Proceedings of the Annual Meeting of the Cognitive Science Society

**Title**

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**Journal**

Proceedings of the Annual Meeting of the Cognitive Science Society, 4(0)

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**Publication Date**

1982

# CONSTRUCTING RUNNABLE MENTAL MODELS

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A core idea in the literature on mental models (Brown, Burton, & Zdybel, 1973; deKleer, 1977, 1979; Forbus, 1981; Hayes, 1978; Stevens & Collins, 1980) is the notion of mental simulation. In all these approaches mental simulation is accomplished by dividing a system into a set of states whose transition rules from state to state are known. Given the transition rules for each state, and the topology of connections between states, it is possible to run the system with different inputs to see what happens. This provides a kind of inferential power not possible with the static data structures implied in much of the literature on frames, scripts, and semantic networks (e.g., Collins & Loftus, 1975; Minsky, 1975; Quillian, 1968; Schank & Abelson, 1977).

## The Metaphor Hypothesis

In this paper we propose a specific role for metaphor in constructing runnable mental models. It can be stated as follows: Metaphors map the set of transition rules from one domain (the base) into another domain (the target) so that it is possible to construct a mental model to run simulations in the target domain. This is a special case of Gentner's (1980, 1982) more general claim that metaphor is a mapping of structural relations from a base domain to a target domain.

We can illustrate the hypothesis by showing how three metaphors can be used to construct a runnable version of the microscopic model of evaporation discussed by Stevens and Collins (1980). Then, in the next section, we compare the model derived from these metaphors with the model one of our subjects used to reason about evaporation in an experiment where we asked subjects novel questions about evaporation processes.

The first metaphor states that water molecules (or air molecules) are like billiard balls bouncing around in space. The warmer the water is, the more velocity (or greater energy) the average molecule has. The same metaphor applies to the water and air molecules in the air mass above a body of water. This model is incomplete insofar as it includes no notion of the attractive forces between different molecules and the polarity of the electrical charges on different sides of the molecule. But as a first approximation, it is a perfectly good model.

The second metaphor states that a molecule escaping from the water is like a rocket ship escaping from earth. That is to say whether or not it actually escapes is a function of its initial velocity and its angle. In this way the model builds in a rudimentary notion of the attractive forces between molecules, by likening the notion of escape from the attraction of the other water molecules to escape from gravity. However, to understand some aspects of evaporation, this gravity notion of attraction is not enough.

The third metaphor states that the molecules in the air mass over the water can be thought of as people inside a room. As more water molecules collect in the air mass, the room becomes more crowded with water and air molecules. The warmer the air mass, the larger the room. Thus, warm air masses are less dense then cold air masses. The boundary between the air and water is the entry into the room, and if everyone crowds along that border it is hard to get in. This crowded-room metaphor leads to many correct predictions, but is wrong in some fundamental ways. In fact, the space between molecules in a cool air mass never becomes crowded. Cool air masses hold less moisture because the water molecules in them tend to lose energy with each interaction. Then the attractive forces between water molecules tend to attract the molecules back to the water surface or to form raindrops or dew.

Now we want to show how these three metaphors enable a person to construct a runnable model of evaporation processes. We would argue that people usually know certain interaction rules of billiard balls such as those depicted in Figure 1. Velocity of each ball in the interaction is represented by a vector, and the transition rule of the interaction by the large arrow. Rule 1 shows that without collision, speed and direction are maintained. Rule 2 shows a head-on collision with a non-moving ball where momentum is transferred from one ball to the other. Rules 3 and 4 show how momentum is transferred as a moving ball strikes a non-moving ball at different angles. Rules 5 and 6 show typical interactions when both balls are moving. These rules summarize one's local knowledge about how billiard balls interact.

From these local interaction rules, one can derive certain global properties of how a container full of molecules will behave. That is we can construct an aggregate model of molecular interaction (Stevens & Steinberg, 1981) based on the mechanical model of billiard-ball interaction. The most important properties of this aggregate model are that there is variability of speed and direction of the molecules. This produces randomness of motions of the molecules, with some going toward the surface, some not. There is elasticity of interaction so that energy can be transferred from molecule to molecule, but not lost. Finally, there is no change in direction or velocity without a collision. In our view, people can either imagine molecules moving in this aggregate fashion (like seeing dust particles moving in the sunlight) or by following a single molecule moving around and encountering other molecules according to the local interaction rules shown in Figure 1.

