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20

The shift from metaphor to analogy in Western science

DEDRE GENTNER AND MICHAEL JEZIORSKI

Analogy and metaphor are central to scientific thought. They figure in discovery, as in Rutherford's analogy of the solar system for the atom or Faraday's use of lines of magnetized iron filings to reason about electric fields (Nersessian, 1984; Tweney, 1983). They are also used in teaching: novices are told to think of electricity as analogous to water flowing through pipes (Gentner & Gentner, 1983) or of a chemical process as analogous to a ball rolling down a hill (Van Lehn & J. S. Brown, 1980). Yet for all its usefulness, analogical thinking is never formally taught to us. We seem to think of it as a natural human skill, and of its use in science as a straightforward extension of its use in commonsense reasoning. For example, William James believed that "men, taken historically, reason by analogy long before they have learned to reason by abstract characters" (James, 1890, vol. II, p. 363). All this points to an appealing intuition: that a faculty for analogical reasoning is an innate part of human cognition, and that the concept of a sound, inferentially useful analogy is universal.

In this essay we question this intuition. We analyze the way in which analogy and metaphor have been used at different points in the history of Western scientific thought, tracing their use backward from the present time. We begin by laying out the current framework for analogical reasoning, followed by two examples that conform to the modern aesthetic, those of Sadi Carnot (1796–1832) and Robert Boyle (1627–1691). We go on to consider a very different way of using analogy and metaphor in science, that practiced by the alchemists (about 300 B.C.–1600 A.D.). Based on these examples, we conclude that there are important differences in the kinds of similarities that were felt to warrant inferences about the world and in the kinds of predictions that were drawn from comparisons. In short, there appear to have been significant historical changes in what has counted as the scientific use of analogy and metaphor.

We will suggest that although an appreciation of similarity (including metaphorical similarity) is almost surely universal in human cognition, what to do with this sense of similarity is not. Opinions on how to tame the raw perception of likeness have varied. Many great thinkers have simply banned it. Berkeley pronounced that "a philosopher should abstain from metaphor" and Aristotle, although willing to permit metaphor as ornament, held that nonliteral language should not be used in argumentation. (He did concede, however, that the perception of similarities between disparate things could be a source of special insight.) At the opposite pole, the alchemists, as we will see, embraced metaphor and analogy with unbridled eagerness. Their excess was both quantitative and qualitative. They used vast numbers of metaphors and they imbued them with great power. They were, as Vickers (1984) puts it, owned by their analogies, rather than owning them. Finally, the modern view, as represented by Boyle and Carnot, values metaphorical similarity but observes firm constraints on its use in scientific reasoning. It can be summed up as follows: "And remember, do not neglect vague analogies. But if you wish them respectable, try to clarify them" (Polya, 1954, p. 15). Our focus is on the evolution in Western science from the alchemists' pluralistic use of all sorts of metaphorical similarities to the more austere modern focus on structural analogy. We begin by laying out what we take to be the current cognitive aesthetics for analogical reasoning.

A framework for analogy and similarity

Analogy can be viewed as a kind of highly selective similarity. In processing analogy, people implicitly focus on certain kinds of commonalities and ignore others. Imagine a bright student reading the analogy "a cell is like a factory." She is unlikely to decide that cells are buildings made of brick and steel. Instead she might guess that, like a factory, a cell takes in resources to keep itself operating and to generate its products. This focus on common relational abstractions is what makes analogy illuminating.

Structure-mapping and ideal analogical competence

Structure-mapping is a theory of human processing of analogy and similarity. It aims to capture both the descriptive constraints that characterize the interpretation of analogy and similarity (Gentner, 1982, 1983, 1989), and the processes humans engage in when understanding a similarity comparison (Markman & Gentner, in press). The central idea is that an analogy is a

mapping of knowledge from one domain (the base) into another (the target) such that a system of relations that holds among the base objects also holds among the target objects. In interpreting an analogy, people seek to put the objects of the base in one-to-one correspondence with the objects of the target so as to obtain the maximal structural match. The corresponding objects in the base and target need not resemble each other; rather, object correspondences are determined by like roles in the matching relational structures. Thus, an analogy is a way of aligning and focusing on relational commonalities independently of the objects in which those relations are embedded. Central to the mapping process is the principle of *systematicity:* people prefer to map systems of predicates governed by higher-order relations with inferential import, rather than to map isolated predicates. The systematicity principle reflects a tacit preference for coherence and inferential power in interpreting analogy.

Consider, for example, Rutherford's analogy between the solar system and the hydrogen atom. A person hearing it for the first time (assuming some prior knowledge about the solar system) must find a set of relations common to the base and the target that can be consistently mapped and that is as deep (i.e., as systematic) as possible. Here, the deepest common relational system is the central-force causal system:

> CAUSE {AND [ATTRACTS (sun, planet), MORE-MASSIVE (sun, planet)], REVOLVES-AROUND (planet, sun)}

Isolated relations, such as HOTTER-THAN (sun, planet), that do not belong to this connected system, are disregarded. The descriptions of individual objects [e.g., YELLOW (sun)] are also disregarded. The object correspondences arrived at are those dictated by the system of relational matches: sun → nucleus, and planet → electron.

Although there are some differences in emphasis, there is a fair amount of convergence on the kinds of structural principles discussed above (Burstein, 1983; Hesse, 1966; Hofstadter, 1981; Holyoak & Thagard, 1989; Keane, 1985, 1988; Reed, 1987; Rumelhart & Norman, 1981; Winston, 1980, 1982). There is widespread agreement on the basic elements of one-to-one mappings of objects with carryover of predicates, and many researchers use some form of systematicity to constrain the interpretation of analogy (although there are exceptions; see Anderson, 1981). There is also empirical support for the psychological predictions of structure-mapping theory. Three findings are of particular relevance here. First, adults tend to include relations and omit attributes in their interpretations of analogy, and they judge analogies as more apt and more sound if they share systematic relational structure (Gentner, 1988; Gentner & Clement, 1988; Gentner & Landers, 1985; Gentner & Rattermann, 1991). Second, adults (and children) are more accurate in analogical transfer when there is a systematic relational structure in the base domain that can be used to guide the map-

Table 20.1. *Modern principles of analogical reasoning*

1. **Structural consistency.** Objects are placed in one-to-one correspondence and parallel connectivity in predicates is maintained.
2. **Relational focus.** Relational systems are preserved and object descriptions disregarded.
3. **Systematicity.** Among various relational interpretations, the one with the greatest depth – that is, the greatest degree of common higher-order relational structure – is preferred.
4. **No extraneous associations.** Only commonalities strengthen an analogy. Further relations and associations between the base and target – for example, thematic connections – do not contribute to the analogy.
5. **No mixed analogies.** The relational network to be mapped should be entirely contained within one base domain. When two bases are used, they should each convey a coherent system.
6. **Analogy is not causation.** That two phenomena are analogous does not imply that one causes the other.

ping (Gentner & Toupin, 1986; Markman & Gentner, in press; Ross, 1987). Third, adults asked to make new predictions from an analogy base their predictions on common relational structure. They are more likely to hypothesize a new fact in the target when the corresponding fact in the base is causally connected to a common structure (Clement & Gentner, 1991).

Analogical soundness. The foregoing discussion suggests a set of tacit constraints that modern scientists use in analogical reasoning. We believe there are six such principles, as given in Table 20.1. The first three principles, *structural consistency, relational focus,* and *systematicity,* have already been discussed. The fourth principle, *no extraneous relations,* expresses the point that analogy is about *commonalities.* Discovering other relationships between the base and target does not improve the analogy. For example, the fact that the sun and planets are made up of atoms does not strengthen the atom/solar system analogy.

The *no mixed analogies* principle reflects the sense that analogies constructed by mapping from several base domains into the same target are rarely sound. In the best case, such mixed comparisons tend to lack coherent higher-order structure, and in the worst case they contain contradictory mappings, as in these examples quoted in the *New Yorker:*

This college is sitting on a launching pad flexing its muscles.

The U.S. and the Middle East are on parallel but non-convergent paths.

In inferential reasoning we prefer that the relational system mapped into a target be drawn from a single base domain. There are exceptions in cases when different analogies are used to capture *separable* aspects or subsystems of the target (Burstein, 1983; Collins & Gentner, 1987). But such multiple analogies require firm rules of intersection to avoid inconsistent

mappings (see Coulson, Feltovich, & Spiro, 1986, for a medical example). Unruly fusions violate the consensual rules of sound thinking.[1]

Finally, *analogy is not causation.* In our current cognitive practice, the presence of an analogy between two situations has no bearing on whether there is a causal relation between the two situations. Conversely, evidence of a causal relation between two analogous domains has no bearing on how similar or analogous they are. This point can be confusing, since *common* causal relations do contribute to the goodness of analogy. For example, given two possibly analogous situations A and B, the analogy between A and B is strengthened by adding like causal relations to both terms. Thus, analogy (2) is better than analogy (1).

	A	B
(1)	Ida pushed Sam. Sam hit a tree.	Flipper pushed Shamu. Shamu hit a buoy.
	A′	B′
(2)	Ida pushed Sam. CAUSED Sam hit a tree.	Flipper pushed Shamu. CAUSED Shamu hit a buoy.

Adding common causal relations makes analogy (2) superior to (1) for three reasons: (*a*) adding common features increases the goodness of a match (Tversky, 1977); (*b*) more specifically, adding common features *that are connected to common systems* increases the goodness of a match more than does adding other commonalities, since interconnected elements support each other in the evaluation process; and (*c*) still more specifically, adding common *higher-order constraining relations* (such as the causal relation) increases the goodness of a match more than adding other connected commonalities, since the coherence and systematicity of the analogy is thereby increased (Clement & Gentner, 1991; Forbus & Gentner, 1989).

