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Authors

Hollan, James D.
Hutchins, Edwin L.

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Reservations about Qualitative Models

James D. Hollan

Edwin L. Hutchins

Navy Personnel Research and Development Center
San Diego, California 92152

Abstract

Very little of the knowledge that an operator of a complex physical system brings to the job is purely quantitative in form. Virtually all of an operator's knowledge can be represented as qualitative relations or quasi-quantitative relations such as rough proportionalities. The realization that computer-based instruction systems need to provide instructions and explanations in terms that students can use, that is, often in qualitative terms, has led to recent efforts in cognitive science and artificial intelligence to develop qualitative simulation models of complex dynamic systems. In this paper we discuss theoretical and pragmatic problems involved in using qualitative models to support automated explanation facilities.

Much recent work in cognitive science has addressed the nature of qualitative reasoning. A number of studies have provided detailed analyses of protocols of subjects reasoning about a variety of physical systems (Larkin, 1983; Williams, Hollan, and Stevens, 1983) and have documented the extensive use of qualitative forms of reasoning. In addition, there have been many recent attempts by AI researchers to develop qualitative calculi which might be used by a program to permit it to reason about various classes of physical devices or to provide qualitative explanations of the operation of such devices (de Kleer, 1975; de Kleer, 1979; Forbus, 1981; Forbus, 1982; de Kleer & Brown,1983). The fact that such qualitative forms of reasoning appear to be important in understanding the operation of physical systems might lead one to believe that qualitative simulations will be the most effective way of building automated qualitative explanation systems. Our experience in the development of Steamer (Hollan & Hutchins, 1984), however, leads us to a quite different view of human reasoning about physical systems and motivates us to discuss a number of limitations of qualitative models for supporting qualitative explanations.

We have two fundamental reservations about the use of qualitative models as the basis of qualitative explanation facilities. While there is strong evidence that mental arithmetic plays little role in everyday calculation tasks (Lave, Murtaugh, & de la Rocha, in press), we are struck by how much of human reasoning seems to rely on the use of judgements that are more precise than could be produced by purely qualitative calculation. Much reasoning that at first blush appears totally qualitative can, upon closer inspection, be seen to involve approximate magnitude estimates. Our first reservation is that since purely qualitative simulations will not support the processing of even approximate quantities, they cannot be the basis of explanations that contain such quasi-quantitative information.

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Second, purely qualitative models are underdetermined in the sense that they cannot account for many qualitative aspects of the behavior of some systems. For example, in negative feedback systems the qualitative character of the response of the system to perturbation (damping versus hunting) is not determined by the device topology alone but is dependent upon the actual *quantitative settings* of a number of component parts. Certain settings will result in a damping behavior and other settings will result in hunting.

Quasi-quantitative Reasoning

Close observation of people reasoning about physical systems shows that there is considerable reliance on the use of quasi-quantitative knowledge. Consider for example the knowledge and models that people use to give *ball-park* estimates of the rough magnitudes of various aspects of events. The knowledge that supports such predictions is not entirely qualitative, since quantity is roughly specified, and yet not entirely quantitative since the quantities are not computed exactly. Such models are essential for our predictions about many aspects of everyday as well as technical life. Examples abound: *How far can I step? How long will it take to bring this water to a boil? How much rudder is required to turn a ship around.* We are all quite capable of making these types of predictions. We do not make exact predictions but we have a very definite *feel* for the general magnitude of the quantities involved.

These types of *ballpark* estimates appear well designed to interact with feedback from the world. One produces an estimate that is in the neighborhood of the actual value. That estimate is applied and can then be tuned based upon the feedback received from having made an action based on the estimate. Much of what goes under the heading of *getting the feel of it* is probably the acquisition and tuning of this sort of quasi-quantitative knowledge. We believe that it underlies much of the reasoning in many domains. For example, the mental computations that Micronesian navigators make to determine the distance they have covered along their course seem to depend on the use of this type of knowledge (Hutchins, 1983). Likewise, the reasoning involved in understanding the operation of a heat exchanger (Williams, Hollan, & Stevens, 1983) or a steam reducing valve concerns predictions not only about the direction of changes but also the approximate magnitudes of the changes. The important connection between these domains is in the specification of the *units* in which the change is expressed. Just as the navigator expresses the changes he monitors in terms of units that suit the computations he needs to make (nautical miles or location under star bearings, depending on the computational apparatus he has at his disposal) so the user of a mental model of a steam plant or any other device is likely to assess the changes of variables about which he is concerned in terms of units tailored to support the necessary subsequent computations. Such units might express something like *sufficient to cause a state transition* or, in the more familiar domain of driving, a speed increase might be specified as *enough to get me past that car before the on-coming truck arrives.*

How are such units arrived at and how are measurements made using them? Imagine, for example, a golfer involved in trying to sink a put. He has never had just this lie but he has to calculate how hard to hit the ball and where to hit it to account for the speed and slope of the green. One might conjecture that he mentally imagines the trajectory of the ball and has a model of the effects along the way. A model of the initial velocity of the ball (not expressed in feet per sec, but in terms of visualizing it moving across the surface of the green: *analog* units) and a model of how the ball will lose speed (depending upon the hardness of the green, the length of the grass, etc) and a model (also in terms of the imagined effects on the trajectory of the ball) of the accelerative effects of the slope of the surface. One can construct the same kind of scenario to account for numerous other everyday and technical endeavors. The important point though is the omnipresence of such quasi-quantitative units in reasoning about physical phenomena. Currently we know virtually nothing about how they are processed, how they are managed, or how they are connected to a performance.

