to mark several differences. Philosophers are accustomed to thinking of sets in the mathematical sense, as abstracta. If we consider collections simply to be sets then we are in danger of collapsing the distinction I wish to make between entities and kinds. But as we will see in the next chapter, kinds are quite different from these collections. Kinds are counterfactual-supporting because they are intensional, while the collections I have in mind are purely extensional, nothing more than the sum of their parts. There are sets of sets but I see no need to posit collections of collections. To combine two or more collections were merely take the union of their members.

While there are many debated questions about the nature of entities and their role in science, all sides must account for the facts about the references to entities in the scientific literature. Scientists seem to refer to entities in the same way that we do in everyday language: treating them as concrete particulars; using proper names and definite descriptions; and referring to singular entities and collections.

5.3 Entities in *Science*

The examples given above cover a range of cases from my samples of the *Science* data set. In case A10 we have a number of entities. “[T]he Tagish Lake specimens” refers to a collection of fragments of a single meteorite (the Tagish Lake meteorite, referred to here as the “parent body”) that fell on Tagish Lake at 16:43 p.m. UTC on 18 January 2000.[1] The authors propose that differences in the samples are due to differences among the parts of the parent body, which was modified by various natural processes between the time of its formation and the time of impact. This is an example of the use of “specimens” where the specimens are from a single entity. Although it does not occur explicitly in my samples from *Science*, the alternative use of “specimens” is as specimens of a kind. In both cases the specimens form a collection in my sense.

Case B63 includes references to entities by definite description, specified by reference to a particular underwater ridge. While the authors must have measured or observed the larval supply and mass flux in some way, here they refer to the processes rather than their data about the processes. Likewise “hydrodynamic transport” could be a kind, but here I believe that it refers to a particular current.

The quotation for case B100 uses the indexical “this” in a description of a single piece of carbonate formed during the Hirnantian age. The authors say that this “unit . . . records” information about two other entities: the Earth’s ocean and an unnamed “large positive carbon isotope excursion”. The latter is a somewhat strange elliptical reference to some process, perhaps volcanic or biological, that changed the ratios of carbon isotopes in the atmosphere of the Earth.

In case B60 we have an implicit reference to a concrete particular pulse of photons inside a vacuum input control field. Whether we consider the pulse to be a singular entity or a collection of particular photons is a difficult question that raises important issues from the philosophical literature on reduction and emergence. This seems to be an exceptional case from this area of physics, which is an experimental science. We would expect to have data about a large sample of pulses that would be run through various statistical tools and used to make a strong claim about pulses in general. Instead we seem to have a single observation used to make a *possibility* claim about

---

[1] See `http://en.wikipedia.org/wiki/Tagish_Lake_(meteorite)`.

the kind.

Finally, case B13 is quite different and may in fact fall outside my account of scientific explanation. Here we have a discussion of the history of ideas in the field of solar dynamics. The authors explain how previous simplistic models of the Sun were shown to be inadequate and this led to the creation of more complex models. The explicit use of the word "model" suggests that we are not talking about entities at all. But the word "inspired" suggests that there was some form of causal relation between the old and the new models. As I will discuss further in chapter 7, models are abstract, and not the sorts of things that have causal powers. As abstracta models are neither created nor destroyed. But models in the sense used here clearly are created.

My preferred interpretation of this case is that we have the concretization of the old and the new models in the minds of scientists and on the pages of their papers and textbooks. The concretizations of these models are entities, and each has causal powers and exists for a period of time. This introduces metaphysical complexities that I have not discussed above and do not wish to pursue in depth. If this interpretation of the case fails, then it is one more case from sample B for which I cannot account as a scientific explanation. Perhaps it is an explanation of some other sort, or not an explanation at all.

In summary, entities are concrete particulars. They can either be singular or collections of singular entities. Singular entities can be substances, processes, periods of time, or regions of space. References to entities can be proper names or definite descriptions, but in the latter case there is often syntactic ambiguity between a reference to an entity and a reference to a kind. When definite descriptions include words such as "specimen", "sample", or "unit" we have an additional clue that the referent is an entity.

5.4 Forms of Explanation

When the explanans is an entity there are two possible forms of explanation. The primary form takes us from an entity to data about that entity. The secondary form takes us from one entity to another, or perhaps between different qualities of the same entity.

5.4.1 Primary: Entity-Data

The primary relations between entities and the data about them are measurement and observation, supported by chains of singular causation. The singular causal chains that connect an entity to a measuring device or an observer can be very long and complex. As Bogen and Woodward point out, we are rarely in a position to offer a comprehensive explanation of these chains. But our inability to trace these details need not be an obstacle. If we design our experiments carefully, cross-checking the reliability of our measurements and observations, then we can be confident that the details of the causal chains do not matter. What is important in such a case is that there is the *right sort* of causal link between the measurement device or observer and the target entity.

Spelling out the details of what kind of causal link is required is difficult and beyond the scope of the current project. Instead I will point to Dretske's analysis, which takes an information-theoretic approach to important general questions in epistemology (Dretske 1981). An interesting consequence of Dretske's account is that information can be transmitted by the *lack* of a causal link in some situations, for example when an expected signal does not arrive. Dretske is one author among many who have considered the relations between causation and epistemology.

There is a significant philosophical literature on the topic of measurement, particularly on the measurement problem in quantum mechanics. Along with the nature of sense data, the acquisition of such data has also been an important topic for empiricists. Van Fraassen devotes several chapters of *Scientific Representation* to such questions (van Fraassen 2008). As the title implies, van Fraassen is centrally interested in the connections between measurement and "scientific representation".

For my purposes the key point is that entities and data are different sorts of things, and acts of measurement or observation mark the transition between the two categories. By measuring we switch from the realm of entities to the realm of statements about entities. (There are, of course, sciences such as linguistics where the entities of interest are statements.) This distinction is also important in the philosophical literature on representation, especially in the philosophy of mind. Not coincidentally, Dretske's information-theoretic approach to epistemology is the platform on which he builds his theory of mental representation (Dretske 1988).

There are many important open questions about the nature and role of measurement and observation. My main goal is to establish them as counterfactual supporting relations. This is trivial on a pre-theoretic understanding of measurement and observation: the result of a measurement or observation process *depends* on the target entity. If the entity were different we expect that the measurement or observation would have been different. Even taking into account various sorts of error (an important topic I must leave aside), this dependence holds. If the dependence fails then we have a case of misrepresentation – we were mistaken in thinking that they were measurements or observations of the target entity.

In my samples of the *Science* data set the evidential data-entity form was about twice as common as the explanatory entity-data form. I take this to be the more natural way of phrasing closely related claims: something about the data *shows* something about the entity, and something about the entity *explains* something about the data.

Case B100 has data-entity form. This is not entirely clear, because the quotation does not mention the details of the data. The authors measured various isotopes in the sample of carbonate in order to determine the origins of various layers of sediment. Isotope ratios can provide a "fingerprint" that distinguishes between various sources of carbon. There is a staggeringly complex causal chain connecting those sources of carbon to the processes of deposition, the storage, the recovery by scientists, the sampling process, and the elaborate processes inside a mass spectrometer. But if the experiment was conducted properly then many of those details do not matter. The key is that there was the right sort of causal link between the source and the measuring device. The right kind of link supports counterfactual reasoning about the sources of carbon and the levels of the sea 445 million years ago.

In short, data are statements of measurements or observations of target entities. Complex singular causal processes are involved in measurement and observation. But the key for my account is the transition from the realm of entities into the realm of statements about entities. Entity-data explanations, and data-entity inferences to the best explanation, connect the two realms.

5.4.2 Secondary: Entity-Entity

There are many relationships that can hold between two entities or two qualities of the same entity. Here I will focus on two: parthood and singular causation. The latter, of course, is very general.

The discussion in the previous section was about measurement and observation, but neither is possible without chains of singular causation. There must be a causal link between the target entity and the measuring device or the observer. Even in Dretske's cases where information flows without a direct causal link there must always be some prior causal structure in place that links the target to the observer. But singular causal chains are not limited to linking entities to observers and measurement devices. The world is full of innumerable causal interactions between entities. Some of these are important for scientific experiments.

Given a particular scientific experiment we can think of any number of singular causal chains that are relevant. However my samples show that scientists do not often comment directly on these links. B63 is one case of this sort, where I believe the authors are referring to a particular process of larval supply and mass flux, and to a particular current, where changes in the current caused changes in the supply and flux. B13 is a somewhat peculiar case where there is a singular causal relationship between concrete instances of models, where one model historically "inspired" another.

There are certainly many cases of causal language used in explanations among the samples. Not all of these are indicative of entity-entity explanations, since some may be general causal claims about kinds rather than about singular causes. I discuss such cases in the following chapters.

The other relation between entities that is critical for understanding the sampled cases is parthood. There are many ways in which qualities of a whole depend upon properties of the parts and vice versa. Case A19 provides an example, where properties of the meteorite samples are explained by changes made to the parent body. This case shows that the parthood relation is often just part of the story and some other causal relations will be important.

Scientific experiments are ultimately performed on concrete particular entities. The focus of scientific reasoning, however, is not on the particulars themselves, but on the general *kinds*.

Chapter 6

Kinds

Although scientists collect data about particular entities, their goal is usually a more general understanding about *kinds* of entities. After discussing some examples in the context of the long history of philosophical thinking about kinds, I characterize my "kind" category and present the primary and secondary forms of kind explanations.

6.1 Examples

B68 Although **2** [Mn_4CaO_2] is insoluble in tetrahydrofuran (THF), addition of $Ca(OTf)_2$ [OTf is trifluoromethanesulfonate] leads to partial dissolution of the suspended material, suggesting the formation of a more soluble Ca-Mn intermediate. (Kanady et al. 2011, p. 733)

Chemical kinds are among the most straightforward examples of kinds. The authors use the present tense to describe what happens in general when one mixes Mn_4CaO_2 with other compounds.

B42 The evidence from *Darwinopterus* supports this hypothesis [about sexual dimorphism in pterosaurs]. (J. Lü et al. 2011, p. 323)

Here we have evidence from one species of pterosaur (flying reptiles from the age of the dinosaurs) used to support a more general claim about many pterosaur species.

B14 When male and female gene expression profiles were analyzed separately, the strain effect on males accounted for the differential expression of 1172 genes (9.3%), whereas only 7 genes (∼0.06%) were

> significant for the strain effect on female gene expression. (Innocenti, Morrow, and Dowling 2011, p. 846)

Mitochondria are organelles in eukaryotic cells with their own genomes, transmitted from mother to child along with other cellular material. This paper uses a fruit-fly experiment to show that this creates a strong sex-specific selective pressure, allowing the accumulation of deleterious male-specific mutations in the mitochondrial genome.

B52 MH2 [Malapa Hominin 2] shares with other australopiths and *Homo* asymmetry of the metacarpal heads that is associated with the human-like ability of the fingers to accommodate to an object via the metacarpal phalangeal joints. (Kivell et al. 2011, p. 1413)

Malapa Hominin 2 is a fossil specimen of the wrist and hand of an adult female *Australopithecus sediba*, found in Malapa, South Africa and dating to approximately 2 million years ago. The authors discuss her anatomy in the context of the evolution of the human hand.

B95 In cuprates [superconductors with a copper anion] the angular dependence of the wave functions is primarily set by the d orbitals of Cu, which hybridize with properly symmetrized combinations of p orbitals on nearest-neighbor oxygens. (Sakurai et al. 2011, p. 700)

6.2 Discussion

For Plato knowledge of the Forms of things was true knowledge. While Plato's Forms are not my "kinds", he recognized the importance of finding general truths that could bring some sense of order to the staggering diversity of particular things. When scientists classify a group of entities as belonging to the same kind they are saying that those entities are the same in some important respects, and thus that what we say for one goes for the others in these respects at least.

The kinds I have in mind are closer in spirit to Aristotle's revisions of Plato's ideas. But Aristotle's ideas have also been taken up and modified by generations of philosophers and scientists seeking to understand the world. Philosophers have asked metaphysical questions about the status of kinds and developed logics for dealing with the properties and instances of kinds. Scientists following Aristotle have put these ideas into practise by developing elaborate taxonomies of the kinds of things in the world. In everyday language our common nouns name various kinds with which we classify entities. The ubiquity, centrality, and generality of kinds in our thinking actually makes them somewhat difficult to discuss.

Plato's Forms are supposed to be timeless and unchanging. This is still a widely accepted starting point for thinking about kinds. Plato's core examples were unchanging Forms such as Justice, but for Aristotle biological species were central examples. While individual horses come and go, he considered the kind *horse* to be eternal and unchanging, outside the temporal and causal order of the world. The modern understanding of species throws this into question.

Plato and Aristotle distinguished between universals and particulars. Universals are distinct from particulars because universals *have* instances while particulars *are* instances, and cannot have instances of their own. The ancients raised questions about the nature of this mysterious instantiation relation. How can acausal universals influence causal particulars? One solution is to reject the reality of universals. Perhaps it is only particulars that are real, and when we say that they belong to the same kind we are really just giving a name to the similarities between them. The denial of the reality of universals is called "nominalism", of which there are many sorts.

Contemporary philosophers are perhaps more likely to invoke a distinction between types and tokens. The standard example is that the string 'AAA' contains three tokens of one type. In her book *Types and Tokens* Wetzel discusses examples from science and notes the ubiquity of type-talk both in science and everyday language (Wetzel 2009). While the type/token distinction is more recent and so not as burdened with philosophical implications as the distinction between universals and particulars, it is not clear whether types differ from universals or how great those differences may be (Wetzel 2011).

My account of scientific explanation requires a distinction between particular entities and the kinds to which they belong. Entities are created, cause and undergo changes, and are destroyed. Kinds are timeless and acausal (even when they are historically contingent, as I discuss below), and a single kind can have many entities as its instances. Thus kinds are universals or types of some sort. While philosophers offer competing accounts, the basic distinction is fundamental, and I believe that my account of explanation is compatible with a wide range of views including Aristotelean realism and at least some forms of nominalism.

In philosophy of science it is natural kinds that have seen the most attention. Bird and Tobin list four characteristics often thought to apply to natural kinds:

1. Members of a candidate natural kind should have some (natural) properties in common.
2. Natural kinds should permit inductive inferences.
3. Natural kinds should participate in laws of nature.
4. Members of a natural kind should form a kind. (Bird and Tobin Spring 2009, §1.1)

Items 2 and 3 are particularly important for scientific reasoning. If a natural kind permits inductive reasoning, then by performing a well-designed experiment on a properly chosen sample of a kind we are licensed to make inferences about the kind itself. Based on the facts discovered about natural kinds we can draw inferences about the natural laws that govern them. On accounts of explanation such as D-N, where natural laws are central, natural kinds have a privileged place.

The standard examples of natural kinds were once the biological species. Modern biology has shown that a simple view of species along these lines is no longer sufficient. There are several alternative species concepts that biologists work with today, and on some views species are to be considered as individuals undergoing change rather than as timeless kinds (Ereshefsky 2010).

In place of biological species, chemical kinds are now considered by many to be the prototypical natural kinds. Consider the chemical kind Mn_4CaO_2. Since every instance of Mn_4CaO_2 shares so many properties of interest with every other instance, chemists are happy to talk in the timeless present tense about the behaviour of Mn_4CaO_2 in the past and present, as example B68 above shows. While instances are created and destroyed, the kind Mn_4CaO_2 is eternal and changeless. Other chemical kinds, such as “metals”, may be more vague and problematic (Bird and Tobin Spring 2009, §2.2).

Using the present tense to refer in general to kinds allows scientists to include not only the past and the present but also future and counterfactual behaviours of kinds. I take this to be part of points 2 and 3 above. Natural kinds support reasoning about what would have happened if an entity were an instance of a kind. We can imagine finding a new instance of that kind and just by knowing that it belongs to that kind we could reason about the properties it would have, or what possible changes it could undergo. Reasoning counterfactually with kinds is central to scientific argumentation.

Many chemical kinds such as Mn_4CaO_2 fit the standard criteria for natural kinds. Not coincidentally, I think, many chemical laws fit the standard criteria for natural laws. But the traditional criteria for laws and kinds are quite stringent, and the vast majority of scientific reasoning does not conform. For instance, there is widespread doubt that there are natural laws of biology in this strict sense (Smart 1959; Beatty 1995). In fact, laws in the classical sense are hard to find in most of the special sciences, even in cases where there is strong empirical and predictive success.

Sandra Mitchell's response is to weaken the notion of a natural law so that it better fits scientific practise. Her "pragmatic law" concept does not require exceptionless universality but allows for empirical, contingent generalizations (Mitchell 1997; Mitchell 2000). Rejecting the forced choice between natural necessity or nothing, Mitchell allows for nested layers of contingency, showing how biological laws can be contingent on chemical laws and chemical laws on physical laws (Mitchell 2009, p. 58).

Without committing to all of the details of Mitchell's view, the notion of kinds that I have in mind is also one that relaxes the strict constraints of the traditional natural kind concept. I count chemical elements and kinds of molecules under my "kinds" category. I also include biological species, which I consider to be contingent on the history of evolution. Allowing that *Homo sapiens* might never have existed, there are properties that hold in sufficient generality across the members of the species such that it makes sense to use that kind for scientific reasoning. While there were times when no instances of *Homo sapiens* existed, and in the future this may happen again, the kind itself is timeless. There are many other kinds referred to in the *Science* data set that meet this more pragmatic standard.

On my view a kind is an abstract universal. Although they may be contingent, kinds are timeless and acausal. The instances of kinds are the concrete particular entities described in the previous chapter. When we ascribe qualities such as *negatively charged* to the kind *electron* we are asserting that all the entities that are instances of that kind share that property. As in Mitchell's account, these assertions may fall short of universality. There may be exceptions. But the assertion is meant to apply not only to instances past and present but also future and counterfactual instances.

The support for counterfactual reasoning distinguishes kinds from collections of entities. If we know that x is a mouse then we know many things: it is a warm-blooded multicellular organism with a spine, fur, two eyes, etc. If we learn that x is a member of a collection of mice then we know very little more about x than we did before. We can also consider the collection of all mice that have ever or will ever live, and this is still distinct from the counterfactual-supporting kind *mouse*. Philosophers have often contrasted natural kinds with arbitrary sets, and a similar contrast holds here.

The distinction between kinds and collections is clear in theory but in practise it can be difficult to tell whether an author intended to refer to the kind in general or some collection of members of that kind. Syntax alone does not always mark the shift from the kind Mn_4CaO_2 to the collection of all the Mn_4CaO_2 in *this* test tube at *this* time. When we talk about the "average" member of a kind we are often making this shift from the kind in its generality to the collection of instances of that kind that we have measured. One key syntactic clue is verb tense. Since kinds are timeless, the present tense is usually used. Since articles in *Science* report on research that has already been conducted, the past tense is usually used for collections.

One last characteristic of kinds on my account is that they often have sub-kinds. The kinds in a particular area of research often from a hierarchy of sub-kinds, which can be further connected by other relations between them. Biological taxonomies demonstrate such a hierarchy, but I think that a great deal of important scientific work can be described as finding the various sub-kinds of a given kind and articulating the differences between them. We can also restrict kinds by time or location without switching the reference to a collection, although this can invite confusion. In general it makes sense to talk about "kinds of kinds".

Kinds are the ubiquitous universals that we use to classify the world of particular things. Whatever their ontological status, knowing that two entities belong to the same kind tells us that they are similar in some respects, and helps us to predict the behaviour of the one based on the other. Much of the business of science is discovering how to group similar things into kinds that explain their similarities and differences, and then extending those kinds into new territory as the scope and power of science increases. Mark Wilson's *Wandering Significance* is an extended meditation on the ways in which our concepts grow and stretch as we face new challenges to prior ways of thinking (Wilson 2006).

6.3 Kinds in *Science*

The *Science* data set contains references to many different kinds. There are kinds of organisms, kinds of molecules, kinds of elements, kinds of proteins, kinds of genes and gene functions, kinds of viruses, kinds of stars, etc. The examples above demonstrate just a fraction of this diversity.

In case B68 we have three kinds of molecules (Mn_4CaO_2, tetrahydrofuran, and $Ca(OTf)_2$) and the suggestion of a fourth ("a more soluble Ca-Mn intermediate"). As discussed above, these chemical kinds are prototypical natural kinds, where we usually care little about the differences between individuals and focus instead on their shared properties. The present tense of the verb "leads" is evidence that the reference here are to the kinds and not to collections of particular molecules.

Case B42 involves two kinds: the biological species *Darwinopterus* and the biological order Pterosauria. *Darwinopterus* belongs to the genus *Wukongopteridae*, which belongs in turn to the order Pterosauria, and so *Darwinopterus* is a sub-kind of Pterosauria.

In case B14 we have kinds of mitochondria. They are strains rather than species, and the differences between the strains result in more differences in the expression of genes in males than in females. I consider genes and alleles to be kinds that are instantiated by concrete particular sequences of base pairs.

The entity MH2 in case B52 is an instance of the biological species *Australopithecus sediba.* The authors are interested in the kind of ability to grasp and thus in the kinds of shapes in the bones of homonid hands.

Finally, in case B95 we have a kind of superconductor called a "cuprate" because of the kind of element in its anion. The d and p orbitals are also kinds, while the wave function is stranger sort of abstract mathematical object I discuss in the next chapter.

6.4 Forms of Explanation

When the explanans is a kind we can have kind-kind, kind-entity, and kind-data explanations. I consider the kind-data form to be a composite of the kind-entity and entity-data forms. One key difference is that the entity may be implicit, and this is often the case. Kind-data explanations are significantly more common in the samples than kind-entity explanations and I propose that this is because the implicit reference to a sample or specimen is very clear – the key information is in the data. While the kind-entity form is rare, it is essential to understanding the nature of scientific explanation. The kind-kind form also gives us insights into models, which is the topic of the next chapter.

6.4.1 Primary: Kind-Entity

The relationship between kinds and entities is instantiation. Entities are instances of kinds and kinds are instantiated by entities. As mentioned above, the nature of this relation has been somewhat mysterious since it was propsed by the ancients. However both kinds and entities are important for scientific explanation and most explanations would not be possible without some link between general kinds and particular entities.

In my analysis of the sampled cases from *Science* nearly every entity that is mentioned is also analyzed as an instance of some kind. These instantiation relations are usually part of the base of the explanation, the part of the explanatory structure that the explanans and explanandum share. Despite being present in a large number of cases, there are very few cases where instantiation is the core relation. While belonging to the kind is important for reasoning about entities and data, it is not the *belonging* that is the focus of these explanations, but rather something about a model or theory of the kind.

Case B14 is a rare example of this form where it is the strain of the mitochondria that explains the differences of the expression of genes in a sample of male fruit-flies. For particular cells in particular fruit-flies it is their particular mitochondria that cause the differences in the expression of genes. But the most natural way to read the explanatory claim is that the instantiation of some strain of mitochondria in the cells of a particular male fruit-fly explains explains the differences in the expression of his genes when compared to his cohorts.

Inferences from kinds to entities are central to scientific reasoning and are present in a large number of the sampled cases. The instantiation relations in the bases of these explanations makes this clear. But it is rarely the focus of the explanation, and so instantiation is rarely the core relation that supports the explanatory claim.

6.4.2 Secondary: Kind-Kind

There are many relations that can hold between concrete particulars. For many of these we can also have a general form that holds between kinds. For instance, the parthood relation between entities, e.g. this lung is part of this chest, can be generalized to a claim that holds between the kinds *lung* and *chest* (restricted, perhaps, to humans or some other kind). This information could help us to reason about a concrete particular instance of a lung. Such general rules can have exceptions, such as when the lung has been surgically removed, and these complications were noted by Aristotle in his writing on the relations between kinds and entities. Despite these exceptions this kind of reasoning can be very useful.

Along these lines, different sorts of singular causal relations between entities can be generalized to become general causal relations among entities. As I discuss in the next chapter, we have to be careful when instantiating general causal loops in singular causal chains (which cannot loop). But this sort of reasoning about general causation is useful and fairly common in the *Science* data set.

However, once we have a general causal relationship between kinds we step away from the "kinds" category and into the "models" category. In the next chapter I present models as abstracta that describe the relations between kinds and their qualities. A kind-kind explanation can be a trivial model or mechanism with just two kinds and one link between them.

An example of this is case B95. The relationship asserted between the d and p orbitals is perhaps not causal, but "primarily set by" does indicate a dependence of the explanandum on the explanans. This relationship is a trivial fragment of the larger model of the structure of copper atoms in cuprates.

There is a second important relation between kinds that is distinctive of them. The sub-kind or sub-type relation is essential for reasoning about kinds. Using just this relation, elaborate taxonomies of kinds can be built. By learning that an entity belongs to one of the kinds in such a taxonomy we can learn a great deal about its properties and relationships. When enriched with information about other kind-kind relations such as general parthood, such a taxonomy becomes an "ontology". This sense of ontology is the focus of important current work in bioinformatics.

Case B42 is one where the core relation of the explanation is the sub-kind relation. *Darwinopterus* is a kind of *Wukongopteridae* which is a kind of pterosaur. Claims about the sexual dimorphism of *Darwinopterus* are evidence about sexual dimorphism in pterosaurs more generally, because facts about *Darwinopterus* depend upon facts about pterosaurs in general.

Reasoning about kinds is central to science. But when we want to describe complex relationships between kinds and their qualities the abstract tools that we use are *models.*

Chapter 7

Models

While kinds are often the targets of scientific explanation, the relationships between them can be complex. Models are abstracta that articulate the relationships between kinds.

7.1 Examples

B49

> Hence, we reject the hypotheses of Brownian walk and composite Brownian walk and conclude that mussel movement is best described by a Lévy walk. (de Jager et al. 2011, p. 1552)

As young mussels search for a place to settle they must balance the protection of nearby neighbours against the competition for food resources. Mussels form clustered beds that strike such a balance. The authors of this paper tested mathematical models of the mussels' search patterns. The three "walks" are algorithms for creating a path in discrete steps where the direction and size of the next step is randomly selected from a certain probability distribution.

A6

> Two broad classes of models have been proposed to explain the patterning of the proximal-distal axis of the vertebrate limb (from the shoulder to the digit tips). ... One, exemplified by the progress zone model, posits that progressive distalization of limb pattern is based on an autonomous clocklike mechanism inherent to the undifferentiated mesenchymal cells. The second postulates that instructive cues from surrounding tissues are responsible for specifying the PD segments. (Cooper et al. 2011, p. 1083)

The topic here is the development of limbs in vertebrates, and specifically how cells know where they are with respect to the body or the tip of the limb. The authors refer to "two broad classes of models" that explain how the proximal-distal axis is determined. The first class of models uses timing information while the second uses spatial diffusion of signals.

B45

> In his seminal paper, Alan Turing aimed to provide a mechanism for self-regulated pattern formation in biology by showing that sets of reaction-diffusion equations with appropriate kinetics and diffusion coefficients could spontaneously evolve to spatially periodic structures. (Bánsági, Vanag, and Epstein 2011, p. 1309)

The target here is a very broad kind: spatially periodic biological structures. The class of models is also quite broad: sets of reaction-diffusion equations with carefully balanced kinetics and diffusion coefficients.

B34

> Specifically, we simulated the coupled perturbations of increased N_2O abundance, leading to stratospheric ozone (O_3) depletion, altered solar ultraviolet radiation, altered stratosphere-to-troposphere O_3 flux, increased tropospheric hydroxyl radical concentration, and finally lower concentrations of CH_4. (Prather and Hsu 2010, p. 952)

Here we have a complex model of the upper atmosphere implemented in a computer simulation. The authors describe very briefly a chain of interactions from the input of interest to the output of interest.

B39

> Hair offers a suitable experimental model because hair follicles (HFs) cycle through phases of growth (anagen) and rest (telogen). (Plikus et al. 2011, p. 586)

The authors of this paper on general properties of stem cells justify their choice of a specific experimental model.

7.2 Discussion

For many years the focus of the philosophy of science literature explanation was on the explanatory power of theories. In recent decades it is models of various sorts that are usually invoked as explanatory, particularly in the special sciences. Philosophers of science have discussed a wide range of different models in different contexts and theories have faded into the background. Margaret Morrison discusses this shift in her "Where Have All the Theories Gone?" (Morrison 2007).

Theories were traditionally considered by philosophers of science to be sets of logical axioms, and preeminent among these were statements of the laws of nature. Starting in the 1960s this "syntactic view" (or "received view") of theories was challenged by the "semantic view" of theories (Suppes 1960). The semantic view is explicitly about models – in one sense of "model". The claim was that, rather than focusing on the uninterpreted linguistic theory, we should instead be looking at the models that provide an interpretation of the theory.

But the sense of "model" here is drawn from the branch of logic called "model theory". It seems to me (and to Morrison) that the sense of "model" used by scientists is quite different. In model theory the model and the theory have an exact correspondence: they share the same deductive structure. Shifting emphasis from logical theories to logical models does not provide much insight into the uses of models in science. "Because the use and construction of theories/models in scientific contexts bears little, if any, resemblance to model-theoretic structures, it becomes difficult to see how the latter aid in understanding the former" (Morrison 2007, pp. 202-203). I see no evidence of the model-theoretic sense of "model" in my samples of the *Science* data set.

Morrison points out that scientific models often contain assumptions, additional structures, and idealizations that we would not like to call parts of our scientific theories (Morrison 2007, p. 203). She sees models primarily as applications of theories, and the added structure is required to connect the generalities of the theory to the details of the target system. There is a critical distinction to be drawn here but it is not the distinction between an uninterpreted logical calculus and its interpretations.

The model-theoretic sense of "model" is not what I intend for the "models" category of my account of scientific explanation. There is another standard sense of "model" that is not what I intend: the scale model. A scale model is a replica of some original where the main change is in size. A scale model of a battleship is much smaller than the original, while James Watson's scale model of the double helix of DNA was very much larger. In both cases one physical system is provided as a representation of another (a specific battleship or DNA in general). While I accept that there are cases where scale models have been used in scientific explanations, and one can think of many examples from engineering, there is no evidence of scale models in my samples from the *Science* data set. I believe that such uses are a vanishing minority compared the ubiquity of the scientific models I am interested in. Understanding how behaviours change as phenomena change in scale is very important for many branches of science, but this requires a more nuanced concept of "scale model" than the standard sense that I am rejecting (Batterman Fall 2007; Wilson 2010).

The models referred to my samples of the *Science* data set are predominantly abstract descriptions of the qualities and behaviours of the instances of kinds. Most of them are mathematical in a broad sense that includes systems of equations, networks, and algorithms. I will discuss these first before turning to other important varieties.

Physics provides the standard examples of models as equations. Morrison's example in the paper under discussion is the pendulum equation (Morrison 2007, p. 203 ff.). Theories about gravitation, mass, and friction all play a role, but the model is more than the intersection of the theories. The resulting differential equation relates various qualities of the pendulum, such as the position and momentum of the bob, in a systematic way. This sort of model can be considered in input/output terms. Given an initial position and momentum together with a specified duration as the input, the output is the position and momentum of the bob at the end of that time.

Differential equations are very commonly used for modelling in mechanics and other branches of physics, as well as in chemistry, parts of biology, and elsewhere. Other mathematical formalisms apply to other sorts of models. Example B49 above involves algorithms for generating random walks, and the three different algorithms referred to differ in the probability distributions that govern the choices of step direction and length. My sampled cases show a wide range of mathematical modelling techniques.

Another important class that I include under my "models" category is the mechanism. Biologists and neuroscientists frequently invoke mechanisms as explanatory. Example A6 above is one case in point, as is example A4 in chapter 3. Philosophers of science have analyzed the mechanism concept used in such cases and shown how it differs substantially from the traditional notions of "mechanism" from 17th century science (Craver and Darden 2005). The most prominent philosophical account of mechanisms is Machamer, Darden, and Craver 2000, known as "MDC". MDC mechanisms are characterized as "entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions" (Machamer, Darden, and Craver 2000, p. 3).

In my "Mechanisms, Types, and Abstractions" I argue that MDC mechanisms are best understood as mathematical graph structures where kinds of substances are the vertices and kinds of processes are the edges (Overton 2011).[1] The key to my argument is noting that many mechanisms include cycles, which should not be

---

[1] In that paper I use the language of types and tokens, but the lessons translate directly into this discussion of kinds and entities.

understood as loops in singular causal chains. Instead mechanisms specify general relations among kinds that are instantiated by various chains of singular causation (without any loops).

Understood in this way, the key differences between the graph of a mechanism and the equation of a different sort of model are in the mathematical operations one can perform. Differential equations are best for relating real-valued magnitudes while graphs show patterns of causal links. With a differential equation we predict how one magnitude will affect another and with a graph we predict the cascading effects of removing or adding links.

What these mathematical models have in common is that they articulate the relations between qualities of one or more kinds. The pendulum equation relates the position and momentum of the bob over time. The spatial diffusion mechanism in A6 relates the diffusion of signals between cells to their developmental trajectories. I discuss more examples below. For each of these models we can provide a *target* kind, the kind that it is a model *of*, e.g. pendulums, mussel movement, the patterning of the proximal-distal axis of the vertebrate limb. But each of the models is distinct from its target kind because of the additional structure in the model that describes the relationships among qualities of the target kind or its parts.

Before turning to other classes of models, I want to distinguish between mathematical models and simulations. It is increasingly common for scientists to implement their models in complex computer simulations and run the simulations against a range of actual and fictional inputs. For predicting the behaviour of complex systems such as the Earth's climate, the structure of stars, or the formation of planets, simulations are often the best tools available. It is worth noting that the use of simulations seems to have been most prominent in historical sciences, where the simulations are a feasible alternative to impossible experiments. But as the cost of simulations decreases they may become a viable alternative to a wider range of experiments across the sciences.

Simulations are implementations of models. One model can have many different implementations in code and the code can be run many times under different conditions on different computing platforms. Variations such as the size of the floating point numbers used to represent real-valued magnitudes can make a significant difference in the output of otherwise identical simulations. In order for the simulation to run on limited computer hardware in a reasonable amount of time, simplifying assumptions will often be necessary. And the translation of a mathematical model into software is rarely straightforward, often involving a number of significant choices by the programmer. In short, implementing a mathematical model in a computer simulation is usually an involved process with many contingencies. The resulting simulation should be recognized as distinct from the abstract model that it was based on.

While I have focused on mathematical models so far, there are many other ways to express systematic relations between kinds. One possibility is an informal narrative structure where we have a story about the ways in which an instances of a kind changes over time, or how one kind influences another. The difficulty is distinguishing narratives as complete but informal models from theories, which I consider to be incomplete as models. I discuss theories in more detail in the next chapter. With my method of sampling single sentences I was not able to recognize this difference, but more detailed case studies could do so. I have classified several possible cases of narrative models as theory-x forms of explanation.

Another important sort of model, quite different from mathematical models, is the model organism. The most familiar examples are mice, rats, and monkeys, which are used in medicine as models of human physiology. But a diversity of model organisms is used by biologists to study genetics, development, evolution, disease, and so on. The *modelling* done by a model organism relies on some sort of analogy between the model organism and the target organism. The relation could be homology, but sometimes more distantly related species are more similar in some respect than closer cousins are. I accept that there are important differences in the relations that support the pendulum model and the relations that support mouse models of human cancer. As Ankeny and Leonelli discuss, model organisms are a distinct and interestingly different sort of scientific model (Ankeny and Leonelli 2011). But modelling with model organisms still expresses relations between kinds (e.g. the kind *mouse liver* and the kind *human liver*) that support explanations.

