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The Uses of Analogies in Seventeenth and Eighteenth Century Science

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The object of this paper is to look at the extent and nature of the uses of analogy during the first century following the so-called scientific revolution. Using the research tool provided by JSTOR we systematically analyze the uses of “analog” and its cognates (analogies, analogous, etc.) in the Philosophical Transactions of the Royal Society of London for the period 1665–1780. In addition to giving the possibility of evaluating quantitatively the proportion of papers explicitly using analogies, this approach makes it possible to go beyond the maybe idiosyncratic cases of Descartes, Kepler, Galileo, and other much studied giants of the so-called Scientific Revolution. As a result a classification of types of uses is proposed. Relations between types of analogies and research fields are also established. In this paper we are less interested in discussing the “real nature” or “essence” or even the cognitive limitations of analogical thinking than in describing its various uses and different meanings as they changed over the course of a century.

1. Introduction

The uses of analogy are ancient. It can even be argued that analogical thinking is the most basic cognitive tool humans have to move from the unknown to the known (Gentner et al. 2001). As Olson succinctly puts it, “analogies are useful when it is desired to compare an unfamiliar system with one that is better known” (Olson 1943, p. i). Analogical thinking is

1. The authors would like to thank the referees for their useful comments and suggestions.

thus ubiquitous and found in many texts at least since Homer in Antiquity (Lloyd 1966). For example, it is well known that to explain the properties of atoms, Aristotle compared them to the letters of alphabets, something much better known to his readers than invisible atoms (Hallyn 2000).

Many studies have looked at particular uses of analogies among the major actors in the emergence of modern science at the beginning of the 17th century (see for example Daston 1984; Galison 1984; Shea 2000; Simon 2000). The object of this paper is not to add another name to that list but to describe more generally the various uses that have been made of analogies in 17th and 18th century science (before the emergence of distinct scientific disciplines) among general scientific practitioners who published their results in the journal of the Royal Society of London. By looking at the presence of the word “analogy” and its cognates “analogical,” “analogous,” “analogue,” in all the papers published in the *Philosophical Transactions of the Royal Society of London* (hereafter *PT*) from its beginnings in 1665 to 1780, we can assess the spread of analogical thinking among the “rank and file” of the scientific field during the period covered. We are thus interested in the taken-for-granted practices of the natural philosophers who made the results of their inquiries into nature known through the venue of one of the first scientific journals. Our approach takes advantage of the access to full texts and search engine now accessible through JSTOR. In addition to giving the possibility of evaluating quantitatively the proportion of papers explicitly using analogies, this approach makes it possible to go beyond the maybe idiosyncratic cases of Descartes, Kepler, Galileo, and other much studied giants of the so-called Scientific Revolution. For despite the frequent use of the expression “scientific community” we have in fact few tools for really taking it as an object of inquiry. The method used here provides us with such a possibility.

We should also stress that we are less interested in discussing the “real nature” or “essence” or even the cognitive limitations of analogical thinking much discussed in philosophy of science than in describing its various uses and different meanings as they changed over the course of a century. In order to do this we distinguish two levels: the first is that of the practical use of an analogy between two systems, which philosophers of science often call the “source” and the “target” of the analogy (Holyoak & Thagard 1995). At this practical and taken-for-granted use of analogy as a tool for thinking, we identify six different types of uses. The second level concerns the reflexive discussions by the actors themselves on the nature and limitations of analogical thinking in science. As we will see, this reflexive turn on an otherwise spontaneous use of analogy in scientific practice is relatively rare in the pages of the *PT*.

2. Corpus and Method

In this study, we focus our attention on the *PT* from the first issue in 1665 to approximately 1780. The choice of this source, as a good representative of the practices and results of scientific inquiries is based on the fact that: (1) The *PT* is published on an almost continuous basis and covers all kinds of sciences. During the chosen period, it publishes papers that would now fall into the modern categories of physics, biology, medicine, chemistry, linguistics, economy, astronomy, mathematics, architecture, geology, and engineering. (2) Even if most contributions come from the United Kingdom and Ireland, many contributions are written by notable continental and American natural philosophers like Leeuwenhoek or Banister. (3) Important papers or lectures appearing first on the continent were often published in translation or reviewed in the *PT*. For example, extracts of *Le Journal des Sçavans* or lectures at the *Académie Royale des Sciences* were translated. (4) The *PT* publishes reviews of English and foreign scientific books. For example, a substantial review of Christian Huygens book *Cosmotheoros* was published. For all those reasons, the *PT* seems to provide a very good sample of the whole spectrum of inquiries into nature for the period.

Even if the *PT* papers are in general representative of the natural philosophy of the period, they can nevertheless have a specific style that could possibly introduce a systematic distortion in our analysis. For example, the evidential form that many papers take in the *PT* could be specific to the Royal Society's empiricism (Dear 1985; Licoppe 1996). In the context of this research we believe this worry to be unfounded for two reasons. (1) Though it is true that the *PT* publishes less mathematical formula and theoretical explanations than the *Mémoires de l'Académie Royale des Sciences* or the *Journal des Sçavans*, the general content of the papers do not differ much from homologous publications (Gross et al 2000). (2) What we propose is a taxonomy of the types of uses. For this analysis we think that the *PT* provides a representative sample of papers covering all the possible types of analogy even if the actual distribution of the different kinds of uses could differ from journal to journal, due to local traditions. When the *Journal des Sçavans* will be available in full text like *PT*, we could compare the results for the two journals, something that is not possible at this time. One could also think that the distribution of topics in the *PT* makes it more probable that some types of analogies will be used to the detriment of others. But again, only further studies can show that. Here we offer a first analysis of a large corpus of texts using explicit analogical reasoning, thus going well beyond the usual focus on a few major thinkers.

As for the method employed in this study, we systematically looked for

occurrences of the string of letters “analog*” in the full text version of the *PT* available on JSTOR.² This technique allows us to identify self-conscious uses of analogy. It is of course possible to use analogies without using the word and simply say for example that one “compares x to y” or that “x is like y.” Though our method obviously misses all these cases, we think that by picking all the explicit uses of the concept of analogy we can get a large enough sample to have access to all the spectrum of uses.³ We see no reason to think that the implicit uses would have a different structure than the explicit ones. And even with this possible limitation, our approach is certainly more general than the usual concentration on major actors. We stop our analysis around 1780 because we think that by that time the different types of uses have been identified. Moreover, the progressive rise in the use of analogies observed after 1780 suggests a change of regime in scientific argumentation. Figure 1 shows that, for the period 1665–1780, the words “analog*” were present in about 6% of the papers and reviews. However, after 1780 there is a rapid increase in frequency though no new type of use emerges at least before the middle of the 19th century when mathematical analogies will become more frequent in physics. Though this period falls outside the scope of this paper, we think the rise in the uses of analogies maybe related to the progressive disappearance of the stigma associated with the use of analogy in occult researches still present during the 17th century. By 1780 occult sciences are no longer a legitimate reference and one could probably use analogies without the danger of being attacked for invoking occult qualities or making ontological connections between different orders of things. By comparison, for the decade 1991–2000, around 36% of papers in *PT* contain at least once the word *analog**, a proportion similar to that obtained during the 19th century. Note that during the period 1665–1780 only about half of the papers contain illustrations like images of natural objects or geometrical figures. Though one could use illustrations to make analogies, this is not the case here, as they serve to illustrate directly the object under study or they are mathematical figures helping in the demonstrations. Therefore we do not analyse the figure as such and concentrate on the texts where analogical arguments are developed.

So by choosing to concentrate on the *PT* from 1665 to 1780 we can:

- (1) get a representative characterization of the early uses of analogy;
- (2) capture these uses for a significant period of time when the sciences

2. In this paper “analog*” represents the group of words: “analogy”, “analogical”, “analogically”, etc.

3. As we expected, the analysis of a sample of papers in the *PT* using the expressions “is like” and “compare(s)” did not show new kinds of use of analogy. Moreover, these expressions are often used in conjunction with the term “analogy” itself.

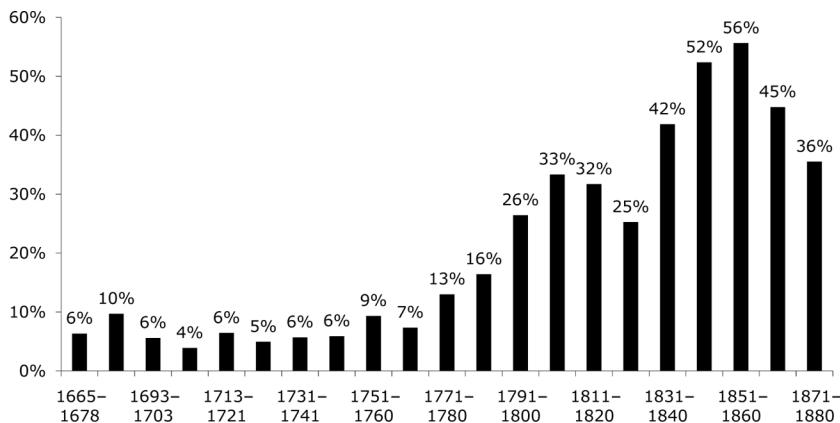


Figure 1. Proportion of documents in *PT* where analog* is used.

were not yet well-defined disciplines, and where the actors (natural philosophers) were not yet “scientists” trained in a more homogenous and specialized manner.

3. The Meanings of “Analogy”

Before analysing the content of the *PT* papers, we will first look at the definition of analogy provided by the major dictionaries of the times in order to see if its meaning has significantly changed over the period studied. Unsurprisingly for such an abstract word, all dictionaries do not give identical definitions. However they tend to refer to two basic concepts: proportionality and similarity. In the first case analogy is defined as an equality of ratios, which corresponds to the first meaning of the Greek term “analogy.” The second one is more informal and refers to the fact that two objects are similar to each other under some aspect. Thus Cockeram’s definition is: “*Analogie, Proportion, likenesse of one thing to another*” (Cockeram 1650). Moreover these two forms have been associated with different disciplines. A century after Cockeram, Paulian, in his *Dictionnaire de physique portatif*, explicitly ascribed the proportionality form to mathematics and the similarity form to physics (Paulian 1767, p. 27). Looking at previous publications, this attribution seems often shared.

