The Copycat Project: A Model of Mental Fluidity and Analogy-Making*

Douglas R. Hofstadter
Melanie Mitchell

1. COPYCAT AND MENTAL FLUIDITY

1.1. Analogy Problems in the Copycat Domain

Copycat is a computer program designed to be able to discover insightful analogies, and to do so in a psychologically realistic way. Copycat's architecture is neither symbolic nor connectionist, nor a hybrid of the two; rather, the program has a novel type of architecture situated somewhere in between these extremes. It is an *emergent* architecture, in the sense that its top-level behavior emerges as a statistical consequence of myriad small computational actions, and the concepts that it uses in creating analogies can be considered to be a realization of "statistically emergent active symbols" (Hofstadter, 1985). The use of parallel, stochastic processing mechanisms and the implementation of concepts as distributed and probabilistic entities in a network make Copycat somewhat similar in spirit to connectionist systems. However, as will be seen, there are important differences, and we claim that the middle ground in cognitive modeling occupied by Copycat is at present the most useful level at which to attempt to understand the fluidity of concepts and perception that is so clearly apparent in human analogy-making.

* We thank past and present members of the Fluid Analogies Research Group, and in particular, Robert French, for contributions to the Copycat project. This research has been supported by grants from the National Science Foundation (Grant OCR 8410409); the University of Michigan; Mitchell Kapor. Ellen Poss, and the Lotus Development Corporation; Apple Computer, Inc.; and Indiana University. The second author also thanks the Michigan Society of Fellows for its support.

The domain in which Copycat discovers analogies is very small but surprisingly subtle. Not to beat around the bush for a moment, here is an example of a typical, rather simple analogy problem in the domain:

1. Suppose the letter-string **abc** were changed to **abd;** how would you change the letter-string **yk** in "the same way"?

Note that the challenge is essentially "Be a copycat"—that is, "Do the same thing as I did," where "same" of course is the slippery term. Almost everyone answers **yl.**[1] It is not hard to see why; most people feel that the natural way to describe what happened to **abc** is to say that *the rightmost letter was replaced by its alphabetic successor;* that operation can then be painlessly and naturally "exported" from the **abc** framework to the other framework, namely ijk, to yield the answer **yl.** Of course this is not the only possible answer. For instance, it is always possible to be a "smart aleck" and to answer **ijd** (rigidly choosing to replace the rightmost letter by d) or **yk** (rigidly replacing all c's by d's) or even **abd** (replacing the whole structure blindly by **abd),** but such "smart-alecky" answers are suggested rather infrequently, and when they are suggested, they seem less compelling to virtually everybody, even to the people who suggested them. Thus, **yl** is a fairly uncontroversial winner among the range of answers to this problem.

There is much more subtlety to the domain than that problem would suggest, however. Let us consider the following closely related, but considerably more interesting analogy problem:

2. Suppose the letter-string **aabc** were changed to **aabd;** how would you change the letter-string **ykk** in "the same way"?

Here, as in Problem 1, most people look upon the change in the first framework as *the rightmost letter was replaced by its alphabetic successor.* Now comes the tricky part: should this rule simply be transported rigidly to the other framework, yielding **y"kl?** Although rigid exportation of the rule worked in Problem 1, here it seems rather crude to most people, because it ignores the obvious fact that the k is doubled. The two k's together seem to form a natural unit, and so it is tempting to change *both* of them, yielding the answer **y'H.** Using the old rule literally will simply not give this answer; instead, under pressure, one "flexes" the old rule into a very closely related one, namely *replace the rightmost group by its alphabetic successor.* Here, the concept *letter* has "slipped," under pressure, into the related concept *group of letters.* Coming up with such a rule and corresponding answer is a good example of human mental

[1] Though the popularity of this answer can easily be predicted by one's intuition, we have carried out many surveys, both formal and informal, of people's answers to this and other problems. The **results of** toe formal surveys are given in Mitchell (1993).

fluidity (as contrasted with the mental rigidity that gives rise to **ykl).** There is more to the story of Problem 2, however.

Many people are perfectly satisfied with this way of exporting the rule (and the answer it furnishes), but some feel dissatisfied by the fact that the doubled **a** in **aabc** has been ignored. Once one focuses in on this consciously, it jumps to mind easily that the aa and the **kk** play similar roles in their respective frameworks. From there it is but a stone's throw to "equating" them (as opposed to equating the c with the kk), which leads to the question, "What then is the counterpart of the c?" Given the already-established mapping of *leftmost* object (aa) onto *rightmost* object (kk), it is but a small leap to map *rightmost* object (c) onto *leftmost* object (i). At this point, we could simply take the successor of the i, yielding the answer **jjkk.**

However, few people who arrive at this point actually do this; given that the two crosswise mappings (aa <=> kk, c O i) are an invitation to read **ijkk** in reverse, which reverses the alphabetical flow in that string, most people tend to feel that the conceptual role of alphabetical *successorship* in **abcc** is now being played by that of *predecessorship* in **ijkk.** In that.case, the proper modification of the i would not be to replace it by its successor, but by its alphabetical *predecessor,* yielding the answer **hjkk.** And indeed, this is the answer most often reached by those people who consciously try to take into account *both* of the doubled letters. Such people under pressure, have flexed the original rule into this variant of itself: *replace the <u>leftmost</u> letter by its alphabetic <u>predecessor.</u>* Another way of saying this is that a very fluid transport of the original rule from its home framework to the new one has taken place; during this transport, two concepts "slipped," under pressure, into neighboring concepts: *rightmost* into *leftmost,* and *successor into predecessor.* Thus, being a copycat—that is, "doing the same thing"—has proven to be a very slippery notion, indeed.

1.2. Mental Fluidity: Slippages Induced by Pressures

Hopefully, the pathways leading to these two answers to Problem 2—**ц!1** and **hjkk**—convey a good feeling for the term "mental fluidity." There is, however, a related notion used above that still needs some clarification, and that is the phrase "under pressure." What does it meant to say "concept A *slips* into concept B *under pressure" 1* It might help to spell out the intended imagery behind these terms. An earthquake takes place when subterranean structures are under sufficient pressure that something suddenly slips. Without the pressure, obviously, there would be no slippage. An analogous statement holds for pressures bringing about conceptual slippage: only under specific pressures will concepts slip into related ones. For instance, in Problem 2, pressure results from the doubling of the a and the k; one could look upon the doubling as an "emphasis" device, making the left end of the first string and the right end of the second one stand out and in some sense "attract" each other. In Problem 1, on the other hand, there is nothing to suggest mapping the a onto the k—no pressure. In the absence of such pressure, it would make no sense at all to slip *leftmost* into *rightmost* and then to read **ijk** in reverse, which would in turn suggest a slippage of *successor* into *predecessor,* all of which would finally lead to the downright bizarre answer **hjk.** That would be *unmotivated* fluidity, which is not characteristic of human thought.

Copycat is a thoroughgoing exploration of the nature of mental pressures, the nature of concepts, and their deep interrelationships, focusing particularly on how pressures can engender slippages of concepts into "neighboring" concepts. When one ponders these issues, many questions arise, such as the following: What is meant by "neighboring concepts"? How much pressure is required to make a given conceptual slippage likely? Just how big a slippage can be made—that is, how far apart can two concepts be and still be potentially able to slip into each other? How can one conceptual slippage create a new pressure leading to another conceptual slippage, and then another, and so on, in a cascade? Do some concepts resist slippage more than others? Can particular pressures nonetheless bring about a slippage of such a concept while another concept, usually more "willing" to slip, remains untouched? Such are the questions at the very heart of the Copycat project.

1.3 The Intended Universality of Copycat's Microdomain

This project, which sprang out of two predecessors, Seek-Whence (Meredith, 1986, 1991) and Jumbo (Hofstadter, 1983), has been under development since 1983 (see Hofstadter, 1984a, for the first detailed description of the project). A casual glance at the project might give the impression that since it was specifically designed to handle analogies in a particular tiny domain, its mechanisms are not general. However, this would be a serious misconception. All the features of the Copycat architecture were in fact designed with an eye to great generality. A major purpose of this article is to demonstrate this generality by describing the features of Copycat in very broad terms, and to show how they transcend not just the specific microdomain, but even the very task of analogy-making itself. That is, the Copycat project is not about simulating analogy-making per se, but about simulating the very crux of human cognition: fluid concepts. The reason the project focuses upon analogy-making is that analogy-making is perhaps the quintessential mental activity where fluidity of concepts is called for, and the reason the project restricts its modeling of analogy-making to a specific and very small domain is that doing so allows the general issues to be brought out in a very clear way—far more clearly than in a "real-world" domain, despite what one might think at first.

Copycat's microdomain was designed to bring out very general issues—issues that transcend any specific conceptual domain. In that sense, the microdomain was designed to "stand for" other domains. Thus, one is intended to conceive of, say, the *successor (or predecessor)* relation as an idealized version of *any* nonidentity relationship in a real-world domain, such as "parent of," "neighbor of," "friend of," "employed by," "close to," etc. A *successor group* (e.g., **abc)** then plays the role of any conceptual chunk based on such a relationship, such as "family," "neighborhood," "community," "workplace," "region," etc. Of course, inclusion of the notion of *sameness* needs no defense; sameness is obviously a universal concept, much as is *opposite.* Although any real-world domain clearly contains many more than two basic types of relationship, two already suffice to make an inexhaustible variety of structures of arbitrary complexity.

Aside from the idealized repertoire of *concepts* in the domain, there are also the *structures,* such as **ijkk,** out of which problems are made. In particular, allowed structures are linear strings made from any number—usually a small number—of instances of letters of the alphabet. Thus, one immediately runs into the *type/token distinction,* a key issue in understanding cognition. The alphabet can be thought of as a very simple "Platonic heaven" in which exactly 26 letter *types* permanently float in a fixed order; in contrast to this, there is a very rudimentary "physical world" in which any number of letter *tokens* can temporarily coexist in an arbitrary one-dimensional juxtaposition. In this extremely simple model of physical space, there are such physical relationships and entities as *left neighbor, leftmost edge, group of adjacent letters,* and so on (as contrasted with such relationships and entities in the Platonic alphabet as *predecessor, alphabetic starting-point, alphabetic segment,* etc.). Both the Platonic heaven and the physical world of Copycat are very simple on their own; however, the psychological processes of perception and abstraction bring them into intimate interaction, and can cause extremely complex and subtle mental representations of situations to come about.

Copycat's alphabetic microworld is meant to be a tool for exploring general issues of cognition rather than issues specific to the domain of letters and strings, or domains restricted to linear structures with precise distances in them. Thus, certain aspects specific to people's knowledge of letter strings—such as shapes, sounds or connotations, or words that strings of letters might happen to form—haVe not been included in this microworld. Moreover, problems should not depend on arithmetical facts about letters, such as the fact that t comes exactly 11 letters after i, or that m and η flank the midpoint of the alphabet. Arithmetical facts, while they are universal truths, are not common enough in analogy-making to be worthwhile modeling. This may seem to eliminate almost everything about the alphabet, but as Problems 1 and 2 show (and further problems will show even better), there is still plenty left to play with. Reference to the alphabet's *local* structure is fine; for example, it is perfectly legitimate to exploit the fact that u comes immediately after t. It is also legitimate to exploit the fact that the Platonic alphabet has two distinguished members—namely, a and z, its starting and ending points. Likewise, inside a string such as **hagizk,** local relationships such as "the g is the right neighbor of the a," can be noticed, but long-distance observations, such as "the a is four letters to the left of the k," are considered out of bounds.

Although arithmetical operations such as addition and multiplication play no role in the Copycat domain, numbers themselves—small whole numbers, that is—are included in the domain. Thus, Copycat is capable of recognizing not only that the structure fgh is a successor group," but also that it consists of *three* letters. Just as the program knows the immediate neighbors of every letter in the alphabet, it also knows the successors and predecessors of small integers. Under the appropriate pressures, Copycat can even treat small integers as it does letters—it can notice relationships between numbers, group numbers together, map them onto each other, and so on. However, generally speaking, Copycat tends to resist bringing numbers into the picture, unless there seems to be some compelling reason to do so—and *large* numbers, such as five, are resisted even more strongly. The idea behind this is to reflect the relative ease humans have of recognizing pairs and perhaps trios of objects, but the relative insensitivity to such things as quintuples, let alone septuples and so on.

Finally, while humans tend to scan strings of roman letters from left to right, are much better at recognizing forwards alphabetical order than backwards alphabetical order, and have somewhat greater familiarity with the beginning of the alphabet than its middle or end, the Copycat program is completely free of these biases. This should not be regarded as a defect of the program, but a strength, because it keeps the project's focus away from domain-specific and nongeneralizable details.

1.4. A Perception-Based, Emergent Architecture for Mental Fluidity

When one describes the Copycat architecture in very abstract terms, the focus is not only on how it discovers mappings between situations, but also on how it perceives and makes sense of the miniature and idealized situations which with it is presented. The present characterization will therefore read very much like a description of a computer model *ofperception.* This is not a coincidence; one of the main ideas of the project is that even the most abstract and sophisticated mental acts deeply resemble perception. In fact, the inspiration for the architecture comes in part from a computer model of low-level and high-level auditory perception: the Hearsay II speech-understanding project (Erman, Hayes-Roth, Lesser, & Reddy, 1980).

The essence of high-level perception is the awakening from dormancy of a relatively small number of prior concepts—precisely the relevant ones. The essence of understanding a situation is very similar; it is the awakening from dormancy of a relatively small number of prior concepts—again, precisely the relevant ones—and applying them judiciously so as to identify the key entities, roles, and relationships in the situation. Creative human thinkers manifest an exquisite selectivity of this sort—when they are faced with a novel situation, what bubbles up from their unconscious and pops to mind is typically a small set of concepts that "fit like a glove," without a host of extraneous and irrelevant concepts being consciously activated or considered. To get a computer model of thought to exhibit this kind of behavior is a great challenge.

The remainder of this chapter is structured as follows. Section 2 is a description of the three main components of the architecture and their interactions. Section 3 deals with the notion of conceptual fluidity and shows how this architecture implements a model, albeit rudimentary, thereof. Section 4 tackles the seeming paradox of randomness as an essential ingredient of mental fluidity and intelligence. Section 5 views the Copycat program at a distance, summarizing thousands of runs on a few key problems in the letter-string microworld. Section 6 affords a close-up view of Copycat's workings, describing in detail the pathways followed by Copycat as it comes up with subtle answers to two particularly challenging analogy problems. Section 7 compares Copycat with selected other computer models of analogy-making, and discusses Copycat's position along the symbolic/subsymbolic spectrum. Section 8 concludes the article with a discussion of the generality of Copycat's mechanisms.

2. THE THREE MAJOR COMPONENTS OF THE COPYCAT ARCHITECTURE

There are three major components to architecture: the Slipnet, the Workspace, and the Coderack. In very quick strokes, they can be described as follows:

1. The Slipnet is the site of all *permanent Platonic concepts.* It can be thought of, roughly, as Copycat's long-term memory. As such, it contains only concepts *types,* and no instances of them. The distances between concepts in the Slipnet can change over the course of a run, and it is these distances that determine, at any given moment, what slippages are likely and unlikely.
2. The Workspace is the locus of *perceptual activity.* As such, it contains *instances* of various concepts from the Slipnet, combined into *temporary perceptual structures.* It can be thought of, roughly, as Copycat's short-term memory or working memory, or, to borrow a term from Hearsay II, itSj "blackboard."
3. Finally, the Coderack can be thought of a "stochastic waiting room," in which small agents who wish to carry out tasks in the Workspace wait to be called. It has no close counterpart in other architectures, but one can liken it somewhat to an *agenda* (a queue containing tasks to be executed in a specific order). The critical difference is that agents are selected *stochastically* from the Coderack, rather than in a determinate order. The reasons for this initially puzzling feature will be spelled out and analzyed in detail below. They turn out to be at the crux of mental fluidity.

We now shall go through each of the three components once again, this time in more detail. (The finest level of detail—complete lists of algebraic formulas, numerical parameters, and their exact values—is not given here, but can be found in Mitchell, 1993.)

2.1. The Slipnet—Copycat's Network of Platonic Concepts

The basic image for the Slipnet is that of a network of interrelated concepts, each concept being represented by a *node* (caveat: what a concept is, in this model, is actually a bit subtler than just a pointlike node, as will be explained shortly), and each conceptual relationship by a *link* having a numerical length, representing the "conceptual distance" between the two nodes involved. The shorter the distance between two concepts is, the more easily pressures can induce a slippage between them.

The Slipnet is not static; it dynamically responds to the situation at hand as follows. Nodes *acquire* varying levels of activation (which can be thought of as a measure of relevance to the situation at hand), *spread* varying amounts of activation to neighbors, and over time *lose* activation by decay. In sum, the perceived relevance of each concept is a sensitive, time-varying function of the way the program currently understands the situation it is facing.

In addition, conceptual links in the Slipnet adjust their lengths dynamically. Thus, conceptual distances gradually change under the influence of the evolving perception (or conception) of the situation at hand, which of course means that the current perception of the situation enhances the chance of certain slippages taking place, while rendering that of others more remote.

Each node in the Slipnet has one very important static feature called its *conceptual depth.* This is a number intended to capture the generality and abstractness of the concept. For example, the concept *opposite* is deeper than the concept *successor,* which is in turn deeper than the concept a. It could be said roughly that the depth of a concept is how far that concept is from being directly perceivable in .situations. For example, in Problem 2, the presence of instances of a is trivially perceived; recognizing the presence of *successorship* takes a little bit of work; and recognition of the presence of the notion *opposite* is a subtle act of abstract perception. The further away a given aspect of a situation is from direct perception, the more likely it is to be involved in what people consider to be the *essence* of the situation. Therefore, once aspects of greater depth are perceived, they should have more influence on the ongoing perception of the situation than aspects of lesser depth.

Assignment of conceptual depths amounts to an *a priori* ranking of "best-bet" concepts. The idea is that a deep concept (such as *opposite}* is normally relatively hidden from the surface and cannot easily be brought into the perception of a situation, but that once it *is* perceived, it should be regarded as highly significant. There is, of course, no guarantee that deep concepts will be relevant in any particular situation, but history has demonstrated that such concepts crop up over and over again across many different types of situations, and that the best insights come when deep concepts "fit" naturally. There is thus built into the architecture a strong drive, if a deep aspect of a situation is perceived, to try to use this aspect in constructing an overall understanding of the situation.

Note that the hierarchy defined by different conceptual-depth values is quite distinct from abstraction hierarchies such as

poodle=> dog =>*mammal* =>*animal* => *living thing*=> *thing.*

These terms are all potential descriptions of a particular object at different levels of abstraction. By contrast, the terms a, *successor,* and *opposite* are not descriptions of one particular object in Problem 2, but of different aspects of that situation, at different levels of abstraction.

Likewise, conceptual depth is not the same as Centner's notion of "abstractness" (Centner, 1983). In Centner's theory, attributes (e.g., "the leftmost letter has value a") are invariably less abstract than relations (e.g., "the next-to-leftmost letter is the successor of the leftmost letter"), which are in turn invariably less abstract than relations between relations (e.g., *"successor* is the opposite of *predecessor").* This heuristic, based on syntactic structure, often agrees with our conceptual-depth hierarchy, but in Copycat certain "attributes" are considered to be conceptually deeper than certain "relations"—for example, *alphabetically first* has a greater depth than *successor* because we consider the former to be less directly perceivable than the latter. For further comparisons with Centner's work, see Section 7.

Conceptual depth has a second important aspect—namely, the deeper a concept is, the more resistant it is (all other things being equal) to slipping into another concept. In other words, there is a built-in propensity in the program to prefer slipping shallow concepts rather than deep concepts, when slippages have to be made. The idea of course is that insightful analogies tend to link situations that share a deep *essence,* allowing shallower features to slip if necessary. This basic idea can be summarized in a motto: "Deep stuff doesn't slip in good analogies." There are, however, interesting situations in which specific constellations of pressures arise that cause this basic tendency to be overriden.

Some details about the flow of activation include: (a) each node spreads activation to its neighbors according to their distance from it, with near neighbors getting more, distant neighbors less; and (b) each node's conceptual-depth value sets its *decay rate,* in such a way that deep concepts always decay slowly and shallow concepts decay quickly. This means that, once a concept has been perceived as relevant, then, the deeper it is, the longer it will remain relevant, and thus the more profound an influence it will exert on the system's developing view of the situation—as indeed befits an abstract and general concept likely to be close to the essence of the situation.

Some details about the Slipnet's dynamical properties include: (a) there are a variety of *link types,* and for each given type, all links of that type share the same *label;* (b) each label is itself a concept in the network; and (c) every link constantly adjusts its length according to the activation level of its label, with high activation giving rise to short, links, low activation to long ones. Stated another way: If concepts A and B have a link of type L between them, then as concept L's relevance goes up (or down), concepts A and B become conceptually closer (or further apart). Since this is happening all the time all throughout the network, the Slipnet is constantly altering its "shape" in attempting to mold itself increasingly accurately to fit the situation at hand. An example of a label is the node *opposite,* which labels the link between nodes *right* and *left,* the link between nodes *successor* and *predecessor,* and several other links. If the node *opposite* gets activated, these links will all shrink in concert, rendering the potential slippages they represent more probable.

The length of a link between two nodes represents the conceptual proximity or degree of association between the nodes: the shorter the link, the greater the degree of association, and thus the easier it is to effect a slippage between them. There is an implicit probabilistic "cloud" surrounding any node, which represents the likelihood of slippage to other nodes; the cloud's density is highest for near-neighbor nodes and rapidly tapers off for distant nodes. Neighboring nodes can be seen as being included in a given concept probabilistically, as a function of their proximity to the central node of the concept.

This brings us back to the caveat mentioned above. Although it is tempting to equate a concept with a pointlike node, a concept is better identified with this probabilistic "cloud" or halo *centered* on a node and extending outwards from it with increasing diffuseness. As links shrink and grow, nodes move into and out of each other's halos (to the extent that one can speak of a node as being "inside" or "outside" a halo). This image suggests conceiving of the Slipnet not so much as a hard-edged network of points and lines, but rather as a space in which many diffuse clouds overlap each other in an intricate, time-varying way.

Conceptual proximity in the Slipnet is thus context-dependent. For example, in Problem 1, no pressures arise that bring the nodes *successor* and *predecessor* into close proximity, so that a slippage from one to the other is highly unlikely; by contrast, in Problem 2, there is a good chance that pressures will activate the concept *opposite,* which will then cause the link between *successor* and *predecessor* to shrink, thus bringing each more into the other's halo, and enhancing the probability of a slippage between them. Because of this type of context-dependence, concepts in the Slipnet are *emergent,* rather than explicitly defined.

