The Problem of Existence

Kenneth D. Forbus
Department of Computer Science, University of Illinois
1304 W. Springfield Avenue, Urbana, Illinois, 61801
Arpanet: forbus@UIUC

Abstract: Reasoning about changes of existence in objects, such as steam appearing and water disappearing when boiling occurs, is something people do every day. Discovering methods to reason about such changes in existence is a central problem in Naive Physics. This paper analyzes the problem by isolating an important case, called *quantity-conditioned existence*, and presents a general method for solving it. An example generated by an implemented program is exhibited, and remaining open problems are discussed.

1. Introduction An important feature of the physical world is that objects come and go. If we boil water steam appears, and if the boiling continues long enough the water completely disappears. Modeling changes in existence is a central problem in qualitative physics, yet most theories avoid it. de Kleer & Brown (1984) and Williams (1984) define it away by basing their formalisms on *system dynamics*. In system dynamics, the model builder constructs a network of "devices" to represent the system under study. Many systems are not represented naturally by system dynamics (such as boiling water), and they do not address the crucial issue of generating the initial device network from what a person sees when walking around in the everyday world. Kuipers (1984) represents a system by a collection of constraint equations; objects are only represented implicitly by the names chosen for variables in the equations, so his system provides no help on this issue either. Simmons (1984) provides a means of specifying that objects appear and vanish in his representation of occurrences of processes, but in a way that precludes discovering changes in existence not explicitly foreseen by the modeller. Weld (1984) provides a similar notion in his elegant theory of discrete processes, but with similar limitations. No general solution currently exists. Given the range of phenomena (including state changes, chemical reactions, and fractures in solids) this is not too surprising. This paper presents a solution to an important special case, based on the framework provided by Qualitative Process theory (Forbus 1981; 1984a). First we describe a general logic of existence, extending notions of histories introduced by Hayes (1979) and then introduce the idea of quantity-conditioned existence. Next we describe a *temporal inheritance procedure* for reasoning about changes in existence, and illustrate its operation with an example. Finally, we suggest a direction in which to look for further solutions to the problem of existence.

2. A Logic of Existence Objects in the world are represented by *individuals*. In general criteria for what constitutes an individual depends on the domain. *Histories* represent how objects change over time. The history of an object describes its "spatio-temporal extent" and is annotated with the properties that hold for the object at various times. We futher assume the extensions described in (Forbus 1984a).

We begin by distinguishing between two related notions of existence. The first is logical existence, which simply means that it is not inconsistent for there to be some state of affairs in which a particular individual exists. A square circle is something which logically cannot exist. The second notion is physical existence, which means that a particular individual actually does exist at some particular time. Clearly an individual which physically exists must logically exist, and an individual which logically cannot exist can never physically exist. An example of an individual which logically exists but which (hopefully) never physically exists is the arsenic solution in my coffee cup.

The predicate **Individual** indicates that its argument is an individual. Being an individual means that its properties and relationships with other things can change with time, and that it may not always physically exist. The relation **Exists-In(i, t)** indicates that individual i exists at, or during, time t. The import of this relationship is the creation of a *slice* to represent the properties of **i** at **t**. A slice of an object **B** at time **t** is denoted by **at(B, t)**. All predicates, functions, and relationships between objects can apply to slices to indicate their temporal extent, i.e., the span of time they are true for.

Hayes' original treatment of histories did not address the interaction between existence and predication. What is the truth of a predicate applied to a slice when the individual is not believed to physically exist at the time corresponding to that slice? Allowing all predicates to be true of an individual when it doesn't physically exist has the problem that every fact **F** which depends on a predicate **P** must now also be explicitly justified by a statement of existence, such as

P(at(obj, t)) and Exists-in(obj, t) → F

rather than just

P(at(obj, t)) → F

To avoid this, we simply indicate that certain predicates which depend on physical existence imply that the individual does exist at that time, i.e.