Example B39 mentions an “experimental model”. The authors are investigating stem cells in general, but in order to perform experiments they must chose some specific population of stem cells as a target. In the quoted sentence they are justifying their choice of hair follicles as an experimental model on the grounds that they exemplify the growth and rest cycles of stem cells populations in general. This use of model seems to me to be relevantly similar to the model organism case.

Though diverse, the equations, graphs, narratives, and animal models I have been discussing are supposed to be similar to the extent that are all *models*. The relation between a model and a kind is *modelling* – the model is a *model* of the kind. But just what is the modelling relation?

Much of the philosophical work on modelling has focused on representation. If a model represents its target then it says true things about the target, and some of those true things might be explanatory. The challenge to the representational view of models is that many models in science contain idealizations. A standard distinction in the literature is between abstractions, which merely omit irrelevant details, and idealizations, which introduce falsehoods into the model (Jones 2005). On the idealization side we can distinguish "Galilean" idealizations that can be de-idealized to restore an accurate representation (McMullin 1985), and ineliminable idealizations that cannot be removed without undermining the whole explanation (Batterman 2002; Batterman 2009; Bokulich 2009). If idealized models contain falsehoods and these falsehoods cannot be removed, then how can they tell us truths about their targets? Alternative non-representational accounts of modelling must provide some other relation between models and their targets that can support explanation.

It seems to me that much of the philosophical discussion of models focuses on the relationship between models and concrete particular entities. We ask whether the pendulum equation is a model of some particular pendulum that we imagine exists. Does the model make true claims about this entity? Instead I prefer to break the problem in two. The model is a model of a kind of pendulum and the concrete particular pendulum on my desk is an instance of a kind of pendulum. The key question is then whether it is the same *kind* that is modelled and instantiated – whether the model applies to the entity in virtue of the shared kind.

It might seem that we now have two problems: what is modelling and what is instantiation? But the second problem is one that we already had, and one we are familiar with. We are used to dealing with nested kinds of varying generality, such as the pattern of species, genus, family, order, class, phylum, and kingdom. We can describe Fluffy as a member of *Animalia* or *Chordata* but we include more information by describing her as a member of *Felis catus*. Likewise we get more information about the pendulum on my desk by describing it using a detailed pendulum equation including a term for air resistance. And it turns out that we get more information about the behaviour of breaking drops by describing them as continuous fluids rather than describing them as clouds of molecules, despite the fact that concrete particular drops do not belong to the kind *continuous fluid* (Batterman 2005). This is just a new twist on the old problem of deciding what kinds an entity belongs to.

Once we shift these problems to the instantiation relation, the modelling relation becomes (I think) far less mysterious. A model is an abstract description of the relationships between kinds and their qualities. The model articulates the kind, enriching it with structure that allow us to reason about it in greater depth and detail. The structure of the model allows us to predict (and retrodict) the behaviours of the entities that instantiate the kind.

The change of perspective I propose does not solve the problems with idealization, but I think it shifts the focus of the debate in a valuable way. The problem is not whether the model accurately represents this or that entity. Instead we should ask what kind we should pick out of the many available if we want to accurately describe the entity, and how that choice can be justified. This is a question of the relevant similarities between the entities that instantiate the kind rather than the similarities between the model and the entity.

The point of this discussion is that the modelling relation holds between models and kinds, not directly between models and entities. This makes it easier to answer the question *what is modelling?* – I describe it as *articulation* – but raises a range of problems with the instantiation relation between kinds and entities. As I noted in the previous chapter, there are long-standing mysteries about instantiation that lie at the heart of the debate between realism and nominalism. But rather than having *two* deeply problematic relations (modelling and instantiation) I propose that we really have just one: instantiation.

The distinction between a model and its target kind is that the kind is an undifferentiated whole while the model has articulated parts. The modelling relation marks the shift from dealing with kinds to dealing with models *of* kinds, just as the measurement relation marks the shift from entities to data about the entities.

References to models in the *Science* data set are usually indicated by key words such as the common "mechanism" and "model" or the less common "equation". But such indicator words are not always present and sometimes the reference is entirely implicit.

There are many important topics in the philosophical literature on models that I have not addressed here, but my goal here has been to establish in a rough way the distinct category of models that my account of scientific explanation relies upon. While there is a diversity of opinions among philosophers regarding models, as with the other categories I think that there is widespread acceptance that models form a distinct category that is important for understanding scientific practise.

In sum, models are abstracta that articulate the relations between qualities of one or more kinds. Models come in many forms, from differential equations relating magnitudes, to mechanisms articulating networks of causal links, to model organisms offering exemplars for similar processes. Models usually have inputs and outputs, allowing them to be used for prediction. For any model we can cite its *target* kind, the kind that it models. But a model is always distinct from its target kind because it has additional structure.

As with kinds, models can have various degrees of generality. Example A6 refers to broad classes of models while B49 cites quite specific models. But with increasing generality the distinction between models and theories can become blurred. I discuss this in the next chapter.

7.3 Models in *Science*

There are many examples of models in my samples of the *Science* data set. Here I discuss the examples given at the beginning of this chapter and some of the others mentioned in previous chapters.

Case B49 above is included as a straightforward case of mathematical modelling. The target kind is the movement of mussels. The three models are algorithms for random walks, differing in the probability distributions that govern the choice of step direction and length. The authors collected data about the patterns of actual beds of mussels, then ran simulations using these three models and decided that the closest match for actual mussel movement is the Lévy walk. The Lévy walk is clearly distinct from the kind *mussel movement*, but it models that kind in the sense that the model allowed the prediction of patterns in the movement of actual mussels. Other straightforward cases of models discussed in previous chapters include the Benfield geometric model of catalysts in A9 and the mathematical model of the entrainment of the circadian clocks of cyanobacteria in A4.

In case A6 we have a comparison between two much more general models. The two broad classes of models are perhaps general enough that they are better called theories. In any case, more specific models within each class will have in common the general features that distinguish the classes: they will either use timing information or spatial diffusion of signals to model the target kind, which is the patterning of the proximal-distal axis of the vertebrate limb. The specific models will likely take the form of a mechanism. Case A14 is similar, with two broad classes of model for monoclonal conversion of populations of epithelial stem cells in intestines.

The generality increases with case B45 where the target kind is spatially periodic biological structures. Rather than one model we have another broad class of models involving sets of reaction-diffusion equations with carefully balanced kinetics and diffusion coefficients. Each of these is a mathematical model.

The model in case B34 is considerably more complex than the previous cases. The target kind is the upper atmosphere. The model articulates the target kind in terms of a number of other kinds: the abundance of N_2O, stratospheric ozone, solar ultraviolet radiation, stratosphere-to-troposphere O_3 flux, tropospheric hydroxyl radical concentration, and CH_4 concentration. Presumably, these kinds are linked in various feedback loops of different strengths that make the relation between input N_2O abundance and output CH_4 concentration difficult to infer. The authors implemented a simulation of their model in order to discover the answer.

Finally, in case B39 we have an "experimental model". As discussed in the previous section, I see this case as essentially similar to the model organism case. Ankeny and Leonelli distinguish model organisms from scale models and I would do the same here. But these three sorts of model (organism, experimental, and scale) are distinct from the mathematical descriptions of the relations of kinds that form the bulk of the models referred to in my samples of the *Science* data set.

7.4 Forms of Explanation

When a model is the explanans we can have four forms of scientific explanation: model-model, model-kind, model-entity, and model-data. I consider the latter two to be composite forms. A model-entity explanation is composed of a model-kind and a kind-entity explanation, and a model-data explanation is composed of three parts: model-kind, kind-entity, and entity-data. In these composite cases some of the middle steps may be implicit. It may not be completely clear what kind the model is modelling or what entity the data are about.

Model-kind explanation is the prototypical form of scientific explanation. Instances are twice as numerous in my samples of the *Science* data set as the next most numerous form of explanation, which happens to be kind-kind explanation. As discussed at the end of the previous chapter, some kind-kind explanations are actually trivial models.

Model-model explanations, on the other hand, are rare. Only one such case occurs in my sample. Below I consider that case, and suggest other core relationships that could link models.

7.4.1 Primary: Model-Kind

There are many examples of model-kind explanation in my sampled cases. B49 is a straightforward case of mathematical modelling. Cases A6 and B45 are more general models of more general kinds, under which a wide range of entities will fall. In each case the model articulates the target kind. For instance, the Lévy walk describes the kind *mussel movement* in terms of the size and direction of the steps. In A6 it is the timing or spatial diffusion, and in B45 it is the kinetics and diffusion coefficients that articulate the target kinds.

Why are model-kind explanations so prevalent in the *Science* data set, both in general and as the main claim of the abstracts in sample C? I think that scientists value this form of explanation because models can provide clear predictions that are easy to test and can lead to practical applications. Certainly the shift in emphasis in the philosophical literature from theories to models is supported by the prevalence and importance of model-kind explanations in science.

7.4.2 Secondary: Model-Model

While there are many possible relationships between models, or between qualities of a model, model-model explanations are rare in *Science* articles. I describe the single such case I sampled and then speculate on other possible core relations.

The one case of model-model explanation I discovered was B34. The authors performed a complex simulation of the upper atmosphere in order to determine the relationship between N_2O and CH_4. Their explanation articulates the kind “gases in the stratosphere and troposphere” by describing the various gases and the chemical reactions they undergo. At each step we have general causal relations between kinds, but the whole model is a complex network of these relations. The target of the explanation is the model itself, where the explanans is one part of the model and the explanandum another part of the same model.

Another relation could be a sub-model relation between a parent and child model. The details depend on the mathematical formalism involved. Given a parent model B, a sub-model A could be one where certain parameters that were free in B have been set in A. If we take mechanisms to be graphs, as I propose, then a sub-mechanism could be a sub-graph (for which I offer a definition in Overton 2011). Both of these cases support the counterfactual dependence we require, where model A depends on model B.

We have seen that models are the focus of much of the explanatory practise revealed in the *Science* data set. But in order to understand how models are built, and what similar models have in common, we should look to *theories*.

Chapter 8

Theories

Collecting data and establishing theories are perhaps the two most characteristic scientific practises in the eyes of the layperson. Philosophers have taken many different approaches to understanding scientific theories but there is no strong consensus on their nature and their role. In this chapter I provide some examples of the use of theories from my samples of the *Science* data set and characterize the "theories" category for my account of scientific explanation.

8.1 Examples

C8 Catastrophic ecological regime shifts may be announced in advance by statistical early warning signals such as slowing return rates from perturbation and rising variance. The theoretical background for these indicators is rich, but real-world tests are rare, especially for whole ecosystems. We tested the hypothesis that these statistics would be early warning signals for an experimentally induced regime shift in an aquatic food web. We gradually added top predators to a lake over 3 years to destabilize its food web. An adjacent lake was monitored simultaneously as a reference ecosystem. Warning signals of a regime shift were evident in the manipulated lake during reorganization of the food web more than a year before the food web transition was complete, corroborating theory for leading indicators of ecological regime shifts. (Carpenter et al. 2011, p. 1079)

B78 Particles can create stable flocculated networks in suspensions through the effects of the van der Waals forces; they are much smaller than the capillary force between particles considered here. (Koos and Willenbacher 2011, p. 899)

The authors of this paper appeal to van der Waals forces to explain one kind of stable flocculated network of suspended particles. The focus of their interest in this paper is another kind, where van der Waals forces are not dominant.

A24 Precipitation can also explain the rebrightening observed later in some places as different areas drain (by overland flow or infiltration) or dry at different rates. (Turtle et al. 2011, p. 1416)

Observations of Saturn's moon Titan by the Cassini probe reveal patches of changing brightness. The authors propose that precipitation of methane can explain this.

B2 A Fermi gas of atoms with resonant interactions is predicted to obey universal hydrodynamics, in which the shear viscosity and other transport coefficients are universal functions of the density and temperature. (Cao et al. 2011, p. 58)

The project in this paper is to experimentally test the mathematical model in regimes of extreme temperatures. This quotation comes from the first line of the abstract where the authors describe in general terms how the theory of universal hydrodynamics is used to build models of Fermi gases.

B54 Despite their great length, the canines were not fragile. These could have served to manage food items before processing, to deter attacks from predators, or for intraspecific display and combat, as seen in extant antlerless water deer (*Hydropotes* sp.; Fig. 2E) and musk deer (*Moschus* sp.) from Asia. (Cisneros et al. 2011, p. 1604)

This paper reports on the skull and teeth of *Tiarajudens*, a sabre-tooth therapsid that lived approximately 250 million years ago. The authors appeal to general principles about the creature's needs for managing food, defence, and display in order to explain the size of the canine teeth.

B21 Because changes in chromosomal supercoiling also may have widespread pleiotropic effects, it seemed likely that interactions with the *topA* alleles specific to the EW [eventual winners] and EL [eventual losers] backgrounds might explain these epistatic effects. (Khan et al. 2011, p. 1435)

The topic of this paper is a long-term evolution study in *E. coli* of "evolvability" as a second-order trait in populations. Here the authors try to explain how the

> *topA* allele in the eventual winners could be responsible for a large difference in the fitness benefit of a second gene, *spotT*, that was present in both the winners and the losers. The explanation involves changes in the shape of chromosomes that in turn cause many changes in gene expression.

8.2 Discussion

Of the five categories that my account of scientific explanation depends upon, characterizing "theories" is the most difficult. The nature and role of scientific theories has been a focal point of the philosophy of science throughout its history as a sub-discipline of philosophy and in the various traditions that were its predecessors. Not only is the literature vast, it is exceedingly diverse. At the core is the received view of theories mentioned in the previous chapter, where theories are taken to be sets of logical axioms. But that view has been widely rejected and there is no consensus that has taken its place. Instead we seem to have a diversity of views about theories and laws that reflects the diversity of the special sciences. Theories and laws in physics are handled in one way, distinct from biology, which is distinct from psychology, and so on. While "theory" and "law" are words shared across scientific disciplines, it is no longer clear that they refer to the same sorts of things. This problem is part of the motivation for Morrison's call to redress the imbalance between models and theories in the philosophy of science (Morrison 2007).

The breadth, depth, and diversity of philosophical treatments of theories is a major obstacle. But even within the scheme I propose it can be difficult to distinguish between theories and models or theories and kinds in certain cases. Finally, there are few uses of "theory" in the sense I intend among my samples of the *Science* data set. As discussed in section 3.3.10, I have had to add implicit claims about theories to my case analyses, and I expect that these are the additions that readers will find the most surprising.

For these reasons I have considered collapsing the "theories" category into the "models" category. This is the closest fit, since models involve the laws, empirical principles, and formalisms that I wish to include under "theories". However I have decided that the distinction between theories and models is well worth keeping. Even if it may be difficult to recognize at times, and often lies below the surface of the statements that scientists make when explaining, there is an important difference between the models that are applied in order to explain the qualities of kinds and the theories that are the building blocks of models.

Laws of nature have traditionally been at the centre of philosophical discussions of theories. Universal natural laws are central to the D-N account of scientific explanation and important in may other accounts, particularly unification. As we saw in the chapter on kinds, the notion of a universal natural law is quite strict and not a good fit for the practises of most of the special sciences. Sandra Mitchell's "pragmatic laws" weaken the concept, giving it a much wider range of applicability (Mitchell 1997; Mitchell 2009). Mitchell makes room for different levels of contingency in such laws and this allows her to include strong empirical generalizations alongside strictly necessary natural laws. Without committing to all of the details of Mitchell's account, it is laws understood in this weaker sense that I wish to include under my "theories" category.

It is sometimes difficult to distinguish laws from models. For example, Newton's second law is often expressed as an equation, $f = ma$. We saw in the previous chapter that many models are also expressed by equations, such as the pendulum equation. Models have target kinds, some of which are very general, and this law could be said to have the target kind *physical body* or perhaps *point particle*. The notion of a *minimal model* blurs the distinction further. It is very easy to slip from talking about the law itself to talking about a minimal model of a single particle in empty space under the influence of disembodied forces. The minimal model is built from the law together with a small number of innocuous assumptions. It is the addition of these assumptions that differentiates the minimal model from the law, but they can be implicit and go unnoticed.

Laws are the most straightforward but not the only things I include under "theories". A set of laws does not make a model. In the case of D-N explanations we also need the rules of first order predicate logic, and on my account some sort of logical system can also be part of the theory behind a model. In the case of mathematical explanations we need the relevant parts of mathematics. In narrative models we might have a more general theory of causation supporting our reasoning from one step to the next. I include systems of inference such as these under my "theories" category.

A model is built by combining various laws, empirical generalizations, explanatory principles, and assumptions together with systems of inference. In some situations there are clear "recipes" to follow. For instance, Sheldon Smith and Mark Wilson describe the "Euler recipe" for building models of planetary motion and solving the "Kepler problem":

1. Specify the class of bodies (let them be point particles) whose behavior one is concerned with.

2. Specify what types of special force laws hold between these particles (e.g. Gravitation and the Coulomb force).
3. Choose a set of Cartesian coordinates along which to decompose the special forces. That is, specify, say, the force of gravity acting on the first particle from the second particle acting along the x-axis.
4. For each particle, sum the special forces acting on that particle along a certain coordinate axis.
5. Set the sum for each particle equal to $m\frac{d^2x}{dt^2}$. (Smith 2002, p. 244)

The result is a differential equation that can be integrated to find the temporal trajectory of the planet.

The Euler recipe could be considered a very general model or a very specific theory. Considered as a model of the motion of planets it has many free parameters that must be specified in particular cases. Considered as a theory, most of the model-building work has already been done by selecting laws, making assumptions, and establishing the system of inference. In this way it is similar to the "broad classes of models" from cases A6 and A14 discussed above. In my opinion the Euler recipe falls into the "theory" category, but I do not believe that much is at stake here. We can recognize the ambiguous middle ground of recipes and schemata as lying at the vague boundary between theories and models without undermining the larger project of accounting for practises scientific explanation.

If recipes and schemata are near the "models" end of a spectrum of theories, at the other end there are theories that are much more general and poorly defined. For example, in case A24 the authors refer to "precipitation" as an explanation for changes in brightness observed on the surface of Saturn's moon Titan. "Precipitation" seems to refer to a very broad *kind*. But I think that it actually refers in a general way to a body of theory about the hydrological cycle on Earth and the extension of that theory to other climate systems with large bodies of liquid, evaporation, clouds, condensation, rain, and drainage back into the large bodies of liquid. In the case of Titan the liquid is not water but methane at extremely low temperatures. This broad theory could be used to build narrative models of such a cycle on Titan or more formal models of drainage and evaporation based on specifics of the topology and atmosphere. While "precipitation" could easily refer to the kind, here I believe it refers to a body of theory *about* the kind.

A theory alone, without the additional assumptions, idealization, and structure of a model, can only provide an incomplete explanation of a kind. Phrases such as "may explain in part" often indicate that the explanans is a theory, and "in part" occurs in many of my sampled cases. While scientists prefer to offer models with robust explanatory and predictive power, sometimes they can only point to a theory that may turn out to play a role in a complete explanation.

The vague boundaries between kinds and models and theories might be sharper if I had a more detailed account of scientific theories to offer. I do not have any individuation conditions to propose for theories, and so I cannot say if there is one theory of precipitation in general or various theories of precipitation on Earth, Titan, and other planets. Although I would be happy to have sharp individuation conditions and rigorous definitions for each of my categories, that has not been my goal. The characterizations I have given seem to me to be sufficient for the coarse categorizations I require to support my account of scientific explanation.

In sum, laws, empirical generalizations, explanatory principles, and assumptions, together with systems of inference such as logical and mathematical formalisms, are theories that are used for building scientific models. Although the category is disjunctive and its boundaries are vague, theories are distinct from the models that they are used to build and from the kinds that they are theories of.

8.3 Theories in *Science*

The first example that I introduced of a theory from the *Science* data set was case A10 and the theory of luminance of the star HIP 13044. In that case the authors were not presenting a theory, but rather appealing to the possibility that further developments in the theory of the luminance of stars similar to HIP 13044 could explain the odd length of the signals that they observed. They do not have a particular theory in mind, nor a particular model, but instead are looking to general principles used in modelling stars to account for an unexpected feature of their data.

Many appeals to theories in my samples were similar. Where possible, scientists seem to prefer to offer models. Articles in *Science* may not be the best place to look for discussions of theory. It may be that textbooks and other genres of scientific writing are more explicitly focused on the articulation and application of theories, while articles focus more on data, entities, kinds, and models.

In case C8 we have a fascinating example where a body of theory about ecological changes has been tested by experimentally manipulating the ecosystem of a lake and comparing it to a control. The authors tracked expected warning signs of major shifts in the ecology and were able to corroborate the theoretical predictions. In this case the “theory” referred to in the final sentence might encompass a large portion of all the theories in the field of ecology.

Case B78 mentions van der Waals forces. While van der Waals forces are also a broad kind, here I think the reference is to the theory of those forces. This use of “van der Waals forces” is similar to the use of “precipitation” in case A24. In both cases the named kind is just the most relevant kind to which the theory applies: precipitation also involves evaporation, and van der Waals forces are just one way in which particles interact.

In B2 we have a reference to the theory of universal hydrodynamics applied to the kind “Fermi gas of atoms with resonant interactions”. Also important are some of the parts of the theory, including “shear viscosity and other transport coefficients”. Universal hydrodynamics is the kind of broad physical theory that philosophers have often sought to understand as a set of axioms, but the reference here is quite elliptical.

In case B54 we have three theories of the function of the sabre-teeth: managing food, deterring attacks from members of other species, and display and combat with members of the same species. These are functional explanations that focus on the need of an organism to perform these tasks as a reason that it would have the appropriate tools. A5 is a similar case.

B21 is especially complicated. The explanation involves the interaction of multiple alleles, some of which were present in both the eventual winners and eventual losers, and some of which differed. The authors are interested in “evolvability” as a second-order trait, by which they mean the ability of populations to adapt quickly and successfully to changes in their environments. The key to this explanation is that an interaction of just two genes can change the way in which chromosomes coil and thus influence the expression of a large number of other genes. Quick changes in the expression of large numbers of genes may not always be a benefit for a population, but can allow for greater “evolvability”. I consider the authors’ discussion to be theoretical because the claims being made are quite general. While they can offer an explanation after the fact, they are not proposing a model robust enough to make strong predictions.

8.4 Forms of Explanation

When the explanans is a theory we can have five forms of explanation: theory-theory, theory-model, theory-kind, theory-entity, and theory-data. The latter three I consider composites, built from chains of primary forms of explanation. The other two forms, theory-theory and theory-model, are rare in my samples, but still important for understanding the structure of scientific explanation.

8.4.1 Primary: Theory-Model

The relation between theories and models is *model building* or *justification* of models. As philosophers have often discussed in the context of D-N explanation, scientists have to justify their models by reference to something even more general that is shared between models. I gave the example of the Euler recipe as one case in point.

Despite the importance of model building there are very few theory-model explanations in my samples. Case B2 is one of them. The quoted sentence comes from the beginning of the abstract where the authors are setting the context of their paper. Their project is to test the standard theory empirically at extreme temperatures. This requires building specific models based on the shared general theory.

Because theory-model explanations are so rare, the question arises again whether this counts as "explanation". Philosophers have not always considered the arguments that model building involves to be explanations. But I think that D-N explanation sets a precedent here, and philosophers concerned with explanation have often looked at the relations between theory and models. As before, the structure of these explanations is essentially the same as the other forms of explanation on my account, and I think that they deserve to be included in a general account of scientific explanation.

8.4.2 Secondary: Theory-Theory

Philosophers have considered many ways in which theories may be related. Logical relations such as deduction have been important examples and so have mathematical relations. Batterman's work on cases such as breaking droplets, shock-fronts in gases, the rainbow, and renormalization are detailed studies of the ways in which theories can be justified. The key to these cases is the peculiar nature of the justification. While the phenomena are made up of discrete and finite components, our best models of these phenomena require taking infinite limits, such as the continuum limit, the thermodynamic limit, or the semi-classical limit. These interesting cases of theoretical justification raise important philosophical problems about idealization and explanation. But it is not surprising that my sampling did not reveal any cases of this type in *Science*.

A more familiar relation between theories is unification, as proposed by Friedman and Kitcher. The core idea here is that theories are more explanatory when they unify disparate phenomena under one explanatory schema. While unification may be a core relation in some theory-theory explanations, I did not find any examples of it in my samples of *Science*.

The one example I did find of theory-theory explanation is B21. While the details are complex, the heart of the explanation is a justification of a theoretical assumption on the basis of another more general theory. The authors propose that an interaction of genes explains the differences in fitness benefits that they observed and justify their proposal on the basis that supercoiling of chromosomes can cause widespread changes in gene expression. The justification relation here is similar to (and might be the same as) the justification relation in theory-model explanations, but the explanandum is a general theory rather than a specific model. The vagueness at the boundary between models and theories might be at play in this case, or it may be that the core relation for theory-theory and theory-model explanations is sometimes the same.

"Theories" is the most general of the five categories and "data" the most specific. With the characterizations of these five categories I have filled out my general philosophical account of scientific explanation and shown examples the primary and secondary forms of explanation that my account requires.

Chapter 9

Conclusions

In these last five chapters I have laid out five coarse categories that are sufficient to capture a wide range of cases sampled from *Science*. I have provided characterizations of each and the means to distinguish members of one from members of another. Each of the five categories is widely recognized by philosophers. But for each there are outstanding philosophical problems concerning the nature and the role they play in science. I have tried to point to these problems and locate my position in the wider literature. To address and try to resolve all of these philosophical problems would be a very ambitious undertaking. But the resolution of all of these philosophical problems is not a necessary precondition for the useful application of my account of scientific explanation. My characterizations of the five categories allow me to answer the question *what is a scientific explanation?*

A scientific explanation is the triple of an explain-relation, an explanans, and an explanandum. The explain-relation expresses the dependence of the explanandum qualities on the explanans qualities. A core relation between the explanans and explanandum supports the explain-relation and our counterfactual reasoning about it. There are many core relations that can support the explain-relation. We can classify them by looking at the categories of the explanans and explanandum in a given case. The five categories range from the very specific to the very general: data, entities, kinds, models, and theories. Between theories and data there are four primary forms of explanation, representing shifts from general theories to specific models, from models to the kinds they are models of, from universal kinds to particular entities, and from entities to the data about them. The five secondary forms of explanation apply when the explanans and explanandum share the same category, and each of these forms allows for multiple core relations. The rest of the forms of explanation are composites of the primary and the secondary forms.

In chapter 3 I have laid out the general structure of scientific explanations on my account. A wide range of cases support the account and show that the various forms of explanation are actually used by scientists.

The results of chapters 2 and 3 allow me to answer the three main questions about scientific explanation that I raised in the introduction. Scientific explanation is important: explanations and inferences to the best explanation are ubiquitous in *Science* and (I infer) in science more generally. We cannot understand science without understanding scientific explanation. Explanation is also general, and explanations occur in articles across a wide range of disciplines sampled from *Science*. While the core relations differ, the explain-relation remains the same. And explanation is a goal of science. The main claims of all the abstracts in sample C are either explanations or inferences to the best explanation, expressing the explanatory claims that the authors have tried to establish by their research.

My general philosophical account also addresses the problem of fragmentation. Several of the philosophical accounts of scientific explanation that I surveyed can be understood to be specific cases of my general account, focused on one or a few of the forms of scientific explanation. The striking diversity of the accounts corresponds to the actual diversity of forms in scientific practise. But my general account and the evidence I have collected do rule out several other philosophical views. Scientific explanations are diverse, but not just anything goes.

In the two appendices that follow I present the details of my analysis and the programs I used to perform it. The interested reader is welcome to check them. But I expect that many of the objections to my account will not be in these details that I have included but rather in the details I have omitted. How does inference to the best explanation work, on this account? How can we distinguish between good and bad explanations? How do the core relations of measurement, instantiation, modelling, and model building work? How should we understand idealized explanations or explanations involving fictions? These are just some of the questions I would like to have full answers to.

I consider explanation to be a core topic in the philosophy of science. By better understanding scientific explanation we begin to better understand many other important topics in the field. Although the account I have given does not answer these important questions, it brings them together in interesting ways. If some of the answers I give are right, then we can see that questions about modelling and instantiation are connected; that there is a place for some idealizations and fictions among the counterfactual instances of kinds; that there are many forms of inference to the best explanation that will differ according to the form of the explanation they propose; that good and bad explanations are distinguished in part by the sorts of counterfactual reasoning they support. I leave these important questions to future research.

Philosophical analysis can provide insight into scientific explanation, but so can psychology, computer science, and the wisdom of practising scientists. By better understanding these aspects of scientific explanation we can develop better scientific practises and, ultimately, better science.

Appendix A

Appendix A: Case Studies

As described in chapter 3, I have randomly selected three samples from the *Science* data set to help develop and test my account of scientific explanation. For each of the sampled cases I provide the relevant quotation and citation. For the short quotations in samples A and B I provide a brief paragraph with some context for the quotation, but for the abstracts in sample C this was not necessary. When my account does not apply to the case, I provide a note giving the reasons.

When my account of scientific explanation does apply to the quotation, I provide a list of the relevant explanations and inferences to the best explanation (IBEs). For sample A these are just the explanations involving "explain" words. For sample B these are all the relevant explanations and IBEs in the quotation. For sample C these are the explanations and IBEs made in the main claim of the abstract.

For each explanation and IBE I provide a gloss and a table. While the information contained in each is essentially the same, the gloss is easier to read while the table emphasizes the structure. The parts of the structure that I see as explicit in the quotation are in normal roman type. The parts that I see as implicit in the quotation are in *italic* type. The parts that mark data, entities, models, or theories are in **bold** type (even when they are also implicit). In the table items are sometimes indented to indicate nested clauses. Finally, in the gloss the explanatory or evidential phrase is set in SMALL CAPS.

A.1 Index of Cases by Form

data	data	B71.1 B71.2
data	entity	B9.1 B25.1 B25.2 B25.3 B70.1 B100.1 B100.2 C7.1 C20.1 C20.2 C23.1
data	kind	B23.1 B66.1
data	model	B11.1
data	theory	B1.1 B5.1 C5.1 C8.1 C15.1 C16.1 C18.1
entity	data	A15.1 A15.2 B15.1 B16.1 B16.2 B59.1 B80.1
entity	entity	A3.2 A19.1 A22.1 B13.1 B32.1 B38.1 B63.1 B63.2 B77.1 B81.1
entity	kind	B44.1 B48.1 B60.1
entity	model	B4.1
entity	theory	C22.1
kind	data	A12.1 B56.1 B56.2 B56.3 B58.1 C24.2
kind	entity	A3.1 B14.1 C19.1
kind	kind	A18.1 A20.1 A21.1 B31.1 B42.1 B83.1 B95.1 C9.1 C14.1 C17.1 C24.1
kind	model	B6.1 B62.1 B76.1 C1.1
kind	theory	B68.1 B75.1 C3.1
model	data	A4.1 A7.1 A9.1 A11.1 A17.1 B3.1
model	entity	A1.1 B79.1
model	kind	A5.1 A5.2 A5.4 A6.1 A6.2 A13.1 A14.1 A14.2 A23.1 B45.1 B49.1 B49.2 B49.3 B52.1 C4.1 C6.1 C10.1 C11.1 C12.1 C12.2 C12.3 C12.4 C13.1 C25.1
model	model	B34.1
model	theory	B51.1
theory	data	A10.1 A24.1 B84.1
theory	entity	A8.1 B21.2 C2.1
theory	kind	A5.3 B36.1 B36.2 B53.1 B54.1 B54.2 B54.3 B78.1 C21.1
theory	model	B2.1 B39.1
theory	theory	B21.1
failures		A2 A16 A25 B7 B8 B10 B12 B17 B18 B19 B20 B22 B24 B26 B27 B28 B29 B30 B33 B35 B37 B40 B41 B43 B46 B47 B50 B55 B57 B61 B64 B65 B67 B69 B72 B73 B74 B82 B85 B86 B87 B88 B89 B90 B91 B92 B93 B94 B96 B97 B98 B99

A.2 Sample A

Case A1

> Note that the wetting layer of ILE [ionic liquid-based electrolyte] on the nanowire surface is so thin (less than 10 nm) that the flux of Li^+ transported by this layer is outmatched by the flux from solid-state diffusion in the amorphous Li_2O reaction product. This explains why the reaction occurred along the longitudinal direction rather than along the radial direction. (Huang et al. 2010, p. 1519)

This paper describes the behaviour of a nanowire under a transmission electron microscope. Here the authors give a reason for the direction of the reaction front that they observed. There is a three step explanation here, but I focus on the second and third steps. (The second sentences was selected, and the first is included as containing the referent of “this”.)

1. Explanation: model – entity

   The relative strength of the flux of solid-state diffusion in the amorphous Li_2O product of the oxidation reaction of lithium *in a* ***model*** of the wetting layer of ILE on the surface of the **nanowire** EXPLAINS the radial direction of the oxidation reaction of lithium in the **nanowire.**

explains

The relative strength	the radial direction
of the flux	of the oxidation reaction
of solid-state diffusion	of lithium
in the amorphous Li_2O product	
of the oxidation reaction	
of lithium	
in a ***model***	
of the wetting layer	
of ILE	
on the surface	
of the **nanowire**	in the **nanowire.**

Case A2

> For each value of T_c, we compute [equation 4] where the errors in the experimental and lattice QCD [quantum chromodynamics] quantities are obtained as explained above. (S. Gupta et al. 2011, p. 1527)

This use of "explain" in this physics paper amounts to a description of how a calculation was performed.

Failure: description

Case A3

> Furthermore, coexistence of substantial south polar ice sheets with tropical SSTs [sea surface temperatures] regionally in excess of 30°C implies a steeper meridional temperature gradient than during other major glacial episodes. … Both of these observations could plausibly be explained by nonlinear changes in the intensity of oceanic meridional overturning circulation, similar to those previously invoked to explain changes in the behavior of the Hirnantian carbon cycle. (Finnegan et al. 2011, p. 906)

This paper on pre-historic climate change discusses ocean temperatures and continental ice volumes. Here the authors propose an explanation that resolves a tension between two sets of observations, and which has been invoked in another related context. (The second sentence was selected, and the first was included to provide the referent for "both of these observations". See also case B100.)

1. Explanation: kind – entity

   The nonlinearity of changes in the intensity of meridional overturning in the circulation of oceans COULD PLAUSIBLY EXPLAIN the coexistence of substantial south polar ice sheets with tropical SSTs regionally in excess of 30°C in the oceans *of **Earth** which are oceans.*

could plausibly explain

The nonlinearity	the coexistence
of changes in the intensity of meridional overturning in the circulation	of substantial south polar ice sheets with tropical SSTs regionally in excess of 30°C in the oceans *of **Earth***
of oceans	*which are oceans.*

2. Explanation: entity – entity

The nonlinearity of changes in the intensity of meridional overturning in the circulation of oceans *of **Earth** in the **Hirnantian era*** WAS PREVIOUSLY INVOKED TO EXPLAIN changes in the behaviour of the carbon cycle *of **Earth*** in the **Hirnantian era.**

was previously invoked to explain

The nonlinearity	changes
of changes in the intensity of meridional overturning in the circulation of oceans	in the behaviour of the carbon cycle
*of **Earth*** *in the **Hirnantian era***	*of **Earth*** in the **Hirnantian era.**

Case A4

> Physiological concentrations of ADP [adenosine diphosphate] inhibit kinase activity in the oscillator, and a mathematical model constrained by data shows that this effect is sufficient to quantitatively explain entrainment of the cyanobacterial circadian clock. (Rust, Golden, and O'Shea 2011, p. 220)

This is the last sentence of the abstract of a paper on the cyanobacterial circadian clock. It expresses the main explanatory claim that their model explains the entrainment (i.e. synchronization) of that clock.

