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How people construct mental models[1]

Allan Collins & Dedre Gentner

Analogies are powerful ways to understand how things work in a new domain. We think this is because analogies enable people to construct a structure–mapping that carries across the way the components in a system interact. This allows people to create new mental models that they can then run to generate predictions about what should happen in various situations in the real world. This paper shows how analogies can be used to construct models of evaporation and how two subjects used such models to reason about evaporation.

As Lakoff and Johnson (1980) have documented, our language is full of metaphor and analogy. People discuss conversation as a physical transfer: (e.g., "Let's see if I can get this across to you" (Reddy 1979). They analogize marriage to a manufactured object: (e.g., "They had a basic solid foundation in their marriages that could be shaped into something good" (Quinn this volume). They speak of anger as a hot liquid in a container (Lakoff & Kövecses this volume); and they describe their home thermostat as analogous to the accelerator on a car (Kempton this volume).

Why are analogies so common? What exactly are they doing for us? We believe people use them to create generative mental models, models they can use to arrive at new inferences. In this paper, we first discuss the general notion of a generative mental model, using three examples of artificial intelligence models of qualitative physics; second, we lay out the analogy hypothesis of the paper, which we illustrate in terms of the component analogies that enter into mental models of evaporation; and finally, we describe how two subjects used these analogies in reasoning about evaporation.

The notion of running a generative model can be illustrated by an example from Waltz (1981). People hearing "The dachshund bit the mailman on the nose" spontaneously imagine scenarios such as the dachshund standing on a ledge, or the mailman bending down to pet the dachshund. Similarly, if you try to answer the question, "How far can you throw a potato chip?" your thought processes may have the feel of a mental simulation. Examples such as these suggest that simulation and generative inference are integral to language understanding (Waltz 1981). However, such

Table 10.1. *Examples of liquids in different states (after Hayes 1985)*

	Supported on surface	Supported in space	Unsupported
Still, in Bulk	Liquid on a wet surface	Liquid in a container	–
Moving, in Bulk	Liquid flowing on a surface, e.g., a roof	Liquid pumped in pipe	Liquid pouring from a container
Still, Divided	Dew drops on a surface	Mist filling a valley?	Cloud
Moving, Divided	Raindrops on a window	Mist rolling down a valley?	Rain

imagistic descriptions have a magical quality, which we try to resolve in terms of the formalisms of mental models research.

Inference and qualitative simulation become possible when the internal structure of a model is specified in terms of connections between components whose input–output functions are known. Hayes (1985) and de Kleer (1977) have independently tried to characterize how people decompose different systems in order to reason about the world. Both came up with tacit partitions of the world in order to simulate what will happen in a particular situation. Hayes attacked the problem of how people reason about liquids and de Kleer how they reason about sliding objects. Forbus (1981) later extended the de Kleer analysis to bouncing balls moving through two dimensions. Understanding these ideas is central to our argument about the role of analogies in constructing mental models, so we briefly review the way these three authors partition the world in order to construct qualitative simulations.

Hayes (1985) partitions the possible states of liquids into a space with three dimensions: (1) whether the liquid is moving or still; (2) whether it is in bulk or divided (e.g., a lake vs. mist); and (3) whether it is on a surface, supported in space, or unsupported. For example, rain is liquid that is moving, divided, and unsupported, whereas pouring liquid is moving, in bulk, and unsupported. Spilled liquid is still, in bulk, and on a surface except when it is first moving on the surface. Hayes gives examples for most of the possible states in these three dimensions (see Table 10.1), except some that are impossible (e.g., bulk liquid that is both still and unsupported).

Hayes shows how one can construct transitions between different liquid states using a small number of possible transition types in order to construct "a history" of some event. He illustrates this with the example of pouring milk from a cup onto a table. Initially, the milk is contained in

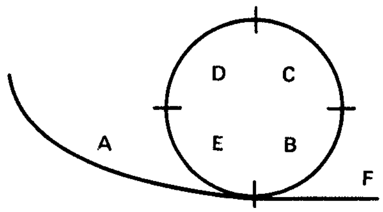

Figure 10.1. Partitioning of loop-the-loop track (after de Kleer 1977)

bulk in the cup as it is tipped. When the surface reaches the lip of the cup, there begins a falling from the cup to the table, which extends through time until the cup is empty, except for the wetness on its surface. Beginning at the point when the falling liquid hits the table, there is a spreading of the liquid on the table top until the pool of liquid reaches the table edge. At that point, another falling starts along the length of the edge that the spreading reaches. This falling continues until there is only a wetness on the table top. The falling also initiates a spreading on the floor, which lasts until there is a nonmoving wetness covering an area of the floor. Because people can construct this kind of history out of their knowledge of liquid states and the transitions between them, they can simulate what will happen if you pour a cup of milk on a table. Alternatively, if they find liquid on the floor and table, they can imagine how it got there.

In the roller coaster world that de Kleer (1977) has analyzed, he partitions the kinds of track a ball might roll along into concave, convex, and straight tracks. de Kleer uses a small number of allowable transitions – for example, slide forward, slide back, and fall – to construct a simulation of the behavior of a ball on a loop-the-loop track such as shown in Figure 10.1. In the figure, the track starts in segment *A* and continues up and around through segments *B, C, D, E,* and *F.*

By constructing all possible continuations for a given input, one forms a directed graph, which de Kleer calls the *envisionment.* Each alternative transition is a branch that can be followed out. Suppose one starts a ball rolling at the end of segment *A*. It will slide forward to segment *B*. From *B,* it can slide forward into *C* or slide back to *A*. If a slide forward occurs, then the ball can either slide forward into *D* or fall. Sliding backward from *B* into *A* leads to oscillation.

The same sort of branching of possible states occurs in Hayes's physics of liquids. For example, in the milk-pouring episode, the spread of milk on the table may never reach the edge, in which case the episode ends with wetness on the table and in the cup. Thus, using qualitative models can allow a person to generate all the different possible events that might happen.