Underdetermined Qualitative Models

Another precipitating motivation for this paper is a consideration for how difficult qualitative simulations are to construct. An appreciation for this difficulty arises from our experience with the Steamer system, from efforts we have made in building qualitative simulations (Williams, Hollan, & Stevens 1983), and from a lack in qualitative simulations of the types of quasi-quantitative reasoning devices that we have detailed above. The very interesting representational advances of de Kleer and Brown (1982, 1983) bear witness to the difficulty of constructing purely qualitative calculi that can support reasoning about physical devices. Part of this difficulty arises from the desire to make the qualitative calculi general and to avoid assumptions of system function in the specification of component device structure. This makes it possible for a single set of device models to qualitatively simulate the behavior of a large class of systems.The *no-function-in-structure* principle, while crucial to the construction of the *physics* that de Kleer and Brown (1982) are in search of, engenders a number of problems for supporting a qualitative explanation system and for capturing important qualitative and non-qualitative aspects of people's reasoning processes. For example, people normally violate this principle in reasoning about physical devices and systems. In fact, in dealing with a reducing valve, as they do in a recent paper (de Kleer & Brown, 1982), even they appear to need to violate their principle in order to explain the damping that occurs in this system. Their envisioning treatment of the reducing valve pulls a *damping rabbit* out of a hat. They provide an English language rendering of their program's explanation:

> An increase in source pressure increases the pressure drop across the valve. Since the flow through the valve is proportional to the pressure across it, the flow through the valve also increases. This increased flow will increase the pressure at the load. However, this increased pressure is sensed by [the sensing line] causing the diaphragm to move downward against the spring pressure. The diaphragm is mechanically connected to the valve , so the downward movement of the diaphragm will tend to close the valve, thereby pinching off the valve. *Because the flow is now restricted the output pressure will rise much less than it otherwise would have and thus remain approximately constant.* (de Kleer & Brown, 1982, p2; emphasis added)

There is, in fact, no way to predict from a purely qualitative analysis whether a negative feedback system is stable or unstable. This aspect of the behavior of the device depends upon the *quantitative* relationship of the controlled variable and the controlling action. Without knowing this relationship it is impossible to know if the value of the controlled variable will stabilize or continue to oscillate.

Others have also noted limitations with qualitative modeling. For example, Simmons (1983) has pointed out difficulties in expressing features, such as shape, in qualitative terms, that qualitative models are necessarily ambiguous "in that a single qualitative representation maps to many real-world situations", and that most users of qualitative representations have needed to make use of quantitative knowledge to deal with ambiguities (Simmons, 1983; Simmons & Davis, 1983).

Function in Structure

When an expert explains the behavior of such a device he assumes it is either working properly or somehow malfunctioning. Within the context provided by that assumed behavior a description of the propagation of effects in qualitative terms can be rendered. The determining variables are not described quantitatively, but are described relative to functionally embedded criteria. Consider the following typical statement about the behavior of a reducing valve: "If the gain is too high, then the system will hunt." The surface form of this statement is that of a prediction, but it is, in fact, not a prediction because the criteria for deciding the truth of the antecedent (whether or not the gain is too high) are based on the observation of the consequent. Seen in this light, the statement is a tautology, but a very useful one. It is based on the premise that there are correct settings for these parameters that will produce appropriate behavior. Certain abnormal behaviors are seen as diagnostic of deviations of parameters from their "correct" settings.

The utility of such functionally embedded specifications of parameter settings is that the device may be tuned without quantitative knowledge, as long as it was designed so that it will work with some settings. The tuning process need only be capable of interpreting the observed behavior as a symptom of a particular qualitative relation of a parameter to its "correct" setting. Based on this information, the operator can often hill climb to the correct setting without having any idea of its actual quantitative value. But notice that this strategy requires the assumption that the device can function properly. It also requires a description of proper functioning and a set of correspondences between device behavior patterns on the one hand and the relations of controlling parameters to their correct settings on the other. As we mentioned earlier, it is our contention that there is something very important about this form of interaction with the world. One begins with what is essentially open-loop ballistic behavior in the world, which requires quasi-quantitative representations and assumptions about function, and then one becomes part of a closed loop system, making use of qualitative evaluations to control the tuning process.

Conclusions

Qualitative physics is an important line of AI research, but models based on qualitative calculi may be inappropriate as a base for providing qualitative explanation in automated tutorial systems because 1. qualitatative calucli fail to represent important classes of features of events and objects, 2. they are fundamentally underdetermined with respect to some physical behaviors, and 3. the principles that guide the representation of events and devices in qualitative models (*no-function-in-structure* and the derivation of device behavior from component interactions) conflict with observed structures of human interpretation and explanation of device behavior.

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