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Dedre Gentner

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The goal of this paper is to provide a structural characterization of analogy in science, contrasting good science analogies with literary metaphors and with poorer examples of science analogies. The paper first presents a theoretical approach in which complex metaphors and analogies are treated as structure-mappings between domains. Within this framework, metaphor and analogy are contrasted with literal similarity. Then, a set of distinguishing structural characteristics is proposed and applied in a series of comparisons. To illustrate the points, analogies of historical importance

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Are Scientific Analogies Metaphors?

Dedre Gentner

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Are Scientific Analogies Metaphors?

And I cherish more than anything else the Analogies, my most trustworthy masters. They know all the secrets of Nature, and they ought to be least neglected in Geometry.

-Kepler (quoted in Polya, 1973)

Isaac Newton likened the moon to a ball thrown so hard that its downward fall misses the earth and it passes into orbit. Galileo compared the moon, were it to fall out of its orbit, to a rock dropped from the mast of a moving ship: its motion would have both a falling component and a forward component shared with the ship. Both these analogies made the moon's motion appear a combination of falling and moving forward. It became clear that, to preserve a circular path, in each instant the moon's tangential displacement must compensate for its inward displacement. These analogies played a role in the shift away from the deeply held Aristotelian view that a body could have only a single motion, and that circular motion was an essential quality of heavenly bodies, to the view that the orbits of the moon and planets are composite motions.

Models that explain a new topic by analogy with a familiar domain are common in science. Other examples are

Rutherford's comparison of the atom to the solar system; the analogy between propagation of sound in air and propagation of waves in water, and the further analogy to propagation of light through space; and the hydraulic model of electric circuitry. Current work in nuclear physics likens weak interactions among elementary particles to a field induced by a weak, uncharged electric current. Finally, a familiar but useful example is the standard mathematical technique of analogizing from two- or three-dimensional spaces to n-dimensional spaces.

Yet metaphorical thinking can foster vagueness. In alchemical analogy, chemical processes were explained in terms of correspondences with life processes and psycho-spiritual processes such as debasement and redemption. For example, in the putrefaction stage of a chemical reaction, a black, foul-smelling chemical was supposed to give rise to a more vital material, just as rotting mud was believed to engender life. This set of correspondences persisted for a very long time, and may have impeded progress in chemistry (Cavendish, 1967). There are examples closer to hand of analogies whose usefulness is debatable. There is the "urban blight" metaphor by which terms like "afflicted" and "organically sound" metaphor by which terms like "afflicted" and "organically sound" are applied to neighborhoods (Lakoff & Johnson, in press; Schon, 1979). Psychology has used terms such as "reverberating circuits", "mental distance", "perceptual defense", "memory capacity", "mental image" and "depth of processing" that have at least a partly metaphorical status. Some of these analogies have suggested deep research, while others have merely provided a kind of spurious feeling of comfort (see Pylyshyn, 1979).

What makes some analogies useful in scientific thinking and others useless or harmful? One might propose the straightforward criterion that good analogies are those that make correct predictions while bad analogies make false predictions. But this proposal is inadequate. As we will see, good analogies make incorrect as well as correct predictions; and even primarily incorrect analogies can lead to useful research. Moreover we typically must decide whether an explanatory analogy is promising or not before checking the validity of its predictions. There indications all point to other characteristics that distinguish good and bad analogies.

The goal of this paper is to provide a structural characterization of analogy in science, contrasting good science analogies with literary metaphors and with poorer examples of science analogies. The plan is, first, to present a theoretical approach in which complex metaphors and analogies are treated as structure-mappings between domains. Within this framework, metaphor and analogy are contrasted with literal similarity. Then, a set of distinguishing structural characteristics is proposed and applied in a series of comparisons. To illustrate the points, analogies of historical importance are analyzed. Although the focus is on theory, some empirical findings will also be discussed.

Models as Structure Mappings

The first point is a terminological one. There is no good term for "nonliteral similarity comparison." The term "metaphor" conveys an artistic or expressive nonliteral comparison of a certain form; the term "model" conveys an explanatory-predictive nonliteral comparison, often mathematically stated. Since I want to discuss the structure of both metaphors and models, I need a neutral term. I will use the term "analogy" as a general term for nonliteral similarity comparisons, including metaphors, similes, and models. In cases when the narrow sense of "analogy" as a comparison of the form A:B::C:D. is needed, I will use the term "simple analogy."

The models used in science belong to a large class of analogies that can be characterized as structure-mappings between complex systems. Typically, the target system to be understood is new or abstract, and the base system in terms of which the target is described is familiar and perhaps visualizable. In these analogies, the objects of the known domain are mapped onto the objects of the domain of inquiry, allowing the predicates of the first domain--primarily the relational predicates--to be applied in the other domain. A structure-mapping analogy asserts that identical operations and relationships hold among nonidentical things. The relational structure is preserved, but not the objects (or parts of objects). For example, Polya (1973) states " . . . /In/ the most typical case of clarified analogy, . . . two systems are analogous, if they agree in clearly definable relations of their parts."

The structure-mapping approach makes a strong distinction between objects and their attributes, on the one hand, and relationships, on the other hand. This approach thus requires fairly well-elaborated propositional representations of meaning in both domains. For present purposes, the most useful representation of knowledge is as a propositional network of nodes and predicates. (Bobrow, 1975; Rumelhart & Norman, 1975; Rumelhart & Ortony, 1977; Schank & Abelson, 1977) The nodes represent concepts treated as wholes and the predicates express propositions about the nodes. These representations are hierarchical: a node at one level may decompose at a lower level into another netowrk of nodes and relationships. At any given level of representation a topic area can be characterized in terms of nodes and predicates, where the predicates can be either attributes--predicates taking one argument--or relations--predicates taking two or more arguments. For example, COLLIDE (x,y) is a relation, while RED (x) is an attribute.

Given such a propositional representation, we can proceed with the characterization of a metaphor or analogy as a structure-mapping between a known domain (the base domain) and a domain of inquiry (the target domain). (cf. Brown, Collins & Harris, 1978; Gentner, 1977ab, 1980; Miller, 1979; Rumelhart, 1979.) A structure-mapping analogy between a target system T and a base system B is an assertion that

(1) there exists a mapping M of the nodes b_1, $b_2, \ldots, b_n$ of system B into the (different) nodes t_1, $t_2, \ldots, t_m$ of system T.

(2) The mapping is such that substantial parts of the relational-operational structure of B apply in T: that is, many of the relational predicates that are valid in B must also be valid in T, given the node substitutions dictated by M:

$$\text{TRUE } [F(b_i, b_j)] \text{ implies TRUE } [F(t_i, t_j)].$$

Assertions (1) and (2) define the basic structure-mapping. However, they are also compatible with a general similarity relationship between the domains T and B. To specify that the match is one of analogical relatedness and not literal similarity, we need a further stipulation:

(3) Relatively few of the valid attributes (the one-place predicates) within B apply validly in T.

$$\text{TRUE } [A(b_i)] \text{ does not imply TRUE } [A(t_i)].$$

Assertions (2) and (3), taken together, state that relational predicates, and not object attributes, carry over in analogical mappings. This follows from the central assertion that such mappings apply the same relations to <u>dissimilar</u> objects. (Object attributes can map across only to the degree that the objects themselves, as opposed to their roles in their systems, are similar.)

Given the importance of scientific analogies it is perhaps surprising that they have received so little attention in psychology. The major reason, I suspect, is that science analogies must be viewed as comparisons between systems and cannot be analyzed as simple object comparisons. Most psychological treatments of metaphor are aimed at object-object comparisons, such as "The sun is like an orange," or "Stars are Diamonds." These metaphors, at least to some extent, can be treated as pure attribute-mappings. They lend themselves to psychological treatments based either on feature-list representations (e.g., Ortony, 1979) or on multidimensional space representations of the domains (e.g., Sternberg, Tourangeau & Nigro, 1979), both of which can deal with object attributes but not with relations between objects. Whether or not such limited representational systems are adequate to characterize metaphor use in ordinary conversation, I will argue here that science analogy requires a richer representation of meaning. Similar arguments can be made for literary metaphor (See Miller, 1979). Some experimental evidence for structure-mapping is reported in Gentner (1980).

Analogy versus similarity. The degree of matching among objects versus relations determines whether a comparison statement will convey literal similarity or analogical relatedness. When both the component object attributes and the relational structure overlap, the comparison is one of literal similarity. An example is

(1) The helium atom is like the neon atom.

This is a literal similarity comparison, because there is considerable overlap both in the component objects - protons, neutrons and electrons - and in the relations between those objects - e.g., "electron REVOLVES AROUND (proton AND neutron)". Of course, not all the objects and relations correspond perfectly; if they did, the statement would convey identity, not similarity.[2]

If the relationships correspond, but the objects do not, the comparison is analogical. An example is

(2) The hydrogen atom is like the solar system.

Here, the component objects are totally different; what the statement conveys is overlap in the relational structures of the two systems.

The final possibility is to have overlap among objects but not among relationships. This represents neither literal nor analogical similarity. Such comparisons are chiefly used in relating histories, in which the same entities pass from one configuration into another configuration. Perhaps the clearest instances in science are chemical equations, in which atoms (the objects) are rearranged from one molecular grouping (set of structural relations) to another; for example,

(3) $CaCO_3 = CaO + CO_2$.