Forbus (1981) has made a similar analysis of bouncing balls in two-dimensional space. To do this, he developed a vocabulary for partition-

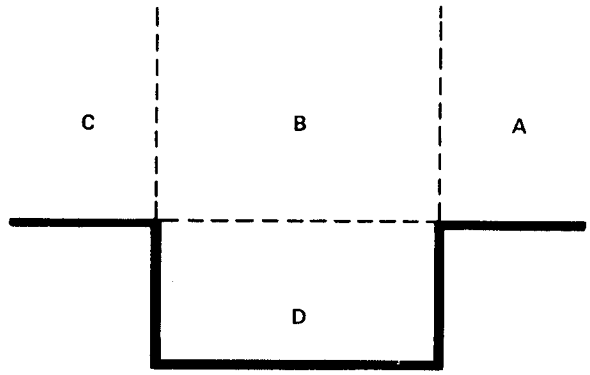

Figure 10.2. Partitioning of two-dimensional space above a well (after Forbus)

ing space into places in which significantly different behaviors can occur. In this model, the qualitative state of an object at a given moment consists of a place, an activity (e.g.: *fly* or *collide*), and a direction (e.g., *left and up*). As in the other two models discussed, simulation rules specify the allowable transitions between qualitative states. Figure 10.2 shows his example of how a space above a well would be partitioned into regions.

Table 10.2 shows the allowable state transitions for a ball moving in a region. The table shows the region in which the ball will be next (including "same") and its next direction. What the ball will do next – its next activity – depends on the kind of place it enters next. If the next place is a surface, the next activity is a collision; otherwise, the next activity will be a continuation of its present motion. If we begin with a ball in region *A* that is headed left and down, it can either go downward and collide with the surface below *A*, or go into the middle region *B*, where its direction will also be left and down. From *B*, going left and down, it can either go into the lower region *D* or into the left region *C*, still heading left and down. If it goes into *D*, it can collide either with the left side wall or with the bottom. Collisions with vertical walls reverse the left–right direction; collisions with horizontal walls reverse the up–down direction. As should be evident, it is possible to imagine a number of different paths for the ball to travel, only some of which end up with the ball caught in the well.

The point of these examples is that they illustrate how people might be able to construct mental models that have the introspective feel of manipulating images (Kosslyn 1980). Put in the terms of Hayes, de Kleer, and Forbus, there is no magic to starting a ball moving or a liquid flowing mentally and seeing what happens. You do not have to know in advance what happens, and you do not have to store a mental moving picture of the events. Indeed, you may decide that a particular candidate event 'e a well (after Forbus)

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Table 10.2. *Transition rules for a ball moving from region to region in Forbus's (1981) bouncing ball world showing next place and next direction for the case of a ball moving in some region of space*

Direction	Next Place	Next Direction
none	same	D
D	down	D
LD	down	LD
	left	LD
L	same	LD
LU	same	L
	left	L
	left	LU
	up	LU
U	same	D
	up	U
RU	same	R
	right	R
	right	RU
	up	RU
R	same	RD
RD	right	RD
	down	RD

Note: Regions are represented by words and directions by capital letters. Each line represents a next-place, next-direction pair.

could not ever have occurred. All you have to know is what inputs lead to what outputs for each state transition and how those kinds of states are connected together.

The analogy hypothesis

It should by now be clear that qualitative-state models provide a powerful, versatile way for people to reason about familiar domains in which the states and transitions are known. But what happens when people want to go beyond familiar physical situations and reason about domains, such as evaporation, in which the states and transitions may be unfamiliar or even invisible? Here, we come to the central proposal of this paper, the analogy hypothesis. According to this hypothesis, a major way in which people reason about unfamiliar domains is through analogical mappings. They use analogies to map the set of transition rules from a known domain (the base) into the new domain (the target), thereby constructing a mental model that can generate inferences in the target domain. Any system whose transition rules are reasonably well specified can serve as an analogical model for understanding a new system (Collins & Gentner, 1982; Gentner 1982).

So far, this analogy hypothesis is a special case of Gentner's (1982; 1983; Gentner & Gentner 1983) more general claim that analogy is a mapping of structural relations from a base domain to a target domain that allows people to carry across inferences from the base to the target. To construct a mental model in a new domain, a particularly powerful set of relations to map across is the transition rules between states. These rules allow one to generate inferences and create simulations in the target domain analogous to the ones that can be performed in the base domain.

However, the situation is often more complicated. Often, no one base domain seems to provide an adequate analogy for all the phenomena in the target domain. In these cases, we find that people partition the target system into a set of component models, each mapped analogically from a different base system. As we demonstrate, people vary greatly in the degree to which they connect these component models into a consistent whole. An extreme case of inconsistency is the *pastiche model,* in which a target domain model is given by a large number of minianalogies, each covering only a small part of the domain and each somewhat inconsistent with the others. At the other extreme, some people connect together their component models into a consistent overall model. Thus, they can combine the results of their mappings to make predictions about how the overall target system will behave.

The remainder of this paper illustrates the analogy hypothesis by showing how analogies can be used to construct different versions of a molecular model of evaporation (see Stevens & Collins 1980). We then show how two subjects used these analogies to reason about evaporation.

A molecular model of evaporation involves a set of component subprocesses:

1. How molecules behave in the water
2. How molecules escape from the water to the air
3. How molecules behave in the air
4. How molecules return to the water from the air
5. How molecules go from liquid to vapor, and vice versa

Notice that this analysis bears some similarity to the Forbus analysis of bouncing balls. There are two regions, the water and the air, and the transitions (i.e., escape and return) between them. The behavior of the molecules in the water and air describes the transitions that keep the molecules in the same region. There is also a second kind of transition, from liquid to vapor and vice versa. Thus, there are two types of state transi-

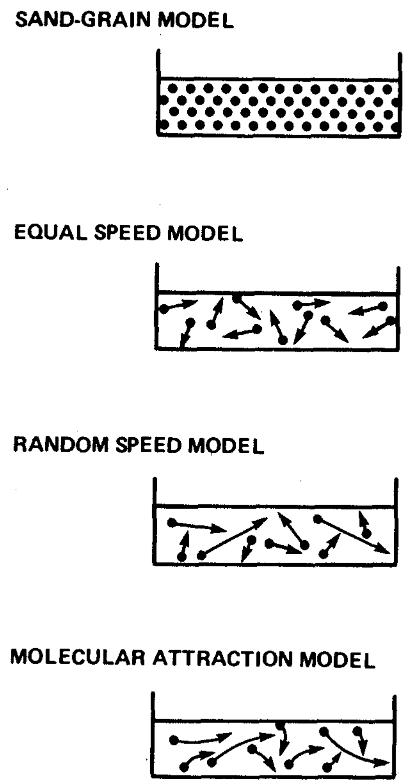

Figure 10.3. Component models of the behavior of molecules in water

tions that occur for evaporation processes: from one region to another, and from one phase to another.