But although adding like causal relations *within* two situations strengthens an analogy, adding causal relations *between* them does not. Thus, analogy (3) between A and B is not better than analogy (1) between the same two event sets, even though analogy (3) has an additional causal relation between the analogs:

	A		B
(3)	Ida pushed Sam. Sam hit a tree.	CAUSE	Flipper pushed Shamu. Shamu hit a buoy.

That is, the analogy does not improve if we are told that Sam's hitting a tree caused Shamu to hit the buoy. That A causes B may be an interesting connection, but it does not make A and B more similar or more analogous. In our current cognitive aesthetic, adding common causal relations to each of the domains increases the goodness of an analogy, but adding causal connections between the analogs does not.[2]

Analogy in reasoning. The constraints on analogical reasoning are closely related to the process of making new inferences. As mentioned above, analogical inferences are typically made by a process of *system completion* after some degree of match has been established. We have modeled this process in a computer simulation called SME (the structure-mapping engine) (Falkenhainer, Forbus, & Gentner, 1989; Forbus & Gentner, 1990; Forbus & Oblinger, 1990; Gentner, Falkenhainer, & Skorstad, 1988). The system first makes all possible local matches between like components and then attempts to link these into structurally consistent systems of matches. The largest and deepest global interpretation wins. Given such a common system, a new *candidate inference* is generated if a predicate belongs to the base system but its counterpart does not yet appear in the target system. That is, the partially matching system is completed in the target.

Candidate inferences are only conjectures. The six principles of analogical reasoning are concerned with whether the analogy is structurally sound, not with whether its inferences are factually correct. Verifying the factual status of the analogy is a separate process. Soundness principles simplify the task, however, because they specify what must be true in order for the analogy to hold. In a system of interconnected matches, even one significant disconfirmation can invalidate a whole analogy.

Metaphor and other similarity matches. Other kinds of similarity matches can be distinguished in this framework. Whereas *analogies* map relational structure independently of object descriptions, *mere-appearance matches* map aspects of object descriptions without regard for relational structure. *Literal similarity matches* map both relational structure and object descriptions. We view *metaphor* as a rather broad category, encompassing analogy and mere-appearance, as well as a variety of other kinds of matches. On this view, analogy is a special case of metaphor, one based on a purely relational match. The large-scale communication metaphor analyzed by Reddy (this volume), as well as other conceptual metaphors analyzed by Lakoff and Johnson (1980) and by Lakoff (this volume), are examples of systematic relational metaphors, that is, metaphors that could also qualify as analogies. There are also attributional metaphors – mere-appearance matches, based on shared object descriptions – for example, "her arms were pale swans," as well as metaphors based on mixtures of object and relational commonalities. Further, there are metaphors that cannot be analyzed in the simple terms we have used so far: for example, "the voice of your eyes is deeper than all roses" (e.e. cummings); or "On a star of faith pure as the drifting bread / As the food and flames of the snow" (Dylan Thomas). These metaphors are not bound by the one-to-one mapping constraint and can include mixtures of several bases, as well as thematic and metonymic relations (Gentner, 1982; Gentner, Falkenhainer, & Skorstad, 1988).

Historical uses of analogy

Despite the plurality of possible match types, the guidelines for use of analogy in scientific discovery and reasoning are quite selective. The strength of an analogy in licensing scientific prediction rests on the degree of systematic structural match between the two domains. We now ask whether western scientists have always adhered to these principles. We will consider evidence that the ascendancy of analogy over metaphor in scientific reasoning was not always the case. We begin with Carnot, a fairly recent example, and progress in reverse chronological order.

Sadi Carnot

The French scientist Sadi Carnot (1796–1832) was one of the pioneers of modern thermodynamics. He described the Carnot cycle for heat engines, still taught as an ideal energy conversion system, and laid the foundation for the later discovery of the equivalence of heat and work. In his treatise on heat, Carnot presented an analogy between heat and water that clarified his position and generated new questions. His use of analogy is prototypical of the rules of rigor described above and can stand as an example of the modern use of analogy. In 1824, Carnot published *Reflexions sur la puissance motrice du feu* (*Reflections on the Motive Power of Fire*). In this book, he describes the functioning of a hypothetical engine that can convert heat energy to work. This engine consists of a cylinder filled with gas and fitted with a frictionless piston that can move freely inside the cylinder. During a four-stage cycle, the gas inside is expanded by contact with a heat source (isothermal expansion) and allowed to continue dilating after the source is removed (adiabatic expansion). The gas is then compressed by transmission of heat to a colder body (isothermal compression), and the volume further decreases after removal of the cold body (adiabatic compression), restoring the original conditions of the system. During this period, the engine has absorbed a certain amount of heat and converted it to mechanical work through the movement of the piston. The operation of this ideal engine, known as the Carnot cycle, was an important theoretical contribution to the early development of thermodynamics.

In the *Reflexions,* Carnot utilized an analogy between water falling through a waterfall and caloric (heat) "falling" through a heat engine. The analogy between heat and fluid was not new. Indeed, the dominant theory of heat at the time was the caloric theory,[3] which defined heat as a weightless fluid that shared the properties of ordinary matter. Like other matter, caloric was considered a conserved quantity that could be neither created nor destroyed. Carnot's contribution was not the idea of viewing heat as a fluid but rather the thoroughness of his development of the heat/water analogy – the extent to which he applied explicit causal structures from the water domain to the heat domain:

1. According to established principles at the present time, we can compare with sufficient accuracy the motive power of heat to that of a waterfall. Each has a maximum that we cannot exceed, whatever may be, on the one hand, the machine which is acted upon by the water, and whatever, on the other hand, the substance acted upon by the heat.

2. The motive power of a waterfall depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what may be termed, on what in fact we will call, the *height of its fall*, that is to say, the difference of temperature of the bodies between the higher and lower reservoirs.

3. In the waterfall the motive power is exactly proportional to the difference of level between the higher and lower reservoirs. In the fall of caloric the motive power undoubtedly increases with the difference of temperature between the warm and the cold bodies; but we do not know whether it is proportional to this difference. We do not know, for example, whether the fall of caloric from 100 to 50 degrees furnishes more or less motive power than the fall of this same caloric from 50 to zero. It is a question which we propose to examine hereafter. (Carnot, 1977, p. 15; numbers and paragraph breaks are inserted for convenience; the original passage is continuous)

In section 1, Carnot introduces the analogy between the motive power of heat and the motive power of water and establishes and notes a simple yet important parallel: just as the amount of power produced by a given fall of water is limited, the power attainable from a given transfer of heat is limited. In section 2, Carnot establishes further correspondences and a shared higher-order principle. He compares the difference in temperature between two connected bodies to the height of the fall in a waterfall.[4] Carnot uses this correspondence in a proposed higher-order relation: he asserts that, in each case, the power produced by the system depends on both the amount of the substance (water or caloric) that "falls" and the distance of the "drop" between levels.

This qualitative combination – the fact that power depends on both the difference in level and the amount of "substance" involved – further sharpens the analogy. Figure 20.1 shows the common relational structure that holds for water and heat. Figure 20.2 sets forth the corresponding terms and assertions.

So far the enterprise has been one of *matching* structures between heat and water. In Section 3, a new candidate inference is *transferred* from water to heat, that is, the analogy is used to suggest a new hypothesis. Carnot notes a higher-order relation in the domain of water (the fact that the power produced by a given fall of water is directly proportional to the difference between levels). He asks whether the same relation exists for heat engines; that is, whether the power produced by a given "fall" of

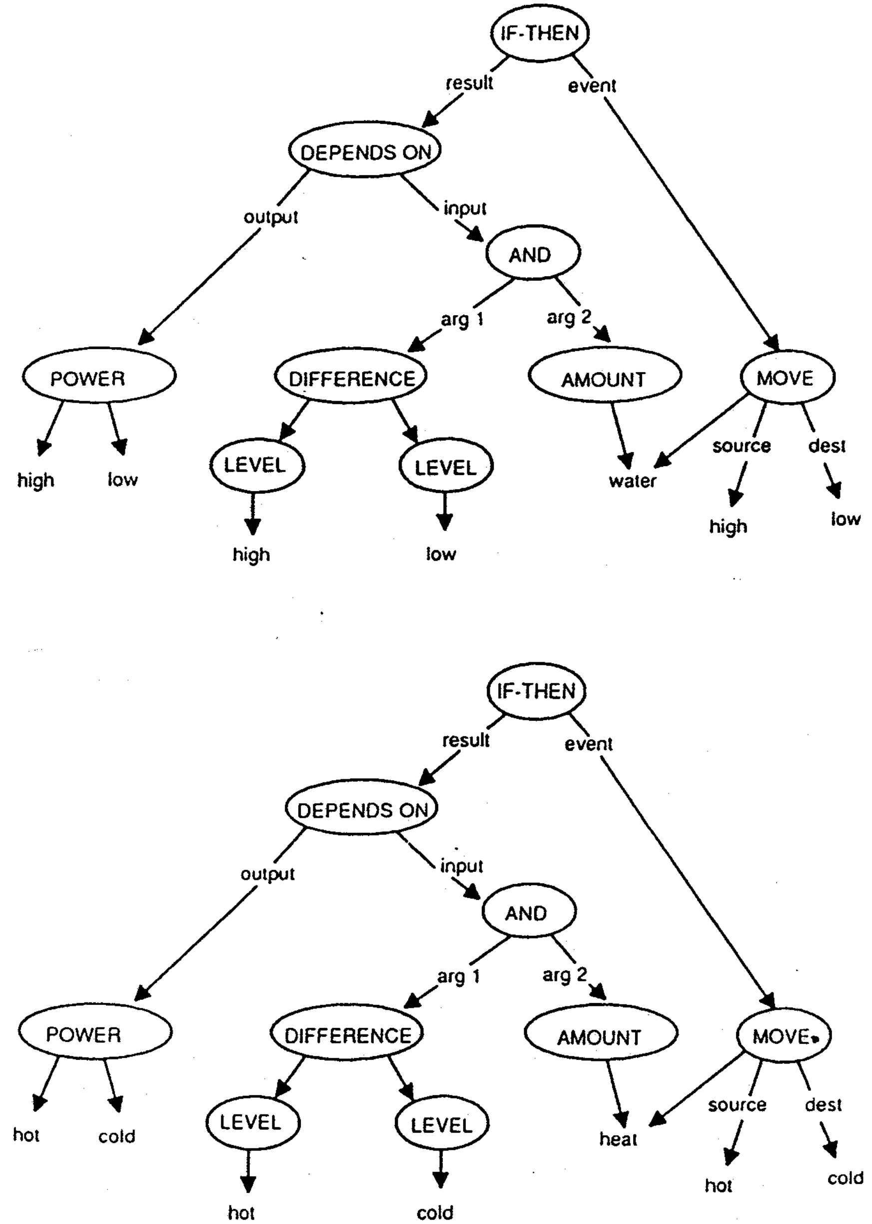

Figure 20.1. Carnot's analogy: the common relational structure for water and heat.