The existence of an explicit core to each concept is a crucial element of the architecture. Specifically, slippability depends critically on the discrete jump from one core to another. Diffuse regions having no cores would not permit such discrete jumps, as there would be no specific starting or ending point. Even an explicit *name* attached to a coreless diffuse region could serve as a substitute for a core—it would permit a discrete jump. In any case, however, slippage requires each concept to be attached to some identifiable "place" or entity. One might liken the core of a concept to the official city limits of a large city, and the halo to the much vaguer metropolitan region surrounding the city proper, stretching out in all directions, and clearly far more subjective and context-dependent than the core.

It may be useful to briefly compare Copycat's Slipnet with connectionist networks. In localist networks, a concept is equated with a node rather than with a diffuse region centered on a node. In other words, concepts in localist networks lack halos. This lack of halos implies that there is no counterpart to slippability in localist networks. In distributed systems, on the other hand, there would seem to be halos, since a concept is equated with a diffuse region, but this is somewhat misleading. The diffuse region representing a concept is not explicitly centered on any node, so there is no explicit *core* to a concept, and in that sense no halo. But since slippability depends on the existence of discrete cores, there is no counterpart to slippability even in distributed connectionist models.

The lack of any explicit center to a concept would probably be found to be quite accurate if one could examine concepts on the neural level. However, Copycat was not designed to be a neural model; it aims at modeling cognitive-level behavior by simulating processes at a subcognitive but superneural level. We believe that there is a subcognitive, superneural level at which it is realistic to conceive of a concept as having an explicit core surrounded by an implicit, emergent halo.

Another temptation might be to liken Copycat's context-dependent link lengths to the changing of internode weights as a connectionist net adapts to training stimuli. One might even liken the effect of a label node in Copycat to a multiplicative connection (where some node's activation is used as a multiplicative factor in calculating the new weight of a link). To be sure, there is a mathematical analogy here, but conceptually there is a significant difference. As connectionist networks adapt and "learn" by changing their weights, there is no sense of departing from a norm and no tendency to return to an earlier state. By contrast, in Copycat, any changing of link lengths takes place in response to a temporary context, and when that context is removed, the Slipnet tends to revert to its "normal" state. The Slipnet is thus "rubbery" or "elastic" in this sense; it responds to context but has a built-in tendency to "snap back" to its original state. We know of no corresponding tendency in connectionist networks.

Note that whereas the Slipnet changes over the course of a single run of Copycat, it does not retain changes from run to run, or create new permanent concepts. This program starts out in the same initial state on every run. Thus Copycat does not model *learning* in the usual sense. However, this project does concern learning if that term is taken to include the notion of adaptation of one's concepts to novel contexts.

Although the Slipnet responds sensitively to events in the Workspace (described in a moment) by constantly changing both its "shape" and the activations of its nodes, its fundamental topology remains invariant. That is, no new structure is ever built, or old structure destroyed, in the Slipnet. The next subsection discusses a component of the architecture that provides a strong contrast to this type of topological invariance.

2.2. **The Workspace—Copycat's Locus of Perceptual Activity**

The basic image for the Workspace is that of a busy construction site in which structures of many sizes and at many locations are being worked on simultaneously by independent crews, some occasionally being torn down to make way for new, hopefully better ones. (This image comes essentially from the biological cell; the Workspace corresponds roughly to the cytoplasm of a cell, in which enzymes carrying out diverse tasks all throughout the cell's cytoplasm are the construction crews, and the structures built up are all sorts of hierarchically structured biomolecules.)

At the start of a run, the Workspace is a collection of unconnected raw data representing the situation with which the program is faced. Each item in the Workspace initially carries only bare-bones information. That is, for each letter token, just its alphabetic type is provided, as well as—for those letters at the very edges of their strjngs—the descriptor *leftmost* or *rightmost.* Other than that, all objects are absolutely barren. Over time, through the actions of many small agents "scouting" for features of various sorts (these agents, called "codelets," are described in the next subsection), items in the Workspace gradually acquire various *descriptions,* and are linked together by various *perceptual structures,* all of which are built entirely from concepts in the Slipnet.

Objects in the Workspace do not by any means all receive equal amounts of attention from codelets—the probability than an object will attract a prospective codelet's attention is determined by the object's *salience,* which is a function of the set of descriptions it currently has. There are two factors that contribute to salience. An object is *important* to the extent that its descriptions are built out of highly activated concepts in the Slipnet. The more descriptions an object has and the more activated the nodes involved, the more attention that object would seem to deserve. However, there is a second factor, *unhappiness,* that modulates this tendency. Unhappiness is a measure of how integrated the object is with other objects. An unhappy object is one that has few or no connections to the rest of the objects in the Workspace, and thus seems to cry out for more attention. Salience is a dynamic quantity that takes into account both an object's importance and its unhappiness, and it determines how attractive that object will appear to codelets. Note that salience depends intimately on both the state of Workspace and the state of the Slipnet.

A constant feature of the processing is that pairs of *neighboring objects* (inside a single framework—i.e., letter-string) are probabilistically selected (with a bias favoring pairs that include salient objects) and scanned for similarities or relationships, of which the most promising are likely to get "reified" (i.e., realized in the Workspace) as inter-object *bonds.* For instance, the two k's in ykk in Problem 2 are likely to get bonded to each other rather quickly by a *sameness* bond. Similarly, the i and the j are likely to get bonded to each other, although not as fast, by a *succesorship bond* or a *predecessorship bond.*

The existence of differential rates of speed of bond-making is meant to reflect realities of human perception. In particular, people are clearly quicker to recognize two neighboring objects as identical than as being related in some abstract way. Thus, the architecture has an intrinsic speed-bias toward sameness bonds: it tends to construct them more quickly than it constructs bonds representing other kinds of relationships. (How the speeds of rival processes are dynamically controlled will be dealt with in more detail in the next subsection.)

Any bond, once made, has a dynamically varying *strength,* reflecting not only the activation and conceptual depth of the concept representing it in the Slipnet (in the case of kk, the concept *sameness,* and in the case of ц, either *successor* or *predecessor)* but also the prevalence of similar bonds in its immediate neighborhood. The idea of bonds is of course to start weaving unattached objects together into a coherent mental structure.

A set of objects in the Workspace bonded together by a uniform "fabric" (i.e., bond type) is a candidate to be "chunked" into a higher-level kind of object called a *group.* A simple example of a *sameness group* is ii, as in Problem 2. Another simple group is abc, as in Problem 1. This one, however, is a little ambiguous; depending on which direction its bonds are considered to go in, either it is perceived as having a left-to-right *successorship* fabric and is thus seen as a left-to-right *successor group,* or it is perceived as having a right-to-left *predecessorship* fabric and is thus seen as a right-to-left *predecessor group.* (It cannot be seen as both at once, although the program can switch from one vision to the other relatively easily.) The more salient a potential group's component objects and the stronger its fabric, the more likely it is to be reified.

Groups, just like more basic types of objects, acquire their own descriptions and salience values, and are themselves candidates for similarity-scanning, bonding to other objects, and possibly becoming parts of yet higher-level groups. As a consequence, hierarchical perceptual structures get built up over time, under the guidance of biases emanating from the Slipnet. A simple example would be the successor (or predecessor) group ykk in Problem 2, made up of three elements, the i, the j, and the short sameness group kk.

Another constant feature of the processing is that pairs of objects in *different frameworks* (i.e., strings) are probabilistically selected (again with a bias favoring salient objects) and scanned for similarities, of which the most promising are likely to get reified as *bridges* (or *correspondences)* in the Workspace. Effectively, a bridge establishes that its two end-objects are considered each other's counterparts—meaning either that they are intrinsically similar objects or that they play similar roles in their respective frameworks (or hopefully both).

Consider, for instance, the aa and **kk** in Problem 2. What makes one tempted to equate them? One factor is their intrinsic similarity—both are doubled letters (sameness groups of length two). Another factor is that they fill similar roles, one sitting at the left end of its string, the other at the right end of its string. If and when a bridge gets built between them, concretely reifying this mental correspondence, it will be explicitly based on both these facts. The fact that a and k are unrelated letters of the alphabet is simply ignored by most people. Copycat is constructed to behave similarly. Thus, the fact that aa and **kk** are both sameness groups will be embodied in an *identity mapping* (here, *sameness* <=> *sameness);* the fact that one is leftmost while the other is rightmost will be embodied in a *conceptual slippage* (here, *leftmost* O *rightmost);* the fact that nodes a and k are far apart in the Slipnet is simply ignored.

Whereas identity mappings are always welcome in a bridge, conceptual slippages always have to overcome a certain degree of resistance, the precise amount of which depends on the proposed slippage itself and on the circumstances. The most favored slippages are those whose component concepts not only are shallow but also have a high degree of overlap (i.e., are very close in the Slipnet). Slippages between highly overlapping *deep* concepts are more difficult to build, but pressures can certainly bring them about.

Once any bridge is built, it has a *strength,* reflecting the ease of the slippages it entails, the number of identity mappings helping to underpin it, and its resemblance to other bridges already built. The idea of bridges is of course to build up a coherent mapping between the two frameworks.

As the Workspace evolves in complexity, there is increasing pressure on new structures to be *consistent,* in a certain sense, with preexistent structures, especially with ones in the same framework. For two structures to be consistent sometimes means that they are instances of the very same Slipnet concept, sometimes that they are instances of very close Slipnet concepts, and sometimes it is a little more complex. In any case, the Workspace is not just a hodge-podge of diverse structures that happen to have been built up by totally independent codelets; rather, it represents a coherent vision built up piece by piece by many agents all indirectly influencing each other. Such a vision will henceforth be called a *viewpoint.* A useful image is that of highly coherent macroscopic structures (e.g., physical bridges) built by a colony of thousands of myopic ants or termites working semi-independently but nonetheless cooperatively. (The "ants" of Copycat—namely, codelets—will be described in the next subsection.)

There is constant competition, both on a local and a global level, among structures vying to be built. A structure's likelihood of beating out its rivals is determined by its *strength,* which has two facets: a context-independent facet (a contributing factor would be, for instance, the depth of the concept of which it is an instance) and a context-dependent facet (how well it fits in with the rest of the structures in the Workspace, particularly the ones that would be its neighbors). Out of the rough-and-tumble of many, many small decisions about which new structures to build, which to leave intact, and which to destroy comes a particular global viewpoint. Even viewpoints, however, are vulnerable; it takes a very powerful rival to topple an entire viewpoint, but this occasionally happens. Sometimes these "revolutions" are, in fact, the most creative decisions that the system as a whole can carry out.

As was mentioned briefly above, the Slipnet responds to events in the Workspace by selectively activating certain nodes. The way activation comes about is that any discovery made in the Workspace—creation of a bond of some specific type, a group of some specific type, etc.—sends a substantial jolt of activation to the corresponding concept in the Slipnet. The amount of time the effect of such a jolt will last depends on the concept's decay rate, which depends in turn on its depth. Thus, a deep discovery in the Workplace will have long-lasting effects on the activation pattern and "shape" of the Slipnet; a shallow discovery will have but transient effects. In Problem 2, {pr example, if a bridge is built between the groups **aa** and kk, it will very likely involve an *opposite* slippage *(leftmost* <=> *rightmost).* This discovery will reveal the hitherto unsuspected relevance of the very deep concept *opposite,* which is a key insight into the problem. Because *opposite* is a deep concept, once it is activated, it will. remain active for a long time and therefore exert powerful effects on subsequent! processing.

It is clear from all this that the Workspace affects the Slipnet no less than the Slipnet affects the Workspace; indeed, their influences are so reciprocal and' tangled that it is hard to tell the chicken from the egg.

2.3. The Coderack—Source of Emergent Pressures in Copycat

All acts of describing, scanning, bonding, grouping, bridge-building, destruction, and so forth in the Workspace are carried out by small, simple agents called *codelets.* (As was mentioned earlier, a codelet can be likened to an enzyme in a biological cell or an ant in an ant colony.) The action of a single codelet is always but a tiny part of a run, and whether any particular codelet runs or not is not of much consequence. What matters is the collective effect of many codelets.

There are two types of codelets: *scout codelets* and *effector codelets.* A scout merely looks at a potential action and tries to estimate its promise; the only kind of effect it can have is to create one or more codelets—either scouts or effectors—to follow up on its findings. By contrast, an effector codelet actually creates (or destroys) some structure in the Workspace.

Each codelet, when created, is placed in the *Coderack,* which is a pool of codelets waiting to run, and is assigned an *urgency value*—a number that will determine its probability of being selected from that pool as the next codelet to run. The urgency is a function of the estimated importance of that codelet's potential action, which in turn reflects the biases embodied in the current state of the Slipnet and the Workspace. Thus, for example, a codelet whose purpose is to seek instances of some lightly activated Slipnet concept will be assigned a low urgency and will therefore most probably have to wait a long time, after being created, to get run. By contrast, a codelet likely to further a Workspace viewpoint that is currently strong will be assigned a high urgency and will therefore have a good chance of getting run soon after being created.

It is useful to draw a distinction between *bottom-up* and *top-down* codelets. Bottom-up codelets (or "noticers") look around in an unfocused manner, open to what they find, whereas top-down codelets (or "seekers") are on the lookout for a particular kind of phenomenon, such as successor relations or sameness groups. Codelets can be viewed as *proxies* for the pressures in a given problem. Bottom-up codelets represent pressures present in *all* situations (the desire to make descriptions, to find relationships, to find correspondences, and so on). Top-down codelets represent specific pressures evoked by the specific situation at hand (e.g., the desire, in Problems 1 & 2, to look for more successor relations, once some have already been discovered). Top-down codelets can infiltrate the Coderack only when triggered' from "on high"—i.e., from the Slipnet. In particular, activated nodes are given the chance to "spawn" top-down scout codelets, with a node's degree of activation determining the codelet's urgency. The mission of such a codelet is to scan the Workspace in search of instances of its spawning concept.

It is very important to note that the calculation of a codelet's urgency takes into account (directly or indirectly) numerous factors, which may include the activations of several Slipnet nodes as well as the strength or salience of one or more objects in the Workspace; it would thus be an oversimplification to picture a top-down codelet as simply a proxy for the particular concept that spawned it. More precisely, a top-down codelet is a proxy for one or more *pressures* evoked by the situation. These include *workspace pressures,* which attempt to maintain and extend a coherent viewpoint in the Workspace, and *conceptual pressures,* which attempt to realize instances of activated concepts. It is critical to understand that pressures, while they are very *real,* are not represented *explicitly* anywhere in the architecture; each pressure is spread out among urgencies of codelets, activations, and link-lengths in the Slipnet, and strengths and saliences of objects in the Workspace. Pressures, in short, are implicit, emergent consequences of the deeply intertwined events in the Slipnet, Workspace, and Coderack.

Any run starts with a standard initial population of bottom-up codelets (with preset urgencies) on the Coderack. At each time step, one codelet is chosen to run and is removed from the current population on the Coderack. As was said before, the choice is probabilistic, biased by relative urgencies in the current population. Copycat thus differs from an "agenda" system such as Hearsay II, which, at each step, executes the waiting action with the highest estimated priority. The urgency of a codelet should not be conceived of as representing an estimated *priority;* rather, it represents the estimated relative *speed* at which the pressures represented by this codelet should be attended to. If the highest-urgency codelet were always chosen to run, then lower-urgency codelets would never be allowed to run, even though the pressures they represent have been judged to deserve *some* amount of attention. (More is said on this in Section 4.)

Since any single codelet plays but a small role in helping to further a given pressure, it never makes a crucial difference that a particular codelet be selected; what really matters is that each *pressure* move ahead at roughly the proper speed over time. Stochastic selection of codelets allows this to happen, even when judgments about the intensity of various pressures change over time. Thus, allocation of resources is an emergent statistical result rather than a pre-programmed deterministic one. The proper allocation of resources could not be programmed ahead of time, since it depends on what pressures emerge as a given situation is perceived.

The Coderack would obviously dwindle rapidly to zero if codelets, once run and removed from it, were not replaced. However, replenishment of the Coderack takes place constantly, and this happens in three ways. Firstly, *bottom-up* codelets are continually being added by Coderack. Secondly, codelets that run can, among other things, add one or *моκ follow-up* codelets to the Coderack before being removed. Thirdly, active nodes in the Slipnet can add *top-down* codelets. Each new codelet's urgency is assigned by its creator as a function of the estimated promise of the task it is to carry out. Thus, the urgency of a follow-up codelet is a function of the amount of progress made by the codelet that posted it, as gauged by that codelet itself, while the urgency of a top-down codelet is a function of the activation of the node that posted it. (The urgency of bottom-up codelets is context-independent.) Thus, as the run proceeds, the population of the Coderack adjusts itself dynamically in response to the system's needs as judged by previously run codelets and by activation patterns in the Slipnet, which themselves depend on the current structures in the Workspace.

The shifting population of the Coderack bears a close resemblance to the shifting enzyme population of a cell, which evolves in a sensitive way in response to the ever-changing makeup of the cell's cytoplasm. Just as the cytoplasmic products of certain enzymatic processes trigger the production of new types of enzymes to act further on those products, structures built in the Workspace by a given set of codelets cause new types of codelets to be brought in to work on them. And just as, at any moment, certain genes in the cell's DNA are allowed to be expressed (at varying rates) through enzyme proxies, while other genes remain essentially repressed (dormant), certain Slipnet nodes get "ex-

Much the same could be said for Copycat: an outside observer is free, after a run is over, to "parse" the run in terms of specific, discrete processes, and to attempt to impose such a vocabulary on the system's behavior; however, that parsing and labeling is not intrinsic to the system, and such interpretations are in no way unique or absolute, any more than in a basketball game. In other words, a long sequence of codelet actions can add up to what could be perceived *a posteriori* and by an outsider, as a single coherent drive towards a particular goal, but that is the outsider's subjective interpretation.

3.2. The Parallel Terraced Scan

One of the most important consequences of the commingling of conceptual pressures is *the parallel terraced scan.* The basic image is that of many "fingers of exploration" simultaneously feeling out various potential pathways at different speeds, thanks to the coexistence of pressures of different strengths. These "fingers of exploration" are tentative probes made by scout codelets, rather than actual events realized by effector codelets. In the Workspace, there is one *actual* viewpoint, at any given time. However, in the background, a host of nearby variants of the actual viewpoint—*virtual* viewpoints—are constantly flickering probabilistically. If any virtual viewpoint is found sufficiently promising by scouts, then they create effector codelets that, when run, will attempt to realize that alternative viewpoint in the Workspace. This entails a "fight" between the incumbent structure and the upstart; the outcome is decided probabilistically, with the weights being'determined by the strength of the current structure as opposed to the promise of the rival.

This is how the system's actual viewpoint develops with time. There is always a probabilistic "halo" of many *potential* directions being explored; the most attractive of these tend to be the *actual* directions chosen. Incidentally, this aspect of Copycat reflects the psychologically important fact that conscious experience is essentially unitary, although it is of course an outcome of many parallel unconscious processes.

A metaphor for the parallel terraced scan is provided by the image of a vast column of ants marching through a forest, with hordes of small scouts at the head of the column making small random forays in all directions (although exploring some directions more eagerly and deeply than others) and then returning to report; the collective effect of these many "feelers" will then determine the direction to be followed by the column as a whole. This is going on at all moments, of course, so that the column is constantly adjusting its pathway in slight ways.

The term "parallel terraced scan" comes from the fact that scouting expeditions are structured in a *terraced* way; that is, they are carried out in stages, each stage contingent upon the success of the preceding one, and probing a little more deeply than the preceding one. The first stage is computationally cheap, so the system can afford to have many first-stage scouts probing in all sorts of directions, including quite unlikely directions. Succeeding stages are less and less cheap; consequently the system can afford fewer and fewer of them, which means it has to be increasingly selective about the directions it devotes resources to looking in. Only after a pathway has been deeply explored and found to be very promising are effector codelets created, which then will try to actually swerve the whole system down that pathway.

The constellation of conceptual (i.e., top-down) pressures at any given time controls the biases in the system's exploratory behavior, and also plays a major role in determining the actual direction the system will move in; ultimately, however, top-down pressures, no matter how strong, must bow to the reality of the situation itself, in the sense that prejudices alone cannot force inappropriate concepts to fit to reality. Conceptual pressures must adapt when the pathways they have urged turn out to fail. The model is made explicitly to allow this kind of intermingling of top-down and bottom-up processing.

3.3. Time-Evolving **Biases**

At the very start of a run, the Coderack contains exclusively bottom-up similarity-scanners, which represent no situation-specific pressures. In fact, it is their job to make small discoveries that will then start generating such pressures. As these early codelets run, the Workspace starts to fill up with bonds and small groups and, in response to these discoveries, certain nodes in the Slipnet are activated. In this way, situation-specific pressures are generated and cause top-down codelets to be spawned by concepts in the Slipnet. Thus, top-down codelets gradually come to dominate the Coderack.

At the outset of a run, the Slipnet is "neutral" (i.e., in a standard configuration with a fixed set of concepts of low depth activated), meaning that there are no situation-specific pressures. At this early stage, all observations niade in the Workspace are very local and superficial. Over the course of a run, the Slipnet moves away from its initial neutrality and becomes more and more biased toward certain organizing concepts—*themes* (highly activated deep concepts, or constellations of several such concepts). Themes then guide processing in many pervasive ways, such as determining the saliences of objects, the strengths of bonds, the likelihood of various types of groups to be made, and iri general, the urgencies of all types of codelets.

It should not be imagined, incidentally, that a "neutral" Slipnet embodies no biases whatsoever; it certainly does (think of the permanent inequality of various nodes' conceptual depths, for instance). The fact that at the outset, a sameness group is likely to be spotted and reified faster than a successor group of the same length, for instance, represents an initial bias favoring sameness over successorship. The important thing is that at the outset of a run, the system is more open than at any other time to *any* possible organizing theme (or set of themes); as processing takes place and perceptual discoveries of all sorts are made, the system loses this naive, open-minded quality, as indeed it ought to, and usually ends up being "closed-minded"—that is, strongly biased towards the pursuit of some initially unsuspected avenue.

In the early stages of a run, almost all discoveries are on a very small, local scale: a primitive object acquires a description, a bond is built, and so on. Gradually, the scale of actions increases: small groups begin to appear, acquire their own descriptions, and so on. In the later stages of a run, actions take place on an even larger scale, often involving complex, hierarchically structured objects. Thus, over time there is a clear progression, in processing, from locality to globality.