We contrast different possible views of each of these component processes. Some of these views we have clearly identified in subjects' protocols; others are only alluded to. Where the protocols were unclear as to which of two alternative models was implied, we have generally included both models. This is not an exhaustive set of all possible component models but only of those that were suggested in subjects' protocols. However, they do show how people can derive their views from different analogies.

BEHAVIOR IN WATER

Figure 10.3 shows four different analogical models that subjects might have of how molecules behave in water. The first view we call the *sand-grain model* – the molecules just sit there like grains of sand, moving and slipping when something pushes on them. The temperature of the water

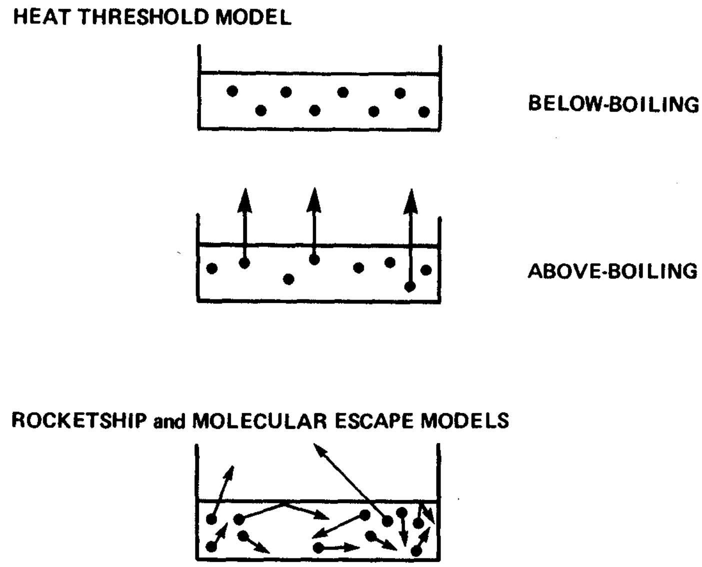

Figure 10.4. Component models of how water molecules escape from water to air

is the average temperature of the individual molecules. This is a very primitive model. The next two views assume that the molecules are bouncing around in the water like billiard balls in random directions (Collins & Gentner 1983). In both views, the speed of the molecules reflects the temperature of the water. The difference is that in one version – the *equal speed model* – all the molecules are moving at the same speed. The other version is a *random speed model,* which allows for differences in speed for different particles. On this view, temperature reflects the average speed of a collection of molecules. The fourth view, called the *molecular attraction model,* incorporates attraction between molecules into the random speed model. In it, molecules move around randomly, but their paths are highly constrained by the attractive (or repulsive) electrical forces between molecules. This view is essentially correct.

ESCAPE FROM THE WATER

Figure 10.4 shows three possible component models for escape (pictorially, two are the same). What we labeled the *heat-threshold* model is a threshold view of escape: The molecules have to reach some temperature, such as the boiling point of the liquid, and then they pop out of the liquid, the way popcorn pops out of the pan when it is heated. The remaining two models focus on molecular velocity, rather than on the incorrect notion of molecular temperature. The *rocketship model* is based on the assumption that the molecules in the water are moving in random direc-

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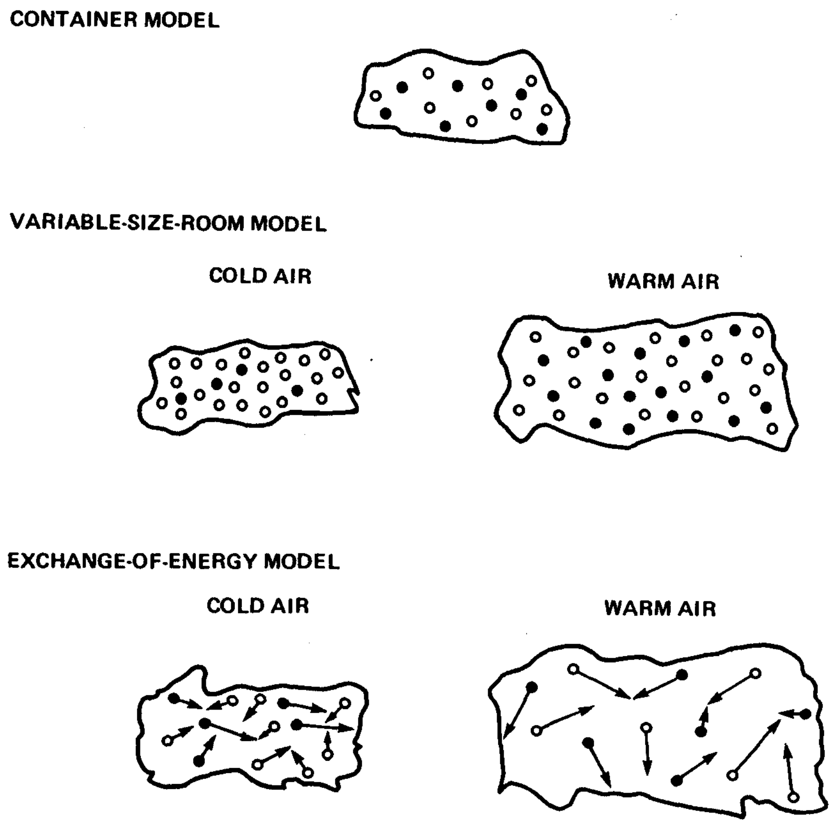

Figure 10.5. Component models of the behavior of water molecules in air (water molecules are filled circles, air molecules are open circles)

tions. To escape from the water (like a rocketship from the earth), a molecule must have an initial velocity in the vertical direction sufficient to escape from gravity. The third view, the *molecular escape model,* posits that the initial velocity must be great enough to escape from the molecular attraction of the other molecules. Both latter models are in part correct, but the major effect is due to the molecular attraction of the water.