1. Explanation: model – data

   The physiological concentration of ADP in the mathematical **model** of the activity of kinase in circadian clocks of cyanobacteria IS SUFFICIENT TO QUANTITATIVELY EXPLAIN *the rate* of entrainment *in the* ***measurements*** of the circadian clocks *in a* ***sample*** of cyanobacteria.

is sufficient to quantitatively explain	
The physiological concentration	*the rate*
of ADP in the mathematical **model** of the activity of kinase in circadian clocks	of entrainment *in the* ***measurements*** of the circadian clocks *in a* ***sample***
of cyanobacteria	of cyanobacteria.

Case A5

> This use of lean mass can be explained by a variety of factors, including (i) a beneficial reduction in mass in order to minimize energy costs and to increase flight range, (ii) the requirement for gluconeogenesis and anaplerosis of Kreb's cycle intermediates, (iii) endogenous protein turnover, and (iv) the production and liberation of endogenous water for the maintenance of water balance. (Gerson and Guglielmo 2011, p. 1434)

This is an interesting case from a paper on the metabolism of migratory birds in conditions of low ambient humidity. Here are four explanations with the same explanandum. Each of the four is expressed in terms of a benefit to the organism, but they work on four different scales: molecular, cellular, organismal, and biomechanical.

1. Explanation: model – kind

   The benefits of minimized energy costs and of increased flight range of the reduction of mass *in a* ***model*** *of the dynamics of the flight* of migratory birds during migration CAN EXPLAIN the use of lean mass in conditions of low ambient humidity in the metabolism of migratory birds during migration.

can explain

The benefits	the use
of minimized energy costs and of increased flight range of the reduction of mass *in a **model*** *of the dynamics* *of the flight*	of lean mass in conditions of low ambient humidity in the metabolism
of migratory birds during migration	of migratory birds during migration.

2. Explanation: model – kind

The requirement of gluconeogenesis and of anaplerosis of Kreb's cycle intermediates *in a **model** of Kreb's cycle in the metabolism of migratory birds during migration* can explain *the occurrence of catabolism of proteins* in the use of lean mass in conditions of low ambient humidity in the metabolism of migratory birds during migration.

can explain

The requirement	*the occurrence*
of gluconeogenesis and of anaplerosis of Kreb's cycle intermediates *in a **model*** *of Kreb's cycle*	*of catabolism* *of proteins* in the use of lean mass in conditions of low ambient humidity
in the metabolism *of migratory birds* *during migration*	in the metabolism of migratory birds during migration.

3. Explanation: theory – kind

The requirement for endogenous turnover of proteins *in the **theory** of protein synthesis and protein degradation in **models** of the metabolism of migratory birds during migration* can explain *the occurrence of catabolism of proteins* in the use of lean mass in conditions of low ambient humidity in the metabolism of migratory birds during migration.

can explain

The requirement	*the occurrence*
for endogenous turnover	*of catabolism*
of proteins	*of proteins*
in the ***theory***	in the use
of protein synthesis and protein degradation	of lean mass
in ***models***	in conditions of low ambient humidity
of the metabolism	in the metabolism
of migratory birds	of migratory birds
during migration	during migration.

4. Explanation: model – kind

The requirement for production and liberation of endogenous water *in a* ***model*** of the maintenance of water balance *in the metabolism of migratory birds during migration* CAN EXPLAIN the use of lean mass in conditions of low ambient humidity in the metabolism of migratory birds during migration.

can explain

The requirement	the use
for production and liberation	of lean mass
of endogenous water	in conditions of low ambient humidity
in a ***model***	
of the maintenance	
of water balance	
in the metabolism	in the metabolism
of migratory birds	of migratory birds
during migration	during migration.

Case A6

> Two broad classes of models have been proposed to explain the patterning of the proximal-distal axis of the vertebrate limb (from the shoulder to the digit tips). ... One, exemplified by the progress zone model, posits that progressive distalization of limb pattern is based on an autonomous clocklike mechanism inherent to the undifferentiated mesenchymal cells. The second postulates that instructive cues from surrounding tissues are responsible for specifying the PD [proximal-distal] segments. (Cooper et al. 2011, p. 1083)

The topic of this paper is the mechanism by which developing vertebrate limbs are organized into their proximate and distal parts. The qualified assertion here is that models from the two classes can explain the phenomenon. These "broad classes of models" are in the middle ground between models and theories. (The first sentence was selected, and the other two included for context.)

1. Explanation: model – kind

   The timing of signals of an autonomous clocklike **mechanism** of undifferentiated mesenchymal cells *during the development of the limbs of vertebrates* is proposed to explain the progression of the distalization of the limb pattern during the development of the limbs of vertebrates.

   is proposed to explain

The timing	the progression
of signals	of the distalization
of an autonomous clocklike **mechanism**	of the limb pattern
of undifferentiated mesenchymal cells	
during the development	during the development
of the limbs	of the limbs
of vertebrates	of vertebrates.

2. Explanation: model – kind

   The spatial diffusion of signals *in a **model*** of communication with surrounding tissues *during the development of the limbs of vertebrates* is proposed to explain the progression of the distalization of the limb pattern during the development of the limbs of vertebrates.

   is proposed to explain

The spatial diffusion	the progression
of signals	of the distalization
*in a **model***	of the limb pattern
of communication with surrounding tissues	
during the development	during the development
of the limbs	of the limbs
of vertebrates	of vertebrates.

Case A7

> As above, the cooperative species responded to C [carbon] rewards with a reciprocal P [phosphorus] increase, whereas the less-cooperative species stored P in the host-inaccessible form of long-chained polyphosphates. Finally, we compared the ratio of C costs to P transferred in both species, confirming that colonization by the less-cooperative species resulted in significantly higher host costs. These results support our whole plant SIP [stable isotope probing] experiments and explain why the plant host consistently allocated more C to the cooperative species when given a choice. (Kiers et al. 2011, p. 882)

The complex relations between plant root systems and symbiotic fungi are the topic of this paper. Here the authors state one of their main conclusions, that a cost-benefit analysis of reciprocal rewards explains the allocation of resources in such systems. (The final sentence was selected and the other two are included for context.)

1. Explanation: model – data

   The reciprocity of rewards *in a **model** of the allocation of resources to symbionts by plant hosts* EXPLAINS the consistently greater size *of the **measurements*** of the allocation of carbon to cooperative species *in a **sample*** of the allocation of carbon to symbionts by plant hosts.

explains

The reciprocity	the consistently greater size
of rewards *in a **model***	*of the **measurements*** of the allocation of carbon to cooperative species *in a **sample***
of the allocation *of resources to symbionts* *by plant hosts*	of the allocation of carbon to symbionts by plant hosts.

Case A8

> Genetic interactions that reduce the benefit of certain regulatory mutations in the eventual losers appear to explain, at least in part, why they were outcompeted. (Khan et al. 2011, p. 1193)

This is the final sentence of the abstract of a paper reporting on second-order selection for greater "evolvability" in a large population of *E. coli.* The authors state their main conclusion that regulatory mutations that reduced second-order "evolvability" were responsible for the loss of that population in a competition. (See also case B21.)

1. Explanation: theory – entity

   The reduction by the interactions of genes of the benefit of certain mutations *in the* ***theory*** of regulatory genes *in* ***models*** of the **losing lineages** of *E. coli* APPEARS TO EXPLAIN, AT LEAST IN PART the failure in the **evolutionary competition** of the **losing lineages** *of E. coli.*

   appears to explain, at least in part

The reduction	the failure
by the interactions	in the **evolutionary competition**
of genes	
of the benefit	
of certain mutations	
in the ***theory***	
of regulatory genes	
in ***models***	
of the **losing lineages**	of the **losing lineages**
of *E. coli*	*of E. coli.*

Case A9

> The exact origin of the size dependence activity is not yet known, and our measurements cannot be explained by the change in coordination number based on the Benfield geometric model. (Tedsree et al. 2011, pp. 226-227)

The authors describe a new technique for measuring adsorption energy when screening for catalysts. Here they block a possible alternative explanation.

1. Explanation: model – data

   Changes of coordination number in the Benfield geometric **model** *of the atomic structure of catalysts* CANNOT EXPLAIN the occurrence of a size dependence effect *in chemical shift* in the **measurements** *of the adsorption energy of a* ***sample*** *of a catalyst.*

	cannot explain
Changes	the occurrence
of coordination number in the Benfield geometric **model** *of the atomic structure*	of a size dependence effect *in chemical shift* in the **measurements** *of the adsorption energy* *of a* ***sample***
of catalysts	*of a catalyst.*

Case A10

> No clear theoretical predictions for a star with parameters similar to those for HIP 13044 exist, hence it is possible that some high-order oscillations can explain the 1.4- or 3.5-day signal. (Setiawan et al. 2010, p. 1643)

This paper reports on the discovery of a large planet around a star based on photometric data. Here the authors try to account for two unexplained signals in their data.

1. Explanation: theory – data

The high-order of oscillations *of luminance in the* ***theory*** *of stellar dynamics in* ***models*** of stars CAN POSSIBLY EXPLAIN the length of the **measurements** of the oscillations *of luminance* of **HIP 13044** *which is a star.*

	can possibly explain
The high-order	the length
of oscillations *of luminance* *in the* ***theory*** *of stellar dynamics* *in* ***models***	of the **measurements** of the oscillations *of luminance* of **HIP 13044**
of stars	*which is a star.*

Case A11

> Averaging this cross-validation from all three subsets, the model explained over 61% of the variance in the abundance of the community members ... (Faith et al. 2011, p. 102)

A mouse model of the microflora in the human gut was investigated across a range of diets. Here the authors claim that their mathematical model of diet can account for 61% of the variance observed in the abundance of species of gut flora.

1. Explanation: model – data

   The diet parameters in a mathematical **model** of the abundance of species of flora *in the guts of mice* EXPLAINED a 61% portion of the variance *in the **measurements*** of the abundance *in **samples*** of species of flora *in the guts of mice.*

explained

The diet parameters	a 61% portion
in a mathematical **model** of the abundance	of the variance *in the **measurements*** of the abundance *in **samples***
of species of flora *in the guts* *of mice*	of species of flora *in the guts* *of mice.*

Case A12

> In summary, changes in water mass formation processes are not necessarily required to explain the high GNAIW [Glacial North Atlantic Intermediate Water] end-member δ^{13}C values. (Olsen and Ninnemann 2010, p. 659)

The authors show how the Industrial Revolution modified δ^{13}C isotope values in the North Atlantic. This accounts for some of the differences between the modern ocean and prehistoric glacial oceans, and so those differences no longer need be explained.

1. Explanation: kind – data

Changes in the processes of formation of water masses ARE NOT NECESSARILY REQUIRED TO EXPLAIN the large size of **measurements** of δ^{13}C in end-members of **GNAIW** *which is a water mass.*

are not necessarily required to explain

Changes	the large size
in the processes of formation	of **measurements** of δ^{13}C in end-members of **GNAIW**
of water masses	*which is a water mass.*

Case A13

> To explain the observed deletion pattern, it was suggested that the Top1-generated ends are processed into a gap corresponding in size to that of the ensuing deletion. (Kim et al. 2011, pp. 1561-1562)

This paper reports on the mechanism of the Top1 topoisomerase in relaxing supercoils of DNA in yeast, and the role this may have in mutation and human disease. The explanation here is of one small part of the mechanism.

1. Explanation: model – kind

The correspondence in size to the ensuing deletion of a gap *in a **model*** of the processing of Top1-generated ends *in the formation of ribonucleoside monophosphates* EXPLAINS the pattern of deletions of base pairs *in the formation of ribonucleoside monophosphates.*

explains

The correspondence	the pattern
in size to the ensuing deletion of a gap *in a **model*** of the processing of Top1-generated ends	of deletions of base pairs
in the formation *of ribonucleoside monophosphates*	*in the formation* *of ribonucleoside monophosphates.*

Case A14

> Monoclonal conversion rules out a simple model of tissue maintenance that originates from a population of long-lived stem cells following a strict pattern of asymmetric division, and can be explained by two classes of behavior. First, crypts could be maintained by a hierarchy in which a single stem cell generates, through a sequence of asymmetric divisions, stem cells with a more limited proliferative potential. Second, tissue could be maintained by an equipotent stem cell population, in which stem cell loss is perfectly compensated by the multiplication of others. (Lopez-Garcia et al. 2010, p. 822)

Intestinal epithelial tissues are maintained by populations of stem cells. This paper discusses the mechanism by which those stem cell populations coordinate. Monoclonal conversion is the eventual complete domination of crypts by cells sharing a single (recent) common ancestor. Here the authors mention three possible models for monoclonal conversion, the first of which they dismiss. (The first sentence was selected and the others included as the referents of “two classes of behavior”.)

1. Explanation: model – kind

   The hierarchy of proliferative potential in a **model** of asymmetric divisions of crypts of stem cells *in the maintenance of epithelial tissue of intestines* CAN EXPLAIN the occurrence of monoclonal conversion in crypts of stem cells *in the maintenance of epithelial tissue of intestines.*

   can explain

The hierarchy	the occurrence
of proliferative potential in a **model** of asymmetric divisions	of monoclonal conversion
of crypts of stem cells *in the maintenance* *of epithelial tissue* *of intestines*	in crypts of stem cells *in the maintenance* *of epithelial tissue* *of intestines.*

2. Explanation: model – kind

The balance of the population in a **model** of perfect compensation in the multiplication of equipotent stem cells by crypts of stem cells *in the maintenance of epithelial tissue of intestines* CAN EXPLAIN *the eventual occurrence* of monoclonal conversion in crypts of stem cells *in the maintenance of epithelial tissue of intestines.*

can explain

The balance	*the eventual occurrence*
of the population	of monoclonal conversion
in a **model**	
of perfect compensation	
in the multiplication	
of equipotent stem cells	
by crypts	in crypts
of stem cells	of stem cells
in the maintenance	*in the maintenance*
of epithelial tissue	*of epithelial tissue*
of intestines	*of intestines.*

Case A15

> Thus, the main sources of CO [carbon monoxide] able to explain our signals are biomass burning and NMHC [nonmethane hydrocarbon] oxidation. (Z. Wang et al. 2010, p. 1663)

The authors used ice core data about atmospheric carbon monoxide to draw conclusions about biomass burning. Here they conclude that only two sources are available to explain their data. (See also case B10.)

1. Explanation: entity – data

Patterns in the generation of CO by burning of biomass *in the atmosphere of the* ***Earth*** CAN EXPLAIN *patterns* in the **measurements** *of ratios of isotopes of CO in* ***samples*** *of the atmosphere of the* ***Earth.***

can explain

Patterns	*patterns*
in the generation	in the **measurements**
of CO	*of ratios*
by burning	*of isotopes*
of biomass	*of CO*
	*in **samples***
in the atmosphere	*of the atmosphere*
*of the **Earth***	*of the **Earth.***

2. Explanation: entity – data

Patterns in the generation of CO by oxidation of nonmethane hydrocarbons *in the atmosphere of the **Earth*** CAN EXPLAIN *patterns* in the **measurements** *of ratios of isotopes of CO in **samples** of the atmosphere of the **Earth.***

can explain

Patterns	*patterns*
in the generation	in the **measurements**
of CO	*of ratios*
by oxidation	*of isotopes*
of nonmethane hydrocarbons	*of CO*
	*in **samples***
in the atmosphere	*of the atmosphere*
*of the **Earth***	*of the **Earth.***

Case A16

> Thus, these results provide direct structural information that explains the previous mutagenesis study, illustrating the power of 2D-IR [two-dimensional infrared spectroscopy] as a structural tool. (Remorino et al. 2011, p. 1209)

The authors applied a new technique to determine the structure of a protein. Here they compare their results to another study. This use of "explain" is beyond the scope of my account.

Failure: justifying a result from a previous study

Case A17

> These compound potentials had nonmonotonic falling phases, explained by an additional indirect inhibitory component … (Papadopoulou et al. 2011, p. 724)

This sentence is from a study of how odour information is encoded in insect brains. The authors propose an additional component of the neural network to explain the behaviour of the observed neurons.

1. Explanation: model – data

   The inhibition by an additional indirect component of GGN neurons *in the* ***model*** *of the network of synapses in the olfactory system of locusts* EXPLAINS the nonmonotonicity *of the* ***measurements*** of the falling phases of the compound potentials *of the* ***specimens*** of GGN neurons *in the network of synapses in the olfactory system of locusts.*

explains

The inhibition	the nonmonotonicity
by an additional indirect component	*of the* ***measurements***
	of the falling phases
of GGN neurons	of the compound potentials
in the ***model***	*of the* ***specimens***
	of GGN neurons
of the network	*in the network*
of synapses	*of synapses*
in the olfactory system	*in the olfactory system*
of locusts	*of locusts.*

Case A18

> In this additional experiment, we show that cognitive load also increases the need for structure and that load-based stereotyping effects may best be explained in terms of changes in structure striving. (Stapel and Lindenberg 2011, p. 253)

In this paper the authors associate behaviours of discrimination and stereotyping with disordered contexts. Note: D. A. Stapel, one of the authors of this paper, has admitted to widespread scientific misconduct. In this dissertation I am primarily concerned with the structure of explanatory claims, not their truth, and so I have decided not to remove this case.

1. Explanation: kind – kind

   Changes in structure striving *in the psychology of humans in disordered contexts* MAY BEST EXPLAIN *occurrence* of load-based stereotyping effects *in the psychology of humans in disordered contexts.*

	may best explain
Changes	*occurrence*
in structure striving	of load-based stereotyping effects
in the psychology *of humans* *in disordered contexts*	*in the psychology* *of humans* *in disordered contexts.*

Case A19

> The differences in MCAs [monocarboxylic acids] among the Tagish Lake specimens may be explained by differing degrees of parent body modification. (Herd et al. 2011, p. 1305)

The Tagish Lake specimens are meteorite fragments that the authors discuss in the context of the origins of life. Here the authors try to account for chemical differences between the specimens in terms of the chemical modifications that the parent asteroid underwent.

1. Explanation: entity – entity

   The differences in the degree of the modification of the **parent body** of the **Tagish Lake specimens** *of meteorites* MAY EXPLAIN the differences in MCAs of the **Tagish Lake specimens** *of meteorites.*

may explain

The differences	the differences
in the degree of the modification of the **parent body**	in MCAs
of the **Tagish Lake specimens** *of meteorites*	of the **Tagish Lake specimens** *of meteorites.*

Case A20

> The apparent plant host and habitat specificity demonstrated by many OTUs [operational taxonomic units, roughly equivalent to species] is not necessarily explained by specificity toward the plant, but may instead reflect an association with other root-associated fungi. (Rosling et al. 2011, p. 879)

In this paper the authors try to find the location of a little known but ubiquitous soil fungus in the fungal tree of life. Here they propose that it is the fungal community and not the plant that explains the specificity observed among root-associated fungi. Here we have two explanations, the first negative and the second positive, but only the first uses the word “explain”.

1. Explanation: kind – kind

   The specificity of the association with the plant itself of root-associated fungi DOES NOT NECESSARILY EXPLAIN the specificity of the association with the plant hosts and habitats of root-associated fungi.

does not necessarily explain

The specificity	the specificity
of the association with the plant itself	of the association with the plant hosts and habitats
of root-associated fungi	of root-associated fungi.

Case A21

> The relative increase in *C. quinquefasciatus* gene number is explained in part by the presence of substantially more expanded gene families, including olfactory and gustatory receptors, immune-related genes, and genes with possible xenobiotic detoxification functions . . . (Bartholomay et al. 2010, p. 87)

This paper reports on the sequencing of the genome of *Culex quinquefasciatus*, the southern house mosquito, which is an important disease vector. The authors found that the genome is substantially larger than other genera of mosquitos, and here they offer an explanation in terms of gene families. There are more genes in this genus than related genera because there are more families of genes in this genus, associated with different groups of functions.

1. Explanation: kind – kind

The relative increase in the number and size of families of genes in *Culex quinquefasciatus* EXPLAINS IN PART the relative increase in the number of genes in *Culex quinquefasciatus.*

explains in part

The relative increase	the relative increase
in the number and size of families	in the number
of genes in *Culex quinquefasciatus*	of genes in *Culex quinquefasciatus.*

Case A22

> Differences in weight loss in response to the tumors were not explained by variable food intake because it was similar in all animals during the initial phase of the experiment and decreased uniformly in all tumor-carrying mice during the final 2 to 4 days. (Das et al. 2011, p. 234)

A mouse model was used to better understand the genetic basis of cachexia, a wasting disease that occurs in human cancer patients. Here the authors block an alternative explanation for weight loss among the mice that would undermine their experimental design.

1. Explanation: entity – entity

Variations in the intake of food *by the **sample*** of tumor-carrying mice DO NOT EXPLAIN the differences in the loss of weight *by the **sample*** of tumor-carrying mice.

do not explain	
Variations	the differences
in the intake of food	in the loss of weight
*by the **sample*** of tumor-carrying mice	*by the **sample*** of tumor-carrying mice.

Case A23

> We found that tonic release of the major inhibitory transmitter, GABA [γ-aminobutyric acid], is due to direct permeation of GABA through the anion channel, Best1, and that this release originates predominantly from glial cells. Our proposed mechanism can account for each of these properties: (i) the nonvesicular nature of tonic GABA release is consistent with a channel-mediated mechanism; (ii) the independence from neuronal activity can be explained by the glial origins of tonic inhibition; and (iii) the apparent lack of dependence on external Ca^{2+} arises from substantial activation of Best1 at resting levels of intracellular Ca^{2+} … (S. Lee et al. 2010, p. 795)

This paper describes the mechanism for the release of the GABA neurotransmitter. Here the authors state the three main explananda that their proposed mechanism can explain. Since "explain" is used only under item (ii), I have included only that explanation in my analysis. (The second sentence was selected, and the first is included for context. See also case C11.)

1. Explanation: model – kind

The origins in glial cells of tonic inhibition in the proposed **mechanism** of GABA/Best1 inhibition of the major inhibitory transmitter GABA CAN EXPLAIN the independence from neural activity of tonic release of the major inhibitory transmitter GABA.

can explain

The origins	the independence
in glial cells	from neural activity
of tonic inhibition	of tonic release
in the proposed **mechanism**	
of GABA/Best1 inhibition	
of the major inhibitory transmitter GABA	of the major inhibitory transmitter GABA.

Case A24

> Precipitation can also explain the rebrightening observed later in some places as different areas drain (by overland flow or infiltration) or dry at different rates. (Turtle et al. 2011, p. 1416)

The Cassini probe has observed rapid and extensive changes on the surface of Saturn's moon Titan. Here the authors propose that methane rainfall explains this data.

1. Explanation: theory – data

   The differences in the rates in draining and drying of fluid *in the* ***theory*** of precipitation *in* ***models*** *on the surface of* ***Titan*** CAN EXPLAIN the differences over time *of the* ***observations*** of the brightness *of the surface of* ***Titan.***

can explain

The differences	the differences over time
in the rates	*of the* ***observations***
in draining and drying	of the brightness
of fluid	
in the ***theory***	
of precipitation	
in ***models***	
on the surface *of* ***Titan***	*of the surface* *of* ***Titan.***

Case A25

> As explained in the SOM [supporting online materials], the limited force available (400 N) and response time of the drive system (inertial effects) make the present setup most suitable for measuring viscosities in the range from 104 to 107 Pa·s. (W. L. Johnson et al. 2011, p. 832)

The authors used novel methods to observe the crystallization of metal alloy glasses. The use of "explained" here is synonymous with "described", and outside the scope of my account of explanation.

Failure: description

A.3 Sample B

Case B1

> Surface-layer Mn, however, showed little if any shift (0.008 ± 0.008 V), again suggesting that such impurities do not respond to TIBB [tip-induced band bending]. (D. H. Lee and J. A. Gupta 2010, p. 1808)

This paper is about manipulation of electromagnetic fields of single atoms in doped semiconductors. TIBB is a change in the semiconductor bands caused by the tip of the scanning tunnelling microscope. I classify TIBB as a theory because it is only one factor in a model of semiconductor band behaviour. Here the authors state that TIBB does not change the magnetic field of Mn atoms, in contrast to Zn atoms where it plays a role. This is a case of negative explanation: lack of one property explains the lack of another property. TIBB is not required to model the semiconductor bands.

1. Evidence: data – theory

   The small size or absence of a shift *in the* ***measurements*** of the voltage of the resonance peaks *in a* ***sample*** of the Mn atoms on the surface layer *of doped semiconductors* SUGGESTS *the lack* of a response *in the* ***theory*** of TIBB *in* ***models*** *of the semiconductor bands* of Mn atoms on the surface-layer *of doped semiconductors.*

suggests

The small size or absence	*the lack*
of a shift	of a response
*in the **measurements***	*in the **theory***
of the voltage	of TIBB
of the resonance peaks	*in **models***
*in a **sample***	*of the semiconductor bands*
of the Mn atoms	of Mn atoms
on the surface layer	on the surface-layer
of doped semiconductors	*of doped semiconductors.*

Case B2

> A Fermi gas of atoms with resonant interactions is predicted to obey universal hydrodynamics, in which the shear viscosity and other transport coefficients are universal functions of the density and temperature. (Cao et al. 2011, p. 58)

The project in this paper is to experimentally test the mathematical model at extreme temperatures. This quotation comes from the first line of the abstract where the authors describe in general terms how the theory of universal hydrodynamics is used to build models of Fermi gases.

1. Explanation: theory – model

Multiple qualities of the universal functions of density and temperature in the **theory** of universal hydrodynamics EXPLAIN *the values* of the shear viscosity and other transport coefficients *in a **model*** of a Fermi gas of atoms with resonant interactions *which is a hydrodynamic system.*

explain

Multiple qualities	*the values*
of the universal functions	of the shear viscosity and other transport coefficients
of density and temperature	
in the **theory**	*in a **model***
	of a Fermi gas
	of atoms with resonant interactions
of universal hydrodynamics	*which is a hydrodynamic system.*

Case B3

> Finally, between the two Arnold tongues ($T_f = 24$ min), the rate of phase drift was even faster and almost uniform because the phases of most oscillators did not lock to the arabinose signal. (Mondragón-Palomino et al. 2011, p. 1317)

The authors measured the response of a large number of synthetic genetic oscillators to a single stimulus (the arabinose signal) and compared them to models of biological oscillators ("biological clocks"). The Arnold tongues are regions in phase space where the natural period of the oscillator and the period of the stimulus match or are resonant and the oscillator is expected to become "entrained" to the stimulus. Here the authors describe the phase drift of the oscillators outside of those regions.

1. Explanation: model – data

   The failure of the phases to lock to the arabinose signal in the Arnold tongues *of the **model** of the entrainment* of biological oscillators EXPLAINS the fast and uniform speed of the rate *in the **measurements*** of the drift of the phase *of the **sample*** of synthetic genetic oscillators *which are biological oscillators.*

explains	
The failure	the fast and uniform speed
of the phases	of the rate
to lock	*in the **measurements***
to the arabinose signal	of the drift
in the Arnold tongues	of the phase
*of the **model***	*of the **sample***
of the entrainment	of synthetic genetic oscillators
of biological oscillators	*which are biological oscillators.*

Case B4

> The fit to P_2 [a degree-2 Legendre polynomial] is excellent in all cases (correlation coefficient $R^2 > 0.93$), and two additional observations allow us to confirm that the terrain is indeed described by P_2. (Garrick-Bethell, Nimmo, and Wieczorek 2010, p. 949)

The farside highlands of the Moon have a distinct topology and crust structure for which the authors propose a mathematical model. The mathematical model is a good fit with the data and allows prediction of the terrain shape.

1. Evidence: entity – model

   The high quality of the fit of the P_2 polynomial *to the shape of the terrain of the farside highlands of the* ***Moon*** ALLOWS US TO CONFIRM THAT *the shape* of the P_2 polynomial *is a* ***model*** *of the shape of the terrain of the farside highlands of the* ***Moon.***

allows us to confirm that	
The high quality	*the shape*
of the fit of the P_2 polynomial	of the P_2 polynomial *is a* ***model***
to the shape *of the terrain* *of the farside highlands* *of the* ***Moon***	*of the shape* *of the terrain* *of the farside highlands* *of the* ***Moon.***

Case B5

> Pollen data from Erazo reveal two major types of vegetation association.
> (Cárdenas et al. 2011, p. 1055)

Ecological responses to prehistoric climate change are explored here using pollen samples. Differences in the pollen found at different strata are evidence that the region around Erazo changed from grassland to forest and back to grassland. Conversely, the association of grassland species and forest species explain (in part) the stratification of pollen.

1. Evidence: data – theory

   The stratification of the pollen in the **observations** *of the* ***samples*** *of soil* from **Erazo** REVEAL *a division* of two major types *in the* ***theory*** of associations *in* ***models*** of the vegetation *in* ***Erazo.***

reveal

The stratification	*a division*
of the pollen	of two major types
in the **observations**	*in the **theory***
*of the **samples***	of associations
of soil	*in **models***
	of the vegetation
from **Erazo**	*in **Erazo.***

Case B6

> Taken together, our data suggest that CR8020 [a human monoclonal antibody] blocks fusion by sequestering the fusion peptide and preventing its release at low pH. (Ekiert et al. 2011, p. 849)

CR8020 is a human antibody that acts against group 2 influenza viruses. Here the authors propose a mechanism by which the antibody may disable the virus. (See also cases B32 and B44 from the same paper.)

1. Evidence: kind – model

   Multiple qualities of the blocking of fusion by CR8020 SUGGEST the sequestering and prevention of release at low pH of fusion peptide *in a **model** of the activity* of CR8020.

suggest

Multiple qualities	the sequestering and prevention of release at low pH
of the blocking	of fusion peptide
of fusion	*in a **model***
	of the activity
by CR8020	of CR8020.

Case B7

> Understanding how comets work – what drives their activity – is crucial to the use of comets in studying the early solar system. (A'Hearn et al. 2011, p. 1396)

This is the first sentence of the abstract of a paper describing robotic probe observations of comet 103P/Hartley 2. The authors are perhaps explaining their motivation, but not anything about comets.

Failure: motivation

Case B8

> Using an automated detection code, we found 2434 RBEs [rapid blueshifted events] occurring in the active-region plage footpoints of coronal loops during a 1-hour-long time series on 25 April 2010. (De Pontieu et al. 2011, p. 55)

Computers were used to detect movements of hot plasma in the solar corona. Here the authors describe their method and results, but do not explain them. (See also case C15.)

Failure: method and results

Case B9

> In nectin-3 KO [gene knock-out] mice, two or three hair cells aberrantly attached to each other, as revealed by staining for F-actin and the tight-junction marker ZO-1. (Togashi et al. 2011, p. 1145)

The paper examines the function of nectin-1 and -3 molecules using a gene knock-out method. Here the authors describe a phenotype with aberrant hair cell attachment in the auditory epithelia (inner-ear skin), implying (but not stating) that one function of nectin-3 is attachment of hair cells. What we do have is data about a number of hair cells, where a property of the cells explains features of the data.

1. Evidence: data – entity

   Multiple qualities of ***observations*** from staining for F-actin and the tight-junction marker ZO-1 *of* ***samples*** *from nectin-3 KO mice* REVEAL the abberant attachment of hair cells *in a* ***sample*** of nectin-3 KO mice.

reveal

Multiple qualities	the abberant attachment
of ***observations*** from staining for F-actin and the tight-junction marker ZO-1	of hair cells
of ***samples*** *from nectin-3 KO mice*	*in a* ***sample*** of nectin-3 KO mice.

Case B10

> This is contrary to the observations. (Z. Wang et al. 2010, p. 1664)

The authors use ice core data about atmospheric carbon monoxide to draw conclusions about biomass burning. With this statement they block appeal to an alternative source for the CO other than burning. (See also case A15.)

Failure: statement

Case B11

> Although the concordant effects of prior manipulations and therapies on canonical and noncanonical TGFβ [transforming growth factor-β] signaling made it impossible to dissect their relative contributions, the differential effects of enalapril treatment suggest that TGFβ-mediated ERK1/2 [extracellular signal-regulated kinase] activation is the predominant driver of aneurysm progression in MFS [Marfan syndrome]. (Habashi et al. 2011, p. 364)

Marfan syndrome is a genetic disease that weakens connective tissue, especially in heart muscles. Using a mouse model of MFS the authors tested the effects of TGFβ for preventing aneurysms in the aorta and propose a mechanism for its operation. The proposed mechanism explains the data collected.

1. Evidence: data – model

   The differential effects *in the* ***observations*** of enalapril treatment *in the* ***sample*** *of mice with Marfan syndrome* SUGGEST the predominance *the* ***mechanism*** of the mediation by TGFβ of the activation of ERK1/2 in the progression of aneurysms *in organisms* with Marfan syndrome.

	suggest
The differential effects	the predominance
*in the **observations*** of enalapril treatment *in the **sample*** *of mice*	*the **mechanism*** of the mediation by TGFβ of the activation of ERK1/2 in the progression of aneurysms *in organisms*
with Marfan syndrome	with Marfan syndrome.

Case B12

> Notably, the solid-state structure of guanidinium nitrate is isomorphous with the hexagonal guanidinium-sulfonate network, and the separation between guanidinium hydrogen bond donors along each edge of a hexagonal $[\mathrm{G_3NO_3}]^{2+}$ unit ($d_{\mathrm{G...G}} \sim 7.5$Å) is comparable to the distance between sulfonate hydrogen bond acceptors on each edge of the HSPB^{6-} (the average distance between substituents on neighboring phenyl rings of 39 derivatives of hexaphenylbenzene suggests that $d_{\mathrm{S...S}} \sim 7.5$Å...). (Liu et al. 2011, p. 437)

In this paper the authors describe a technique for reliably building nano-structure “cages”. In this sentence they describe and compare the structure of several molecules.

Failure: description

Case B13

> Seismic analysis of the Sun has already shown that merely reproducing the luminosity and temperature of a star will not guarantee that the internal structure, and hence the underlying physics, is correct. This inspired the inclusion of additional physics, such as the settling over time of chemical elements because of gravity, in stellar models. (Chaplin et al. 2011, p. 215)

Data from the NASA Kepler mission about stellar masses, radii, and ages undermine predictions of stellar evolution. Here the authors mention the history of increasing complexity in stellar models. This is an interesting and unusual case. The earlier and later seismic analyses of the Sun are particular historical events that fall under my "entity" classification. So here we have a singular causal claim about one thing leading to another. (See also case B93.)

1. Explanation: entity – entity

   The failure *of* ***previous analyses*** to capture internal structure and physics with simpler stellar **models** of the luminosity and temperature of the **Sun** INSPIRED the inclusion *in* ***later analyses*** of additional physics in more complex stellar **models** *of the* ***Sun.***

   inspired

The failure	the inclusion
of ***previous analyses*** to capture internal structure and physics with simpler stellar **models** of the luminosity and temperature	*in* ***later analyses*** of additional physics in more complex stellar **models**
of the **Sun**	*of the* ***Sun.***

Case B14

> When male and female gene expression profiles were analyzed separately, the strain effect on males accounted for the differential expression of 1172 genes (9.3%), whereas only 7 genes (∼0.06%) were significant for the strain effect on female gene expression. (Innocenti, Morrow, and Dowling 2011, p. 846)

Mitochondria are organelles in eukaryotic cells that are transmitted from mother to child along with other cellular material. Mitochondria have their own genomes. This paper uses a fruit-fly model to show that maternal transmission creates a strong sex-specific selective pressure, allowing the accumulation of deleterious male-specific mutations in the mitochondrial genome. This sentence summarizes one of the main experimental results: the effect of the strain of mitochondria on the expression of genes in the nucleus of the cell is much greater in males. (See also case C1.)