3.4. Temperature as a Regulator of Open-Mindedness

At the start of a run, the system is open-minded, and for good reason: it knows nothing about the situation it is facing. It does not matter all that much *which* codelets run, since one wants many different directions to be explored; hence decision making can be fairly capricious. However, as swarms of scout codelets and local effector codelets carry out their jobs, that status gradually changes; in particular, as the system acquires more and more information, it starts creating a coherent viewpoint and focusing in on organizing themes. The more informed the system is, the more important it is that top-level decisions not be capriciously made. For this reason, there is a variable that monitors the stage of processing, and helps to convert the system from its initial largely bottom-up, open-minded mode to a largely top-down, closed-minded one. This variable is given the name *temperature.*

What controls the temperature is the *degree of perceived order* in the Workspace. If, as at the beginning of every run, no structures have been built, then the system sees essentially no order, which translates into a need for broad, open-minded exploration; if, on the other hand, there is a highly coherent viewpoint in the Workspace, then the last thing one wants is a lot of voices clamoring for irrelevant actions in the Workspace. Thus, temperature is essentially an inverse measure of the quality of structure in the Workspace: the more structures there are, and the stronger (and thus more coherent) they are, the lower the temperature. Note that although the overall trend is for temperature to wind up low at the end of a run, a *monotonic* drop in temperature is not typical; often, the system's temperature goes up and down several times during a run, reflecting the system's uncertain advances and retreats as it builds and destroys structures in its attempts to home in on the best way to look at a situation.

What the temperature itself controls is the *degree of randomness used in decision making.* Decisions of all sorts are affected by the temperature. Consider a codelet, for instance, trying to decide where to devote its attention. Suppose that Workspace object A is exactly twice as salient as object B. The codelet will thus tend to be more attracted to A than to B. However, the precise discrepancy in attractive power between A and B will depend on the temperature. At some midrange temperature, the codelet will indeed be twice as likely to go for A as for B. However, at very *high* temperatures, A will be hardly any more attractive than B to the codelet. By contrast, at very *low* temperatures, the probability of choosing A over B will be much greater than two to one. For another example, consider a codelet trying to build a structure that is incompatible with a currently existing strong structure. Under low-temperature conditions, the strong structure will tend to be very stable (i.e., hard to dislodge), but if the temperature should happen to rise, the strong structure will become increasingly susceptible to being swept away. In "desperate times," even the most huge and powerful structures and worldviews can topple.

The upshot of all this is that at the start of a run, the system explores possibilities in a wild, scattershot way; however, as it builds up order in the Workspace and simultaneously homes in on organizing themes in the Slipnet, it becomes an increasingly conservative decision maker, ever more deterministic and serial in its style. Of course, there is no magic crossover point at which nondeterministic parallel processing turns into deterministic serial processing; there is simply a gradual tendency in that direction, controlled by the system's temperature.

Note that the notion of temperature in Copycat differs from that in simulated annealing, an optimization technique sometimes used in connectionist networks (Hinton & Sejnowski, 1986; Kirkpatrick, Gelatt, & Vechhi, 1983; Smolensky, 1986). In simulated annealing, temperature is used exclusively as a top-down randomness-controlling factor, its value falling monotonically according to a predetermined, rigid "annealing schedule." By contrast, in Copycat, the value of the temperature reflects the current quality of the system's understanding, so that temperature acts as a *feedback mechanism* that determines the degree of randomness used by the system.

Long after the concept of temperature had been conceived and implemented in the program, it occurred to us that temperature could serve an extra, unanticipated role: *thefinal* temperature in any run could give a rough indication of how good the program considered its answer to be (the lower the temperature, of course, the more desirable the answer). The idea is simply that the quality of an answer is strongly correlated with the amount of strong, coherent structure underpinning that answer, and temperature is precisely an attempt to measure that quantity. From the moment we realized this, we kept track of the final temperatures of all runs, and those data provided some of the most important insights into the program's "personality," as will be apparent in Section 5.

3.5. Overall Trends During a Run

In most runs, despite local fluctuations here and there, there is a set of overall tendencies characterizing how the system evolves in the course of time. These tendencies, although they are all tightly linked together, can be roughly associated with different parts of the architecture, as follows:

- In the Slipnet, there is a general tendency for the initially activated concepts to be *conceptually shallow,* and for concepts that get activated later to be increasingly *deep.* There is also a tendency to move from *no themes* to *themes* (i.e., clusters of highly activated, closely related, high-conceptual depth concepts).
- In the Workspace, there is a general tendency to move from a state of *no structure* to a state with *much structure,* and from a state having *many local, unrelated objects* to a state characterized by/<?w *global, coherent structures.*
- As far as the processing is concerned, it generally exhibits, over time, a gradual transition from *parallel* style toward *serial* style, from *bottom-up* mode to *top-down* mode, and from an initially *nondeterministic* style toward a *deterministic* style.

4. THE INTIMATE RELATION BETWEEN RANDOMNESS AND FLUIDITY

It may seem deeply counterintuitive that randomness should play a central role in a computational model of intelligence. However, careful analysis shows that it is inevitable if one believes in any sort of parallel, emergent approach to mind.

4.1. Randomness as Lack of Bias

A good starting point for such analysis is to consider the random choice of codelets (biased according to their urgencies) from the Coderack. The key notion, stressed in earlier sections, is that the urgency attached to any codelet represents the estimated proper *speed* at which to advance the pressures for which it is a proxy. Thus, it would make no sense at all to treat higher urgencies as higher *priorities*—that is, always to pick the highest urgency codelets first. If one were to do that, then lower urgency codelets would never get run at all, so the effective speeds of the pressures they represent would all be zero, which would totally defeat the notion of commingling pressures, the parallel terraced scan, and temperature.

A more detailed analysis is the following. Suppose we define a "grass-roots" pressure as a pressure represented by a large swarm of low-urgency codelets, and an "elite" pressure as one represented by a small coterie of high-urgency codelets. Then a policy to select high-urgency codelets most of the time would arbitrarily favor elite pressures. In fact, it would allow situations wherein any number of grass-roots pressures could be entirely squelched by just *one* elite pressure—even if the elite pressure constituted but a small fraction of the *total* urgency (the sum of the urgencies of all the codelets in the Coderack at the time), as it most likely would. Such a policy would result in a very distorted image of the overall makeup (i.e., the distribution of urgencies among various pressures) of the Coderack. In summary, it is imperative that during a run, low-urgency codelets get mixed in with higher-urgency codelets, and in the right proportion—namely, in the proportions dictated by urgencies, no more and no less. As was said earlier, only by using probabilities to choose codelets can the system achieve (via statistics) *a fair* allocation of resources to each pressure, even when the strengths of various pressures change as processing proceeds.

4.2. Randomness and Asynchronous Parallelism

One might well imagine that the need for such randomness (or biased nondeterminism) is simply an artifact of this architecture's having been designed to run on a sequential machine; were it redesigned to run on parallel hardware, then all randomness could be done away with. This turns out to be not at all the case, however. To see why, we have to think carefully about what it would mean for this architecture to run on parallel hardware. Suppose that there were some large number of parallel processors to which tasks could be assigned, and that each processor's speed could be continuously varied. It is certainly not the case that one could assign *processes* to *processors* in a one-to-one manner, since, as has been stressed, there is no clear notion of "process" in this architecture. Nor could one assign *one pressure* to each processor, since codelets are not univalent as to the pressures that they represent. The only possibility would be to assign a processor to every single codelet, letting it run at a speed defined by that codelet's urgency. (Note that this requires a very large number of co-processors—hundreds, if not thousands. Moreover, since the codelet population varies greatly over time, the number of processors in use at different times will vary enormously. However, on a conceptual level, neither of those poses a problem in principle.)

Now notice a crucial consequence of this style: since all the processors are running at speeds that are completely independent of one another, they are effectively carrying out *asynchronous* computing, which means that relative to one another, the instants at which they carry out actions in the (shared) Workspace are totally decoupled—in short, entirely random relative to one another. This is a general fact: asynchronous parallelism is inseparable from processors' actions being random relative to one another (as pointed out in Hewitt, 1985). Thus, parallelism provides no escape from the inherent randomness of this architecture. When it runs on serial hardware, some *explicit* randomizing device is utilized; when it runs on parallel hardware, the randomness is *implicit,* but no less random for that.

The earlier image of the swiftly changing panorama of a basketball game may help to make this necessary connection between asynchronous parallelism and randomness more intuitive. Each player might well feel that the snap decisions being made constantly inside their own head are anything but random—that, in fact, their decisions are rational responses to the situation. However, from the point of view of *other* players, what any one player does is not predictable—a player's mind is far too complex to be modeled, especially in real time. Thus, because all the players on the court are complex, independent, asynchronously acting systems, each player's actions *necessarily* have a random (i.e., unpredictable) quality from the point of view of all the other players. And obviously, the more unpredictable a team seems to its opponents, the better.

4.3. A Seeming Paradox: Randomness in the Service of Intelligence

Even after absorbing all these arguments, one may still feel uneasy with the proposition that greater intelligence can result from making *random* decisions than from making *systematic* ones. Indeed, when the architecture is described this way, it sounds nonsensical. Isn't it always wiser to choose the *better* action than to choose at *random?* However, as in so many discussions about mind and its mechanisms, this appearance of nonsensicality is an illusion caused by a confusion of levels.

Certainly it would seem extremely counterintuitive—in fact, downright nonsensical—if one suggested that a melody-composition program (say) should choose its next note by throwing dice, even weighted dice. How could any global coherence come from such a process? This objection is of course totally valid—good melodies cannot be produced in that way (except in the absurd sense of millions of monkeys plunking away on piano keyboards for trillions of years and coming up with "Blue Moon" once in a blue moon). But our architecture in no way advocates such a coarse type of decision-making procedure!

The choice of next note in a melody is a *top-level* macrodecision, as opposed to a low-level act of "micro-exploration." The purpose of micro-exploration is to efficiently explore the vast, foggy world of possibilities lying ahead without getting bogged down in a combinatorial explosion; for this purpose, randomness, being equivalent to nonbiasedness, is the *most efficient* method. Once the terrain has been scouted out, then a lot of information has been gained, and in most cases some macroscopic pathways have been found to be much more promising than others. Moreover—and this is critical—the more information that has been uncovered, the more the temperature will have dropped—and the lower the temperature is, the less randomness is used. In other words, the more confidently the system believes, thanks to lots of efficient and fair micro-scouting in the fog, that it has identified a particular promising pathway ahead, the more certain it is to make the macro-decision of picking that pathway. Only when there is a very close competition is there much chance that the favorite will not win, and in such a case it hardly matters since, even after careful exploration, the system is not persuaded that there is a clear best route to follow.

In short, in the Copycat architecture, hordes of random forays are employed on a microscopic level when there is a lot of fog ahead, and their purpose is precisely to get an evenly distributed sense of what lies out there in the fog rather than simply plunging ahead blindly, at random. The foggier things are, the more unbiased should be the scouting mission, hence the more randomness is called for. To the extent that the scouting mission succeeds, the temperature will fall, which in turn means that the well-informed macroscopic decision about to be taken will be made nonrandomly. Thus, randomness is used *in the service of,* and not in opposition to, intelligent nonrandom choice.

A subtle aspect of this architecture is that there are all shades between complete randomness (much fog, high temperature) and complete determinism (no fog, low temperature). This reflects the fact that one cannot draw a clean, sharp line between micro-exploratory scouting forays and confident, macroscopic decisions. For instance, a smallish, very local building or destruction operation carried out in the Workspace by an effector codelet working in a midrange temperature can be thought of as lying somewhere in between a micro-exploratory foray and a well-informed macroscopic decision.

As a final point, it is interesting to note that nonmetaphorical fluidity—that is, the physical fluidity of liquids like water—is inextricably tied to random microscopic actions. A liquid could not flow in the soft, *gentle, fluid* way that it does, were it not composed of tiny components whose micro-actions are completely random relative to one another. This does not, of course, imply that the top-level action of the fluid *as a whole* takes on any appearance of randomness; quite the contrary! The flow of a liquid is one of the most nonrandom phenomena of nature that we are familiar with. This does not mean that it is by any means *simple;* it is simply familiar and natural-seeming. Fluidity is an emergent quality, and to simulate it accurately requires an underlying randomness.

5. COPYCAT'S PERFORMANCE: A FOREST-LEVEL OVERVIEW

5.1. The Statistically Emergent Robustness of Copycat

Now that the architecture of the Copycat program has been laid out, we can take a tour through the program's performance on a number of problems in its letter-string microworld. As was discussed earlier, Copycat's microworld was designed to isolate, and thus bring out very clearly, some of the essential issues in high-level perception and analogy-making in general. The program's behavior on the problems presented here demonstrates how it deals with these issues, how it responds to variations in pressures, and how it is able, starting from exactly the same state on each new problem, to fluidly adapt to a range of different situations.[2] (The program's performance on a much larger set of problems and some comparisons with people's performance on the same problems are given in Mitchell, 1993.)

On any given run on a particular problem, Copycat settles on a specific answer; however, since the program is permeated with nondeterminism, different answers (to the same problem) are possible on different runs. The nondeterministic decisions the program makes (e.g., which codelet to run next, which objects a codelet should act on, etc.) are all at a microscopic level, compared with the macroscopic-level decision of what answer to produce on a given run. Every run is different at the microscopic level, but statistics lead to far more deterministic behavior at the macroscopic level. For example, there are a huge number of possible routes (at the microscopic level of individual codelets and their actions) the program can take to arrive at the solution **ijl** to Problem 1, and a large number of micro-biases tend to push the program down one of those routes rather than down one of the huge number of possible routes to **ijd.** Thus, in this problem, at a macroscopic level the program is fairly deterministic: it gets the answer **ijl** almost all the time.

The phenomenon of macroscopic determinism emerging from microscopic nondeterminism is often demonstrated in science museums by means of a contraption in which several thousand small steel balls tumble down through a dense grid of pins; eventually, each ball falls into one of a number of adjacent bins forming a horizontal row at the bottom. Though each ball takes a unique path at the microlevel, nonetheless, as more and more balls fall, the pattern of balls in the bins at the bottom gradually becomes a perfect gaussian curve, with most of the balls falling into the central bins, and very few into the edge bins. In Copycat, the set of bins corresponds to the set of different possible answers, and the precise pathway an individual ball follows, probabilistically bouncing left and right many times before "choosing" a bin at the bottom, corresponds to the many stochastic micro-decisions made by the program (at the level of individual codelets) during a single run. Given enough runs, a reliably repeatable pattern of answer frequencies will emerge, just as a near-perfect gaussian curve regularly emerges in the bins of a "Gaussian pinball machine."

[2] The current version of the Copycat program can deal only with problems whose initial change involves areplacementof at most one letter (e.g., **abc фаЬд, огааЬсф aabd;** of course *the answer* can involve a change of more than one letter, as in **aabc => aabd, ijkk** => ijll) This is a limitation of the program as it now stands; in principle, the letter-string domain is much larger. But even given this limitation, a very large number of interesting problems can be formulated, requiring considerable mental fluidity. For a number of examples of such problems, see Hofstadter, 1984b, or Mitchell, 1993.

5.2. Copycat's "Personality" is Revealed through Bar Graphs

We present these patterns in the form of bar graphs, one for each problem, giving the frequency of occurrence (representing surface appeal) and the average end-of-run temperature (representing quality) for each different answer. For each problem, a bar graph is given, summarizing 1,000 runs of Copycat on that problem. The number 1,000 is somewhat arbitrary; after about 100 runs on each problem, the basic statistics do not change much. The only difference is that as more and more runs are done on a given problem, certain bizarre and improbable "fringe" answers, such as ijj in Problem 1 (see Figure 1.1. below), begin to appear very occasionally. If 2,000 runs were done on Problem 1, the program would give perhaps one or two other such answers, each once or twice. This allows the bar graphs to make a very important point about Copycat: even though the program has the potential to get strange and crazy-seeming answers, the mechanisms it has allow it to steer clear of them almost all of the time. It is critical that the program (as well as people) be allowed the *potential* to follow risky (and perhaps crazy) pathways, in order for it to have the flexibility to follow *insightful* pathways, but it also has to avoid following bad pathways at least most of the time.

Copycat's performance on Problem 1 is given in Figure 2.1. Each bar's height gives the relative frequency of the answer it corresponds to, and printed above each bar is the actual number of times that answer was given. The average final temperature appears below each bar. The frequency of a given answer roughly corresponds to how *obvious* or *immediate* it is, given the biases of the program. For example, ijl, produced 980 times, is much more immediate to the program than **ijd,** produced 19 times, which is in turn much more obvious than the strange answer yj, produced only once. (To get this last answer, the program decided to replace the rightmost letter by its predecessor rather than by its

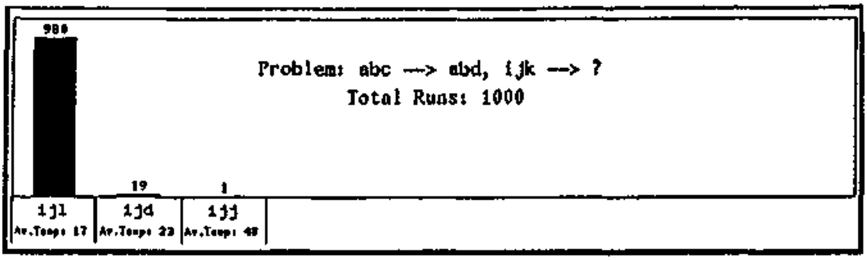


Figure 1.1.
Statistics summarizing 1,000 runs of Copycat on Problem 1. For each answer found by the program, its frequency and average final temperature are indicated.

successor. This slippage is always possible in principle, since *successor* and *predecessor* are linked in the Slipnet. However, as can be seen by the rarity of this answer, it is extremely unlikely in this situation: under the pressures evoked by this problem, *successor* and *predecessor* are almost always considered too distant for a slippage to be made between them.)

The frequencies shown in the bar graph are not meant to be strictly compared with the frequencies of various answers given by people to this problem, since, as we said earlier, the program is not meant to model the domain-specific mechanisms people use in solving these letter-string problems. Rather, what is interesting here is that the program does have the potential to arrive at very strange answers (such as iij),yet manages to steer clear of them almost all the time.

As we said earlier, the average final temperature of an answer can be thought of as the program's own assessment of that answer's quality, with lower temperatures meaning higher quality. For instance, the program assesses ijl (average final temperature 17) to be of somewhat higher quality than ijd (temperature 23), and of much higher quality than yj (temperature 48). (Temperatures are in the range 0-100.)

One can get a sense for what a given numerical value of temperature represents by seeing how various sets of perceptual structures built by the program affect the temperature. This will be illustrated in the next section when a detailed set of screen dumps from a run of Copycat is presented. Roughly speaking, an average final temperature below 30 indicates that the program was able to build a fairly strong, coherent set of structures—that it had, in some sense, a reasonable "understanding" of what was going on in the problem. Higher final temperatures usually indicate that some structures were weak, or perhaps that there was no coherent way of mapping the initial string onto the target string.

The program decides probabilistically when to stop running and produce an answer, and although it is much more likely to stop when the temperature is low, it sometimes stops before it has had an opportunity to build all appropriate structures. For example, there are runs on Problem 1 in which the program stops before the target string has been grouped as a whole; the answer is still often yl, but the final temperature is higher than it would have been if the program had continued. This kind of run increases the average final temperature for this answer. The lowest possible temperature for answer ijl is about 7, which is about as low as the temperature ever gets.[3]

' There is a problem with the way temperature is calculated in the program as it now stands. As can be seen, the answer **yd** has an average final temperature almost equal to that of **ijl** (even though it is much less frequent), whereas most people feel it is a far worse answer. This, along with other problems with the current program, is discussed in detail in Mitchell (1993),

5.3. Systematically Studying the Effects of Variant Problems

Systematic studies can be done in which a given problem is slightly altered in various ways. Each such variant tampers with the pressures that the original problem evokes, and one can expect effects of this to show up in the bar graph for that problem. For instance, Problem 2, discussed above, is a variant of Problem 1 in which the doubling of letters shifts the "stresses" in the strings abc and **yk;** one might expect this to make the **aa** and the **kk** far more salient and more similar to each other than the a and k were in Problem 1, thus pushing toward a crosswise mapping in which the two double letters correspond.

In Figure 1.2, one sees that despite the pressure towards a crosswise mapping, the "Replace rightmost group by successor" answer **(ijll)** is still the most common answer and the "Replace rightmost letter by successor" answer **(ijkl)** is second, indicating the lingering appeal of the straightforward *leftmost* ф *leftmost, rightmost* ф *rightmost* view, even here. However, the pressure is felt to some extent: **jjkk** makes a good showing and **hjkk** has some representatives as well, as well as having by far the lowest average temperature. (This is to be contrasted with the results on Problem 1: note than in 1,000 runs, the program *never* gave an answer involving a replacement of the leftmost letter.) The answers on the fringe here include **jkkk** (which is similar to **jjkk,** but results from grouping the *two* leftmost letters — a far-fetched and, to most people, unappealing way of "parsing" the string); **ijkd** and **ijdd** (both based on the rule "Replace the rightmost letter by d," but flexed in different ways because of different bridges built from the c); ijkk (replacing all c's by d's); and **djkk** (replacing the i by a d instead of by its successor or predecessor).

Another variant on Problem 1 is the following:

3. Suppose the letter-string **abc** were changed to **abd;** how would you change the letter-string **kji** in "the same way"?

Here a literal application of the original rule ("Replace rightmost letter by successor") would yield **kjj,** which ignores an abstract similarity between **abc**

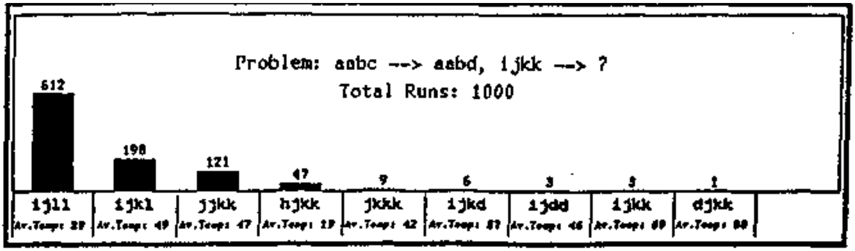
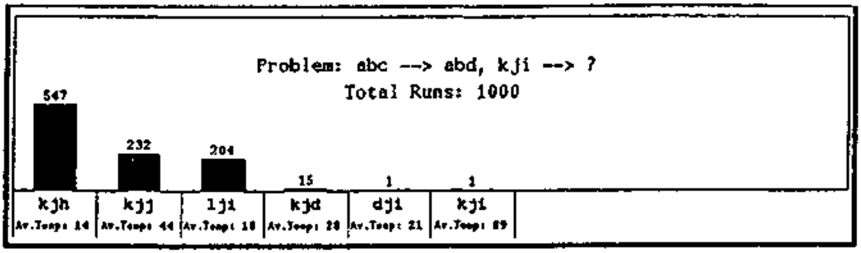


Figure 1.2.
Statistics summarizing 1,000 runs of Copycat on Problem 2.