BEHAVIOR IN THE AIR

Three component models of how the water molecules behave in the air are depicted in Figure 10.5. The *container model* posits that the air holds water molecules and air molecules mixed together until it is filled up (at 100% humidity). The *variable-size-room model* is a refinement of the container model to account for the fact that warm air holds more moisture than cold air. In this model, molecules in warm air are further apart and

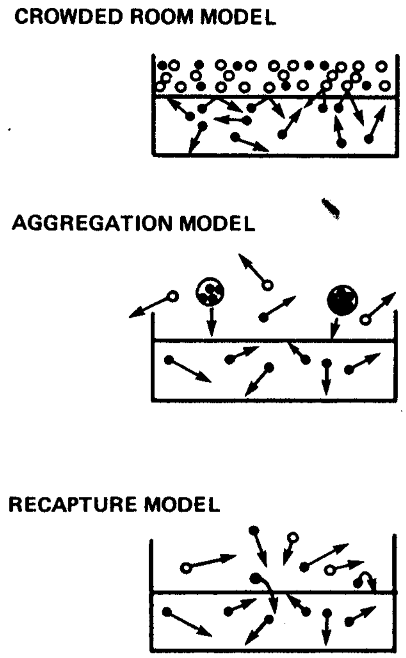

Figure 10.6. Component models of how water molecules return from air to water

so are less dense than molecules in cold air. That leaves more space to put water molecules in warm air than in cold air. In the *exchange-of-energy model,* the chief reason that cold air holds less moisture than warm air is that its air molecules are less energetic. When water molecules in the air collide with air molecules, they are more likely to give up energy if the air is cold (and hence less energetic) than if it is warm. If the water molecules become less energetic, they are more easily captured by the molecular attraction of other water molecules (or a nucleus particle) in the air. When enough water molecules aggregate, they will precipitate. This latter view is essentially correct.[2]

RETURN TO THE WATER

Figure 10.6 shows three models of how water molecules return to the water. The *crowded room model* assumes that when all the space in the air is filled, no more water molecules can get in. This is more a prevention-of-escape model than a return model. The *aggregation model* assumes that water molecules move around in the air until they encounter a nucleus or particle (which could be another water molecule) around which water accumulates. The less energetic the molecule, the more likely it is to be caught by the molecular attraction of the particle. As these particles accumulate water, gravitational forces overcome the random movement of

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the particles and they precipitate. The *recapture model* assumes that particles are attracted by the surface of the water (or other surfaces). The less energy they have, the more likely they are to be recaptured. The action in this view takes place near the surface, unlike the aggregation view. A fourth possibility is to ignore return processes altogether. Some of our subjects described evaporation solely in terms of water leaving the liquid state and appeared unaware of any need to consider the other direction, of water vapor returning to the liquid state. Both the aggregation and the recapture models are essentially correct, but the aggregation model takes place over a long time period with relatively high humidities, whereas the recapture model is applicable in any situation in which evaporation is occurring.

LIQUID-VAPOR TRANSITION

Figure 10.7 shows four different views we have identified for the transition from liquid to vapor and from vapor to liquid. One view, *the coterminus model,* is that the transition occurs when the molecules leave the

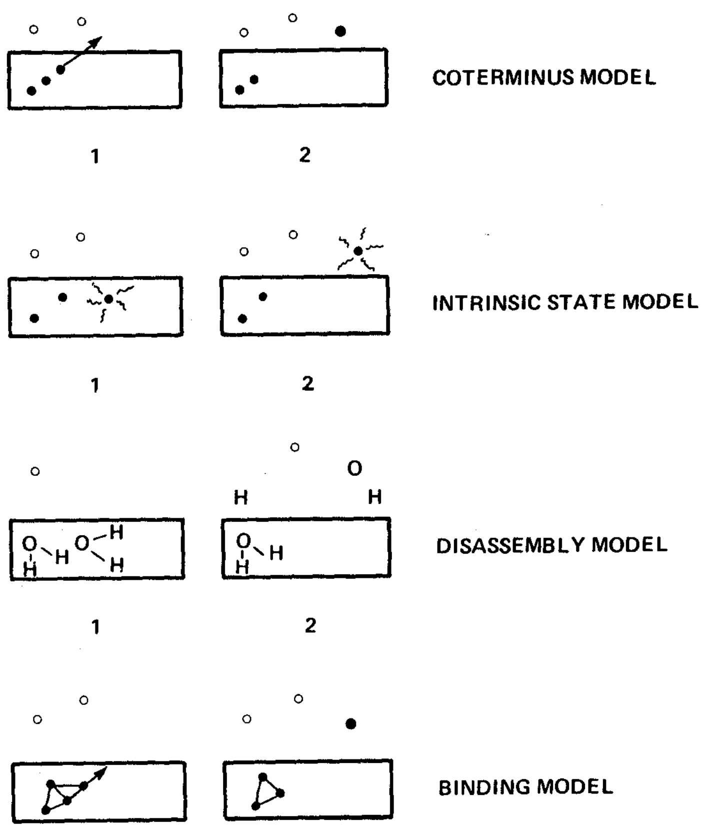

Figure 10.7. Component models of the liquid-vapor transition

water and escape to the air, and vice versa. In this view, the two transitions, between water and air, and between liquid and vapor, are the same transition. In other words, whether a molecule is in the vapor or liquid state depends solely on the location: All molecules beneath the surface of the water are liquid, and all molecules above the surface of the water are vapor. A second view, *the intrinsic state model,* treats the liquid or gas state as an intrinsic property of the molecule. If the molecule becomes hot enough, it changes from liquid to vapor, and if it becomes cold enough, it changes from vapor to liquid. Location is correlated with state in that molecules in the vapor state tend to move into the air, whereas molecules in the liquid state remain in the water. A third view, *the disassembly model,* is based on a little chemistry: In it, liquid water is thought of as made up of molecules of H_2O, whereas the hydrogen and oxygen are thought to be separated in water vapor. The expert view, which we call the *binding model,* is based on molecular attraction: Water molecules in the liquid state are partially bound together by electrical attraction of the neighboring molecules, whereas molecules in the gaseous state bounce around rather freely. The bubbles in a boiling pan of water are thus water molecules that have broken free of each other to create a small volume of water vapor, and clouds and mist are microscopic droplets of liquid water that have condensed but are suspended in the air.