Also, in apparent continuation with these early uses, some authors suggest that if two objects are analogous, then an ontological relation is connecting them. In a certain sense they belong to the same category (Anonymous 1657). This suggests that the identification of an analogy can be, in certain circumstances, scientifically significant. It could go beyond the subjective perception of resemblance. For example, in his *Physical Dictio-*

nary, Blancard proposes the following definitions: “*Analogia*, see *Analogismus*. *Analogismus*, a comparison and perception of causes that help by likeness” (Blancard 1693, p. 10). Through the perception of likeness we are in a better position to perceive and compare causes (see also Coles 1677). To produce an analogy can thus serve as an explanation because behind the similarity lies an eventual causal order (Johnson 1755). Others insist on the epistemological aspect of scientific analogies. Analogical reasoning is a scientific tool, because a hypothesis is more probable (or at least looks more probable) if we can produce similar cases. In this context, reasoning by analogy is a kind of induction founded on the uniformity of nature (Chambers 1728; Diderot and d'Alembert 1751, pp. 399–400). This uniformity of nature is also the justification of the ontological implications of analogy. By the end of the studied period all these aspects of the analogy concept were described in authoritative works like the first edition of the *Encyclopaedia Britannica* (Society of Gentlemen 1771, p. 142).

It should be noted that this diversity of meanings for “analogy” is not strictly an English phenomenon. In its first edition, *Le dictionnaire de l'Académie Française* defines “analogie” as: ratio, resemblance, conformity, proportion of one thing to another (Académie française 1694, p. 38). In the second edition of the dictionary “analogie” is now limited to its mathematical meaning: ratio, proportion (Académie française 1718). However in the fourth edition both aspects, proportionality and similarity, are present but in two distinct definitions (Académie française 1762, pp. 69–70). The range of definitions also increased during the period studied. For example in 1694, only “analogie” and “analogique” were given definitions. In 1718, definitions were also provided for “analogue” and “analogiquement.” This probably reflects an increasing use of these terms but may also denote an increased institutional approval of the use of analogies. This brief survey of the major dictionaries thus confirms that the meaning of analogy has not radically changed during the 17th and the 18th centuries⁴.

4. To confirm that the meaning given to “analogy” did not differ significantly in English and in French, we also looked at some English translations of French papers using the word “analogy” in the *Journal des savans* to see how that word was rendered in English. In the three chosen papers (Anonymous 1666b, 1666c; Cassini 1677a, 1677b; Cassini 1686a, 1686b) *analog** appears five times: twice “analogous” is the translation of “analogue,” twice “analogy” is used to translate “analogie,” and once the expression “analogy and uniformity” is used to translate “harmonie.” Moreover our corpus contains four bilingual French-English papers (Dicquemare & Maty 1774; Dicquemare 1775; Dicquemare 1777; Le Cerf and Mahon 1778). In these papers “analogie” is translated six times as “analogy” and once as “similarity”; “analogue” is translated one time as “analogous” and one time is not translated in the English version. Even if our survey is not exhaustive we are confident

4. Types of Uses

Between 1665 and 1780, 358 documents (articles, review, letters) containing at least one word of the analog* family appeared in the *PT*.⁵ If we use actual definitions of disciplines, the discipline most represented in our corpus is by far the duo biology-medicine, followed by astronomy-physics, and then by mathematics. Other research fields, like geology and chemistry, are represented only to a limited extent. We propose in this section a classification of the uses of analogy that focus on their meaning and function. We divide these uses in two broad categories: reflexive and practical uses. The occurrence of the word analog* is taken as reflexive when its use itself is discussed. On the other hand, when the use of analogy is taken for granted, when its limits, meaning or validity are not explicitly discussed, the occurrence is classified as practical. Practical uses are divided into six categories. An analogy can refer to (1) a general scientific principle or (2) to a concrete model; it can (3) illustrate or clarify an argument, (4) refer to a proportionality relation or (5) serve as a basis for a classification. Finally, an analogy can (6) be used to propose and justify a prediction. The following sections will discuss these different types in turn and the conclusion will compare our classification scheme based on the spontaneous uses of analogies by practitioners with other uses constructed by philosophers based on *a priori* epistemological considerations.

4.1 Reflexive Uses of Analogy

In the chosen corpus the use of specific analogies is the norm. What is far less frequent (around 4% of the documents containing analog*) are explicit comments on the use of analogy itself in science. Most of these are warnings about the unreliability of reasoning by analogy. For example, the opinion of the physician Caspari Bartholini is approvingly reported: anatomists of the past have neglected “to consult Nature herself, and acquiesce in nothing but Experiment” (Anonymous 1676, p. 768). They relied too much on analogies based on “light observation of a few circumstances” (p. 769). Analogy, even if it can be used, is in general a bad alternative to direct observation and experimentation. The use and abuse of analogy should not surprise us. According to Tuberville Needham (1748), we have a propensity to infer by analogy. He argues that:

The Method of Reasoning by Analogy is but too apt to lead us into Mistakes, and therefore we ought to be very diffident of conse-

that the English and French uses of words like “analogy” and “analogous” cover the same semantic field.

5. In the chosen corpus the terms analog* appear 615 times. In most documents (66%), the term occurs only once.

quences deduced this Way. Every new Appearance that has no known Cause, immediately fixes, and but to often at last puts the Thoughts of the Observer upon the Rack. When the Mind arrives at this Intensity of Action, how natural is it to free ourselves from a painful Uncertainty at any rate, and that with as little Expense of Reflection as may be? The most obvious and easy Method is to class, if it admits it, and to reduce it to some other known *Phenomena*. (p. 617)

The singularity of the unknown is thus diminished by the use of an analogy, but without a careful investigation this satisfaction rests, Needham argues, on a self-deception.

It could seem paradoxical that their mistrust of the reasoning by analogy did not stop Needham or Bartholini from using them. Indeed we do not find in the chosen corpus a general critique of the uses of analogy. In other words, the problem cannot be the use of reasoning by analogy in general, but its use as a means of demonstration above its heuristic value. Limited heuristic uses are perfectly acceptable. In order to establish a causal relation between a state of the intestine and a specific disease, St. André (1717) asserts that the symptoms should be compared to symptoms of other diseases “by Analogy of the Parts, Reason and repeated Experience” (p. 581). In a field where causal relations are difficult to demonstrate, analogy can be used in a complementary way with Reason and Experiment. Another example can be found in Horsley (1775). He asserts that the hypothesis about the Moon’s influence upon the changes of weather is highly improbable because it is “so destitute of all foundation in physical theory, so little supported by any plausible analogy” (p. 178). Horsley implicitly refers to a sort of principle of analogy, which asserts that a hypothesis is more probable if you present one or more similar cases.⁶ The fact that Horsley insists that the analogy needs to be “plausible” implies that not all analogies will do. One that is at least compatible with the “physical theory” is probably required, though the author is not specific on that point.

However, in the corpus studied here, the heuristic value of analogy is not acknowledged explicitly by many authors and seems taken for granted. We would look in vain for an opinion as clear as Joseph Priesley’s for whom analogy “is the great key to unlock the secrets of nature” (Priesley 1781, p. 259). It is possible that a strong praise of reasoning by

6. A modern example of such a principle of analogy can be found in (Carnap 1963, p. 225): “the probability that an object b has a certain property, is increased by the information that one or more other objects, which are similar to b in other respects, have this property.”

analogy would have been considered as giving ammunition to the adepts of occult sciences. As argued by Vickers (1984), the occult and the scientific mentalities did not disagree about the usefulness of analogy. The contested point was that the occult tradition collapses analogy to identity thus making analogy a metaphysical principle. Most natural philosophers were against that position. One thing is clear though: most uses of analogy are found at the practical level where it is taken for granted as a valid way of thinking which does not have to be explicitly justified.

4.2 Analogy as a General Scientific Principle

A first type of practical use found in our corpus of texts is one that has now become obsolete and foreign to the modern way of scientific thinking. In contemporary scientific discourse scientists do not use the word “analogy” to refer to a general principle of uniformity of nature. Until at least the second half of the 18th century however, we find references to a principle of “analogy of nature.” It is worth noting however that the number of occurrences in the corpus where the word “analogy” seems to refer to a unification principle is very small (around 3% of documents containing analog*).

Our first example is provided by Giovanni Domenico Cassini (1686b, p. 85) who, after exposing new discoveries about Saturn’s satellites, and in particular the fact that all satellites (except the first which is closest to the planet) perform their revolutions in less time than Jupiter’s satellites compared in their order from the planet, concludes from these discoveries that “the admirable Analogy and Uniformity of the parts of the Universe are most evident, and the Infinite Wisdome and Power of the Creator is demonstrated to the Contemplative.” By his use of “Analogy,” Cassini refers to a principle of cosmic order or harmony. This order can be understood on the basis of two principles: (1) a nomological principle: the same physical laws are equally valid in every parts of the universe. In particular, satellites of different planets are subject to the same laws. (2) A similarity principle: the different parts of the universe are furnished in an equivalent or at least structurally similar way.⁷ Based on these two principles we are justified in applying what we know about “here” to what we do not know about “over there.” It is useful to distinguish the two principles rather than to amalgamate them in a single principle of uniformity of nature’s action. The other planets could be ontologically similar to Earth but not obey exactly the same laws. On the other hand, other planetary systems could be furnished in a different way, because of their origins, but obey the same phys-

7. In a deterministic world if the first principle holds the second principle implies a similarity of initial conditions in the different parts of the universe.

ical laws as our solar system. Both principles are implied by the use of “Analogy.” In the above example, Cassini is not reasoning by analogy to explain or predict something. Rather, he is asserting the uniformity and unification of nature in the celestial realm. In the same way Thomas Molyneux (1697), observing similarities between the animal and the vegetal realms, notes the “Analogy that Nature observes in casting the Horns of Beasts and dropping the Fruits of Trees” (p. 495). This Analogy is strengthening the nomological principle that Nature is using the same mechanisms in different contexts.