1. Explanation: kind – entity

The sex-selectivity of the effect of the strain *of mitochondria* on the expression of genes in fruit-flies ACCOUNTS FOR the differential expression of 1172 genes in males *in a **sample** of fruit-flies.*

accounts for

The sex-selectivity	the differential expression
of the effect of the strain *of mitochondria* on the expression of genes	of 1172 genes in males *in a **sample***
in fruit-flies	*of fruit-flies.*

Case B15

> Moreover, 30 μM of ruthenium red and gadolinium, which are known blockers of many cationic MA [mechanically activated] currents, blocked $74.6 \pm 2.5\%$ ($n = 6$ cells) and $84.3 \pm 3.8\%$ ($n = 5$ cells) of Piezo1-induced MA current, respectively. (Coste et al. 2010, p. 58)

In this paper the authors establish the importance of Piezo1 genes for mechanically activated cation channels, required for neural cells that detect touch and pain. Here we have a causal claim that some amount of ruthenium red and gadolinium blocked some portion of these particular MA currents. (See also case B87.)

1. Explanation: entity – data

The amount (30 μM) of ruthenium red and gadolinium *in the **sample** of neural cells* CAUSED the blocking of the portion of the **measurements** of Piezo1-induced MA currents *in the **sample** of neural cells.*

caused

The amount (30 μM)	the blocking
of ruthenium red and gadolinium	of the portion of the **measurements** of Piezo1-induced MA currents
*in the **sample*** *of neural cells*	*in the **sample*** *of neural cells.*

Case B16

> Ectopic expression of wild-type TDG [thymine-DNA glycosylase] diminished the amount of 5caC [5-carboxylcytosine] generated by cotransfected Tet2 [ten eleven translocation dioxyegnase 2] but did not significantly reduce 5hmC [5-hydroxymethylcytosine]. (He et al. 2011, p. 1306)

The availability of portions of DNA for transcription is controlled in part by its methylation, i.e. the presence of a methyl group at the site. 5caC and 5hmC are molecules that result from demethylation, which the Tet proteins may cause. In this sentence the authors assert that TDG in Tet2 acts on 5caC but not on 5hmC.

1. Explanation: entity – data

   The ectopic expression of wild-type TDG *in the **sample** of cells* CAUSED the reduction *in the **measurements*** of the amount of 5caC generated by cotransfected Tet2 *in the **sample** of cells.*

   caused

The ectopic expression	the reduction
of wild-type TDG	*in the **measurements*** of the amount of 5caC generated by cotransfected Tet2
*in the **sample*** *of cells*	*in the **sample*** *of cells.*

2. Explanation: entity – data

   The ectopic expression of wild-type TDG *in the **sample** of cells* DID NOT CAUSE the lack of a significant reduction *in the **measurements*** in the amount of 5hmC generated by cotransfected Tet2 *in the **sample** of cells.*

did not cause

The ectopic expression	the lack
of wild-type TDG	of a significant reduction *in the **measurements*** in the amount of 5hmC generated by cotransfected Tet2
*in the **sample*** *of cells*	*in the **sample*** *of cells.*

Case B17

> Buttermilk Creek Complex biface technology includes three trajectories – preform, chopper/adze, and discoidal core production. (Waters et al. 2011, p. 1601)

The Buttermilk Creek Complex is a collection of archaeological artifacts collected in Texas and dating to between 13 and 15.5 thousand years ago. This sentence states a distinction between three "trajectories" in the production of stone tool artifacts. Although classification systems can play a role in explanation, there is no explicit explanation here.

Failure: statement of classification

Case B18

> A puckered $D_{2\mathrm{d}}$ structure and its valence isomer, tetrasilatetrahedrane, were calculated to be local energy minima; a planar rectangular $D_{2\mathrm{h}}$ structure with two Si=Si double bonds and a planar rhombic $C_{2\mathrm{h}}$ structure emerged as saddle point structures. (Suzuki et al. 2011, p. 1307)

This paper describes the peculiar structure of cyclobutadiene (C_4H_4) molecules. This sentence is part of the description of a molecule with related structure called tetrasilacyclobutadiene (SiH_4).

Failure: description, prediction

Case B19

> We estimate that the actual genome size is ∼120 Mb, corresponding to 140-fold coverage of the *Blumeria* genome. (Spanu et al. 2010, p. 1543)

Blumeria is a family of powdery mildews distinguished by their extreme parasitism. The authors sequenced the *Blumeria* genome and discuss how extreme parasitism has affected genome size and gene loss. Here they provide their estimate of the actual genome size based on their sequencing methods.

Failure: calculation, estimate

Case B20

> In a second approach, we analyzed the phylogenies of genes known to function in *Arabidopsis* development. (Banks et al. 2011, p. 962)

This paper reports on the sequencing of the genome of *Selaginella moellendorffii*, a nonseed vascular plant, and compares its evolution to other lineages. In this sentence the authors describe one of their methods. (See also case B31.)

Failure: method

Case B21

> Because changes in chromosomal supercoiling also may have widespread pleiotropic effects, it seemed likely that interactions with the *topA* alleles specific to the EW [eventual winners] and EL [eventual losers] backgrounds might explain these epistatic effects. (Khan et al. 2011, p. 1435)

The authors studied second-order selection for greater "evolvability" in a large population of *E. coli*. One of the significant differences observed was the *topA* allele, which alters chromosomal supercoiling, and which in turn changes the transcription of many genes. Another was that the *spotT* allele confers a large fitness benefit to the EW group but not the EL group. In this sentence the authors propose the hypothesis that an interaction of *topA* and *spoT* explains the fitness benefit of *spoT*. (This sample B quotation happens to include the word "explain". See also case A8.)

1. Evidence: theory – theory

   The breadth of pleiotropic effects *in the **theory*** of supercoiling of chromosomes *in the transcription of genes* SUGGESTS *the possibility* of epigenetic interactions *in the **theory** of the interactions* of *topA* and *spoT* alleles *on the transcription of genes.*

suggests

The breadth	*the possibility*
of pleiotropic effects	of epigenetic interactions
*in the **theory***	*in the **theory***
of supercoiling	*of the interactions*
of chromosomes	of *topA* and *spoT* alleles
in the transcription	*on the transcription*
of genes	*of genes.*

2. Explanation: theory – entity

   The possibility of epigenetic interactions *in the **theory** of the interactions* of *topA* and *spoT* alleles *on the transcription of genes in **models** of the evolution of populations* MIGHT EXPLAIN *the differences the fitness benefit* of the *spoT* allele *in **EW and EL** which are populations.*

might explain

The possibility	*the differences*
of epigenetic interactions	*the fitness benefit*
*in the **theory***	of the *spoT* allele
of the interactions	*in **EW and EL***
of *topA* and *spoT* alleles	
on the transcription	
of genes	
*in **models***	
of the evolution	
of populations	*which are populations.*

Case B22

> An alternative way of viewing these comparisons would be in terms of the total quantities of occupation material generated per 1000-year interval in each demographic period, for which an appropriate mathematical formula would involve the total numbers of recorded sites, multiplied by the average densities of occupation residues documented in the sites, multiplied by the average recorded areas of the occupation deposits in the sites. (Mellars and French 2011, p. 626)

The authors describe a tenfold increase in modern human populations of Western Europe circa 40 000 years ago, and propose that simple numerical supremacy may explain the replacement of Neandertals by modern humans. Here they say how they built one of their mathematical models for comparing populations over time. The sense of "explain" that might apply here is synonymous with "describe in detail", and that is not the sense I am concerned with in this dissertation.

Failure: model building

Case B23

> Cryo-electron microscopy (cryo-EM) images of these crystals revealed notable ring-shaped (or, less likely, spiral-shaped) assemblies. (van Breugel et al. 2011, p. 1198)

Using x-ray microscopy methods the authors determined the structure of the SAS-6 protein, which forms the centriole structure required to build cilia and flagella. Circular patterns in the cryo-electron microscopy images *reveal* rings or spirals, and conversely the ring or spiral structure *explains* the patterns in the images.

1. Evidence: data – kind

   The circularity of the patterns in the cryo-electron microscopy **images** of the crystals *of the SAS-6 protein* REVEAL the ring- or spiral-shapes of the assemblies of the oligomers *of the SAS-6 protein.*

reveal

The circularity	the ring- or spiral-shapes
of the patterns in the cryo-electron microscopy **images** of the crystals	of the assemblies of the oligomers
of the SAS-6 protein	*of the SAS-6 protein.*

Case B24

> Instead, the monkey received a reward for directing a saccade to the search target (an oriented bar) if it was present at any location, or for maintaining fixation if no target was present. (Schafer and Moore 2011, p. 1570)

The topic of this paper is voluntary attention, studied in a portion of rhesus monkey prefrontal cortex that is associated with eye-muscle control. Here the authors describe part of one of their experimental methods.

Failure: method

Case B25

> Histological and quantitative analysis of whole ankle joints demonstrated a significant increase in synovitis, pannus formation, and destruction of bone and cartilage in *Grn*$^{-/-}$ [gene knock-out] mice, compared with controls. (Tang et al. 2011, p. 479)

A mouse model of arthritis was used to study the effects of the growth factor progranulin (PGRN). The experimental group of mice was genetically modified to knockout the *Grn* gene and make the mice PGRN deficient. Here we have a statement that the histological and quantitative analysis demonstrated various increases in symptoms of arthritis. The implication is that PGRN deficiency explains these effects, but that is not stated here.

1. Evidence: data – entity

   Multiple properties of the ***observations*** in the histological and quantitative analysis of the whole ankle joints *of the* ***specimens*** *of Grn*$^{-/-}$ *mice* DEMON-

STRATE a significant increase compared to controls in synovitis in the whole ankle joints *of the **specimens** of Grn*$^{-/-}$ *mice.*

demonstrate

Multiple properties	a significant increase compared to controls
*of the **observations*** in the histological and quantitative analysis of the whole ankle joints	in synovitis in the whole ankle joints
*of the **specimens*** *of Grn*$^{-/-}$ *mice*	*of the **specimens*** *of Grn*$^{-/-}$ *mice.*

2. Evidence: data – entity

*Multiple properties of the **observations*** in the histological and quantitative analysis of the whole ankle joints *of the **specimens** of Grn*$^{-/-}$ *mice* DEMONSTRATE a significant increase compared to controls in the formation of pannus in the whole ankle joints *of the **specimens** of Grn*$^{-/-}$ *mice.*

demonstrate

Multiple properties	a significant increase compared to controls
*of the **observations*** in the histological and quantitative analysis of the whole ankle joints	in the formation of pannus in the whole ankle joints
*of the **specimens*** *of Grn*$^{-/-}$ *mice*	*of the **specimens*** *of Grn*$^{-/-}$ *mice.*

3. Evidence: data – entity

*Multiple properties of the **observations*** in the histological and quantitative analysis of the whole ankle joints *of the **specimens** of Grn*$^{-/-}$ *mice* DEMONSTRATE a significant increase compared to controls in the destruction of bone and cartilage in the whole ankle joints *of the **specimens** of Grn*$^{-/-}$ *mice.*

demonstrate

Multiple properties	a significant increase compared to controls
of the ***observations*** in the histological and quantitative analysis of the whole ankle joints	in the destruction of bone and cartilage in the whole ankle joints
of the ***specimens*** *of* $Grn^{-/-}$ *mice*	*of the* ***specimens*** *of* $Grn^{-/-}$ *mice.*

Case B26

> Further characteristics of P_B mobilization in vivo are shown in fig. S4. (Rad et al. 2010, p. 1106)

This sentence is case of “shown” in reference to a figure, and is not an explanation.

Failure: reference to figure

Case B27

> Furthermore, the deuterium effect documented for C_3H_6 in the small-scale V nitrogenase reaction was duplicated for α-C_4H_8 and n-C_4H_{10} in the scaled-up Mo nitrogenase reaction. (Hu, C. C. Lee, and Ribbe 2011, p. 1106)

The topic of the paper is the building of hydrocarbons out of carbon monoxide using various biological catalysts. Here the authors state that they duplicated one of their results at larger scale.

Failure: duplication of results

Case B28

> These experiments, which revealed no substantial change in the compound I decay rate, suggested that CYP119-I could be prepared at millimolar concentrations by use of freeze-quench techniques. (Rittle and Green 2010, p. 934)

This paper discusses the pharmaco-kinetics of cytochrome P450 enzymes. Here the authors describe part of the process by which their methods were developed.

Failure: method development

Case B29

> *Clostridia* became prominent after weaning and persisted in the adult animals, in contrast to *Lactobacillus* or *Enterobacteriaceae*, which were more abundant during the neonatal period and declined thereafter. (Atarashi et al. 2011, p. 339)

Here the authors describe the progression of populations of bacteria in their experiments on microfauna in the colons of mice.

Failure: description

Case B30

> Cells with visible YFP [yellow fluorescent protein] expression had >70% reduced $Ca_V1.2$-mediated Sr^{2+} [strontium] entry, and almost all mutant STIM1 was within clearly discernible junctions. (Y. Wang et al. 2010, p. 108)

This paper describes the STIM proteins that detect and regulate calcium within cells. This sentence describes the association observed between mutant STIM1 proteins and reduced activity in voltage operated calcium channels. The explanation that mutant STIM1 reduces $Ca_V1.2$-mediated Sr^{2+} entry is implied here but not stated. (See also case B81.)

Failure: description

Case B31

> The 27 vascular plant-specific orthologous groups likely represent genes associated with developmental innovations of vascular plants. (Banks et al. 2011, p. 962)

This paper reports on the sequencing of the genome of *Selaginella moellendorffii*, a nonseed vascular plant, and compares its evolution to other lineages. The authors show that families of vascular and non-vascular land-plants share a large number of genes. Here they speculate that the differences between vascular land-plant groups lie mainly in the genes that regulate development. (See also case B20.)

1. Evidence: kind – kind

   The occurrence of orthologous groups of specific genes of vascularity in plants LIKELY REPRESENTS *the occurrence* of associations of genes for innovations in the development of vascularity in plants.

likely represents *The occurrence*	 *the occurrence*
of orthologous groups of specific genes	of associations of genes for innovations in the development
of vascularity in plants	of vascularity in plants.

Case B32

> Prophylaxis using 3 mg/kg CR8020 protected mice against challenge with a high, lethal dose of either mouse-adapted H3N2 or H7N7 virus. (Ekiert et al. 2011, p. 845)

CR8020 is a human antibody that acts against group 2 influenza viruses. Here the authors state the causal capacity of CR8020 to block against influenza in mice. (See also cases B6 and B44 from the same paper.)

1. Explanation: entity – entity

   The use of prophylaxis with 3 mg/kg of CR8020 *on the* ***sample*** of mice CAUSED the protection against challenge with a high, lethal dose of mouse-adapted H3N2 or H7N7 virus *in the* ***sample*** of mice.

caused

The use	the protection
of prophylaxis with 3 mg/kg of CR8020	against challenge with a high, lethal dose of mouse-adapted H3N2 or H7N7 virus
*on the **sample*** of mice	*in the **sample*** of mice.

Case B33

> At 25°C the majority (66%) of spindles in *tub4-S360D* large-budded mitotic cells had not extended past metaphase length [$\sim$1.5 μm], whereas WT [wild type] cells (91%) had normal elongated anaphase spindles [6 to 10 μm]. (Keck et al. 2011, p. 1561)

This paper discusses the structure of the yeast centrosome, a cellular structure critical for mitosis. Here they contrast the mitotic spindles in *tub4-S360D* genetic variations with wild-type yeast. Emphasizing *tub4-S360D* as the difference-maker implies a causal explanation for the differences, but no explanation is stated in this sentence.

Failure: statement of correlation, only implying an explanation

Case B34

> Specifically, we simulated the coupled perturbations of increased N_2O abundance, leading to stratospheric ozone (O_3) depletion, altered solar ultraviolet radiation, altered stratosphere-to-troposphere O_3 flux, increased tropospheric hydroxyl radical concentration, and finally lower concentrations of CH_4. (Prather and Hsu 2010, p. 952)

This quotation is from the abstract of a simulation study on the relation between nitrous oxide (N_2O) and methane (CH_4) as greenhouse gases. The authors provide a telegraphic list of a sequence of factors in their model, ultimately linking increased N_2O to reduced CH_4.

1. Explanation: model – model

> The increase in abundance of N_2O *in the **model** of the gases in the stratosphere and troposphere* EXPLAINS the decrease in concentrations of CH_4 *in the **model** of the gases in the stratosphere and troposphere.*

explains

The increase	the decrease
in abundance of N_2O	in concentrations of CH_4
*in the **model*** *of the gases* *in the stratosphere and troposphere*	*in the **model*** *of the gases* *in the stratosphere and troposphere.*

Case B35

> Our study indicates that fire ants have been introduced on no fewer than nine separate occasions to California, Asia, and Australia from the southern United States, where *S. invicta* populations previously were confined for decades. (Ascunce et al. 2011, p. 1068)

Solenopsis invicta – the fire ant – is an invasive species originally from South America. The authors of this paper use genetics to trace the global history of invasions. Here they restate their conclusion. One could read “indicates” to mean that the *study* explains the conclusions, but that usage falls outside my model of explanation.

Failure: statement of conclusion

Case B36

> An alternative view, however, suggests that memory loss after brain damage may be better understood, not in terms of loss of a system dedicated to a specific type of memory – for example, long- versus short-term memory, or memory processes such as encoding, storage/consolidation, or retrieval – but in terms of the stimulus representations that the different regions contain. (McTighe et al. 2010, p. 1409)

This quotation comes from a study of object recognition after brain damage in rats. Here the authors propose a new approach that better accounts for their data than the received view in the field. Their proposal falls short of a model, but highlights a new theoretical factor.

1. Explanation: theory – kind

The differences in the representations of stimuli among regions *in the **theory*** of the brain *in **models*** of the loss of memory after brain damage MAY EXPLAIN the differences in the loss of memory after brain damage.

may explain	
The differences	the differences
in the representations	
of stimuli	
among regions	
*in the **theory***	
of the brain	
*in **models***	
of the loss	in the loss
of memory	of memory
after brain damage	after brain damage.

2. Explanation: theory – kind

The loss of a dedicated system for a specific type of memory *in the **theory*** of the brain *in **models*** of the loss of memory after brain damage MAY NOT EXPLAIN the differences in the loss of memory after brain damage.

may not explain	
The loss	the differences
of a dedicated system	
for a specific type	
of memory	
*in the **theory***	
of the brain	
*in **models***	
of the loss	in the loss
of memory	of memory
after brain damage	after brain damage.

Case B37

> Taken together, the total surface area buried between Ffh [a protein] and the 4.5S RNA is 780 Å^2, which is similar to the extent of interaction between FtsY and the distal portion of the 4.5S RNA. (Ataide et al. 2011, p. 882)

This paper describes the 3D structure of the signal recognition particle ribonucleoprotein complex together with it signal receptor. This quotation contains a comparison of the size of two structures.

Failure: comparison, description

Case B38

> Alternatively, thermal metamorphism of subsurface organic-rich strata, associated with sill intrusions and flood basalt emplacement, was proposed as a major source of ^{13}C-depleted thermogenic methane to the end-Permian, Rhaetian, Toarcian, and Eocene atmosphere. (Ruhl et al. 2011, p. 431)

The authors used carbon isotope measurements as evidence that intensive volcanism caused major carbon-cycle disruptions at the end of the Triassic period, and in turn the end-Triassic mass extinction. Here they present one proposed mechanism as part of the explanation.

1. Explanation: entity – entity

> *The occurrence* of thermal morphism of subsurface organic-rich strata *of the **Earth** in the end-Permian, Rhaetian, Toarcian, and Eocene eras* WAS PROPOSED TO EXPLAIN *the presence* of the majority of ^{13}C-depleted thermogenic methane in the atmosphere *of the **Earth*** in the end-Permian, Rhaetian, Toarcian, and Eocene eras.

was proposed to explain

The occurrence	*the presence*
of thermal morphism	of the majority
of subsurface organic-rich strata	of ^{13}C-depleted thermogenic methane
	in the atmosphere
of the ***Earth***	*of the* ***Earth***
in the end-Permian, Rhaetian, Toarcian, and Eocene eras	in the end-Permian, Rhaetian, Toarcian, and Eocene eras.

Case B39

> Hair offers a suitable experimental model because hair follicles (HFs) cycle through phases of growth (anagen) and rest (telogen). (Plikus et al. 2011, p. 586)

The topic of this paper is coordination in stem cell populations, and the empirical test case is hair follicle stem cells. Here the authors are justifying their choice of test case.

1. Explanation: theory – model

The occurrence of cycles of phases of growth (anagen) and rest (telogen) *in the* ***theory*** of hair follicles *which are stem cells* EXPLAINS The suitability of hair as the experimental **model** *for stem cells.*

explains

The occurrence	The suitability
of cycles	of hair
of phases	as the experimental **model**
of growth (anagen) and rest (telogen)	
in the ***theory***	
of hair follicles	
which are stem cells	*for stem cells.*

Case B40

> Formate in the periplasm can still cross the membrane to reach a vestibule that is sealed off from the cytoplasm only by the N-terminal helix. (W. Lü et al. 2011, p. 354)

This paper describes the molecular structure of the FocA formate channel in *Salmonella typhimurium*. Here the authors state a causal capacity of formate but nothing is being explained.

Failure: statement of causal capacity

Case B41

> Using this technique, we have created imbalanced systems with fidelities similar to those in the balanced case. (Serwane et al. 2011, p. 337)

The authors describe a method for highly-controlled preparation and manipulation of physical systems consisting of a small number of fermions [e.g. electrons, protons, and neutrons]. Here they state a special capability of their technique.

Failure: statement of a technical capability

Case B42

> The evidence from *Darwinopterus* supports this hypothesis [about sexual dimorphism in pterosaurs]. (J. Lü et al. 2011, p. 323)

The authors use evidence from new fossil finds to draw conclusions about the sexual dimorphism, egg structure, and reproductive behaviour of a species of pterosaur. Here they state that their evidence from *Darwinopterus* supports broader hypotheses about sexual dimorphism in pterosaurs. Conversely, we can infer that sexual dimorphism in pterosaurs generally explains sexual dimorphism in this species specifically.

1. Evidence: kind – kind

   The occurrence of a large female pelvis and large male crests in *Darwinopterus* which is a pterosaur SUPPORTS *the occurrence* of a large female pelvis and large male crests in pterosaurs.

supports	
The occurrence	*the occurrence*
of a large female pelvis and large male crests in *Darwinopterus*	of a large female pelvis and large male crests
which is a pterosaur	in pterosaurs.

Case B43

> We simulated the cross correlation result using Eq. 1 [omitted] where a_0 is the amplitude of $E_{\mathrm{I}}(t)$, and b_n, ϕ_{bn}, and ϕ_{ceb} are the amplitudes and the relative phases of the nth component and the CEP of $E_{\mathrm{b}}(t)$. (Chan et al. 2011, p. 1167)

The authors present techniques for fine control of light fields. Here they explain the meaning of variables in an equation used for modelling cross correlation. The sense of "explain" in "explain the meaning" is similar to "define" and outside the scope of my account of explanation.

Failure: description of a model

Case B44

> Crystal structures of CR6261 in complex with H1 and H5 HAs [hemagglutinin] revealed a highly conserved epitope in the HA stalk. (Ekiert et al. 2011, p. 844)

CR8020 is a human antibody that acts against group 2 influenza viruses. Here the authors refer to previous work in which they described how the CR6261 antibody binds to hemagglutinin (the major glycoprotein in the envelopes of influenza A viruses, which most antibodies target) in H1 and H5 families of influenza. Although the phrasing here is evidential, we can infer the converse explanatory relation: the highly conserved epitope explains the crystal structures. (See also cases B6 and B32 from the same paper.)

1. Evidence: entity – kind

The structures of the crystals *of the* ***samples*** of CR6261 in complex with H1 and H5 HAs *which are HAs* REVEALED *the occurrence* of a highly conserved epitope in the stalk of HAs.

revealed

The structures	*the occurrence*
of the crystals	of a highly conserved epitope
of the ***samples***	in the stalk
of CR6261	
in complex	
with H1 and H5 HAs	
which are HAs	of HAs.

Case B45

> In his seminal paper, Alan Turing aimed to provide a mechanism for self-regulated pattern formation in biology by showing that sets of reaction-diffusion equations with appropriate kinetics and diffusion coefficients could spontaneously evolve to spatially periodic structures. (Bánsági, Vanag, and Epstein 2011, p. 1309)

This paper describes 3D structures in liquid systems in terms of patterns first described mathematically by Alan Turing. In this first sentence of the paper the authors refer to a class of mathematical models of spatially periodic structures that Turing first proposed.

1. Explanation: model – kind

The appropriate choices of kinetics and diffusion coefficients for sets of reaction-diffusion equations *in* ***models*** *of the structure of biological systems* EXPLAIN *the possibility* of the spatial periodicity of the structures of biological systems.

explain

The appropriate choices	*the possibility*
of kinetics and diffusion coefficients	of the spatial periodicity
for sets	
of reaction-diffusion equations	
in ***models***	
of the structure	of the structures
of biological systems	of biological systems.

Case B46

> A recording with a narrower-resolution bandwidth in the low-frequency region is shown in the inset of Fig. 3B, illustrating a detection limit of $20p\epsilon_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$ and $10p\epsilon_{\mathrm{rms}}/\sqrt{\mathrm{Hz}}$ at 50 mHz and 200 mHz, respectively. (Gagliardi et al. 2010, p. 1083)

This paper describes advances in fibre-optic strain sensors. Here we have a description of some of the contents of a figure.

Failure: description of figure

Case B47

> Regardless, it is clear that Ir[iridium]-depleted metals are present in the returned Itokawa samples. (Ebihara et al. 2011, p. 1121)

This paper reports on a chemical analysis of a sample from the asteroid Itokawa. After considering whether the iridium they detected was internal or external to grains in the sample, they reassert that iridium was present in the sample.

Failure: assertion about data

Case B48

> Most researchers conclude that the 3.6-million-year-old footprints in the Upper Laetolil Beds at Laetoli, Tanzania, evince a medial longitudinal arch. (Ward, Kimbel, and Johanson 2011, p. 752)

The authors present a bone from the foot of an *Australopithecus afarensis* and discuss its structure in the context of the evolution of bipedalism. Here they refer to a set of preserved footprints and state the consensus view that they were made by a foot that had a medial longitudinal arch.

1. Evidence: entity – kind

   The shapes of the prints *of a* ***specimen*** of the feet *of an Australopithecus afarensis* EVINCE *the occurrence* of a medial longitudinal arch in the feet *of Australopithecus afarensis.*

evince	
The shapes	*the occurrence*
of the prints *of a **specimen***	of a medial longitudinal arch
of the feet *of an Australopithecus afarensis*	in the feet *of Australopithecus afarensis.*

Case B49

> Hence, we reject the hypotheses of Brownian walk and composite Brownian walk and conclude that mussel movement is best described by a Lévy walk. (de Jager et al. 2011, p. 1552)

The topic of this paper is the movement of mussels as they create their beds, considered in the context of the interaction with complex environments and the effects on selection. Here the authors assert their conclusion that the mathematical model of Lévy walks describes mussel movements while the alternatives do not. Despite the use of the word "description", this seems to be a clear case of model-kind explanation.

1. Explanation: model – kind

   The shapes of the paths in the Lévy walk **model** *of the movement of mussels* BEST EXPLAIN *the shapes of the paths* of the movement of mussels.

best explain	
The shapes	*the shapes*
of the paths in the Lévy walk **model**	*of the paths*
of the movement *of mussels*	of the movement of mussels.

2. Explanation: model – kind

   The shapes of the paths in the Brownian walk **model** *of the movement of mussels* DO NOT EXPLAIN *the shapes of the paths* of the movement of mussels.

do not explain

The shapes	*the shapes*
of the paths in the Brownian walk **model**	*of the paths*
of the movement *of mussels*	of the movement of mussels.

3. Explanation: model – kind

The shapes of the paths in the composite Brownian walk **model** *of the movement of mussels* DO NOT EXPLAIN *the shapes of the paths* of the movement of mussels.

do not explain

The shapes	*the shapes*
of the paths in the composite Brownian walk **model**	*of the paths*
of the movement *of mussels*	of the movement of mussels.

Case B50

> A National Oceanic and Atmospheric Administration (NOAA) WP-3D research aircraft made airborne measurements of the gaseous and aerosol composition of air over the Deepwater Horizon (DWH) oil spill in the Gulf of Mexico that occurred from April to August 2010. (Gouw et al. 2011, p. 1295)

This paper discusses the formation of organic aerosols in the wake of the Deepwater Horizon oil spill. Here the authors describe their main method of data collection.

Failure: description of method

Case B51

> Yet given that the methylated CTD [carboxy-terminal domain] is a substrate for subsequent phosphorylation and that phosphorylated RNAPII

> [RNA polymerase II] exhibits this methylation state, it is highly probable that R1810me is preserved on the transcribing polymerase, not having a major impact on CTD phosphorylation. (Sims et al. 2011, p. 101)

The authors provide details of the mechanism whereby the CTD section of the common RSNAPII enzyme is modified after its transcription and before it becomes active. Here they provide a speculative explanation for two of their discoveries (note the present tense).

1. Evidence: model – theory

   The conjunction of the role of methylated CTD as substrate for subsequent phosphorylation with the methylation state *in the **model*** of phosphorylated RNAPII SUGGESTS the preservation of R1810me on the transcribing polymerase *in the **theory** of the methylation of CTD on phosphorylated RNAPII.*

   suggests

The conjunction	the preservation
of the role	of R1810me
of methylated CTD	on the transcribing polymerase
as substrate	*in the **theory***
for subsequent phosphorylation	*of the methylation*
with the methylation state	*of CTD*
*in the **model***	
of phosphorylated RNAPII	*on phosphorylated RNAPII.*

Case B52

> MH2 [Malapa Hominin 2] shares with other australopiths and *Homo* asymmetry of the metacarpal heads that is associated with the human-like ability of the fingers to accommodate to an object via the metacarpal phalangeal joints. (Kivell et al. 2011, p. 1413)

Malapa Hominin 2 is a fossil specimen of the wrist and hand of an adult female *Australopithecus sediba*, found in Malapa, South Africa and dating to approximately 2 million years ago. The authors discuss the structure of this hand in the context of the evolution of hands among hominids. Here they have an implicit model of the kinetics of the hand in mind when they attribute the shape of some bones to the manipulation of objects. Despite the use of the word “associated” to mean a mere correlation, I believe that this is a case of scientific explanation.

1. Explanation: model – kind

   The human-like ability to accommodate to an object via the joints between the bones of the metacarpus and the phalanges *in a **model** of the kinematics of the hands of homonids* EXPLAINS the asymmetry of the heads *of the bones* of the metacarpus *of the hands of homonids.*

   explains

The human-like ability	the asymmetry
to accommodate	of the heads
to an object	*of the bones*
via the joints	of the metacarpus
between the bones	
of the metacarpus and the phalanges	
*in a **model***	
of the kinematics	
of the hands	*of the hands*
of homonids	*of homonids.*

Case B53

> The encoding of CTA [conditioned taste aversion] in the IC [insular cortex] was reported to be distributed, and specific associations are estimated to engage plastic changes in about 25% of the neurons, suggesting that the level of overexpression that we obtained in the IC in the present study could affect multiple behaviorally relevant representations. (Shema et al. 2011, pp. 1209-1210)

An experiment in rats shows how long-term memory can be enhanced or disrupted by the over-expression of proteins, including the protein kinase C isozyme protein kinase Mζ (PKMζ).

1. Explanation: theory – kind

   The level of the overexpression *in the **theory*** of PKMζ in IC *in **models** of long-term memory* COULD AFFECT *multiple qualities* of multiple behaviorally relevant representations *in long-term memory.*

could affect

The level	*multiple qualities*
of the overexpression *in the **theory*** of PKMζ in IC *in **models***	of multiple behaviorally relevant representations
of long-term memory	*in long-term memory.*

Case B54

> Despite their great length, the canines were not fragile. These could have served to manage food items before processing, to deter attacks from predators, or for intraspecific display and combat, as seen in extant antlerless water deer (*Hydropotes* sp.; Fig. 2E) and musk deer (*Moschus* sp.) from Asia. (Cisneros et al. 2011, p. 1604)

The authors discuss the scull and teeth of *Tiarajudens* – a newly described sabre-tooth therapsid. Therapsids belong to a group of reptile ancestors of mammals from the mid-Permian (around 250 million years ago). Here the authors offer (in abbreviated and speculative form) several functional explanations for the size of the canine teeth. The explanans in each case is the need or benefit of the function for the individual. (The second sentence was selected and the first is included for context.)

1. Explanation: theory – kind

   The need for the management of items *in the **theory*** of the processing of food *in **models** of the behaviour of Tiarajudens* COULD EXPLAIN the length and strength of the canine teeth *of Tiarajudens.*

could explain

The need	the length and strength
for the management of items *in the **theory*** of the processing of food *in **models*** *of the behaviour*	of the canine teeth
of Tiarajudens	*of Tiarajudens.*

2. Explanation: theory – kind

The need to deter attacks from predators *in the **theory** of defence in **models** of the behaviour of Tiarajudens* COULD EXPLAIN the length and strength of the canine teeth *of Tiarajudens.*

could explain

The need	the length and strength
to deter attacks from predators *in the **theory*** *of defence* *in **models*** *of the behaviour*	of the canine teeth
of Tiarajudens	*of Tiarajudens.*

3. Explanation: theory – kind

The need for display and combat *in the **theory*** of intraspecific behaviour *in **models** of the behaviour of Tiarajudens* COULD EXPLAIN the length and strength of the canine teeth *of Tiarajudens.*

could explain

The need	the length and strength
for display and combat *in the **theory*** of intraspecific behaviour *in **models*** *of the behaviour*	of the canine teeth
of Tiarajudens	*of Tiarajudens.*

Case B55

> To investigate this coupling experimentally, we measured the time evolution of the center-of-mass mean square displacements (MSDs) parallel (Δs^2) and perpendicular (Δn^2) to the orientation of the reptation tube, averaged over the same time window. (Fakhri et al. 2010, p. 1806)

This paper describes the behaviour of single-walled carbon nanotubes in crowded environments as a model of, for example, the creation of the cytoskeleton of a cell. Here they describe one of their methods.

Failure: method

Case B56

> As predicted by the size-based model, larger aggregates appeared with Sup35-GFP [Sup35 prion tagged with green fluorescent protein] overexpression, and this size shift induced a ∼50% decrease in propagons, a decrease in phenotypic stability by a factor of 70, and a ∼50% decrease in Sup35-GFP transmission. (Derdowski et al. 2010, p. 681)

Prions are misfolded proteins that can replicate by causing other proteins to misfold, sometimes resulting in aggregate plaques that cause diseases such as Creutzfeldt-Jakob disease. This paper discusses how size and not abundance affects the behaviour of prions in yeast, including heritable prions (propagons). Here they state one horn of their argument, that a shift in size explains three sorts of data they collected.

1. Explanation: kind – data

   The shift in size of the Sup35-GFP propagon CAUSED the ∼50% decrease *in the **measurements*** of the number *in a **sample*** of Sup35-GFP propagons.

   caused

The shift	the ∼50% decrease
in size	*in the **measurements*** of the number *in a **sample***
of the Sup35-GFP propagon	of Sup35-GFP propagons.