COMBINING COMPONENT MODELS

Table 10.3 summarizes all the component models described here. Subjects can combine these component models in different ways. The following section shows two subjects, *RS* and *PC,* who had different models. *RS* had a model constructed from the random speed model of water, the rocketship or molecular escape model of escape, the variable-size-room-model of the air, the crowded room model of return, and the coterminus model of the liquid–vapor transition. The other subject, *PC,* had a less consistent and less stable model of evaporation. His view included something like the heat-threshold model of escape, the container model of the air, the recapture model of return, and the intrinsic state model of the liquid–vapor transition. In contrast, as we have indicated, the expert view is made up of the molecular attraction model of water, the rocketship and molecular escape models of escape, the exchange-of-energy model of the air, the aggregation and recapture models of return, and the binding model of the liquid–vapor transition.

An experiment on mental models

Four subjects were asked eight questions (shown in Table 10.4) about evaporation. They were asked to explain their reasoning on each question. The

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Binding Model

Table 10.4. *Evapc*

Question 1. Which
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Table 10.3. *Component models of evaporation*

Models of Water
- Sand–Grain Model
- Equal Speed Model
- Random Speed Model
- Molecular Attraction Model

Models of Escape
- Heat-Threshold Model
- Rocketship Model
- Molecular Escape Model

Models of Air
- Container Model
- Variable-Size-Room Model
- Exchange-Of-Energy Model

Models of Return
- Crowded Room Model
- Aggregation Model
- Recapture Model

Models of Liquid–Vapor Transition
- Coterminus Model
- Intrinsic State Model
- Disassembly Model
- Binding Model

Table 10.4. *Evaporation questions*

Question 1. Which is heavier, a quart container full of water or a quart container full of steam?

Question 2. Why can you see your breath on a cold day?

Question 3. If you put a thin layer of oil on a lake, would you increase, decrease, or cause no change in the rate of evaporation from the lake?

Question 4. Which will evaporate faster, a pan of hot water placed in the refrigerator or the same pan left at room temperature and why?

Question 5. Does evaporation affect water temperature, and if so how? Why or why not?

Question 6. If you wanted to compress some water vapor into a smaller space but keep the pressure constant, what would you do? Why?

Question 7. On a hot humid day, you must sweat *more* or *less* or *the same amount* as on a hot dry day at the same temperature. Why?

Question 8. If you had two glasses of water sealed in an air-tight container, and one was half filled with pure water, while the other half was filled with salt water, what would you expect to happen after a long period of time (say about a month)? Why?

subjects were two male Harvard undergraduates, one female secretary with a college degree, and one female doctoral student in history. All were reasonably intelligent but were novices about evaporation processes. Our analysis centers on the first two subjects because they best illustrate the kind of reasoning we see in novice subjects.

ANALYSIS OF SUBJECT *RS*'S MODEL OF EVAPORATION PROCESSES

The first subject (*RS*) has a model of evaporation processes based on (1) the random speed model of water, (2) some variation of either the rocketship or the molecular escape model of escape, (3) the variable-size-room model of the air, (4) the crowded room model of return, and (5) the coterminus model of the liquid–vapor transition. His view includes notions of the energy needed for molecules to escape from a body of water and the difficulty water molecules have in entering a cold air mass because of the higher density. He seems to share a common misconception with the second subject: namely, that visible clouds (such as one sees coming out of a boiling kettle) are made up of water vapor rather than recondensed liquid water. This misconception forced him into several wrong explanations, even though his reasoning powers are impressive. As we show, he seems to check out his reasoning by running different models of evaporation processes (Stevens & Collins 1980) and to try to account for any differences in results when he finds them.

We present the most relevant portions of his responses to three of the questions and our analysis of his reasoning processes (omitted portions of his response are indicated by dots).

Q2: On a cold day you can see your breath. Why?

RS: I think again this is a function of the water content of your breath that you are breathing out. On a colder day it makes what would normally be an invisible gaseous expansion of your breath (or whatever), it makes it more dense. The cold temperature causes the water molecules to be more dense and that in turn makes it visible relative to the surrounding gases or relative to what your breath would be on a warmer day, when you don't get that cold effect causing the water content to be more dense. . . . So I guess I will stick with that original thinking process that it is the surrounding cold air – that the cold air surrounding your expired breath causes the breath itself (which has a high water content and well I guess carbon dioxide and whatever else a human being expels when you breathe out), causes the entire gaseous matter to become more dense and as a consequence become visible relative to the surrounding air.

What in fact happens on a cold day is that the invisible water vapor in one's breath condenses, because it is rapidly cooled. This condensed liquid water is visible as clouds or mist. However, the subject did not know that the clouds were liquid rather than water vapor, since he seems to think of water molecules in the air as vapor by definition (i.e., the coterminus model), so he needed to find some other account of what happens. For

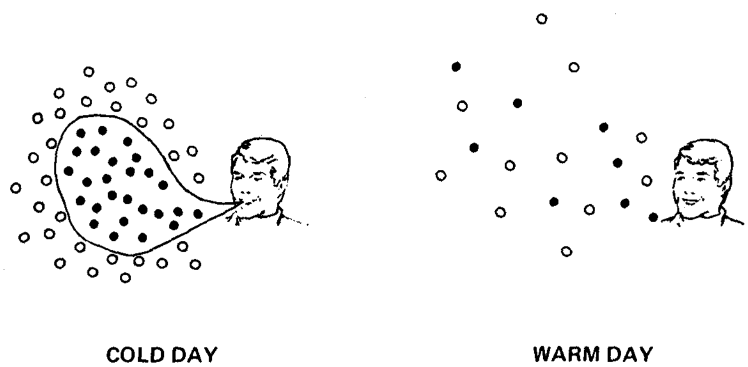

Figure 10.8. *RS*'s model of why you see your breath on a cold day

that, he turned to his knowledge that cold air masses are more dense than warm air masses – his protocol includes a clear statement of the variable-size-room model of the air. Our depiction of the process he imagined is shown in Figure 10.8.