Another well known natural philosopher, Edmond Halley uses a slightly different expression to name a similar principle. Speaking of possible discrepancies between actual measures and his map of “variations of the magnetical compass,” Halley (1714, pp. 166–67) writes: “‘Tis true, that I never observed my self in those parts; and ‘tis from the Accounts of others, and the Analogy of the Whole, that in such Cases I was forc’d to supply what was wanting; and ‘tis possible that there may be more Variation on the Coast than I have allowed.” Halley invokes “the Analogy of the Whole” to justify interpolations between compass measures. Thus, this expression seems to refer to a principle of regularity implying smooth variations of physical magnitudes in appropriate circumstances.⁸ This principle is closely connected to Cassini’s, but it is a different one. In fact, we can imagine using Halley’s principle to, at least partly, justify Cassini’s principles, since the absence of sharp variation of physical properties is a requisite for the possibility of uniformity principles.

Two interesting occurrences can be found in Alexander Stuart’s lectures on muscular motion. The first case is a justification of inductive inferences. “And therefore a few experiments clearly explained, and supported by the analogy of nature (which in all its operations is constantly similar to itself) are sufficient for the purpose of a demonstration *a posteriori*, or from the effect to the cause” (Stuart 1738, pp. v–vi). In this context, Stuart’s principle seems to be equivalent to the fusion of Cassini’s nomological principle and Halley’s regularity principle. Stuart also supports an ontological principle since he invokes “an universal analogy in the structure of all the moving parts in the animal oeconomy, visible in the heart, lungs, stomach, intestines, urinary bladder” (Stuart 1738, p. xl). In consequence, at least in the restrictive domain of animal anatomy and physiology, an ontological equivalence principle is sustained. By 1747 the principle is even stronger. Emanuel Mendez Da Costa, discussing Belemnites fossils, writes:

8. Of course, this does not exclude the possibility that some phenomena are discrete.

Nature bears an Analogy through all her Works; and though all the Species of any one *Genus* is not known to any Man, yet that Analogy nevertheless capacitates us to judge of those undiscover'd by those we know. (p. 400)

The space of possible species in one Genus is sufficiently structured and varies in a sufficiently smooth way that we can infer properties of unknown species based on already discovered species.

It is significant to note that a similar use of the word “analogy” appears in the 1713 edition of the *Principia*: “Certainly idle fancies ought not to be fabricated recklessly against the evidence of experiments, nor should we depart from the analogy of nature, since nature is always simple and ever consonant with itself” (Newton 1999, p. 795). About this passage, McGuire (1970) argues that here Newton uses the expression “analogy of nature” to refer to an ontological unification principle. It allows Newton to assert that from observable phenomena we can legitimately infer properties of unobservable entities like atoms. Where Cassini was unifying parts of the celestial realms, Newton is relating different scales in the chain of beings.

All these principles, which are confirmed by observations and experiments, are used to justify general conclusions based on a limited set of data. Here analogy plays on two levels. (1) Analogous, or more precisely similar, observations and experiments are invoked to justify a general theoretical framework, like the mechanical framework (this is, in part, what Cassini and Molyneux are arguing). (2) Once the framework is assumed, the included scientific principles allow the natural philosophers to interpret the newly encountered phenomenon as part of an analogous class (this is, in part, what Halley, Stuart and Mendez Da Costa are doing).⁹ In our corpus, we mostly see cases where analogies are expression of a commitment to the given framework (level 2).

4.3 Analogies as Concrete Models

In order to represent a phenomenon it is not uncommon to resort to a concrete object (a model). The cases discussed here are all examples where the model is said to be analogous to the phenomenon under study. In fact, it is *because* they are analogous that they represent. Let us see some examples.

In a paper published in 1704 in the *PT* van Leeuwenhoek, the well known natural philosopher, explains how he built a model of a whale's crystalline lens and exactly how this model represents:

9. A similar point is defended by Dorolle (1949, pp. 161–165).

Now, in order to have a clearer Idea of the Course of the Fibrous Matter in the Cristaline Humor of a Whale's Eye, which Fibres, as I have said before, lye in so many folds upon each other, I took a common Ball (for I could not make the Painter comprehend in any other way) and divided it into such parts as were analogous, or corresponded with the Divisions of the Fibrous Matter in the Cristallin Humor, and then wound it about with a single small Thread, which was to represent the Fibrous Matter that compos'd a small Scale of the said Humor. (van Leeuwenhoek 1704, pp. 1726–1727)

The analogous model represents a whale's eye not because they share substantive properties (for example the model is not transparent), but rather because they exhibit a similar structure. Fibres in a whale's crystalline lens and the ball's parts in the model are organised in a similar way. It is a usual feature of modelling that only a selected set of properties are represented. In this case the ones that support the analogous relation. If models are essentially concrete objects in the corpus, some examples show the way toward abstract modelling. In his discussion of Malpighius' *Philosophi et Medici Boniensis*, the anonymous reviewer writes:

This *Zootomy* he shews to be serviceable to Physick; those Parts that are not so discoverable in one Animal, being more evident in another; and tho' possibly they may differ something in the Figuration, yet they are Analogically reducible to the same Machine: Of this he gives several Instances in the Structure of the Lungs, Brain, Eyes, the use of the Gall, Circulation of the Blood, Etc. which are more visible in one Animal than another. (1697, p. 557)

Under one genus, animal structures are analogical to the same machine. Therefore this imagined machine is a model for all animals under the same genus. This machine is not strictly speaking a concrete object but could, at least theoretically, be built. The concept of machine is not a pure metaphor here.

The next example is more complex because the model does not simply represent a phenomenon, but also explains it:

Suppose a vessel full of water, having any thing lying at the bottom, such as a shilling, the water being at rest; you will perceive the image of the shilling distinctly; but if you give any commotion to the water, the image of the shilling will then appear indistinct and confused. Somewhat analogous to this is this other appearance: If you look thro' a telescope at any of the planets, when the stars

appear hazy, dim, and languid, you will see them distinctly: but look at them again, when the stars appear most bright and sparkling, you will then find their images less distinct. (Short 1753, pp. 365–366)

The explanation for indistinct planet observation that James Short proposes can be broken down into two moments: (1) there is a similarity of appearances between seeing an object through water and observing a planet through the sky. (2) If hazy observations in water are caused by the agitation of the medium then, hazy planet observations are analogically caused by air commotion. The model explains the phenomenon. However, the correspondence between the model and what he wants to explain is not straightforward. It is probably for this reason that Short uses the expression “somewhat analogous.” The optical properties of water are sufficiently different from air that an argument is needed to justify the model. Short argues that an “infinite number of heterogeneous particles” continually float in the air (p. 366). At least in part, it is the movement of these particles that is analogous to water movement. The enormous quantity of air that light has to cross to get to the telescope makes the analogy with the small vessel of water plausible. The difference in the optical properties of the medium is compensated by the difference of quantity of that medium crossed by light in both cases. For the explanation to work, Short thus presumes that the optical properties of water and air + particles are similar in appropriate conditions. The Short case is a paradigmatic case where from analogous appearances one induces, on a probabilistic basis, analogous causal relations. We will return to this type of inference below when discussing the last type of analogy.

Another way to use analogical models is possible when a model is believed to represent adequately scientifically relevant features of a phenomenon. In such a case, it is possible to learn something about the phenomenon represented by studying the model. The surgeon Benjamin Gooch (1775) proposed to do experiments on animals to obtain useful knowledge to treat aneurysms in the thigh of humans:

I communicated my thoughts upon this subject to some of my brethren, wishing to have experiments made upon brutes, that might ascertain as far as possible, by analogy, a matter which appeared to us of great importance. (p. 380)

By practicing different surgical procedures on animals, he hoped to develop, by analogy, the best way to proceed on humans. The epistemological strategy of Gooch can be reconstructed using the steps developed by Hughes (1997): (a) Denotation: the phenomenon (human aneurysm) is

represented by a model (induced aneurysms in animal thigh); (b) Demonstration: a surgical procedure is developed by working on the model; (c) Interpretation: what has been learned about the model is transposed to the phenomenon under study. The confidence in the developed surgical procedure comes from the belief that the animal aneurysms are identical in most relevant ways to human aneurysms. Nevertheless in this context animal aneurysms are not strictly identical to human aneurysms. We are justified in using the term “model” because we do not know if induced aneurysms have exactly the same relevant properties as naturally occurring aneurysms.

The desire to construct models more accessible to experimentation did not stop with animal models. Some natural philosophers, like the Abbé Mazeas are even more ambitious:

The nature of the vapours, which compose thunder, is not absolutely unknown to us. Would not the mixture of salts, sulphur, pyrites, Etc. produce vapours capable to electrifying a bar of iron? By suspending a bar of iron upon silken cords, and causing a wire to descend into a large glass recipient, wherein pyrites and other analogous matters, as sea-salt with oil of vitriol, may be made to ferment, in order to produce a vapour, which would contain spirit of salt, or which might develop the electrical matter; might not we come to produce the same phenomenon with that produced in a storm? (Mazeas & Parsons 1752, p. 538)

To have at our disposition an artificial cloud able to produce electrical phenomena would be an enormous advantage for the development of electrical science, even if the chemical composition of the artificial cloud is only analogous to the real ones.

By making an analogy between a not well understood phenomenon and a better known or more accessible concrete model, many things can be achieved. The model can represent, explain, or even demonstrate some aspects of the phenomenon under study. This seems possible because the analogy relates structurally similar aspects in the model and in the phenomenon.

4.4 Analogies as Illustrations

In the previous section we have shown cases where an analogous object serves as a model of a phenomenon. Typically, a model goes beyond a simple representation because it allows demonstration. It can be studied in order to learn something new about the thing represented. An analogous object can also superficially represent a phenomenon. If this representation does not go beyond mere appearances, it is not a full fledged model, but

simply an illustration. In our corpus, such analogies are mainly used to clarify or explain a particular point in an argument. The distinction between analogies as concrete model and analogies as illustration is not clear cut. Both are analogies understood as representation tools. An illustrative analogy could at a later time become a model. The reverse is also possible but much less likely.