This equation conveys that the molecules of calcium, carbon and oxygen that make up limestone (calcium carbonate, $CaCO_3$) can be rearranged so that the same molecules form lime (CaO) and carbon dioxide (CO_2). The point here is that the two sides of the equation, though they contain the same objects, are neither literally nor analogically similar. We do not say that limestone is <u>like</u> lime and carbon dioxide. Their connection seems rather one of chronological relatedness: the two configurations can apply to the same objects (atoms) at different times.

To summarize, overlap in relations is necessary for the perception of similarity between two systems. Overlap in <u>both</u> object attributes and inter-object relationships is seen as literal similarity; overlap in <u>relationships</u> but not objects is seen as analogical relatedness; and overlap in <u>objects</u> but not relationships is seen as temporal relatedness, not as similarity. According to this brief demonstration, no featural treatment of analogical or metaphorical similarity can be complete without distinguishing between object features and relational features: that is, between relational predicates and one-place attributive predicates.[3] A further implication is that literal similarity versus metaphorical relatedness is a continuum, not a dichotomy. Given that two domains overlap in relationships, they are more literally similar to the extent that their object-attributes also overlap.[4]

A simple analogy. An arithmetic analogy, such as 3:6::2:4, is the simplest case of structure-mapping. If we make the mapping of 2 onto 3 and 4 onto 6, we find that the relation "denominator TWICE AS LARGE AS numerator" holds between 3 and 6 as it does between 2 and 4. Dissimilar objects exist in the same relationships. This is a particularly simple case, first because the class of relevant relations (proportionality) is understood by convention, and second, because very few relationships are involved. In complex analogies, it can be harder to identify the relations that are to be mapped; and there may be several different mapped relationships.

The atom/solar system analogy. An example of a complex analogy is Rutherford's solar system model of the hydrogen atom. Figure 1 shows the structure-mapping conveyed by this analogy. Starting with the known base domain of the solar system, the object-nodes of the base domain (the sun and planets) are mapped onto object-nodes (the nucleus and electrons) of the atom. Given this correspondence of nodes, the analogy conveys that the relationships that hold between the nodes in the solar system also hold between the nodes of the atom: for example, that there is a force attracting the

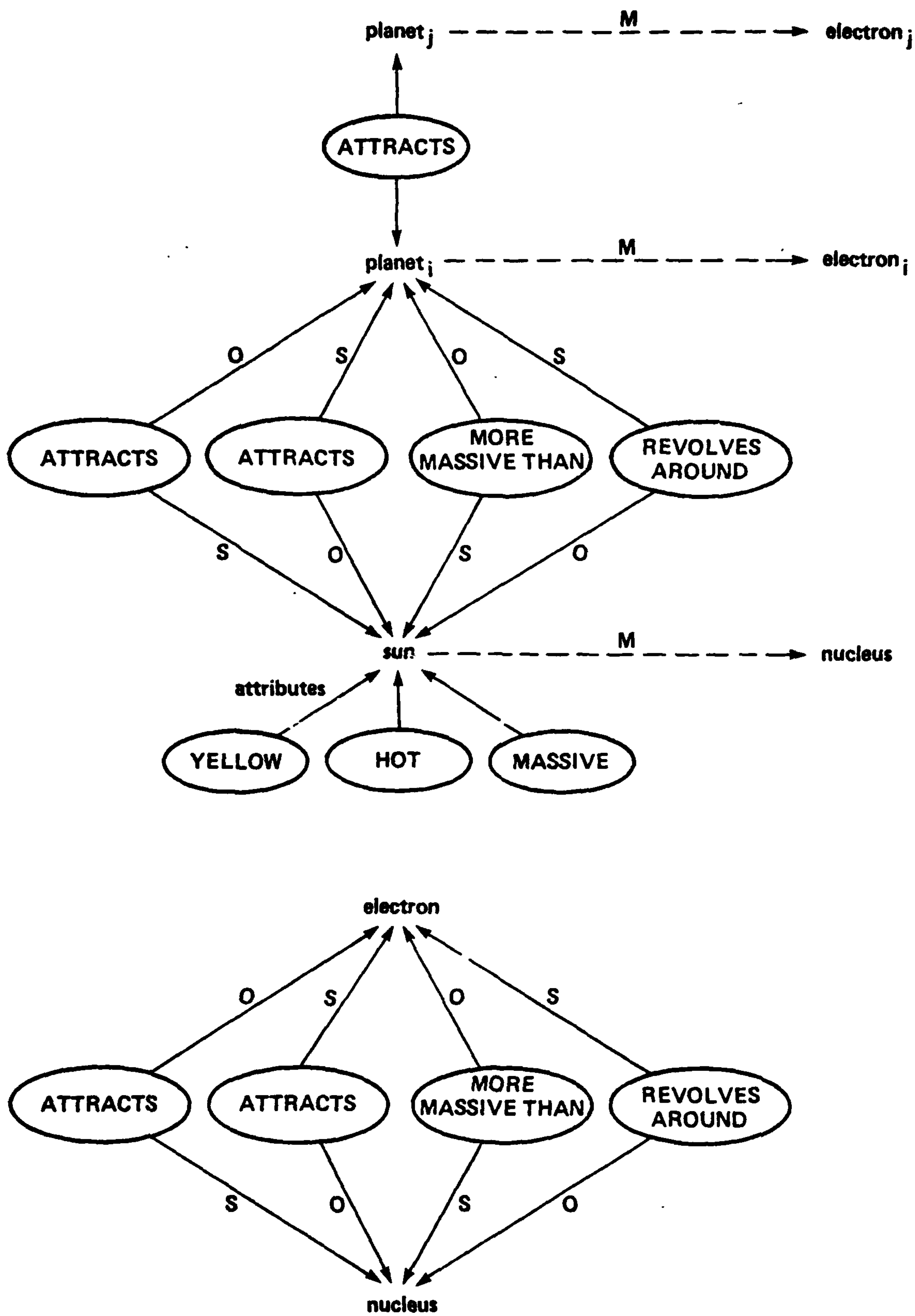


Figure 1. Representation of the atom-solar system model.

peripheral objects to the central object; that the peripheral objects revolve around the central object; that the central object is more massive than the peripheral objects; and so on.

This example shows how objects and their attributes are treated differently from relations in the mapping process. Base objects are mapped onto quite dissimilar target objects (e.g., the sun onto the nucleus). It is the relations in the base domain that are preserved. For example, the ATTRACTS relation and the REVOLVES AROUND relation between planet and sun are carried across to apply between electron and nucleus, while the separable attributes of the base objects, such as the color or temperature of the sun, are left behind. Mass provides a good illustration: The relation "MORE MASSIVE THAN" between sun's mass and planet's mass carries over, but not the absolute mass of the sun. We do not expect the nucleus to have a mass of 10^{30} kilograms, any more than we expect it to have a temperature of 25,000,000°F. The analogy conveys that the two domains, though composed of different objects, share much of their relational structure.

Characteristics of Scientific Analogies

Given the structure-mapping description as a framework, we can now pursue the question of what makes a good scientific analogy. The first thing that comes to mind is whether the model is valid, i.e., whether the relations imported from the base are true in the target. However, on reflection it becomes clear that validity, though clearly important, is the wrong place to start. We don't judge an analogy by checking every possible mapping, or even every possible relational mapping, from base to target. For example, in Galileo's earth/ship analogy, we do not attempt to map the ratio between the volume of the ship and the volume of the mast; it is clearly irrelevant, and whether it does or does not correspond to the same ratio in the earth-tower system does not affect our judgement of the analogy. Before we check validity, we make implicit decisions concerning which set of relationships is important.

The point is not that validity is unimportant, but that there are other factors. A science analogy must be seen as a system of mappings, not an undifferentiated set of predicates to be judged simply by their correctness in isolation. Therefore, in this section we turn to the structural qualities of a good science analogy, holding validity constant for now.

A consideration which arises at the outset is base specificity. This refers to the degree to which the structure of the base is explicitly understood. The better analyzed the base, the clearer the candidate set of mappable relations will be. This is one reason that the base is usually a familiar domain. However, familiarity is no guarantee of specificity; for example, sometimes in introductory chemistry texts, molecular bonding is explained by analogy with interpersonal attraction (e.g., "The lonely sodium ion searches for a compatible chloride ion."). Interpersonal attraction is certainly familiar, but its rules are unfortunately unclear; so this analogy does not tell the student precisely what to map from the base.

The degree of base specificity imposes an obvious limit on the usefulness of an analogy, since the predicted target relations mirror the base relations. Therefore the predicted target structure cannot be better specified than the base structure. However, it can certainly be worse specified. It is perfectly possible to construct a poor analogy using a well-specified base. This brings us to the first internal-structure consideration, that of the clarity of the mapping.

Internal Structural Characteristics. The first and most fundamental structural consideration is clarity. The clarity of an analogy refers to the precision with which the mappings are defined, i.e., it is concerned with exactly how the base nodes map onto the target nodes and which predicates get carried across. Any case in which it is unclear which base nodes map onto which target nodes violates clarity. One such violation occurs if one base node maps to two or more relationally distinct target nodes (the one-to-many case) or if two or more relationally distinct base nodes map to the same target node.[5] One variation of a many-to-one violation occurs when a base term is productively polysemous, with different senses entering into different relationships. Such an analogy is unfalsifiable, since any challenge can be met by a shift to the other relational framework. Clarity, I will argue, is the sine qua non of predictive analogy.