Figure 1.3.
Statistics summarizing 1,000 runs of Copycat on Problem 3.



and **kji.** An alternative many people prefer is Iji ("Replace the leftmost letter by its successor"), which is based on seeing both strings in terms of a *successorship* fabric, in one string running to the right and in the other one to the left; thus there is a slippage from the concept *right* to the concept *left,* which in turns gives rise to the "cousin" slippage *rightmost* φ *leftmost.* Another answer given by many people is **kjh** ("Replace the rightmost letter by its predecessor"), in which one string is seen as having a *successorship* fabric and the other as having a *predecessorship* fabric (both viewed as moving in the same spatial direction), thus involving a slippage of the concept *successor* into the concept *predecessor.*

As can be seen in Figure 1.3, there are three answers that predominate, with **kjh** being the-most common (and having the lowest average final temperature), and **kjj** and **Iji** almost tying for second place (the latter being a bit less common, but having a much lower average final temperature). The answer **kjd** comes in a very distant fourth. Then there are two "fringe" answers with but one instance apiece. One is **dji,** an implausible blend of insight and rigidity in which the opposite spatial direction of the two successor groups **abc** and **kji** was seen, but instead of the leftmost letter being replaced by its successor, it was replaced by a d. Notice the relatively low temperature on this answer, indicating that a strong set of structures was built. The other is **kji,** reflecting the literal-minded rule "Replace c by d," where there are no c's in **kji.** This answer has a very high temperature of 89, indicating that on this particular run, almost no structures were built before the program chanced, against very high odds, to stop.

5.4. How Hidden Concepts Emerge from Dormancy

Consider now the following problem, which involves a very different set of pressures from those in the previous problems:

4. Suppose the letter-string **abc** were changed to **abd;** how would you change the letter-string **mrrjjj** in "the same way"?

There is a seemingly reasonable, straightforward solution: **mrrkkk.** Most people give this answer, reasoning that since **abc's** rightmost letter was replaced by its successor, and since **mrrjjj's** rightmost "letter" is actually a *group* of j's, one should replace *all* the j's by k's. Another possibility is to take the phrase "rightmost letter" literally, thus replacing only the rightmost j by k, giving **mrrjjk.** However, neither answer is very satisfying, since neither takes into account the salient fact that **abc** is an alphabetic sequence (i.e., a successor group). This fabric of **abc** is an appealing and seemingly central aspect of the string, so one would like to use it in making the analogy, but there is no obvious way to do so. No such fabric seems to weave **mrrjjj** together. So either (like most people) one settles for **mrrkkk** (or possibly **mrrjjk),** or one looks more deeply. But where to look when there are so many possibilities?

The interest of this problem is that there happens to be an aspect of **mrrjjj** lurking beneath the surface that, once recognized, yields what many people feel is a deeply satisfying answer. If one ignores the *letters* in **mrrjjj** and looks instead at *group lengths,* the desired successorship fabric is found: the lengths of groups increase as "1-2-3." Once this hidden connection between **abc** and **mrrjjj** is discovered, the rule describing the change abc Φ abd can be adapted to apply to **mrrjjj** as "Replace the *length* of the rightmost group by its successor," yielding "1-2-4" at the abstract level, or, more concretely, **mrrjjjj.**

This problem demonstrates how a previously irrelevant, unnoticed aspect of a situation can emerge as relevant in response to pressures. The crucial point is that the process of perception is not just about deciding which *clearly apparent* aspects of a situation should be ignored and which should be taken into account; it is also about deciding how aspects that were initially considered to be irrelevant—or rather, that were initially so far out of sight that they were not even recognized as being irrelevant!—can *become* apparent and relevant in response to pressures that emerge as the understanding process is taking place.

Sometimes, given certain pressures, a concept that one initially had no idea was germane to the situation will emerge seemingly from nowhere and turn out to be exactly what was needed. In such cases, however, one should not feel upset about not having suspected its relevance at the outset. In general, unlikely ideas (or even ideas *slightly* past one's defaults) ought not continually occur to people for no good reason; in fact, a person to whom this happens is classified as crazy or crackpot.

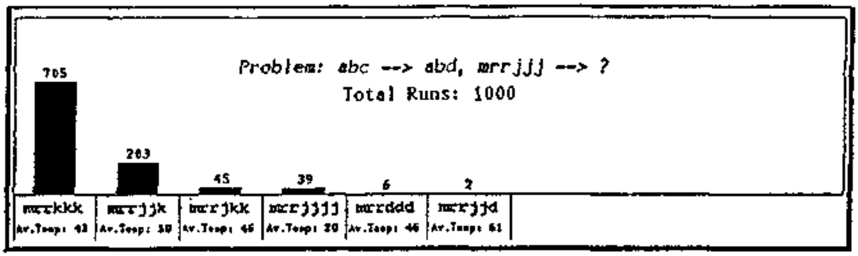
Time and cognitive resources being limited, it is vital to resist nonstandard ways of looking at situations without strong pressure to do so. You don't check the street sign at the corner, every time you go outdoors, to reassure yourself that your street's name hasn't been changed. You don't worry, every time you sit down for a meal, that perhaps someone has filled the saltshaker with sugar. You don't worry, every time you start your car, that someone might have stuck a potato in its tailpipe or attached a bomb to its chassis. However, there are pressures—such as receiving a telephone threat on your life—that would make such a normally unreasonable suspicion start to seem reasonable. (These ideas overlap with Kahneman and Miller's [1986], treatment of counterfactuals, and are also closed related to the frame problem in artificial intelligence, as discussed in McCarthy & Hayes, 1969.)

Not only is pressure needed to evoke a dormant concept in trying to make sense of a situation, but the concepts brought in are often clearly related to the source of the pressure. For example, when one looks carefully at Problem 4 (as we will do in Section 6), one can see how certain aspects of it create pressures that, acting in concert, stand a decent chance of evoking the concept of group length. Some critical aspects of the story (not in any particular order) are these: (a) once successor relations have been noticed in **abc,** there arises a top-down pressure to look for them in **mrrjjj** as well; (b) once the **rr** and **jjj** sameness groups have been perceived in **mrrjjj,** the normally dormant concept *length* becomes weakly active and lingers in the background; (c) the perception of these sameness groups leads to top-down pressure to perceive other parts of the same string as sameness groups as well, and the only way this can be done is the unlikely possibility of perceiving the m as a sameness group consisting *of only one letter;* and (d) after standard concepts have failed to yield progress in making sense of the situation at hand, resistance to bringing in nonstandard concepts decreases.

People occasionally give the answer **mrrkkkk,** replacing *both* the letter category *and* the group length of the rightmost group by their successors (k and 4, respectively). Despite its interest, this answer confounds aspects of the two situations. What counts in establishing the similarity of **abc** and **mrrjjj** is their shared successorship fabric. In **mrrjjj,** that fabric has nothing to do with the specific letters m, r, and j; the letter sequence m-r-j is merely acting as a *medium* in which the *numerical* sequence "1-2-3" can be expressed. It is thus misguided to focus on the *alphabetic* level of **mrrjjj,** when one has just established that the essence of that string, in this context, is not its letters but its higher-level *numerical* structure. If the relations between lengths are perceived, then the answer at the level of lengths is "1-2-4." Translated back into the language of the carriers, this yields **mrrjjjj.** Additionally converting the four j's into k's simply blends the alphabetic view with the numerical view in an inappropriate manner.

People have also proposed answers such as **mrryyyy,** where the three j's are replaced by four copies of a randomly chosen letter—here, y. The reasoning is that since the successorship fabric in **mrrjjj** has noting to do with the specific letters m, r, and j, it doesn't matter *which* letter-value is used to replace the j's. Such reasoning is too sophisticated for the current version of Copycat, which does not have the concept "randomly chosen letter"—but even if Copycat could produce such an answer, we would still argue that **mrrjjjj** is the best answer to this problem. The letters m, r, and j serve as the medium for expressing the message " 1 -2-3," and we feel the most elegant solution is one that *preserves* that

Figure 1.4.
Statistics summarizing 1,000 runs of Copycat on Problem 4.



medium in expressing the modified message " 1-2-4." Otherwise, why wouldn't и88УУУУ be just as good as, if not better than, **mrryyyy?**

As can be seen in Figure 1.4, by far the most common answer is the straightforward **mrrkkk,** with **mrrjjk** coming in a fairly distant second." For Copycat, these are the two most immediate answers; however, the average final temperatures associated with them are fairly high because of the lack of any coherent structure tying together the target string as a whole.

Next come two answers with roughly equal frequencies': **mrrjkk,** a rather silly answer that comes from grouping only the rightmost two **j's** in **mrrjjj** and viewing this group as the object to be replaced; and **mrrjjjj.** The average final temperature associated with this answer is much lower than that of the other answers; this shows that the program assesses it to be the most satisfying answer, though far from the most immediate. As in many aspects of real life, the immediacy or obviousness of a solution is by no means perfectly correlated with its quality. The other two answers produced in this series of runs, **mrrddd** and **mrrjjd,** come from replacing either a letter or a group with d's, and are on the fringes.

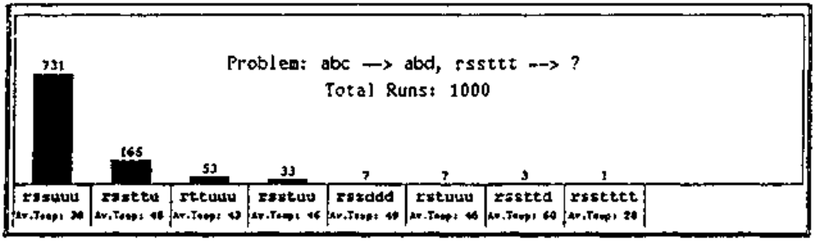
In Problem 4, the successorship fabric is between group lengths rather than between letters, and is thus not immediately apparent. A simple variant on Problem 4 involves a successorship fabric both at the level of letters and at the level of lengths:

5. Suppose the letter-string **abc** were changed to **abd;** how would you change the letter-string **rssttt** in "the same way"?

The strong pressures evoked in Problem 4 by the lack of any alphabetical fabric are missing in this variant, and the effect on Copycat can be seen in the bar

' The differences between the frequencies given in this figure and those given for the same problem in Mitchell & Hofstadter, 1990b, are due to several improvements in the program—in particular, improvements in the way letter-groups and bridges are constructed.

Figure 1.5.
Statistics summarizing 1,000 runs of Copycat on Problem 5.



graph given in Figure 1.5: the program gave the *length* answer **rsstttt** only once in 1,000 runs (as contrasted with 39 instances of **mrrjjjj** in Problem 4). In Problem 5, the program is much more satisfied with the *letter-level* answer **(rssuuu),** which dominates and has a relatively low average final temperature. The other answers are similar to the answers given in the previous problem (plus there are a few additional answers based on strange groupings of the target string).[5]

5.5. **Paradigm Shifts in a Microworld**

A different set of issues comes up in the following problem:

6. Suppose the letter-string abc were changed to abd; how would you change the letter-string xyz in "the same way"?

Naturally, the focus is on the letter z, and one immediately feels challenged by its lack of successor—or more precisely, by the lack of a successor to *Platonic* z, the abstract concept (as opposed to the instance thereof found inside the string xyz). Many people, eager to *construct* a successor to Platonic z, invoke the commonplace notion of circularity, thus conceiving of a as the successor of z, much as January can be considered the successor of December, the digit 'O' the successor of the digit '9', an ace the successor of a king, or, in music, the note A the successor of the note G. Invoking circularity in this way to deal with Problem 6 is a small type of creative leap, and not to be looked down upon. However, the general notion of circularity is not available to the program, as it is to people, for borrowing and insertion into the alphabet world. In fact, for important reasons,

[5] The current version of Copycat is not able to create two simultaneous bonds between two given objects (e.g., both the *alphabetical* and *numerical* successorship bonds between r and ss), so the program is at present unable to get what many people consider to be the best answer—namely, **rssuuuu.**

it is strictly stipulated that Copycat's alphabet is linear and just stops dead at z, immutably. We deliberately set this roadblock, because one of our main goals from the very conception of the project was to model the process whereby people deal with impasses.

At this point, quite a variety of thoughts can and do occur to people, such as: replace the z by nothing at all, thus yielding the answer xy. Or replace the z by the literal letter d, yielding answer xyd. (In other circumstances, such a resort to literality would be considered a rigid-minded and rather crude maneuver, but here it suddenly appears quite fluid and certainly reasonable.) Other answers, too, are possible, such as xyz itself (since the z cannot move farther along, just leave it alone); xyy (since you can't take the *successor* of the z, why not take its *predecessor,* which seems like second best?); xzz (since you can't take the successor of the z itself, why not take the successor of the letter sitting next to it?); and many others.

However, there is one particular way of looking at things that, to many people, seems like a genuine insight, whether or not they come up with it themselves. Essentially this is the idea that **abc** and xyz are "mirror images" of each other, each one being "wedged" against its own end of the alphabet. This would imply that the z in xyz corresponds not to the c but to the a in **abc,** and that it is the x rather than the z that corresponds to the c. (Of course, the b and the y are each other's counterparts as well.) Underlying these object-to-object correspondences (i.e., bridges) is a set of three conceptually parallel slippages: *alphabetic-first* ф *alphabetic-last, rightmost* ф *leftmost,* and *successor* ф *predecessor.* Under the profound conceptual reversal represented by these slippages, the raw rule flexes exactly as it did in Problem 2—namely, into "Replace the *leftmost* letter by its alphabetic *predecessor."* This yields the answer wyz, which many people (including the authors) consider elegant and superior to all the other answers proposed above.

Note how similar and yet how different Problems 2 and *6* are. The key idea in both is to effect a double reversal (i.e., to reverse one's perception of the target string both spatially and alphabetically). However, it seems considerably easier for people to come up with this insight in Problem 2, even though in that problem there is no "snag," as there is in Problem *6,* serving *toforce* a search for radical ideas. The very same insight is harder to come by in Problem 6 because the cues are subtler; the resemblance between a and z lurks quite far beneath the surface, whereas the resemblance between **aa** and **kk** is quite immediate. In a sense, answer wyz to Problem 6 seems like a miniature "conceptual revolution" or "paradigm shift" (Kuhn, 1970), whereas answer **hjkk** to Problem 2 seems elegant but not nearly as radical. Any model of mental fluidity and creativity must faithfully reflect this notion of distinct "levels of subtlety." We will return to these issues of snags, cues, radical perceptual shifts, and levels of subtlety in Section 6, where we discuss the way in which Copycat succeeds, at least occasionally, in carrying out this miniature paradigm shift.

djk. However, in 1,000 runs on Problem 1, Copycat never produced any of those answers, nor have we ever run into a human who has suggested any of them as an answer to Problem 1. (Actually, one person once *did* propose **hjk** in answer to Problem 1, but this was under the influence of having just seen the wyz answer to Problem 6.) In colloquial terms, answers to Problem 1 based on a crosswise mapping seem completely "off the wall."

In Problem 7, of course, things are different, because there is, after all, a snag, and hence a kind of "desperation." The various emergency measures—especially the persistent high temperature—make the normally unappealing **r-z** bridge slightly more likely, and so, once in a while, it gets built. From that point on, the whole paradigm shift goes through exactly as in Problem 6, and wyz is the outcome.

In some sense, Problem 7 lies halfway between Problems 1 and 6, so answer **wyz** in Problem 7 represents an intermediate stage between unmotivated and motivated fluidity. It is most gratifying to us that Copycat responds to the different constellations of pressures in these problems in much the way that our intuition feels it ought to.

5.6. Families of Problems as a "Miniature Turing Test"

It cannot be overestimated how critical we feel is this method of probing Copycat through various families of subtly related problems. When we began running Copycat on a large 'number of problems, we had no clear idea of what its performance would be, and we were, frankly, somewhat nervous. To us, the experience of watching Copycat reacting to each new problem had the feel of a kind of "miniature Turing Test," in the sense that each new problem posed to Copycat was like a question and answer in the Turing Test that would inevitably bring out some new and unanticipated aspect of the program's "personality" (this analogy to the Turing Test is further discussed in French, 1992; see also Hofstadter, 1991). Copycat's mechanisms were truly put to the test by the families of problems we challenged it with, and by and large it came through with flying colors. A much more complete discussion of those tests can be found in Chapters IV and V of Mitchell (1993).

The bar graphs that have been presented in this section demonstrate something of the range of Copycat's abilities, and how different constellations of pressures affect its behavior. They demonstrate the degree to which the program exhibits rudimentary fluid concepts that are able to adapt to different situations in a microworld that, though idealized, captures much of the essence of real-world analogy-making. They further reveal, by displaying *bad* analogies Copycat makes, some of the program's internal flaws and weaknesses. But they also demonstrate that although Copycat has the *potential* to get far-fetched answers—a potential that is essential for flexibility—it still manages to *avoid* them almost all the time, which demonstrates its robustness.

It is important to emphasize once again that our goal is not to model specifically how people solve these letter-string analogy problems (it is clear that the microworld involves only a very small fraction of what people know about letters and might use in solving these problems), but rather to propose and model mechanisms for fluid concepts and analogy-making in *general.* These mechanisms, described in Section 2, will be illustrated in detail in the next section, which follows the temporal progression of Copycat as it solves two problems. First we take a particular run of the program on Problem 4 and present it through a series of screen dumps; then we move to Problem 6 and discuss the abstract pathway followed by almost all runs that lead to answer **wyz.**

6. COPYCAT'S PERFORMANCE: A TREE-LEVEL CLOSE-UP

6.1. A Problem where Perception Plays a Crucial Role is Chosen as a Focus

We now illustrate the mechanisms described in this article by presenting a detailed set of screen dumps from a single run of Copycat on Problem 4. As was discussed above, this problem has a seemingly reasonable, straightforward solution, **mrrkkk,** but neither this answer nor the more literal **mrrjjk** is very satisfying, since neither reflects an underlying successorship structure in **mrrjjj** analogous to that in **abc.** Such a successorship fabric can be found only if relationships between group lengths are perceived in **mrrjjj.** But how can the notion of group length, which in most problems remains essentially dormant, come to be seen as relevant by Copycat?

Length is certainly in the halo of the concept *group,* as are other concepts, such as *letter category* (e.g., j for the group jjj), *string position* (e.g., *rightmost),* and *group fabric* (e.g., *sameness* between letters). Some of these concepts are more closely associated with *group* than others; in the absence of pressure, the notion of *length* tends to be fairly far away from *group* in conceptual space. Thus, in perceiving a group such as rr, one is virtually certain to notice its letter category (namely, r), but not very likely to notice, or at least attach importance to, its length (namely, 2). However, since the concept *length* is in *group's* halo, there is some possibility that lengths will be noticed and used in trying to make sense of the problem. One might, for instance, consciously notice a group's length at some point, but if this doesn't turn out to be useful, *length's* relevance will diminish after a short while. (For example, this might happen in the variant problem **"abc Φ abd, mrrrrjj** ф ?".) This dynamic aspect of relevance is very important: even if a new concept is at some point brought in as potentially relevant, it is counterproductive to continue spending much of one's time exploring avenues involving that concept if none seems promising.

6.2. The Story in Quick Strokes

One way Copycat arrives at mrrjjjj is now sketched (of course, since the program is nondeterministic, there are many possible routes to any given answer). The input consists of three "raw" strings (here, abc, abd, and mrrjjj) with no preattached bonds or preformed groups; it is thus left to the program to build up perceptual structures constituting its understanding of the problem in terms of concepts it deems relevant.

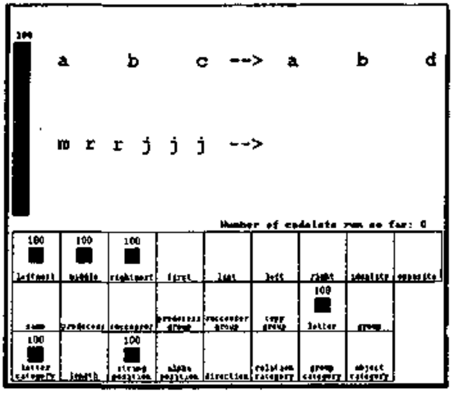
On most runs, the groups rr and jjj get built (the program tends to see sameness groups quite fast). Each group's letter category (r and j respectively) is noted, since the concept *letter category* is relevant by default. Although there is some chance for length to be noticed when a group is made, it is low, as *length* is only weakly associated with *group.* Once the groups rr and jjj are constructed, *sameness group* becomes very relevant, which creates top-down pressure for the system to describe other objects, especially in the same string, as sameness groups, if possible. The only way to do this here is to describe the m as a sameness group having just one letter. But this is resisted by a strong opposing pressure: a single-letter group is an intrinsically weak and far-fetched construct. It would be disastrous if Copycat were willing to bring in unlikely notions such as single-letter groups without strong pressure: it would then waste huge amounts of time exploring ridiculous avenues in every problem. However, the existence of two other strong sameness groups in the same string, coupled with the system's unhappiness at its failure to incorporate the lone m into any large, coherent structure (evidenced by a persisting high temperature), pushes against this intrinsic resistance.

These opposing pressures fight; the outcome is decided only as a statistical result of probabilistic decisions made by a large number of codelets. If the m chances to be perceived as a single-letter sameness group, that group's length will very likely be noticed (single-letter groups are noteworthy precisely because of their abnormal length), making *length* more relevant in general, and thus increasing the probability of noticing the other two groups' lengths. Moreover, *length,* once brought into the picture, has a good chance of staying relevant, since descriptions based on it turn out to be useful. (Without reinforcement, a node's activation decays over time. Thus, for instance, had the target string been mrrrrjj, *length* might get brought in at some point, but it would not turn out useful, so it would likely fade back into obscurity.)

In mrrjjj, once lengths are noticed, the (numerical) successor relations among them might be spotted by bottom-up codelets, ever-present in the Coderack, continually seeking new relations in the Workspace. (Note that such spontaneous bottom-up noticing could happen only in a parallel architecture where many types of properties are continually being looked for at once without a need for explicit prompting.) Another way, perhaps more likely, that the noticing of successor relations in **mrrjjj** could come about is through top-down pressure caused by the already seen successor relations in **abc.** In any case, as soon as the numerical successorship relations are seen and a much more satisfying view **of mrrjjj** begins to emerge, the importance of the groups' letter-categories fades and *length* becomes their most salient aspect. Thus, the crux of finding this solution lies in the triggering of the concept *length.*

6.3. Screen Dumps Tell the Story in Detail

In the following pages we give a series of screen dumps from a run of the program, showing one way it arrives at the answer **mrrjjjj** (note that this answer is not very typical: according to Figure 1.4, this answer is given only about four percent of the time).

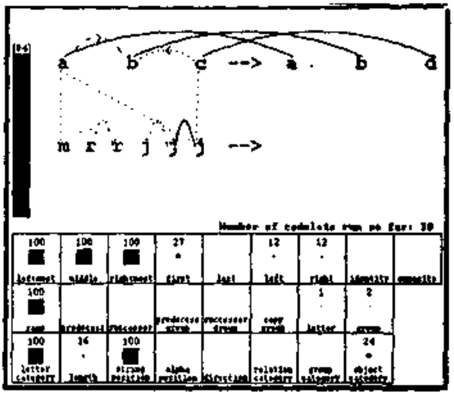


1. The problem is presented. Temperature, shown on a "thermometer" (at the left), is at its maximum of 100, since no structures have yet been built. At the bottom, some Slipnet nodes are displayed. (Note: links are not shown. Also, due to limited space, many nodes are not shown, e.g., those for a, b, etc.) A black square represents a node's current activation level (the numerical value, between 0 and 100, is shown above the square).