For example, Gould writes about a polypus found in the heart of a person:

[T]he Fibres of the *blood* not being sufficiently sustain'd and kept asunder by a due motion of the intercepted fluid parts, may either barely upon the account by *Rest* cling together, or else may be by degrees connected so an *austere astringent acid* (always to be found in cachectical Bodies) for the same reason as (an *analogous liquor*) milk is curled, only with the difference that in this, the coagulation is brittle, [...] where it may be very tough in *blood*. (Gould 1684, p. 548)

In this passage blood is compared to milk but only in a superficial way. Indeed, milk, like blood, curdles, but in a different way. There could be a similar cause involved (“austere astringent”) in both liquid but this is not strongly argued. Milk (“an analogous liquor”) is essentially invoked to illustrate the coagulation of blood. However, if the causal process of coagulation was proven to be the same in blood and milk the analogy would change status.

The physician Andrew Cantwell (1737), when describing a tumour he found during an autopsy, uses an analogy: “At first Sight I took it for a *Parenchyma*, but, upon Dissection, found it analogous to the Liver in Substance, Colour and Consistence” (p. 141). The tumour’s interior looks like a liver but has nothing to do with the patient’s actual liver or its function. The liver analogy is strictly illustrative.

In a paper about cartilages’ diseases, the surgeon William Hunter compares the texture of cartilage to a pile of velvet. To help the reader visualize cartilage he also writes:

If another Comparison was necessary, we might instance the Flower of any corymbiferous Plant, where the *Flosculi* and *Stamina* represent the little Bundles of cartilaginous Fibres; and the *Calyx*, upon which they are planted, bears Analogy to the Bone. (1743, p. 116)

In this passage Hunter is not proposing that a certain kind of plant could serve as model for the cartilage/bone structure but rather is using the plant as a support for the imagination.

Another similar example can be found in the review of McLaurin's *Treatise of Fluxions* (Anonymous 1743, p. 326):

[A] Proposition is demonstrated, and rendered more general, concerning the Area of the Spiral that is generated on a spherical Surface by the Composition of Two uniform motions analogous to those by which a Spiral of *Archimedes* is described on a Plane.

The spiral of Archimedes is put forward to illustrate McLaurin's result about spherical surface. The assumed known result on a plane helps to illustrate the new result on a spherical surface. In the text, the analogy is not used in a formal way. If a common framework relates these two geometrical settings, it is not discussed, as if the author did not want to develop a full analogy between the two cases but simply illustrate a particular point.

Our next example comes from an abstract of Charles Bonnet's *Some new observations upon insects* published in the *PT*. In this paper, Bonnet describes a distemper that affects worms. "I have further observed, that they are subject also to a sort of Distemper, analogous to the Gangrene, that sometimes rots off considerable Parts of their Body" (Bonnet 1743, p. 485). This worm disease is analogous to gangrene because it appears to act on the body in a similar way. Nothing in Bonnet's analysis suggests that both diseases have the same cause or a similar cure. Their symptoms just look the same. This analogy is thus illustrative. It helps the reader to understand the action on worm of this specific disease.

As we have said, the distinction between a model and an illustrative analogy is not always easy to make on the sole basis of the textual evidence. Our last example comes from an anatomical study of a rattle-snake:

The Structure of the Parts and its Distance from the Fang make it unlikely to be design'd for separating the *poisonous Fluid*, but rather a *Saliva* to moisten the Aliment, in order to make it pass down the *Oesophagus* with Ease, the Stomach of those Animals being but small, and the Gullet considerably larger; not without some Analogy to the *Ingluvies* or Crop of Carnivorous Fowls, where the Food stops for some time and is moistened, before it is capable of descending into the Stomach. (Sloane and Randy 1728, p. 378)

The analogy plays here two roles: (1) it is an illustration helping the reader to imagine the anatomical parts described, especially since this section of the snake is not represented in the figures included in the paper. (2) It proposes a model to explain the function of these parts. However, this second role is suggested en passant and is not developed in the paper.

These illustrations are analogies in the classical sense of the term used

by most philosophers (see for example Hesse 1966). A known object is invoked in order to claim something about a less known object. The relation between the two objects is based on similarity. However, contrary to the previous type of analogy (concrete models), these examples are not limited to the context of scientific representation where the analogous model is structurally isomorphic to the thing represented.¹⁰

4.5 Analogy as Proportion

The cases that fall into this type refer to one of the original meanings of the Greek term “analogon”: proportionality. These analogies take the form: A is to B as C is to D (noted A/B::C/D), where A, B, C and D are quantifiable magnitudes. The form A/B::C/D can of course be used to express analogies that do not involve mathematical relations. The scholastic corpus contains a multitude of such examples. However, our type is limited to quantifiable relations, since these were considered by natural philosophers like Kepler and Leibniz to have a special status (Knobloch 1991). Let us see an example. The Irish physician Thomas Molyneux (1700) discusses the size of a giant on the basis of the size of one of his bone:

[A]ny one may make a probable conjecture at least in this matter, if he but compute according to the dimensions of such Bones, what must be the true size or bulk of the Man, whose Body, as is pretended, when intire, was composed of parts and Limbs, analogous or answering in a due proportion of these Remains. (p. 490)

Molyneux is proposing to compute the size of a giant using this analogy: the size of the giant is to the size of the found bone as the size of the human is to the size of the equivalent bone. In this relation, only the size of the giant is unknown, so the analogy can be used to compute this unknown quantity. In this case the proportionality relation holds because giants are supposed to be structurally similar to humans.

As a means to approximate the distance of fixed stars, John Michell (1767) makes the hypothesis that the intrinsic brightness of stars is equal to the intrinsic brightness of the sun. Using this hypothesis he then describes an empirical proof that confirms the relatively gigantic distance between fixed stars and us. But this assumed equality of intrinsic brightness does not seem probable. Many stars differ in size and colour. To solve this difficulty, Michell defends another analogy relating whiteness and intrinsic or native brightness (p. 238):

10. On the status of models compared to other kinds of scientific representation, see Suppes (2002).

We find however in general, that those fires, which produce the whitest light, are much the brightest, and that the Sun, which produces a whiter light than any fires we commonly make, vastly exceeds them all in brightness; it is not therefore improbable, from this general analogy, that those stars, which exceed the Sun in the whiteness of their light, may also exceed him in their native brightness; now this is the case with regard to many of them; and, on the contrary, there are some that are of a redder colour.

In other words, the whiter a star, the intrinsically brighter it is. Note that contrary to the last case, this analogy mixes quantities that do not refer to the same ontological domain (brightness and whiteness). By combining transitively this analogy and the preceding proof, Michell hopes to compute the distance of fixed stars *if* a reference case is known. It should be noted that the transitivity of Michell's inferences is guaranteed by the fact that we are dealing with quantifiable magnitudes. If it were not the case, the transitivity could still be valid but would have to be verified case by case. As usual, the mathematical formalization allows us to deduce general conclusions from a singular case.

This use of a proportionality relation in order to infer or predict a quantifiable aspect of a phenomenon is also illustrated in the review of J.J. Zimmermanni's *Cometo-Skopia*. Zimmermanni, using a proportional analogy, wrongly predicts the position of a comet:

Also by some other *Observations* communicated to him, the *Comet* was the sixteenth of *November* in 1° degree of *Libra* Latitude $\frac{1}{2}$ degrees *Austral*: From whence by the Analogy of its *Diurnal Motion* of five degrees, it should have been the fourteenth of *November* a little above the least *Star* in the left Wing of *Virgo*, as the first term or place of its Appearance. (Anonymous 1683 p. 270)

In spite of this failure, the anonymous reviewer does not critique Zimmermanni's inference method, but rather attacks his religious interpretation of the discrepancy in the comet's positions.

By keeping some magnitudes fixed, the proportional analogy collapses in a simpler expression. For example, in "A/B::C/D", if B and D are kept fixed, the relation becomes "A varies proportionally to B." If the proportionality factor is one, we have a case of covariation. A good example of this can be found in Newton's "Answer to some considerations upon his doctrine of light and colors" (1672, p. 5103). In this paper Isaac Newton affirms: "the strict Analogy between the degrees of Refrangibility and Colours." Newton is not arguing a similarity of nature or function. What is proposed is rather that these two things strictly covary. There is a bijec-

tion between the intensity of these phenomena: colours and degrees of refrangibility. A corollary is that colours are indirectly quantifiable through the bijection. This covariation is the core of the analogy and suggests a deep physical connection between both phenomena, possibly a common cause. Newton believes his theory of light is reinforced by the fact it includes this analogy.

Jean-Jacques Dortous de Mairan provides another example of covariation that is attributed to a common cause (his book is reviewed in Eames 1734):

May not the Spots, so often of late observed in the Surface of the Sun, be owing to these Precipitations of the grosser Parts of the *Zodiacal Light*, since there seems to be some Analogy or Correspondence between the Frequency, Cessation and Returns of these Spots, with the Cessation, Returns and Apparitions of the *Zodiacal Light*? (Eames 1734, p. 256)

Since Mairan believes that the cause of zodiacal light is the solar atmosphere: “the *Zodiacal Light* is the purer unmixed Atmosphere of the Sun” (Eames, p. 244), the analogy between the apparition of zodiacal light and sun spots suggests that the solar atmosphere is also the cause of the latter. In this context, the analogy is also the sign of a deep physical connection, here of a possible common cause.

Once covariation is understood to be a kind of analogy, the following argument from a book review of McLaurin’s *Treatise of Fluxions*, is easy to interpret:

When the Water is supposed to be supplied in a Cylinder, so as to stand always at the same Altitude above the Orifice, there is an Analogy between the Acceleration of the Motion of the Water that issues at the Orifice, and the Acceleration of a Body that descends by its Gravity in a Medium which resists in the duplicate *Ratio* of the Velocity. (Anonymous 1743, p. 354)

The accelerations in these cases are proportional. For these accelerations to be equal, ratios of parameters of the cylinder of water (area of the orifice and the base, height of the cylinder) have to be adjusted to ratios of parameters of the falling body. Hidden behind these equivalences is the assertion that both systems are governed by similar equations. However, this is never clearly stated in the paper. A more abstract approach, which will be developed in physics during the second half of the 19th century, is to represent different systems by the same equation (or formal structure), without the necessity for the terms of the equation to refer to the same magnitudes. William Thomson, in a paper published in 1842, provides

the first example of such a systematic formal analogy between two heterogeneous systems when he compares the equation of heat with the equation valid for magnetism (Thomson 1872, pp. 2–14; Buchwald 1977).