What his view seems to involve is a vapor-filled gas cloud being emitted from a person's mouth. On a cold day, the surrounding air cools the emitted breath, causing it to compact into a small visible cloud. The denser the breath, the more visible it is. This latter inference has its analogue with smoke or mist: The more densely packed they are, the more visible they are. In fact, as the breath disperses, the particles become less visible. This suggests that the subject may be invoking an analogy, not explicitly mentioned, to the behavior of smoke or mist in constructing his model.

The next protocol segment clearly illustrates his belief in the variable-size-room model of the air and the crowded room model of return.

Q4: Which will evaporate faster, a pan of hot water placed in the refrigerator or the same pan left at room temperature? Why?

RS: When I first read that question, my initial impression, that putting a pan of hot water in the refrigerator you suddenly have these clouds of vapor in it, threw me off for a second. I was thinking in terms of there is a lot of evaporation. Well I guess, as I thought through it more, I was thinking that it was not an indication of more evaporation, but it was just (let us say) the same evaporation. Immediately when you put it in anyway, it was more visible. Ahmm, as I think through it now, my belief is that it would evaporate less than the same pan left standing at room temperature and my reasoning there is that the air in the refrigerator is going to be relatively dense relative to the room temperature air, because at a colder temperature again its molecules are closer together and that in effect leaves less room to allow the molecules from the hot water to join the air. . . .

Here, the subject first simulates what happens at the macroscopic level when you put a pan of hot water in the refrigerator. He imagines clouds

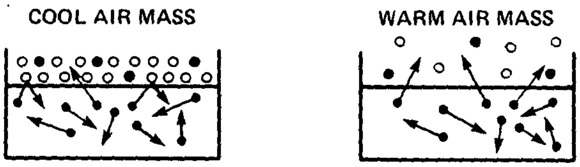

Figure 10.9. *RS*'s model of evaporation from a hot pan of water in the refrigerator

of steam coming out of the pan and initially thinks there must be more evaporation. It is unlikely he would ever have seen what happens when you put a pan of hot water in a refrigerator. He probably constructed this process from some analogous situation(s), such as warm breath on a cold day, running hot water in a cold room, or mist rising off a lake, for example. He is correct about the visible clouds of vapor, but as he concluded later, these clouds do not represent more evaporation. In fact, they represent condensation of the evaporated moisture (which he did not know).

This subject frequently considers different perspectives on a question. Thus, he did not stop with his macroscopic analysis; he also simulated what would happen at a microscopic level. Figure 10.9 shows his view of why cold air leads to less evaporation. It is a clear statement of what we have called the crowded room model. There is not enough space, so some of the water molecules bounce back into the water, as shown in the picture, whereas they do not when the air is warm. This is an incorrect model that *RS* probably constructed on his own. However, it leads to a correct prediction in this case.

The last protocol segment shows *RS* following three different lines of reasoning:

Q5: Does evaporation affect water temperature? If so, in what way, and why?
RS: . . . My initial impression is that it doesn't. It does not affect the water temperature. The surfaces of that water, the exterior surfaces of that water are in contact with air or some other gaseous state, which allow molecules from the water to evaporate into that other gaseous substance. So I guess I don't see where the loss of water molecules would affect the water temperature.

In a way, however, I guess those water molecules that do leave the surface of the water are those that have the highest amounts of energy. I mean, they can actually break free of the rest of the water molecules and go out into the air. Now if they have a, if they are the ones with the most energy, I guess generally heat is what will energize molecules, then that would lead me to believe that maybe, although it may not be measurable, maybe with sophisticated instruments it is, but maybe it would be measurable after your most energetic molecules have left the greater body of water. Those that remain are less energetic and therefore their temperature perhaps is less than when all of the molecules that have already left or were a part of the whole. So I guess that has led me into a circle to perhaps change my initial response – maybe now I could im-

> agine where even if not measurable because of a lack of a sensitive enough instrument, maybe my logic or nonlogic (whichever the case may be) has allowed me to believe that maybe there is an effect on the water temperature. So I feel pretty good about it . . . . I guess even the original model with the sun striking the surface of water, that I thought initially, threw me off. Maybe that is accurate too, because the sun's rays certainly don't go down to the bottom. So I guess it depends how deep we are talking, of course. But it would penetrate only so far into the surface of the lake and energize those layers that are at the top surface of the lake or water, whatever the body of water is. So those top layers would then be more energized than deeper layers, and it would obviously be more able to evaporate off. As they evaporate off, assuming conditions are constant and you have got a situation where the succeeding layers get struck by the same heat energy, in this case the sun, from the sun. And they become as the preceding layers were, they become energized and then go off. You are left with less and less water, where a surface is at a given temperature and the rest is at a lower temperature, but your volume is less. So therefore it sounds like again, I am getting to the point where the average temperature would increase, ahmn, because you have less volume, but the surface is at a higher energy level then as a percentage of the whole.

Initially, he cannot think of any way in which evaporation affects the temperature of the water and starts to conclude that there is no effect. This is a lack-of-knowledge inference, that we discuss elsewhere (Collins 1978; Gentner & Collins 1981).

Then, based on the random speed model of water and either the rocketship or molecular escape model of escape (which make the same prediction here), he infers that the higher energy molecules are the ones that will escape, leaving behind molecules with less energy. This, he infers correctly, will cool the water. Said in another way, molecules headed up from the surface with less energy will not escape, whereas those with more energy will escape. This is a subtle inference that follows directly from the rocketship and molecular escape models. Notice he does not have the misconception that all molecules in the water are moving at the same speed (i.e., the equal speed model). His reasoning depends crucially on variation in speed (i.e., the random speed model).