1 water: DIFFERENCE (level<h>, level<l>)
heat : DIFFERENCE (temp<h>, temp<l>)

2. water: FLOW (h,l)
heat : FLOW (h,l)

3 water: POWER (h,l)
heat : POWER (h,l)

4. water: MAX POWER (h,l)
heat : MAX POWER (h,l)

5. water: αQ(POWER (h,l), DIFFERENCE (level<h>, level<l>))
heat : αQ(POWER (h,l), DIFFERENCE (temp<h>, temp<l>))

6. water: αQ(POWER (h,l), ami<h>)
heat : αQ(POWER (h,l), ami<h>)

7. water: AND (αQ(POWER (h,l), DIFFERENCE (level<h>,level<l>)), αQ((POWER(h,l), ami<h>)

heat : AND (αQ(POWER (h,l), DIFFERENCE (temp<h>, temp<l>)), αQ(POWER (h,l), ami<h>)

Figure 20.2. Terms and propositions derivable from Carnot's water/heat analogy. *Note:* αQ denotes qualitative proportionality (Forbus, 1984). A αQ B signifies that A is a monotonic function of B, but does not specify the nature of the function or whether other variables may also affect A.

caloric remains constant, regardless of the temperature at which that fall takes place.[5]

Carnot's development of his analogy is indistinguishable from the modern scientific use of analogy. It meets the six principles of rigorous analogical reasoning discussed earlier. Carnot paired the objects in the two domains in one-to-one correspondence. In so doing, he disregarded object-attribute matches. He was not concerned with whether corresponding components shared surface qualities, but with achieving a common systematic relational structure. Having explicated a higher-order relational system common to the two domains, Carnot was able to exploit that system to map across further hypotheses from the base to the target. Between-domain relations, such as "water can be hot," were avoided, as was any hint of a mixed analogy. In short, Carnot's use of analogy conforms to modern scientific practice.

Robert Boyle

We now move back another century and a half to the English scientist Robert Boyle (1627–1691). Boyle is considered among the founders of modern chemistry. He is best known for his work on the ideal gas law, but he also contributed to other domains, such as the theory of acids and

alkalies. Probably his most influential work was the *Sceptical Chymist,* in which he criticized both the Greek division of matter into four elements and the later division into three principles. Appearing anonymously in 1661 and again in 1679 with additions, it "did more than any other work of the century to arouse a truly critical spirit of scientific logic in chemical thinking" (Stillman, 1960, p. 395). Boyle was a prolific writer, interested in philosophy and religion as well as the sciences. He was also a prolific analogizer. He often put forth several examples or analogies for each principle he wanted to prove.

A characteristic example of Boyle's use of examples and analogies occurs in his book *Of the great effects of even languid and unheeded local motion,* published in 1690. His purpose in this book was to demonstrate the importance of "local motion," the motions of many tiny particles. Boyle wanted to establish that the combined effects of the motion of many tiny particles – each invisible and insignificant in itself – can cause large-scale changes. He saw such effects as a unifying principle across domains such as light, sound, fire, and fluids. Although some of his points now seem to need no defense, such was not the case in his time. To marshal sufficient evidence for his conjecture, Boyle cited examples from one domain after another.

Boyle's examples appear to function in two ways. First, they serve as instances of local motion and its effects – that is, as instances of a principle that can be effectively applied to several domains. The more numerous and varied the instances, the more faith we can presumably have in the principle. Second, the examples serve as analogies that can be aligned with one another to yield common structural abstractions. By juxtaposing separate instances of local motion, Boyle led his reader to focus on the common causal system. The following excerpt illustrates his style of analogizing:

(Chap. IV) Observat. III. *Men undervalue the motions of bodies too small to be visible or sensible, notwithstanding their* Numerousness, *which inables them to act in Swarms.*

1. [Boyle grants that most men think of the particles of bodies as like grains of dust, which, although invisible, cannot penetrate the bodies they fall on. As a result, these grains cannot affect the bodies.]

But we may have other thoughts, if we well consider, that the Corpuscles we speak of, are, by their minuteness, assisted, and oftentimes by their figure inabled, to pierce into the innermost recesses of the body they invade, and distribute themselves to all, or at least to multitudes of the minute parts, whereof that body consists. For this being granted, though we suppose each single *effluvium* or particle to be very minute; yet, since we may suppose, even solid bodies to be made up of particles that are so too, and the number of invading particles to be not much inferior to that of the invaded ones, or at least to be exceedingly great, it not need seem incredible, that a multitude of little Corpuscles in motion (whose motion, may, for ought we know, be very swift) should be able to have a considerable operation upon particles either quiescent, or that have a motion too slow to be perceptible by sense. Which may perhaps be the better conceived by the help of this gross example:

2. *Example of the anthill*

If you turn an Ant-hill well stocked with Ants-eggs, upside down, you may sometimes see such a heap of eggs mingled with the loose earth, as a few of those Insects, if they were yoaked together, would not be able at once to draw after them; but if good numbers of them disperse themselves and range up and down, and each lay hold of her own egge, and hurry it away, 'tis somewhat surprizing to see (as I have with pleasure done) how quickly the heap of eggs will be displaced, when almost every little egge has one of those little Insects to deal with it.

3. *Example of wind in trees*

And in those cases, wherein the invading fluid does not quite disjoin and carry off any great number of the parts of the body it invades, its operation may be illustrated by that of the wind upon a tree in *Autumn:* for, it finds or makes it self multitudes of passages, for the most part crooked, not onely between the branches and twigs, but the leaves and fruits, and in its passing from the one side to the other of the tree, it does not onely variously bend the more flexible boughs and twigs, and perhaps make them grate upon one another, but it breaks off some of the stalks of the fruit, and makes them fall to the ground, and withall carries off divers of the leaves, that grew the least firmly on, and in its-passage does by its differing act upon a multitude of leaves all at once, and variously alters their situation.

4. *Example of sugar and amber dissolving*
5. *Example of mercury compound dissolving*
6. *Example of flame invading metal*

But to give instances in Fluid bodies, (which I suppose you will think far the more difficult part of my task,) though you will easily grant, that the flame of Spirit of wine, that will burn all away, is but a visible aggregate of such *Effluvia* swiftly agitated, as without any sensible Heat would of themselves invisibly exhale away; yet, if you be pleased to hold the blade of a knife, or a thin plate of Copper, but for a very few minutes, in the flame of pure Spirit of wine, you will quickly be able to discern by the great Heat, that is, the various and vehement agitation of the minute Corpuscles of the metal, what a number of them must have been fiercely agitated by the pervasion of the igneous particles, if we suppose, (what is highly probable,) that they did materially penetrate into the innermost parts of the metal; and whether we suppose this or no, it will, by our experiment, appear, that so fluid and yielding a body, as the flame of Spirit of wine, is able, almost in a trice, to act very powerfully upon the hardest metalls.

7. *Example of animal spirits moving animals*
8. *Example of rope contracting from humidity* (Boyle, 1690, pp. 27–35)

Boyle begins by noting that laymen may find it implausible that local motion could have large-scale effects. Laymen, he observes, consider such motion similar to the ineffectual motion of dust in air. By analogy with dust, if particles are very small, then although they can be moved easily, their movements are inconsequential. Having set forth the lay intuition – that local motion is ineffective – Boyle then defends the opposite position by differentiating the analogy further. The ineffectiveness of dust particles, he claims, is the result of their failure to penetrate other bodies and thereby to affect those bodies. He suggests that there are other kinds of particles involved in local motion that *are* small enough to diffuse through solid objects, and that it is this penetration that allows them to create large effects. (That is, he argues that dust is not small *enough*!) He then proceeds to present instances of this kind of local motion.

In paragraph 2, Boyle compares the ability of small particles to move large masses to that of ants to move their eggs. Although each ant is much smaller than the mass of eggs, the ability of each ant to "penetrate" the egg mass and move one egg causes the entire mass of eggs to be displaced. This example conforms well to the principles of analogizing (Table 20.1). There are clear one-to-one correspondences, based not on characteristics of individual objects but on relations between the objects, as shown in Figure 20.3. For example, Boyle does not suggest that the corpuscles involved in local motion are *like* ants – they are not living organisms, they do not have six legs, and so forth – nor does he suggest that particles of matter are white or soft or otherwise egglike. The only required matches are for the *relative sizes* of the ant, the egg mass, and the egg. The important commonality is a structural one: namely, that very large numbers can compensate for a very great size disadvantage, provided that penetration of the larger by the smaller can occur. Under these circumstances, many small bodies in motion can carry off a much larger body.