2. Explanation: kind – data

   The shift in size of the Sup35-GFP propagon CAUSED the factor of 70 decrease *in the **measurements*** of the stability of phenotypes *in a **sample*** of Sup35-GFP propagons.

caused

The shift	the factor of 70 decrease
in size	*in the* ***measurements*** of the stability of phenotypes *in a* ***sample***
of the Sup35-GFP propagon	of Sup35-GFP propagons.

3. Explanation: kind – data

The shift in size of the Sup35-GFP propagon CAUSED the ∼50% decrease *in the* ***measurements*** of hereditary transmission *in a* ***sample*** of Sup35-GFP propagons.

caused

The shift	the ∼50% decrease
in size	*in the* ***measurements*** of hereditary transmission *in a* ***sample***
of the Sup35-GFP propagon	of Sup35-GFP propagons.

Case B57

> Such reactivity offers the opportunity to develop triazoles as mechanically labile protecting groups or for use in readily accessible materials that respond to mechanical force. (Brantley, Wiggins, and Bielawski 2011, p. 1606)

This quotation from the end of the paper's abstract gestures at a technological application of triazoles (a small chemical compound), which the body of the paper describes in detail.

Failure: application

Case B58

> The severity of the Fog phenotype in +/*fem-1*(*Df*) heterozygotes depended not only on the identity of the deficiency but also on the history of the *fem-1*(+) allele. (C. L. Johnson and Spence 2011, p. 1314)

This paper describes an experiment on the role of RNA in the genetics of *C. elegans* nematode worms. *C. elegans* worms are usually either male or self-fertile hermaphrodites, both of which require the *fem-1* gene for development. Here they discuss their finding that not only the presence of the *fem-1* gene, but also the history of the allele among ancestors was significant. This is evidence of a heritable epigenetic effect.

1. Explanation: kind – data

   The presence and history of the *fem-1*(+) allele in +/*fem-1*(*Df*) heterozygotes *of C. elegans* EXPLAINS the severity of the Fog phenotype *in* ***observations*** *of* ***specimens*** of +/*fem-1*(*Df*) heterozygotes *of C. elegans.*

explains

The presence and history	the severity
of the *fem-1*(+) allele	of the Fog phenotype *in* ***observations*** *of* ***specimens***
in +/*fem-1*(*Df*) heterozygotes *of C. elegans*	of +/*fem-1*(*Df*) heterozygotes *of C. elegans.*

Case B59

> In addition, because teachers selected their focal class in the post-intervention year (albeit with clear guidance to select their most challenging course), it remains possible that this selection in some unmeasured way biased results of the study. (Allen et al. 2011, p. 1036)

The authors describe a randomized control trial on secondary school teaching, reporting significant student test score improvement. Here they raise the possibility that there was some source of selection bias.

1. Explanation: entity – data

The selection by teachers of the focal class in the post-intervention year of the **study** EXPLAINS the possibility of unmeasured bias in the **results** of the **study.**

explains

The selection	the possibility
by teachers	of unmeasured bias
of the focal class	in the **results**
in the post-intervention year	
of the **study**	of the **study.**

Case B60

> Although the absolute delay τ, corresponding to a group velocity of $v = 1600$ m/s, is small in the present system because of the relatively small optical depth $\mathcal{N}$, the observation nonetheless establishes experimentally that a vacuum input control field can delay a probe pulse. (Tanji-Suzuki et al. 2011, p. 1268)

The authors describe a technique for varying the rate of interactions between photons passing through an optical cavity. Here they reassert their conclusions in the face of a possible objection.

1. Evidence: entity – kind

The occurrence of a delay *in a **sample*** of a pulse of a probe *of photons in a vacuum input control field* ESTABLISHES EXPERIMENTALLY *the possibility* of a delay of a pulse of a probe *of photons in a vacuum input control field.*

establishes experimentally

The occurrence	*the possibility*
of a delay	of a delay
*in a **sample***	
of a pulse	of a pulse
of a probe	of a probe
of photons	*of photons*
in a vacuum input control field	*in a vacuum input control field.*

Case B61

> Interestingly, though the (3,8) species is a minor product in the mixture of SWNTs used in our experiments, HexCoil-Ala and HexCoil-Gly show a dominant peak corresponding to this chirality. (Grigoryan et al. 2011, p. 1074)

This paper describes a computational design system for engineering nano-structures. Here we have a statement of a surprising piece of data. It raises the expectation of an explanation.

Failure: remarking on some surprising data

Case B62

> Broad regions of low seismic velocity detected under ridges imply that the mantle is relatively impermeable with a porosity of ∼0.02. (Zhu et al. 2011, p. 88)

In order to better understand the geology of the Earth's mantle the authors studied the geochemical properties of small samples of molten rock. They studied their samples with porosity near 0.02, and here they state the reason: because that is the porosity value the mantle is believed to have based on seismic evidence. As in other cases we can reverse the evidential relation to get an explanatory relation: the porosity of 0.02 explains the low seismic velocity detected under ridges.

1. Evidence: kind – model

   The breadth of the regions of low seismic activity in the mantle is evidence for *the value* of ∼0.02 *of the parameter* for porosity *in **models*** of the mantle.

is evidence for	
The breadth	*the value*
of the regions of low seismic activity	of ∼0.02 *of the parameter* for porosity *in **models***
in the mantle	of the mantle.

Case B63

> The concurrent decreases in larval supply and mass flux were most likely due to hydrodynamic transport away from the ridge rather than changes in source production. (Adams et al. 2011, p. 580)

This paper describes how large-scale ocean eddies caused by atmospheric events such as El Niño can change deep-ocean currents and affect the ecologies of hydrothermal vents. Here the authors propose that these transporting currents better explain the changes they observed than would changes at the source. I have analyzed the contrastive explanation as the pair of a positive and a negative explanation.

1. Evidence: entity – entity

   The concurrency of the decreases in larval supply and mass flux *in the* ***ridge*** WAS MOST LIKELY DUE TO *the direction* of the hydrodynamic transport away from the **ridge.**

   was most likely due to

The concurrency	*the direction*
of the decreases in larval supply and mass flux	of the hydrodynamic transport
in the ***ridge***	away from the **ridge.**

2. Evidence: entity – entity

   The concurrency of the decreases in larval supply and mass flux *in the* ***ridge*** WAS MOST LIKELY NOT DUE TO changes in the source of the production *of larval supply and mass flux in the* ***ridge.***

   was most likely not due to

The concurrency	changes
of the decreases in larval supply and mass flux	in the source of the production *of larval supply and mass flux*
in the ***ridge***	*in the* ***ridge.***

Case B64

> We present benthic foraminiferal isotopes with Mg/Ca [magnesium/calcium] data from two North American Atlantic continental slope locations . . . with well-preserved foraminifera and excellent age control . . . , providing a continuous record from the late middle Eocene to early Miocene: (i) Ocean Drilling Program (ODP) Site 1053 (Blake Nose, 1629 m present depth, ∼1500 to 1750 m paleodepth); and (ii) Atlantic Slope Project corehole 5 (ASP-5; 250 m present depth, 600 m paleodepth, North Carolina slope) . . . . (Katz et al. 2011, p. 1077)

Here the authors describe the sources of their data about the structure of the Antartic Circumpolar Current in the distant past.

Failure: description of data sources

Case B65

> Nontrivial planarization and strategic doping were used to overcome the issues arising from this roughness. (McCarthy et al. 2011, p. 571)

The authors describe an improved method for building organic light-emitting transistors. Here they state two methods that were used to overcome a particular difficulty that they faced. While the difficulties could count as an explanation of their reasons for using these methods, that usage is beyond the scope of my model.

Failure: justifying methods

Case B66

> This process [blue-shifted gas clouds absorbing light] might be evident in our observations of CC SNe [core-collapse supernovae], which show an excess of strong (and even saturated) absorption compared to the SNe Ia [type Ia supernovae]. (Sternberg et al. 2011, p. 859)

Type Ia supernovae are "standard candles" used for measuring distance in astronomy and this paper investigates the mechanisms behind those stupendous explosions. Here the authors distinguish between core-collapse and type Ia supernovae. Blue-shifted gas clouds near core-collapse supernovae explain an excess of strong sodium absorption compared to type Ia supernovae.

1. Evidence: data – kind

    The excess of strength in the absorption *of the spectra of sodium* in the **observations** *of the light in a* ***sample*** of CC SNe IS EVIDENCE OF the absorption of light by blue-shifted gas clouds around CC SNe.

is evidence of

The excess	the absorption
of strength in the absorption *of the spectra* *of sodium* in the **observations** *of the light* *in a* ***sample***	of light by blue-shifted gas clouds
of CC SNe	around CC SNe.

Case B67

> Children who made a correct prediction (green box) and gave a sensible explanation were scored as correct. (Perner, Mauer, and Hildenbrand 2011, p. 475)

In this cognitive science paper the author report on a study using false-belief tasks to ascertain links between concepts of sense, reference, belief, and identity. Despite the use of “explanation” in this sentence, here we have a description of a method.

Failure: method

Case B68

> Although **2** [Mn_4CaO_2] is insoluble in tetrahydrofuran (THF), addition of $Ca(OTf)_2$ [OTf is trifluoromethanesulfonate] leads to partial dissolution of the suspended material, suggesting the formation of a more soluble Ca-Mn intermediate. (Kanady et al. 2011, p. 733)

This paper discusses the chemistry of Mn_4CaO_n compounds and their role in photosynthesis. Here the authors provide one piece of evidence and one step in their argument that Mn_4CaO_2 has a certain structure.

1. Evidence: kind – theory

The partial dissolution with the addition of $Ca(OTf)_2$ in THF of **2** SUGGESTS the formation of a more soluble intermediate of Ca-Mn *in the* ***theory*** *of the reaction in* ***models*** of **2**.

	suggests
The partial dissolution	the formation
with the addition	of a more soluble intermediate
of $Ca(OTf)_2$	of Ca-Mn
in THF	*in the* ***theory***
	of the reaction
	in ***models***
of **2**	of **2**.

Case B69

> Consider an edge dislocation formed by the removal of two planes of atoms . . . viewed along [1100] and [0001], respectively, or the similarly formed 30° dislocation . . . (Heuer, Jia, and Lagerlöf 2010, p. 1230)

The topic of this paper is the structure of deformed sapphire crystals. The quoted sentence is the first step in the description of a model of the core structure, but does not include an explanation.

Failure: description

Case B70

> The STM [scanning tunnelling microscope] topographic images . . . revealed atomically flat and defect-free Se-terminated [selenium-terminated] (001) surfaces with large terraces. (Song et al. 2011, p. 1411)

Observations of molecular structures of an iron-selenide superconductor are described in this paper. Here we have a reference to a set of scanning tunnelling microscope topographic images that reveal a structure. Conversely the structure explains patterns in the images.

1. Evidence: data – entity

Multiple qualities of the **images** from the STM of the topography *of the surfaces of a **sample** of films of stoichiometric FeSe single-crystals* REVEALED the large-terraced, atomically flat and defect-free qualities *of the surfaces of a **sample** of films of stoichiometric FeSe single-crystals.*

	revealed
Multiple qualities	the large-terraced, atomically flat and defect-free qualities
of the **images** from the STM of the topography	
of the surfaces *of a **sample*** *of films* *of stoichiometric FeSe* *single-crystals*	*of the surfaces* *of a **sample*** *of films* *of stoichiometric FeSe* *single-crystals.*

Case B71

> Using 10-min sliding window calculations, we found a clear similarity in the time course between theta power and gridness . . . and a consistent relationship between the power of theta and the gridness score . . . . (Brandon et al. 2011, p. 597)

This paper describes an association between theta oscillations and the periods of "grid" and "head" cells in the brains of rats. These cells are thought to track spatial location and head movement. Here the authors state some of the details of the association the observed. Although phrased in terms of "similarity" and "consistency", I believe that the authors are making modal, explanatory claims. However they are restricting their claims to associations in the data.

1. Explanation: data – data

The patterns in the time course of the theta power *in the **data** in a **sample** of the medial cortex of rats* EXPLAIN *the patterns* in the time course of the gridness [spiking rate of grid cells] *in the **data** in a **sample** of the medial cortex of rats.*

explain

The patterns	*the patterns*
in the time course	in the time course
of the theta power	of the gridness [spiking rate of grid cells]
in the ***data***	*in the* ***data***
in a ***sample***	*in a* ***sample***
of the medial cortex	*of the medial cortex*
of rats	*of rats.*

2. Explanation: data – data

   The patterns in the time course of the theta power *in the* ***data*** *in a* ***sample*** *of the medial cortex of rats* EXPLAIN *the patterns* in the time course *of gridness score in the* ***data*** *in a* ***sample*** *of the medial cortex of rats.*

explain

The patterns	*the patterns*
in the time course	in the time course
of the theta power	*of gridness score*
in the ***data***	*in the* ***data***
in a ***sample***	*in a* ***sample***
of the medial cortex	*of the medial cortex*
of rats	*of rats.*

Case B72

> Thus, FM2 [frequency-modulation harmonic 2] is weaker than FM1 [frequency-modulation harmonic 2] in echoes from objects located off the central axis or at greater distances. (Bates, Simmons, and Zorikov 2011, p. 628)

Here the authors distinguish some of the characteristics of two types of sound *Eptesicus fuscus* bats use in echolocation.

Failure: distinction

Case B73

> In all of these cases, the perturbation index shows high peaks only for a narrow time interval of the pre-emergence phase, but it stays very low after the start of emergence . . . (Ilonidis, Zhao, and Kosovichev 2011, p. 994)

The authors describe a pattern in their observations of emerging sunspot regions, without offering an explanation for the pattern in this quotation or saying what this is evidence of.

Failure: pattern in the data

Case B74

> The helical axis of the complex is nearly straight through the transitions between the triple helix and the flanking ENE stems. (Mitton-Fry et al. 2010, p. 1246)

This paper describes the mechanism by which part of a herpes virus prevents RNA decay in another part of the virus. Here we have a description of the structure of one of the parts.

Failure: description

Case B75

> The findings that none of the three types of *SLF* [*S-locus F-box*] genes of either S_7 or S_{11} haplotype caused competitive interaction in S_5 pollen suggest that some other type(s) of *SLF* in S_7 and S_{11} haplotypes mediate detoxification of S_5-RNase, allowing them to be compatible with S_5 styles. (Kubo et al. 2010, p. 798)

Flowering plants are able to recognize their own pollen in order to prevent inbreeding. This paper describes how this done, which involves the *S-locus F-box* gene and its various S_n alleles. Here the authors propose that an unknown factor is at play.

1. Evidence: kind – theory

   The lack of competition in the interaction with S_5 styles of S_7 and S_{11} haplotypes SUGGESTS the mediation of detoxification of S_5 pollen *in the* ***theory*** of *SLF in* ***models*** of S_7 and S_{11} haplotypes.

suggests

The lack	the mediation
of competition in the interaction with S_5 styles	of detoxification of S_5 pollen *in the **theory*** of *SLF* *in **models***
of S_7 and S_{11} haplotypes	of S_7 and S_{11} haplotypes.

Case B76

> Simple calculations imply that 10-fold contrasts in $\dot{e}$ along valley profiles … most likely correspond to a parameter r value in the range $\sim$1 to $\sim$3. (Shuster et al. 2011, p. 88)

In this study of changes in the geophysics of alpine landscapes by erosion and glaciation the authors propose a mathematical model of the topology with key parameters of $\dot{e}$ and r.

1. Evidence: kind – model

The 10-fold contrasts in the values of $\dot{e}$ along the profiles of valleys ARE EVIDENCE FOR a range of $\sim$1 to $\sim$3 for the values of the parameter r *in the mathematical **model** of the topology of the valleys.*

are evidence for

The 10-fold contrasts	a range of $\sim$1 to $\sim$3
in the values of $\dot{e}$ along the profiles	for the values of the parameter r *in the mathematical **model*** *of the topology*
of valleys	*of the valleys.*

Case B77

> Second, RNA interference-mediated depletion of the key pathway molecules, PGRP-LC, Imd, and REL2, did not rescue *P. falciparum* oocyst development in the presence of *Esp_Z*. (Cirimotich et al. 2011, p. 856)

The malaria parasite *Plasmodium falciparum* goes through several stages in its lifecycle, some of which take place in the lumen of the midgut of mosquitos. This paper reports on a bacterium *Esp_Z* that lives in the midgut of some mosquitoes and that interferes with the parasite's development. This quotation is from an argument that the mosquito's immune deficiency innate immune pathway is not how *Esp_Z* acts on the parasite.

1. Explanation: entity – entity

   The depletion by RNA interference of the key pathway molecules *of the immune deficiency innate immune pathway in a **sample** of mosquitoes* DID NOT CAUSE the rescue of the development of the oocyst of *P. falciparum* in the presence of *Esp_Z in a **sample** of mosquitoes.*

did not cause

The depletion	the rescue
by RNA interference	of the development
of the key pathway molecules	of the oocyst
of the immune deficiency innate immune pathway	of *P. falciparum*
	in the presence
	of *Esp_Z*
*in a **sample***	*in a **sample***
of mosquitoes	*of mosquitoes.*

Case B78

> Particles can create stable flocculated networks in suspensions through the effects of the van der Waals forces; they are much smaller than the capillary force between particles considered here. (Koos and Willenbacher 2011, p. 899)

This paper describes a model of the interactions of solid particles dispersed in a fluid and a method to control those interactions. Here we have a very general explanation of one type of such a system that the authors distinguish from their own topic of interest.

1. Explanation: theory – kind

The effects of van der Waals forces *in the **theory** of particle interactions in **models*** of particles in liquid suspensions CAN CAUSE the creation and stability of flocculated networks of particles in liquid suspensions.

can cause

The effects	the creation and stability
of van der Waals forces *in the **theory*** *of particle interactions* *in **models***	of flocculated networks
of particles in liquid suspensions	of particles in liquid suspensions.

Case B79

> Due to the finite contact angles of gold on anorthite and sapphire, during thermal annealing the gold film broke up into small particles dispersed on the substrate . . . (Luo et al. 2011, p. 1730)

This paper reports on the discovery of nanometer-thick films in equilibrium states. Here we have an explanation for the break-up of a thicker gold film during the creation of the thin gold film.

1. Explanation: model – entity

The finite values of the contact angles *in a **model** of the structure* on anorthite and saffire of gold EXPLAIN the break-up into small particles and dispersal onto the substrate during thermal annealing *of **samples*** of films of gold.

explain

The finite values	the break-up into small particles
of the contact angles *in a **model*** *of the structure* on anorthite and saffire	and dispersal onto the substrate during thermal annealing *of **samples*** of films
of gold	of gold.

Case B80

> The dish-shaped leaf showed the same X-shaped pattern ... originating from its left and right edges ..., but, in addition, it had two higher-amplitude peaks from within its cavity – a single reflection from its center and a double reflection bouncing off both sides .... (Simon et al. 2011, pp. 631-632)

As this paper describes, some flowers have dish-shaped leaves to better reflect echoes and attract bat-pollinators. Here we have an explanation of the two acoustic peaks observed.

1. Explanation: entity – data

The position at the center and both sides of a single reflection and a double reflection of sound *in the* ***specimen*** from the dish-shaped leaf CAUSED the position of the peaks *in the* ***observations*** of high-amplitude sound *in the* ***specimen*** of the dish-shaped leaf.

	caused
The position	the position
at the center and both sides of a single reflection and a double reflection of sound	of the peaks *in the* ***observations*** of high-amplitude sound
in the ***specimen*** from the dish-shaped leaf	*in the* ***specimen*** of the dish-shaped leaf.

Case B81

> Ionomycin-mediated store depletion for 5 min induced mCherry-STIM1 to move into clearly defined ER-PM junctional areas .... (Y. Wang et al. 2010, p. 108)

This paper describes the STIM proteins that detect and regulate calcium within cells. Here the authors state a result of their high-resolution imaging study examining the distribution of mCherry-tagged STIM1 proteins within cells. When calcium stores were depleted using ionomycin, the STIM moved into distinct locations. (See also case B30.)

1. Explanation: entity – entity

   The depletion with Ionomycin for 5 minutes of stores of Ca^{2+} *in the **sample** of cells* INDUCED the movement into clearly defined ER-PM junctional areas by Ca^{2+} *in the **sample** of cells.*

   induced

The depletion	the movement
with Ionomycin for 5 minutes of stores	into clearly defined ER-PM junctional areas
of Ca^{2+} *in the **sample*** *of cells*	by Ca^{2+} *in the **sample*** *of cells.*

Case B82

> The oldest fossils that can be more confidently assigned to *H. habilis* and/or *H. rudolfensis*, in this case relatively intact or complete cranial remains, date to approximately the same age as *H. erectus* at ∼1.88 to 1.90 Ma at Koobi Fora. (Pickering et al. 2011, p. 1421)

Here the authors make an assertion about the state of evidence about classification of specimens at the origins of the *Homo* genus. (See also case C7.)

Failure: description

Case B83

> The overall reaction sequence is complicated owing to the presence of many reaction steps (more than a hundred reactions). (Sutton et al. 2011, p. 1428)

This paper describes a chemical reaction with potential for use in hydrogen fuel cells. This quotation is taken from a section describing calculations of the reaction sequence, and explains part of the difficulty of building a model.

1. Explanation: kind – kind

The presence of a large number of steps in the reaction EXPLAINS the overall complexity of the sequence of the reaction.

explains

The presence	the overall complexity
of a large number of steps	of the sequence
in the reaction	of the reaction.

Case B84

> The suppression in the NCRIF [non-classical rotation inertial frequency] became noticeable when the rotation speed exceeded 1 mm/s, which is much greater than the ac critical velocity of 10 μm/s. One reasonable way to explain this difference is that dc [continuous] rotation results in a different mechanism for the suppression of NCRIF than does ac oscillation. (Choi et al. 2010, p. 1514)

A strange property of solid helium-4 is "supersolidity" – a special quantum state with a zero-viscosity flow. The paper establishes this property of helium experimentally. Here the authors note a difference between two experimental conditions and propose two different mechanisms. (The second sentence was randomly sampled and the first sentence is included to provide context.)

1. Explanation: theory – data

The differences between dc rotation and ac oscillation *in the **theory** of quantum mechanics* in the **mechanisms** of suppression of NCRIF EXPLAINS *the differences* in the velocities of the **observations** of the suppression in the NCRIF.

explains

The differences	*the differences*
between dc rotation and ac oscillation *in the* ***theory*** *of quantum mechanics* in the **mechanisms**	in the velocities of the **observations**
of suppression of NCRIF	of the suppression in the NCRIF.

Case B85

> Remarkably, 7 of the 15 hubs of degrees greater than 50 (hubs_{50}) in AI-1_{MAIN} were targeted by effectors from both pathogens ($P = 6.5 \times 10^{-13}$) . . . , and 14 of the 15 hubs_{50} were targeted by effectors from at least one pathogen ($P = 6.9 \times 10^{-18}$) . . . , consistent with observations of human-virus infection systems. (Mukhtar et al. 2011, p. 597)

This quotation describes the relations between pathogen proteins (effectors) and hubs in plant immune systems, noting their similarity to human-virus relations.

Failure: description

Case B86

> In much of this region, snowpack declined since the 1950s, and continued reductions are expected throughout the 21st century and beyond. (Pederson et al. 2011, p. 332)

The authors of this study used tree-ring data from areas of runoff to measure the melts from mountain snowpacks in North America. This quotation from the beginning of their paper sets the context for the paper.

Failure: statement of observations and predictions

Case B87

> The current-pressure relationship is characterized by maximal opening at -60 mmHg, with a pressure for half-maximal activation (P_{50}) of -28.0 ± 1.8 mmHg . . . . (Coste et al. 2010, p. 56)

In this paper the authors establish the importance of Piezo1 genes for mechanically activated cation channels, required for neural cells that detect touch and pain. Here they state two of the parameters for one of their mathematical models. (See also case B15.)

Failure: model parameters

Case B88

> The derived dust mass is about 10^3 times as large as and about 20 times as cold as that measured at mid-infrared wavelengths around 600 days after the explosion was observed, soon after it first condensed out of the ejecta. (Matsuura et al. 2011, p. 1261)

Here we have a description of the differences in size and temperature over time of dust ejected from supernova 1987A.

Failure: description

Case B89

> If e_1 is always chosen, then the process simply adds a uniformly random edge at each step. (Riordan and Warnke 2011, p. 323)

This mathematics paper studies a network phase-change effect called “explosive percolation”. Here the authors describe a small part of their model of an Achlioptas process, a much-studied class of models.

Failure: method

Case B90

> For comparison, we also generated a MG [metallic glass] without LRO [long-range structural order] by quenching a melt directly from 1500 K to 300 K without the fcc [face-centered cubic crystal structure] constraining step, . . . (Zeng et al. 2011, p. 1406)

Glass has amorphous rather than crystalline structure, but this paper shows one kind of cesium-aluminum metallic glass transitions from amorphous to crystalline structure when put under high pressures. Here the authors describe their method for generating a sample with contrasting properties.

Failure: method

Case B91

> This result is especially noteworthy because the seed-sowing plots were all placed within a few meters of adult *R. solandri* plants, where natural seed rain should already be at a maximum, but were not necessarily near adult *M. ramiflorus* or *G. ligustrifolium*. (Anderson et al. 2011, p. 1070)

This ecology paper describes the cascading effects that sharp reduction in bird populations have on pollination and the density of plant populations. Here the authors highlight a particular piece of data as being noteworthy, and provide some reasons for this, without forming a complete explanation.

Failure: highlighting a piece of data

Case B92

> To further illustrate how the time series approach can provide new insights from manipulative immunological experiments, we calculated surfaces of immune efficacy for control mice and for mice treated with antibodies to interleukin-10 receptor (anti-IL-10R) . . . (Metcalf et al. 2011, p. 987)

The authors of this paper studied the relationships between rodent malaria parasite growth and immune system resource limitations. Here they describe one step in their methodology.

Failure: method

Case B93

> Figure 2 shows all the stars on a conventional Hertzsprung-Russell diagram, which plots the luminosities of stars against T_{eff} [effective temperature of the star]. (Chaplin et al. 2011, p. 213)

Data from the NASA Kepler mission about stellar masses, radii, and ages undermine predictions of stellar evolution. This sentence simply describes a figure. (See also case B13.)

Failure: description of a figure

Case B94

> The most heavily targeted genes are associated with increased pleiotropy [multiple influences on phenotype], as measured by the number of distinct functional processes and tissues with which they are associated. (Roy et al. 2010, p. 1793)

This paper reports on a large functional genomics project studying fruit flies: *Drosophila* model organism Encyclopedia of DNA Elements (modENCODE). Here the authors make a general observation about their data set: the genes that are the targets of the largest numbers of transcription factors are associated with pleiotropy. This somewhat implies but falls short of an explanation for either *pleiotropy* or *being heavily targeted*.

Failure: general observation

Case B95

> In cuprates [superconductors with a copper anion] the angular dependence of the wave functions is primarily set by the d orbitals of Cu, which hybridize with properly symmetrized combinations of p orbitals on nearest-neighbor oxygens. (Sakurai et al. 2011, p. 700)

In this quotation one quality of the kind *cuprate* explains another quality of that kind.

1. Explanation: kind – kind

   The hybridization of d orbitals of Cu in cuprates EXPLAINS the angular dependence of the wave functions of cuprates.

   explains

The hybridization	the angular dependence
of d orbitals of Cu	of the wave functions
in cuprates	of cuprates.

Case B96

> Preserved samples of whiteflies from several sites in Arizona, New Mexico, and California show that the frequency of infection rose from 1% in 2000 to 51% in 2003 and to 97% in 2006 .... (Himler et al. 2011, p. 254)

This paper describes the infection of a population of sweet potato whiteflies (an invasive agricultural pest) with a inheritable bacterial symbiont. Here the authors say what they measured and what their results were.

Failure: method

Case B97

> In all cases, the alkylation reaction predictably and selectively afforded the coupling products without any additives or formation of wasteful by-products. (D.-H. Lee, Kwon, and Yi 2011, p. 1614)

Here we have a summary of an experiment demonstrating an efficient chemical reaction. The authors state that the reaction generated the products. While this involves some sort of causal relation, nothing is being explained.

Failure: causation without explanation

Case B98

> *Rasgrf1* is imprinted in mice and rats but not in other rodent species. (Watanabe et al. 2011, p. 851)

Here we have a statement of the prevalence of a particular gene in the context of an epigenetic study of rodent DNA.

Failure: statement

Case B99

> Previous global simulations have been able to capture observed features of geomagnetic storms, isolated substorms, and other events. (Brambles et al. 2011, p. 1183)

This paper provides a formal model of Earth's magnetosphere. Here the authors describe the explanatory power of previous models, but do not say what it is about them that is explanatory.

Failure: description of explanatory power

Case B100

> This Hirnantian-aged unit [a sample of carbonate] records a major drop in sea level and a large positive carbon isotope excursion; both are recognized globally in other sedimentary successions. (Finnegan et al. 2011, p. 904)

The topics of this paper are historical ocean temperatures and surface ice volumes. The sample of carbonate they refer to provides evidence of a sea level drop and a change in the sources of atmospheric carbon. Conversely, the drop in sea level explains properties of the sample. (See also case A3.)

1. Evidence: data – entity

   The values of the ***measurements*** *of the isotopes* in the **Hirnantian-aged unit** *from the sea in the* ***Hirnantian era*** ARE EVIDENCE OF a major drop in the level *of the sea in the* ***Hirnantian era.***

   are evidence of

The values	a major drop
of the ***measurements*** *of the isotopes* in the **Hirnantian-aged unit**	in the level
from the sea *in the* ***Hirnantian era***	*of the sea* *in the* ***Hirnantian era.***

2. Evidence: data – entity

   The values of the ***measurements*** *of the isotopes* in the **Hirnantian-aged unit** *from the sea in the* ***Hirnantian era*** ARE EVIDENCE OF the large size and positive direction of an excursion of isotopes of carbon *in the* ***Hirnantian era.***

are evidence of

The values	the large size and positive direction
of the ***measurements***	of an excursion
of the isotopes	of isotopes
in the **Hirnantian-aged unit**	of carbon
from the sea	
in the ***Hirnantian era***	*in the* ***Hirnantian era.***

A.4 Sample C

Case C1

> Mitochondria are maternally transmitted; hence, their genome can only make a direct and adaptive response to selection through females, whereas males represent an evolutionary dead end. In theory, this creates a sex-specific selective sieve, enabling deleterious mutations to accumulate in mitochondrial genomes if they exert male-specific effects. We tested this hypothesis, expressing five mitochondrial variants alongside a standard nuclear genome in *Drosophila melanogaster*, and found striking sexual asymmetry in patterns of nuclear gene expression. Mitochondrial polymorphism had few effects on nuclear gene expression in females but major effects in males, modifying nearly 10% of transcripts. These were mostly male-biased in expression, with enrichment hotspots in the testes and accessory glands. Our results suggest an evolutionary mechanism that results in mitochondrial genomes harboring male-specific mutation loads. (Innocenti, Morrow, and Dowling 2011, p. 845)

(See also case B14.)

1. Evidence: kind – model

The male-specificity of mutation loads in the genomes of mitochondria in *Drosophila melanogaster* SUGGEST the sex-selectivity of a **mechanism** of evolution in *Drosophila melanogaster.*

suggest

The male-specificity	the sex-selectivity
of mutation loads	of a **mechanism**
in the genomes	of evolution
of mitochondria	
in *Drosophila melanogaster*	in *Drosophila melanogaster.*

Case C2

> Deepwater formation in the North Atlantic by open-ocean convection is an essential component of the overturning circulation of the Atlantic Ocean, which helps regulate global climate. We use water-column radiocarbon reconstructions to examine changes in northeast Atlantic convection since the Last Glacial Maximum. During cold intervals, we infer a reduction in open-ocean convection and an associated incursion of an extremely radiocarbon (^{14}C)-depleted water mass, interpreted to be Antarctic Intermediate Water. Comparing the timing of deep convection changes in the northeast and northwest Atlantic, we suggest that, despite a strong control on Greenland temperature by northeast Atlantic convection, reduced open-ocean convection in both the northwest and northeast Atlantic is necessary to account for contemporaneous perturbations in atmospheric circulation. (Thornalley et al. 2011, p. 202)

1. Explanation: theory – entity

The reduction of the convection *in the **theory*** of the open-ocean of the northwest and northeast of the **Atlantic** *in **models** of the climate of the **Earth*** is necessary to account for the contemporaneity of the perturbations in the circulation of the atmosphere *of the **Earth.***

is necessary to account for

The reduction	the contemporaneity
of the convection	of the perturbations
*in the **theory***	in the circulation
of the open-ocean	of the atmosphere
of the northwest and northeast	
of the **Atlantic**	
*in **models***	
of the climate	
*of the **Earth***	*of the **Earth.***

Case C3

Transcription by eukaryotic RNA polymerases (Pols) II and III and archaeal Pol requires structurally related general transcription factors TFIIB, Brf1, and TFB, respectively, which are essential for polymerase recruitment and initiation events. A TFIIB-like protein was not evident in the Pol I basal transcription machinery. We report that TAF1B, a subunit of human Pol I basal transcription factor SL1, is structurally related to TFIIB/TFIIB-like proteins, through predicted amino-terminal zinc ribbon and cyclin-like fold domains. SL1, essential for Pol I recruitment to the ribosomal RNA gene promoter, also has an essential postpolymerase recruitment role, operating through TAF1B. Therefore, a TFIIB-related protein is implicated in preinitiation complex assembly and post-polymerase recruitment events in Pol I transcription, underscoring the parallels between eukaryotic Pol I, II, and III and archaeal transcription machineries. (Naidu et al. 2011, p. 1640)

1. Evidence: kind – theory

The presence of a TFIIB-related protein in the Pol I of eukaryotes is further evidence of the breadth of the parallels between eukaryotic Pol I, II, III, and archaeal Pol *in the **theory*** of the machinery of transcription *in **models*** of Pol I in eukaryotes.

	is further evidence of
The presence	the breadth
of a TFIIB-related protein	of the parallels between eukaryotic Pol I, II, III, and archaeal Pol *in the **theory*** of the machinery of transcription *in **models***
in the Pol I of eukaryotes	of Pol I in eukaryotes.

Case C4

During protein synthesis, the ribosome controls the movement of tRNA and mRNA by means of large-scale structural rearrangements. We describe structures of the intact bacterial ribosome from *Escherichia coli* that reveal how the ribosome binds tRNA in two functionally distinct states, determined to a resolution of ∼3.2 angstroms by means of x-ray crystallography. One state positions tRNA in the peptidyl-tRNA binding

> site. The second, a fully rotated state, is stabilized by ribosome recycling factor and binds tRNA in a highly bent conformation in a hybrid peptidyl/exit site. The structures help to explain how the ratchet-like motion of the two ribosomal subunits contributes to the mechanisms of translocation, termination, and ribosome recycling. (Dunkle et al. 2011, p. 981)

1. Explanation: model – kind

The ratchet-like quality of the motion *in **models*** of the structures of the subunits of the ribosome EXPLAINS IN PART *multiple qualities* of the translocation, termination, and recycling of the ribosome.