The first structural characteristic is richness: roughly, the quantity of predicates that are mapped. More precisely, the

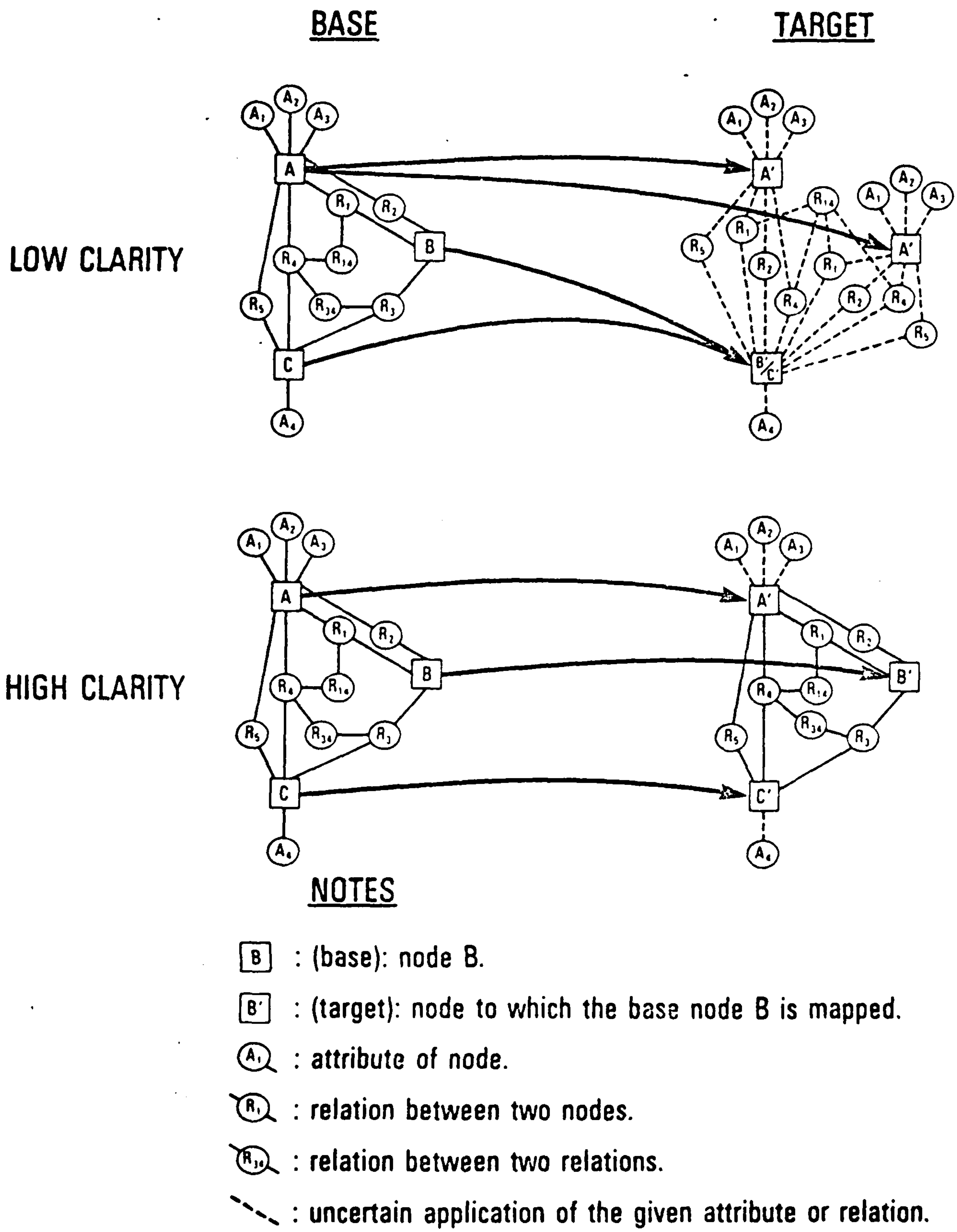
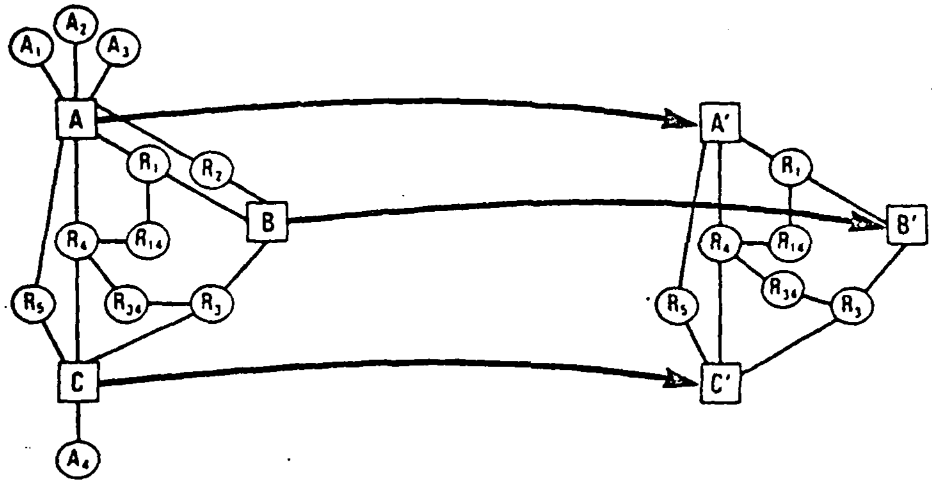
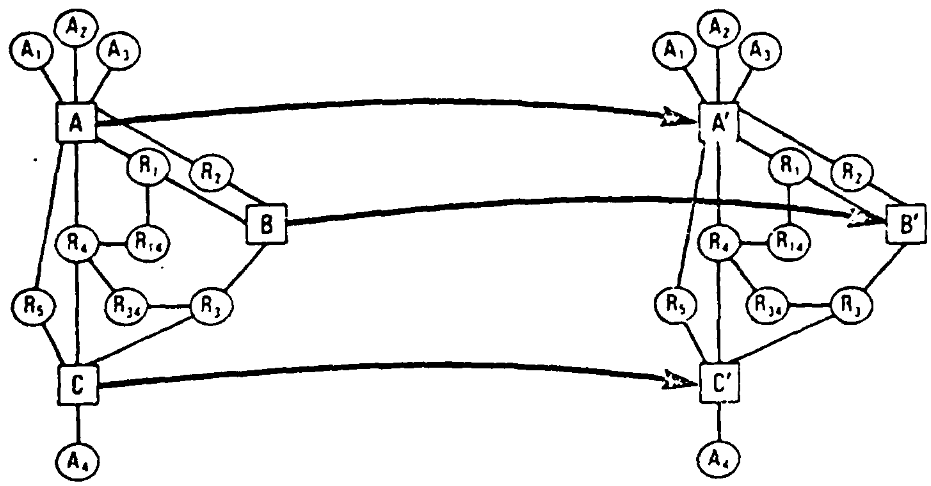


Figure 2. Schematic depiction of structural distinctions involved in clarity, richness, abstractness and systematicity.

LOW RICHNESS



HIGH RICHNESS



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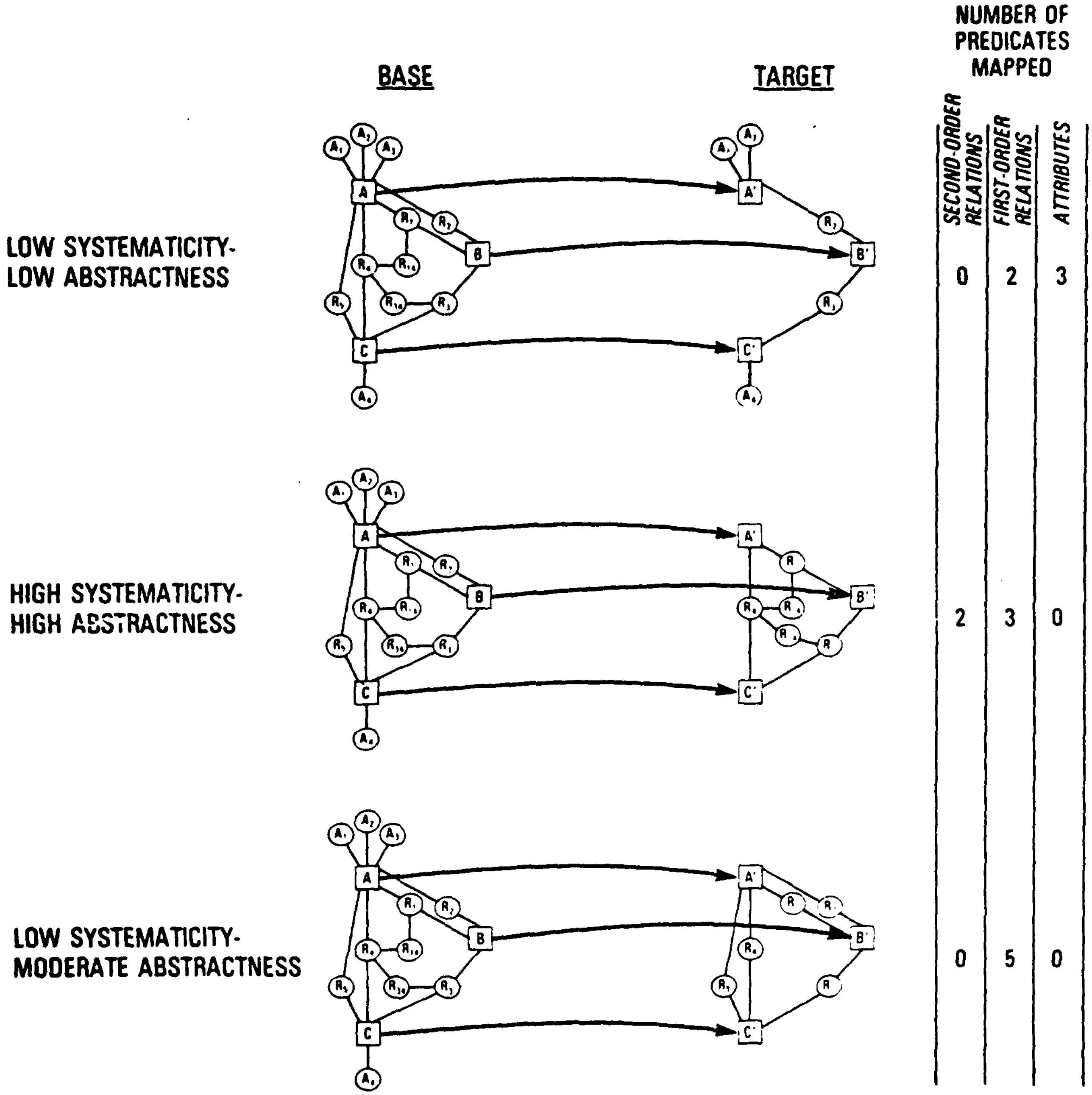