The remaining sections provide several additional analogous examples of the effects of local motion. For example, in paragraph 3, Boyle cites the example of wind passing through (penetrating) a tree, blowing off leaves and breaking branches. In paragraph 6, Boyle presents the effects of fire on a knife blade as an instance of local motion. He perceives fire as comprised of many small particles and explains the heating of metal in terms of the invasion of igneous particles into the metal, with the result that the corpuscles of metal themselves become "fiercely agitated" and the blade becomes hot. The remaining two paragraphs, which describe "animal spirits" and the contraction of rope, respectively, make analogous points. Boyle observes that although animal spirits may be minute enough to be invisible they are capable of propelling large animals such as elephants. He describes seeing hemp shrink in moist weather, and states that the "aqueous and other humid particles, swimming in the air, entering the pores of the hemp in great numbers, were able to make it shrink, though a weight of fifty, sixty or even more pounds of lead were tied at the end to hinder its contraction." Table 20.2 shows the correspondences across Boyle's set of examples.

Boyle's style of analogizing is very different from Carnot's. Rather than dwelling on one pair of examples, carefully explicating the critical common relational structure, he uses a rapid succession of analogies and examples

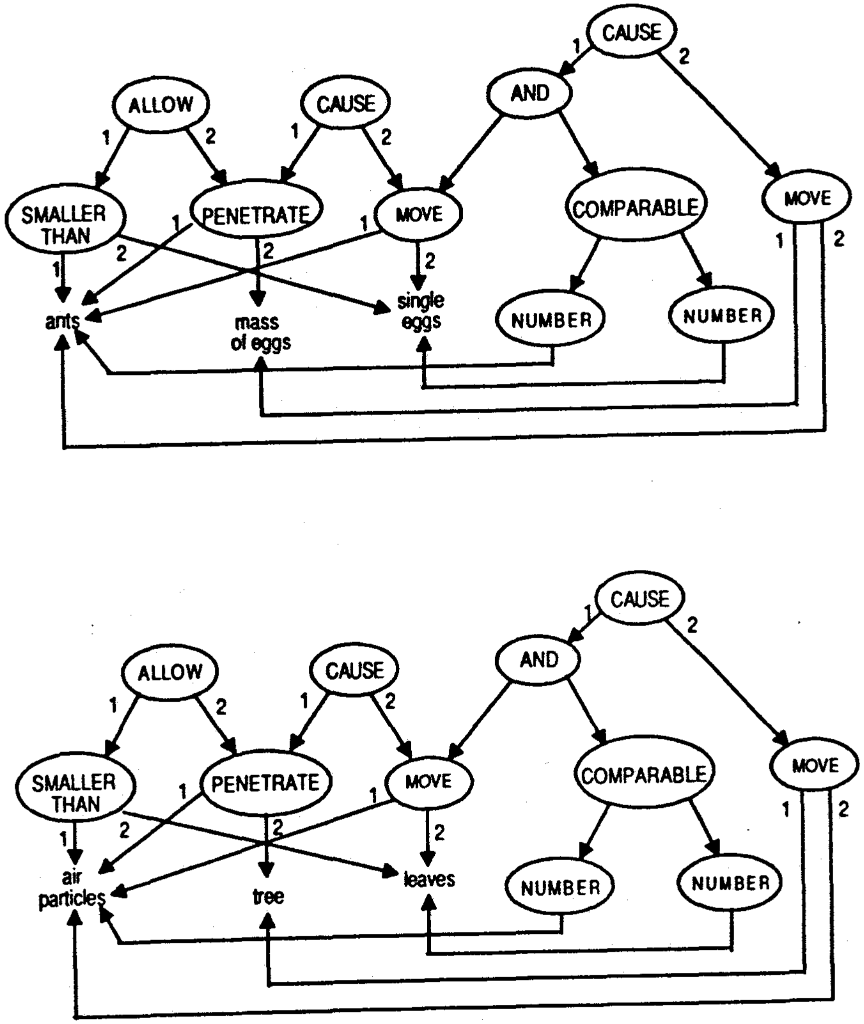

Figure 20.3. Boyle's analogy: the common relational structure for ants moving eggs and wind blowing leaves.

to demonstrate a central principle. The implicit message is that if all these phenomena occur, the model that summarizes them must be plausible. Each paragraph contains an instance of local motion, or contrasts situations in which the principles do or do not apply. By standards of modern knowledge, not all the comparisons are equally convincing. There is little surface similarity between these examples; they relate to one another by virtue of their common abstraction. They can be compared with one another to reveal an abstract model of local motion.

Table 20.2. *An overview of Boyle's series of analogies concerning local motion*

Abstract model	Layman's view (1)	Analogs (2)	(3)	(4)	(5)	(6)	(7)
Small particles	Dust	Ants	Air particles	Aqueous particles	Igneous particles	Animal spirits	Aqueous corpuscles
Penetrate							
Large bodies	Large bodies	Mass of eggs	Tree	Mercury oxide	Metal	Animals	Rope
And move							
Fragments of bodies	Fragments of bodies	Single eggs	Leaves	Grains of oxide	Metal corpuscles	Animal (inner parts)	Rope (inner parts)

Despite these differences, Boyle's use of analogy falls roughly within the modern standards discussed in Table 20.1. In each of his analogies, the objects are placed in one-to-one correspondence. Object attributes are discarded, as in the wind analogy. Indeed, the sheer variety of the examples virtually guarantees that any specific object characteristics will cancel out. The analogies, as in the modern tradition, are about common relational systems. The complexity of the analogies is not great – they are no so deep as Carnot's, for example – but this is in part due to the state of knowledge of the subject matter. Boyle's point was to establish that the motion of many small particles can combine to produce powerful visible effects, and further, that the requirement for this to occur is that the smaller particles penetrate the larger matter. Boyle demonstrates that this system of commonalities holds throughout these examples. Finally, in spite of the large number of examples, there are no mixed analogies or between-analog relations; each example stands on its own as a separate instantiation of the relational structure.

Carnot and Boyle: A summary

At first glance, Boyle and Carnot seem to differ rather sharply in their use of analogy. Carnot uses one analogy, explaining it precisely and then going on to use the principles in further inferencing. Boyle, in contrast, offers a whole family of analogies, one after the other. It could be maintained that this sustained analysis marks Carnot as a more modern analogizer than Boyle.[6] Yet despite their stylistic differences, both Boyle and Carnot are essentially modern in their view of what constitutes a sound analogy.

The alchemists

We have moved back in time from Carnot (1796–1832) to Boyle (1627–1691). So far, the comparisons we have considered conform to the modern notion of a sound analogy. Now we move back still further, to the work of the alchemists, and analyze the forms of similarity they used in making their predictions. The alchemists were enthusiastic in their embrace of similarity, but as we shall see, their sense of how to use similarity differed markedly from the modern sense.[7]

Alchemy grew out of the fusion of Egyptian chemistry with Greek theory in about 300 B.C., continued in Persia after about 500 A.D., and entered the European sphere again after the first crusades at the end of the eleventh century A.D. It was a dominant force in western science, or prescience, until the seventeenth century A.D. Although there were many variants, there were some common themes.[8] Based on certain works of Plato and Aristotle, alchemical thought postulated a primordial source of all earthly matter. This First Matter was manifested in a small number of primary elements – fire, air, water, and earth – each of which combined two of the primary qualities, hot, cold, wet, and dry. Fire was hot and dry, water was cold and wet, and so on (see Figure 20.4). A transmutation could occur if the proportions of the qualities changed: for example, fire (hot and dry) could be changed into earth (specifically, into ash) by losing heat to become cold and dry. The alchemists were particularly interested in transmutations of metals, especially the transmutation of base metals into gold, often with the help of a hypothesized catalyst known as the Philosopher's Stone (Redgrove, 1922). Besides bringing wealth, achieving such a transmutation would validate the theory.

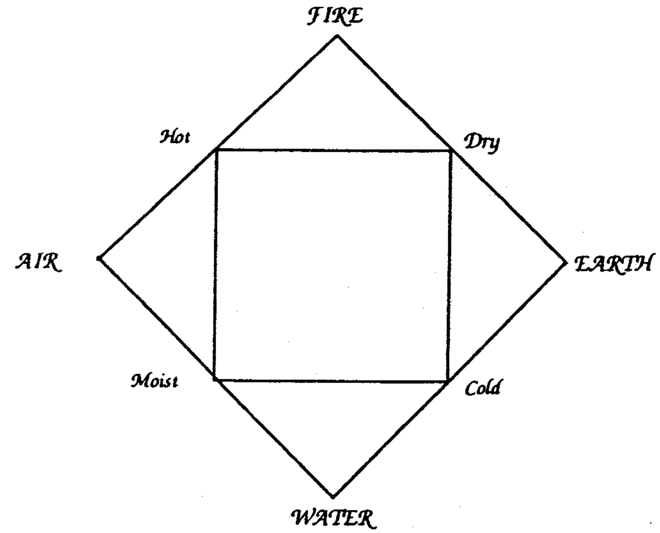

Figure 20.4. Schematic of the doctrine of four elements and four qualities.

The alchemists were peerless in their enthusiasm for analogy and metaphor. Their comparisons were numerous and striking. Metals were often held to consist of two components: mercury, which was fiery, active, and male, and sulphur, which was watery, passive, and female. Thus the combination of two metals could be viewed as a marriage (Taylor, 1949). This male-female division was extremely influential; with the addition of a third principle, it formed the *tria prima* of mercury, sulphur, and salt, which Paracelsus and other sixteenth-century alchemists held to underlie all matter. Metals were also compared to heavenly bodies or to mythological figures, as discussed below. Still other metaphors were taken from animals and plants. The eagle was used to convey volatility. Sal ammoniac, for example, was called *aquila coelestis* (heavenly eagle). In another metaphor, the raven, the swan, and the eagle stood for earth, water, and air (Crosland, 1978, p. 16).