P(at(obj, t)) → Exists-in(obj, t)

This allows the implications of the predication to be stated simply, while also providing a useful constraint for detecting inconsistencies. However, taxonomic constraints must be specified carefully. Consider the statement that an object is either rigid or elastic. If we simply assumed

For-All sl ∈ slice, Rigid(sl) or Elastic(sl)

we would be asserting the existence of the object at the time represented by that slice, since one of the alternatives must be true. These statements must always be placed in the scope of some implication which will guarantee existence, such as

For-All sl ∈ slice Physob(sl) → [Rigid(sl) or Elastic(sl)]

to avoid inappropriate presumptions of physical existence.

Situations describe a collection of objects being reasoned about at a particular time. A situation simply consists of a collection of slices corresponding to a set of objects existing at a particular time.[1]

An individual's existence is *quantity-conditioned* if inequality information is required to establish or rule out its existence. An example is Hayes' (1979) contained-liquid ontology. In this ontology a liquid exists in a container if there is a non-zero amount of it inside. It can be extended to a *contained-stuff* ontology that models solids and gasses as follows. Let the function **amount-of-in** map from states, substances, and containers to quantities, such that **A[amount-of-in(sub,st,c)]** is greater than zero exactly when there is some substance **sub** in state st in container **c**.[2] Let the function C-S denote an individual of a particular substance in a particular state inside a particular container. For instance, a coffee cup typically contains two individuals, denoted **C-S(coffee, liquid, cup)** and **C-S(air, gas, cup)**. The individual denoted by C-S exists exactly when the appropriate **amount-of-in** quantity is greater than zero. (See Forbus (1984b) for details.) Other kinds of material objects also seem to be captured by quantity-conditioned existence, including objects subject to sublimation, evaporation, or other changes in amount which do not cause "structural" changes. Examples include contained powders, heaps of sand, and ice cubes. A block of wood, however, provides a counter-example. Under certain conditions the block's existence can be modeled as quantity-conditioned, for instance when sanding or grinding down surfaces of it. But several ways of changing the block's existence cannot be so modeled -- consider sawing the block in half or bending it until it breaks. We will return to this issue later.

---

[1] Qualitative Process theory provides a way to determine what objects must be considered together for accurate prediction. Here we assume situations contain slices for all objects that exist at the time in question.

[2] In QP theory a quantity consists of an amount and a derivative, and the function A maps a quantity into its amount. Similarly, the function D maps a quantity into its derivative.

3. Modeling Changes of Existence In QP theory, processes are the ultimate source of all changes that happen in the physical world. Processes act by causing changes in continuous parameters of objects. A liquid flow, for instance, causes the amount of one liquid to increase and the amount of another to decrease. These changes in parameters will cause inequality relationships[3] to change. These in turn can lead to changes in the collection of active processes, as when the pressures in two containers equalize as a result of flow between them. They can also cause individuals whose existence is quantity-conditioned to appear and vanish. These changes are computed by a temporal inheritance procedure that determines what the world looks like after a change. This procedure solves the frame problem for simulation within the QP ontology.

A few remarks will make the procedure clearer. First, the statements which must be true for a process to act are divided into *quantity conditions* (which refer to inequalities and other relations defined within QP theory) and *preconditions* (all other statements a process depends on). We assume the facts stated in preconditions remain unchanged, although the procedure can be easily modified to track such changes (and the implemetation does so). Second, we assume that unless we know otherwise, individuals which exist remain in existence. Finally, the inequality relationships in the Quantity Spaces can be divided into two classes, those relationships in the current state which might change and those which cannot. Call the set of inequality relationships which might change Ω. Importantly, assuming that a particular change occurs implies that the relationships between the quantities it mentions change and that no other inequalities from Ω change.