Nodes here displayed include *leftmost, middle, and rightmost* (the possible *string positions* of objects in the Workspace);//>ii and *last* (the distinguished *alphabetic positions* of Platonic letters a and z); *left* and *right* (the possible *directions* for bonds and groups); *identity* and *opposite* (two of the possible relations between concepts); *same, predecessor,* and *successor* (the possible *bond categories* for bonds between Workspace objects); *predecessor group, successor group,* and *copy group'* (the various *group categories); letter* and *group* (the possible *object categories* for Workspace objects); and in row 3, nodes representing these various categories of descriptions, including *length.*

Every letter comes with some preattached descriptions: its *letter category* (e.g., m), its *string position (leftmost, middle, rightmost,* or none—e.g., the fourth letter in **mrrjjj** has no string-position description), and its *object category* (letter, as opposed to *group).* These nodes start out highly activated.

[1] Note that the term *copy group,* in this set of screen dumps and captions, means *sameness group,* in the terminology of the text.



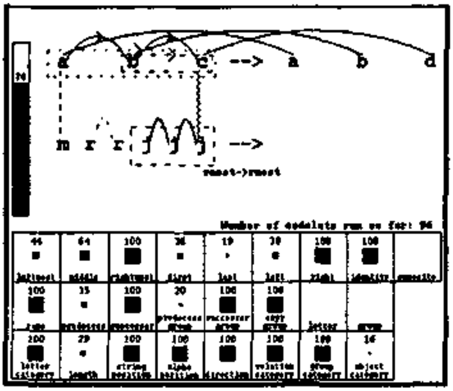
Number of codelets run so far: 30

100 leftmost	100 middle	100 rightmost	27 first	last	12 left	12 right	identity	opposite
100 same	predecessor	successor	predecessor group	successor group	sameness group	1 letter	2 group	
100 letter category	16 length	100 string position	alpha position	direction	relation category	group category	24 object category	

2. The 30 codelets so far run have begun exploring many possible structures. *Dotted* lines and arcs represent structures in early stages of consideration; *dashed* lines and arcs represent structures in more serious stages of consideration; finally, *solid* lines and arcs represent structures actually built, which can thus influence temperature as well as the building of other structures. Various bonds and bridges between letters are being considered (e.g., the dotted a-j bridge, which is based on the relatively long *leftmost-rightmost* Slipnet link; being implausible, it won't be pursued much further).

Bridges connecting letters in abc with their counterparts in **abd** have been built by bottom-up codelets, as has a j-j sameness bond at the right end of **mrrjjj;** this latter discovery activated the node *same,* resulting in top-down pressure (i.e., new codelets) to seek instances of sameness elsewhere.

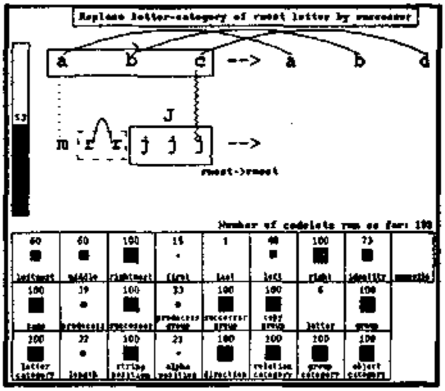
Some nodes have become lightly activated via spreading activation (e.g., the node *first,* via activation from the node a [not shown]). The activation of *length* comes from its weak association with *letter category* (letters and numbers form linear sequences and are thus similar; numbers are associateoywith *length).* The temperature has fallen in response to the structures so far built. It should be pointed out that many fleeting explorations are constantly occurring (e.g., "Are there any relations of interest between the m and its neighbor r?"), but they are not visible here.



3. The successorship fabric of abc has been observed, and two rival groups based on it are being considered: be and abc. Although the former got off to an early lead (it is dashed while the latter is only dotted), the latter, being intrinsically a stronger structure, has a higher chance of actually getting built.

Exploration of the crosswise a-j bridge was aborted, since it was (probabilistically) judged to be too weak to merit further consideration. A more plausible c-j bridge has been built (jagged vertical line); its reason for existence (namely, both letters are *rightmost* in their respective strings) is given beneath it, in the form of an identity mapping.

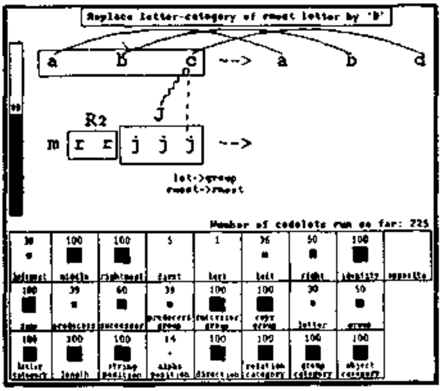
Since *successor* and *sameness* bonds have been built, these nodes are highly active; they in turn have spread activation to *successor group* and *copy group* (i.e., *sameness group),* which creates top-down pressure to look for such groups. Indeed, a jjj copy group is being strongly considered (dashed box). Also, since *first* was active, *alphabetic position* became highly active (a probabilistic event), making alphabetic-position descriptions likely to be considered.



4. Groups abc and jjj have been built (the bonds between their letters still exist, but for the purposes of graphical simplicity are no longer being displayed). An rr copy-group is being considered. The already-built copy-group jjj strongly supports this potential move, which accelerates it, in the sense that codelets investigating the potential structure will be assigned higher urgency values.

Meanwhile, a *rule* (shown at the top of the screen) has been constructed to describe how abc changed. The current version of Copycat assumes that the example change involved the replacement of exactly one letter, so rule-building codelets fill in the template "Replace————by————," choosing probabilistically from descriptions that the program has attached to the changed letter and its replacement, with a probabilistic bias toward choosing more abstract descriptions (e.g., usually preferring *rightmost letter* to c).

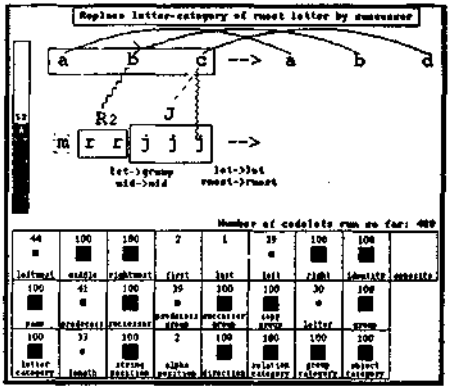
Since the nodes *first* and *alphabetic position* didn't turn out useful, they have faded. Also, although *length* received additional activation from *group,* it is still not very activated, and so lengths are still unlikely to be noticed.



Replace letter-category of rmost letter by 'd'

Number of codelets run so far: 225

30 leftmost	100 middle	100 rightmost	5 first	1 last	36 left	50 right	100 identity	opposite
100 same	39 predecessor	60 successor	39 predecessor group	100 successor group	100 copy group	30 letter	50 group	
100 letter category	100 length	100 string position	14 alpha position	100 direction	100 relation category	100 group category	100 object category	



Replace letter-category of rmost letter by successor

Number of codelets run so far: 400

44 leftmost	100 middle	100 rightmost	7 first	1 last	35 left	100 right	100 identity	opposite
100 same	41 predecessor	100 successor	39 predecessor group	100 successor group	100 copy group	30 letter	100 group	
100 letter category	33 length	100 string position	2 alpha position	100 direction	100 relation category	100 group category	100 object category	

5. Now, some 225 codelets into the run, the letter-to-letter c-j bridge has been defeated by the stronger letter-to-group c-J bridge, although the former possibility still lurks in the background. Meanwhile, an IT copy group has been built whose length (namely, 2) happened to be noticed (a probabilistic event); therefore, a '2', along with the group's letter category (namely, r), is displayed just above the group. *Length* is now fully active, and for this reason the '2' is a salient Workspace object (indicated by boldface).

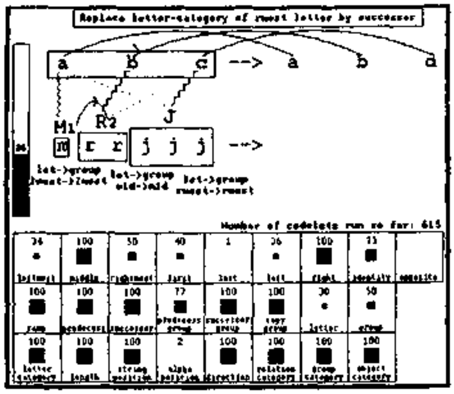
A new rule, "Replace the letter category of the rightmost letter by d," has replaced the old one at the top of the screen. Although this rule is weaker than the previous one, fights between rival structures (including rules) are decided probabilistically, and this one simply happened to win. However, its weakness has caused the temperature to go up.

If the program were to stop now (which is quite unlikely, since a key factor in the program's probabilistic decision when to stop is the temperature, which is now relatively high), the rule would be adapted for application to the string mrrjjj as "Replace the letter category of the rightmost *group* by d" (the c-J bridge establishes that the role of *letter* in abc is played by *group* in mrrjjj), yielding the answer mrrddd (an answer that Copycat does indeed produce, on rare occasions).

6. The previous, stronger rule has been restored (again the result of a fight having a probabilistic outcome), but at the same time, the strong **c-J** bridge also happened to get defeated by its weaker rival, the **c-j** bridge. As a consequence, if the program were to stop at this point, its answer would be **mrrjjk.** This, incidentally, would also have been the answer in screen dump #4.

In the Slipnet, the activation of *length* has decayed a good deal, since the length description given to **rr** wasn't found to be useful. In the Workspace, the.diminished salience of the rr's length description '2' is represented by the fact that the '2' is no longer in boldface.

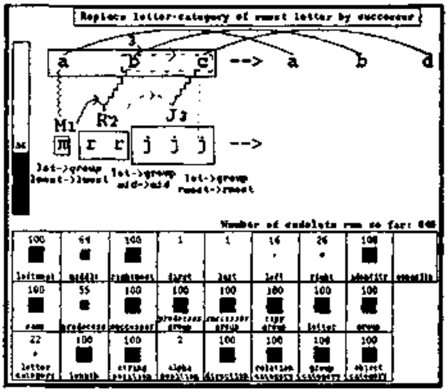
The temperature is still fairly high, since the program is having a hard time making a single, coherent structure out of **mrrjjj,** something that it did easily with abc. That continuing difficulty, combined with strong top-down pressure from the two copy groups that have been built inside **mrrjjj,** makes it now somewhat tempting for the system to flirt with the *a priori* extremely unlikely idea of making a single-letter copy group (this flirtation is represented by the dashed rectangle around the letter m).



Replace letter-category of rmost letter by successor

Number of codelets run so far: 615

34 leftmost	100 middle	50 rightmost	40 first	1 last	36 left	100 right	13 identity	opposite
100 same	100 predecessor	100 successor	77 predecessor group	100 successor group	100 copy group	30 letter	50 group	
100 letter category	100 length	100 string position	2 alpha position	100 direction	100 relation category	100 group category	100 object category	



Replace letter-category of rmost letter by successor

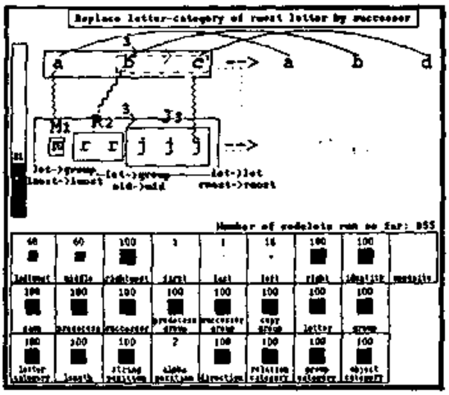
Number of codelets run so far: [illegible]

100 leftmost	64 middle	100 rightmost	1 first	1 last	16 left	26 right	100 identity	opposite
100 same	55 predecessor	100 successor	100 predecessor group	100 successor group	100 copy group	100 letter	100 group	
22 letter category	100 length	100 string position	2 alpha position	100 direction	100 relation category	100 group category	100 object category	

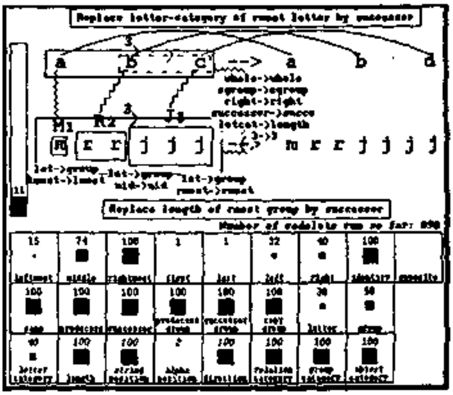
7. As a result of these combined pressures, the *a priori* extremely unlikely single-letter copy group m happened to get built, and its length of 1, being very noteworthy, has been attached to the group as a description. A successorship bond between that T and its right-neighbor '2' has already been built; all of this is helping *length* to stay active. A consistent trio of *letter* =J> *group* bridges has now been made, and as a result of these promising new structures, the temperature has fallen to the relatively low value of 36, which in return helps to lock in this emerging view.

If the program were to halt in this screen dump or in the following one, it would produce the answer **mrrkkk,** which is its most frequent answer.

8. As a result *of length's* continued activity, length descriptions have been attached to the remaining two groups in the problem (jjj and abc), and a successorship bond between the '2' and the '3' (for which there is much top-down pressure coming from both **abc** and the emerging view of mrrjjj) is being considered (dashed arc). *Letter category* has decayed, indicating that it hasn't lately been of use in building structures.


Replace letter-category of rmost letter by successor

Number of codelets run so far: 855


Replace letter-category of rmost letter by successor

Replace length of rmost group by successor

Number of codelets run so far: 890

9. The '2'–'3' bond was built, whereupon a very abstract, high-level numerical successor group involving the group lengths in **mrrjjj** was perceived (large solid rectangle surrounding the three copy groups). Also, a bridge (dotted vertical line to the right of the two strings) is being considered between strings **abc** and **mrrjjj** in their entireties.

Ironically, just as these sophisticated ideas seem to be converging toward a highly insightful answer, a small renegade codelet, totally unaware of the global momentum, has had some good luck: its bid to knock down the **c-J** bridge and replace it with a c-j bridge was accepted. Of course, this is a setback on the global level. If the program were forced to stop at this point, it would answer **mrrjjk**—the same rather dull answer as it would have given in screen dumps # 6 and # 4. However, at either of those stages, that answer would have been far more excusable than it is now, since the program hadn't yet made the subtle discoveries it has now made about the structure of **mrrjjj.** It would seem a shame for the program to have gotten this far and then to "drop the ball" and answer in a relatively primitive way. However, 31 is a high enough temperature that there is a good chance that the program will get back on track and be allowed to explore the more abstract avenue to its logical conclusion.

10. Indeed, the aberrant bridge from the c was quickly destroyed and replaced by a rebuilt **c-J** bridge, in keeping with the emerging sophisticated view. Also, the high-level bridge between **abc** and **mrrjjj** as wholes, which in the previous screen dump was merely a dotted candidate, has now been promoted through the dashed state and actually built. Its six component concept-mappings, including identity mappings (such as rigAf ^> *right,* meaning that both strings are seen as flowing rightwards) as well as conceptual slippages (such as *letter category* Φ *length,* meaning that letters are mapped onto numbers—specifically, onto group lengths), are listed in the middle of the screen, somewhat obscuring the bridge itself.

The original rule has been translated, according to the slippages, for application to the target string **mrrjjj.** The translated rule, "Replace the length of the rightmost group by its successor," appears just above the Slipnet, and the answer **mrrjjjj** appears at the right. The very low final temperature of 11 reflects the program's unusually high degree of satisfaction with this answer.

Although the preceding run may look quite smooth, there were many struggles involved in coming up with this answer: it was hard not only to make a single-letter group, but also to bring the notion of *length* into the picture, to allow it to persist long enough to trigger the noticing of all three group lengths, and to build bonds between the group lengths. The program, like people, usually gives up before all these hurdles can be overcome, and gives one of the more obvious answers.

The moral of all this is that in a complex world (even one with the limited complexity of Copycat's microworld), one never knows in advance what concepts may turn out to be relevant in a given situation. This dilemma underscores the point made earlier: it is imperative not only to avoid dogmatically open-minded search strategies, which entertain all possibilities equally seriously, but also to avoid dogmatically closed-minded search strategies, which in an ironclad way rule out certain possibilities a priori. Copycat opts for a middle way, which of course leaves open the potential for disaster—and indeed, disaster occurs once in a while (as was evidenced by some of the far-fetched answers displayed earlier). This is the price that must be paid for flexibility. People, too, occasionally explore and even favor peculiar routes. Copycat, like people, has to have the potential to concoct strange and unlikely solutions in order to be able to discover subtle and elegant ones like mrrjjjj. To rigidly close off any routes a priori would necessarily remove critical aspects of Copycat's flexibility. On the other hand, the fact that Copycat so rarely produces strange answers demonstrates that its mechanisms manage to strike an effective balance between open-mindedness and closed-mindedness, imbuing it with both flexibility and robustness.

Hopefully, these screen dumps have made clearer the fundamental roles of nondeterminism, parallelism, noncentralized and simple perceptual agents (i.e., codelets), the interaction of bottom-up and top-down pressures, and the reliance on statistically emergent (rather than explicitly programmed) high-level behavior. Large, global, deterministic decision are never made (except perhaps towards the end of a run). The system relies instead on the accumulation of small, local, nondeterministic decisions, none of which alone is particularly important for the final outcome of the run. As could be seen in the screen dumps, large-scale effects occur only through the statistics of the lower levels: the ubiquitous notion of a "pressure" in the system is really a shorthand for the statistical effects over time of a large number of actions carried out by codelets, on the one hand, and of activation patterns of nodes in the Slipnet, on the other.

As was seen in the screen dumps, as structures are formed and a global interpretation coalesces, the system gradually makes a transition (via gradually falling temperature) from being quite parallel, random, and dominated by bottom-up forces to being more deterministic, serial, and dominated by top-down forces. We believe that such a transition is characteristic of high-level perception in general. The importance of such a transition was indicated by three experiments we performed on the model (described in Mitchell, 1993), in which temperature was clamped throughout a run, in the first experiment at a very high value, in the second at an intermediate value, and in the third at a very low value, effectively preventing such a transition from taking place. In these experiments, the program came up with the answer **mrrjjjj** much less frequently than before, almost never giving this answer in the first and third experiments, and giving it slightly more than half as often as before in the second experiment.

6.4. Microanatomy of a Paradigm Shift

We now turn our attention from Problem 4 to Problem 6, and give a sketch of how Copycat can, on occasion, come up with the answer **wyz.** It turns out to be a surprisingly intricate little tale. The reason for this is that it is an attempt to show in slow motion how a human mind, under severe pressure, can totally transform its perception of a situation in a blinding flash. Since such paradigm shifts are often found at the core of deeply creative acts, one should expect their microstructure to be very complex! Indeed, the challenge of getting Copycat to produce wyz *properly*—faithfully to what we believe really goes on in a human mind at the most informative subcognitive level of description—has, from the very outset, been the central inspiration in guiding the development of the Copycat architecture.

The very cursory justification for wyz given in the previous section lies at far too high and coarse-grained a level to be informative about the mental mechanisms responsible for paradigm shifts. The following detailed story, by contrast, evolved hand in hand with the architecture itself, and is intended not only as a description of Copycat, but hopefully as an accurate description of the underpinnings of a typical paradigm shift in a human mind. (An annotated series of screen dumps of a particular run on Problem 6 is given in Mitchell, 1993.)

6.5. Emergency Measures Convert a Serious Snag into a Set of Exploratory Pressures

Things start out essentially analogously to a typical run on Problem 1, in terms of bonding, grouping, bridge-building, and such—that is, both source and target strings cotne quite quickly to be perceived as successor groups, and the raw rule "Replace the rightmost letter by its successor" is effortlessly produced. Everything thus proceeds pretty smoothly up to the point of trying to take the successor of z, which is impossible. This serious snag causes several coordinated "emergency measures" to be taken:

- the *physical* trouble spot—here, the instance of ζ in the Workspace—is highlighted, in the sense that its salience is suddenly pumped up so high that, to codelets, it becomes the most attractive object in the entire Workspace;

- the *conceptual* trouble spot—here, the node z in the Slipnet—is highlighted, in the sense that a jolt of activation is pumped into it, and as a consequence, its halo broadens and intensifies, meaning that related concepts are more likely to be considered, at least fleetingly;
- the temperature is pumped up to its maximum value of 100 and temporarily clamped there, thus encouraging a broader and more open-minded search;
- the high temperature enables previously dormant "breaker" codelets to run, whose purpose it is to arbitrarily break structures that they find in the Workspace, thus reducing the system's attachment to a viewpoint already established as being problematic.

Note the generality of these "impasse-handling" mechanisms: they have nothing to do with this snag itself, with the particular problem, or with the domain. The reason for this is ofcourse that running into an impasse is a critical and common event that any cognitive system must be capable ofdealing with. To be sure, no set of mechanisms can be guaranteed to resolve *all* snags (otherwise we would be dealing with omniscience, not intelligence). The best that can be hoped for is that the impasse itself can be "read" as a source of *cues*—possibly very subtle ones—that may launch tentative forays down promising new avenues. A "cue," in the Copycat architecture, is essentially the creation of a *pressure* that pushes for exploration along a certain direction. Thus, the idea of *interpreting the snag as a source ofpressures* is the philosophy behind the four mechanisms above, especially the first two.

Although these emergency measures are not powerful enough to guide Copycat to come up with wyz all that often, when it does get there it does so essentially according to the following scenario. The spotlight focused on Platonic z has the effect of making all concepts in z's halo—including the closely related concept *alphabetic last*—somewhat more likely to be looked at by description-building codelets. The probability is thus significantly increased that the instance of ζ in the Workspace will get explicitly described as *alphabetic last.*

Note that in most problems—even ones that involve one or more instances of the letter ζ—there is little or no reason to pay attention to the notion *alphabetic last,* and therefore, this conceptually deep neighbor of Platonic ζ usually remains—and *should* remain—dormant (as it did in Problems 1-5). After all, as was brought out in the discussion of Problem 4, it is extremely crucial to avoid cluttering up the processing with all sorts of extraneous interfering notions, no matter how conceptually deep they may be. But now, under the emergency measures, unusual things are more likely to happen.