It should be noted that proportional analogies are not limited, in the corpus, to algebraic relations but can also be found in geometrical contexts. For example, William Brakenbridge (1759) makes numerous proportional analogies based on ten geometrical figures included in his paper. Some are naturally translated into an equation but not all are, though they could be. The fact that these “geometrical analogies” can always be translated is significant. It implies that proportional analogies based on geometrical figures do not constitute a new type of analogy. It should also be noted that when an analogy is based on a figure, at least one of the words “analogy,” “analogical,” or “analogia” appears in the text.

As a last example of analogy as proportionality, let us look at one of the rare cases where the *absence* of a proportional analogy can convey valuable information. This analogy comes from an account of the several species of infinity by Edmond Halley (1692). In this short paper, Halley argues for the existence of three kinds of infinite quantities: “These three sorts of infinite Quantity are analogous to a Line, a Surface and Solid, and after the same manner cannot be compared, or have no proportion to one another” (p. 558). The fact that these kinds of infinity are not proportional to each other implies that they are not analogous. Therefore, the absence of analogy is significant because it indicates that these infinities are incommensurable in the classical sense.

To sum up, proportional analogy is mainly an equivalence of relations among quantities. From this definition it seems almost inevitable that this equivalence would be generalized to all sorts of formal relations. Once the formal path is taken, the power of abstraction allows scientists to interpret as an analogy all shared syntactic structures among objects or phenomena, leading to the complex formal analogies now used, for example, in modern physics (Gingras 2001, 2005). In very few sciences outside optics, astronomy, and physics being mathematized during the period studied here, did we find many examples of such formal analogies in our corpus, though it is possible that the empirical orientation of the *PT* biased our sampling of these formal analogies and that the *Journal des Sçavans* or the *Mémoires de l'Académie Royale des Sciences* could contain more of them.

4.6 Analogy as a Tool of Classification

Using analogies as a way to distribute objects into classes is by far the most frequent case found in our corpus. It is possible to establish that a phenomenon A is part of a category of phenomena X if an analogy between A and members of X can be empirically grounded. In this context

the analogy can be understood as a classification tool. It is also a means of generalisation because the use of an analogy allows the extension of the application domain of the category X. A similar type of analogy is described by Dorolle (1949, Book 2, Chap. 3–4). In our corpus, analogies are used to extend two sorts of categories: natural kinds and functional categories. A natural kind is a category based on the common nature of phenomena. A functional category implies that all members share a common or similar function in their respective system.

Before going further, we want to dissipate a possible misunderstanding. An illustrative analogy is based on common appearances. The first step to establish a classificatory analogy is most of the time to point to the common appearances between the compared phenomena. Are illustrative analogies a special kind of classificatory analogy? We do not believe so. The first aim of illustrative analogies is to notice the common appearances pointing to the source and the target systems, since the analogy is essentially used to clarify the author's argument or discussion. For classificatory analogies, by contrast, the common appearances are just one of the possible premises of the argument supporting the common nature or function of the compared phenomena. Their specific objective is thus different. On the other hand, a model analogy could lead to a classificatory analogy. A model's main function is to represent a phenomenon in order to learn about it through studying the model. This is not the function of a classificatory analogy. Nevertheless two phenomena in the same class are, by their common nature or function, especially well suited to serve as models for each other. It is why a model analogy could in certain circumstances lead to a classificatory analogy and vice versa. But the function of each kind of analogy is clearly different in the scientific discourse. Let us see a few examples.

In his review, William Watson (1753) summarizes the Abbé Nollet : “[His] sixth letter to Mr. Franklin is upon the analogy of thunder with electricity. This is a fact at present well established, as to admit of no doubt” (p. 207). In this passage the analogy, or more precisely the common nature, between thunder and electricity is supposed to have been empirically demonstrated by Benjamin Franklin. Thunder and electricity are analogous because they both induce similar observable phenomena.

In the same vein, after describing numerous experiments involving the mixture of two liquors, Frederick Slare (1694) proposes the following analogy:

That the Spirit of Wine does not take fire, seems to proceed from the same Impediment which hinders light Oyls from coming up to an Accension, because they are so suddenly thrown off; and there

seems to be a great Analogy betwixt Aetherial Oyls and the Spirit of Wine, both as to Specific Gravity, and as to other Properties, Spirit of Wine seems to be a more thin and diluted Essential Oyl, that contains some Water and more Air in its Pores, they seem to own the same material Cause. (p. 217)

The spirit of wine (ethanol) and the aetherial oils differ in their properties. However, they fall in the same chemical class because they “seem to own the same material Cause.” They participate in the same manner to combustion.

More generally, if two phenomena follow the same physical laws they are in the same scientific category and the experiments confirming this similarity are analogous:

This Experiment I take to be very Analogous to those lately made on the seeming spontaneous Ascent of Water between Glass, Marble, and Brass Planes, as also with those made in Capillary Tubes; since it seems to proceed from the same Principle, and subject to the same Laws, as appears by matter of Fact. (Hauksbee 1709, p. 262)

Since water behaves in a similar lawful way, ascending capillary tubes or a compact ashes column, then these experiments are analogous.

Sometimes further empirical studies can generate some doubts about the proper inclusion of a phenomenon into a given category based on analogy:

The resemblance and the analogy, which the figure of a cluster of *Polypi* bears to the figure of a plant, would induce any observer, for sometime to imagine, that the *Polypi* which he sees fixed to the branches of the cluster, do really proceed and spring from those branches, in the same manner as the leaves, the flowers, and the fruit of a vegetable, spring from the branches of the same. It is nevertheless the contrary of all this, that is true. The branches, composing the clusters of the *Polypi*, spring from the *Polypi* which are at their extremities. (Trembley 1747, p. 642)

Here, Abraham Trembley argues that the strong analogy of appearances between a plant and a cluster of polyps does not automatically imply an identity of nature. By observation and experiments, Trembley shows that the growth of polyp differs greatly from that of plant. Polyp properties seem more compatible with animal properties. However, Trembley is careful not to conclude that polyps are of an animal nature. He prefers to wait for more empirical information about plants and animals.

In other cases, an analogy is not used to establish a common nature but rather a common or similar function. For example, using an ingenious method to dissect leaves, Frank Nicholls (1730) shows that each fibre in a leaf is composed of two distinct fibres and that this separation is continued through all the fibres and stem of the leaf, so as to form two distinct planes of similar fibre networks:

Though this Duplication of the Vessels in Leaves seems to point out an Analogy between them and the Veins and Arteries of Animals, yet I see no probable Means of guessing which are the arterial and which the venal Fibres. (p. 372)

For Nicholls, the discovery of the duplication of fibres points out a possible analogy between leaf fibres and the vascular system in animals. This suggests a similar function. The leaf fibre system would be responsible for the circulation of the sap. The next research step, inspired by the analogy, is to find an empirical way to identify which network corresponds to arteries and which to veins.

Another example can be found in the famous description of the bulbourethral glands (also called Cowper's glands) by William Cowper (1699):

The main design of Nature in framing these Glands seems to respect the grand Work of Generation, which will be more evident if we examin the Analogous Organs in other Animals [. . .] It is remarkable we don't find these Glands in Females like those in Males, tho' they have something Analogous to them, which are described in Women by *De Graaf*, and call'd *Prostatae Mulierum*. (p. 366)

By studying similar (analogous) glands in male animals, Cowper asserts that the newly discovered glands in men share a similar function in reproduction. Moreover, these glands, only present in men, are analogous to female glands called "Prostatae Mulierum," a set of glands that is now believed to refer to the Skene's paraurethral glands. According to Cowper, these two kinds of glands are not even located in the same relative position in the body. They do not share the exact same function in reproduction. However Cowper seems to assume that these female glands are the closest functional equivalent to the new found male glands. If they do not have the same function, they seem to possess a similar function in reproduction.

An example of argument against a certain analogy but for another one is found in James Johnstone's article on the ganglions of the nerves (1764). Johnstone argues against the analogy between ganglion and muscle. According to him they cannot share the same function since we cannot reasonably assign muscular power to ganglions. Ganglions do not have the

required fibre structure to act as muscles (p. 178). On the other hand, he tries to establish an analogy between ganglia of the nerves and the brain:

May we not then reasonably conclude, that Ganglia are the instruments, by which the motions of the heart and intestines are [...] rendered uniformly involuntary; and that to answer this purpose is their use, which they subserve by a structure unknown to us, no less than that of the brain, though it seems not improbable the first may be analogous to the last? (p. 181)

Ganglia seem responsible for involuntary movements, the brain for the voluntary ones. They are analogous. However, Johnstone remains careful in his conclusions since he does not have strong evidence to support this sharp division of tasks.

What all these examples show is that the establishment of analogies in order to extend a classification is considered a valuable and valid scientific enterprise. The analogy can be a clue pointing to the fact that the two apparently unrelated analogous phenomena are part of the same causal network. On the epistemological side, an analogy, for example of function, allows one to apply to the lesser known system patterns of explanation developed in the context of the better known system. For example, if fibres in a leaf and the vascular system share the same function, then the fibres bring nutriments to the leaf. We could then infer, from the analogy, that there should be less nutriments in the sap when it returns to the branch. This type of reasoning, where the analogy is used to make a prediction, is the subject of the next section.