Think of the facts which comprise a situation as consisting of a collection of assumptions and consequences of those assumptions. Finding the results of a change involves carefully modifying the assumptions. Two factors complicate this. First, the procedure which generates possible changes[4] is local, and thus sometimes hypothesizes changes which are not actually possible. The procedure described below filters out impossible changes. Second, the indirect consequences of the known changes will invalidate a subset of the previously held assumptions. For instance, an assumption about the level of water in a cup relative to some other height is moot if the water in the container no longer exists. The procedure correctly detects moot assumptions.

In what follows, "When consistent, assume **P**" means "if you don't already believe $\neg$ **P**, assume P. Otherwise, do nothing." The temporal inheritance procedure is:
(1) Assume that individuals whose existence is not quantity-conditioned remain in existence and that all preconditions remain the same.
(2) Assume the inequalities represented by the hypothesized change are true, and that all other relationships in Ω remain true.
(3) When consistent, assume quantity-conditioned individuals remain in existence.
(4) When consistent, assume that inequalities not in Ω hold.
If any required assumption leads to a contradiction, then assert that the proposed change is inconsistent. The algorithm is subtle, and is best understood by analyzing an example.

4. An Example Consider an open can partially filled with water sitting on a stove, such that the burner of the stove provides a heat path between them. Assume the water is initially below its boiling temperature and cooler than the stove. Figure 1 shows the possible behaviors (the envisionment) produced by GIZMO.[5] In the envisionment, **IS** indicates the set of quantity-conditioned individuals that exist in a situation. The set of active processes is indicated by **PS**. Possible changes are indicated by the prefix **QH**. The function **Ds** maps from a quantity to the sign of its derivative, which corresponds to the intuitive notion of direction of change (i.e., **-1** indicates decreasing, **0** indicates constant, and **1** indicates increasing). The Process Vocabulary used here consists of heat-flow and boiling, as described in Forbus (1984b).

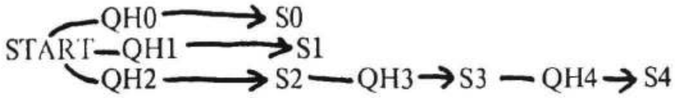
---

[3] In QP theory, numerical values are represented by collections of ordering relations called *Quantity Spaces.*

[4] Limit Analysis generates possible changes by looking at quantity space information and the signs of derivatives to determine all the possible ways the inequalities can change. While several domain-independent constraints, such as continuity, reduce the number of hypothesized changes domain-dependent information is sometimes required. The temporal inheritance algorithm provides a way to use such infonnation.

[5] GIZMO implements the basic operations of Qualitative Process theory, including facilities for making predictions and interpreting measurements taken at a single instant. See Forbus (1984b) for details.

Figure 1 --- Predicted behaviors



Abbreviations:
T = temperature A-of = amount-of
TB = boiling temperature ST = stove
WC = C-S(water, liquid, can) HF1 = heat-flow(stove, WC, burner)
SC = C-S(water, gas, can) HF2 = heat-flow(stove, SC, burner)

Start: IS: {WC}, PS: {HF1}, Ds[T(WC)] = 1
S0: IS: {WC}, PS: {}, A[T(WC)] = A[T(ST)], all Ds values 0
S1: IS: {WC}, PS: {}, A[T(WC)] = A[T(ST)], A[T(WC)] = A[TB(WC)], all Ds values 0
S2: IS: {WC, SC}, PS: {HF1, HF2, Boiling}, Ds[T(WC)] = Ds[T(SC)] = 0 Ds[A-of(WC)] = -1, Ds[A-of(SC)] = 1
S3: IS: {SC}, PS: {HF2}, Ds[T(SC)] = 1
S4: IS: {SC}, PS: {}, all Ds values 0

QH0: A[T(WC)] < A[T(ST)] becomes =. QH1: QH0 and QH2 occur simultaneously.
QH2: A[T(WC)] < A[TB(WC)] becomes =. QH3: A[A-of(WC)] > zero becomes =.
QH4: A[T(SC)] < A[T(ST)] becomes =.