If the description *alphabetic last* does indeed get attached to the z, which is a dicey matter, then a further boost is given to the node *alphabetic last,* as the system has deemed it potentially relevant. So now that *alphabetic last* (part of the halo of Platonic z) has been lifted considerably out of dormancy, concepts in *its* halo will in turn receive more activation, and thus more attention from codelets (probabilistically speaking). One such concept is *alphabeticfirst,* which is now briefly given the chance to show its relevance. If there were no instance of a in the problem, this concept would of course be found to be completely irrelevant and would decay back to dormancy, but since there is an a inside abc, it has a fair chance of getting explicitly described as *alphabeticfirst,* in much the same way as the ζ in xyz got described as *alphabetic last.*

If both these descriptions get attached—and that is a big "if"—then both letters become even more salient than before; in fact, they almost cry out to be mapped onto each other—not because the system appreciates the *basis* for such a mapping, but simply because both are so salient! Once the system tries it out, however, the great appeal of the tentative mapping instantly becomes apparent. Specifically, a pair of conceptual slippages are entailed in the act of "equating" the a with the z: *alphabeticfirst* into *alphabetic last,* and *leftmost* into *rightmost.*

6.6. How Resistance to a Deep Slippage is Overcome—A Tricky Matter

Although normally the slippage of *alphabeticfirst* into *alphabetic last* would be quite valiantly resisted (recall the motto given earlier, "Deep stuff doesn't slip in good analogies"), here a special circumstance renders it a bit easier: the companion would-be slippage *leftmost* φ *rightmost* is of the same type—namely, each of them involves slipping a concept representing an extremity into its opposite concept. These two would-be slippages are thus conceptually parallel, and hence each reinforces the other's plausibility. This fact helps to overcome the usual resistance to a deep slippage. (Incidentally, this is the kind of subtlety that was not at all apparent to us before the computer implementation was largely in place; only at that point were Copycat's flailings and failures able to give us pointers as to what kinds of additional mechanisms were needed.)

Another fact that helps overcome the usual resistance to the deep slippage in this bridge is that *any* two slippages, whether parallel or not, provide more justification for building a bridge than either one alone would. Altogether, then, there is a fairly good chance that this bridge, once tentatively suggested, will actually get built. Once this critical step has taken place, essentially it's all downhill from there. This is why we have paid particularly close attention to the pathway via which such a bridge can emerge.

6.7. Locking-in of *a* New View

The first thing that is likely to happen as a result of an a-z bridge getting built is that the temperature will get undamped from its value of 100. In general, what unclamps the temperature is the construction of any strong structure different from those that led up to the snag—in other words, a sign that an alternative way of looking at things may be emerging—and this bridge is a perfect example of such a structure. Like most actions in Copycat, the unclamping of temperature is probabilistic. In this case, the stronger the novel structure is, the more likely it is to trigger the unclamping. Since the a-z bridge is both novel and very strong, unclamping is virtually assured, which means that the temperature falls drastically right after the bridge is built. And when the temperature falls, decisions tend to get more deterministic, which means that the emerging new view will tend to get supported. In short, there is a powerful kind of *locking-in* effect that is triggered by the discovery of an a-z bridge. This is a critical effect.

Another aspect of locking-in is the following idea. The building of this first bridge involving the simultaneous slippage of two concepts into their opposites sends a burst of activation into the very deep concept *opposite,* and as a result, all pairs of concepts connected via links labeled *opposite* are drawn much closer together, facilitating the slippage of one into the other. Such slippages will still not happen without reason, of course, but now they will be much easier to make than in ordinary circumstances. Thus, in a sense, making *one* bridge based on conceptual opposites sets a tone making it easier to make *more* of them. The emerging theme of the concept *opposite* can fairly be characterized as a kind of "bandwagon."

Given all this, one of the most likely immediate consequences of this first crosswise bridge is the building of the "mirror" bridge connecting the x with the c. It, too, depends on the slippage between *leftmost* and *rightmost,* and is thus facilitated; in addition, once built, it strongly reinforces the emerging relevance of the concept *opposite.* Moreover, the temperature will fall significantly because this bridge, too, will be very strong. Thanks to all of this, the locking-in effect may by now be so strong that it will be hard to stop the momentum towards building a completely new view of the situation.

The reversals taking place become a near stampede at this point, and significant pressure emerges to flip the direction of the fabric of the group xyz from *rightwards* to *leftwards,* which means also that the perceived fabric itself would switch from *successor* to *predecessor.* Thus, at this point, Copycat has carried out both a spatial and an alphabetical reversal of its vision of xyz. The paradigm shift has been completed. At this point, Copycat is ready to translate the raw rule, and, as was said above, the result is the new rule "Replace the *leftmost* letter by its *predecessors,* which yields the answer wyz.

It must be stressed that all the multifarious activity just described—shifting degrees of activation of various key concepts; deep slippages; interrelated spatial and conceptual reversals—all this takes place in a flash in a human mind. There is no hope of making out all the details of this paradigm shift (or any other) in one's own mind by merely introspecting. In fact, it has taken the authors several years to settle on the above account, which represents our current best stab at the true story's intimate details.

6.8. How Hard Is it to Make this Paradigm Shift?

As was pointed out a moment ago, the motto "Deep stuff doesn't slip in good analogies" is violated by answer wyz, in that *alphabetic first* is a deep concept and yet is allowed to slip into *alphabetic last* here. This is one reason that makes it so hard for many people to discover it on their own. \fet many people, when they are shown this answer, appreciate its elegance and find it very satisfying. Problem 6 is thus a circumstance where a constellation of pressures can occasionally overcome the powerful natural resistance expressed by the motto; in fact, making such a daring move results in what many people consider to be a deep and insightful analogy.

There is an important irony here. In particular, even though slippages tend to be (and should be) *resisted* in proportion to their depth, once a very deep slippage has been made, then it tends to be (and should be) *respected* in proportion to its depth. We consider this to be characteristic of creative breakthroughs in general. More specifically, we consider the process of arriving at answer wyz to be very similar, on an abstract level, to the process whereby a full-scale conceptual revolution takes place in science (Kuhn, 1970).

Now we come back to the point raised in our earlier discussion of Problem 6 about "levels of subtlety" of answers. Specifically, we claimed above that, because finding the answer wyz to Problem 6 is far subtler *for people* than finding the similar answer **hjkk** to Problem 2, any model of mental fluidity should respect this difference in levels of subtlety. Yet when one compares the bar graphs for these problems, one discovers that wyz was found far more often than **hjkk** was found (a ratio of 137 to 47, when both problems were run 1,000 times). This seems to completely contradict the claim that the former answer is subtler than the latter. How can one account for this unexpected ratio?

There are two basic factors that explain it. The first has to do with the fact that there was a snag in one problem and no snag in the other. In attacking Problem 6, Copycat *was forced* to look for solutions other than taking the successor of the rightmost letter, because that route turned out to be impossible. By contrast, all sorts of superficially attractive routes led directly to solutions in Problem 2. There was no snag that prevented any attractive route from being taken all the way to its natural conclusion. Had all or most of the easy routes been barred, then of course **hjkk** would have constituted a much larger percentage of the answers found.

The second factor is that the average *length of time* taken to find various solutions (measured in terms of number of codelets run) is a key notion. This fact is not apparent, because average run-lengths are not given in the bar graphs. When Copycat came up with **hjkk** in Problem 2, it was essentially always a relatively direct process involving no backtracking or getting stuck for a while in a loop. To be specific, the average number of codelets taken to get **lykk** was 899. By contrast, the average number of codelets taken to get **wyz** was 3,982—over four times as long. The reason for this is that in most runs, the program came back time and time again to the standard way of looking at **xyz,** and thus hit the snag over and over again: it was stuck in a kind of rut. This means that on runs where Copycat was lucky enough to come across the double reversal, by the time it did so it had usually tried out all sorts of other pathways in vain beforehand. In this sense of *time needed to make the discovery,* wyz was an extremely elusive answer for the program, whereas **hjkk** was not at all elusive. In sum, wyz was indeed far subtler for Copycat than **hjkk** was, as ought to have been the case.

How is the performance—both tree-level and forest-level—that has been described in the last two sections to be judged? Of course, the ultimate criterion of its validity has to be whether our results jibe with general and universal characteristics of human analogy making (we do not mean a literal-minded comparison with human data on the same problems, since as we have said, precise simulation of human performance in this specific microdomain is *not* our goal). However, there is another way our work can and ought to be set in perspective: by comparison with other projects. Therefore, we turn now to a description of various types of related research.

7. COMPARISONS WITH RELATED WORK

In this section, the Copycat project is compared with other research on computer models of analogy-making; then follows a discussion of Copycat's place in the spectrum of computer models of intelligence, ranging from high-level symbolic models to low-level subsymbolic models. (Further comparisons with related work are given in Mitchell, 1993.)

7.1. Comparisons with Other Research on Analogy-Making

A fair amount of research has been done in artificial intelligence and cognitive science on constructing computer models of analogy-making, most of it concentrating on the use of analogical reasoning in problem-solving. The majority of models concentrate on how a mapping is made from a source problem (whose solution is known) to a target problem (whose solution is desired), with some kind of representation of the various objects, descriptions, and relations in the source and target problems given to the program ahead of time. Very few (if any) other computer models focus, as Copycat does, on how the *construction* of representations for the source and target situations interacts with the mapping process, and how new, previously unincluded concepts can be brought in and can come to be seen as relevant in response to pressures that emerge as processing proceeds. In short, no current computer model of analogy-making of which we are aware attempts, as Copycat does, to integrate high-level perception, concepts, and conceptual slippage. Because of this fundamental difference in philosophy, it is not at all straightforward to compare Copycat with other projects. Nonetheless, there are a couple of interesting models whose similarities and contrasts to Copycat definitely bear commenting upon.

In this section, rather than giving a complete survey of computer models of analogy-making, we will discuss (and compare with Copycat) in detail two different projects, chosen for their prominence in cognitive science and for their relevance with respect to the Copycat project. This leaves out many other models of analogy-making less related to Copycat; a good number of these are described by Hall (1989) and by Kedar-Cabelli (1988).

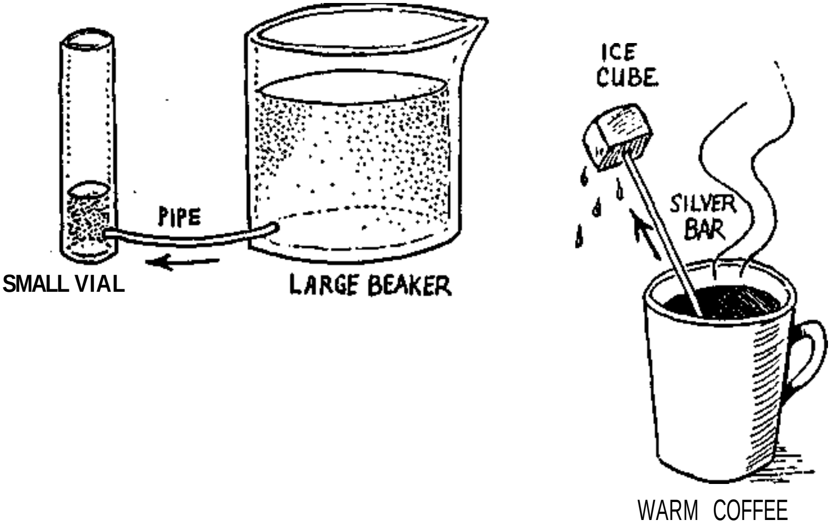
7.2. **A Quick Sketch of Centner's Structure-Mapping Theory and the SME Program**

Dedre Centner's research is perhaps the best-known work in cognitive science on analogy. She has formulated a theory of analogical mapping, called the "structure-mapping" theory (Centner, 1983), and she and her colleagues have constructed a computer model of this theory: the Structure-Mapping Engine, or SME (Falkenhainer, Forbus, & Centner, 1989). The structure-mapping theory describes how mapping is carried out from a source situation to a (sometimes less familiar) target situation. The theory gives two defining criteria for what counts as true analogical mapping: (a) *relations* between objects rather then *attributes* of objects are mapped; and (b) relations that are part of a coherent interconnected system are preferentially mapped over relatively isolated relations (the "systematicity" principle). Centner's very definition of analogy in effect presupposes these properties. According to her, there is a range of kinds of comparison: an *analogy* is a comparison in which only systematic relations are mapped, whereas a comparison in which both attributes and relations are mapped is a *literal similarity,* not an analogy.

One of Centner's examples of an analogy is illustrated in Figure 1.8 (from Falkenhainer, Forbus, & Centner, 1989). The idea "heat flow is like water flow" is illustrated by constructing correspondences between a situation in which water flows from a beaker to a vial through a pipe and a situation in which heat flows from coffee in a cup to an ice cube through a metal bar.

The predicate-logic representations given by Falkenhainer, Forbus, and Centner for these two situations are displayed in Figure 1.9. The idea is that the causal-relation tree on the left (representing the fact that greater pressure in the beaker causes water to flow from the beaker to the vial through the pipe) is a *systematic* structure and should thus be mapped to the heat-flow situation, whereas the other facts ("the diameter of the beaker is greater than the diameter of the vial," "water is a liquid," "water has a flat top," etc.) are irrelevant and should be ignored. Ideally, mappings should be made between *pressure* and *temperature;* between *coffee* and *beaker;* between *vial* and *ice cube;* between *water* and *heat;* between *pipe* and *bar;* and more obviously, between *flow* and *flow.* Once these mappings are made, a conjecture about the cause of heat flow in the situation on the right can be made by analogy with the causal structure in the situation on the left. Centner claims that if people recognize that this causal structure is the deepest and most interconnected system for this analogy, then they will favor it for mapping.

Figure 1.8.
Water-flow and heat-flow situations. (Adapted from 'The Structure-Mapping Engine," by B. Falkenhainer, K.O. Forbus, & 0. Centner, 1989, *Artificial Intelligence, 41(1}·* Adapted by permission.)

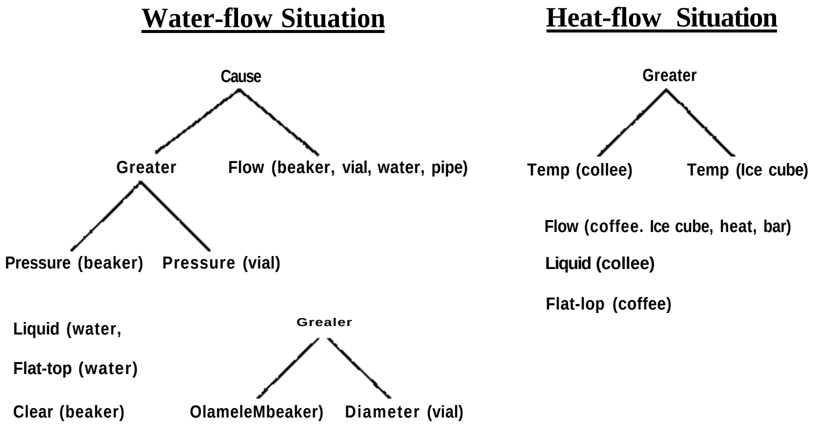


Centner gives the following (possibly conflicting) criteria for judging the quality of an analogy:

- *Clarity*—a measure of how clear it is which things map onto which other things;
- *Richness*—a measure of how many things in the source are mapped to the target;
- *Abstractness*—a measure of how abstract the things mapped are, where the degree of "abstractness" of an attribute or relation is its "order": attributes (e.g., "flat-top" in the example above) are of the lowest order, relations whose arguments are objects or attributes (e.g., "flow") are of higher order, and relations whose arguments are relations (e.g., "cause") are of even higher order;
- *Systematicity*—the degree to which the things mapped belong to a coherent interconnected system.

The computer model of this theory (SME) takes a predicate-logic representation of two situations (such as the representation given in Figure 1.9), makes a mapping between objects, attributes, and relations in the two situations, and then makes inferences from this mapping (such as "the greater temperature of

Figure 1.9.
Predicate-logic representations for the two situations shown in Figure 1.8.



the coffee causes heat to flow from the coffee to the -ice cube"). The only knowledge the program has of the two situations is their syntactic structures (e.g., the tree structures given for the water-flow and heat-flow situations displayed above); it has no knowledge of any of the *concepts* involved in the two situations. In other words, there is no prior structure containing any facts about water, liquids, heat, flow, or even physical objects. All processing is based solely on syntactic structural features of the two given representations.

SME first uses a set of "match rules" (provided to the program ahead of time) to make all "plausible" pairings between objects (e.g., *water* and *heat)* and between relations *(e.g., flow* of water and *flow* of heat). Typical match rules are: "if two relations have the same name, then pair them"; "if two objects play the same role in two already paired relations (i.e., are arguments in the same position), then pair them"; "pair any two functional predicates" (e.g., *pressure* and *temperature).* It then gives a score to each of these pairings, based on factors such as: Do the two things paired have the same name? What kind of things are they (objects, relations, functional predicates, etc.)? Are they part of systematic structures? The kinds of pairings allowed and the scores given to them depend on the set of match rules given to the program; different sets can be supplied.

Once all plausible pairings have been made, the program makes all possible sets of consistent combinations of these pairings, making each set (or "global match") as large as possible. "Consistency" here means that each element can match only one other element, and a pair (e.g., *pressure* and *temperature)* is allowed to be in the global match only if all the arguments of the two paired elements are also paired up in the global match. Such consistency ensures "clarity" (in Centner's sense), and the fact that the sets are maximal induces a preference for "richness." After all possible global matches have been formed, each is given a score based on the individual pairings it is made up of, the inferences it suggests, and its degree of systematicity. Centner and her colleagues have compared the relative scores assigned by the program with the scores people give to the various analogies (Skorstad, Falkenhainer, & Centner, 1987).

7.3. **Points of Agreement Between Copycat and SME**

Analogy-making as modeled in the Copycat program is in agreement with several aspects of Centner's theory. We agree with the main idea of systematicity: that in general, the essence of a situation—the part that should be mapped—is a high-level coherent whole, not merely a collection of isolated low-level facts. In Copycat, there is a definite pressure toward systematicity, which is itself an emergent result of several pressures:

- the pressure, coming from codelets, to perceive relations and groupings within strings;
- the pressure to see things abstractly (which itself emerges from the preference for using descriptions of greater conceptual depth, and from the tendency of deeper concepts to stay active longer);
- the pressure to describe the change from the initial to the modified string in terms of relationships and roles, since these tend to be deeper than attributes (e.g., in formulating a rule for the change abc Φ abd, it is in general better to describe the d as "the successor of the rightmost letter" rather than as "an instance of d");
- the greater salience of larger relational structures (e.g., a group consisting of an entire string), which makes them more likely to be paid attention to by codelets, and hence mapped;
- the high strength of correspondences between large relational structures (such as whole-string groups): such correspondences are strong not only because they involve large structures, but also because they are based on many concept-mappings;
- the pressure toward forming a set of compatible correspondences that, taken together, form a coherent worldview;
- the system's overall drive to achieve as low a temperature as possible, which pushes for the building-up of deep hierarchical perceptual structures, and thus for the construction of an abstract, conceptually deep view of the situations.

Centner captures several important notions in her four-point characterization of a "good" analogy, and corresponding pressures exist in Copycat: her pressure toward "clarity" is enforced by Copycat's prohibition of many-to-one or one-to-many mappings without first chunking the "many" into a group; her pressure toward "richness" corresponds to Copycat's preference for having many correspondences and many concept-mappings underlying a correspondence; and Copycat's drives toward abstraction and systematicity were just described above. But note that Centner's definition of "abstraction" (order of a relation) is not the same as the notion in Copycat of "conceptual depth." In Copycat, there is no logic-based definition for conceptual depth; rather, these values are assigned by hand, with quite high values sometimes going to concepts that Gentner might call "attributes" (such as *alphabeticfirst,* which could be seen as an attribute of the letter a).

7.4. Points of Disagreement Between Copycat and SME

Despite some points of agreement, there are several fundamental issues on which our approach and that of Gentner and her colleagues disagree; moreover, some of the most important aspects of analogy-making addressed in the Copycat project are not dealt with in any way by the structure-mapping theory nor by SME.

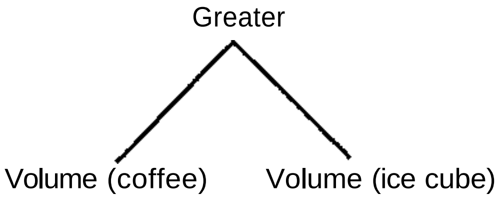
Centner's abstractness and systematicity principles capture something important about analogy-making, but there are often other pressures in an analogy: both superficial and abstract similarities that may not be parts of systematic wholes, but are still strong contenders in a competition. An example of this in the Copycat domain is Problem 2:

aabc=> aabd; ijkk => ?

The abstractness and systematicity principles would, it seems, argue for the answer jjll, since the label *sameness group* describing the group of a's and the group of k's is firstly merely an *attribute,* and secondly is not related to the systematic set of successor relations in each string; according to the systematicity principle, it should thus not be mapped, but should be ignored. However, as was discussed earlier, many people feel that the two groups should map onto each other nonetheless, and that the best answer is hjkk, in spite of what would be, it seems, an *a priori* dismissal by the structure-mapping theory. Making any analogy involves a competition between rival views, and one cannot be certain ahead of time that the mapping with the highest degree of systematicity (in Centner's sense) will have the highest quality.

Another problem with Centner's theory is that for any complex situation, there are many possible sets of relations that exhibit systematicity, and it is not explained how certain ones are considered for mapping and not others, on syntactic grounds alone. For example, suppose the heat-flow domain had contained the relation displayed in Figure 1.10.

Figure 1.10.
A Mghw order relation that might be added to the predicate-logic representation of heat flow shown in Figure 1.9.



There would be no reason, based on syntax alone, to prefer the structure concerning temperature over this structure for mapping; if this structure were chosen, the analogy-maker would mistakenly conclude that, just as the pressure differential causes the water flow, the volume differential causes the heat flow. SME has no semantic connection between *temperature* and *heat* that might guide it to suspect the possible role of temperature in the phenomenon of heat flow; semantic connections play no role in the structure-mapping theory. However, as this example shows, syntactic structure alone is insufficient to determine which facts are part of a relevant systematic whole, and which are isolated and irrelevant.

By contrast, in Copycat, the mechanisms for deciding which things to concentrate on and which mappings to make involve *semantics:* they involve activation of concepts in the Slipnet both in response to perception of instances of those concepts in the letter-strings and through spreading activation to associated concepts. They also involve competition among objects clamoring to be noticed and among various descriptions of objects and relationships between objects. They also involve certain *a priori* notions of salience. For SME, not only are the attributes and relations in each situation laid out in advance, but there is no notion of differential relevance among them: which ones get used in an analogy is entirely a function of the syntactic structure connecting them. In Copycat, the notions of differential relevance and "shaded" (as opposed to black-or-white) inclusion of concepts in a situation (via probabilities as a function of differential activation in the Slipnet)—and of the program *itself* bringing in the concepts to be used to describe the situation—are fundamental, since Copycat is a model of how situations, are interpreted as well as how mappings are made between them, and of how the two processes interact. The philosophy of Centner and her colleagues is that the interpretation stage and the mapping stage can be modeled independently; that there are, in effect, separate "modules" for each. In contrast, a philosophy underlying the Copycat project is that the two are inextricably intertwined; the way in which the two situations are understood is affected by how they are mapped onto each other, and vice versa. The necessity of integrating these two processes is discussed further by Chalmers, French, and Hofstadter (1992).