Figure 2 - continued

richness of an analogy is its predicate density: for a given set of nodes, the average number of predicates per node that can be plausibly mapped from base to target. Richness is defined independently of internal consistency; a set of predicates can all contribute to richness even if they involve contradictory mapping assumptions. Moreover, a predicate can contribute to richness even if it is false or does not possess a truth value in the target, as long as it has enough plausible appeal to be mapped. For example, affective relations can contribute to richness. Therefore, the richness of an analogy, like its clarity, can be discussed before assessing its validity.

Next there are two considerations, abstractness and systematicity, that deal with the kinds of predicates mapped, in terms of their structural role. First is the abstractness of the mapping: where in the structural hierarchy the mapped predicates are found. This means first, whether they are attributes or relations; and second, if they are relations, whether they are higher-order or lower-order relations. (A relation among objects is a first-order relation. A relation among first-order relations is a second-order relation, etc.; see Smith, in preparation.) The greater the proportion of higher-order relations, the more abstract the mapping.

The next consideration is the systematicity of the mapping--the degree to which the predicates mapped belong to a known mutually constraining conceptual system. An analogy in which separate or ad hoc relationships are mapped is less systematic than one in which a set of coherent, mutually constraining relationships are mapped. A mapping is systematic to the degree that any given predicate can be derived or at least partly constrained by the others. Clearly, the systematicity of an analogy is limited by that of its base domain; there must first exist a set of mutually constraining relations before they can be mapped.

To see the usefulness of this kind of structural redundancy, consider the Rutherford model, a highly systematic analogy. Here the mapped relationships--ATTRACTS (sun, planet), ORBITS AROUND (planet, sun), etc.--form a connected system, together with the abstract relationship INVERSE-SQUARE CENTRAL FORCE BETWEEN (sun, planet). Many lower-order relations could be predicted from this higher-order relation.

The systematicity of an analogy is limited by that of its base domain. If the predicates of the base are abstract and systematic enough, they can sometimes be stated mathematically. Some of the interrelations within this solar system are described in equation[6] (1),

$$(1) \quad F_{grav} = Gmm'/r^2$$

This equation embodies a set of simultaneous constraints on the parameters of the objects, where m is the mass of the sun, m' the mass of the planet, G is the gravitational constant, and F_{grav} is the gravitational force. For example, if F_{grav} decreases while the masses are constant, then the distance r between the sun and the planet must increase. When a highly systematic domain is used as the base of an analogy, the equation that summarizes its interrelations can sometimes be mapped into a corresponding target equation, such as equation (2).

$$(2)\ F_{elec} = -\,qq'/r^2$$

where q is the charge on the proton, q' the charge on the electron, r the distance between the two objects, and F_{elec} is the electromagnetic force. Notice the neatness of the mapping from base domain to target domain: m maps onto q, m' onto q', r onto r, F_{grav} onto F_{elec} and G, the gravitational constant, onto the electromagnetic constant, -1. Once this mapping is performed, the basic analogical assumption that relationships that hold within the base will also hold in the target allows us to construct the target equation parallel to the base equation with a similarly powerful set of mutual constraints.

There is a partial correlation between abstractness and systematicity. To be systematic, an analogy must include abstract relations (since the constraints between lower-order predicates are structurally represented by higher-order (i.e., abstract) relations between those predicates). However, the reverse is not true: an analogy can be abstract without being systematic, since systematicity has the further stipulation of mutual constrainedness. If an analogy involved many high-level relations that were too general to provide constraints on their lower-level arguments, it would be abstract but not systematic.

To summarize, the list if important considerations starts before the analogy is really underway with base specificity: how well the base is understood. Once the analogy is given, without stopping to assess its validity we can ask about the structural issues of (1) clarity--how rigorously the mapping is specified; (2) richness--how many predicates are mapped for every target node; (3) abstractness--what hierarchical level are the mapped predicates from; and (4) systematicity--how much is each of the mapped predicates constrained by the others. Figure 2 shows in schematic form the structural distinctions involved in clarity, richness, abstractness and systematicity. The figure largely recapitulates the text; however there are a few points to notice. First, in the low-clarity analogy the uncertainty as to how to map the predicates is greater the higher-order the relation, since the indeterminacies propagate. This fits with the intuition that an unclear mapping is difficult to formalize. Second, the clarity distinction is unique in that it concerns the node-mappings; the other characteristics concern which predicates are mapped, given a particular correspondence among nodes.

Scope and validity. So far the discussion has focused on the structural properties of the domains and of the mapping. To judge the usefulness of an analogy in science we must also know its validity and the scope of the mapping. Validity, as discussed above, refers to the correctness of the predicates in the target. Scope refers to the number of different cases to which the model validly applies. For example, the solar system model works reasonably well for the hydrogen atom, but less well for heavier atoms; and it is simply not applied at the molecular level. The scope of an analogy is in principle unrelated to its internal structural characteristics.

However, in practice, it is hard to design an analogy that conveys a high density of predicates over a broad range of different target instances without allowing the definitions of objects and predicates to slide about. There tends to be a three-way trade-off between scope, richness and clarity.

Explanatory analogy versus expressive analogy. The next portio of the paper is devoted to using these structural distinctions to contrast explanatory analogy--analogy intended to explain and predict--and expressive analogy--analogy intended to evoke or descri' e.

According to the above account, explanatory analogy could diffe from expressive along any or all five structural dimensions: (1) higher base specificity: tending to utilize better-understood domain as the base domains; (2) higher clarity: being more consistent and more liable to clarification; (3) greater abstractness: conveying higher-level relations among objects, as opposed to object-attribute and first-order relations; (4) greater richness: conveying more predicates, whether attributes or relations; or (5) higher systematicity: being more constrained to utilize a single coherent system of relations. We will consider four representative analogies: (1) n explanatory analogy of Galileo's; (2) an expressive analogy of T.S. Eliot's; (3) Rutherford's explanatory analogy; and (4) an expressive analogy of Shakespeare's.

Galileo's earth/ship analogy. Another historical example of complex modelling is an analogy that Galileo uses in a dialogue concerning whether the earth rotates (Galileo, 1638;

translated by Drake, 1967; p. 126-145). The scientist Salviati, Galileo's surrogate, argues the new Copernican view that the earth does rotate. The philosopher Simplicius defends the prevailing Aristotelian view that the earth is the unmoving center of the universe. Salviati offers Simplicius a seeming proof that the earth stands still: the fact that a stone dropped from a high tower drops straight down, instead of falling behind the tower, as it surely would if the earth moved. In support of this argument, Salviati presents an analogy between dropping a stone from a tower on the earth and dropping a rock from the mast of a ship. Simplicius accepts the analogy, which seems to support the Aristotelian view. Obviously the rock will fall straight down if the ship is still, but "will strike at that distance from the foot of the mast which the ship will have run during the time of fall" (p. 126) if the ship is moving (See Figure 3). Analogously, if the earth were rotating then the rock should fall well behind the tower; since it does not, we infer that the earth is still.