Later in his response, however, he comes up with an argument that leads to a conclusion opposite to the one above. He realizes that as water evaporates away, there is less water left for the sun to heat. Thus, given a fixed input of energy, the temperature of the water will rise. Why does he adopt this line of reasoning, given that nothing in the question supposed there was any further input of energy? *RS* seems here to be considering a canonical example of evaporation: the sun's warming a lake. Under these conditions, the temperature of the remaining water will indeed rise.

Here, two generative models come into conflict. The first view is based on a microscopic model of molecules escaping. The second view is based on layers of water evaporating, leaving behind less water to be heated by the sun. As in the previous protocol, the subject worked on the problem from different viewpoints; but in this case, two opposing conclusions seemed correct and he did not know how to choose between them.

We have tried to show how *RS* drew on a set of underlying component models to construct his molecular model of evaporation and how he used his model to find answers to novel questions. Based on this model, *RS* was able to deal quite successfully with the eight questions (he gave essentially correct answers on seven of eight questions). Nevertheless, his model was incorrect in the ways we have described.

ANALYSIS OF SUBJECT *PC*'S MODEL OF EVAPORATION PROCESSES

The second subject, *PC* had many more difficulties in dealing with these questions. His view was much less coherent. He relied frequently on local analogies to phenomena he had observed or things he had heard about, shifting among them without checking their consistency. This shifting made it difficult to ascertain his models, especially his model of water itself. However, most of his responses suggest that he combined (1) the sand-grain model of water, (2) the heat-threshold model of escape, (3) the container model of the air, (4) the recapture model of return, and (5) the intrinsic state model of the liquid–vapor transition. What is most striking about his view is how he treats heat as an intrinsic property of individual molecules rather than as a property of aggregates of molecules, as experts do.

The first protocol shows *PC*'s response to question two:

Q2: On a cold day you can see your breath; why?

PC: The reason is because the air that you breathe, or rather the air that you should breathe out, comes from your body and is hot air. The air which surrounds your body, because it is a cold day, will be cold air. When the hot air that you breathe meets with the cold air of the atmosphere, it will tend to vaporize almost like steam from a kettle, which of course, can be seen. Thus unlike on a hot day, when there is hot air around you and the hot air that you breathe are the same temperature, roughly, you cannot see your breath because the steam will not be formed, but on a cold day because of the variation in the temperatures and the vaporization of your breath, you can see when you are breathing. This phenomenon would not occur on a hot day because of the similarity in temperature.

This response would be correct as far as it goes if the words *vaporize* and *vaporization* were replaced by the words *condense* and *condensation*. This could be a simple lexical confusion, but other answers suggest it is a conceptual confusion (i.e., he really does think that the visible cloud formed is vapor). One piece of evidence for this belief occurs in answer to question four, where he refers to "the water which has already condensed in the refrigerator" (see below), suggesting he does understand the distinction between vaporizing and condensing. Furthermore, it is a common misconception to think of a cloud of steam as water vapor, rather than recondensed liquid water. His response suggests he does not have a coterminus model of the liquid–vapor transition, as *RS* had, since he sees the transition occurring in the air. Rather, he appears to have constructed a version of the intrinsic state model, where the transition depends on a temperature difference between the air and the liquid water.

His analysis relies on an analogy to a core observation he has seen many times – steam from a kettle. To solve the problem, he has to find some factor in common between one's breath on a cold day and steam from the kettle that is different from one's breath on a warm day. The factor he comes up with is the temperature difference. Boiling water from a kettle is much warmer than room air. Likewise, warm breath is much warmer than air on a cold day. But warm breath is about the same temperature as air on a warm day. Since he believes that steam is vaporized water, he therefore concludes that the temperature difference must somehow cause vaporization of water. He does not push his analysis down to a microscopic level, as did *RS*, to account for how this might be. Instead, he stops with identifying the analogous factor in the two situations.

PC's response to the fourth question shows some of the conceptual problems he has:

Q4: Does a pan of hot water in the refrigerator evaporate more, less, or the same amount as the same pan left standing at room temperature? Why?

PC: Hmmmm. Hot water, when it meets with – wait a second. Hot water will only evaporate if it is sufficiently heated. By placing the hot water in a refrigerator you are not heating it, you are cooling it, and in fact the reverse process will occur. That is, the water will decrease in temperature and the refrigerator's temperature itself will also decrease. Not only that, but also the water which has already condensed in the refrigerator, because of the heat from the hot water when you put it in the refrigerator, will go into water itself because of the difference in the temperatures. To sum up, the pan of water in the refrigerator will not evaporate at the same rate, but will evaporate at a lesser rate than the same pan left standing at room temperature for the above reason.

This question came soon after the question about breath on a cold day, and *PC* starts out answering the same way, "Hot water, when it meets with – ." This line of reasoning would conclude "the cold air, vaporizes to produce clouds of steam, and so there is more evaporation" just as *RS* has at first imagined and *PC* had argued in response to question two. But *PC* aborted that line of reasoning, whereas *RS* pursued it and ruled it out as incorrect.

The next sentence reveals *PC*'s heat-threshold model of escape: that the temperature of the water has to be sufficiently high (presumably boiling) for evaporation to occur. Sometimes in his answers, *PC* invoked this heat-threshold notion, and other times he violated it.

In answer to the question, *PC* concludes that evaporation will decrease for two reasons. First, the water in the pan will cool, and hence evaporate less or not at all. Second, the water that has condensed in the refrigerator will tend to "return to the pan of water." Both ideas are essentially correct, but there are several incorrect statements associated with the latter argument. One is that the refrigerator's temperature will decrease (just like the water's temperature) because a warm pan of water is put in it – the opposite is in fact true. Then he seems to conclude that the warm temperature of the water will cause condensation because of the temperature difference with the air: a kind of inverse process from the one he argued for in response to question two. In fact, the warmth from the pan of water will tend to reduce condensation.