A central comparison was a macrocosm–microcosm analogy (or metaphor) by which man (the microcosm) was likened to the natural world. For example, it was said that copper, like a human being, has a spirit, a soul, and a body, with the spirit being the tincture (Crosland, 1978, p. 13). In a related vein, metals were compared with human states of health. Thus, gold corresponded to a man in perfect health and silver to "leprous gold" (Crosland, 1978, p. 15). In another analogy between the heavenly and the earthly planes, some alchemists counted twelve processes necessary to produce gold from base metal (calcination, solution, separation, conjunction, putrefaction, etc.), corresponding to the twelve signs of the zodiac. Others counted seven processes, corresponding to the seven days of creation and to the seven planets, each of which was held to generate its special metal in the earth (Cavendish, 1967, p.159). The importance of the microcosm–macrocosm metaphor stemmed partly from the fact that alchemy took as its domain the spiritual world as well as the physical world. A central belief was that the purification of base metals into gold was analogous to the spiritual purification of man (Redgrove, 1922). This analogy could be run in either direction, so that "some men pursued the renewal and glorification of matter, guiding themselves by this analogy, others the renewal and glorification of man, using the same analogy" (Taylor, 1949, p. 144).

The alchemists' willingness to heed similarities of all kinds derived in part from their belief that all things above and below are connected, and that similarity and metaphor are guides to those connections. This dogma was codified in the medieval *doctrine of signatures*, the sense that "It is through similitudes that the otherwise occult parenthood between things is manifested and every sublunar body bears the traces of that parenthood impressed on it as a signature" (Eco, 1990, p. 24). Vickers (1984) suggests that the alchemists invested analogy with extraordinary importance, even equating analogy with identity.

What were the rules that governed the alchemists' use of analogy and metaphor? We begin with a family of comparisons that used as the base domain the egg or the seed, and as the target domain either (or both) the principles of matter or the components of a human being.

The egg

The egg was used widely in alchemical analogies. Taken as a whole, the egg could symbolize the limitlessness of the universe, or infinity itself. The Philosopher's Stone was often called an egg (Cavendish, 1967; Stillman, 1960). The egg could also be divided into components. For example, Stillman (1960) notes that the shell, skin, white, and yolk of the egg were thought to be analogous to the four metals involved in transmutation: copper, tin, lead, and iron (although no pairings were specified between

Table 20.3. *Alchemical analogies of the Egg*

	Dienheim's analogy			Further analogies	
Domain	The Egg	Components of the Philosopher's Stone	Elements of matter	Male-female principles	Primary qualities
Number of elements	(3)	(?)	(3)	(2)	(4)
Correspondences					
	White	Soul	Sulphur	Male	Fire
	Yolk	Spirit	Mercury	Male-female	Air/Water
	Shell	Body	Salt (Arsenic)	Female	Earth

the components and the metals). Several additional correspondences are apparent in the following excerpt from the manuscript of St. Mark's in the tenth or eleventh century (copied in 1478, translated from Bertholet's [1887] *Collection des Anciens Alchemistes Grecs*).[9] The "egg" described is in fact the Philosopher's Stone:

Nomenclature of the Egg. This is the mystery of the art.

1. It has been said that the egg is composed of the four elements, because it is the image of the world and contains in itself the four elements. It is called also the "stone which causes the moon to turn," "stone which is not a stone," "stone of the eagle" and "brain of alabaster." .
2. The shell of the egg is an element like earth, cold and dry; it has been called copper, iron, tin, lead. The white of the egg is the water divine, the yellow of the egg is couperose [sulfate], the oily portion is fire.
3. The egg has been called the seed and its shell the skin; its white and its yellow the flesh, its oily part, the soul, its aqueous, the breath of the air. (Stillman, 1960, pp. 170–171; notation in brackets added)

This brief excerpt illustrates the style of analogizing displayed by many alchemists. First, the egg is compared to several different analogs. The use of multiple analogs would not in itself differentiate this passage from the work of Boyle. However, what is distinctive here is that the number of components involved in the correspondence varies from analog to analog, as shown in Figure 20.5. (See also Table 20.3.) The first paragraph maps the "egg" first onto the four elements and then onto a series of single entities (e.g., "the stone which is not a stone," the "brain of alabaster"). In paragraphs 2 and 3, the components of the egg are successively compared to the four elements of ancient Greek philosophy (earth, water, air, and fire),[10] the layers of a seed, and the aspects of a human being. These multiple analogies are quite different from those of Boyle; the alchemist

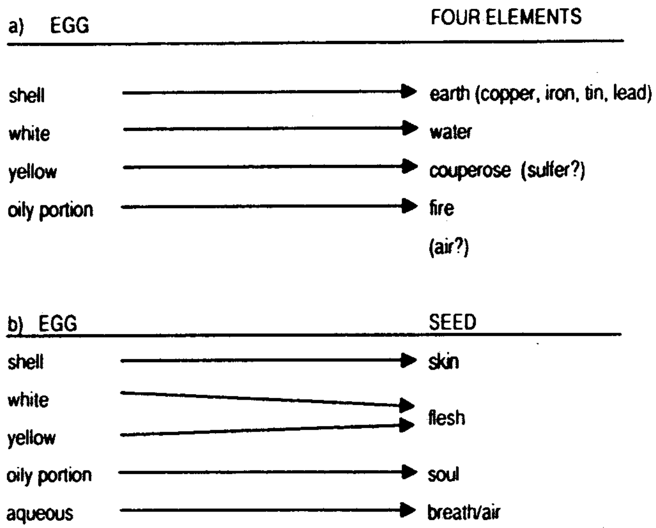

Figure 20.5. Object correspondences in the egg analogy.

does not attempt to delineate a common structure that holds across the several systems. (It would probably not be possible to do so.)

But a more striking difference arises when we consider the issue of one-to-one mappings. Figure 20.5 shows the object correspondences used in the above set of analogies. It is apparent that achieving one-to-one correspondence is not of primary concern. For example, as Figure 20.5a shows, the object correspondences for the analogy between the egg and the four elements of matter are such that the element of air must either be omitted or else placed in correspondence with a previously used element of the egg, yielding a mapping of four objects onto five. As Figure 20.5b shows, the mapping from the egg to the four divisions of the seed (or aspects of a human being) is also not one-to-one, since both the white and the yellow parts of the egg correspond to the flesh. Thus Figure 20.5b shows a $5 \rightarrow 4$ mapping, whereas Figure 20.5a shows a $4 \rightarrow 5$ mapping. When an analogy yields two or more competing mappings, the modern practice is to choose between them or to note that there are alternative interpretations. In contrast, the alchemists resolved the tension by combining both interpretations into a fused whole. This failure to preserve a one-to-one correspondence differentiates this reasoning sharply from that of modern scientists.

The alchemists invested metaphor with great importance. The belief that metaphors reveal essential categories, as discussed by Glucksberg and Keysar (1990), was taken to extreme lengths. For example, an attractive aspect of the egg was that it was recognized as something vital, as symbolic of a beginning. Any system that could be related to the egg was imbued

with a similar significance. When some alchemists shifted from the Greek theory of four elements to the theory that three "principles" – usually defined as sulphur, mercury, and salt (or arsenic) – composed all matter, it was still possible to use the egg analogy:

> As an egg is composed of three things, the shell, the white, and the yolk, so is our Philosophical Egg composed of a body, soul, and spirit. Yet in truth it is but one thing [one mercurial genus], a trinity in unity and unity in trinity – Sulphur, Mercury, and Arsenic. (Dienheim, quoted in Hamilton-Jones, 1960, p. 79; brackets are his)

Here the alchemist suggests a series of parallel analogies among the egg, the Philosopher's Stone, man, and matter, and gives the object correspondences among the (now three) parts of the egg, the three aspects of man, and the three principles of matter. Other alchemists extended the analogy, mapping the three parts of the egg onto the male-female principles and the four primary qualities, as shown in Table 20.3 (Cavendish, 1967, p. 169).

Analogies with symbols

Another striking aspect of alchemical analogizing was a willingness to use similarities between symbols and their referents. Vickers (1984) suggests that the alchemists were influenced by the occult tradition in which the word or symbol does not merely stand for its referent, but is *identical in essence* to it. This in turn led to a belief in the causal powers of words and other symbols. For example, Kriegsmann (1665) offered an analysis of the properties of the three principles – sulphur, mercury and salt – in terms of their symbology (Crosland, 1978, p. 233). Given the suppositions that a straight line denoted earth, a triangle fire, a semicircle air, and a circle water, he attempted to analyze the symbols for sulphur, mercury, and salt into the four basic elementary symbols. Even as late as 1727, Boerhaave analyzed copper by the following chain of thought. First, he noted that a circle indicates perfection, whereas a cross denotes something sharp and corrosive. It follows that gold is symbolized as a circle, and since copper is symbolized by a circle plus a cross, it can be seen to be "intimately Gold" but combined with some crude, sharp, and corrosive material. That this system was believed to be predictive, not merely conveniently iconic, can be seen in this passage by Boerhaave concerning iron (symbolized by a circle plus an outward arrow):

> that this too is intimately Gold; but that it has with it a great deal of the sharp and corrosive; though with but half the degree of Acrimony as the former, as you see that it has but half the sign that expresses that quality. . . . Indeed it is almost the universal opinion of the adepts that the *Aurum vivum* or *Philosophorum* does lye concealed in Iron; and that here therefore we must seek for metalline Medicines, and not in Gold itself. (Crosland, 1978, p. 233)

That metaphors between symbols and material objects were held to be informative is a marked difference from the present aesthetic. It is related to the doctrine of signatures, the sense that similarity virtually guarantees significant connections. As Eco (1990, p. 24) puts it in his description of Renaissance hermeticism,

> The basic principle is not only that the similar can be known through the similar but also that from similarity to similarity everything can be connected with everything else.