4.7 Prediction from Analogy

In current scientific literature, analogies are often part of what can be called *arguments from analogy*. In such arguments, the analogy is used to support a conclusion, where some properties of a target object are inferred on the basis of analogous properties present in the source object. As is well known, this form of inference is not generally valid in the deductive sense. Nevertheless, it seems that a principle of analogy, like the one mentioned above (see footnote 7), is often assumed in our corpus. It seems generally believed that a hypothesis is more probable when one finds one or more similar cases. Unfortunately, we did not find in the corpus an explicit discussion relating argument from analogy and probability theory. Therefore reasoning from analogy was in practice considered by natural philosophers of the time an acceptable kind of inductive reasoning. Again, the point is not to evaluate its validity from an abstract and modern philosophical

point of view, but to describe the type of arguments from analogy natural philosophers of the 17th and 18th century used in their papers.

In order to make an argument from analogy, the similarity between the target phenomenon and the source must first be established. In our corpus, this is essentially done by pointing out similar observable properties between the target and the source. Once the similarity is established, one can predict something about the target. This prediction can be an observable or an unobservable property, for example a causal relation or even a complete causal network. The confidence that the author puts in his analogy is generally proportional to the strength of the similarity relation established as a precondition. Let us see a few examples.

The American natural philosopher John Banister observes, in a certain kind of snail that possesses a transparent shell, a thin spotted film which contracts and dilates itself. Based on this observation, he makes the following analogy about the possession of similar film:

I suppose the same to be in all, at least the Land-Kind, tho' not easily to be discerned. It is likely also, that the Film, the Nautilus or Carvil (as the Sailors call it) exerts, may be analogous to this. (Banister 1693, p. 671)

The observed snail is a good source for the analogy because it is in the same animal category as other land snails or the nautilus. This category is of course established by referring to their similar observable features. In other cases, the induced analogical property could only be observed using scientific instruments. For example, based on the observed correlation between the electric conductibility and the grain of a few crystals, Benjamin Wilson generalizes his conclusion:

Now, as several of the above gems have different electric poles independent of their shape, and I have not yet been able to vary the direction of the fluid in any one of them, though various methods have been tried, and some of a violent nature; and since the green crystal, or chrysolite, above described, hath likewise the same electric poles, but with this difference only, that the fluid moves always along the slender threads or columns, which is the grain thereof, and without suffering any change from that direction; it seems by analogy, that the electric fluid flowing through all of them, moves in that direction in which the grain happens to lie. (Wilson 1762, p. 445)

We have here an ordinary case of inductive reasoning concerning the properties of crystals. That Wilson qualifies this induction by the word “anal-

ogy" confirms the fact that for the actors of the period an argument from analogy is already considered as a kind of induction.

There is something peculiar in these examples. Common properties are inferred on the basis that objects or phenomena belong to the same category (that they share similar observable properties). But how is a category defined if not by a common set of properties? So, in a sense, to infer by analogy in this context is a way to deploy all aspects of the underlying category. Ultimately all these cases are based implicitly on a general scientific principle like the ones described above on the uniformity and analogy of nature.

Let us now look at two examples where the predicted feature goes beyond an observable property. Predicting the absence of rotation of Jupiter's and Saturn's satellites (a phenomenon that was then considered unobservable), an author wrote in 1666:

But, as for the Secundary Planets, as well those about *Jupiter*, as that about *Saturn*; it is most likely that they have no such Rotation upon their Axis. Not so much, because; by reason of their smallness, no such thing hath been yet observed, (or, indeed, could be, though it were true;) But because they being Analogical to our *Moon*, it is most likely that they are moved in like manner. (Anonymous 1666a, p. 144)

The strength of this analogy is less founded on a clear category of "satellite" than on the hypothesis that the same cause is producing the movement of the moon and of the other satellites. In the next example the author goes further.

Thomas Molyneux wants to prove that the geological phenomenon called the Giant Causeway, which consists of thousands of stone pillars, has been produced by a natural cause. In order to prove this hypothesis he invokes many similar looking phenomena which have a natural origin:

But nothing puts this more out of Dispute, than to make a little Enquiry into other Works of Nature of the like kind; where though perhaps we may find nothing altogether the same, yet we may observe some of her Productions, that at least bear such an *Analogy*, or Resemblances to the Composition and Figure Remarkable in these Stones, that we shall easily conclude These as well as They must certainly be the Architecture of the Regular Hand of Nature. (Foley and Molyneux 1694, p. 177)

Molyneux's argument involves the induction of a kind of cause. Based on the production of many similar (but different) source phenomena to the Giant Causeway (the target), each source phenomenon having a natural

cause, Molyneux concludes that the target has probably a natural cause. This argument from analogy goes beyond the induction of an observable property. It concludes about the natural status of a causal relation.

In more complex cases, the analogy allows the projection from the source to the target of a complete causal structure or network. Let us see two examples. The Irish physician T. Madden (1731) discusses the poisonous effects of laurel-water, a drink produced by distilling water with laurel leaves. The question that Madden proposes to answer is how does this water affect the body? Other physicians suggest that the poison causes an inflammation of the stomach and guts that can be fatal. Madden rejects this hypothesis. His explanation schema is that the effects of laurel-water are analogous to the effects occasioned by epilepsy:

I do not know any thing that will illustrate this Matter, than the Analogy which may be observed between the Convulsions occasioned by the Epilepsy, and those which are the Effect of *Laurel-Water*. (p. 95)

His analogy is sustained by observable facts: the appearances (convulsions) caused by ingestion of laurel-water look like those during an epilepsy crisis and, importantly, the absence of inflammation seen during the autopsies of dogs that died after ingestion of laurel-water is compatible with epilepsy. Using this similarity as a foundation, Madden then projects on the target (the effects of laurel-water) a complex causal network (how epilepsy affects the vascular and muscle system). This analogy is then considered the explanation of the fatal effect of drinking Laurel-Water.

Another example can be found in the book review of Christianus Huygens' *The Celestial World Discover'd, or Conjectures concerning the Inhabitants, Plants, and Productions of the Worlds in the Planets*:

And tho' it be impossible for us ever to see those Planets, by reason of their vast Distance, yet from the Analogy that is between the Sun and Stars, we may judge of the planetary Systems about them, and of the Planets themselves too, which probably are like the planetary Bodies about the Sun, (that is) that they have Plants and Animals, nay, and Rational ones too, as great admirers and Observers of the Heavens as any on Earth. (Anonymous 1699, p. 337)

The analogy between the Sun and stars allows the natural philosopher to make hypotheses about the existence of other planets, plants, and animals that are unobservable with the available telescopes. The projection of properties from the source to the targets implies a very complex network of causes and objects.

In our corpus, some natural philosophers also discuss empirically confirmed analogical inductions, in other words particular inferences by analogy that were discovered as valid. For example:

The Discovery {of the rotation of Jupiter} is one of the best, that have been yet made in the Heavens; and those, that hold the Motion of the earth, find in full Analogy. For, *Jupiter* turning about the Sun, does nevertheless turn about his *Axis*; and although he be much bigger than the Earth, he does nevertheless turn much more swiftly than it, since he makes more than two Turns, and a third part, for its one, and carries with him 4 Moons, as the Earth does one. (Anonymous 1666b, p. 173)

The empirically shown movement of Jupiter extends the properties attributed to the planet category and indirectly reinforces the principle of uniformity of nature. A more complete theoretical framework can also be confirmed by using analogies. For example, Joseph Priestley (1775) explains that:

The manner in which I have used it [air], has been to throw the focus upon the several substances I wished to examine, either *in vacuo*, or when confined by quicksilver, in vessels filled with that fluid, and standing with their mouths immersed in it. I presently found that different substances yield very different kinds of air by this treatment; and though the reasons, or analogies, of the different products, in many of the cases, be sufficiently obvious, and such as I had conjectured *a priori*, yet in other cases I am not a little puzzled and surprized. (1775, p. 387)

Each new successful analogical prediction of chemical products confirms to Priestley the usefulness of his chemical categories and mechanisms. Unfortunately, every surprising result shows that further work is still needed. It should be noted that, in the period studied, disconfirmed analogical predictions do not falsify the principle of the analogy of nature or suggest giving up the method of analogical induction.

5. Conclusion

Any analysis of the frequency of the uses of analogy in scientific papers is probably subject to a bias introduced by the choice of the source journal. However, a normalised measure of the relative frequency of use in different fields can produce a first idea on the distribution of the uses of the different types of analogies among the various research fields. We have constructed an index of use for the seven research fields among which we have

distributed the 335 documents of our corpus (with 20 attributed to an “other” category).¹¹ The normalized index is calculated as the ratio of the proportion of use of a given analogy in a given field to the proportion of total papers in that field. For example, to obtain the value of the index for the case of illustrative analogies in chemistry, we divide the proportion of papers in chemistry that use such an analogy (9/78) by the proportion of chemistry papers in the corpus (17/335). We thus get 2,3, which means that this analogy is used more than twice as often in chemistry as should be expected from a uniform distribution of that use among all the fields. The results are summarized in Table 1. Note that there can be more than one type of analogy used in a given paper so that the total for the types of use is higher than 335. When the index of use of a particular analogy in a research field is higher than one, this means an over-representation, while an index below 1 points to an under-representation of that type of analogy in that field.

Note that the seven types of analogy are not used in the same proportions. Reflexive uses, analogy as principle and analogy as model, account for only 3% each. As much interest as been recently accorded to models in science (Morgan and Morrisson 1999; de Chadarevian and Hopwook 2004), this relative scarcity of explicit modelling during the period studied here (1665–1780), compared to other uses of analogy suggests that such modelling maybe relatively recent. 91% of the uses of analogy are distributed evenly between illustration (18%), proportion (17%), and prediction (22%), with classificatory uses being the most frequent with 32% of the identified uses.¹²

Let us look in more detail at the four uses for which we have the best statistics. Illustrative uses can be found in all research fields, though they are clearly underrepresented in astronomy, mathematics, and geology, and overrepresented in chemistry. This distribution can be expected since illustrative analogies are obviously an appropriate communication device to describe new discoveries, of chemical products for example, for which we do not yet possess a shared descriptive vocabulary. Inversely the deficit of illustrative analogies in the case of geology, astronomy, and mathematics is probably due to the more systematic use in these fields of a shared descriptive vocabulary. Geology predominantly uses analogical models while the two other fields, being more quantitative, use primarily proportional

11. 23 of the 358 corpus documents, most of them written in Latin, were omitted from the analysis because we could not obtain reliable translations. Though Latin texts are thus excluded we see no reason to expect *new* types of analogies to emerge only in Latin texts.