Salviati then gradually turns the analogy against the Aristotelian position. First, he brings up disparities between the base and target domains, such as differences in air and wind behavior. Simplicius considers these disparities and decides that they do not invalidate the analogy. Having

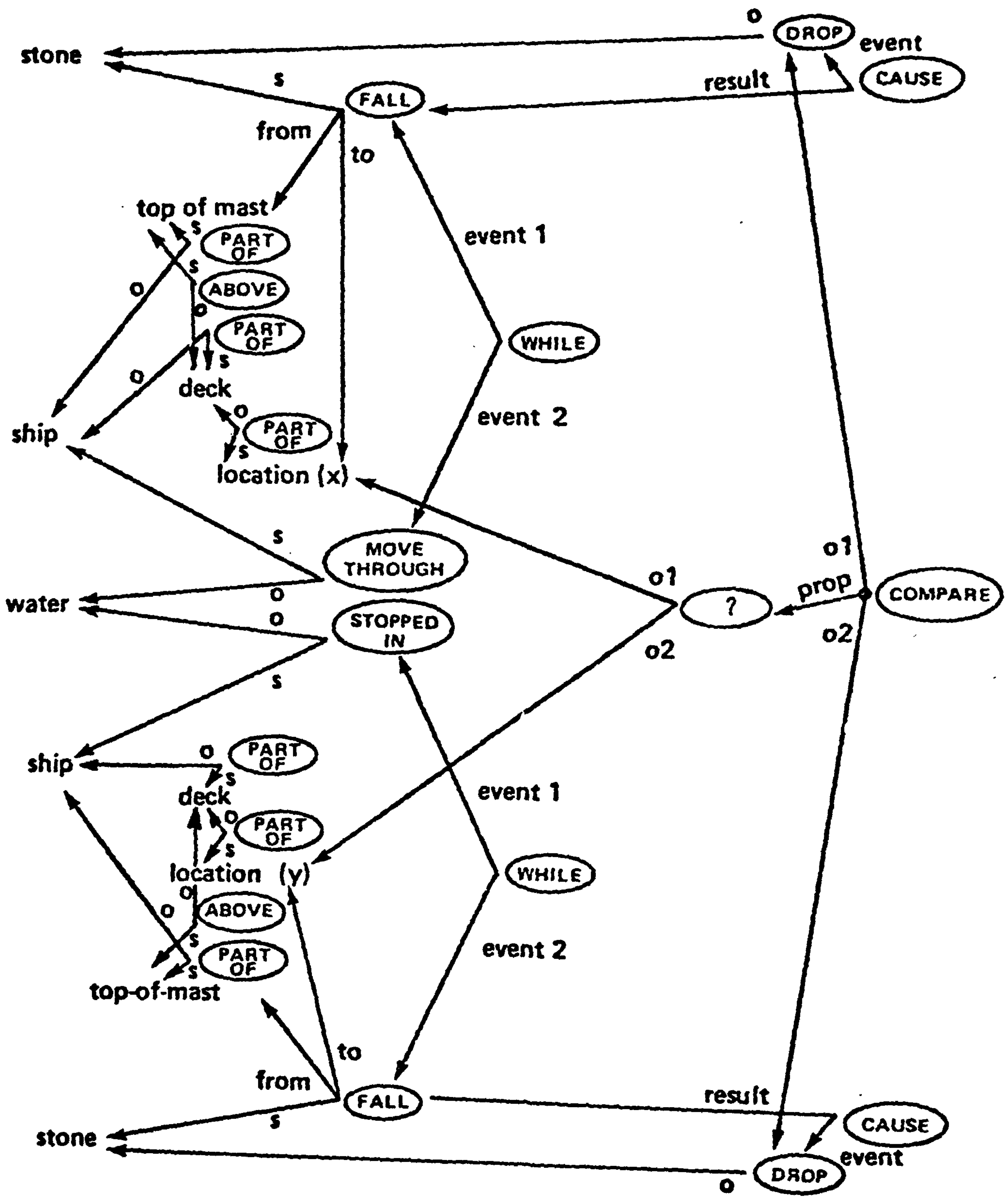

Figure 3a. Representation of Galileo's analogy: a rock dropped from the mast of a ship.

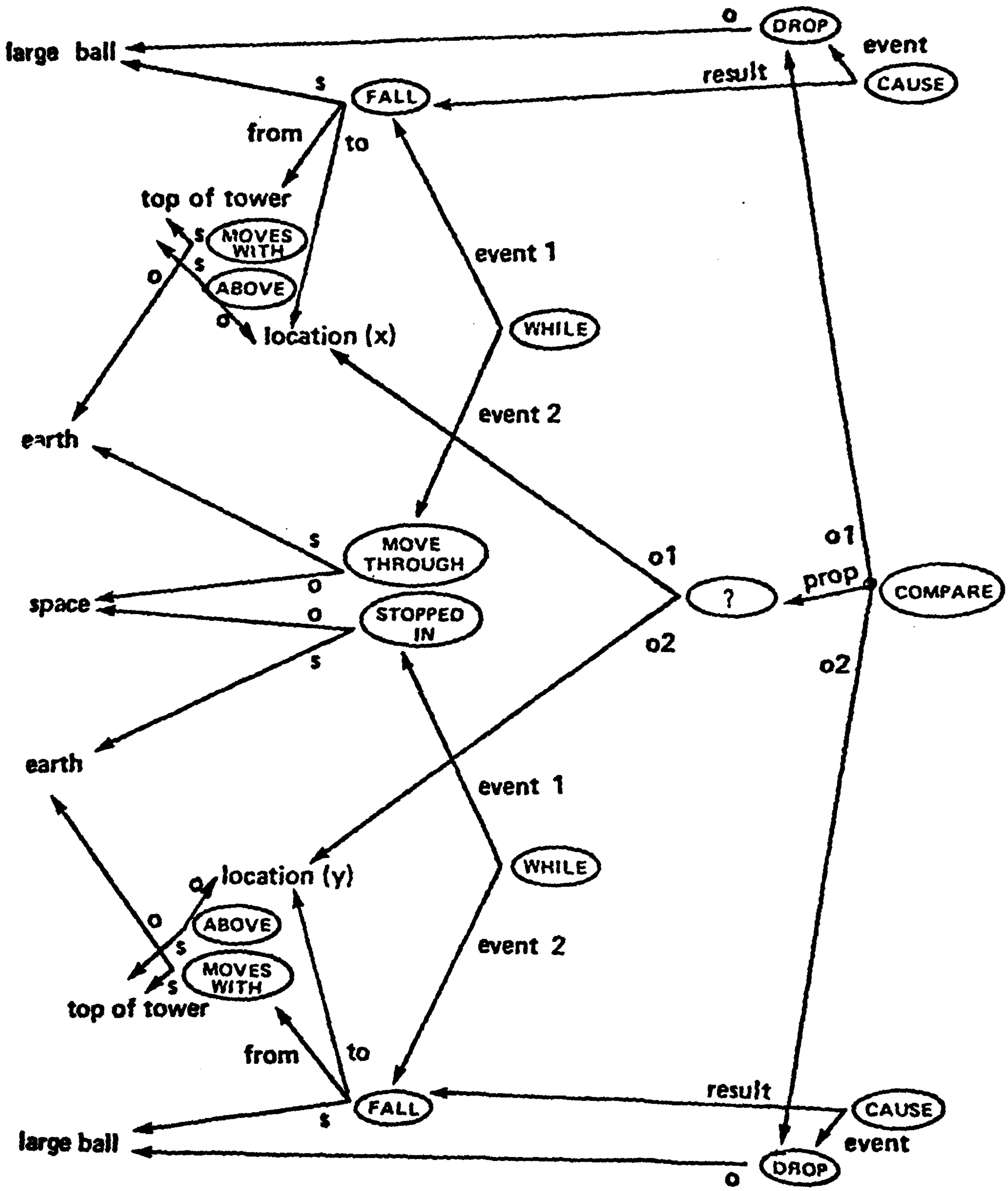

Figure 3b. Representation of Galileo's analogy: a large ball dropped from a tower on the earth.

confirmed that the analogy is binding, Salviati administers the final stroke (pp. 144, 145):

> Salviati: Now tell me: *If the stone dropped from* the top of the mast when the ship was sailing rapidly fell in exactly the same place on the ship to which it fell when the ship was standing still, what use could you make of this falling with regard to determining whether the vessel stood still or moved?
>
> Simplicius: Absolutely none;...
>
> Salviati: Anyone who does will find that the experiment shows . . . that the stone always falls in the same place on the ship, whether the ship is standing still or moving with any speed you please. Therefore, the same cause holding good on the earth as on the ship, nothing can be inferred about the earth's motion or rest from the stone falling always perpendicularly to the foot of the tower.

Since the rock falls straight from mast to deck even when the ship is moving, the straight fall of the stone from the tower cannot be used as evidence for a motionless earth.

This is the opposite of the conclusion originally desired by Simplicius. Yet, having agreed to the mapping of ship onto earth, mast onto tower, and rock onto stone, and to the carryover of relational structure, Simplicius must take the inference seriously. The rules of analogical mappings are such that, unless there is a principled reason to exempt a given predicate, it must be mapped if it belongs to the system.

Galileo's use of analogy fits well with the structure-mapping description. Having explicated the object-correspondences and relational identities clearly, he then derives new predictions by mapping further relationships from the base to the target. We will next compare it with a literary metaphor of Eliot's in order to bring out its structural characteristics.

Galileo's analogy compared with an analogy from Eliot. Consider a very different kind of metaphor, an expressive analogy from T. S. Eliot's The Hollow Men:

"Leaning together
Headpiece filled with straw. Alas!
Our dried voices, when
We whisper together

Are quiet and meaningless
As wind in dried grass
Or rats' feet over broken glass
In our dry cellar."

Like Galileo's analogy, Eliot's metaphor is a nonliteral comparison between a pair of domains, involving object mappings and relational carryover. Galileo's analogy maps ship to earth, mast to tower, and rock to stone. Eliot's analogy maps dried grass and/or rats' feet to voices. Yet there seem to be differences. To begin with, the expressive analogy seems more sensuous--in our terms, more rich, particularly in attribute information. In Galileo's ship-earth comparison the shape of the ship, its color, its smell, its texture are stripped from the mapping. Only some of the causal and spatial relationships--the perpendicular vertical relationship of mast to ship, the motion of the ship relative to the medium, and so on--are preserved. By contrast, in Eliot's lines, a great many sensory attributes--the dry feel, the rustling sounds, the bleached colors--of the dried grasses, broken glass, and rats' feet are menat to be invoked. Eliot's analogy is probably richer, in terms of having more predicates mapped, than Galileo's. Gallileo's analogy, which focuses on a small number of higher-order relations, is more abstract.