Another fundamental difference between our approach and Centner's is that her theory does not include any notion of conceptual similarity or of slippage, notions absolutely central to the Copycat project. In the water-flow/heat-flow example given above, the representations of the two situations are sufficiently abstract to make the analogy a virtual isomorphism. For example, the distinct concepts of *waterflow* and *heatflow* have both been abstracted in advance into a general notion *offlow.* Likewise, in another analogy that Centner describes, in which the hydrogen atom is mapped onto the solar system, all the important predicates in both situations have the same labels (e.g., *attracts, revolves around, mass).* This is necessary because of the theory's reliance on syntax alone. Ifthis "identicality" constraint were to be relaxed, semantics and context-dependence (i.e., some knowledge of conceptual proximity and how it is affected by context) would have to be brought in. But at present, since the concepts contained in the preconstructed representations always come in a sufficiently abstract form, there is no need for a Slipnet-like structure in which various concepts flexibly *become* more or less similar to one another in response to context. The analogy is already effectively given in the representations.

Yet another problem with Centner's theory (and with SME) is that it relies on a precise and unambiguous representation of situations in the language of predicate logic. The structure-mapping theory's reliance on syntax alone requires that situations be broken up very clearly into objects, attributes, functions, first-order relations, second-order relations, and so on. For example, the water-flow/heat flow analogy includes the following correspondences:

- *water* O *heat* (both are objects);
- *coffee* O *beaker* (both are objects);
- *flaw (beaker, vial, water, pipe) Oflow (coffee, ice cube, heat, bar)* (both are four-place relations).

But suppose that, in the heat-flow situation, *heat* had been described not as an object, but as an attribute of *coffee,* as in *holds-heat (coffee);* or suppose that *flow* had been given as a three-place rather than a four-place relation: *flow (coffee, ice cube, heat)* where the medium through which the heat flows is considered to be irrelevant; or suppose that, in the water-flow situation, *water flow* had been given as a five-place relation: *flow (beaker, vial, water, pipe, 10 cclsecond)* where the rate of flow is included. Any of these quite plausible changes would totally block a successful application of the structure-mapping theory. The problem is that in the real world, the labels "object," "attribute," and "relation" are very blurry, and people (if they make such distinctions at all) have to use them very flexibly, allowing initial classifications to slide if necessary at the drop of a hat. And to do this, semantics must be taken into account. (This point is also made by Johnson-Laird, 1989.) For example, the judgment that *heat* belongs to the category "object" is necessary for the water-flow/heat-flow analogy to work, but it is arbitrary; it is rather dubious that all analogy-makers would independently come up with this judgment. Rather, it seems likely that any two people (or even one person, at different times) would produce very different predicate-logic representations of, say, the water-flow situation, no doubt differing on which things were considered to be objects, which were attributes, which were relations, how many arguments a given relation has, and so on. Thus, a serious weakness of the structure-mapping theory is its inability to deal with any flexibility in the representation of situations.

Admittedly, there are ways in which Copycat also breaks up a situation's representation too cleanly into object-attributes (descriptions) and relations between objects (bonds), where many people would not do so. However, we believe that this defect is not a deep aspect of Copycat's architecture, but that it can be remedied without large conceptual revisions. Mitchell (1993) describes problems in which there is a need for structures that fluidly change from being descriptions to being bonds in response to real-time perceptual pressures, and we believe that Copycat can be made to handle such problems. By contrast, the possibility for real-time representational flexibility *\sfundamentally* lacking in a program like SMEj which relies solely on the syntax of predicate-logic representations that are supplied to it before the fact. For such a program to work, the representations have to be tailored carefully. This discrepancy between architectures reflects a significant philosophical difference about analogy-making.

Although SME is meant to simulate human analogy-making, in that it models which types of structures people tend to map from one situation to another and which of the various possible mappings people tend to prefer, it does not attempt to model the underlying concepts or the dynamic perceptual processes in the psychologically realistic manner that Copycat does; certainly, the exhaustive search SME performs through all consistent mappings is psychologically implausible. This brings up one last, and very important, difference between SME and Copycat.

In Copycat, there is a clear distinction between answers that are immediately appealing (high-frequency answers) and answers that are insightful but hard to uncover (low-frequency but also low-temperature answers, such as wyz in Problem 6 and mrrjjjj in Problem 4). This distinction falls out naturally from the nature of the parallel terraced scan, in which, roughly speaking, obvious routes are explored before nonobvious ones. Thus, in Problem 6, there is a definite temporal order that is generally followed, in which an attempt to take the successor of ζ is first made, the snag is hit, and then, thanks to this pressure, other, less-obvious possibilities wind up getting explored. Some of the time the deeply hidden but also deeply insightful answer wyz is discovered. We believe that the story sketched above of this process mirrors the natural stages in human exploration. Likewise, in Problem 4, answers such as **mrrjjk** and **mrrkkk** "pop to mind" for Copycat much more readily than does **mrrjjjj;** the relative ease and the relative rarity of these different answers are comparable to what happens when people consider this problem.

In a brute-force system like SME, by contrast, the distinction between answers of superficial and obvious appeal and answers of deeper but more hidden appeal does not exist. Indeed, in such systems, this type of temporality makes no sense, because *all* answers—that is, all answers that lie within the system's capability—are generated together and evaluated together, and then simply ranked according to their algorithmically assigned scores. If, for instance, such a system were given Problem 6, then not only would it fail to perceive any snag, but if wyz were within its conceptual range, it would get it effortlessly, and its high ranking (which it presumably—and hopefully—would receive) would give no indication of its counterintuitive twist. This is psychologically inaccurate; wyz, if reached at all, is reached only after many other routes have been explored, and this critical fact needs representation if the model is intended to reflect human-style cognition.

Problem 4 presents a similar dilemma for a brute-force exploration strategy such as that of SME, since in order for the answer **mrrjjjj** to be created, a novel concept *(length)* has to be brought into the picture. The difficulty for a brute-force system is that the only way for it to be able to discover the aptness of one *particular* initially absent concept is for it to bring in *all* concepts in its repertoire, regardless of their initial plausibilities, giving equal chances to all of them to prove their worth. Again, this is utterly unrealistic from a psychological point of view, but then so is the opposite strategy—namely, not ever bringing in novel concepts at all. (Note that this latter is the strategy of SME.) A subtler middle way is needed, poised delicately between the absurdity of exploring *every* possible idea with equal enthusiasm, and the sterility of not daring to explore *anything* new. Such a middle way is provided by a probabilistic architecture such as Copycat's, which was inspired specifically by the ubiquitous need for such shades of gray (see Section 8).

In summary, both the architecture and purpose of the Structure-Mapping Engine are extremely different in spirit from those of Copycat. SME is an algorithmic but psychologically implausible way of finding what the structure-mapping theory would consider to be the best mapping between two given representations, and of rating various mappings according to the structure-mapping theory, allowing such ratings then to be compared with those given by people. And as far as the structure-mapping theory itself is concerned, it makes a number of useful points about what features appealing analogies tend to have, but in dealing only with the end result of a mapping while leaving aside the problem of how situations become understood and how this process of interpretation interacts with the mapping process, it leaves out some of the most important aspects of how analogies are made.

7.5. A Quick Sketch of Holyoak and Thagard's ACME Program

Keith Holyoak and Paul Thagard have built a computer model of analogical mapping (Holyoak & Thagard, 1989; Holyoak, Novick, & Melz, this volume), based in part on theoretical and experimental work by Holyoak and his colleagues (Gick & Holyoak, 1983; Holland, Holyoak, Nisbett, & Thagard, 1986), and inspired in part by research by Marr and Poggio on constraint-satisfaction networks used to model stereoscopic vision. The computer model, ACME (Analogical Constraint Mapping Engine), is similar to SME in that it uses representations of a source situation and target situation given in formulas of predicate logic, and makes an analogical mapping consisting of pairs of constants and predicates from the representations. In fact, ACME has been tested on several of the same predicate-logic representations of situations that SME was given, including the water-flow and heat-flow representations.

The model takes as input a set of predicate-logic sentences containing information about the source and target domains (e.g., water flow and heat flow), and it constructs a network of nodes (taking into account a number of constraints) where each node represents a syntactically allowable pairing between one source element and one target element (a constant or a predicate). A node is made for every such allowable pairing.[6] For example, one node might represent the *water* O *heat* mapping, whereas another node might represent the *water* O *coffee* mapping. Links between nodes in the network represent "constraints": a link is weighted positively if it represents mutual support of two pairings (e.g., there would be such a link between the//ow O/tow node and the *water* Φ> *heat* node, since *water* and *heat* are counterparts in the argument lists of the *two flow* relations), and negatively if it represents mutual disconfirmation (e.g., there would be such a link between the/tow <^>*flow* node and the *water* «· *coffee* node). The network also has a "semantic unit": a node that has links to all nodes representing pairs of predicates. These links are weighted positively in proportion to the "prior assessment of semantic similarity" (i.e., assessed by

*** Here, "syntactically allowable" means adhering to the "logical-compatibility constraint," which specifies that a mapped pair has to consist of two elements of the same logical type. That is, constants are mapped onto constants and л-place predicates are mapped onto л-place predicates.**

the person constructing the representations) between the two predicates. In addition, it has a "pragmatic unit": a node that has positively weighted links to all nodes involving elements (e.g., *water)* deemed ahead of time (again by the person constructing the representations) to be "important." Once the network is in place, a spreading-activation relaxation algorithm is run on it, which eventually settles into a final state with a particular set of activated nodes representing the winning matches.

7.6. Agreements and Disagreements between Copycat and ACME

There are several points of agreement between the philosophy of ACME and that of the Copycat program. We share the idea that analogy-making is closely related to perception and should be modeled with techniques inspired by models of perception. We also share the belief that analogies emerge out of a competition among pressures (or "soft constraints"), involving a large number of local decisions that give rise to a larger coherent structuring. And we agree with the philosophy of Holyoak and Thagard that an analogy-making system's pressure toward systematicity (as described by Centner) should emerge from other pressures.

There are, however, deep differences between Copycat and ACME, related to Copycat's differences with SME discussed in the previous subsection. First, like SME, ACME tries all syntactically plausible pairings, a method that is both computationally infeasible and psychologically implausible in any realistic situation. For example, in making an analogy between the Watergate and Iran-Contra scandals, would a human consider a mapping between Nixon and every person involved in the Iran-Contra situation, including Fawn Hall, Daniel Inouye, Ed Meese, and Dan Rather? Or even less plausibly, would a human consider mapping Gerald Ford onto the Contras' base camp in Honduras, or onto the cake taken as a gift to Iran by United States emissaries? Yet these are *all* plausible, according to the logical-compatibility constraint, in which semantics plays no role at all. The existence of this exhaustive (though parallel) search through all possible mappings shows that ACME is not attempting to model how people very selectively search through such possibilities, whereas this is one of the Copycat project's main focuses. In Copycat, although any object in one string can in principle be compared with any object in the other string, an exhaustive search is avoided thanks to the parallel terraced scan, in which comparisons, if they are made at all, are made at different speeds and to different levels of depth, depending on constantly evolving estimates of their promise.

ACME shares with SME the following major problem, discussed above: the representations of knowledge used are rigid, and are also tailored specially for each new analogy. ACME uses the same representation as did SME for the water-flow/heat-flow analogy, so the same issues discussed with respect to SME apply here. Again, the program has no ability to restructure its descriptions or to add new descriptions in the course of making an analogy; the descriptions are constructed by a human ahead of time and are frozen. ACME differs from SME in that it has a "semantic unit" giving semantic similarities, which correspond in some sense to those embodied in Copycat's Slipnet, but the similarities are also decided in advance by the programmer for the purposes of the given analogy, and are frozen. Unlike Centner and her co-workers, Holyoak and Thagard recognize the necessity of considering semantics as well as syntax, but the problem is that it is impossible in general to have a "prior assessment of similarities" (as encoded in ACME's semantic unit); rather, as has been shown in several ways above, analogy-making is all about similarities being reassessed in response to pressures that weren't apparent ahead of time.

ACME also leaves aside the question of how objects in the Workspace and concepts in the Slipnet come to be seen as important in response to pressures; this is instead taken care of by the pragmatic unit, which encodes the programmer's prior assessment of what is important in the given situations. The pragmatic unit could be said to correspond to the activation of Slipnet nodes and to the importance values of objects in the Workspace. But again, unlike in Copycat, where these values *emerge* dynamically in response to what the program perceives, in ACME the pragmatic unit is set up by a human and then *frozen* for each new problem. Thus, like SME, ACME does not deal with another of Copycat's main focuses: how concepts adapt to different situations. ACME, like SME, models only the "mapping stage" of analogy-making, but, as was said before, a philosophy underlying Copycat is that the mapping process cannot be separated from the processes of perceiving and reformulating perceptions and assessments of similarities in response to pressures. Holyoak and Thagard (1989) themselves point out that their model does not address this issue—they call it the issue of "re-representation"—and acknowledge that it will often be necessary to interleave mapping with manipulation of the representations, taking into account top-down pressures. This is essentially just what Copycat does.

Since ACME's knowledge is set up ahead of time, the program's success, like that of SME, is totally dependent on the representations it is given. In the examples given by Holyoak and Thagard (1989), the representations of the source and target matched each other almost perfectly; the essence had been distilled in exactly the right form for making an analogy. As with SME, it is very doubtful that the representations given to ACME could have been made by someone who didn't already have the mapping in mind, and it is very likely that the program would not succeed if the representations of the source and target situations were made independently by two different people.

Finally, the same criticisms as were leveled at SME regarding the absence of temporality hold equally for ACME. That is to say, ACME, no less than SME, is based on brute-force full-width exploration strategies, and in it there simply is no counterpart to the natural distinction in Copycat between immediately obvious answers and insightful answers whose discovery requires deeper, longer search. More specifically, ACME, like SME, has no counterpart to the snags and paradigm shifts that can occur in Copycat runs on Problem 6, and no counterpart to the highly selective awakening of novel concepts from dormancy that can occur in Copycat runs on Problem 4. This "temporal" flatness of both ACME and SME is psychologically inaccurate. Those program's creators might reply that they are not trying to model this aspect of analogy-making; our response would be that we see such temporality as central to the nature of analogy, and therefore critical to include in one's model.

7.7. **How Real are These "Real-World" Analogies, Anyway?**

A criticism often leveled against Copycat is that it makes analogies in an idealized microworld, whereas other analogy-making programs work in more complex, real-world domains. On the surface it would seem that SME and ACME make real-world analogies that are much more complex than the "toy" problems Copycat deals with. But if one looks below the surface (as we did here for the water-flow/heat-flow example), it is clear that the knowledge possessed by these programs (that is, the knowledge given to them for each new problem, in the form of sentences of predicate logic), in spite of the real-world aura of words like "pressure" and "heat flow," is even more impoverished than Copycat's knowledge of its letter-string microworld. The programs know virtually nothing about concepts such as heat and water—much less than Copycat knows about, say, the concept *successor group,* which is embedded in a network and can be recognized and used in an appropriate way in a large variety of diverse situations. For example, each one of the strings **abc, aabbcc, cba, abbbc, mrrjjj, mmrrrjjjj, jjjrrm, abbccc, xpqefg,** and **k** can be recognized as an instance of *successor group,* given the appropriate pressures.[7] Nothing like this is the case for, say, SME's and ACME's notion of *heat* as given for the purpose of making a water-flow/heat-flow analogy. There, the notion of *heat* has essentially no semantic content and certainly cannot be adapted to any other situation. Nor can these programs recognize heat or a heat-like phenomenon. These programs

[7] Myriad other examples of successor groups, with different degrees of abslruseness, can be formed in the letter-string domain. Many are beyond Copycat's current recognition capabilities, although the same perceptual mechanisms the program has now could, we believe, be extended to recognize more complex instances, such as ace (a "double-successor" group), **aababc** (which can be seen as a "coded" version of abc when parsed as a-ab-abc), **kmxxrreeetll** (which could be described as "11-22-33"), axbxcx (where the x's form a "ground" for the "figure" abc), **abcbcdcde** (which could be parsed as abc-bcd-cde), and so on.

ate purported to make very high-level analogies involving the concepts *heat* and *water,* and yet, ironically, the programs have absolutely no sense of the meaning of *heat* or *water,* that is, the much more fundamental ability to recognize *instances* of these categories is completely absent from the programs.

This can be put in a slightly different way. Consider a computer program that manipulates complex data structures in which the Lisp atoms "NUCLEUS," "ELECTRON," "SUN," and "PLANET" (among others) occur, and suppose the data structures are intended to encode a few basic propositions about the hydrogen atom and the solar system. Now suppose the program comes up with a mapping in which the Lisp atom "NUCLEUS" corresponds with the atom "SUN," and similarly, "ELECTRON" with "PLANET." The computer would, of course, have done its job as easily if the names of Greek letters, say, had been used in the place of English words. Then the program would have made the following "scientific analogy": "NU maps to SIGMA; EPSILON maps to PI." Neither reading this result nor any amount of watching the program's behavior, no matter how long, would give a human any reason to suspect that the Lisp atom "NU" stood, in the programmer's mind, for the idea of an atomic nucleus, and that "SIGMA" stood for the concept of the sun. There is simply nothing in the program itself, or in its behavior, that makes these symbols stand for anything in a recognizable way. Only the person who used them to encode "pieces of knowledge" sees them as standing for anything.

Why can't this exact argument be turned word for word against Copycat? Could one not argue that when *successor* slips to *predecessor* in Problem 2, for instance, it might as well simply be the Lisp atom "SIGMA" slipping to the Lisp atom "PI"? What would the machine care? Of course, the machine would not care at all, but that misses the point entirely. An astute human watching the performance of Copycat and seeing the term "SIGMA" evoked over and over again by the presence of successor relationships and successorship groups in many diverse problems would be likely to make the connection after a while, and then might say, "Oh, I get it—it appears that the Lisp atom 'SIGMA' stands for the idea of successorship." In other words, whether or not an English *faqade* is used, the symbols in Copycat acquire at least some degree of genuine meaning, thanks to their correlation with actual phenomena, even if those phenomena take place in a tiny and artificial world. By contrast, in other analogy-making programs, there is no tiny and artificial world (let alone a big and real one) that serves to imbue the symbols they manipulate with any meanings.

Thus, the claim that Copycat's microworld is a "toy domain" whereas these other programs are solving real-world problems is truly unfounded and is based on a tendency of people to attribute much more intelligence to a program than it deserves based simply on real-world-sounding words it uses (such as "heat")—words that are extremely rich in imagery and connotations for people, but are almost completely empty as far as the program is concerned. Any program that uses words that exude real-world connotations but that are in reality completely devoid of semantic content as far as the program is concerned has the potential to be highly misleading—misleading not just to lay people, but to professionals as well. (This point about AI research has been trenchantly made by McDermott, 1981.) An "all the cards are on the table" quality is one of the advantages of using explicit microworlds for research in artificial intelligence.

7.8. Copycat's Position Along the Symbolic/Subsymbolic Spectrum

The philosophy behind the Copycat project is similar in many ways to that of various connectionist or "parallel distributed processing" (PDF) models (Rumelhart, McClelland, & the PDF Group, 1986) and to that of classifier systems (Holland, 1986; Holland, Holyoak, Nisbett, & Thagard, 1986). Connectionist networks and classifier systems are examples of *subsymbolic* (also called *subcognitive)* architectures. Smolensky (1988) characterizes the difference between the symbolic and subsymbolic paradigms as follows. In the symbolic paradigm, descriptions used in representations of situations are built of entities that are *symbols* both in the semantic sense (they refer to categories or external objects) and in the syntactic sense (they are operated on by "symbol manipulation"). In the subsymbolic paradigm, such descriptions are built of *subsymbols:* fine-grained entities (such as nodes and weights in connectionist networks or classifiers in a classifier system) that give rise to symbols. In a symbolic system, the symbols used as descriptions are explicitly defined (e.g., a single node in a semantic network represents the concept *dog).* In a subsymbolic system, symbols are statistically emergent entities, represented by complex patterns of activation over large numbers of subsymbols. (Similar characterizations have been made by Hofstadter, 1985, and by McClelland, Rumelhart, & Hinton, 1986.) Smolensky (1988) makes the point that subsymbolic systems are not merely "implementations, for a certain kind of parallel hardware, of symbolic programs that provide exact and complete accounts of behavior at the conceptual level" (p. 7). Symbolic descriptions are too rigid or "hard," and a system can be sufficiently flexible to model human cognition only if it is based on the more flexible and "soft" descriptions that emerge from a subsymbolic system.

The faith of the subsymbolic paradigm is that human cognitive phenomena are emergent statistical effects of a large number of small, local, and distributed subcognitive events with no global executive. This is the philosophy underlying connectionist networks, classifier systems, and Copycat as well. Fine-grained parallelism, local actions, competition, spreading activation, and distributed and emergent concepts are essential to the flexibility of all three types of architecture (although in classifier systems, spreading activation is not explicit, but rather emerges from the joint activity of many classifiers). Some connectionist networks (e.g., Boltzmann machines, Hinton & Sejnowski, 1986, and Harmony-Theory networks, Smolensky, 1986) have an explicit notion of computational temperature with some similarity to Copycat's (although, as was explained in Section 2, there is a significant difference between the use of temperature in Copycat and in simulated annealing, which is essentially the temperature notion used by Hinton & Sejnowski and by Smolensky). In classifier systems, something akin to a parallel terraced scan emerges from probabilistically decided competitions among classifiers and from the genetic algorithm's implicit search through schemata (i.e., templates for classifiers) at a rate determined by each schema's estimated promise (Holland, 1975). In addition, the interaction of top-down and bottom-up forces is central both in connectionist systems (see, e.g., McClelland & Rumelhart's [1981] interactive-activation model of letter perception), and in classifier systems (for example, as discussed in Chapter 2 of Holland, Holyoak, Nisbett, & Thagard, 1986).

The philosophy underlying the Copycat project is more akin to that of the subsymbolic paradigm than that of the symbolic paradigm, but the actual *program* fits somewhere in between (although as we said at the outset, Copycat is not a hybrid of the two). As an oversimplified but nonetheless useful characterization of the two ends of the spectrum, one could say that concepts in subsymbolic systems are highly distributed, being made up of individual nodes that have no semantic value in and of themselves, whereas in symbolic systems, concepts are represented as simple unitary objects (e.g., as Lisp atoms). Concepts in Copycat could be thought of as "semi-distributed," since a concept in the Slipnet is probabilistically distributed over only a small number of nodes—a central node (e.g., *successor)* and the nodes in its probabilistic halo (e.g., *predecessor),* to which it can probabilistically slip.