<table>
<tr><th colspan="2">explains in part</th></tr>
<tr><th>The ratchet-like quality</th><th><i>multiple qualities</i></th></tr>
<tr><td>of the motion
<i>in models</i>
of the structures
of the subunits</td><td>of the translocation, termination,
and recycling</td></tr>
<tr><td>of the ribosome</td><td>of the ribosome.</td></tr>
</table>

Case C5

> The role of electrical synapses in synchronizing neuronal assemblies in the adult mammalian brain is well documented. However, their role in learning and memory processes remains unclear. By combining Pavlovian fear conditioning, activity-dependent immediate early gene expression, and in vivo electrophysiology, we discovered that blocking neuronal gap junctions within the dorsal hippocampus impaired context-dependent fear learning, memory, and extinction. Theta rhythms in freely moving rats were also disrupted. Our results show that gap junction-mediated neuronal transmission is a prominent feature underlying emotional memories. (Bissiere et al. 2011, p. 87)

1. Evidence: data – theory

Multiple qualities of the **results** of the **study** of emotional memories SHOW the prominence of gap junction-mediation *in the **theory*** of neuronal transmission *in **models*** of emotional memories.

show

Multiple qualities	the prominence
of the **results** of the **study**	of gap junction-mediation *in the* ***theory*** of neuronal transmission *in* ***models***
of emotional memories	of emotional memories.

Case C6

> Voltage- and store-operated calcium (Ca^{2+}) channels are the major routes of Ca^{2+} entry in mammalian cells, but little is known about how cells coordinate the activity of these channels to generate coherent calcium signals. We found that STIM1 (stromal interaction molecule 1), the main activator of store-operated Ca^{2+} channels, directly suppresses depolarization-induced opening of the voltage-gated Ca^{2+} channel $Ca_V1.2$. STIM1 binds to the C terminus of $Ca_V1.2$ through its Ca^{2+} release-activated Ca^{2+} activation domain, acutely inhibits gating, and causes long-term internalization of the channel from the membrane. This establishes a previously unknown function for STIM1 and provides a molecular mechanism to explain the reciprocal regulation of these two channels in cells. (Park, Shcheglovitov, and Dolmetsch 2010, p. 101)

1. Explanation: model – kind

Multiple qualities of the molecular **mechanism** of STIM1 in Ca^{2+} channels EXPLAIN the reciprocity of the regulation of voltage- and store-operated Ca^{2+} channels *which are* Ca^{2+} *channels.*

explain

Multiple qualities	the reciprocity
of the molecular **mechanism** of STIM1	of the regulation of voltage- and store-operated Ca^{2+} channels
in Ca^{2+} channels	*which are* Ca^{2+} *channels.*

Case C7

> Newly exposed cave sediments at the Malapa site include a flowstone layer capping the sedimentary unit containing the *Australopithecus sediba* fossils. Uranium-lead dating of the flowstone, combined with paleomagnetic and stratigraphic analysis of the flowstone and underlying sediments, provides a tightly constrained date of 1.977 ± 0.002 million years ago (Ma) for these fossils. This refined dating suggests that *Au. sediba* from Malapa predates the earliest uncontested evidence for *Homo* in Africa. (Pickering et al. 2011, p. 1421)

(See also case B82.)

1. Evidence: data – entity

The earliness of the refined dates *in the **measurements*** of the **fossils** of *Australopithecus sediba* in **Africa** SUGGESTS the predating of *Homo* by *Australopithecus sediba* in **Africa.**

suggests

The earliness	the predating
of the refined dates *in the **measurements*** of the **fossils**	of *Homo*
of *Australopithecus sediba* in **Africa**	by *Australopithecus sediba* in **Africa.**

Case C8

> Catastrophic ecological regime shifts may be announced in advance by statistical early warning signals such as slowing return rates from perturbation and rising variance. The theoretical background for these indicators is rich, but real-world tests are rare, especially for whole ecosystems. We tested the hypothesis that these statistics would be early warning signals for an experimentally induced regime shift in an aquatic food web. We gradually added top predators to a lake over 3 years to destabilize its food web. An adjacent lake was monitored simultaneously as a reference ecosystem. Warning signals of a regime shift were evident in the manipulated lake during reorganization of the food web more than a year before the food web transition was complete, corroborating theory for leading indicators of ecological regime shifts. (Carpenter et al. 2011, p. 1079)

1. Evidence: data – theory

The presence of warning signals of shifts in ecological regime in the **observations** of the **manipulated lake** *which is an ecosystem* CORROBORATE *multiple qualities* of the leading indicators in the **theory** of the shifts of ecological regimes *in **models** of ecosystems.*

corroborate

The presence	*multiple qualities*
of warning signals	of the leading indicators
of shifts	in the **theory**
in ecological regime	of the shifts
in the **observations**	of ecological regimes
of the **manipulated lake**	*in **models***
which is an ecosystem	*of ecosystems.*

Case C9

> The Tammar wallaby (*Macropus eugenii*) harbors unique gut bacteria and produces only one-fifth the amount of methane produced by ruminants per unit of digestible energy intake. We have isolated a dominant bacterial species (WG-1) from the wallaby microbiota affiliated with the family Succinivibrionaceae and implicated in lower methane emissions from starch-containing diets. This was achieved by using a partial reconstruction of the bacterium's metabolism from binned metagenomic data (nitrogen and carbohydrate utilization pathways and antibiotic resistance) to devise cultivation-based strategies that produced axenic WG-1 cultures. Pure-culture studies confirm that the bacterium is capnophilic and produces succinate, further explaining a microbiological basis for lower methane emissions from macropodids. This knowledge also provides new strategic targets for redirecting fermentation and reducing methane production in livestock. (Pope et al. 2011, p. 646)

1. Explanation: kind – kind

The capnophilic and succinate-producing qualities of the metabolism of the Succinivibrionaceae bacterium WG-1 in *Macropus eugenii which is a macropodid* EXPLAINS the microbiological basis for lower methane emissions in macropodids.

explains

The capnophilic and succinate-producing qualities	the microbiological basis
of the metabolism of the Succinivibrionaceae bacterium WG-1 in *Macropus eugenii*	for lower methane emissions
which is a macropodid	in macropodids.

Case C10

> Cultivated beets (*Beta vulgaris* ssp.*vulgaris*) are unable to form reproductive shoots during the first year of their life cycle. Flowering only occurs if plants get vernalized, that is, pass through the winter, and are subsequently exposed to an increasing day length (photoperiod) in spring. Here, we show that the regulation of flowering time in beets is controlled by the interplay of two paralogs of the *FLOWERING LOCUS T (FT)* gene in *Arabidopsis* that have evolved antagonistic functions. *BvFT2* is functionally conserved with *FT* and essential for flowering. In contrast, *BvFT1* represses flowering and its down-regulation is crucial for the vernalization response in beets. These data suggest that the beet has evolved a different strategy relative to *Arabidopsis* and cereals to regulate vernalization. (Pin et al. 2010, p. 1397)

The final sentence makes a "suggest" evidential claim, but I believe that the main claim in the abstract is about the mechanism for vernalization in beets.

1. Explanation: model – kind

   The repression of flowering *in a* ***model*** *of the function* of the *BvFT1* gene *in the vernalization of Beta vulgaris* EXPLAINS *multiple qualities* of the vernalization of *Beta vulgaris*.

explains

The repression	*multiple qualities*
of flowering *in a* ***model*** *of the function* of the *BvFT1* gene	
in the vernalization *of Beta vulgaris*	of the vernalization of *Beta vulgaris*.

Case C11

> Synaptic inhibition is based on both tonic and phasic release of the inhibitory transmitter γ-aminobutyric acid (GABA). Although phasic GABA release arises from Ca^{2+}-dependent exocytosis from neurons, the mechanism of tonic GABA release is unclear. Here we report that tonic inhibition in the cerebellum is due to GABA being released from glial cells by permeation through the Bestrophin 1 (Best1) anion channel. We demonstrate that GABA directly permeates through Best1 to yield GABA release and that tonic inhibition is eliminated by silencing of Best1. Glial cells express both GABA and Best1, and selective expression of Best1 in glial cells, after preventing general expression of Best1, fully rescues tonic inhibition. Our results identify a molecular mechanism for tonic inhibition and establish a role for interactions between glia and neurons in mediating tonic inhibition. (S. Lee et al. 2010, p. 790)

I believe that the main claim in this abstract is about the mechanism they describe, made most clearly in the third sentence. (See also case A23.)

1. Explanation: model – kind

The release of GABA through the Best1 anion channel *in a **model*** of glial cells in the cerebellum EXPLAINS *multiple qualities* of tonic inhibition in the cerebellum.

explains

The release	*multiple qualities*
of GABA through the Best1 anion channel *in a **model*** of glial cells	of tonic inhibition
in the cerebellum	in the cerebellum.

Case C12

> An International Polar Year aerogeophysical investigation of the high interior of East Antarctica reveals widespread freeze-on that drives substantial mass redistribution at the bottom of the ice sheet. Although the surface accumulation of snow remains the primary mechanism for ice sheet

> growth, beneath Dome A, 24% of the base by area is frozen-on ice. In some places, up to half of the ice thickness has been added from below. These ice packages result from the conductive cooling of water ponded near the Gamburtsev Subglacial Mountain ridges and the supercooling of water forced up steep valley walls. Persistent freeze-on thickens the ice column, alters basal ice rheology and fabric, and upwarps the overlying ice sheet, including the oldest atmospheric climate archive, and drives flow behavior not captured in present models. (Bell et al. 2011, p. 1592)

1. Explanation: model – kind

   The persistence of freeze-on *in a **model** of ice columns* CAUSES the increase in the thickness of the ice column.

   causes

The persistence	the increase
of freeze-on *in a **model***	in the thickness
of ice columns	of the ice column.

2. Explanation: model – kind

   The persistence of freeze-on *in a **model** of ice columns* CAUSES alterations in the rheology of the basal ice of the ice column.

   causes

The persistence	alterations
of freeze-on *in a **model***	in the rheology of the basal ice
of ice columns	of the ice column.

3. Explanation: model – kind

   The persistence of freeze-on *in a **model** of ice columns* CAUSES the upwarping of the overlying ice sheet of the ice column.

causes

The persistence	the upwarping
of freeze-on *in a* ***model***	of the overlying ice sheet
of ice columns	of the ice column.

4. Explanation: model – kind

The persistence of freeze-on *in a* ***model*** *of ice columns* EXPLAINS *multiple qualities* of the flow behaviour of the ice column.

explains

The persistence	*multiple qualities*
of freeze-on *in a* ***model***	of the flow behaviour
of ice columns	of the ice column.

Case C13

> Circadian rhythms in mammals are generated by a feedback loop in which the three PERIOD (PER) proteins, acting in a large complex, inhibit the transcriptional activity of the CLOCK-BMAL1 dimer, which represses their own expression. Although fundamental, the mechanism of negative feedback in the mammalian clock, or any eukaryotic clock, is unknown. We analyzed protein constituents of PER complexes purified from mouse tissues and identified PSF (polypyrimidine tract-binding protein-associated splicing factor). Our analysis indicates that PSF within the PER complex recruits SIN3A, a scaffold for assembly of transcriptional inhibitory complexes and that the PER complex thereby rhythmically delivers histone deacetylases to the *Per1* promoter, which repress *Per1* transcription. These findings provide a function for the PER complex and a molecular mechanism for circadian clock negative feedback. (Duong et al. 2011, p. 1436)

1. Explanation: model – kind

Multiple qualities of the molecular **mechanism** of the PER protein complex *in the circadian clocks of mammals* EXPLAIN *multiple qualities* of the negative feedback in the circadian clocks *of mammals.*

explain

Multiple qualities	*multiple qualities*
of the molecular **mechanism** of the PER protein complex	of the negative feedback
in the circadian clocks *of mammals*	in the circadian clocks *of mammals.*

Case C14

Two laboratory and two randomized field experiments tested a psychological intervention designed to improve students' scores on high-stakes exams and to increase our understanding of why pressure-filled exam situations undermine some students' performance. We expected that sitting for an important exam leads to worries about the situation and its consequences that undermine test performance. We tested whether having students write down their thoughts about an upcoming test could improve test performance. The intervention, a brief expressive writing assignment that occurred immediately before taking an important test, significantly improved students' exam scores, especially for students habitually anxious about test taking. Simply writing about one's worries before a high-stakes exam can boost test scores. (Ramirez and Beilock 2011, p. 211)

1. Explanation: kind – kind

The occurrence of writing about exam worries *by students* CAN CAUSE a boost in exam test scores *for students.*

can cause

The occurrence	a boost
of writing about exam worries	in exam test scores
by students	*for students.*

Case C15

The Sun's outer atmosphere, or corona, is heated to millions of degrees, considerably hotter than its surface or photosphere. Explanations for this

> enigma typically invoke the deposition in the corona of nonthermal energy generated by magnetoconvection. However, the coronal heating mechanism remains unknown. We used observations from the Solar Dynamics Observatory and the Hinode solar physics mission to reveal a ubiquitous coronal mass supply in which chromospheric plasma in fountainlike jets or spicules is accelerated upward into the corona, with much of the plasma heated to temperatures between ∼0.02 and 0.1 million kelvin (MK) and a small but sufficient fraction to temperatures above 1 MK. These observations provide constraints on the coronal heating mechanism(s) and highlight the importance of the interface region between photosphere and corona. (De Pontieu et al. 2011, p. 55)

(See also case B8.)

1. Evidence: data – theory

The range of values *in the* ***measurements*** of the temperature of chromospheric plasma in the corona of the **Sun** PROVIDE constraints *on the* ***theory*** of the heating *in* ***models*** *of the corona of the* ***Sun.***

The range	provide constraints
of values	*on the* ***theory***
in the ***measurements***	of the heating
of the temperature	*in* ***models***
of chromospheric plasma	
in the corona	*of the corona*
of the **Sun**	*of the* ***Sun.***

Case C16

> The effects of a large igneous province on the concentration of atmospheric carbon dioxide (P_{CO_2}) are mostly unknown. In this study, we estimate P_{CO_2} from stable isotopic values of pedogenic carbonates interbedded with volcanics of the Central Atlantic Magmatic Province (CAMP) in the Newark Basin, eastern North America. We find pre-CAMP P_{CO_2} values of ∼2000 parts per million (ppm), increasing to ∼4400 ppm immediately after the first volcanic unit, followed by a steady decrease toward preeruptive levels over the subsequent 300 thousand years, a pattern that is repeated after the second and third flow units. We interpret each P_{CO_2}

> increase as a direct response to magmatic activity (primary outgassing or contact metamorphism). The systematic decreases in P_{CO_2} after each magmatic episode probably reflect consumption of atmospheric CO_2 by weathering of silicates, stimulated by fresh CAMP volcanics. (Schaller, Wright, and Kent 2011, p. 1404)

1. Evidence: data – theory

The systematic decreases in the **measurements** of P_{CO_2} after episodes *of volcanism in **samples** of the atmosphere of the **Earth*** PROBABLY REFLECT the consumption of CO_2 *in the **theory*** of the weathering of silicates *in **models** of the effects of volcanism in the atmosphere of the **Earth.***

probably reflect

The systematic decreases	the consumption
in the **measurements**	of CO_2
of P_{CO_2}	*in the **theory***
after episodes	of the weathering
of volcanism	of silicates
*in **samples***	*in **models***
	of the effects
	of volcanism
of the atmosphere	*in the atmosphere*
*of the **Earth***	*of the **Earth.***

Case C17

> Nano-grained (NG) metals are believed to be strong but intrinsically brittle: Free-standing NG metals usually exhibit a tensile uniform elongation of a few percent. When a NG copper film is confined by a coarse-grained (CG) copper substrate with a gradient grain-size transition, tensile plasticity can be achieved in the NG film where strain localization is suppressed. The gradient NG film exhibits a 10 times higher yield strength and a tensile plasticity comparable to that of the CG substrate and can sustain a tensile true strain exceeding 100% without cracking. A mechanically driven grain boundary migration process with a substantial concomitant grain growth dominates plastic deformation of the gradient NG structure. The extraordinary intrinsic plasticity of gradient NG structures offers their potential for use as advanced coatings of bulk materials. (Fang et al. 2011, p. 1587)

1. Explanation: kind – kind

The migration and growth of the boundary of the grain of the gradient NG film EXPLAINS IN LARGE PART the plastic deformation of the structures of the gradient NG film.

explains in large part	
The migration and growth	the plastic deformation
of the boundary of the grain	of the structures
of the gradient NG film	of the gradient NG film.

Case C18

> One of the most intriguing features of some high-temperature cuprate superconductors is the interplay between one-dimensional "striped" spin order and charge order, and superconductivity. We used mid-infrared femtosecond pulses to transform one such stripe-ordered compound, non-superconducting $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$, into a transient three-dimensional superconductor. The emergence of coherent interlayer transport was evidenced by the prompt appearance of a Josephson plasma resonance in the *c*-axis optical properties. An upper limit for the time scale needed to form the superconducting phase is estimated to be 1 to 2 picoseconds, which is significantly faster than expected. This places stringent new constraints on our understanding of stripe order and its relation to superconductivity. (Fausti et al. 2011, p. 189)

1. Evidence: data – theory

Multiple qualities of the **measurements** of the cuprate superconductor PROVIDE constraints on the order of the stripes *in the* ***theory*** of spin and charge order *in* ***models*** *of the cuprate superconductor.*

Multiple qualities	provide constraints
of the **measurements**	on the order of the stripes *in the* ***theory*** of spin and charge order *in* ***models***
of the cuprate superconductor	*of the cuprate superconductor.*

Case C19

> Transition metal complexes catalyze many important reactions that are employed in medicine, materials science, and energy production. Although high-throughput methods for the discovery of catalysts that would mirror related approaches for the discovery of medicinally active compounds have been the focus of much attention, these methods have not been sufficiently general or accessible to typical synthetic laboratories to be adopted widely. We report a method to evaluate a broad range of catalysts for potential coupling reactions with the use of simple laboratory equipment. Specifically, we screen an array of catalysts and ligands with a diverse mixture of substrates and then use mass spectrometry to identify reaction products that, by design, exceed the mass of any single substrate. With this method, we discovered a copper-catalyzed alkyne hydroamination and two nickel-catalyzed hydroarylation reactions, each of which displays excellent functional-group tolerance. (Robbins and Hartwig 2011, p. 1423)

1. Explanation: kind – entity

The effectiveness of the experimental method for the discovery of catalytic reactions EXPLAINS *the ease* of the **discovery** of copper-catalyzed alkyne hydroamination and two nickel-catalyzed hydroarylation reactions *which are catalytic reactions.*

explains

The effectiveness	*the ease*
of the experimental method for the discovery	of the **discovery** of copper-catalyzed alkyne hydroamination and two nickel-catalyzed hydroarylation reactions
of catalytic reactions	*which are catalytic reactions.*

Case C20

> Deep-ocean carbonate ion concentrations ($[{CO_3}^{2-}]$) and carbon isotopic ratios ($\delta^{13}C$) place important constraints on past redistributions of carbon in the ocean-land-atmosphere system and hence provide clues to the causes of atmospheric CO_2 concentration changes. However, existing deep-sea $[{CO_3}^{2-}]$ reconstructions conflict with one another, complicating paleoceanographic interpretations. Here, we present deep-sea $[{CO_3}^{2-}]$ for five cores from the three major oceans quantified using benthic foraminiferal boron/calcium ratios since the last glacial period. Combined benthic $\delta^{13}C$ and $[{CO_3}^{2-}]$ results indicate that deep-sea-released CO_2 during the early deglacial period (17.5 to 14.5 thousand years ago) was preferentially stored in the atmosphere, whereas during the late deglacial period (14 to 10 thousand years ago), besides contributing to the contemporary atmospheric CO_2 rise, a substantial portion of CO_2 released from oceans was absorbed by the terrestrial biosphere. (Yu et al. 2010, p. 1084)

1. Evidence: data – entity

Multiple qualities of the **measurements** of $\delta^{13}C$ and $[{CO_3}^{2-}]$ *in* ***samples*** *from the deep-sea of the atmosphere in the early deglacial period of the* ***Earth*** INDICATE the preferential storage of deep-sea-released CO_2 in the atmosphere in the early deglacial period of the **Earth.**

indicate

Multiple qualities	the preferential storage
of the **measurements** of δ^{13}C and $[CO_3{}^{2-}]$ *in **samples*** *from the deep-sea*	of deep-sea-released CO_2
of the atmosphere *in the early deglacial period* *of the **Earth***	in the atmosphere in the early deglacial period of the **Earth.**

2. Evidence: data – entity

Multiple qualities of the **measurements** of δ^{13}C and $[CO_3{}^{2-}]$ *in **samples** from the deep-sea of the atmosphere in the late deglacial period of the **Earth*** INDICATE the absorption of a substantial portion of deep-sea-released CO_2 in the terrestrial biosphere in the late deglacial period of the **Earth.**

indicate

Multiple qualities	the absorption
of the **measurements** of δ^{13}C and $[CO_3{}^{2-}]$ *in **samples*** *from the deep-sea* *of the atmosphere*	of a substantial portion of deep-sea-released CO_2 in the terrestrial biosphere
in the late deglacial period *of the **Earth***	in the late deglacial period of the **Earth.**

Case C21

Chronic mucocutaneous candidiasis disease (CMCD) is characterized by recurrent or persistent infections of the skin, nails, and oral and genital mucosae caused by *Candida albicans* and, to a lesser extent, *Staphylococcus aureus*, in patients with no other infectious or autoimmune manifestations. We report two genetic etiologies of CMCD: autosomal recessive deficiency in the cytokine receptor, interleukin-17 receptor A (IL-17RA), and autosomal dominant deficiency of the cytokine interleukin-17F (IL-17F). IL-17RA deficiency is complete, abolishing cellular responses to IL-17A and IL-17F homo- and heterodimers. By contrast, IL-17F deficiency is

> partial, with mutant IL-17F-containing homo- and heterodimers displaying impaired, but not abolished, activity. These experiments of nature indicate that human IL-17A and IL-17F are essential for mucocutaneous immunity against *C. albicans*, but otherwise largely redundant. (Puel et al. 2011, p. 65)

The main explanatory claim here is about the two genetic etiologies for CMCD.

1. Explanation: theory – kind

The autosomal recessive deficiency of the cytokine receptor, interleukin-17 receptor A *in the* ***theory*** of cellular responses to IL-17A and IL-17F homo- and heterodimers *in* ***models*** *of chronic mucocutaneous candidiasis disease* CAUSES *the occurrence of infections* in chronic mucocutaneous candidiasis disease.

causes

The autosomal recessive deficiency	*the occurrence*
of the cytokine receptor, interleukin-17 receptor A *in the* ***theory*** of cellular responses to IL-17A and IL-17F homo- and heterodimers *in* ***models***	*of infections*
of chronic mucocutaneous candidiasis disease	in chronic mucocutaneous candidiasis disease.

Case C22

> We present a high-resolution magnesium/calcium proxy record of Holocene sea surface temperature (SST) from off the west coast of Baja California Sur, Mexico, a region where interannual SST variability is dominated today by the influence of the El Niño-Southern Oscillation (ENSO). Temperatures were lowest during the early to middle Holocene, consistent with documented eastern equatorial Pacific cooling and numerical model simulations of orbital forcing into a La Niña-like state at that time. The early Holocene SSTs were also characterized by millennial-scale fluctuations that correlate with cosmogenic nuclide proxies of solar variability, with inferred solar minima corresponding to El Niño-like (warm) conditions, in apparent agreement with the theoretical "ocean dynamical thermostat" response of ENSO to exogenous radiative forcing. (Marchitto et al. 2010, p. 1378)

1. Evidence: entity – theory

The millennial-scale and correlations with solar variability of the fluctuations of the temperatures of the surfaces of the seas off Baja California Sur, Mexico in the **Holocene era** *which is a sea* ARE IN APPARENT AGREEMENT WITH *multiple qualities* of the **theory** of the “ocean dynamical thermostat” response of ENSO to exogenous radiative forcing *in **models** of the fluctuations of the temperatures of the surfaces of seas.*

are in apparent agreement with

The millennial-scale and correlations with solar variability	*multiple qualities*
of the fluctuations of the temperatures of the surfaces of the seas off Baja California Sur, Mexico in the **Holocene era**	of the **theory** of the “ocean dynamical thermostat” response of ENSO to exogenous radiative forcing *in **models*** *of the fluctuations* *of the temperatures* *of the surfaces*
which is a sea	*of seas.*

Case C23

Large earthquakes produce crustal deformation that can be quantified by geodetic measurements, allowing for the determination of the slip distribution on the fault. We used data from Global Positioning System (GPS) networks in Central Chile to infer the static deformation and the kinematics of the 2010 moment magnitude (Mw) 8.8 Maule megathrust earthquake. From elastic modeling, we found a total rupture length of ∼500 kilometers where slip (up to 15 meters) concentrated on two main asperities situated on both sides of the epicenter. We found that rupture reached shallow depths, probably extending up to the trench. Resolvable afterslip occurred in regions of low coseismic slip. The low-frequency hypocenter is relocated 40 kilometers southwest of initial estimates. Rupture propagated bilaterally at about 3.1 kilometers per second, with possible but not fully resolved velocity variations. (Simons et al. 2011, p. 1421)

This is a rare case of an abstract in which the authors are mainly describing the data they collected about an event.

1. Evidence: data – entity

   Multiple qualities of geodetic **measurements** from the networks of the GPS system in **Central Chile** SHOW *multiple qualities* of the **2010 moment magnitude (Mw) 8.8 Maule megathrust earthquake** in **Central Chile.**

show	
Multiple qualities	*multiple qualities*
of geodetic **measurements** from the networks of the GPS system	of the **2010 moment magnitude (Mw) 8.8 Maule megathrust earthquake**
in **Central Chile**	in **Central Chile.**

Case C24

> Seismic discontinuities in Earth typically arise from structural, chemical, or temperature variations with increasing depth. The pressure-induced iron spin state transition in the lower mantle may influence seismic wave velocities by changing the elasticity of iron-bearing minerals, but no seismological evidence of an anomaly exists. Inelastic x-ray scattering measurements on ($Mg_{0.83}Fe_{0.17}$)O-ferropericlase at pressures across the spin transition show effects limited to the only shear moduli of the elastic tensor. This explains the absence of deviation in the aggregate seismic velocities and, thus, the lack of a one-dimensional seismic signature of the spin crossover. The spin state transition does, however, influence shear anisotropy of ferropericlase and should contribute to the seismic shear wave anisotropy of the lower mantle. (Antonangeli et al. 2011, p. 64)

1. Explanation: kind – kind

   The limitation to the shear moduli of the elastic tensor of pressure-induced spin state transitions in iron EXPLAINS the absence of deviation in the aggregate of seismic velocities *in iron.*

explains

The limitation	the absence
to the shear moduli	of deviation
of the elastic tensor	in the aggregate
of pressure-induced spin state transitions	of seismic velocities
in iron	*in iron.*

2. Explanation: kind – data

The limitation to the shear moduli of the elastic tensor of pressure-induced spin state transitions in iron EXPLAINS the lack of a one-dimensional seismic signature on **measurements** *of a* ***sample*** *of iron.*

explains

The limitation	the lack
to the shear moduli	of a one-dimensional seismic signature
of the elastic tensor	on **measurements**
of pressure-induced spin state transitions	*of a* ***sample***
in iron	*of iron.*

Case C25

> Vernalization is an environmentally-induced epigenetic switch in which winter cold triggers epigenetic silencing of floral repressors and thus provides competence to flower in spring. In *Arabidopsis*, winter cold triggers enrichment of tri-methylated histone H3 Lys^{27} at chromatin of the floral repressor, *FLOWERING LOCUS C* (*FLC*), and results in epigenetically stable repression of *FLC*. This epigenetic change is mediated by an evolutionarily conserved repressive complex, polycomb repressive complex 2 (PRC2). Here, we show that a long intronic noncoding RNA [termed COLD ASSISTED INTRONIC NONCODING RNA (COLDAIR)] is required for the vernalization-mediated epigenetic repression of *FLC*. COLDAIR physically associates with a component of PRC2 and targets PRC2 to *FLC*. Our results show that COLDAIR is required for establishing stable repressive chromatin at *FLC* through its interaction with PRC2. (Heo and Sung 2011, p. 76)

1. Explanation: model – kind

Multiple qualities of COLDAIR *in the **model*** of interaction with PCR2 *in vernalization in Arabidopsis* EXPLAIN the stability of the repressive chromatin at *FLC in vernalization in Arabidopsis.*

explain

Multiple qualities	the stability
of COLDAIR *in the **model*** of interaction with PCR2	of the repressive chromatin at *FLC*
in vernalization *in Arabidopsis*	*in vernalization* *in Arabidopsis.*

Appendix B

Appendix B: Code Listings

These programs were written in the Python 2.7 programming language using the standard library and these third-party libraries:

- Natural Language Toolkit (nltk) version 2.0.1rc1 (`http://www.nltk.org`).
- Numeric Python (numpy) version 1.5.1 (`http://numpy.scipy.org`).
- matplotlib (pylab) version 1.1.0 (`http://matplotlib.sourceforge.net`).
- BeautifulSoup version 3.2.0 (`http://www.crummy.com/software/BeautifulSoup/`).

B.1 Articles

File: articles.py

```
from BeautifulSoup import BeautifulSoup
import codecs, os, re, string, pickle, unicodedata
import nltk

# Set the data directory
datadir = '/Users/james/Documents/School/Philosophy/PhDThesis/Thesis/data/'

# Normalize the whitespace in the content of an HTML paragraph.
def cleanParagraph(p):
  texts = p.findAll(text=True)
  output = ''.join(texts).strip()
  output = re.sub(r'\s+', ' ', output)
  return output

# Convert some HTML to LaTeX.
def cleanLine(p):
  texts = []
```

```
  for c in p.contents:
    if c.__class__.__name__ == 'NavigableString':
      texts.append(c)
    elif c.name == u'em':
      texts.append(r"\emph{%s}" % c.string)
    elif c.name == u'sup':
      texts.append(r"$^{%s}$" % c.string)
    elif c.name == u'sub':
      texts.append(r"$_{%s}$" % c.string)
    else:
      pass
  output = ''.join(texts).strip()
  output = re.sub(r'\s+', ' ', output)
  output = re.sub(u'\u03b1', r'$\\alpha$', output)
  output = re.sub(u'\u03b4', r'$\\delta$', output)
  output = re.sub(u'\u03B6', r'$\\zeta$', output)
  return output

def cleanAuthor(p):
  return "{%s}" % cleanLine(p)

def makeCiteKey(last_name, year, letter=''):
  output = unicodedata.normalize('NFKD',
    last_name).encode('ascii', 'ignore') + year + letter
  return re.sub('}', '', output)

# Match certain tricky content.
def finder(doc, regex, nodeid):
  match = re.search(regex,
    doc.find('span', nodeid).string.strip()
  )
  if match:
    return match.group(0)
  else:
    return ''

# Extract article data from a Science HTML page.
def parseScienceReport(html):
  d = BeautifulSoup(html)

  # A list of author names
  authors = map(lambda n: n.string.strip(), d.findAll('a', 'name-search')) + \
      map(cleanAuthor, d.findAll('span', 'collab'))
  year = finder(d, r'\d{4}', 'slug-pub-date')
  last_name = authors[0].split()[-1]
  cite_key = makeCiteKey(last_name, year)

  # The field of science -- this selector is fragile.
  science = d.find(text='More in Collections').findNext('a').string.strip()

  paragraphs = d.find('h1', {'id':'article-title-1'}).findNextSiblings('p')
  cleanParagraphs = [cleanParagraph(p) for p in paragraphs]

  abstract = cleanParagraph(d.find('div', 'abstract').p)
```

```
  body = u'\n\n'.join(cleanParagraphs)
  content = u'\n\n\n'.join([abstract, body])

  article = {
    'journal': 'Science',

    # The format is either 'Report' or 'Research Article'
    'format': d.find('ul', 'subject-headings').li.string.strip(),

    'title':  cleanLine(d.find('h1', {'id':'article-title-1'})),

    'doi':    d.find('span', 'slug-doi').string.strip(),
    'volume': finder(d, r'\d+', 'slug-vol'),
    'number': finder(d, r'\d+', 'slug-issue'),
    'pages':  finder(d, r'\d+-\d+', 'slug-pages'),
    'year':     year,
    'cite_key': cite_key,

    'authors':    authors,
    'authorLine': ', '.join(authors),

    'science':  science,
    'keywords': [science],

    'abstract': abstract,
    'body':     body,
    'content':  content
  }

  return article

# Generate a plain text version of the article.
def formatArticle(article):
  return u'''%(journal)s %(format)s %(doi)s
%(title)s
%(authorLine)s
Keywords: %(keywords)s

Abstract: %(abstract)s


%(body)s

''' % article

# Generate a BibTeX entry for the article.
def formatBibTeX(article):
  article['bibtex_authors'] = ' and '.join(article['authors'])
  return """@article{%(cite_key)s,
  Author = {%(bibtex_authors)s},
  Title = {%(title)s},
  Journal = {Science},
  Publisher = {American Association for the Advancement of Science},
  Volume = {%(volume)s},
```

```
  Number = {%(number)s},
  Pages = {%(pages)s},
  Year = {%(year)s}}""" % article


# Load a stored article or parse it from HTML.
def loadArticle(basename, refresh=False):
  # If the file has already been parsed and pickled, just load it
  p = os.path.join(datadir, 'pickle', '%s.pickle' % basename)
  if os.path.exists(p) and not refresh:
    f = open(p, 'r')
    article = pickle.load(f)
    f.close()
    return article

  print 'Parsing article %s' % basename

  # Read the HTML
  f = open(os.path.join(datadir, 'html', '%s.html' % basename), 'r')
  html = f.read()
  f.close()

  # Parse it
  article = parseScienceReport(html)
  article['basename'] = basename

  # Spit it out as text
  f = codecs.open(os.path.join(
        datadir, 'text', '%s.txt' % basename), 'w', 'utf-8')
  f.write(formatArticle(article))
  f.close()

  storeArticle(article, basename)

  return article

# Store the data object for later use
def storeArticle(article, basename):
  f = open(os.path.join(
        datadir, 'pickle', '%s.pickle' % basename), 'w')
  pickle.dump(article, f)
  f.close()


# Load the full set of Science articles.
def loadArticles(refresh=False):
  articles = []
  cite_keys = {}

  for fullname in os.listdir(os.path.join(datadir, 'html')):
    path, filename = os.path.split(fullname)
    basename, extension = os.path.splitext(filename)

    if not basename.startswith('science'):
```

```
      continue

    article = loadArticle(basename, refresh)

    # Ensure the cite_key is unique.
    key_count = 0
    while article['cite_key'] in cite_keys:
      key_count += 1
      base = article['cite_key'].split('-')[0]
      article['cite_key'] = base +'-'+ str(key_count)

    if key_count > 0:
      storeArticle(article, basename)
      print '  New cite_key %s' % article['cite_key']
    cite_keys[article['cite_key']] = article

    articles.append(article)

  return articles

# Break the article content into words and sentences.
def tokenize(article):
  if not 'sentences' in article:
    article['sentences'] = [nltk.word_tokenize(s) for s in
                             nltk.sent_tokenize(article['content'])]
  if not 'words' in article:
    article['words'] = []
    for s in article['sentences']: article['words'].extend(s)
  return article

# Generate a complete BibTeX file.
def generateBibTeX():
  articles = loadArticles()
  results = [formatBibTeX(a) for a in articles]
  output = u'\n\n\n'.join(results)
  f = codecs.open(os.path.join(
        datadir, '..', 'build', 'articles.bib'), 'w', 'utf-8')
  f.write(output)
  f.close()
```