Base specificity seems roughly comparable in the two analogies; both analogies make use of familiar base domains. Yet the two analogies differ considerably with respect to charity. The Galileo example is quite high in clarity. The correspondence between the elements of the base and the elements of the target is plainly laid out, and the object correspondences are 1-1 mappings, with no disjunctive mappings. Since every base node maps unambiguously onto a target node, the set of potentially mappable relations is clear. Clarity is conspicuously lower in the Eliot poem. The richness of the context leaves us unclear as to exactly which aspects of the base domains enter into the comparison. A particularly straightforward suspension of the clarity principle is the treatment of the target node voices, which is given two different base objects as omparisons: wind in dried grass, rats' feet over broken glass. This n-to-1 mapping means that a maniacally precise reader would be frustrated in her attempt to decide exactly which predicates should map across to voices; should it be all the predicates from both wind and rats' feet? If so there will be contradictions, for wind and rats' feet can participate in very different relationships. Should the reader map only some of the possible predicates from each of these base terms? If so, which ones? Of course, such a ferocious attitide on the part of the reader would be to miss the point. The multiply related terms in the Eliot poem interact with each other and with the passage to produce a rich web of connections. Precisely defining these relationships does not seem to be important or even appropriate; they are intended to be appreciated without too much analysis.

Systematicity provides another difference between these analogies. Galileo's analogy, while not as systematic as the mathematical version of Rutherford's atom/solar system analogy, is moderately systematic. There are local sets of mutually constraining predicates, as shown in Figure 3. For example, the PART OF relation between top of mast and ship can be used to infer that MOVE (ship) implies MOVE (top of mast). In contrast, the Eliot analogy is quite low in systematicity, partly by virtue of its lack of clarity and partly because there are a great many connective relationships between hollowness/stuffing/straw/dry grass/dry cellars/rats' feet and so on, which seem to enter into the mapping, but which cannot easily be spelled out.

These contrasts suggest some possible structural differences between expressive and explanatory analogy. The first of these lies in the relative values placed on richness versus clarity in the predicate structure. In expressive analogy there may be greater value in richness--in the sheer number and density of relationships conveyed--than in ensuring that all the mappings are clear and consistent. There may be greater emphasis on clarity in explanatory analogy. These contrasts also suggest a difference in abstractness: in the kinds of predicates mapped, aside from the sheer density of predicates and the clarity of the mapping. It may be that surface sensory attributes figure more strongly in expressive analogies than in explanatory analogies, so that their abstractness will in general be lower.

Finally, systematicity may be more valued in explanatory analogy.

The suggestion, then, is that in expressive analogy, a rich collection of associations is valued; while in explanatory analogy, an abstract, well-clarified, coherent system of relations is valued. This fits with Boyd's (1979) observation that for science analogies, further explication and analysis is taken as a community enterprise, while literary metaphors are often treated as wholes, their dissection left to critics, rather than being part of the writer's enterprise.

Notice that an unweighted validity check--that is, a simple average of the validity of all the base predicates as applied in the target--would not be a good differentiator between these two analogies. Both kinds of analogy include invalid as well as valid potential predicate-mappings. (For example, Galileo worries about the fact that the ships' motion is artificially caused while the earth's motion is natural; and as mentioned earlier, not all of the spatial relations in the ship domain are valid in the earth domain.

An analogy from Shakespeare. Literary metaphors differ in clarity. Any attempt to generalize about expressive versus explanatory analogy must take into account writers like Shaekspeare and Donne, whose analogies are often elegantly worked out. As our fourth example we will consider Shakespeare's comparison:

But, soft! what light through yonder window
  breaks?
It is the east, and Juliet is the sun! -
Arise, fair sun, and kill the envious moon,
Who is already sick and pale with grief,
That thou her maid art far more fair than she:
Be not her maid, since she is envious;
Her vestal livery is but sick and green,
And none but fools do wear it; cast it off. -
    (Romeo and Juliet, Act II, Scene 1)

It is immediately clear that this analogy is fairly abstract, and not meant to convey low-level sensory attributes. It does not lead us to assume that Juliet is hot and gaseous, for example, nor large, nor yellow in color. It is primarily relationships that are conveyed: the spatial relation of Juliet appearing above the window, as the sun rises above the eastern horizon, and the affective relations of her causing hope and gladness in Romeo as the sun causes them in earthly creatures.

Locally, clarity is fairly high: the sun maps to Juliet, the window to the horizon, and so on. However, the passage goes on to shift the set of mappings. The target system remains Juliet and the moon, but the base shifts from the sun and moon to maid and mistress. Juliet is now the maid of an inferior mistress (the moon) and is urged to cast off her servant's costume. The mapped relationship between Juliet and the moon thus shifts from CAUSE (RISE (Juliet), DISAPPEAR (moon)), on the sun-moon based analgoy, to ENVY (moon, Juliet) and CAST OFF (Juliet, appearance (BELONG (moon, appearance))), based on the maid-mistress analogy. Thus in spite of the local clarity and a fair degree of abstractness, large-scale clarity is not preserved here.[7]

Another difference is that none of the mappings here is high in systematicity; the mapped predicates do not strongly constrain one another. For example, in the maid-mistress domain the fact that a mistress envies her maid clearly need not necessarily imply that the maid should quit her post; there are many equally plausible possibilities. This lack of strong mutual constraints--i.e., a lack of systematicity--may be an important difference between literary and scientific analogy.

Summary of the structural differences between explanatory and expressive analogy. Though these comparisons are too few in number to be totally convincing, they suggest a set of structural differentiations between analogies intended for explication and prediction and analogies intended for description and evocation. Judging from these examples, explanatory analogies are high in clarity, abstractness, scope and systematicity, but not in richness. In the richness-clarity tradeoff, expressive analogies seem more committed to richness and less committed to clarity than explanatory analogies. Expressive analogies are unlikely to be systematic, or abstract, or high in scope (in the materialist sense of accounting for large numbers of general phenomena).

Experimental comparison of clarity and richness in explanatory vs. expressive analogies. To test for some of these hypothesized structural differences between scientific and literary analogy, we asked 20 subjects to rate scientific and literary metaphors for richness and for clarity. The metaphors included twenty scientific analogies and twenty literary analogies. Ten of the science analogies were, in the experimenters' opinion, good analogies. The other ten were poor analogies in use either currently or historically. The literary comparisons were similarly chosen to include ten good and ten poor analogies. Samples of the materials are shown in Table 1.

As a check on these assignments, half of the subjects rated the metaphors for scientific explanatory value, and the other half rated them for literary expressiveness. Table 2 shows the mean richness and clarity ratings for the four *a priori* classes of metaphor; good science, poor science, good literature and poor literature. The subjects' mean ratings of scientific explanatory value and literary expressiveness are also shown.

As predicted, the scientific and literary analogies ahve an almost opposite relationship to richness and clarity. For science analogies, good exemplars are rated both higher in clarity and lower in richness than poor exemplars. For literary metaphors, good exemplars are rated higher in richness and essentially the same in clarity as poor exemplars. This pattern fits with the prediction: clarity *must* be present in good explanatory analogy, and *may* be present in good expressive analogy. Or the other hand, richness contributes strongly to the goodness of expressive analogy, but not to explanatory analogy.

Table 1

Sample comparisons of different kinds showing subject's mean ratings of scientific explanatory value (S.E.V.), literary expressiveness (L.E.), clarity and richness

Comparisons	S.E.V.	L.E.	Clarity	Richness
Good Science				
An electric circuit is like a system of water flowing through pipes; the water is the current; the reservoir is like the power source, the dams are like resistors, the potential energy in the stored water is like the voltage in the circuit, and so on.	4.5	4.4	4.7	3.2
Echoes are like big balls of air that bounce off walls.	3.3	2.8	4.1	2.3
Good Literature				
With a light soul to cover him, this jolly fellow lives in fun, and sorrow and care blow over him like a breeze over a warm comforter.	2.7	3.7	2.9	3.0
In this mortal state of imperfection, fig leaves are as necessary for our minds as for our bodies; it is as indecent to show all we think as all we have.	2.7	4.6	4.0	3.9

Table 1- continued

Sample comparisons of different kinds showing subject's mean ratings of scientific explanatory value (S.E.V.), literary expressiveness (.L.E.), clarity and richness

Comparison	S.E.V.	L.E.	Clarity	Richness
Poor Science				
Forging a rare metal is like planting a garden. Seeds of metal are planted over a furnace within flasks, with a low fire beneath them, and are kept warm day and night. From these little eggs there will be produced enormous shining chicks.	1.9	2.4	2.6	2.7
In a marble statue, marble is the matter and the shape given by the sculptor is the form; similarily, in a calm sea, water is the matter and smoothness is the form. Only because of its form does matter become a thing.	2.8	2.9	3.5	3.6
Poor Literature				
Money is like an arm or a leg -- use it or lose it.	3.3	2.9	4.1	2.1
Any large company must be a changing company. You can't sink anything in concrete because that attitude will slowly seep through to all levels of the organization and all of a sudden you're lying dead in the water.	2.4	2.5	2.7	2.3

Table 2

Mean ratings of different qualities for different classes of metaphors

A priori classifications	Clarity	Richness	Scientific explanatory value	Literary expressiveness
Good science	3.87	2.42	3.53	3.22
Poor science	3.30	2.92	2.94	2.77
Good literature	3.41	3.42	2.91	3.35
Poor literature	3.52	2.76	2.93	2.94

These patterns are based on our _a priori_ judgments of literary and scientific goodness. We also correlated the subjects' own ratings of scientific explanatory value and literary expressiveness with their ratings of richness and clarity. The correlations show the same patterns as the _a priori_ analyses, except that clarity appears more important for literary goodness. Judgments of clarity correlate strongly and positively with judgments of scientific explanatory value ($r = .77$; $p < .0001$ F, two-tailed) and also with judgements of literary expressiveness ($r = .68$; $p < .0001$). Richness is not correlated with scientific explanatory value ($r = .16$; $p < .32$), but is correlated with literary expressiveness ($r = .42$; $p < .005$).