The basic units of subsymbolic systems such as connectionist networks are meant to model mental phenomena further removed from the cognitive, conscious level than those modeled by Copycat's codelets and Slipnet nodes (the basic units out of which pressures and concepts—some of Copycat's main higher level phenomena—emerge). It may be that connectionist networks are neurologically more realistic than Copycat, but their remoteness from the cognitive level makes the problem of controlling their high-level behavior quite difficult. At this time it is dubious whether it would be possible to use connectionist systems similar to those currently in existence to model the types of high-level cognitive behavior exhibited by Copycat. Ideally, a cognitive model should have the property that a high-level semantic structure such as Copycat's Slipnet demonstrably arises as an implicit consequence of a low-level, distributed model, but this is beyond the achievements of current research in connectionism.

Likewise, in classifier systems, several extremely basic notions implanted directly in Copycat (such as nodes, links, and spreading activation) would have to emerge automatically, which would make a high-level task such as Copycat's quite difficult for classifier systems as they are currently conceived. Thus, Copycat models concepts and perception at an intermediate level, in terms of the degree to which concepts are distributed and the extent to which high-level "semantic" behavior emerges from lower level "syntactic" processing.

A major difference between Copycat's architecture and that of connectionist networks is the presence in Copycat of both the Slipnet, containing Platonic concept *types,* and the Workspace, in which structures representing concept *tokens* (i.e., instances of concepts) are dynamically constructed and destroyed. Connectionist networks have no such separate working area; both types and tokens are represented in a single network. This has led to a great deal of research in connectionism on the so-called "variable-binding problem," which is related to the larger question of the relationship between concept types and concept tokens. One reason researchers in connectionism hesitate to make such a separation is that neural plausibility is a central aspect of their research program, and a structure like Copycat's Workspace—a mental region in which representations of situations are constructed—does not have a clear neural underpinning. In contrast, for the purposes of Copycat and related projects, we have been influenced more by *psychological* than *neurological* findings. Based on many pieces of evidence for a separation between, a Platonic-concept memory and a workspace where instances reside (see, e.g., Treisman, 1988, which reports on many experiments on visual perception that strongly point to the existence of a site of temporary episodic structures), we simply *assume* the existence of something like Copycat's Workspace even though we do not know its neural basis, and we investigate how a spreading-activation network with distributed concept *types* interacts with a working area in which ephemeral concept *tokens* can be arranged in complex structures. The lack of such a working area in connectionist networks is another reason why it may turn out to be very difficult to use such systems to model concepts and high-level perception in the way Copycat does.

Connectionist networks and classifier systems learn over time, while Copycat does not. Copycat is not meant to be a model of learning in this strict sense, though it does model some fundamental aspects of learning: how concepts adapt to new situations that are encountered, and how the shared essence of two situations is recognized.

The belief underlying our methodology is that building a model at the level of Copycat's architecture is essential not only for the purpose of providing an account of the mental phenomena under study at its intermediate level of description, but also as a step towards understanding how these phenomena can emerge from even lower levels.

The "connectionist dream"—that of modeling all of cognition using a subsymbolic, neurologically plausible architecture—may be too ambitious at this point in the development of cognitive science. If there is any hope for understanding how intelligence emerges from billions of neurons, or even how it might emerge from connectionist networks, we need to understand the nature of *concepts,* fundamental entities whose operating principles seem to lie somewhere between those of highly parallel neural networks and those of highly symbolic serial cognition.

The question "What is a concept?" could be said to lie at the crux of cognitive science (Hofstadter, 1985), and yet concepts still lack a firm scientific basis. The long-term goal of the Copycat project and related research is to use computer models to help provide such a scientific basis. The hope is that the understanding that results from this approach will not only in its own right contribute to answering long-standing questions about the mechanisms of intelligence, but will also provide a guide to connectionists studying how such intermediate-level structures can emerge from neurons or cell-assemblies in the brain.

In summary, the architecture of Copycat is very different from the more traditional symbolic artificial-intelligence systems, both in its parallel and stochastic processing mechanisms, and in its representation of concepts as distributed and probabilistic entities in a network. These features make it more similar in spirit to connectionist systems, though again there are important differences. The high-level behavior of connectionist systems emerges statistically from a lower level substrate, as in Copycat. However, the fundamental processing units in connectionist systems are more primitive; also, concepts in such networks are distributed to a much higher degree than in Copycat, and finally, concept types and tokens are required to reside in the same network. Consequently, there has not been much success so far in using connectionist systems as models of high-level cognitive abilities such as analogy-making. Copycat explores a middle ground in cognitive modeling between the high-level symbolic systems and the low-level connectionist systems; the claim made for this approach is that this intermediate level is at present the most useful one at which to grapple with the fluid nature of concepts and perception, central aspects of mind that emerge with maximal clarity in analogy-making.

8. CONCLUSION: THE GENERALITY OF COPYCAT'S MECHANISMS

8.1. The Crucial Question of Scaling-Up

As was stated at the outset, the Copycat project was never conceived of as being dependent in any essential way on specific aspects of its small domain, nor even on specific aspects of analogy-making per se. Rather, the central aim was to model the emergence of insightful cognition from fluid concepts, focusing on how slippages can be engendered by pressures.

One of the key questions about the architecture, therefore, is whether it truly is independent of the small domain and the small problems on which it now works. It would certainly be invalidated if it could be shown to depend on the relative smallness of its repertoire of Platonic concepts and the relatively few instances of those concepts that appear in a typical problem. However, from the very conception of the project, every attempt has been made to ensure that Copycat would not succumb to a combinatorial explosion if the domain were enlarged or the problems became bigger. In some sense, Copycat is a caricature of genuine analogy-making. The question is, what makes a caricature faithful? What is the proper way to construct a cognitive model that will scale up?

8.2. **Shades of Gray and the Mind's Eye**

Real cognition of course occurs in the essentially boundless real world, not in a tiny artificial world. This fact seems to offer the following choice to would-be "cognition architects": either have humans scale down all situations by hand in advance into a small set of sharp-edged formal data structures, so that a brute-force architecture can work, or else let the computer effectively do it instead—that is, use a heuristic-based architecture that at the outset of every run makes a sharp and irreversible cut between concepts, pathways, and methods of attack that might eventually be brought to bear during that run, and ones that might not. There seems to be no middle ground between these two types of strategy, because either you must be wijling to give *every* approach a chance (the brute-force approach), or you must choose some approaches while a priori filtering others out (the "heuristic-chop" approach).

The only way out would seem to involve a notion of "shadedness," in which concepts, facts, methods of attack, objects, and so on, rather than being ruled "out" or "in" in a black-and-white way, would be present in shades of gray—in fact, shades of gray that change over time. At first glance, this seems impossible. How can a concept be invoked only *partially?* How can a fact be neither fully ignored nor fully paid attention to? How can a method of attack be merely "sort of" used? How can an object fall somewhere in between being considered "in the situation" and being considered "not in the situation"?

Since we believe that these "shades of gray" questions lie at the crux of the modeling of mind, they merit further discussion. A special fluid quality of human cognition is that often, solutions to a problem—especially the most ingenious ones, but even many ordinary ones—seem to come from far outside the problem as conceived of originally. This is because problems—or more generally, *situations*—in the real world do not have sharp definitions; when one is in, or hears about, a complex situation, one typically pays no conscious attention to the question of what counts as "in" the situation and what counts as "out" of it. Such matters are almost always vague, implicit, and intuitive.

Using the metaphor of the "mind's eye," we can liken the process of considering an abstract situation to the process of visually perceiving a physical scene. Like a real eye, the mind's eye has a limited field of vision, and cannot focus on several things simultaneously, let alone large numbers of them. Thus, one has to choose where to have the mind's eye "look." When one directs one's gaze at what one feels is the situation's core, only a few centrally located things will come into clear focus, with more tangential things being less and less clear, and then at the peripheries there will be lots of things of which one is only dimly aware. Finally, whatever lies beyond the field of vision seems by definition to be outside of the situation altogether. Thus, "things" in the mind's eye are definitely shaded, both in terms of how clear they are and in terms of how aware one is of them.

The very vague term "thing" was used deliberately above; the intent was to include both *abstract Platonic concepts* and *concrete specific individuals*—in fact, to blur the two notions, since there is no hard-and-fast distinction between them. To make this clearer, think for a moment of the very complex situation that the Watergate affair was. As you do this, you will notice (if you followed Watergate .at all) that all sorts of different events, people, and themes float into your mind with different degrees of clarity and intensity. To make this even more concrete, turn your mind's eye's gaze to the Senate Select Committee, and try to imagine each different Senator on that committee. Certainly, if you watched the hearings on television, some will emerge vividly while others will remain murky. Not just *Platonic abstractions* like "senator" are involved, but many *individual* senators have different degrees of mental presence as you attempt to "replay" those hearings in your mind. Needless to say, the memory of anyone who watched the Watergate hearings on teJevision is filled to the brim both with Platonic concepts of various degrees of abstractness (ranging from "impeachment" to "coverup" to "counsel" to "testimony" to "paper shredder") and with specific events, people, and objects at many levels of complexity (ranging from the "Saturday night massacre" to the Supreme Court, from Maureen Dean to the infamous l8'/2-minute gap, and all the way down to the phrase "expletive deleted" and even Sam Ervin's gavel, with which sessions were rapped to order). When one conjures up one's memories of Watergate, all of these "things" have differential degrees of mental presence, which change as one's mind eye scans the "scene."

Note that in the preceding paragraph, all the "things" mentioned were carefully chosen so that readers—at least readers who remember Watergate reasonably well—would give them unthinking acceptance as "parts" of Watergate. However, now consider the following "things": England, France, communism, socialism, the Viet Nam War, the Six-Day War, the Washington Monument, the New York *Times*, Spiro Agnew, Edward Kennedy, Howard Cosell, Jimmy Hoffa, Frank Sinatra, Ronald Reagan, the AFL-CIO, General

Electric, the electoral college, college degrees, Harvard University, helicopters, keys, guns, flypaper, Scotch tape, television, pianos, secrecy, accountancy, and so on. Which of these things are properly thought of as being "in" Watergate, and which ones as "out" of it? It would obviously be ludicrous to try to draw a sharp line. One is forced to accept the fact that for a model of a mind to be at all realistic, it must be capable of imbuing all concrete objects and individuals, as well as all abstract Platonic concepts, with shaded degrees of mental presence—and of course, those degrees of presence must be capable of changing over time.

Like a real eye, the mind's eye can be attracted by something glinting in the peripheries, and shift its gaze. When it does so, things that were formerly out of sight altogether now enter the visual field. By a series of such shifts, "things" that were totally outside of the situation's initial representation can eventually wind up at the very center of attention. This brings us back, finally, to that special fluid quality of human thought whereby initially unsuspected notions occasionally wind up being central to one's resolution of a problem, and reveals how intimately such fluidity is linked with the various "shades of gray" questions given above.

8.3. Copycat's Shaded Exploration Strategy

Let us return to the list of "shades-of-gray" questions given above: How can a concept be invoked only *partially?* How can a fact be neither fully ignored nor fully paid attention to? How can a method of attack be merely "sort of" used? How can an object fall somewhere in between being considered "in the situation" and being considered "not in the situation"? These questions were not asked merely rhetorically; in fact, it was precisely to answer the challenges that they raise that the probabilistic architecture of Copycat was designed. Copycat's architecture has in common with brute-force architectures the fact that every possible concept, fact, method, object, and so on is *in principle* available at all times[8]; it has in common with heuristic-chop architectures the fact that out of all available concepts, facts, methods, objects, and so on, only a few will get very intensely drawn in at any given moment, with most being essentially dormant and an intermediate number having a status somewhere in between. In other words, virtually all aspects of the Copycat architecture are riddled by shades of

' Note that the claim is not that every single concept imaginable to humans is available, but simply that all concepts *within the system's dormant repertoire* are in principle still accessible at any point during a run. The fact that Copycat cannot reach beyond its own conceptual repertoire, thus effectively "transcending itself," is not a defect, but simply a fact of existence that it shares with every finite cognitive system, such as human minds. Put another way, if this property is a defect of Copycat, then it is a defect that copycat shares with human minds.

gray instead of by hard-edged, black-and-white cutoffs. In particular, *activation* (with continuous values rather than a binary on/off distinction) is a mechanism that gives rise to shadedness in the Slipnet, while *salience* and *urgency* serve similar purposes in the Workspace and Coderack, respectively. These are just three of a whole family of related "shades-of-gray mechanisms" whose entire *raison d'etre* is to defeat the scaling-up problem.

An architecture thus pervaded by shades of gray has the very attractive property that although no concept or object (etc.) is ever *strictly om fully* ruled out, only a handful of them are at any time *seriously* involved. Thus, at any moment the system is focusing its attention on just a small set of concepts, objects, etc. However, this "searchlight of attention" can easily shift under the influence of new information and pressures, allowing a priori very unlikely concepts, objects, or methods of attack to enter the picture as serious contenders.

The list below summarizes the various mechanisms in the Copycat architecture that incorporate shades of gray in different ways. In this list, the term "shaded" should be understood as representing the opposite of a binary, black/white distinction; it often means that one or more *real numbers* are attached to each entity of the sort mentioned, as opposed to there being an on/off distinction. The term *dynamic* means that the degree of presence—the "shade," so to speak—can change with time.

Shades of gray in the Slipnet

- shaded, dynamic presence of Platonic concepts (via dynamic activation levels)
- shaded, dynamic conceptual proximities (via dynamic link-lengths)
- shaded, dynamic spreading of activation to neighbor concepts (giving rise to "conceptual halos")
- shaded conceptual depths of nodes
- shaded decay rates of concepts (determined by conceptual depths)
- shaded, dynamic emergence of abstract themes (stable activation patterns of interrelated conceptually deep nodes)

Shades of gray in the Workspace

- shaded, dynamic number of descriptions for any object
- shaded, dynamic importance of each object (via activation levels of descriptors in the Slipnet)
- shaded, dynamic unhappiness of each object (determined by degree of integration into larger structures)
- shaded, dynamic presence of objects (via dynamic salience levels)
- shaded, dynamic tentativity of structures (via dynamic strengths)

Shades of gray associated with the Coderack

- shaded, dynamic degrees of "promise" of pathways
- shaded, dynamic emergence of pressures (via urgencies of codelets and shifting population of the Coderack)
- shaded, dynamic degree of willingness to take risks (via temperature)
- shaded, dynamic mixture of deterministic and nondeterministic modes of exploration
- shaded, dynamic mixture of parallel and serial models of exploration
- shaded, dynamic mixture of bottom-up and top-down processing

There is one further aspect of shadedness in Copycat that is not localized in a single component of the architecture, and is somewhat subtler. This has to do with the fact that higher level structures emerge over time, each of which brings in new and unanticipated concepts, and also opens up new and unanticipated avenues of approach. In other words, as a run proceeds, the field of vision broadens out to incorporate new possibilities, and this feeds on itself: each new object or structure is subject to the same perceptual processes and chunking mechanisms that gave rise to it. Thus, there is a spiral of rising complexity, which brings new items of ever-greater abstraction into the picture "from nowhere," in a sense. This process imbues the Copycat architecture with a type of fundamental unpredictability or "openness" (Hewitt, 1985) that is not possible in an architecture with frozen representations. The ingredients of this dynamic unpredictability form an important addendum to the list of shades of gray given above.

Dynamic emergence of unpredictable objects and pathways

- creation of unanticipated higher level perceptual objects and structures
- emergence of a priori unpredictable potential pathways of exploration (via creation of novel structures at increasing levels of abstraction)
- creation of large-scale viewpoints
- competition between rival high-level structures.

By design, none of the mechanisms in the lists presented above has anything in the least to do with the size of the situations that Copycat is currently able to deal with, or with the current size of Copycat's Platonic conceptual repertoire. Note, moreover, than none of them has anything whatsoever to do with the subject matter of the Copycat domain, or even with the task of analogy-making per se. Yet these mechanisms and their emergent consequences—especially commingling pressures and the parallel terraced scan—are what Copycat is *truly* about. This is the underpinning of our belief in the cognitive generality of the Copycat architecture.

Chalmers, D.J., French, R.M., & Hofstadter, D.R. (1992). High-level perception, representation, and analogy. *Journal for Experimental and Theoretical Artificial Intelligence 4,* 185-211.

Erman, L.D., Hayes-Roth, F, Lesser, VR., & Reddy, D.R. (1980). The Hearsay-II speech-understanding system: Integrating knowledge to resolve uncertainty. *Computing Surveys, 12(2),* 213-253.

Falkenhainer, B., Forbus, K.D., & Centner, D. (1989). The structure-mapping engine. *Artificial Intelligence, 41(1),* 1-63.

French, R.M. (1992). *Tabletop: An emergent, stochastic model of analogy-making.* Unpublished doctoral dissertation, EECS Department, University of Michigan, Ann Arbor.

Centner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 7(2),* 155-170.

Gick, M.L., & Holyoak, K.J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15,* 1-38.

Hall, R.P. (1989) Computational approaches to analogical reasoning. *Artificial Intelligence 39,* 39-120.

Hewitt, C. (1985). The challenge of open systems. *Byte Magazine, IO* (4), 223-242.

Hinton, G.E., & Sejnowski, T.J. (1986). Learning and relearning in Boltzmann machines. In D.E. Rumelhart, J.L. McClelland, & the PDF Research Group (Eds.) *Parallel distributed processing* (pp. 282-317). Cambridge, MA: Bradford/MIT Press.

Hofstadter, D.R. (1983). The architecture of Jumbo. *Proceeding of the International Machine Learning Workshop.* Monticello, IL.

Hofstadter, D.R. (1984a). *The Copycat project: An experiment in nondeterminism and creative analogies* (AI Memo No. 755). Cambridge, MA: AI Laboratory, Massachusetts Institute of Technology.

Hofstadter, D.R. (1984b) *Simple and not-so-simple analogies in the Copycat domain* (CRCC Report No. 9). Bloomington, IN: Center for Research on Concepts and Cognition, Indiana University.

Hofstadter, D.R. (1985). Waking up from the Boolean dream: Subcognition as computation. In *Metamagical themas* (pp. 631-665). New York: Basic Books.

Hofstadter, D.R. (1991). The roots of mental fluidity. *Proceedings of The Turing 1990 Symposium.* Oxford, England: Oxford University Press.

Holland, J.H. (1975). *Adaptation in natural and artificial systems.* Ann Arbor, MI: University of Michigan Press.

Holland, J.H. (1986). Escaping brittleness: The possibilities of general-purpose learning algorithms applied to parallel rule-based systems. In R. Michalski, T. Mitchell, & J. Carbonell (Eds.), *Machine learning: An artificial intelligence approach* (Vol. 2). Los Altos, CA: Morgan Kaufmann.

Holland, J.H., Holyoak, K.J., Nisbett, R.E., & Thagard, P.R. (1986). *Induction.* Cambridge, MA: Bradford/MIT Press.

Holyoak, K.J., & Thagard, P. (1989). Analogical mapping by constraint satisfaction. *Cognitive Science, 13(3),* 295-355.

Johnson-Laird, P. (1989). Analogy and the exercise of creativity. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 313-331). Cambridge, England: Cambridge University Press.

Kahneman, D., & Miller, D.T. (1986). Norm theory: Comparing reality to its alternatives. *Psychological Review, 93* (2), 136-153.

Kedar-Cabelli, S. (1988). Analogy—from a unified perspective. In D.H. Helman (Ed.), *Analogical reasoning* (pp. 65-103). Dordrecht, The Netherlands: Kluwer Academic.

Kirkpatrick, S., Gelatt Jr., C.D., & Vecchi, M.P. (1983). Optimization by simulated annealing. *Science,* 220, 671-680.

Kuhn, T.S. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago, IL: University of Chicago Press.

McCarthy, J., & Hayes, P. (1969). Some philosophical problems from the standpoint of artificial intelligence. In B. Meltzer & D. Michie (Eds.), *Machine intelligence* (Vol. 4). Edinburgh: Edinburgh University Press.

McClelland, J.L., & Rumelhart, D.E. (1981). An interactive activation model of context effects in letter perception: Part I. An account of basic findings. *Psychological Review, 88,* 375-407.

McClelland, J.L., Rumelhart, D.E., & Hinton, G.E. (1986). The appeal of parallel distributed processing. In D.E. Rumelhart, J.L. McClelland, & the PDP Research Group (Eds.), *Parallel distributed processing* (pp. 194-281). Cambridge: Bradford/MIT Press.

McDermott, D. (1981). Artificial intelligence meets natural stupidity. In J. Haugeland (Ed.), *Mind design.* Cambridge, MA: MIT Press.

Meredith, M.J. (1986). *Seek-Whence: A model of pattern perception.* Unpublished doctoral dissertation, Department of Computer Science, Indiana University, Bloomington, IN.

Meredith, M.J. (1991). Data modeling: a process for pattern induction. *Journal for Experimental and Theoretical Artificial Intelligence, 3,* 43-68.

Mitchell, M. (1993). *Analogy-Making as Perception: A Computer Model.* Cambridge, MA: Bradford/MIT Press.

Mitchell, M., & Hofstadter, D.R. (1990a). The emergence of understanding in a computer model of concepts and analogy-making. *Physica D, 42,* 322—334.

Mitchell, M., & Hofstadter, D.R. (1990b). The right concept at the right time: How concepts emerge as relevant in response to context-dependent pressures. *Proceedings of the Twelfth Annual Conference of the Cognitive Science Society.* Hillsdale, NJ: Erlbaum.

Rumelhart, D.E., McClelland, J.L., & the PDP Research Group. (Eds.). (1986). *Parallel distributed processing.* Cambridge, MA: Bradford/MIT Press.

Skorstad, J., Falkenhainer, B., & Gentner, D. (1987). Analogical processing: A simulation and empirical corroboration. *Proceedings of the American Association for Artificial Intelligence, AAAI-87.* Los Altos, CA: Morgan Kaufmann.

Smolensky, P. (1986). Information processing in dynamical systems: Foundations of harmony theory. In D.E. Rumelhart, J.L. McClelland, & the PDP Research Group (Eds.), *Parallel distributed processing* (pp. 194-281). Cambridge, MA: Bradford/MIT Press.

Smolensky, P. (1988). On the proper treatment of connectionism. *Behavioral and Brain Sciences, 11* (1), 1-14.

Treisman, A. (1988). Features and Objects: The Fourteenth Bartlett Memorial Lecture. *Quarterly Journal of Experimental Psychology, 40A,* 201-237.