B.2 Keywords

File: keywords.py

```
from __future__ import division
import os, pickle
import pylab
from articles import loadArticles

sortedKeywords = [
  u'Computers, Mathematics',
  u'Physics',
```

```
  u'Physics, Applied',
  u'Chemistry',
  u'Materials Science',
  u'Engineering',
  u'Astronomy',
  u'Planetary Science',
  u'Geochemistry, Geophysics',
  u'Atmospheric Science',
  u'Oceanography',

  u'Biochemistry',
  u'Molecular Biology',
  u'Microbiology',
  u'Cell Biology',
  u'Genetics',
  u'Development',
  u'Evolution',
  u'Ecology',
  u'Botany',
  u'Paleontology',

  u'Anatomy, Morphology, Biomechanics',
  u'Physiology',
  u'Virology',
  u'Immunology',
  u'Medicine, Diseases',
  u'Epidemiology',
  u'Neuroscience',

  u'Psychology',
  u'Sociology',
  u'Economics',
  u'Anthropology',
  u'Education',
]

# Count the number of articles by keyword
def loadKeywords(filename='keywords.pickle', articles=loadArticles()):
  # Either load the stored data...
  if os.path.exists(filename):
    f = open(filename, 'r')
    keywords, labels, counts = pickle.load(f)
    f.close()

  # Or generate the keyword data.
  else:
    #keywords = sorted(set([a['science'] for a in articles]))
    keywords = sortedKeywords
    counts = {}
    for keyword in keywords:
      counts[keyword] = len([a for a in articles if a['science'] == keyword])

    # Make a list of labels that is slightly modified.
    labels = [x for x in keywords]
```

```
    index = labels.index(u'Anatomy, Morphology, Biomechanics')
    labels[index] = u'Anatomy, Biomechanics'

    if filename:
      f = open(filename, 'w')
      pickle.dump((keywords, labels, counts), f)
      f.close()

  return keywords, labels, counts

# Generate a plot of values for each keyword.
def plotKeywords(filename, title, values, average=None):
  if os.path.exists(filename):
    return False

  keywords, labels, counts = loadKeywords()
  length = len(labels)
  indices = range(length)

  # Generate a barplot of the number of articles by frequency.
  fig = pylab.figure(figsize=(10,5))
  fig.subplots_adjust(left=0.10, right=0.96, bottom=0.5, top=0.96)
  ax = fig.add_subplot(1,1,1)

  ax.bar(indices, values, align='center', facecolor='#cccccc')

  if average != None:
    cover = [-1,length+1]
    ax.plot(cover, [average for x in cover], color='black', linestyle='-', lw=2)

  ax.set_ylabel(title)
  ax.set_xlim(-1, length)
  ax.set_xticks(indices)
  ax.set_xticklabels(labels, rotation='vertical')

  fig.savefig(filename)
  pylab.close()
  return True
```

B.3 Terms

File: terms.py

```
from __future__ import division
import os
import pylab

explainTerms  = ['explain', 'explains', 'explained', 'explaining',
                 'explainable', 'explanation', 'explanations', 'unexplained',
                 'unexplainable', 'explicate', 'explicates', 'explicated',
                 'explicable', 'inexplicable']
becauseTerms  = ['because']
```

```
evidenceTerms = ['evidence', 'evident', 'evidential']
showTerms     = ['show', 'shows', 'showed', 'shown', 'showing']

searchTerms = [
  ('explain',     explainTerms),
  ('because',     becauseTerms),
  ('reason',      ['reason', 'reasons', 'reasoning']),
  ('account',     ['account', 'accounts', 'accounted', 'accounting']),
  ('understand',  ['understand', 'understands', 'understood', 'understanding']),
  ('evidence',    evidenceTerms),
  ('show',        showTerms),
  ('discover',    ['discover', 'discovers', 'discovered', 'discovering',
                    'discovery', 'discoveries']),
  ('reveal',      ['reveal', 'reveals', 'revealed', 'revealing']),
  ('suggest',     ['suggest', 'suggests', 'suggested', 'suggesting']),
  ('implication', ['imply', 'implies', 'implied', 'implying', 'implication',
                    'implications']),
  ('indicate',    ['indicate', 'indicates', 'indicated', 'indicating']),
  ('confirm',     ['confirm', 'confirms', 'confirmed', 'confirming']),
  ('establish',   ['establish', 'establishes', 'established', 'establishing']),
  ('cause',       ['cause', 'causes', 'caused', 'causing', 'causal',
                    'causation']),
  ('theory',      ['theory', 'theories', 'theoretical']),
  ('law',         ['law', 'laws', 'lawful']),
  ('mechanism',   ['mechanism', 'mechanisms']),
  ('model',       ['model', 'models', 'modelled', 'modelling']),
  ('phenomena',   ['phenomena', 'phenomenon']),
  ('effect',      ['effect', 'effects'])
]

terms = [x[0] for x in searchTerms]

# Generate a plot of values for each term.
def plotTerms(filename, title, values, percent=''):
  if os.path.exists(filename):
    return False

  length = len(terms)
  indices = range(length)

  # Generate a barplot of the number of articles by frequency.
  fig = pylab.figure(figsize=(8,4))
  fig.subplots_adjust(left=0.10, right=0.90, bottom=0.3, top=0.96)
  ax = fig.add_subplot(1,1,1)
  ax.bar(indices, values, align='center', facecolor='#cccccc')
  ax.set_ylabel(title)
  if percent:
    ax2 = ax.twinx()
    ax2.set_ylabel(percent)
    ax2.set_ylim(0, 100)
    ax.set_ylim(0, 781)
  ax.set_xlim(-1, length)
  ax.set_xticks(indices)
  ax.set_xticklabels(terms, rotation='vertical')
```

```
  fig.savefig(filename)
  pylab.close()
  return True
```

B.4 Frequencies

File: frequencies.py

```
from __future__ import division
import os, pickle
import nltk
from articles import loadArticles, tokenize
from terms import searchTerms

# Get frequencies for all search terms.
def searchTermsFrequencies(terms, articles):
  frequencies = {}
  for item in terms:
    title, group = item
    frequencies[title] = groupFrequencies(group, articles)
  return frequencies

# Get frequencies for the words in this group.
def groupFrequencies(group, articles):
  articlesByKeyword = nltk.defaultdict(int)
  tokensByKeyword  = nltk.defaultdict(int)

  for article in articles:
    # Break the content into words and sentences
    # then get the frequency distribution.
    tokenize(article)
    article['wordsFD'] = nltk.FreqDist(
      word.lower() for word in article['words'])

    # Count the words of interest
    keyword = article['science']
    fd = article['wordsFD']
    atLeastOne = False
    for word in group:
      if fd[word] > 0:
        tokensByKeyword[keyword] += fd[word]
        atLeastOne = True
    if atLeastOne:
      articlesByKeyword[keyword] += 1

  numberOfArticles = len(articles)
  totalArticles = sum(articlesByKeyword[k] for k in articlesByKeyword.keys())
  totalTokens   = sum(tokensByKeyword[k]   for k in tokensByKeyword.keys())

  return {
    'articles': {
```

```
      'keywords': articlesByKeyword,
      'total':    totalArticles,
      'percent':  100 * totalArticles / numberOfArticles
    },
    'tokens': {
      'keywords': tokensByKeyword,
      'total':    totalTokens,
      'average':  totalTokens / numberOfArticles
    }
  }


def loadFrequencies(filename='frequencies.pickle', terms=searchTerms,
      articles=loadArticles()):
  # Either load the stored data...
  if filename and os.path.exists(filename):
    f = open(filename, 'r')
    frequencies = pickle.load(f)
    f.close()

  # Or generate the data.
  else:
    frequencies = searchTermsFrequencies(searchTerms, articles)
    frequencies['numberOfArticles'] = len(articles)
    frequencies['numberOfWords'] = \
        sum(len(article['words']) for article in articles)

    # Store the data.
    if filename:
      f = open(filename, 'w')
      pickle.dump(frequencies, f)
      f.close()

  return frequencies
```

B.5 Genres

File: genres.py

```
from __future__ import division
import os, pickle
import nltk, pylab
from terms import searchTerms

genreSearchTerms = searchTerms
genreTerms = [x[0] for x in genreSearchTerms]

corpusNames = ['Science', 'Gutenberg', 'Reuters']
corpusColors = {
  'Science': '#cccccc',
  'Gutenberg': '#777777',
  'Reuters': '#333333'
```

```
}

# Get the word frequencies by genre.
def loadGenres(filename='genres.pickle'):
  # Either load the stored data...
  if filename and os.path.exists(filename):
    f = open(filename, 'r')
    genres = pickle.load(f)
    f.close()

  # Or generate the genres data.
  else:
    from nltk.corpus import gutenberg
    from nltk.corpus import reuters
    from frequencies import loadFrequencies
    frequencies = loadFrequencies()

    # Assemble the Science frequency data.
    genres = {
      'Science': {'words': frequencies['numberOfWords']}
    }
    for term in genreTerms:
      count = frequencies[term]['tokens']['total']
      freq = 1000000 * count / frequencies['numberOfWords']
      genres['Science'][term] = {
        'count':     count,
        'frequency': freq
      }

    # Get the data for the other corpora.
    corpora = {
      'Gutenberg': gutenberg,
      'Reuters': reuters
    }
    for corpus in corpusNames[1:]:
      words = corpora[corpus].words()
      fd = nltk.FreqDist(word.lower() for word in words)
      genres[corpus] = {
        'words': len(words),
      }
      for item in genreSearchTerms:
        title, group = item
        count = sum(fd[word] for word in group)
        freq = 1000000 * count / len(words)
        genres[corpus][title] = {
          'count':     count,
          'frequency': freq
        }

    # Store the data.
    if filename:
      f = open(filename, 'w')
      pickle.dump(genres, f)
      f.close()
```

```
  return genres


def plotGenres(filename, title='Tokens per Million Words'):
  if os.path.exists(filename):
    return False

  genres = loadGenres()
  labels = []
  values = []
  colors = []
  for term in genreTerms:
    for corpus in corpusNames:
      labels.append('%s "%s"' % (corpus.capitalize(), term))
      values.append(genres[corpus][term]['frequency'])
      colors.append(corpusColors[corpus])
    labels.append('space')
    values.append(0)
    colors.append('blue')

  length = len(labels) - 1
  indices = range(length)

  # Generate a barplot of the token frequency.
  # More complicated than usual because I want the bars to be different colours.
  fig = pylab.figure(figsize=(8,4))
  fig.subplots_adjust(left=0.10, right=0.96, bottom=0.3, top=0.96)
  ax = fig.add_subplot(1,1,1)
  bars = []
  for i in indices:
    bars.append(
      ax.bar([i], values[i], align='center', facecolor=colors[i]))
  ax.legend(bars[0:len(corpusNames)], corpusNames, loc=1)
  ax.set_ylabel(title)
  ax.set_xlim(-1, length)
  ax.set_xticks([(x*4+1) for x in range(len(genreTerms))])
  ax.set_xticklabels(genreTerms, rotation='vertical')

  fig.savefig(filename)
  pylab.close()
  return True
```

B.6 N-Grams

File: ngrams.py

```
from __future__ import division
import os, pickle
import nltk
from articles import loadArticles, tokenize
```

```
ngramRange = range(2,6)
ngramTerms = [
  ['explain', 'explained'],
  ['show']
]
bases = ['explain', 'be explained', 'show']
modals = ['may','can','could']
phrases = []
for modal in modals:
  for base in bases:
    phrases.append(' '.join([modal, base]))
    phrases.append(' '.join([modal, 'not', base]))

# Test whether a word is in a list of words
def test(t):
  for term in ngramTerms[0]:
    if term in t: return True
  return False

# Get the n-grams
def loadNGrams(filename='ngrams.pickle', articles=loadArticles()):
  # Either load the stored data...
  if os.path.exists(filename):
    f = open(filename, 'r')
    ngrams, ngramTermCounts, ngramPhraseCounts = pickle.load(f)
    f.close()

  # Or generate the n-gram data.
  else:
    # Count the total number of ngramTerms and phrases
    ngramTermCounts = nltk.defaultdict(int)
    ngramPhraseCounts = nltk.defaultdict(int)
    for article in articles:
      tokenize(article)
      for sentence in article['sentences']:
        # Join the words with normalized spaces so we can match phrases.
        sent = ' '.join(word.lower() for word in sentence)
        for phrase in phrases:
          if phrase in sent: ngramPhraseCounts[phrase] += 1
        for word in sentence:
          for terms in ngramTerms:
            if word.lower() in terms: ngramTermCounts[terms[0]] +=1

    # Count the n-grams including the ngramTerms
    ngrams = {}
    for n in ngramRange:
      ngrams[n] = []
      for article in articles:
        for sentence in article['sentences']:
          words = [w.lower() for w in sentence]
          if not test(words): continue
          ngrams[n].extend(
            t for t in nltk.util.ngrams(words,n) if test(t))
```

```
    # Store the data.
    if filename:
      f = open(filename, 'w')
      pickle.dump((ngrams, ngramTermCounts, ngramPhraseCounts), f)
      f.close()

  return ngrams, ngramTermCounts, ngramPhraseCounts
```

B.7 Positions

File: positions.py

```
from __future__ import division
import os, pickle
import nltk, pylab
from articles import loadArticles, tokenize
from terms import searchTerms

# Get the index at which a word occurs in a list of words.
def getIndices(word, words):
  indices = []
  for i in range(0,len(words)):
    if word.lower() == words[i].lower():
      # return an index as a proportion of the article length
      indices.append(i / len(words))
  return indices

# Get the indices for a set of terms.
def searchTermsPositions(terms, articles):
  positions = {}
  for item in terms:
    title, group = item
    positions[title] = groupPositions(group, articles)
  return positions

# Get the indices for a list of words.
def groupPositions(group, articles):
  positions = []

  for article in articles:
    tokenize(article)
    words = article['words']

    # Count the words of interest
    for word in group:
      positions.extend(getIndices(word, words))

  return positions

# Get the positions data.
def loadPositions(filename='positions.pickle', terms=searchTerms,
      articles=loadArticles()):
```

```
  # Either load stored data...
  if os.path.exists(filename):
    f = open(filename, 'r')
    positions = pickle.load(f)
    f.close()

  # Or generate the position data.
  else:
    positions = searchTermsPositions(terms, articles)

    # Store the data.
    if filename:
      f = open(filename, 'w')
      pickle.dump(positions, f)
      f.close()

  return positions

# Plot the positions as a histogram
def plotPositions(filename, data, ymax=0):
  if os.path.exists(filename):
    return False

  fig = pylab.figure(figsize=(8,3))
  fig.subplots_adjust(left=0.10, right=0.96, bottom=0.15, top=0.96)

  ax = fig.add_subplot(1,1,1)
  ax.set_ylabel('Tokens at Position')
  ax.set_xlabel('Position in Article')

  ax.hist(data, bins=20, range=[0,1], facecolor='#cccccc')
  if ymax > 0: ax.set_ylim(0, ymax)

  fig.savefig(filename)
  pylab.close()
  return True
```

B.8 Samples

File: samples.py

```
from __future__ import division
import os, codecs, re, random, subprocess
import nltk
from articles import datadir, loadArticles

# Set the data directory
sampledir = '/Users/james/Documents/School/Philosophy/PhDThesis/Thesis/'

pattern = re.compile(r'\b(explain|explains|explained)\b',
                     re.IGNORECASE | re.MULTILINE)
```

```
articles = []

# Select a random article; collect all matching sentences;
# return a random matching sentence.
def sampleA():
  global articles
  while True:
    sentences = []
    article = random.choice(articles)
    for sentence in article['full_sentences']:
      if pattern.search(sentence):
        sentences.append(sentence)
    if len(sentences) > 0:
      return (article, random.choice(sentences))

# Select a random article and return a random sentence.
def sampleB():
  global articles
  article = random.choice(articles)
  return (article, random.choice(article['full_sentences']))

# Select a random article and return its abstract.
def sampleC():
  global articles
  article = random.choice(articles)
  return (article, article['abstract'])

methods = {
  'A': sampleA,
  'B': sampleB,
  'C': sampleC
}

# Collect a sample using the method provided and save it to a text file.
def generateSample(method, limit=25):
  global sampledir, articles, methods

  articles = loadArticles()

  for article in articles:
    if not 'full_sentences' in article:
      article['full_sentences'] = nltk.sent_tokenize(article['content'])

  samples = []
  results = []
  while len(samples) < limit:
    article, sample = methods[method]()
    # Sample without replacement
    if sample in samples: continue
    else: samples.append(sample)
    metadata = [
      '%s%i' % (method, len(samples)),
      article['doi'],
```

```
      article['basename'],
      '000'
    ]
    results.append(' '.join(metadata) +'\n\n'+ sample)
  file = codecs.open(os.path.join(sampledir, 'A-Sample%s.txt' % method),
            'a', 'utf-8')
  file.write('\n\nfailure: todo\n\n********************\n\n'.join(results))
  file.close()
```

B.9 Cases

File: cases.py

```
from __future__ import division
import os, codecs, re, copy
import nltk
from articles import loadArticle

caseSplitter = re.compile(r'\s+\*{20}\s+', re.MULTILINE)
blockSplitter = re.compile(r'\s*\n\s*\n\s*', re.MULTILINE)

categories = ['data', 'entity', 'kind', 'model', 'theory']
types = [
  ('theory', ['theory']),
  ('model',  ['model', 'mechanism']),
  ('entity', ['!', 'sample', 'specimen']),
  ('data',   ['data', 'measurements', 'observations', 'results', 'images'])
]
highlight = ['theory',
             'models', 'model', 'mechanisms', 'mechanism',
             'samples', 'sample', 'specimens', 'specimen',
             'data', 'measurements', 'observations', 'results', 'images']

# Parse a series of cases from a file.
def parseCases(filename):
  f = codecs.open(filename, 'r', 'utf-8')
  content = f.read()
  f.close()
  cases = caseSplitter.split(content)
  results = []
  for case in cases:
    results.append(parseCase(case))
  return results

# Parse a single case from its text representation.
def parseCase(content):
  blocks = blockSplitter.split(content.strip())
  header = blocks.pop(0).strip()

  try:
    label, doi, basename, page = header.split()
  except:
```

```
    print "Bad Header:", header
    raise

  quotation = blocks.pop(0)

  if blocks[0].startswith('type: '):
    notes = ''
  else:
    notes = blocks.pop(0)

  try:
    explanations = parseExplanations(blocks)
    explanations[0]['type']
  except:
    print "Exception when parsing case", label
    raise

  return {
    'label': label,
    'basename': basename,
    'article': loadArticle(basename),
    'quotation': quotation,
    'page': page,
    'notes': notes,
    'explanations': explanations,
    'success': explanations[0]['type'] != 'failure',
    'content': content
  }

# Parse a block of explanations for a case.
def parseExplanations(blocks):
  explanations = []
  for i in range(len(blocks)):
    block = blocks[i]
    try:
      explanations.append(parseExplanation(block))
    except:
      print "Exception when parsing explanation %s" % (i+1)
      raise
  return explanations

# Parse a single explanation for a case.
# This can be a little tricky.
def parseExplanation(block):
  output = {
    'type': '',
    'phrase': '',
    'relation': '',
    'notes': '',
    'explanans': {
      'type': '',
      'top' : [],
      'core': [],
      'base': []
```

```
  },
  'explanandum': {
    'type': '',
    'top' : [],
    'core': [],
    'base': []
  }
}

lines = block.splitlines()

line = lines.pop(0)
if line.startswith('type: ') and line[6:] in \
    ['failure', 'explanation', 'evidence']:
  output['type'] = line[6:]
else:
  raise ValueError("The first line of an explanation block must "+ \
          " provide the type. This one is invalid: ", line)

if len(lines) and lines[0].startswith('failure: '):
  output['failure'] = lines.pop(0)[9:].strip()
if len(lines) and lines[0].startswith('phrase: '):
  output['phrase'] = lines.pop(0)[8:].strip()
if len(lines) and lines[0].startswith('notes: '):
  output['notes'] = lines.pop(0)[7:].strip()

# The error handling makes this code uglier.
x = 'explanans'
y = 'top'
for line in lines:
  if y == 'top':
    if line.startswith('>'):
      raise ValueError("Extra base marker somewhere.")
    output[x][y].append(line)
    y = 'core'
    continue
  if y == 'core':
    if line.startswith('='):
      raise ValueError("Missing base marker in explanans.")
    if line.startswith('>'):
      y = 'base'
    else:
      if not output[x]['type']:
        t = getType(line)
        if t != '':
          output[x]['type'] = t
      output[x][y].append(line)
      continue
  if y == 'base':
    if line.startswith('='):
      if x == 'explanandum':
        raise ValueError("Too many lines beginning with '='.")
      output['relation'] = line
      x = 'explanandum'
```

```
        y = 'top'
      else:
        if not output[x]['type']:
          t = getType(line)
          if t != '':
            output[x]['type'] = t
        output[x][y].append(line)
      continue
    raise ValueError("Malformed explanation block: " + line)

  if len(lines) and x != 'explanandum' and y != 'base':
    raise ValueError("Malformed explanation block: " + line)
  if len(output['explanans']['base']) != len(output['explanandum']['base']):
    raise ValueError("Mismatched bases.")

  for x in ['explanans', 'explanandum']:
    if not output[x]['type']:
      output[x]['type'] = 'kind'
  if not output['phrase']:
    output['phrase'] = output['relation'][2:] # strip '=' from relation

  return output

# Figure out the type of an explanans or explanandum from its annotation.
def getType(line):
  for t in types:
    label, words = t
    for word in words:
      if word in line:
        return label
  return ''

# Format an item in an explanation as LaTeX.
def formatItem(line):
  line = line.replace(r"= ", '')
  line = line.replace(r"> ", '')
  line = line.replace(r">", '')
  #line = line.replace(r"!", '')
  line = line.replace(r"%", r'\%')
  for word in highlight:
    line = line.replace(word, r"\textbf{%s}" % word)
  if line.strip().startswith('* '):
    i = line.index('*')
    line = line[:i] + r"\emph{%s}" % line[i+2:]
  if line.find('!') > -1:
    i = line.index('!')
    line = line[0:i] + r"\textbf{%s}" % line[i+1:]

  return line

def formatCell(line):
  line = formatItem(line)
  if line.startswith('  '):
    line = "\\hspace{12pt}" + line[2:]
```

```
  return line

# Generate a gloss paragraph.
def formatGloss(explanation):
  gloss = []

  explanans = explanation['explanans']
  for item in explanans['top'] + explanans['core'] + explanans['base']:
    gloss.append(formatItem(item))

  gloss.append(r'{\sc %s}' % formatItem(explanation['relation']))

  explanandum = explanation['explanandum']
  for item in explanandum['top'] + explanandum['core'] + explanandum['base']:
    gloss.append(formatItem(item))

  return ' '.join(gloss)

# Generate a LaTeX table (this gets ugly).
def formatTable(explanation):
  explanans = explanation['explanans']
  explanandum = explanation['explanandum']

  w = '2.5in'
  s = ' \\\\\n\n  '
  table = [r"\begin{tabular}{p{%s}p{%s}}" % (w,w)]
  #table = [r"\begin{tabular}{ll}"]
  table.append(r"\multicolumn{2}{c}{%s} \\" %
    formatCell(explanation['relation']))
  table.append(r"""\begin{minipage*}{t}{%s}
  %s
\end{minipage*} & \begin{minipage*}{t}{%s}
  %s
\end{minipage*} \\ \hline""" % (
    w, formatCell(explanans['top'][0]),
    w, formatCell(explanandum['top'][0])
  ))
  table.append(r"""\begin{minipage*}{t}{%s}
  %s
\end{minipage*}\vspace{6pt} & \begin{minipage*}{t}{%s}
  %s
\end{minipage*}\vspace{6pt} \\ \hline""" % (
    w, s.join(map(formatCell, explanans['core'])),
    w, s.join(map(formatCell, explanandum['core']))
  ))
  #table.append(r"\multicolumn{2}{c}{%s -- %s} \\ \hline" %
  #  (explanans['type'], explanandum['type'])
  #)
  table.append(r"""\begin{minipage*}{t}{%s}
  %s
\end{minipage*} & \begin{minipage*}{t}{%s}
  %s
\end{minipage*} \\""" % (
    w, s.join(map(formatCell, explanans['base'])),
```

```
    w, s.join(map(formatCell, explanandum['base']))
  ))
  table.append(r'\end{tabular}')

  return '\n'.join(table)

# Format an entire case in LaTeX for the Appendix.
def formatCase(case):
  page = case['page']
  # Hack to make case C pages work.
  if page == '000':
    page = case['article']['pages'].split('-')[0]
  output = [r'\hypertarget{%s}{}\subsection*{Case %s}' % (
              case['label'], case['label']
           )]
  output.append(r"""\begin{quote*}
%s
\autocite[%s]{%s}
\end{quote*}
""" % (case['quotation'], page, case['article']['cite_key'])
    )

  if 'notes' in case:
    output.append('\n\\noindent %s\n' % case['notes'])

  if case['success']:
    output.append('\\begin{enumerate}\n')
    i = 0
    for exp in case['explanations']:
      i += 1
      output.append(r"""\item \hypertarget{%s.%i}{} %s: %s -- %s

\vspace{12pt}

%s

\begin{center}
%s
\end{center}

\vspace{12pt}
""" % (
      case['label'], i,
      exp['type'].capitalize(),
      exp['explanans']['type'],
      exp['explanandum']['type'],
      formatGloss(exp),
      formatTable(exp)
    ))
    output.append('\\end{enumerate}\n')

  else:
    output.append('\n\\vspace{12pt}\n\\noindent Failure: %s \n' %
      case['explanations'][0]['failure'])
```

```
  return u'\n'.join(output)

# Format all the cases as LaTeX.
def formatCases(cases):
  output = []
  for case in cases:
    output.append(formatCase(case))
  return u'\n\n\n'.join(output)

# Get the explanations from a case.
def getExplanations(cases):
  explanations = []
  for case in cases:
    if case['success']:
      for e in case['explanations']:
        explanations.append(copy.deepcopy(e))
  return explanations

# Find and count the unique phrases used to mark explanations.
def uniquePhrases(explanations):
  ps = nltk.defaultdict(int)
  for e in explanations:
    ps[e['phrase']] += 1
  phrases = []
  for p in ps.keys():
    if ps[p] > 1:
      p = "%s (%i)" % (p, ps[p])
    phrases.append(p)
  return sorted(phrases)
```

B.10 Analysis

File: analysis.py

```
from __future__ import division
import os
import nltk, pylab, numpy
from utils import tabulate
from keywords import loadKeywords
from samples import sampledir
from cases import categories, parseCases

# Generate plots for a given sample.
def plotSample(sample):
  cases = parseCases(os.path.join(sampledir, 'A-Sample%s.txt' % sample))
  return plotCases(sample, cases)

# Generate a table for a grid of explanatory form data.
def plotTable(filename, data):
  rows = []
  for c1 in categories:
```

```
    fields = [c1]
    for c2 in categories:
      fields.append(data[c1][c2])
    rows.append(tuple(fields))

  return tabulate(filename,
    'r|rrrrr',
    ['data', 'entity', 'kind', 'model', 'theory'],
    '%6s & %2i & %2i & %2i & %2i & %2i',
    rows
  )

# Generate a visualization of a grid of explanatory form data.
def plotVisualization(filename, data):
  if os.path.exists(filename):
    return False

  arr = numpy.array([[data[y][x] for x in categories]
      for y in categories], numpy.int32)

  fig = pylab.figure(figsize=(4,4))
  ax = fig.add_subplot(1,1,1)
  fig.subplots_adjust(left=0.20, top=0.80)

  ax.matshow(arr, cmap=pylab.cm.gray_r)

  rng = range(0, len(categories))
  ax.set_xticks(rng)
  ax.set_yticks(rng)
  ax.set_xticklabels(categories, rotation='vertical', ha='center')
  ax.set_yticklabels(categories, va='center')

  fig.savefig(filename)
  pylab.close()
  return True

def storeValue(sample, name, value):
  filename = "sample%s-%s.tex" % (sample, name)
  f = open(filename, 'w')
  f.write(str(value))
  f.close()

# Store the set of results in an ugly global variable.
results = []

# Generate all sorts of information and plots for a set of cases.
def plotCases(sample, cases):
  global results

  # Store some values
  storeValue(sample, 'total', len(cases))
  successes = len([case for case in cases if case['success']])
  storeValue(sample, 'successes', successes)
  failures = len([case for case in cases if not case['success']])
```

```
storeValue(sample, 'failures', failures)

# Collect some data about the sample.
data = {
  'explanation': nltk.defaultdict(lambda: nltk.defaultdict(int)),
  'evidence':    nltk.defaultdict(lambda: nltk.defaultdict(int)),
  'total':       nltk.defaultdict(lambda: nltk.defaultdict(int)),
  'explanation-cases':     0,
  'evidence-cases':        0,
  'explanation-instances': 0,
  'evidence-instances':    0,
  'success-instances':     0
}

for case in cases:
  if not case['success']: continue
  excase = 0
  evcase = 0
  for exp in case['explanations']:
    try:
      data['success-instances'] += 1
      type1 = exp['type']
      type2 = exp['explanans']['type']
      type3 = exp['explanandum']['type']
      data[type1][type2][type3] += 1
      data['total'][type2][type3] += 1
      data[type1 + '-instances'] += 1
      if type1 == 'explanation':
        excase = 1
      else:
        evcase = 1
    except KeyError:
      print exp
      raise
  data['explanation-cases'] += excase
  data['evidence-cases'] += evcase

# Store some more data.
storeValue(sample, 'explanation-instances', data['explanation-instances'])
storeValue(sample, 'explanation-cases', data['explanation-cases'])
storeValue(sample, 'evidence-instances', data['evidence-instances'])
storeValue(sample, 'evidence-cases', data['evidence-cases'])

# Collect the data in a very large table.
results.append(
r'%s & %4i & %3i & %3i & %3i & %3.1f & %3.1f & %3.1f & %3i & %3i & %3i \\' % (
  sample,
  len(cases),
  data['explanation-cases'],
  data['evidence-cases'],
  successes,
  100 * data['explanation-cases'] / len(cases),
  100 * data['evidence-cases'] / len(cases),
  100 * successes / len(cases),
```

```
    data['explanation-instances'],
    data['evidence-instances'],
    data['success-instances']
  ))

  # Plot three tables for this data.
  plotTable("sample%s-explanation.tex" % sample, data['explanation'])
  plotTable("sample%s-evidence.tex" % sample,    data['evidence'])
  plotTable("sample%s.tex" % sample,             data['total'])

  # Create three heatmaps for this data.
  plotVisualization("sample%s-explanation.pdf" % sample, data['explanation'])
  plotVisualization("sample%s-evidence.pdf" % sample,    data['evidence'])
  plotVisualization("sample%s.pdf" % sample,             data['total'])

  return cases

# Put the global results data into a file.
def plotResults(filename="results.tex"):
  global results
  f = open(filename, 'w')
  f.write('\n'.join(results))
  f.close()

# Generate a table of keyword information.
def tabulateKeywords(allCases, filename="keywords-cases.tex"):
  if os.path.exists(filename):
    return False

  keywords, labels, counts = loadKeywords()

  articles = nltk.defaultdict(lambda: nltk.defaultdict(int))
  casecounts = nltk.defaultdict(int)
  for case in allCases:
    keyword = case['article']['science']
    casecounts[keyword] += 1
    articles[keyword][case['article']['doi']] += 1

  articlesByKeyword = {k:len(articles[k].keys()) for k in keywords}

  successes = nltk.defaultdict(int)
  explanations = nltk.defaultdict(int)
  evidences = nltk.defaultdict(int)
  for case in allCases:
    if not case['success']: continue
    successes[case['article']['science']] += 1
    evcase = 0
    excase = 0
    for exp in case['explanations']:
      if exp['type'] == 'explanation': excase = 1
      if exp['type'] == 'evidence': evcase = 1
    explanations[case['article']['science']] += excase
    evidences[case['article']['science']] += evcase
```

```
  # Store the number of successful cases.
  f = open('cases-successful.tex', 'w')
  f.write(str(sum([successes[k] for k in keywords])))
  f.close()

  portion = nltk.defaultdict(float)
  for k in keywords:
    if casecounts[k] == 0: continue
    portion[k] = successes[k]/casecounts[k]
  numberOfArticles = sum(counts[k] for k in keywords)

  tabulate(filename,
    'r|rrrrrrrrrr',
    ['\# of Articles', '\% of Articles',
      '\# of Articles Sampled', r'\% of Articles Sampled',
      'Sampled Cases', 'Explanation Cases', 'IBE Cases',
      'Successful Cases', r'\% of Successful Cases'],
    '%20s & %4i & %2.2f & %3i & %2.1f & %3i & %3i & %3i & %3i & %s',
    [(
        k,
        counts[k],
        100 * counts[k]/numberOfArticles,
        articlesByKeyword[k],
        100 * articlesByKeyword[k]/counts[k],
        casecounts[k],
        #100 * casecounts[k]/counts[k],
        explanations[k],
        evidences[k],
        successes[k],
        _formatPortion(portion[k], casecounts[k])
      ) for k in keywords
    ]
  )

  return True

def _formatPortion(portion, cases):
  p = '%2.1f' % (100 * portion)
  if cases == 0:
    p = '--'
  return p
```

Bibliography

Adams, Diane K. et al. (2011). "Surface-Generated Mesoscale Eddies Transport Deep-Sea Products from Hydrothermal Vents". In: *Science* 332.6029, pp. 580–583.

A'Hearn, Michael F. et al. (2011). "EPOXI at Comet Hartley 2". In: *Science* 332.6036, pp. 1396–1400.

Allen, Joseph P. et al. (2011). "An Interaction-Based Approach to Enhancing Secondary School Instruction and Student Achievement". In: *Science* 333.6045, pp. 1034–1037.

Anderson, Sandra H. et al. (2011). "Cascading Effects of Bird Functional Extinction Reduce Pollination and Plant Density". In: *Science* 331.6020, pp. 1068–1071.

Ankeny, Rachel A. and Sabina Leonelli (2011). "What's So Special about Model Organisms?" In: *Studies in History and Philosophy of Science* 42.2, pp. 313–323.

Anscombe, G.E.M. (1971). *Causality and determination: An inaugural lecture.* Cambridge: Cambridge University Press.

Antonangeli, Daniele et al. (2011). "Spin Crossover in Ferropericlase at High Pressure: A Seismologically Transparent Transition?" In: *Science* 331.6013, pp. 64–67.

Ascunce, Marina S. et al. (2011). "Global Invasion History of the Fire Ant *Solenopsis invicta*". In: *Science* 331.6020, pp. 1066–1068.

Ataide, Sandro F. et al. (2011). "The Crystal Structure of the Signal Recognition Particle in Complex with Its Receptor". In: *Science* 331.6019, pp. 881–886.

Atarashi, Koji et al. (2011). "Induction of Colonic Regulatory T Cells by Indigenous *Clostridium* Species". In: *Science* 331.6015, pp. 337–341.

Banks, Jo Ann et al. (2011). "The Selaginella Genome Identifies Genetic Changes Associated with the Evolution of Vascular Plants". In: *Science* 332.6032, pp. 960–963.

Bánsági Tamás, Jr., Vladimir K. Vanag, and Irving R. Epstein (2011). "Tomography of Reaction-Diffusion Microemulsions Reveals Three-Dimensional Turing Patterns". In: *Science* 331.6022, pp. 1309–1312.

Bartholomay, Lyric C. et al. (2010). "Pathogenomics of *Culex quinquefasciatus* and Meta-Analysis of Infection Responses to Diverse Pathogens". In: *Science* 330.6000, pp. 88–90.

Bates, Mary E., James A. Simmons, and Tengiz V. Zorikov (2011). "Bats Use Echo Harmonic Structure to Distinguish Their Targets from Background Clutter". In: *Science* 333.6042, pp. 627–630.

Batterman, Robert W. (2002). *The Devil in the Details: Asymptotic Reasoning in Explanation, Reduction, and Emergence.* Oxford: Oxford University Press.