Paracelsus

Paracelsus (Theophrastus Bombastus von Hohenheim, 1493–1541) was a leading alchemist of the sixteenth century and a vigorous proponent of the value of empirical observation as opposed to received dogma. Despite this rather modern spirit, his use of the analogy remains distinctly different from modern usage. Here, he describes how gold and silver can be made:

> Some one may ask, what, then, is the short and easy way whereby Sol and Luna may be made? The answer is this: After you have made heaven, or the sphere of Saturn, with its life to run over the earth, place on it all the planets so that the portion of Luna may be the smallest. Let all run until heaven or Saturn has entirely disappeared. Then all those planets will remain dead with their old corruptible bodies, having meanwhile obtained another new, perfect and incorruptible body. That body is the spirit of heaven. From it these planets again receive a body and life and live as before. Take this body from the life and earth. Keep it. It is Sol and Luna. Here you have the Art, clear and entire. If you do not understand it it is well. It is better that it should be kept concealed and not made public. (quoted in Jaffe, 1967, p. 23)

Here Sol and Luna (the sun and moon, respectively) signify gold and silver, and other metals in the recipe are represented by the other planets, according to a widely used system of alchemical analogies (see below). Paracelsus does not detail the object correspondences between the two domains, nor does he explain how an action in one domain parallels an action in the other. The mappings and the theoretical basis for the procedure are left unstated. Indeed, it is not always clear which actual metals are being referred to. For example, to what do "earth" and "all those planets" refer? Does "heaven, or the sphere of Saturn" refer to tin? If so, is the final "spirit of heaven" derived from the process also tin? This last seems implausible, since the goal is to produce gold and/or silver: yet if the final "spirit of heaven" is gold or silver, then what about the initial "heaven"? Here, and also in the passages below, the alchemists go beyond similarity and into a wider set of what Gibbs (this volume) calls "tropes," including many instances of metonymy.

This passage, though it exemplifies the different rules of analogizing

Table 20.4. *The alchemical system of correspondences among planets, metals, and colors*

Planets	Metals	Colors
Sun	Gold	Gold, yellow
Moon	Silver	White
Mercury	Quicksilver	Gray, neutral
Venus	Copper	Green
Mars	Iron	Red
Jupiter	Tin	Blue
Saturn	Lead	Black

Based on Cavendish 1967, p. 26.

among the alchemists, also raises questions concerning the reasons for these differences. Paracelsus makes it clear that clarity is not his intention. The secretive nature of the enterprise, the fact that it was felt necessary to hide results from the common public and from competitors, could have led to the ambiguity of the writing. Is it possible that this ambiguity shielded a set of informative analogies? To answer this question, we must look more closely at the system of comparisons that supported this reasoning.

The system of correspondences

Since the goal of many alchemists was to transform base metals into higher metals (gold or silver), metals held an important place in alchemical analogy and metaphor. As illustrated above, metals figured in analogies with the principles of matter and with the aspects of human beings, and the transmutation of base metals into gold was felt to be analogous to the spiritual purification of man. A further set of correspondences existed between metals, planets, and colors, as shown in Table 20.4.[11] (This table and much of the surrounding explication are based on Cavendish's discussion [Cavendish, 1967, p. 26].)

The first thing that strikes us about this system is the importance of surface similarity – that is, common color – in determining the correspondences. The Sun, the metal gold, and the color gold are linked by a common color, as are the Moon, the metal silver, and the color white. But an equally striking aspect of this system is that this commonality is not uniformly maintained. The basis for the comparison shifts from one part of the system to another. For example, unlike the two triads just mentioned, the Jupiter/tin/blue triad is not entirely based on common color. Instead, blue (the color of the sky) is matched to Jupiter because Jupiter was lord of the sky. And although the match between Jupiter and tin may be a color match, based on the planet's silvery appearance, it may also have been based on an ancient belief that the sky was made of tin. Thus the set of similarities that figure in the correspondences changes from one row or column to another.

The set of relations that linked the rows of this table was remarkably rich and diverse, as illustrated in this discussion by Cavendish (1967, p. 27):

> Lead, the darkest and heaviest of the metals, was naturally assigned to Saturn, the dimmest and slowest-moving planet, which trudges heavily through its slow path round the sun. In the old cosmology Saturn is the farthest planet from the sun, the ruler of life, and is the lord of death. The analogy between death and night was drawn very early. Black is the colour of night and the colour invariably associated with death in Western countries.

The chain of connections between Saturn and black is a case in point. Saturn is the lord of death, death is similar to night, the color of a night sky is black, and blackness symbolizes death. Thus a chain is made between the planet Saturn and the color black. This rich metonymic chain is quite different from the simple "color of X and Y is Z" relation that holds for Sun/gold/yellow and Moon/silver/white. The heterogeneity of matches that could apply within a single tabular system contrasts sharply with the modern aesthetic. The preference for structural consistency and systematicity in modern analogy would dictate that identical relations should hold across the system: that is, we would expect to find

Moon:white :: Sun:yellow :: Jupiter:blue :: Saturn:black

In the alchemical system there is no such requirement: no two rows need have the same set of relational links.[12]

This example illustrates a further point of difference: the alchemists' system of correspondences violates the "no extraneous relations principle" in that cross connections of all kinds enter into the analogies. For instance, black, lead and Saturn are all linked through the chain described above; but the match between lead and Saturn was improved by the fact that both are slow and heavy. Saturn moves slowly in its orbit and was therefore thought of as massive (heavy); lead was known to be a dense (heavy) metal, which would presumably move slowly. This complex web of similarities was felt to improve the system, though it could not be applied uniformly.

As another instance of the prolific and heterogeneous nature of this relational system, consider the match between Mars and red. Cavendish (1967, p. 27) notes that it is based on several chains of associations: Mars looks red; Mars was the god of war, war is associated with bloodshed, and blood is red; faces are painted red in war; and Mars is held to rule violent energy and activity and red is the color symbolizing energy. These multiple metonymic paths strengthened the analogical connection between Mars and red.

This discussion of the alchemists' system of correspondences illustrates

some marked differences in the rules of the game. The alchemists were not moved by the modern "no extraneous relations" rule. They accepted mixed metaphors and fused interpretations of a single metaphor. In the current aesthetic, once a parallel set of relations is established, adding local relations that hold only for a few cases does not improve the analogy. But for the alchemists, more was always better. A rich set of interrelationships, however idiosyncratic, was felt to strengthen the similarity bond.

Comparison between the alchemists and modern scientists

The alchemists embraced similarity in all its forms in reasoning about the natural world. Yet the examples we have considered show marked deviation from the current style of analogical reasoning as summarized in Table 20.1. Are there then historical differences in analogical reasoning? Before drawing this conclusion we must consider two other factors that may have contributed to the differences. First, the vagueness of alchemical analogy might have stemmed simply from a desire for secrecy, as discussed above. In order to prevent laymen from understanding the mysteries of alchemy, its practitioners disguised their recipes with symbolism and ambiguity. But although this is undoubtedly part of the story, it would be an oversimplification to try to explain all the differences in this way.[13] As discussed below, the alchemists' penchant for chaotic metaphor goes well beyond what a desire for secrecy will account for.

A second and deeper difference between the alchemists and modern scientists is the fact that the alchemists had more complex goals. They were concerned not only with understanding the material world, but with achieving spiritual transcendence. The alchemist invested the analogy between the spiritual and material planes with dual-causal powers and might strive to purify his spirit in order to transmute metals, or strive to transmute metals in order to purify his spirit. Modern science separates personal virtue from excellence in research. This separation has its disadvantages, but it does streamline the research enterprise.

Another possible difference in goals is that the alchemists were probably relatively more interested in the acquisition of power (as opposed to the acquisition of pure knowledge) than are modern scientists. But although the alchemists had a complex (and perhaps mutually incompatible) set of goals, we should not lose sight of the fact that a primary goal was to understand the material universe. The most convincing evidence that the desire to understand was at least part of their agenda is the fact that alchemy produced a large number of factual discoveries: useful compounds, tinctures, alloys, and so forth. We can also see a quest for knowledge in some alchemical writings. The alchemist Roger Bacon (1214–1292, not to be confused with Francis Bacon, quoted below) wrote in 1267:

I have laboured from my youth in the sciences and languages, and for the furtherance of study, getting together much that is useful. I sought the friendship of all wise men among the Latins, and caused youth to be instructed in languages and geometric figures, in numbers and tables and instruments, and many needful matters. (quoted in Crosland, 1978, p. 119)

It is impossible not to recognize in this passage some commonalities with scientists of any period. However complex the alchemists' goals, it is inescapable that among those goals was a desire for knowledge.

With the foregoing cautions, we now consider whether the disparities in analogizing suggest a genuine difference in reasoning style. Some of the differences – notably failure to show relational focus and to seek systematicity – could reasonably be attributed to simple lack of domain knowledge. Lacking deep domain theories, the alchemists perforce had to rely more on surface similarity than later scientists. Indeed, there is considerable evidence from studies of the development of metaphor and analogy (Billow, 1975; Chen & Daehler, 1989; Gentner, 1988; Gentner & Rattermann, 1991) and from novice–expert studies in learning physics (Chi, Feltovich & Glaser, 1981) to suggest that young children and novices judge similarity by common object descriptions, while older children and experts use common relational structure. Many researchers have argued that the relational shift in development may be explainable largely by accretion of domain knowledge (Gentner, 1988; Gentner & Rattermann, 1991; Goswami, 1991; Goswami & A. Brown, 1989; Vosniadou, 1989), and the same arguments may apply here. Similarly, the alchemists' reliance on surface qualities and their failure to show relational focus do not necessarily indicate a different style of thinking; they could be attributable to lack of knowledge.