Our subjects found clarity important in judging the goodness of both expressive and explanatory analogies. Richness, however contributed only to literary expressiveness and not to explanatory value. Thus our expectation that clarity should be important in science analogies was confirmed, as was the expectation that richness would contribute only to literary expressiveness. The only unexpected result was the positive correlation between clarity and literary expressiveness. It may be that both richness and clarity are desirable in expressive analogy, when possible, and that our materials did not force subjects to choose. (We did not include any literary metaphors as rich and low in clarity as Eliot's example.) Further research may reveal exactly how these considerations interact.

Good and bad explanatory analogies. These contrasts between good explanatory analogies and literary analogies may help answer the question of how poor explanatory analogies differ from good ones. Of course, there are always many ways to be a bad exemplar of anything. Still, there are many instances of poor explanatory analogy that seem to show some of the same characteristics that differentiate expressive from explanatory analogies. Consider this example from the alchemist and healer Paracelsus, writing within a century of Kepler and Galileo:

> ... what, then, is the short and easy way whereby Sol (gold) and Luna (silver) can 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 it on 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 the earth. Keep it. It is Sol and Luna.

(Paracelsus, ca 1530, quoted in Jaffe, 1976, p. 23)

The first thing one notices about this analogy is its air of mystery. Although the base domain is the solar system (including earth's moon and excluding then-unknown planets), and a standard, known set of correspondences was used - e.g., Sol/gold; Luna/silver; Saturn/lead - these do not lead to a clear predictive model. Why? One reason is the lack of clarity in the basic object-mappings, manifested, for example, in the interchangeability of "heaven", "the sphere of Saturn" and "Saturn". These comprise a disjunctive triad of base nodes like Eliot's pair "rats' feet"/"wind in dried grass" that results in an indeterminate mapping.

A second reason for the nonpredictive quality of this analogy is its lack of systematicity. Even though the base domain is the solar system, the relations invoked are not the set of spatial-causal relations used in the Rutherford analogy, even as known at the time. Instead of using a mutually constraining system of base relationships Paracelsus applies new relations: e.g., "PLACE ON (heaven, all the planets)"; "MAKE RUN OVER (heaven, earth)". Even if these predicates had unambiguous interpretations, and even if the analogy were clear enough to allow their application, they are not part of an existing connected system of relations in the base and therefore they supply no mutual constraints. The solar system predicates that do figure in the analogy are chiefly the object-attributes of the heavenly bodies; yellow color, for example, maps from Sol (the sun) onto gold. Indeed, Paracelsus's solar system analogy represents almost the opposite set of correspondences from Rutherford's, which drew primarily upon abstract predicates.

On the other hand, Paracelsus's analogy is quite rich, partly because the analogy includes psycho-spiritual predicates such as corruptible as well as physical predicates from the solar system. However, this mix of different kinds of predicates lowers base specificity; it is not clear, at a given moment, whether we are mapping from the solar system as a physical domain or as a celestial-spiritual domain.

Of course, this lack of clarity and specificity may result in part from an understandable desire for obfuscation giving a recipe for producing gold and silver from base metals. But a deeper factor is that the alchemists' worldview did not separate physical processes from psychospiritual processes.

A more modern example of unclarified analogy is Freud's (1973; reprinted from 1955) discussion of anal-eroticism, in which it is claimed that, in unconscious thought, the concepts of feces (money, gift), baby and penis are often treated "as if they were equivalent and could replace one another freely" (1973, p. 86). The case for this correspondence includes linguistic evidence: the phrase "to give someone a baby," showing the correspondence between babies and gifts; phenomenological evidence that feces are the infant's first gift, and that money, as a later gift, comes to be equated with feces; and evidence from shared attributes and first-order relations, such as that feces, penis and baby are all solid bodies that forcibly enter or leave through a membranous passage.

Since there are _five_ corresponding objects, any of whose attributes and relations can be mapped across to any of the others, this analogy is markedly lacking in clarity. The fluidity of the predictions is heightened by the large number of interconnections among the entities. One can shift around among the several object mappings with their rich assortment of predicates to accommodate many disparate phenomena. Of course, Freud meant this set of correspondences to reflect the illogic of the unconscious. But his followers have often failed to make a distinction between a theory _about_ an unclarified thought process and a theory that is itself unclarified.

The analogies of Paracelsus and Freud are lacking in clarity relative to the explanatory analogies of Galileo and Rutherford. This lack of clarity guarantees a lack of systematicity, since in order for predicates to constrain one another, it has to be absolutely clear which predicates are mapped in the first place. On the other hand, the analogies of Paracelsus and Freud are far richer than those of Galileo and Rutherford. Their lack of clarity and systematicity in fact contributes to their richness, for no possible mapping need be ruled out. Mutually contradictory inferences can co-exist. These analogies derive much of their appeal from their richness. Even their lack of systematicity, though it prevents making strict predictions, does not necessarily diminish the aesthetic appeal of these analogies. Indeed, the presence of conflicting inferences can contribute to a feeling of challenging paradox.

These analogies seem, then, to have many of the qualities of literary metaphor. They have opted for a rich, thick, relationally idiosyncratic structure, rather than for the strict simplicity of a scientific analogy. Such a metaphor can be a good artistic metaphor, capable of reverberating in interesting ways, of suggesting new associations, and of being called forth in many different situations. It may well lead to new understandings. What it will not do is make the kind of strong new predictions of a well-clarified analogy. (I emphasize new because when predictions are derived from fuzzy analogies, they are often in remarkably close accord with our a priori intuitions.) Only a well-clarified analogy possesses a firm enough predicate structure to force a new and surprising prediction.

Conclusions

I have argued here that complex analogies can be psychologically characterized as structure-mappings between propositionally represented domains. This framework allows us to state structural distinctions that differentiate good explanatory-predictive analogy from other kinds of metaphor.

This structural characterization is certainly incomplete as it stands, and is itself in need of further clarification. But the avenues toward clarification are open: better psychological representations of the participating domains, more detailed analysis of the analogies used by experts and by novices in science, and more attention to the processes of interpreting different kinds of metaphors.

The answer to the initial question "are scientific analogies metaphors?" appears to be "yes and no." Yes, in that scientific analogy and literary metaphor are more alike than different: they share many of the same structure-mapping processes. But according to thischaracterization, there are important, regularly occurring structural differences: explanatory analogies are typically higher in clarity, abstractness, systematicity, and base specificity and lower in richness than expressive analogies.

These differences raise a number of interesting questions. One application is in characterizing the naive mental models people have about physical phenomena. Our investigations so far indicate that these mental models, like the alchemists' analogies, are more concrete and less clarified than the analogies used by our expert subjects (Collins, Stevens & Brown, 1979; Collins, Stevens & Goldin, 1979; Gentner & Collins, in preparation). This opens intriguing possibilities for further research. For example, do the models of novices develop into those of experts in stages that parallel the historical evolution of the topic area? What about expert scientists who appear to use models successfully? Do they merely possess a set of useful analogies in their own areas of expertise, or do they also have knowledge of general modelling rules?

Finally, what is the course of development of a scientific analogy? Do analogies begin rich and unclarified, so that they require pruning and clarification to become good explanatory analogies? There are indications that this is at least one possible course of development. Accounts of great creators like Kepler, Maxwell, Poincaré and Feynman make it clear that they entertained initially unruly analogies. In the same vein, Polya's advice to those who wish to develop mathematical insight is "And, remember, do not neglect vague analogies. Yet if you wish them respectable, try to clarify them." (Polya, 1973, p. 11). Indeed, it may well be that it is precisely in the process of turning an initially vague, rich, multipurpose feeling of analogy into a well-clarified model that much of the creative process in science takes place.

References

Bobrow, D.G. Dimensions of representation. In D.G. Bobrow & A. Collins (Eds.), Representation and understanding: Studies in Cognitive Science. New York: Academic Press, 1975.

Boyd, R. Metaphor and theory change: What is "metaphor" a metaphor for? In A. Ortony (Ed.), Metaphor and thought. Cambridge, England: Cambridge University Press, 1979, 356-408.

Brown, J.S., & Burton, R.R. Multiple representations of knowledge for tutorial reasoning. In D.G. Bobrow & A. Collins (Eds.), Representation and understanding. New York: Academic Press, 1975.