Batterman, Robert W. (2005). “Critical phenomena and breaking drops: Infinite idealizations in physics”. In: *Studies in History and Philosophy of Modern Physics* 36.2, pp. 225–244.

— (2009). “On the explanatory role of mathematics in empirical science”. In: *The British Journal for the Philosophy of Science* 61, pp. 1–25.

— (Fall 2007). “Intertheory Relations in Physics”. In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Metaphysics Research Lab.

Beatty, John (1995). “The evolutionary contingency thesis”. In: *Concepts, theories, and rationality in the biological sciences: the Second Pittsburgh-Konstanz Colloquium in the Philosophy of Science, University of Pittsburgh, October 1-4, 1993.* Pittsburgh: University of Pittsburgh Press. Chap. 2, pp. 45–82.

Bechtel, William and Adele Abrahamsen (2005). “Explanation: A Mechanist Alternative”. In: *Studies in History and Philosophy of Biological and Biomedical Sciences* 36, pp. 421–441.

Bell, Robin E. et al. (2011). “Widespread Persistent Thickening of the East Antarctic Ice Sheet by Freezing from the Base”. In: *Science* 331.6024, pp. 1592–1595.

Bird, Alexander and Emma Tobin (Spring 2009). “Natural Kinds”. In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Metaphysics Research Lab.

Bissiere, Stephanie et al. (2011). “Electrical Synapses Control Hippocampal Contributions to Fear Learning and Memory”. In: *Science* 331.6013, pp. 87–91.

Bogen, James and James Woodward (1988). “Saving the phenomena”. In: *The Philosophical Review* 97.3, pp. 303–352.

Bokulich, Alisa (2009). “How Scientific Models Can Explain”. In: *Synthese* 180.1, pp. 33–45.

Brambles, O. J. et al. (2011). “Magnetosphere Sawtooth Oscillations Induced by Ionospheric Outflow”. In: *Science* 332.6034, pp. 1183–1186.

Brandon, Mark P. et al. (2011). “Reduction of Theta Rhythm Dissociates Grid Cell Spatial Periodicity from Directional Tuning”. In: *Science* 332.6029, pp. 595–599.

Brantley, Johnathan N., Kelly M. Wiggins, and Christopher W. Bielawski (2011). “Unclicking the Click: Mechanically Facilitated 1,3-Dipolar Cycloreversions”. In: *Science* 333.6049, pp. 1606–1609.

Cao, C. et al. (2011). “Universal Quantum Viscosity in a Unitary Fermi Gas”. In: *Science* 331.6013, pp. 58–61.

Cárdenas, Macarena L. et al. (2011). “The Response of Vegetation on the Andean Flank in Western Amazonia to Pleistocene Climate Change”. In: *Science* 331.6020, pp. 1055–1058.

Carpenter, S. R. et al. (2011). “Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment”. In: *Science* 332.6033, pp. 1079–1082.

Chan, Han-Sung et al. (2011). “Synthesis and Measurement of Ultrafast Waveforms from Five Discrete Optical Harmonics”. In: *Science* 331.6021, pp. 1165–1168.

Chaplin, W. J. et al. (2011). “Ensemble Asteroseismology of Solar-Type Stars with the NASA Kepler Mission”. In: *Science* 332.6026, pp. 213–216.

Choi, H. et al. (2010). “Evidence of Supersolidity in Rotating Solid Helium”. In: *Science* 330.6010, pp. 1512–1515.

Cirimotich, Chris M. et al. (2011). “Natural Microbe-Mediated Refractoriness to *Plasmodium* Infection in *Anopheles gambiae*”. In: *Science* 332.6031, pp. 855–858.

Cisneros, Juan Carlos et al. (2011). “Dental Occlusion in a 260-Million-Year-Old Therapsid with Saber Canines from the Permian of Brazil”. In: *Science* 331.6024, pp. 1603–1605.

Cooper, Kimberly L. et al. (2011). “Initiation of Proximal-Distal Patterning in the Vertebrate Limb by Signals and Growth”. In: *Science* 332.6033, pp. 1083–1086.

Coste, Bertrand et al. (2010). “Piezo1 and Piezo2 Are Essential Components of Distinct Mechanically Activated Cation Channels”. In: *Science* 330.6000, pp. 55–60.

Craver, Carl F. and Lindley Darden (2005). “Introduction”. In: *Studies in History and Philosophy of Biological and Biomedical Sciences* 36, pp. 233–244.

Das, Suman K. et al. (2011). “Adipose Triglyceride Lipase Contributes to Cancer-Associated Cachexia”. In: *Science* 333.6039, pp. 233–238.

de Jager, Monique et al. (2011). “Lévy Walks Evolve Through Interaction Between Movement and Environmental Complexity”. In: *Science* 332.6037, pp. 1551–1553.

De Pontieu, B. et al. (2011). “The Origins of Hot Plasma in the Solar Corona”. In: *Science* 331.6013, pp. 55–58.

Derdowski, Aaron et al. (2010). “A Size Threshold Limits Prion Transmission and Establishes Phenotypic Diversity”. In: *Science* 330.6004, pp. 680–683.

Douven, Igor (2011). “Abduction”. In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Spring 2011.

Dowe, Phil (2000). *Physical Causation*. Cambridge: Cambridge University Press.

Dretske, Fred I. (1981). *Knowledge and the Flow of Information*. Cambridge, MA: MIT Press.

— (1988). *Explaining Behaviour: Reasons in a World of Causes*. Cambridge, MA: MIT Press.

Dunkle, Jack A. et al. (2011). “Structures of the Bacterial Ribosome in Classical and Hybrid States of tRNA Binding”. In: *Science* 332.6032, pp. 981–984.

Duong, Hao A. et al. (2011). “A Molecular Mechanism for Circadian Clock Negative Feedback”. In: *Science* 332.6036, pp. 1436–1439.

Ebihara, M. et al. (2011). “Neutron Activation Analysis of a Particle Returned from Asteroid Itokawa”. In: *Science* 333.6046, pp. 1119–1121.

Ekiert, Damian C. et al. (2011). “A Highly Conserved Neutralizing Epitope on Group 2 Influenza A Viruses”. In: *Science* 333.6044, pp. 843–850.

Ereshefsky, Marc (2010). “Species”. In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Spring 2010.

Faith, Jeremiah J. et al. (2011). “Predicting a Human Gut Microbiota’s Response to Diet in Gnotobiotic Mice”. In: *Science* 333.6038, pp. 101–104.

Fakhri, Nikta et al. (2010). “Brownian Motion of Stiff Filaments in a Crowded Environment”. In: *Science* 330.6012, pp. 1804–1807.

Fang, T. H. et al. (2011). “Revealing Extraordinary Intrinsic Tensile Plasticity in Gradient Nano-Grained Copper”. In: *Science* 331.6024, pp. 1587–1590.

Fausti, D. et al. (2011). “Light-Induced Superconductivity in a Stripe-Ordered Cuprate”. In: *Science* 331.6014, pp. 189–191.

Feynman, Richard P., Ralph Leighton, and Edward Hutchings (1985). *"Surely you're joking, Mr. Feynman!": Adventures of a curious character*. W.W. Norton.

Finnegan, Seth et al. (2011). "The Magnitude and Duration of Late Ordovician–Early Silurian Glaciation". In: *Science* 331.6019, pp. 903–906.

Friedman, Michael (1974). "Explanation and Scientific Understanding". In: *The Journal of Philosophy* 71.1, pp. 5–19.

Frigg, Roman and Stephan Hartmann (Spring 2006). "Models in Science". In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Metaphysics Research Lab.

Gagliardi, G. et al. (2010). "Probing the Ultimate Limit of Fiber-Optic Strain Sensing". In: *Science* 330.6007, pp. 1081–1084.

Garrick-Bethell, Ian, Francis Nimmo, and Mark A. Wieczorek (2010). "Structure and Formation of the Lunar Farside Highlands". In: *Science* 330.6006, pp. 949–951.

Gerson, Alexander R. and Christopher G. Guglielmo (2011). "Flight at Low Ambient Humidity Increases Protein Catabolism in Migratory Birds". In: *Science* 333.6048, pp. 1434–1436.

Gouw, J. A. de et al. (2011). "Organic Aerosol Formation Downwind from the Deepwater Horizon Oil Spill". In: *Science* 331.6022, pp. 1295–1299.

Grigoryan, Gevorg et al. (2011). "Computational Design of Virus-Like Protein Assemblies on Carbon Nanotube Surfaces". In: *Science* 332.6033, pp. 1071–1076.

Gupta, Sourendu et al. (2011). "Scale for the Phase Diagram of Quantum Chromodynamics". In: *Science* 332.6037, pp. 1525–1528.

Habashi, Jennifer P. et al. (2011). "Angiotensin II Type 2 Receptor Signaling Attenuates Aortic Aneurysm in Mice Through ERK Antagonism". In: *Science* 332.6027, pp. 361–365.

Hankinson, Robert J. (2001). *Cause and Explanation in Ancient Greek Thought*. New York: Oxford University Press.

He, Yu-Fei et al. (2011). "Tet-Mediated Formation of 5-Carboxylcytosine and Its Excision by TDG in Mammalian DNA". In: *Science* 333.6047, pp. 1303–1307.

Hempel, Carl G. (1965a). "Aspects of Scientific Explanation". In: *Aspects of Scientific Explanation and Other Essays in the Philosophy of Science*. New York: Free Press, pp. 331–496.

— (1965b). *Aspects of Scientific Explanation: And Other Essays in the Philosophy of Science*. New York: Free Press.

Hempel, Carl G. and Paul Oppenheim (1948). "Studies in the Logic of Explanation". In: *Philosophy of Science* 15.2, pp. 135–175.

Heo, Jae Bok and Sibum Sung (2011). "Vernalization-Mediated Epigenetic Silencing by a Long Intronic Noncoding RNA". In: *Science* 331.6013, pp. 76–79.

Herd, Christopher D. K. et al. (2011). "Origin and Evolution of Prebiotic Organic Matter As Inferred from the Tagish Lake Meteorite". In: *Science* 332.6035, pp. 1304–1307.

Heuer, A. H., C. L. Jia, and K. P. D. Lagerlöf (2010). "The Core Structure of Basal Dislocations in Deformed Sapphire (α-Al_2O_3)". In: *Science* 330.6008, pp. 1227–1231.

Himler, Anna G. et al. (2011). “Rapid Spread of a Bacterial Symbiont in an Invasive Whitefly Is Driven by Fitness Benefits and Female Bias”. In: *Science* 332.6026, pp. 254–256.

Hitchcock, Christopher Read (1996). “The role of contrast in causal and explanatory claims”. In: *Synthese* 107.3, pp. 395–419.

Huang, Jian Yu et al. (2010). “In Situ Observation of the Electrochemical Lithiation of a Single SnO_2 Nanowire Electrode”. In: *Science* 330.6010, pp. 1515–1520.

Hu, Yilin, Chi Chung Lee, and Markus W. Ribbe (2011). “Extending the Carbon Chain: Hydrocarbon Formation Catalyzed by Vanadium/Molybdenum Nitrogenases”. In: *Science* 333.6043, pp. 753–755.

Ilonidis, Stathis, Junwei Zhao, and Alexander Kosovichev (2011). “Detection of Emerging Sunspot Regions in the Solar Interior”. In: *Science* 333.6045, pp. 993–996.

Innocenti, Paolo, Edward H. Morrow, and Damian K. Dowling (2011). “Experimental Evidence Supports a Sex-Specific Selective Sieve in Mitochondrial Genome Evolution”. In: *Science* 332.6031, pp. 845–848.

Johnson, Cheryl L. and Andrew M. Spence (2011). “Epigenetic Licensing of Germline Gene Expression by Maternal RNA in *C. elegans*”. In: *Science* 333.6047, pp. 1311–1314.

Johnson, William L. et al. (2011). “Beating Crystallization in Glass-Forming Metals by Millisecond Heating and Processing”. In: *Science* 332.6031, pp. 828–833.

Jones, Martin R. (2005). “Idealization and Abstraction: A Framework”. In: *Idealization XII: Correcting the Model.* Ed. by Martin R. Jones and Nancy Cartwright. Amsterdam: Rodopi, pp. 173–218.

Josephson, John R. and Susan G. Josephson (1996). *Abductive inference: Computation, philosophy, technology.* Cambridge: Cambridge University Press.

Kanady, Jacob S. et al. (2011). “A Synthetic Model of the Mn_3Ca Subsite of the Oxygen-Evolving Complex in Photosystem II”. In: *Science* 333.6043, pp. 733–736.

Katz, Miriam E. et al. (2011). “Impact of Antarctic Circumpolar Current Development on Late Paleogene Ocean Structure”. In: *Science* 332.6033, pp. 1076–1079.

Keck, Jamie M. et al. (2011). “A Cell Cycle Phosphoproteome of the Yeast Centrosome”. In: *Science* 332.6037, pp. 1557–1561.

Khan, Aisha I. et al. (2011). “Negative Epistasis Between Beneficial Mutations in an Evolving Bacterial Population”. In: *Science* 332.6034, pp. 1193–1196.

Kiers, E. Toby et al. (2011). “Reciprocal Rewards Stabilize Cooperation in the Mycorrhizal Symbiosis”. In: *Science* 333.6044, pp. 880–882.

Kim, Nayun et al. (2011). “Mutagenic Processing of Ribonucleotides in DNA by Yeast Topoisomerase I”. In: *Science* 332.6037, pp. 1561–1564.

Kitcher, Philip (1976). “Explanation, conjunction, and unification”. In: *The Journal of Philosophy*, pp. 207–212.

— (1989). “Explanatory Unification and the Causal Structure of the World”. In: *Scientific Explanation.* Ed. by Philip Kitcher and Wesley C. Salmon. Minnesota Studies in the Philosophy of Science. Minneapolis: University of Minnesota Press, pp. 410–505.

Kivell, Tracy L. et al. (2011). "*Australopithecus sediba* Hand Demonstrates Mosaic Evolution of Locomotor and Manipulative Abilities". In: *Science* 333.6048, pp. 1411–1417.

Koos, Erin and Norbert Willenbacher (2011). "Capillary Forces in Suspension Rheology". In: *Science* 331.6019, pp. 897–900.

Kubo, Ken-ichi et al. (2010). "Collaborative Non-Self Recognition System in S-RNase–Based Self-Incompatibility". In: *Science* 330.6005, pp. 796–799.

Lee, D. H. and J. A. Gupta (2010). "Tunable Field Control Over the Binding Energy of Single Dopants by a Charged Vacancy in GaAs". In: *Science* 330.6012, pp. 1807–1810.

Lee, Dong-Hwan, Ki-Hyeok Kwon, and Chae S. Yi (2011). "Selective Catalytic C–H Alkylation of Alkenes with Alcohols". In: *Science* 333.6049, pp. 1613–1616.

Lee, Soojung et al. (2010). "Channel-Mediated Tonic GABA Release from Glia". In: *Science* 330.6005, pp. 790–796.

Liu, Yuzhou et al. (2011). "Supramolecular Archimedean Cages Assembled with 72 Hydrogen Bonds". In: *Science* 333.6041, pp. 436–440.

Lopez-Garcia, Carlos et al. (2010). "Intestinal Stem Cell Replacement Follows a Pattern of Neutral Drift". In: *Science* 330.6005, pp. 822–825.

Lü, Junchang et al. (2011). "An Egg-Adult Association, Gender, and Reproduction in Pterosaurs". In: *Science* 331.6015, pp. 321–324.

Luo, Jian et al. (2011). "The Role of a Bilayer Interfacial Phase on Liquid Metal Embrittlement". In: *Science* 333.6050, pp. 1730–1733.

Lü, Wei et al. (2011). "pH-Dependent Gating in a FocA Formate Channel". In: *Science* 332.6027, pp. 352–354.

Machamer, Peter K., Lindley Darden, and Carl F. Craver (2000). "Thinking About Mechanisms". In: *Philosophy of Science* 67.1, pp. 1–25.

Marchitto, Thomas M. et al. (2010). "Dynamical Response of the Tropical Pacific Ocean to Solar Forcing During the Early Holocene". In: *Science* 330.6009, pp. 1378–1381.

Matsuura, M. et al. (2011). "Herschel Detects a Massive Dust Reservoir in Supernova 1987A". In: *Science* 333.6047, pp. 1258–1261.

McCarthy, M. A. et al. (2011). "Low-Voltage, Low-Power, Organic Light-Emitting Transistors for Active Matrix Displays". In: *Science* 332.6029, pp. 570–573.

McLaughlin, Brian P. (1992). "The rise and fall of British emergentism". In: *Emergence or Reduction?: Essays on the Prospects of Nonreductive Physicalism.* Ed. by Ansgar Beckermann, Hans Flohr, and Jaegwon Kim. Berlin: Walter de Gruyter, pp. 49–93.

McMullin, Ernan (1985). "Galilean Idealization". In: *Studies in History and Philosophy of Science* 16.3, pp. 247–273.

— (1992). *The Inference that Makes Science.* Milwaukee, WI: Marquette University Press.

McTighe, Stephanie M. et al. (2010). "Paradoxical False Memory for Objects After Brain Damage". In: *Science* 330.6009, pp. 1408–1410.

Mellars, Paul and Jennifer C. French (2011). “Tenfold Population Increase in Western Europe at the Neandertal–to–Modern Human Transition”. In: *Science* 333.6042, pp. 623–627.

Metcalf, C. J. E. et al. (2011). “Partitioning Regulatory Mechanisms of Within-Host Malaria Dynamics Using the Effective Propagation Number”. In: *Science* 333.6045, pp. 984–988.

Mitchell, Sandra D. (1997). “Pragmatic laws”. In: *Philosophy of Science* 64, pp. 468–479.

— (2000). “Dimensions of scientific law”. In: *Philosophy of Science* 67.2, pp. 242–265.

— (2009). *Unsimple Truths: Science, Complexity, and Policy.* Chicago: University Of Chicago Press.

Mitton-Fry, Rachel M. et al. (2010). “Poly(A) Tail Recognition by a Viral RNA Element Through Assembly of a Triple Helix”. In: *Science* 330.6008, pp. 1244–1247.

Mondragón-Palomino, Octavio et al. (2011). “Entrainment of a Population of Synthetic Genetic Oscillators”. In: *Science* 333.6047, pp. 1315–1319.

Morrison, Margaret (2007). “Where have all the theories gone?” In: *Philosophy of Science* 74.2, pp. 195–228.

Mukhtar, M. Shahid et al. (2011). “Independently Evolved Virulence Effectors Converge onto Hubs in a Plant Immune System Network”. In: *Science* 333.6042, pp. 596–601.

Nagel, Ernest (1961). *The Structure of Science: Problems in the Logic of Scientific Explanation.* New York: Harcourt, Brace & World.

Naidu, Srivatsava et al. (2011). “TAF1B Is a TFIIB-Like Component of the Basal Transcription Machinery for RNA Polymerase I”. In: *Science* 333.6049, pp. 1640–1642.

Olsen, Are and Ulysses Ninnemann (2010). “Large δ^{13}C Gradients in the Preindustrial North Atlantic Revealed”. In: *Science* 330.6004, pp. 658–659.

Oppenheim, Paul and Hilary Putnam (1958). “The Unity of Science as a Working Hypothesis”. In: *Concepts, theories, and the mind-body problem.* Ed. by Herbert Feigl, Michael Scriven, and Grover Maxwell. Vol. 2. Minnesota Studies in the Philosophy of Science. Minneapolis: University of Minnesota Press.

Overton, James A. (Dec. 2011). “Mechanisms, Types, and Abstractions”. In: *Philosophy of Science* 78.5, pp. 941–854.

Papadopoulou, Maria et al. (2011). “Normalization for Sparse Encoding of Odors by a Wide-Field Interneuron”. In: *Science* 332.6030, pp. 721–725.

Park, Chan Young, Aleksandr Shcheglovitov, and Ricardo Dolmetsch (2010). “The CRAC Channel Activator STIM1 Binds and Inhibits L-Type Voltage-Gated Calcium Channels”. In: *Science* 330.6000, pp. 101–105.

Pederson, Gregory T. et al. (2011). “The Unusual Nature of Recent Snowpack Declines in the North American Cordillera”. In: *Science* 333.6040, pp. 332–335.

Perner, Josef, M. Christine Mauer, and Monika Hildenbrand (2011). “Identity: Key to Children’s Understanding of Belief”. In: *Science* 333.6041, pp. 474–477.

Pickering, Robyn et al. (2011). “*Australopithecus sediba* at 1.977 Ma and Implications for the Origins of the Genus *Homo*”. In: *Science* 333.6048, pp. 1421–1423.

Pin, Pierre A. et al. (2010). "An Antagonistic Pair of *FT* Homologs Mediates the Control of Flowering Time in Sugar Beet". In: *Science* 330.6009, pp. 1397–1400.

Plikus, Maksim V. et al. (2011). "Self-Organizing and Stochastic Behaviors During the Regeneration of Hair Stem Cells". In: *Science* 332.6029, pp. 586–589.

Pope, P. B. et al. (2011). "Isolation of Succinivibrionaceae Implicated in Low Methane Emissions from Tammar Wallabies". In: *Science* 333.6042, pp. 646–648.

Prather, Michael J. and Juno Hsu (2010). "Coupling of Nitrous Oxide and Methane by Global Atmospheric Chemistry". In: *Science* 330.6006, pp. 952–954.

Puel, Anne et al. (2011). "Chronic Mucocutaneous Candidiasis in Humans with Inborn Errors of Interleukin-17 Immunity". In: *Science* 332.6025, pp. 65–68.

Rad, Roland et al. (2010). "*PiggyBac* Transposon Mutagenesis: A Tool for Cancer Gene Discovery in Mice". In: *Science* 330.6007, pp. 1104–1107.

Ramirez, Gerardo and Sian L. Beilock (2011). "Writing About Testing Worries Boosts Exam Performance in the Classroom". In: *Science* 331.6014, pp. 211–213.

Reisch, George A. (2005). *How the Cold War transformed philosophy of science: To the icy slopes of logic.* Cambridge: Cambridge University Press.

Remorino, Amanda et al. (2011). "Residue-Specific Vibrational Echoes Yield 3D Structures of a Transmembrane Helix Dimer". In: *Science* 332.6034, pp. 1206–1209.

Richardson, Alan W. (2002). "Engineering philosophy of science: American pragmatism and logical empiricism in the 1930s". In: *Philosophy of Science* 69.S3, pp. 36–47.

Riordan, Oliver and Lutz Warnke (2011). "Explosive Percolation Is Continuous". In: *Science* 333.6040, pp. 322–324.

Rittle, Jonathan and Michael T. Green (2010). "Cytochrome P450 Compound I: Capture, Characterization, and C-H Bond Activation Kinetics". In: *Science* 330.6006, pp. 933–937.

Robbins, Daniel W. and John F. Hartwig (2011). "A Simple, Multidimensional Approach to High-Throughput Discovery of Catalytic Reactions". In: *Science* 333.6048, pp. 1423–1427.

Rosling, Anna et al. (2011). "Archaeorhizomycetes: Unearthing an Ancient Class of Ubiquitous Soil Fungi". In: *Science* 333.6044, pp. 876–879.

Roy, Sushmita et al. (2010). "Identification of Functional Elements and Regulatory Circuits by *Drosophila* modENCODE". In: *Science* 330.6012, pp. 1787–1797.

Ruhl, Micha et al. (2011). "Atmospheric Carbon Injection Linked to End-Triassic Mass Extinction". In: *Science* 333.6041, pp. 430–434.

Rust, Michael J., Susan S. Golden, and Erin K. O'Shea (2011). "Light-Driven Changes in Energy Metabolism Directly Entrain the Cyanobacterial Circadian Oscillator". In: *Science* 331.6014, pp. 220–223.

Sakurai, Y. et al. (2011). "Imaging Doped Holes in a Cuprate Superconductor with High-Resolution Compton Scattering". In: *Science* 332.6030, pp. 698–702.

Salmon, Wesley C. (1971). "Statistical Explanation". In: *Statistical Explanation and Statistical Relevance*. Ed. by Wesley C. Salmon. Pittsburgh: University of Pittsburgh Press, pp. 29–87.

Salmon, Wesley C. (1984). *Scientific Explanation and the Causal Structure of the World*. Princeton: Princeton University Press.

— (1989). "Four decades of scientific explanation". In: *Scientific Explanation*. Ed. by Philip Kitcher and Wesley C. Salmon. Vol. XIII. Minnesota Studies in the Philosophy of Science. Minneapolis: University of Minnesota Press, pp. 1–219.

Schafer, Robert J. and Tirin Moore (2011). "Selective Attention from Voluntary Control of Neurons in Prefrontal Cortex". In: *Science* 332.6037, pp. 1568–1571.

Schaller, Morgan F., James D. Wright, and Dennis V. Kent (2011). "Atmospheric P_2 Perturbations Associated with the Central Atlantic Magmatic Province". In: *Science* 331.6023, pp. 1404–1409.

Serwane, F. et al. (2011). "Deterministic Preparation of a Tunable Few-Fermion System". In: *Science* 332.6027, pp. 336–338.

Setiawan, Johny et al. (2010). "A Giant Planet Around a Metal-Poor Star of Extragalactic Origin". In: *Science* 330.6011, pp. 1642–1644.

Shema, Reut et al. (2011). "Enhancement of Consolidated Long-Term Memory by Overexpression of Protein Kinase Mζ in the Neocortex". In: *Science* 331.6021, pp. 1207–1210.

Shuster, David L. et al. (2011). "Thermochronometry Reveals Headward Propagation of Erosion in an Alpine Landscape". In: *Science* 332.6025, pp. 84–88.

Simon, Ralph et al. (2011). "Floral Acoustics: Conspicuous Echoes of a Dish-Shaped Leaf Attract Bat Pollinators". In: *Science* 333.6042, pp. 631–633.

Simons, Mark et al. (2011). "The 2011 Magnitude 9.0 Tohoku-Oki Earthquake: Mosaicking the Megathrust from Seconds to Centuries". In: *Science* 332.6036, pp. 1421–1425.

Sims III, Robert J. et al. (2011). "The C-Terminal Domain of RNA Polymerase II Is Modified by Site-Specific Methylation". In: *Science* 332.6025, pp. 99–103.

Smart, J.J.C. (1959). "Can biology be an exact science?" In: *Synthese* 11.4, pp. 359–368.

Smith, Sheldon R. (2002). "Violated Laws, Ceteris Paribus Clauses, and Capacities". In: *Synthese* 130.2, pp. 235–264.

Song, Can-Li et al. (2011). "Direct Observation of Nodes and Twofold Symmetry in FeSe Superconductor". In: *Science* 332.6036, pp. 1410–1413.

Spanu, Pietro D. et al. (2010). "Genome Expansion and Gene Loss in Powdery Mildew Fungi Reveal Tradeoffs in Extreme Parasitism". In: *Science* 330.6010, pp. 1543–1546.

Spirtes, Peter, Clark Glymour, and Richard Scheines (2000). *Causation, Prediction and Search*. Second Edition. New York: Springer-Verlag.

Stapel, Diederik A. and Siegwart Lindenberg (2011). "Coping with Chaos: How Disordered Contexts Promote Stereotyping and Discrimination". In: *Science* 332.6026, pp. 251–253.

Sternberg, A. et al. (2011). "Circumstellar Material in Type Ia Supernovae via Sodium Absorption Features". In: *Science* 333.6044, pp. 856–859.

Suppes, Patrick (1960). "A comparison of the meaning and uses of models in mathematics and the empirical sciences". In: *Synthese* 12.2, pp. 287–301.

Sutton, Andrew D. et al. (2011). “Regeneration of Ammonia Borane Spent Fuel by Direct Reaction with Hydrazine and Liquid Ammonia”. In: *Science* 331.6023, pp. 1426–1429.

Suzuki, Katsunori et al. (2011). “A Planar Rhombic Charge-Separated Tetrasilacyclobutadiene”. In: *Science* 331.6022, pp. 1306–1309.

Tang, Wei et al. (2011). “The Growth Factor Progranulin Binds to TNF Receptors and Is Therapeutic Against Inflammatory Arthritis in Mice”. In: *Science* 332.6028, pp. 478–484.

Tanji-Suzuki, Haruka et al. (2011). “Vacuum-Induced Transparency”. In: *Science* 333.6047, pp. 1266–1269.

Tedsree, Karaked et al. (2011). “^{13}C NMR Guides Rational Design of Nanocatalysts via Chemisorption Evaluation in Liquid Phase”. In: *Science* 332.6026, pp. 224–228.

Thornalley, David J. R. et al. (2011). “The Deglacial Evolution of North Atlantic Deep Convection”. In: *Science* 331.6014, pp. 202–205.

Togashi, Hideru et al. (2011). “Nectins Establish a Checkerboard-Like Cellular Pattern in the Auditory Epithelium”. In: *Science* 333.6046, pp. 1144–1147.

Trout, J. D. (2007). “The Psychology of Scientific Explanation”. In: *Philosophy Compass* 2.3, pp. 564–591.

Turtle, E. P. et al. (2011). “Rapid and Extensive Surface Changes Near Titan’s Equator: Evidence of April Showers”. In: *Science* 331.6023, pp. 1414–1417.

van Breugel, Mark et al. (2011). “Structures of SAS-6 Suggest Its Organization in Centrioles”. In: *Science* 331.6021, pp. 1196–1199.

van Fraassen, Bas C. (1977). “The pragmatics of explanation”. In: *American Philosophical Quarterly* 14.2, pp. 143–150.

— (1980). *The Scientific Image*. Oxford: Clarendon Press.

— (2008). *Scientific Representation: Paradoxes of Perspective*. Oxford: Oxford University Press.

Wang, Youjun et al. (2010). “The Calcium Store Sensor, STIM1, Reciprocally Controls Orai and Ca_V1.2 Channels”. In: *Science* 330.6000, pp. 105–109.

Wang, Z. et al. (2010). “Large Variations in Southern Hemisphere Biomass Burning During the Last 650 Years”. In: *Science* 330.6011, pp. 1663–1666.

Ward, Carol V., William H. Kimbel, and Donald C. Johanson (2011). “Complete Fourth Metatarsal and Arches in the Foot of *Australopithecus afarensis*”. In: *Science* 331.6018, pp. 750–753.

Watanabe, Toshiaki et al. (2011). “Role for piRNAs and Noncoding RNA in de Novo DNA Methylation of the Imprinted Mouse *Rasgrf1* Locus”. In: *Science* 332.6031, pp. 848–852.

Waters, Michael R. et al. (2011). “The Buttermilk Creek Complex and the Origins of Clovis at the Debra L. Friedkin Site, Texas”. In: *Science* 331.6024, pp. 1599–1603.

Wetzel, Linda (2009). *Types and tokens: On abstract objects*. Cambridge, Massachusetts: The MIT Press.

— (2011). “Types and Tokens”. In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Spring 2011.

Wilson, Mark (2006). *Wandering Significance: An Essay on Conceptual Behaviour*. Oxford: Oxford University Press.

— (2010). “Mixed-Level Explanation”. In: *Philosophy of Science* 77.5, pp. 933–946.

Woodward, James (2003). *Making Things Happen: A Theory of Causal Explanation*. Oxford: Oxford University Press.

— (2011). “Scientific Explanation”. In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Winter 2011. Metaphysics Research Lab.

Yu, Jimin et al. (2010). “Loss of Carbon from the Deep Sea Since the Last Glacial Maximum”. In: *Science* 330.6007, pp. 1084–1087.

Zeng, Qiaoshi et al. (2011). “Long-Range Topological Order in Metallic Glass”. In: *Science* 332.6036, pp. 1404–1406.

Zhu, Wenlu et al. (2011). “Microtomography of Partially Molten Rocks: Three-Dimensional Melt Distribution in Mantle Peridotite”. In: *Science* 332.6025, pp. 88–91.

Curriculum Vitae

James Alexander Overton

Education

- **Degrees**
  - **Doctor of Philosophy**. The University of Western Ontario, 2007 - 2012. Thesis: "Explanation in *Science*."
  - **Bachelor of Mathematics (Honours)**, with Highest Honours. Carleton University, 2004 - 2005. Thesis: "Categories and their Algebra."
  - **Master of Arts in Philosophy**, with Distinction. Carleton University, 2002 - 2004. Thesis: "Toward a Foundation for Interdisciplinary Science: A Model of Special Sciences and Levels of Complexity."
  - **Bachelor of Humanities (Honours)**, with Highest Honours and a Specialization in English Literature. Carleton University, 1998 - 2002.
- **Grants and Fellowships**
  - Visiting Fellowship at the Tilburg Center for Logic and Philosophy of Science (TiLPS), 2011.
  - Gillian Barker, Cesare Romagnoli, and James A. Overton. "The Interdisciplinary Prostate Ontology Project – Stage Two." Joseph L. Rotman Institute of Science and Values Seed Grant, July 2009.
  - Cesare Romagnoli and James A. Overton. "The Interdisciplinary Prostate Ontology Project." London Health Sciences Centre Department of Medical Imaging Project Grant, September 2008.
- **Scholarships and Awards**
  - Canada Graduate Scholarships – Michael Smith Foreign Study Supplement, Social Sciences and Humanities Research Council of Canada ($6000), 2009.
  - Canada Graduate Scholarships – Doctoral Award, Social Sciences and Humanities Research Council of Canada ($105 000 over 3 years), 2007-2010.
  - The University of Western Ontario Department of Philosophy Entrance Scholarship ($4000), 2007.
  - University Medal in Mathematics, Carleton University, 2005.
  - Doctoral Fellowship, Social Sciences and Humanities Research Council of Canada ($80 000 over 4 years, declined to pursue employment), 2005.
  - Ontario Graduate Scholarships ($15 000 each, awarded twice), 2002-2003, 2003-2004.

  - Carleton University Dean of Graduate Studies Entrance Scholarship for Academic Excellence ($2000), 2002.
  - Carleton University Senate Medal for Outstanding Academic Achievement, 2002.
  - Carleton University Deans' Honour List, 1999-2002, 2004 (all years of eligibility).
  - Carleton University Entrance Scholarship ($3200 per annum, renewed three times), 1998-2002.

Publications

- **Journal Articles**
  - James A. Overton, "'Explain' in Scientific Discourse." *Synthese.* Forthcoming.
  - James A. Overton. "Mechanisms, Types, and Abstractions." *Proceedings of the Philosophy of Science Association (2010).* 78(5):941–854, 2011.
  - James A. Overton, Cesare Romagnoli, and Rethy K. Chhem. "Open Biomedical Ontologies Applied to Prostate Cancer." *Applied Ontology.* 6(1): 35-51, 2011.
- **Book Chapters**
  - James A. Overton and Cesare Romagnoli. "Radiology, Philosophy, and Ontology." In Rethy K. Chhem, Heiner Fangerau, Irmgard Müller, and Shih-chang Wang, editors, *Medical Imaging and Philosophy.* Franz Steiner Verlag, Stuggart, 2012.
  - Cesare Romagnoli, James A. Overton, and Rethy K. Chhem. "Philosophy of Radiology: The Ontological Challenge." In Teresa Van Deven, Kathryn M. Hibbert, and Rethy K. Chhem, editors, *The Practice of Radiology Education.* Springer, New York, 2010.
  - Robert Arp, Cesare Romagnoli, Rethy K. Chhem, and James A. Overton. "Radiological and Biomedical Knowledge Integration: The Ontological Way." In Rethy K. Chhem, Kathryn M. Hibbert, and Teresa Van Deven, editors, *Radiology Education: The Scholarship of Teaching and Learning.* Springer, New York, 2009.