12. Note than among the 335 papers we have in fact 430 cases of analogical uses as different types can be used in a single paper, though as we have noted, most papers use only one type of analogy.

Table 1. Normalized relative frequencies of uses of each type of analogy by research field.

Types of Analogy	Astronomy (24)	Biology (143)	Chemistry (17)	Geology (15)	Mathematics (41)	Medecine (24)	Physics (51)	Others (20)
Reflexive (14)	0	1,3	1,4	0	0,6	2	0,9	0
Principle (11)	1,3	1,5	0	0	0	1,3	1,2	0
Model (13)	1,1	0,7	0	3,4	0	1,1	2	1,3
Illustration (78)	0,2	1,3	2,3	0,3	0,3	1,4	0,8	0,6
Proportion (76)	2,6	0	0	0	4,2	0	1,5	1,1
Classification (141)	0,3	1,4	1	1,7	0,1	0,8	0,9	0,6
Prediction (97)	1,3	1,2	1	1,4	0,2	1,3	0,5	1,4

analogies, a type negligible in other fields. Prediction analogies are remarkably well distributed among the different fields, except in mathematics where it is not really useful and where the proportional analogies perform essentially the same function. Its value is also low in physics where models are the dominant type of analogy followed by proportion, since physics tends to be quantitative. Classificatory analogies are most prevalent in descriptive sciences like biology and geology and nearly absent in mathematics, as could be expected. One would expect that it would be dominant in more descriptive disciplines like biology or medicine but it is not the case except marginally for geology. The difference between astronomy and physics can be understood by noting that the necessity to classify new phenomena is relatively less frequent in astronomy than in physics, where a large number of phenomena are not yet mathematized during the period covered here.

We can now compare our classification scheme with those obtained by different means. For example, Holyoak and Thagard (1995, Chap. 8) classify analogies based on their distinguishable purpose: discovery, development, evaluation, and exposition. This classification is a cognitive one. In this context, the same analogy could fall into more than one category. Moreover, the classification of a particular analogy among these categories could require access to information that cannot be found in the scientific texts. For example, perhaps Benjamin Franklin derived not only the idea of an experiment from the analogy between thunder and electricity (an experiment well documented) but also the hypothesis itself that thunder is an electrical phenomenon. To be verified, this proposition would need access to more information than we can actually find in the available texts. In a similar vein, Dorolle (1949) classifies analogies based on their function: invention, generalization, definition and classification, and induction. A function in this context refers to a general form of reasoning or inference. Dorolle's classification is philosophical. Since we have no access to the mind of the scientist, the study of scientific texts rarely provide the information needed to decide into which category a particular analogy would fall. By contrast to these two classifications, which are based on general considerations, our classification is driven by the content of the texts themselves. Our types of analogies are defined on the basis of the observed uses as they appear in the corpus studied. This text-based approach explains why we do not have an invention or a discovery category, as the texts do not permit such an attribution. For the same reason, we distinguish only two categories, classification and prediction, where Dorolle sees three: generalization, definition and classification, and induction. In the corpus studied here, the three Dorolle categories could not easily be distinguished. In fact, our approach does not require access to hidden infor-

mation in order to be applicable. Though more empirical and sensitive to changing historical practices, our approach is complementary to those of Dorolle, Holyoak, and Thagard and others who are more philosophical.

The object of this paper was to look at the extent and nature of the uses of analogy during the first century following the so-called scientific revolution. Using the tool provided by JSTOR we have shown that for the period 1665–1780 the proportion of papers explicitly using the term “analog” and its cognates oscillates around 6% of all the papers. Following that period we observe an important growth of the uses of that term going up to about one half of all papers in *PT*, as if the method of analogy was the most direct way to infer knowledge about a new phenomenon. We have also seen that arguments from analogy are used in all fields of knowledge covered in the *Philosophical Transactions* and that there are many different types of analogical thinking which cover a large spectrum, going from the simple illustration to modelling and making predictions of new properties or phenomena. While illustrative analogies can convey information, they are much less developed than analogical models that go further into the nature of the phenomenon under study. Though they are rarely discussed as such, the different types of use of analogy present a sort of gradation in richness of inference from the mere illustration to the systematic analysis of the comparable aspects of the source and target in order to infer the maximum information on the target and even predict some of its unknown properties. Finally, analogical thinking seems so ingrained and intrinsic to scientific thinking (and probably to common sense as well) that it is most of the time taken for granted as a legitimate mode of thinking and rarely debated as such by the practitioners in their scientific papers, as shown by the scarcity (3%) of the presence of reflexive discussions of analogy during the period analyzed in this paper.

References

Académie Française. 1694. *Le dictionnaire de l'académie françoise dédié au roy* (1st ed.). Paris: J.B. Coignard.

Académie Française. 1718. *Le nouveau dictionnaire de l'académie françoise dédié au roy* (2nd ed.). Paris: Francois S. Regnier-Desmarais.

Académie Française. 1762. *Dictionnaire de l'académie françoise* (4th ed.). Paris: Chez la veuve de Bernard Brunet.

Anonymous. 1657. *A physical dictionary*. London: G.D. for John Garfield.

Anonymous. 1666a. “Some observations concerning Jupiter. Of the shadow of one of his satellites seen, by a telescope passing over the body of Jupiter.” *Philosophical Transactions* 1(8): 143–145.

Anonymous. 1666b. “A more particular account of those observations

about Jupiter, that were mentioned in numb. 8." *Philosophical Transactions* 1(10): 171–173.

Anonymous. 1666c. "Extrait d'une lettre escrive de Rome, touchant les nouvelles découvertes faites dans Jupiter par M. Cassini Professeur d'Astronomie dans l'Université de Boulogne." *Journal des Scavans* February 22: 99–102.

Anonymous. 1676. "Review: an account of some books." *Philosophical Transactions* 11(130): 766–774.

Anonymous. 1683 "Review: an account of four books." *Philosophical Transactions* 13: 259–274.

Anonymous. 1697. "Review: Account of a Book." *Philosophical Transactions* 19(228): 545–560.

Anonymous. 1699. "Review: an account of books." *Philosophical Transactions* 21: 335–342.

Anonymous. 1743. "An account of a book intituled, A treatise of fluxions, in two books, Colin McLaurin." *Philosophical Transactions* 42(468): 325–363.

Banister, J. 1693. "The extracts of four letters from Mr. John Banister to Dr. Lister, communicated by him to the publisher." *Philosophical Transactions* 17: 667–692.

Blancard, S. 1693. *The physical dictionary* (2nd ed.). Printed for S. Crouch.

Brakenridge, W. 1759. "A Letter to the Right Honourable Hugh Earl of Marchmont, F.R.S. Concerning the Sections of a Solid, hitherto not considered by Geometers." *Philosophical Transactions* 51: 446–457.

Buchwald, J. Z. 1977, "William Thomson and the Mathematization of Faraday's Electrostatics." *Historical Studies in the Physical Sciences* 8: 101–136.

Bonnet, C. 1743. "An abstract of some new observations upon insects." *Philosophical Transactions* 42(470): 458–488.

Cantwell, A. 1737. "Extract of a Letter from Andrew Cantwell, M.D. Montpel. To Dr. Stack, dated at Montpellier, June 23. 1732. N.S. Containing an Account of a large Glandular Tumor in the Pelvis; and of the pernicious Effects of crude Mercury given inwardly to the Patient." *Philosophical Transactions* 40(446): 139–142.

Carnap, R. 1963. "Discussion: variety, analogy, and periodicity in inductive logic." *Philosophy of Science* 30(3): 222–227.

Cassini, G. D. 1677a. "Histoire de la découverte de deux planètes autour de Saturne, faite à l'Observatoire Royal." *Journal des Scavans* 6: 70–72

Cassini, G. D. 1677b. "Some new Observations made by Sig. Cassini and deliver'd in the Journal des Scavans, concerning the two Planets about Saturn, formerly discover'd by the same, as appears in N. 92 of the se Tracts." *Philosophical Transactions* 12(133): 831–833.

Cassini, G. D. 1686a. "Nouvelle découverte de deux satellites de Saturne les plus proches, faite à l'Observatoire Royal." *Journal des Scavans* #9: 97–106.

Cassini, G. D. 1686b. "An extract of the Journal des Scavans. of April 22 st. N. 1686. Giving an account of two new satellites of Saturn." *Philosophical Transactions* 16(181): 79–85.

Chadarevian, S. de, and N. Hopwood (Eds). 2004. *Models. The Third Dimension of Science*. Stanford: Stanford University Press.

Chambers, E. 1728. *Cyclopaedia*. Vol. 1. London: Printed for James Knapton et al.

Cockeram, H. 1650. *The English dictionary: or, an interpreter of hard English words* (9th ed.). London: Printed by A. Miller.

Coles, E. 1677. *An English dictionary*. London: Peter Parker.

Cowper, W. 1699. "An account of two glands and their excretory ducts lately discover'd in human bodies." *Philosophical Transactions* 21: 364–369.

Daston, L. J. 1984. "Galilean analogies: imagination at the bounds of sense." *Isis* 75(2): 302–310.

Dear, P. 1985. "Tobius in Verba: rhetoric and authority in the early Royal Society." *Isis* 76(2): 144–161.

Dicquemare, Ab. 1775. "A Second Essay on the Natural History of the Sea Anemonies." *Philosophical Transactions* 65: 207–248.

Dicquemare, Ab. 1777. "A Third Essay on Sea-anemonies." *Philosophical Transactions* 67:56–84.

Dicquemare, Ab., and M Maty. 1774. "An Essay, towards elucidating the History of the Sea-Anemonies." *Philosophical Transactions* 63: 361–403.

Diderot, D., and L. le R. d'Alembert. 1751. *L'Encyclopédie ou dictionnaire raisonné des sciences, des arts et des métiers*. Vol. 1. Paris: Chez Biasson: David Lainé, Le Breton.

Dorolle, M. 1949. *Le raisonnement par analogie*. Paris: Presses Universitaires de France.