Domain knowledge differences, however, will not account for all the differences between the alchemists and modern analogists. The fact that the alchemists felt no need for one-to-one correspondences, their fondness for between-domain relations and mixed metaphors, and their propensity to ascribe causal powers to analogy and similarity all seem to point to a true difference in their sense of the implicit rules of analogizing. One hint that this may be true comes from contemporary comments.

Transition: The discovery of analogy

Toward the end of the alchemists' reign, roughly between 1570 and 1640, there occurred a fascinating period of explicit discussion of the proper use of analogy and similarity. (For an extended discussion, see Vickers, 1984, pp. 95–163.) For example, Francis Bacon in 1605 attacked the Paracelsans' penchant for analogy:

The ancient opinion that man was Microcosmus, an abstract or model of the world, hath been fantastically strained by Paracelsus and the alchemists, as if there were to be found in man's body certain correspondences and parallels, which should have respect to all varieties of things, as stars, planets, minerals, which are extant in the great world. (quoted in Vickers, 1984, p. 134)

Some of this criticism rested on rejecting the seemingly absurd conclusions of the alchemists' analogies, such as the notion that man was made of vegetative or mineral matter. Van Helmont, for example, complained of the vast differences between the objects placed in correspondence, for example, stars mapping onto plants and herbs. (It is interesting that this argument would not be valid in the modern aesthetic.) Another complaint centered on the alchemists' tendency to "heap analogy onto analogy, spiraling off into the void" as Vickers (1984, p. 135) puts it. For example, Andreas Libavius attacked the alchemist Croll for his use of a cabalistic language of signs:

The Cabala is a falsehood and a deceit. For it presents things, not as they are, but as they are compared with other things in an indeterminately external fashion. Thus we are not able to know what constitutes a thing. (quoted in Vickers, 1984, p. 135)

Some critics recommended abandoning similarity altogether. Daniel Sennert (1619) wrote:

Therefore the soul that loves truth is not satisfied with similitudes only, but desires solid demonstrations; and volves things from their own, not from principles of another. . . . There is nothing so like, but in some part it is unlike. (quoted in Vickers, 1984, p. 142)

J. B. Van Helmont (1648) was even firmer, writing, "I have hated Metaphorical Speeches in serious matters," and also, "surely I do not apply figures or moving forces in Mathematicall demonstration unto nature: I shun proportionable resemblance [analogy]" (quoted in Vickers, 1984, p. 144).

Others responded to this crisis of confidence by trying to define the nature of true analogizing. Johannes Kepler was particularly articulate in attempting to explicate the kind of analogy that is warranted in scientific argumentation. Like Van Helmont, he was critical of the alchemical style of analogizing. He wrote in 1619 of Ptolemy's analogy between planetary motions and musical keys:

I have shown that Ptolemy luxuriates in using comparisons in a poetical or rhetorical way, since the things that he compares are not real things in the heavens. (quoted in Vickers, 1984, p. 153)

Kepler argued that analogies should be based on physical, measurable quantities, and not on the symbols that represent them. He rejected metaphors from the symbolic to the real world (such as Boerhaave's mappings of qualities from chemical symbols to the elements themselves, as discussed earlier).

Yet Kepler did not advocate avoiding the use of similarity. On the contrary, he was an ardent analogizer. For example, in 1604 he used an analogy with optics to explain the five conic sections (circle, ellipse, parabola, hyperbola, and straight line), an explanatory framework that is still useful. He notes that he speaks "contrary to normal use" but continues:

> But for us the terms in Geometry should serve the analogy (for I especially love analogies, my most faithful masters, acquainted with all the secrets of nature) and one should make great use of them in geometry, where – despite the incongruous terminology – they bring the solutions of an infinity of cases lying between the extreme and the mean, and where they clearly present to our eyes the whole essence of the question. (quoted in Vickers, 1984, p. 150)

But Kepler's enthusiasm for analogy was tempered by a desire for independent confirmation of the analogical inferences. Later in the passage, giving examples of how to construct the conic sections, he notes "Analogy has shown, and Geometry confirms." In distinction to the alchemists, for whom similitude was sufficient evidence of a deep connection, Kepler regarded analogy as a source of hypotheses.

In a 1608 letter to a colleague, he wrote with great explicitness about the heuristic nature of analogy and of the need for analogies to preserve interrelationships and causal structure:

> I too play with symbols, and have planned a little work, Geometric Cabala, which is about the Ideas of natural things in geometry; but I play in such a way that I do not forget that I am playing. For nothing is proved by symbols . . . unless by sure reasons it can be demonstrated that they are not merely symbolic but are *descriptions of the ways in which the two things are connected and of the causes of this connexion.* (quoted in Vickers, 1984, p. 155; italics added)

Kepler's symbols and principles – that analogies should in general hold between real domains, rather than between symbols and domains, that analogy is a source of hypotheses rather than a guarantor of truth, and that an analogy is useful in virtue of its ability to capture common causal relations – are remarkably modern. Further, this new sense of analogizing is apparent in practice as well as in theory. Both Kepler and his contemporary Galileo made frequent use of analogy, but in a style quite different from the alchemists. For example, Galileo (1629) used the analogy between dropping a ball from a tower on the earth and dropping a ball from the mast of a ship to argue that the earth moves despite the evidence of our senses. (See Gentner, 1982, for further details.) Kepler dealt with the notion of action at a distance with an analogy between light and a force he hypothesized to emanate from the sun. (See Vickers, 1984, for further details.) Like light, this motive force might travel unseen through space yet produce an effect at its destination, and like light, its strength would diminish with distance from the source. In each case, Kepler and Galileo examined the disanalogies as to whether they undermined the analogy, that is, as to whether they affected the common causal system sanctioned by the analogy.

There is a sharp contrast between this playful but stern view of analogy and the profligate metaphor of the alchemists. Kepler (1571–1630) and Galileo (1564–1642), each working within about fifty years of Paracelsus (1493–1541), used analogies as rigorously and systematically as Boyle or Carnot, or indeed as Feynman or Oppenheimer. The striking contrast in analogical style over this brief period, coupled with the intense discussion of the proper use of similarity that occurred during this time, leads us to speculate that a shift in the rules of reasoning by similarity occurred somewhere between 1570 and 1640. Vickers (1984) identifies this period as a transition period in the relation between analogy and identity. We could put it that analogy was (re)discovered in Western science[14] in about 1600.

Conclusions

Despite the seeming inevitability of our current constraints on similarity-based reasoning, they do not appear to be universal. The alchemists relied heavily on similarity and metaphor in their investigations of the nature of matter; but their use of similarity differed sharply from that of modern scientists. In particular, the alchemists lacked a sense that *analogy* in the modern sense had any advantage over surface similarity or over metonymic, richly interconnected but unclarified forms of similarity and metaphor.

A fascinating aspect of this historical change is the period, roughly 1570–1640, during which similarity itself became a focus of discussion among scientists. This period coincides with the waning of alchemical methods[15] and the rise of a more modern spirit. The shift from metaphor to analogy is one aspect of the general change in the style of scientific thought that occurred during this period. There is no way to tell whether the discussion of analogy was the cause or the result (or both) of the general shift in scientific reasoning. Nevertheless, the energy and explicitness with which Kepler, Van Helmont and others discussed the nature of proper analogizing commands attention. Among other things, it offers an opportunity to study the psychological intuitions of scientists 350 years past. The convergence between Kepler's account of analogy and our own current account is as remarkable as the divergence of both approaches with that of Paracelsus.

Cultural differences in the cognitive aesthetics of similarity and analogy

The marked difference in the style of analogizing between the alchemists and later scientists suggests that the uses of analogy and similarity are in part culturally defined. How far might such cultural differences extend? The strongest form of this conjecture would be that some human cultures have lacked the use of true analogy entirely, and that there is a cultural evolution toward such use. We hasten to stress that our evidence is much weaker than this. We do not suggest that the alchemists (or their compatriots) lacked the ability to use analogy; on the contrary, the prevalence of allegories and proverbs suggests that analogy was alive and well in western culture during the middle ages. Where the alchemists differed from modern scientists, we suggest, was in lacking an appreciation of analogy's special value in the pursuit of scientific knowledge.

There are modern instances of cultures that possess the various forms of similarity, including analogy, but use them in a different distribution from current western culture. Homeopathy and contagion (that is, similarity and contiguity/association) are the two pillars of folk magic across cultures (e.g., Rozin & Fallon, 1987). For example, in West Africa, a belief in *juju* – a kind of sympathetic magic that relies heavily on similarity and metonymy – exists side by side with the frequent highly relational use of proverbs in everyday human interactions. Thus our point is not that some cultures have lacked the ability to reason analogically, but that cultures have differed in their tacit theories of when and how to use analogy and other kinds of similarities.

Different kinds of similarities coexist in our own current cognitive practice as well. Although analogy is preferred in science (see note 16), literary metaphors are allowed to be rich, complex, and inconsistent, and to have many-to-one mappings and metonymies (Shen, 1987). (Recall the example from Dylan Thomas cited earlier, or this one from him: "All the moon long I heard, blessed among stables, the nightjars / Flying with the ricks, and the horses / Flashing into the dark.") To see whether people use different criteria for scientific and literary comparisons, we asked subjects to rate scientific and literary comparisons for their *clarity* ("how easy is it to tell what matches with what") and their *richness* ("how evocative is the comparison; how much is conveyed by the comparison"). We also asked them to rate either the scientific explanatory value or the literary expressiveness of the comparisons (Gentner, 1982). In judgments of scientific merit, clarity was considered crucial and richness was unimportant. In judgments of literary merit, both clarity and richness contributed, and neither was essential. These findings suggest a broader tolerance for nonclarified similarity in literary contexts than in scientific contexts.