In the initial state **START GIZMO** deduces that heat flow occurs, since there is assumed to be a temperature difference between the stove and the water. It also deduces that boiling is not occurring, since we assumed no steam exists since **amount-of-in** for that combination of state and substance was zero. Either the heat flow will stop (if the temperature of the stove is less than or equal to the boiling temperature of the water, represented by changes **QH0** and **QH1**, respectively) or boiling will occur (if the temperature of the stove is greater than the boiling temperature, represented by change **QH2**). If boiling occurs (situation S2) then steam will come into existence. Ignoring flows out of the container, the next change is that the water will vanish (**QH3**), ending the boiling. The heat flow from the stove to the steam will continue, raising the steam's temperature until it reaches that of the stove (change **QH4**, resulting in the final state S4). We can see the impact of different aspects of the temporal inheritance method by seeing how this description would change if it were different. Failing to distinguish between changed and inherited quantity conditions (i.e., those in Ω and those in its complement) would rule out **QH0** since we would inherit the initial assumption of no steam. Inheriting beliefs concerning quantity-conditioned individuals before updating changed inequalities would preclude **QH3**, leaving us with water that was boiling away but never completely vanishing.

5. Discussion Quantity-conditioned existence provides a simple solution to the problem of existence for several important classes of material objects in Naive Physics (i.e., contained stuffs). It appears that quantity-conditioned existence can be extended to reason about all changes in existence caused by processes which affect the amount of something without affecting its gross structure. However, it cannot model all changes in existence; banging a rock with a hammer, for instance, results in the rock breaking into several new rocks. The reasons rocks break as they do concern exactly where they are struck and the details of their microstructure. There is no simple description of this change by means of a small set of quantities because geometry is intimately involved. We should not be too discouraged, however, because it is not clear just how deep commonsense models of fracture really are. While we have rough ideas about the number and shape of pieces that result from breaking certain objects, we often cannot make very detailed predictions about exactly what pieces will result when an object breaks Even traditional Materials Science cannot make such predictions in full detail for an arbitrary piece of material, so we shouldn't expect Naive Physics to do so.

The centrality of geometry in the open problems above suggests that another class of answers to the problem of existence lies in *qualitative kinematics*, the theory of places and their spatial relationships which, together with qualitative dynamics (e.g., Qualitative Process theory) may be viewed as providing the large-scale structure of Naive Physics. Configural information becomes even more important when considering more abstractly defined objects (such as a truss or a force balance), so it appears that a theory of qualitative kinematics might solve a large class of existence problems. The need for such a theory is growing clearer, and hopefully this paper will stimulate more work in this area.

6. Acknowledgements Brian Falkenhainer and Jeff Becker provided useful suggestions. This research is sponsored by the Information Sciences Division of the Office of Naval Research.

7. References

de Kleer, J. & Brown, J.S., "A qualitative physics based on confluences", *Artificial Intelligence* **24**, 1984

Forbus, K. "Qualitative reasoning about physical processes" Proceedings of IJCAI-7, Vancouver, B.C., 1981

Forbus, K. "Qualitative Process Theory" *Artificial Intelligence* 24, 1984

Forbus, K. "Qualitative Process theory" TR-789, MIT Artificial Intelligence laboratory, July 1984

Hayes, P. "Naive Physics 1 -- Ontology for Liquids", Memo, Centre pour les Etudes Semantiques et Cognitives, Geneva, Switzerland, 1979

Kuipers, B. "Commonsense reasoning about causality: deriving behavior from structure" *Artificial Intelligence*, 24, 1984

Simmons, R. "Representing and reasoning about change in geologic interpretation" MIT AI Laboratory technical report TR-749, December, 1983

Weld, D. "Switching between discrete and continuous process models to predict genetic activity", MIT AI Laboratory technical report TR-793, May, 1984

Williams, B. "Qualitative analysis of MOS circuits", *Artificial Intelligence*, 24, 1984