Brown, J.S., Collins, A., & Harris, G. Artificial intelligence and learning strategies. In H.F. O'Neil (Ed.), Learning strategies. New York: Academic Press, 1978.

Cavendish, R. The black arts. New York: Capricorn Books, 1967.

Collins, A.M., Stevens, A.L., & Brown, J.S. Multiple conceptual models of a complex system. Journal of Man-Machine Studies, 1979, in press.

Collins, A.M., Stevens, A.L., & Goldin, S. Misconceptions in student's understanding. International Journal of Man-Machine Studies, 1979, 11, 145-156.

deKleer, J. Multiple representations of knowledge in a mechanics problem solver. In the Proceedings of the Fifth International Joint Conference on Artificial Intelligence. Cambridge, Ma.: MIT, 1977, 299-304.

Freud, S. On transformations of instinct as exemplified in anal eroticism. In J. Strachey (Ed.), The standard _edition of the complete psychological words of Sigmund Freud_, Vol. XVII. London, The Hogarth Press Ltd. and the Institute of Psycho-Analysis, 1955. Reprinted in H.N. Mischel and W. Mischel (Eds.), _Readings in Personality_. New York: Holt, Rinehart & Winston, Inc., 1973, pp. 85-89.

Galileo. Dialogue concerning the two chief world systems - Ptolemaic and Copernican, published 1629; translated by S. Drake. Berkeley: University of California Press, 1967.

Gentner, D. Children's performance on a spatial analogies task. _Child Development_, 1977, _48_, 1034-1039.

Gentner, D. If a tree had a knee, where would it be? Children's performance on simple spatial metaphors. _Papers and Reports on Child Language Development_, 1977, _13_.

Gentner, D. & Collins, A.M. Mental models of physical systems. To appear in L. Talmy (Ed.), _Conceptual frameworks: A cross-disciplinary perspective_. In preparation.

Gentner, D. The structure of analogical models in science. BBN Report No. 4451, Cambridge, Mass.: Bolt Beranek and Newman Inc., 1980a.

Gentner, D. Metaphor as structure-mapping. Paper presented at the meeting of the American Psychological Association, Montreal, September 1980b.

Gick, M.L., & Holyoak, K.J. Analogical problem solving. _Cognitive Psychology_, in press.

Grudin, J. _Processes in verbal analogy solution_. _Human Perception and Performance_, 1980, in press.

Hesse, M.B. _Models and analogies in science_. Notre Dame, Indiana: University of Notre Dame Press, 1966.

Hoffman, R.R. Metaphor in science. In R.P. Honeck & R.R. Hoffman (Eds.), The psycholinguistics of figurative language. Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1980.

Jaffe, B. Crucibles: The story of chemistry. New York: Dover Publications, 1976.

Johnson-Laird, P.N. Mental models in cognitive science. Cognitive Science, 1980, 4, 71-115.

Lakoff, G., & Johnson, M. Metaphors we live by, in press.

Larkin, J.H. Problem solving in physics. Unpublished paper, Group in Science and Mathematics Education, Berkeley, California, 1977.

Larkin, K.M. An analysis of adult procedure synthesis in fraction problems. Cambridge, Ma.: Bolt Beranek & Newman Inc, 1978.

Miller, G.A. Images and models: Similes and metaphors. In A. Ortony (Ed.), Metaphor and thought. Cambridge, England: Cambridge University Press, 1979, 202-250.

Ortony, A. Beyond literal similarity. Psychological Review, 1979, 86, 161-180.

Ortony, A. The role of similarity in similes and metaphors. In A. Ortony (Ed.), Metaphor and thought. Cambridge, England: Cambridge University Press, 1979, 186-201.

Palmer, S.E. Fundamental aspects of cognitive representation. In E. Rosch & B.B. Lloyd (Eds.), Cognition and categorization. Hillsdale, New Jersey: Erlbaum Associates, 1978, 259-303.

Polya, G. Mathematics and plausible reasoning, Volume 1. Princeton, New Jersey: Princeton University Press, 1973.

Pylyshyn, Z. Metaphorical imprecision and the "top-down" research strategy. In A. Ortony (Ed.), Metaphor and thought. Cambridge, England: Cambridge University Press, 1979, 420-436.

Reif, F. Problem solving in physics or engineering: Human information processing and some teaching suggestions. American Society for Engineering Education, in press.

Rumelhart, D.E. Some problems with the notion of literal meaning. In A. Ortony (Ed.), Metaphor and thought. Cambridge, England: Cambridge University Press, 1979, 78-91.

Rumelhart, D.E., & Abrahamson, A.A. A model for analogical reasoning. Cognitive psychology, 1973, 5, 1-28.

Rumelhart, D.E., & Norman, D.A. The active structural network. In D.A. Norman, D.E. Rumelhart & the LNR Research Group, Explorations in Cognition. San Francisco: W.H. Freeman & Co., 1975.

Rumelhart, D.E., & Ortony, A. Representation of knowledge. In R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.), Schooling and the acquisition of knowledge. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1977.

Schank, R., & Abelson, R. Scripts, plans, goals, and understanding. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1977.

Schön, D.A. Generative metaphor: A perspective on problem-setting in social policy. In A. Ortony (Ed.), Metaphor and thought. Cambridge, England: Cambridge University Press, 1979, 254-283.

Searle, J.R. Metaphor. In A. Ortony (Ed.), Metaphor and thought. Cambridge, England: Cambridge University Press, 1979, 92-123.

Smith, B.C. Computational reflection. Doctoral dissertation, Electrical Engineering and Computer Science. M.I.T., in preparation.

Sternberg, R.J. Component processes in analogical reasoning. _Psychological review_, 1977, _84_, 353-378.

Sternberg, R.J., Tourangeau, R., & Nigro, G. Metaphor, induction, and social policy: The convergence of macroscopic and microscopic views. In A. Ortony (Ed.), _Metaphor and thought_. Cambridge, England: Cambridge University Press, 1979.

Tourangeau, R., & Sternberg, R.J. Understanding and appreciating metaphors. Technical Report No. 11, Department of Psychology, Yale University, June 1978.

Tversky, A. Features of similarity. _Psychological Review_, 1977, _84_, 327-352.

Verbrugge, R.R., & McCarrell, N.S. Metaphoric comprehension: Studies in reminding and resembling. _Cognitive psychology_, 1977, _9_, 494-533.

Footnotes

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2. An adequate discussion of literal similarity within this framework would require including a negative dependency on the number of <u>nonshared</u> features or predicates as well as the positive dependency on the number of shared predicates (Tversky, 1977). Tversky's valuable characterization of literal similarity does not utilize the relation-attribute distinction; all predicates are considered together, as "features." Whether the distinction is necessary for literal similarity remains to be seen.

3. Because of the hierarchical nature of schemata, there are two possible levels of object-attribution: that of the component objects that make up the system (e.g., "The sun is round."; "Electrons are tiny.") or that of the system taken as a single holistic object (e.g., "The solar system is a huge whirling disc.").

4. The assumption that predicates are brought across as identical matches is crucial to the clarity of this discussion. The position that predicates need only be similar between the base and the domain (e.g., Hesse, 1966; Ortony, 1979) leads to a problem of infinite regress, with similarity of surface concepts defined in terms of similarity of components, etc., I will assume instead that similarity can be restated as partial identity: that predicates can be decomposed into lower-level predicates, and that a high-level similarity match can be reformulated as an identity match among some number of the component predicates.

5. It might be thought that, as with mathematical functions, one-to-many mappings would be disallowed but many-to-one mappings would be allowed. But this is not the case. Analogical clarity is violated by any many-to-one or one-to-many mapping in which the many are relationally distinct. If they are relationally interchangeable, there is no problem. In the Rutherford model, where any of the nine planets can map onto the same electron, the many-to-one mapping poses no

problem in clarity, since the several objects in the base participate in the same relationships. Similarly, a one-to-many mapping is not a problem if there is no structural reason to distinguish among the several target objects. For example, the solar system could reasonably be mapped onto helium, even though there is ambiguity as to which of helium's two electrons a given planet maps into. This ambiguity does not reduce clarity because the target objects -- the two electrons -- are, in terms of this analogy, relationally identical. A reduction in clarity occurs only when the choice makes a relational difference.

6. Mathematical models represent an extreme of clarity and abstractness as well as an extreme of base specificity. The set of mappable relations is strongly constrained, and the rules for concatenating relationships are well-specified. Once we choose a given mathematical system as base, we know thereby which combinatorial rules apply to relations in the base. This enormously simplifies the process of deriving new predictions to test in the target. We know, for example, that if the base relations are addition (R_1) and multiplication (R_2) over the integers, then we can expect distributivity to hold: (c(a+b) = ca + cb, or

$$R_2 [c, R_1 (a,b)] = R_1[R_2 (c,a) , R_2(c,b)]$$

A mathematical model tends to predict a small number of relational types, which are well-specified and systematic enough to be concatenated into long chains of prediction.

7. I hope it is understood that I am not accusing Shakespeare or Eliot of simple-mindedness; indeed in this particular case the shifting metaphors may help convey Romeo's agitation. The point is simply that expressive analogies can fulfill their function without being clear and systematic, whereas explanatory analogies cannot.

8. These remarks are aimed only at multiply-directed undifferentiated analogies. The use of multiple separate analogies, with known points of interaction, can be an extremely powerful technique. Expert problem-solvers, for example, often use one method of solution to check another. But for this to work, the two models must be differentiated between the checkpoints.

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