Primitives for Reasoning about the Behavior of Devices*

Tom Bylander

Laboratory for Artificial Intelligence Research
Department of Computer and Information Science
The Ohio State University
Columbus, Ohio 43210

Given a collection of components connected in a certain way, how can the behavioral descriptions of the components be *composed* into a behavioral description of the collection as a whole? As we shall see, this question points out a need to seek alternatives to qualitative simulation [4, 5, 6, 7], which has been the most common approach to generate behavior from component descriptions. I propose to answer this question by (1) representing the behavior of components using a small number of primitive types of behaviors and (2) inferring behavior based on rules of composition that describe how one type of behavior can arise from a structural combination of other types of behavior. This paper presents a brief description of the motivations and ideas of this research. Further discussion can be found in the following papers [1, 2, 3].

Limitations of Qualitative Simulation

Consider a simple device consisting of two batteries connected in series. Because of the voltages of the batteries and the structural relationship between the batteries, this device has a voltage equal to the sum of the batteries' voltages.

Now consider a qualitative simulation (QS) of this device and the answers that QS can provide. If the batteries are not connected to anything else, a QS can only infer that no change happens. If this device is connected to some circuit, a QS might infer that certain events happen, but should those events be attributed to the batteries, to the circuit, or both? Short of simulating a voltmeter connected to the batteries, can QS tell us what the voltage is? Two factors prevent QS from providing this type of information.

- Initial Conditions. To begin a simulation of a device, QS requires the initial state of each component in the device.
- Outside Interactions. To simulate the behavior of a device, a QS needs to know how the outside world will interact with the device. Without knowledge of what these interactions are, the value of each parameter that can be affected becomes indeterminable.

*This research is supported by Air Force Office of Scientific Research grant AFOSR 82-0255 and by Defense Advanced Research Projects Agency, RADC Contract F30602-85-C-0010.

Consequently, every QS is biased by assumptions about the initial conditions of the device and about the outside interactions with the device. That is, it is unclear whether the results of the simulation should be attributed to the device or to the specifics of the situation.

The difficulty is that QS produces a different kind of information than that required to describe the batteries' voltage. QS outputs a temporal sequence of physical states that the device goes through instead of general characteristics of the device. I call the output of QS "actual behavior" and the desired output in this case "potential behavior." Actual behavior expresses what events happen in what order. Potential behavior expresses behavioral characteristics independent of initial conditions and outside interactions. To simplify the discussion below, I often use "behavior" in place of "potential behavior."

Composing Behaviors

For deriving the potential behavior of devices, my research investigates a method of reasoning called ***consolidation.*** The idea of consolidation is to select a ***composite component*** consisting of two components and infer the behavior of the composite from the behavior of its subcomponents. Successful application of consolidation on increasingly larger composite components results in inferring the behavior of the whole device.

Consolidation works by composing the behavior of components into the behavior of composite components. QS proposals have described behavior as constraints on the components' quantities and derivatives, which would imply that consolidation is constraint simplification. An alternative to constraints, however, is to describe the behavior of a component by the primitive actions that the component performs upon "substances," physical phenomena that move, such as fluids, electricity, heat, light, etc. I propose that a small number of behavior schemas, called "types of behaviors," can directly represent these actions and permit inferences about behavior. It is this inferential capability that gives consolidation credibility. The types of behaviors that have been identified are:

- *Allow.* A substance is permitted to move from one place to another. A pipe has an *allow* water behavior.
- *Expel.* This is an attempt to move a substance from (to) a one place to (from) anywhere. A balloon has a *expel* air behavior.
- *Pump.* This is an attempt to move a substance through some path. A battery has a *pump* electricity behavior.
- *Move.* A substance moves from one place to another. A heat exchanger has a *move* heat behavior.
- *Create.* A substance is created in some place. A light bulb has a *create* light behavior.

- *Destroy.* A substance is destroyed in some place. An acoustic insulator has a *destroy* sound behavior. A transformation can be accomplished by a combination of *create* and *destroy* behaviors.