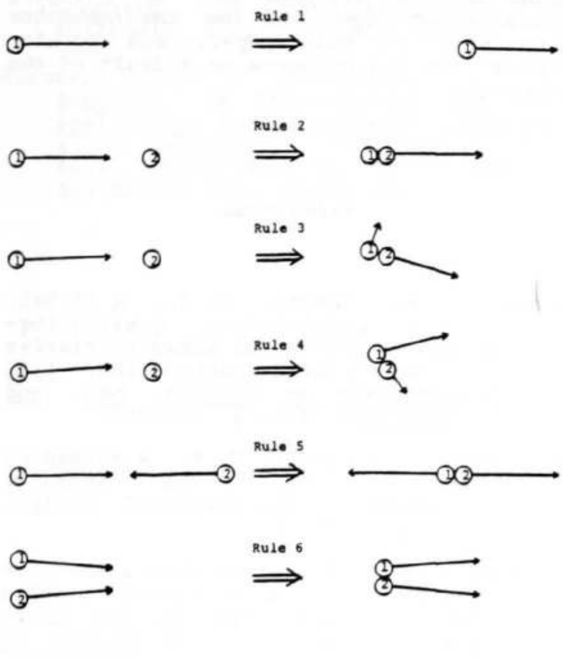

Figure 1. Some interaction rules for perfectly elastic billiard balls.

The rocket-ship metaphor gives a simple three state description of behavior of molecules near the surface. If they have any downward component of velocity, they do not escape. If they are headed straight up, there is some minimum initial velocity they need to escape. If they are headed up at an angle to the surface, the smaller the angle the greater the initial velocity they need to escape (because of the attraction of the surface over a larger part of the trajectory). This three state model summarizes what the rocket-ship metaphor implies about the effects of the water's surface.

The crowded-room metaphor, like the billiard-ball metaphor, leads to construction of an aggregate model at the microscopic level. The model has the following behavior. The warmer the air mass, the larger the room is. As water evaporates into the air mass, it fills up with molecules. Cold air masses take less time to fill up with molecules. When the air mass is filled, then no more water molecules can get in. If the air mass does not mix completely (depending on winds), then water molecules may accumulate in the air along the water's surface and no new molecules can get in, even though the air mass is not filled. If a crowded air mass is cooled, the water molecules may be squeezed out for lack of space. These behavioral properties reflect the way air masses actually behave, even though the model is essentially incorrect.

In an earlier paper (Stevens & Collins, 1980) we described the kind of inferential power that runnable models provide for answering novel questions about the world. In order to see how subjects use models, we conducted an experiment where we asked subjects to reason about such questions.

## Experiment on Mental Models

Four subjects were asked eight questions about evaporation. They were asked to explain their reasoning on each question. All were reasonably intelligent, but were novices about evaporation processes. Our analysis will center on one subject, whose model of evaporation processes was very much like the model we constructed from the three metaphors, if not exactly the same model. His view includes notions of the energy needed for molecules to escape from a body of water and the difficulty of water molecules entering a cold air mass because of the higher density. Nowhere does he mention attractive forces between molecules, which suggests that this notion is not part of his model. He seems to share a common misconception that visible clouds (such as one sees coming out of a boiling kettle) are made up of water vapor rather recondensed liquid water. This misconception forced him into several wrong explanations.

We will present the portions of his responses to three of the questions that illustrate his use of the mental model described above.

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

S: I think again this is 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 (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 . . .

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

S: 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 evaporation. Well I guess, as I thought through it more, I was thinking that it was 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 (what not), and that in effect leaves less room to allow the molecules from the hot water to join the air. . . .

Q5: Does evaporation affect water temperature? If so, in what way, and why?

S: 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 less.

The subject's first two answers manifest the crowded room model: The particles in cold air are crowded together, which acts to make one's breath more visible and to make it more difficult for water molecules from a hot pan to get in. The last answer manifests the rocket ship and billiard ball models: The particles move around and those that escape are the high energy particles, leaving the low energy particles behind and hence cooling the water.

These excerpts illustrate the underlying molecular model of evaporation that the subject had, and how he used it to find answers to novel questions. His model is close to, if not the same as, the model we constructed from the metaphors in the previous section. The hypothesis of the paper is that this subject's underlying model was constructed by pasting together his models of how familiar objects behave. While he may not have drawn upon billiard balls, rocket ships, and crowded rooms, he must have drawn upon some such objects in order to create the model he was using. Based on this model, he was able to deal quite successfully with the questions, even though his model was incorrect in several ways.

## Acknowledgments

This research was supported by the Personnel and Training Programs, Psychological Sciences Division, Office of Naval Research, under contract number N00014-79-C-0338, Contract Authority Identification Number NR 154-428. We thank Michael Williams for an engaging conversation that led to the metaphor hypothesis of this paper, and to Ken Forbus for his comments on a draft of the paper.

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