This should not be taken to imply that unclarified metaphor has no role in scientific contexts in our culture. There is general agreement that unruly metaphors play a role in the discovery process, and that some degree of tolerance for loose analogy is important for creativity, as in Polya's (1954) advice (quoted earlier) to keep vague analogies but try to clarify them.

This speculation fits with recent research that has emphasized the plurality of similarity types and the context-sensitivity of similarity processes. For example, Medin, Goldstone, and Gentner (1993) have suggested that similarity is (implicitly) defined with respect to a large set of variables, and

Gentner, Rattermann, and Forbus (in press) and Ross (1984, 1987) have emphasized that different kinds of similarities participate differentially in different psychological subprocesses. For example, in similarity-based transfer, access to memory appears particularly sensitive to the degree of surface similarity, whereas evaluation of soundness is particularly sensitive to the degree and depth of common relational structure (Gentner, Rattermann, & Forbus, in press). To model a similarity comparison one must specify not merely the two comparands but also the sets from which they are chosen, the contextual goals, the task (e.g., memory access or inference or evaluation), and several other "respects." The present conjecture goes one step further in adding cultural factors to the list of variables that influence similarity.

Does child development parallel historical development?

In Western science we see a historical shift toward the belief that analogy rather than generalized metaphor provides a basis for scientific inquiry. We might ask whether such an evolution also occurs in children. (For related comparisons see Brewer, 1989; Carey, 1985a.) There are many differences between a child growing up in a culture that already possesses the analogical method and a scientist living in a time when the consensual rules for similarity were themselves evolving. But there may be some parallels. For example, Vygotsky (1962) observed that when preschool children are asked to sort varied objects into piles that go together, they tend to utilize thematic and metonymic connections, rather than consistent categories. They shift from one local similarity to another (e.g., the apple goes with the tomato because both are red, the knife goes with the apple because it can cut the apple, the spoon goes with the knife because they co-occur).

A second parallel is that in the development of metaphor and analogy, children show an early focus on surface object commonalities, followed by a developmental shift toward attention to relational commonalities (Gentner, 1988; Gentner & Toupin, 1986). For example, asked "how is a cloud like a sponge?" a preschool child says "both are round and fluffy," whereas older children and adults say "both hold water and later give it back." A similar shift occurs in perceptual similarity tasks, from object similarity to relational similarity and then to higher-order relational similarity (Gentner, Rattermann, Markman, & Kotovsky, in press; Halford, 1987, 1992). Smith (1989) has noted a developmental shift from the use of a vague sort of global magnitude (wherein, for example, *large* and *dark* are interchangeable positive magnitudes) to the use of dimensional orderings (wherein *small/medium/big* is structurally aligned with *light/medium/dark*). It is possible that children recapitulate some of the alchemists' journey in learning how to reason with similarity.

There are other possible parallels. Based on Rozin and Fallon's (1987) findings, we might ask whether young children in our culture are more swayed by homeopathy and contagion than are adults. Further afield, it is possible that children recapitulate the alchemists' journey from seeking *power* to seeking *knowledge*. Young children, even when instructed to find out how a device works, often approach the task in the spirit of gaining control rather than in the spirit of gaining knowledge (Klahr, 1990, personal communication).

But the issue of parallels between cultural evolution and children's development for similarity and analogy raises more questions than it answers. Most current accounts of the causes of the relational shift in similarity have emphasized accretion of domain knowledge, rather than changes in cognitive processing (e.g., A. Brown, 1989; Gentner, 1988; Gentner & Rattermann, 1991; Goswami, 1991; Goswami & A. Brown, 1989; Vosniadou, 1989). But if we take the parallel with alchemists seriously, it suggests that we might also look for changes in children's metacognitive rules about how and when to use similarity. Do children show a shift in their causal uses of similarity from valuing thickly interconnected metaphoric tropes to valuing rigorous analogy? If so, is there a transition period of explicit thought about the nature of explanatory analogy? And finally, if this kind of evolution occurs, what are its causes? Gentner and Rattermann (1991) have suggested that learning relational language is important in bringing about the relational shift in similarity. Other kinds of cultural experiences, including literacy and schooling (Bruner, Goodnow, & Austin, 1956), may be important as well.

Similarity is a central organizing force in mental life. This research implies that although the apprehension of similarity in its various forms may be universal among humans, conventions for how and when to use it are not. There is variation both across and within cultures in the ways humans use similarity to categorize and reason about the world. This survey suggests an evolution in Western science from metaphor to analogy: from profligate use of rich but unruly comparisons to the present preference for structural analogy in scientific reasoning. Finally, this research raises the fascinating question of how our current cognitive aesthetics are learned by children.

NOTES

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1 The *no mixed analogies* rule does not apply to the case of multiple parallel analogies that all embody the *same* relational structure. Such parallel analogies can often illuminate a common abstraction (Elio & Anderson, 1981; Gick & Holyoak, 1983; Schumacher & Gentner, 1987).

2 As with the other principles, the "analogy is not causation" principle is violated occasionally. There are still believers in homeopathy and sympathetic magic, who implicitly subscribe to the belief that likeness implies causal connection. Closer to home, in a survey of the analogies used to explain cognition in the history of psychology, Gentner and Grudin (1985) found that certain analogies between the physical brain and the mind (such as "associations among images are analogous to white matter connecting regions of gray matter" [Starr, 1984]) seemed to take on extra authority because of the known causal connection between brain and mind.

3 The caloric theory was widely accepted until Joule and other experimenters demonstrated the interconvertibility of heat and work in the 1840s (Wilson, 1981). Carnot's reliance on the caloric theory did not invalidate his basic conclusions regarding the cycle, although some later statements in *Reflexions* are incorrect when viewed from the perspective of the mechanical theory of heat (Fox, 1971).

4 Although Carnot refers to a waterfall, his discussion may have been based not merely on waterfalls, but on some kind of water engine, such as a water wheel or a column-of-water engine (Cardwell, 1965).

5 According to Fox (1971), Carnot's answer to this question was affected by his reliance on the questionable data of other scientists.

6 It is possible that at least part of the difference in analogical style between Carnot and Boyle stems from differences in their respective intellectual traditions. As Hesse (1966) points out in her ground-breaking work on analogy in science, the English tradition is far more tolerant of mechanical analogies than the French tradition. Hesse notes that the French academic tradition views analogy as vague and unsatisfactory, at best a crutch to use until a formal model can be devised. In contrast, the English tradition values mechanical analogies as sources of insight, especially with respect to preserving causation. This point is brought home in Nersessian's (1984) analysis of the use of analogy by Faraday and Maxwell and in Tweney's (1983) discussion of Faraday. Thus it is possible that some of the differences in style between Boyle and Carnot may stem from differences in cultural tradition.

7 The alchemists' comparisons are usually referred to as "analogies" but, for reasons that will become clear, they might better be described as "metaphors." We will use both terms.

8 This discussion is culled from several sources, principally Asimov (1965, pp. 15–33), Cavendish (1967, pp. 143–180), Crosland (1978, pp. 3–107), Holmyard (1957), Stillman (1960), and Vickers (1984).

9 Although this passage was copied in 1478, its exact date of origin is difficult to pinpoint. Other manuscripts from this collection are believed to have existed since before the fourth century in one form or another (Stillman, 1960).
10 However, this is an unusual (perhaps a transitional) account of the elements. The elements listed are earth (or metal), water, couperose (or sulfate), and fire, with air not explicitly mentioned.
11 There were several minor variants of this system of correspondences (e.g., Crosland, 1978, p. 80).
12 An alternative way of describing the alchemical aesthetic would be to say that the relations involved are extremely nonspecific: for example, "associated with by some path." Under that description, the alchemists would not be guilty of shifting relations between parallel analogs. However, this degree of nonspecificity of relations would still constitute a marked difference from modern scientific usage.
13 For one thing, it is not clear that the alchemists' analogies are so much less accessible than modern analogies. To the extent that alchemical correspondences were based on surface similarity, they could often be readily guessed. In contrast, in modern scientific analogy the object correspondences are often impossible to grasp without a knowledge of the domain theory, since they are based purely on like roles in the matching relational system.
14 It might be better to say "rediscovered," since the Greeks, including Plato and Aristotle, used analogy in the modern way.
15 Alchemy continued into the eighteenth century and beyond, but with greatly decreased influence.
16 This is apart from variation in the degree to which individuals in our culture conform to our ideal of rationality, as opposed to relying on superstitions based on metaphor and metonymy.

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*Metaphor and theory change: What is "metaphor" a metaphor for?

RICHARD BOYD

Introduction

In the now classic essay "Metaphor" (Black, 1962b), Max Black considers and rejects various formulations of the "substitution view" of metaphor, according to which every metaphorical statement is equivalent to a (perhaps more awkward, or less decorative) literal statement. Black devotes most of his critical attention to a special case of the substitution view, the "comparison view," according to which a metaphor consists in the presentation of an underlying analogy or similarity. It is clear from Black's discussion that he understands the comparison view as entailing that every metaphorical statement be equivalent to one in which some quite definite respect of similarity or analogy is presented, and that successful communication via metaphor involves the hearer understanding the same respect(s) of similarity or analogy as the speaker.

Black argues that, except perhaps in cases of *catachresis* – the use of metaphor to remedy gaps in vocabulary – the comparison view is inadequate. As an alternative, Black proposed the adoption of an "interaction view" of metaphor. According to this view, metaphors work by applying to the principal (literal) subject of the metaphor a system of "associated implications" characteristic of the metaphorical secondary subject. These implications are typically provided by the received "commonplaces" about the secondary subject. Although Black's position has many facets, it is clear that, at a minimum, it differs from the comparison view in denying that the success of a metaphor rests on its success in conveying to the listener or reader some quite definite respects of similarity or analogy between the