- *Change Mode.* A component might have different operating regions, called *behavioral modes*, in which it has different behaviors. For example, a electrical switch has two behavioral modes, only one of which has an *allow* electricity behavior. *Change mode* behaviors describe when a component changes from one mode to another. The switch changes mode when it receives a on or off signal.

Other research has proposed similar behavioral primitives 8, 9. For example, Schank's PROPEL and PTRANS are similar to *pump* and *move*, respectively. The main contribution of this research is the identification of composition rules, called *causal patterns*, that can be used to hypothesize behaviors based on structural combinations of other behaviors. A behavior's existence is confirmed, and its parameters are determined using knowledge about the substance being acted upon. Some of the causal patterns are:

- *Serial/parallel allow.* An *allow* behavior can be caused by two serial or parallel *allow* behaviors. Roughly, two behaviors are "serial" if they share an endpoint; two behaviors are "parallel" if they have the same endpoints. For example, two pipes with both ends connected satisfy the *parallel allow* pattern, as well as the *serial allow* pattern (the pipes form a circuit).

- *Propagate expel.* A *pump* behavior can be caused by an *allow* behavior and an *expel* behavior which is located at an endpoint of the *allow*. For example, the *expel* air behavior of a balloon combines with an *allow* air behavior from the balloon to give rise to a *pump* air behavior over the same path as the *allow*.

- *Propagate pump.* A *pump* behavior can be caused by a *pump* and an *allow* behavior in serial. For example, the *pump* electricity behavior of a battery and the *allow* electricity behavior of a wire connected to the battery results in a *pump* electricity behavior over the wire and battery.

- *Pump move.* A *move* behavior can be caused by a *pump* behavior and an *allow* behavior, both on the same path from one container to another, or both on the same circuit. Two containers of water connected by a horizontal pipe (an *allow* behavior) will result in movement if there is a pressure difference between the containers (a *pump* behavior). A wire connecting both ends of a battery is an example of the *pump move* causal pattern over a circuit.

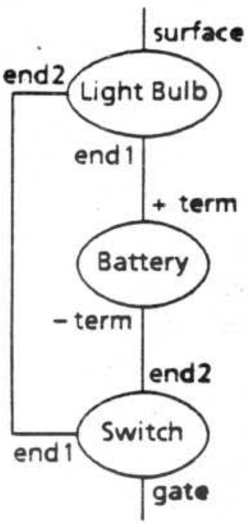
- *Carry move.* A *move* behavior of a substance S1 that can contain a substance S2 (e.g. water can contain heat) can cause a *move* S2 behavior along the same path. For example, when something that contains heat moves from A to B, heat also moves from A to B.

Consolidation controls the inference of behavior by restricting the context (the composite component) in which inference can take place.

The causal patterns are similar to the individual views and the process descriptions developed by Forbus [5]. They all identify the conditions that give rise to behavior. The main difference is that the causal patterns are intended to be generic to all substances. Within Forbus's QP theory, the causal patterns might be expressed as "universal" individual views and process descriptions.

An Example

Consider the device shown in figure 1. The light bulb *allows* electricity to move through it, and *creates* light whenever electricity *moves* through it. The battery *pumps* electricity between its terminals and *allows* electricity to flow between its terminals (otherwise the pumping action would have no effect). The switch *allows* electricity to flow through it when the behavioral mode of the switch is "closed" and *changes mode* from open to closed when it receives an "on" signal. In the figure, "surface" and "gate" are open connections of the device. The details of the representation and other behaviors of these components have been suppressed for explanatory purposes.



Allow electricity *between* end1 *and* end2
Create light *in* light bulb,
dependency [*move* electricity *between* end1 *and* end2]

Pump electricity *from* negative terminal *to* positive terminal
Allow electricity *between* negative terminal *and* positive terminal

Allow electricity *between* end1 *and* end2, *mode* closed
Change mode from open *to* closed
when [*move* signal *from* gate *to* switch, *message* on]

Figure 1: Light Bulb Device

Suppose that a composite component consisting of the light bulb and the switch is selected for consolidation. Because the switch's *allow* electricity behavior is serial to the light bulb's *allow* electricity behavior, the *serial allow* causal pattern is used to infer an *allow* electricity behavior from end1 of the light bulb to end2 of the switch. This *allow* behavior occurs only during the closed mode of the switch, so the composite also has closed and open behavioral modes. In the context of the causal pattern, knowledge about electricity is used to calculate the resistance and other attributes of the inferred *allow* electricity behavior. The switch-light bulb composite also has a *create* light behavior and *change mode* behaviors, which are taken from the behavioral descriptions of the subcomponents.