Eames, J. 1734. "An account of a book entitled, *Traité physique et historique de l'aurore boréale*, par Mr. de Mairan. Suite des Mémoires de l'Académie Royale des Sciences, Année 1731." *Philosophical Transactions* 38(431): 243–257.

Foley, S., and T. Molyneux. 1694. "An account of the Giant Caus-way in the North of Ireland: by Reverend Dr. Sam. Foley. Some notes upon the forgoing account of the Giants Causway, serving to further illustrate the same: by T. Molyneux." *Philosophical Transactions* 18(212): 170–182.

Galison, P. 1984. "Descartes's comparisons: from the invisible to the visible." *Isis* 75(2): 311–326.

Gentner, D., K. L. Holyoak, and B. N. Nokinov (Eds.). 2001. *The analogical mind*. Cambridge: MIT Press.

Gingras, Y. 2001. "What Did Mathematics Do to Physics?" *History of Science* 39(2): 383–416.

Gingras, Y. 2005. "How the Photon Emerged through the Prism of Formal Analogies." *Photons* 3(2): 13–14.

Gooch, B. 1775. "Concerning aneurysms in the thigh." *Philosophical Transactions* 65: 378–383.

Gould, W. 1684. "An account of a polypus found in the heart of a person that died epileptical, at Oxon." *Philosophical Transactions* 14: 537–548.

Gross, A. G., J. E. Harmon, and M. S. Reidy. 2000. "Argument and 17th-century science: a rhetorical analysis with sociological implications." *Social Studies of Science* 30(3): 371–396.

Halley, E. 1692. "An account of the several species of infinite quantity, and of the proportions they bear one to the other." *Philosophical Transactions* 16(195): 556–558.

Halley, E. 1714. "Some remarks on the variation of the magnetical compass published in the Memoirs of the Royal Academy of Science." *Philosophical Transactions* 29(341): 165–168.

Hallyn, F. 2000. "Atoms and Letters." Pp. 53–69 in *Metaphor and analogy in the sciences*. Edited by F. Hallyn. Kluwer Academic.

Hauksbee, F. 1709. "Several Experiments touching the seeming Spontaneous Ascent of Water." *Philosophical Transactions* 26(319): 258–266.

Hesse, M. 1966. *Models and analogies in science*. Notre Dame: University of Notre Dame Press.

Holyoak, K. J., and P. Thagard. 1995. *Mental leaps: analogy in creative thought*. MIT Press.

Horsley, S. (1775). An abridged state of the weather at London in the year 1774. *Philosophical Transactions* 65: 167–193.

Hughes, R. I. G. 1997. "Models and representation." *Philosophy of Science* 64(4): S325–S336. Supplement. Proceedings of the 1996 biennial meeting of the Philosophy of Science Association. Part II.

Hunter, W. 1743. "Of the Structure and Diseases of Articulating Cartilages." *Philosophical Transactions* 42(470): 514–521.

Johnson, A. 1755. *A Dictionary of the English Language*. Vol. 1. London: Printed by W. Strahan.

Johnstone, J. 1764. "Essay on the Use of the Ganglions of the Nerves. Communicated by the Right Rev. Charles Lord Bishop of Carlisle, and F.R.S." *Philosophical Transactions* 54: 177–184.

Knobloch, E. 1991. "L'analogie et la pensée mathématique." Pp. 217–237 in *Mathématiques et philosophie de l'Antiquité à l'âge classique*. Edited by R. Rashed. Éditions du CNRS.

Le Cerf, and Lord Viscount Mahon. 1778. "Account of the Advantages of a newly-invented Machine much varied in its Effects, and very useful for determining the perfect Proportion between different Moveables acting by Levers and Wheel and Pinion." *Philosophical Transactions* 68: 950–998.

Licoppe, C. 1996. *La formation de la pratique scientifique. Le discours de l'expérience en France et en Angleterre (1630–1820)*. Paris: La Découverte.

Lloyd, G. E. R. 1966. *Polarity and analogy*. Cambridge: Cambridge University Press.

Madden, T. 1731. "A letter from T. Madden, M.D. of Dublin, to Cromwell Mortiner, M.D.R.S. secr. giving an account of two women being poisoned by the simple distilled water of laurel-leaves, and of several experiments upon dogs; by which it appears that this laurel-water is one of the most dangerous poisons hitherto known." *Philosophical Transactions* 37(418): 84–100.

Mazeas, G., and J. Parsons. 1752. "Letters of the Abbé Mazeas, F.R.S. To the Rev. Stephen Hales, D.D. F.R.S. Concerning the Success of the late Experiments in France. Translated from the French by James Parsons, M.D. F.R.S." *Philosophical Transactions* 47: 534–552.

McGuire, J. E. 1970. "Atoms and the 'Analogy of Nature'." *Studies in History and Philosophy of Science* 1(1): 3–58.

Mendez Da Costa, E. 1747 "A Dissertation on those fossil figured Stones called Belemnites." *Philosophical Transactions* 44(482): 397–407.

Michell, J. 1767. "An inquiry into the probable parallax, and magnitude of the fixed stars, from the quantity of light which they afford us, and the particular circumstances of their situation." *Philosophical Transactions* 57: 234–264.

Molyneux, T. 1697. "A Discourse concerning the Large Horns frequently found under Ground in Ireland, Concluding from them that the great American Deer, call'd a Moose, was formerly common to that Island: With Remarks on some other things Natural to that Country." *Philosophical Transactions* 19(227): 489–512.

Molyneux, T. 1700. "An essay concerning giants. Occasioned by some further remarks on the large humane os frontis, or forehead-bone, mentioned in the Philosophical Transactions of February, 1684(5), Number 168." *Philosophical Transactions* 22(261): 487–508.

Morgan M. S., and M. Morrison (Eds) 1999) *Models as Mediators. Perspectives on Natural and Social Science*. Cambridge: Cambridge University Press.

Needham, T. 1748. "A summary of some late observations upon the generations, composition, and decomposition of animal and vegetable substances." *Philosophical Transactions* 45: 615–666.

Newton, I. 1672. "Mr. Isaac Newtons answer to some considerations upon his doctrine of light and colors; which doctrine was printed in Numb. 80. Of these tracts." *Philosophical Transactions* 7(88): 5084–5103.

Newton, I. (1726) 1999. *The Principia*. Translated by I. B. Cohen and A. Whitman. Berkeley: University of California Press.

Nicholls, F. 1730. "An account of the veins and arteries of leaves." *Philosophical Transactions* 36(414): 371–372.

Olson, H. F. 1943. *Dynamical analogies*. New York: D. Van Nostrand Company.

Paulian, A.-H. 1767. *Dictionnaire de physique portatif* (3rd ed.). Avignon: Chez la veuve Girard et François Seguin.

Priestley, J. 1775. "An account of further discoveries in air." *Philosophical Transactions* 65: 384–394.

Priestley, J. 1781. *Experiments and observations on different kinds of air* (3rd ed.). London: Printed for J. Johnson.

Shea, W. 2000. "Looking at the Moon as another Earth. Terrestrial analogies and seventeenth-century telescopes." Pp. 83–103 in *Metaphor and analogy in the sciences*. Edited by F. Hallyn. Dordrecht: Kluwer Academic.

Short, J. 1753. "An account of a memoir read at the royal academy of sciences at Paris, by M. de Barros, a Portuguese gentleman, concerning certain phaenomena observed by him at Paris, in the last transit of the Mercury over the Sun." *Philosophical Transactions* 48: 361–367.

Sloane, H., and J. Randy. 1728. "The Anatomy of the Poisonous Apparatus of a Rattle-Snake, made by the Direction of Sir Hans Sloane, Bart. Praef. Soc. Reg. & Coll. Med. Together with an Account of the quick Effects of its Poison; by John Randy, Esq, Surgeon of his Majesty's Household, and F.R.S." *Philosophical Transactions* 35(401): 377–381.

Simon, G. 2000. "Analogies and metaphors in Kepler." Pp. 71–82 in *Metaphor and analogy in the sciences*. Edited by F. Hallyn. Dordrecht: Kluwer Academic.

Society of Gentlemen in Scotland. 1771. *Encyclopaedia Britannica* (1st ed.). Vol. 1. Edinburgh: printed for A. Bell & C. Macfarquhar.

Slare, F. 1694. "An Account of some Experiments relating to the Production of Fire and Flame, together with an Explosion; made by the mixture of two Liquors actually cold." *Philosophical Transactions* 18: 201–218.

St. André, N. 1717. "An account of an extraordinary effect of the cholic." *Philosophical Transactions* 30(351): 580–593.

Stuart, A. 1738. "Three lectures on muscular motion." *Philosophical Transactions* 40(451): i–liv.

Suppes, P. 2002. *Representation and Invariance of Scientific Structures*. Stanford: CSLI Publications.

Thomson, W. 1872. *Reprint of papers on electrostatics and magnetism*. London: Macmillan & Co.

Trembley, A. 1747. "Observations upon several species of small water insects of the polypus kind." *Philosophical Transactions* 44(484): 627–655.

Van Leeuwenhoek, A. 1704. "A letter from Mr Antony van Leeuwenhoek, F.R.S. concerning the flesh of whales, crystalline humour of the eye of whales, fish, and other creatures, and of the use of the eye-lids." *Philosophical Transactions* 24(293): 1723–1730.

Vickers, B. 1984. "Analogy versus identity: the rejection of the occult symbolism, 1580–1680." Pp. 95–163 in *Occult and scientific mentalities in the Renaissance*. Edited by B. Vickers. Cambridge: Cambridge University Press.

Watson, W. 1753. "An account of a treatise, presented to the Royal Society, intituled, letters concerning electricity; in which the latest discoveries upon this subject, and the consequences which may be deduced from them, are examined; by the Abbé Nollet, member of the Royal Academy of Sciences of Paris, fellow of the Royal Society, of the institute of Bologna, &c." *Philosophical Transactions* 48: 201–216.

Wilson, B. 1762. "Observations upon some gems similar to the tourmalin." *Philosophical Transactions* 52: 443–447.