Nowhere in this or other answers does he regard the air as anything other than a passive container for water and air molecules – he does not mention anything like the variable-room-size model that *RS* described, or the exchange-of-energy model that experts hold. In fact, he seems unaware that cooler air holds less moisture than warm air. However, he does seem to have a notion in this and other answers that molecules from the air will return to the water. This notion seems to depend on what he calls "condensation" in this answer, but not so clearly in other statements he makes. We have characterized this as a recapture model of return, rather than an aggregation model. Even though he seems to say that recapture must be preceded by "condensation," it is not clear that his "condensation" involves aggregation of molecules, as in the expert model. Rather, in keeping with his intrinsic state model of the vapor–liquid transition, "condensation" may be a change in state that occurs individually to each molecule.

PC's answer to the sixth question provides the clearest example of his view of heat as an intrinsic property:

Q6: What would you do if you want to compress some water vapor into a smalller space but keep the pressure constant?

PC: Hot air rises. Vapor is air, ok. Therefore, if you have a greater amount of vapor and you want to compress it, all you do is you heat the vapor so that by heating it, one will be causing the molecules to react faster which would increase the temperature of initially some molecules of steam, which will then go to the top and which will eventually increase the temperature overall, which will all – *all* the molecules will want to go to the top of the container, and as a result one will have a level of steam at the very top of the container and a vacuum at the end of the container – now I have got to get that down. Initially, the temperature of some of the molecules of steam, which because hot air, in this case steam, will always rise above in the colder air, the hotter steam will rise to the top of the container. Eventually, all the molecules of steam will be all trying to get to the top of the container, which will cause a greater density of the gas, i.e., steam, leaving a vacuum at the bottom of the container.

Figure 10.10 represents the microscopic model *PC* constructed to answer this question. He makes a classic error: He applies a correct macroscopic rule incorrectly at the microscopic level (Stevens & Collins 1980). He has

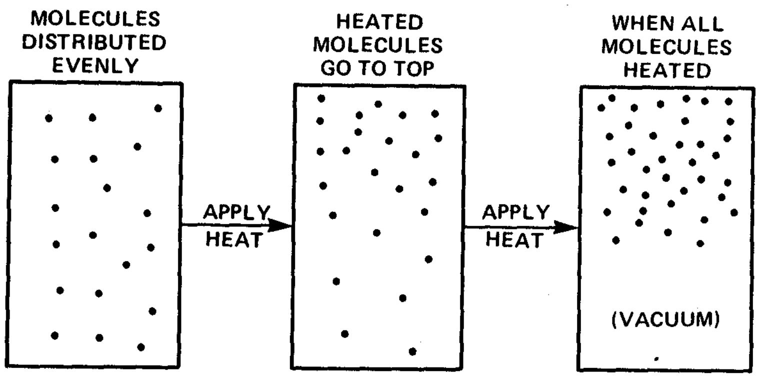

Figure 10.10. *PC*'s model of how to compress water by heating it

learned somewhere that hot air rises. The reason for this is that hot air particles have more energy, on the average, than cold air particles. This causes hot air to be less dense than cool air, and so it rises above cool air. But *PC* applies this aggregate property to individual molecules, where it does not apply. Thus, he imagines that each molecule, if it receives heat energy, will tend to rise to the top. Here, he reveals his view of temperature as intrinsic to individual molecules that underlies his heat-threshold model of escape and his intrinsic state model of the liquid–vapor transition. Eventually, in his view, each molecule will receive heat energy, and so they will all collect at the top, leaving a vacuum at the bottom. The correct answer is just the opposite. Cooling the vapor will cause each molecule to have less energy on the average, and so the same number of molecules will take up less space with no increase in pressure on the side of the container.

PC's reasoning about evaporation is much less consistent than *RS*'s. He shifts around among a variety of principles and models to reason about these questions. Not surprisingly, he is less accurate than *RS:* only three out of eight of his answers were correct, as compared to seven out of eight for *RS.*

Conclusion

This paper traces the way people construct models of evaporation processes by using analogies from other domains. Our thesis is that people construct generative models by using analogy to map the rules of transition and interaction from known domains into unfamiliar domains.

Analogy is a major way in which people derive models of new domains (Gentner 1982; 1983; Gentner & Gentner 1983; Lakoff & Johnson 1980; Rumelhart & Norman 1981; Winston 1980). Analogy can serve to transfer knowledge from a familiar concrete domain to an abstract domain, such as emotions or marriage (cf. Lakoff & Kövecses this volume; Quinn this volume). But even when there are many observable surface phenomena in the target domain, people still rely heavily on analogies in their reasoning. Kempton's (this volume) work on people's models of home thermostats and our research on models of evaporation both show the importance of analogical reasoning in physical domains.

The existence of such analogical models raises two important questions for further research. First, how are different analogies combined? One goal of this paper is to examine how subjects combine component models constructed from different analogies. People vary substantially in the consistency and stability with which they coordinate multiple analogies for a domain. We have shown how one subject, *RS,* combined his component analogies into a relatively consistent model of evaporation and used it to reason fairly correctly about novel questions relating to evaporation processes. His model contrasts with that of another subject, *PC,* with a less coherent understanding of evaporation. *PC* invokes different principles or models for every answer. He aborts one line of reasoning when it contradicts another line of reasoning, without trying to trace the reason for the inconsistency. He uses principles that apply at one level of analysis in reasoning at another level of analysis.

A second, more basic question is, where do these models come from? Although they are partly idiosyncratic, they must be heavily influenced by cultural transmission. If these models were purely experiential, derived independently by each individual, it is unlikely that notions of molecules and temperature would figure so prominently. On the other hand, our subjects' models of such concepts as molecules differ in some rather striking ways from expert models. The interplay between scientific models and the idiosyncratic interpretations that individuals place on them is a topic ripe for serious study.

Notes

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2. It is true that, in normal outdoor conditions, warm air tends to be less dense than cool air, as in the variable-size-room model; but the difference in evaporation rate does not require this density difference. Even in a sealed container, warming the air will enable it to hold more water.

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