When this composite is combined with the battery, the following inferences are made. Using the *serial allow* causal pattern, an *allow* electricity behavior around the circuit is inferred. Using the *propagate pump* causal pattern, a *pump* electricity behavior around the circuit is inferred. Both inferred behaviors occur during the closed mode. They also satisfy the *pump move* causal pattern, giving rise to a *move* electricity behavior around the circuit during the closed mode. This *move* behavior satisfies the dependency of the *create* light behavior, i.e. the device *creates* light while it is in the closed mode.

Every behavior of the components and element of structure that plays some role in the creation of light has been used to infer the creation of light. *The explanation of this inference provides a causal account of the creation of light in the light bulb device in terms of the components' behaviors and the device's structure.*

Limitations of Consolidation

It is important to distinguish two types of limitations: those that are inherent to any consolidation method and those that are due to weaknesses in my particular theory. The main limitation, of course, is that consolidation works on only one type of problem -- deriving the potential behavior of a device. It does not, for example, determine the actual behavior of a device (it does not replace qualitative simulation), nor does it design devices that perform some behavior.

Consolidation is limited by the availability and capability of other reasoning processes. The precision and succinctness of a behavioral description depends, in part, on reasoning about the attributes of behaviors, such as keeping track of ordinal relationships and reasoning about feedback.

Another limitation of consolidation is that all the behaviors of components and substances must be known. For example, if a component has a *pump* water behavior not mentioned in its behavioral description, then a *move* water behavior and its effects might not be inferred. However, all the details about the *pump* water behavior are not required. A lack of detail might result in vague conclusions, but not wrong ones.

Combinatorial problems can arise during consolidation. The behavioral description of a composite component might include more behaviors, more behavioral modes, and more structural elements than either of the subcomponents. My proposal provides for some summarization, but does not prevent a number of combinatorial problems. It is unclear whether additional summarization processes can handle all the possibilities.

The specific consolidation framework that I have developed has several weaknesses not necessarily inherent to consolidation in general. My theory does not provide for spatial reasoning about shape and orientation, for some aspects of reasoning about substances such as mixtures, for certain kinds of summarization and abstraction of behavioral descriptions, and for actions at a distance such as gravity. These difficulties represent the next set of issues that future research needs to resolve.

References

1. T. Bylander and B. Chandrasekaran. Understanding Behavior Using Consolidation. *Proc. Ninth International Joint Conference on Artificial Intelligence*, Los Angeles, 1985, pp. 450-454.

2. T. Bylander. *Consolidation: A Method for Reasoning about the Behavior of Devices.* Ph.D. Th., The Ohio State University, Columbus, Ohio, 1986.

3. T. Bylander. Using Consolidation for Reasoning about Devices. Laboratory for Artificial Intelligence Research, Department of Computer and Information Science, The Ohio State University, Columbus, Ohio, 1987.

4. J. de Kleer and J. S. Brown. A Qualitative Physics Based on Confluences. *Artificial Intelligence 24*(1984), 7-83.

5. K. D. Forbus. Qualitative Process Theory. *Artificial Intelligence 24*(1984), 85-168.

6. B. Kuipers. Commonsense Reasoning about Causality: Deriving Behavior from Structure. *Artificial Intelligence 24*(1984), 169-203.

7. B. J. Kuipers. Qualitative Simulation. *Artificial Intelligence 29*, 3 (1986), 289-338.

8. R. C. Schank. *Conceptual Information Processing.* North Holland, Amsterdam, 1975.

9. Y. Wilks. An Artificial Intelligence Approach to Machine Translation. In R. Schank and K. Colby, Eds., *Computer Models of Thought and Language*, W. H. Freeman, San Francisco, 1973, pp. 114-151.