# The Problem of Existence

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**Abstract:** Reasoning about changes in existence of 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 using the solution is exhibited, and the remaining open problems are discussed.

**Keywords:** Qualitative Reasoning, Naive Physics, Automated Reasoning, Artificial Intelligence

**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. Unfortunately many systems are not represented naturally by system dynamics, such as boiling water and mechanisms. These theories also 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 the form of statement used precludes discovering changes in existence that are not explicitly foreseen by the model builder. 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 (QP) theory (Forbus 1981; 1984a).[1] First we describe a general logic of existence, extending notions of histories introduced in (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 by an implemented example. Finally, we return to the general problem of existence and make suggestions based on our solution to this subproblem.

**2. A Logic of Existence** Objects in the world are represented by individuals. The criteria for what constitutes an individual will in general depend on the domain being represented. Histories represent how objects change over time (Hayes, 1979). 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 take this formalism, as extended in (Forbus 1984a), as our starting point. 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)**, as per (Hayes, 1979). 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. An issue which did not arise in Hayes' original treatment of histories concerns 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

$$\mathbf{P(at(obj,\ t)) \wedge Exists\text{–}in(obj,\ t) \rightarrow F}$$

rather than just

$$\mathbf{P(at(obj,\ t)) \rightarrow F}$$

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

$$\mathbf{P(at(obj,\ t)) \rightarrow Exists\text{–}in(obj,\ t)}$$

This allows the implications of the predication to be stated simply, while also providing a constraint on existence that is useful for detecting inconsistencies. However, care must be taken when specifying taxonomic constraints, such as saying that an object is either rigid or elastic. If we simply assumed

$$\mathbf{\forall\ sl \in slice,\ Rigid(sl) \vee Elastic(sl)}$$

[1] Space does not permit a review of qualitative process theory, see Forbus (1984a).

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

$\forall$ **sl** $\in$ **slice Physob(sl)** $\rightarrow$ **[Rigid(sl)** $\vee$ **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 some set of objects that exist at a particular time.[2]

An individual's existence is quantity–conditioned if inequality information is required to establish or rule out its existence. An example is Hayes' contained–liquid ontology (Hayes, 1979). In this ontology a liquid exists in a container if there is a non–zero amount of it inside. We now show how Hayes' contained–liquid ontology can be extended to a *contained–stuff* ontology that models solids and gasses as well. 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**.[3] 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 full details.

Other kinds of material objects also seem describable 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 counter example is provided by considering a block of wood. Under certain conditions the block's existence can be modeled as quantity–conditioned, for instance when sanding or grinding down surfaces of it. But most 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 at the end of the paper.

**3. Modeling Changes of Existence** Given the collection of objects that exists at some particular time, QP theory uses the concept of *physical processes* to model what is happening. Processes act by causing changes in various continuous parameters of the objects involved. A liquid flow, for instance, causes the amount of one liquid object to increase and the amount of another to decrease. These changes in parameters will cause inequality relationships[4] 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. This section describes how to compute these changes.

The procedure for determining what the world looks like after a change can be thought of as a kind of "temporal inheritance" procedure. It determines what facts will remain true and

[2] Qualitative process theory provides a means of determining what objects must be considered together as a situation for accurate prediction. Here we will simply assume that a situation will contain slices for all objects that exist at the time in question.

[3] 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.

[4] In QP theory, numerical values are represented solely by collections of ordering relationships called *quantity spaces*.

what facts will become true as a consequence of changes in the world. Hence this procedure illustrates how the frame problem is solved for simulation within the QP ontology. Before describing the procedure several remarks are in order. 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.[5] Second, we assume that, unless we know otherwise, individuals which exist remain in existence. Finally, we note that 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 in some particular situation which might change $\Omega$. Importantly, assuming that a particular change occurs implies that the relationships between the quantities it mentions change and that no other inequalities from $\Omega$ change.

Think of the facts which comprise a situation as consisting of a collection of assumptions and consequences of those assumptions. Figuring out what a situation looks like after a change involves carefully changing the assumptions. The assumptions must be changed carefully for two reasons. First, the procedure which generates possible changes[6] is quite local, and thus sometimes hypothesizes changes which are not actually possible. The procedure described below detects these inconsistencies and takes appropriate actions. Second, some assumptions in the old situation will not hold in the new one as an indirect consequence of the changes. For instance, assuming that the level of water in a container stands in a particular relationship to some other height is moot if the water in the container no longer exists. The procedure below also correctly detects such 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 $\Omega$ are true.

3. When consistent, assume that the quantity–conditioned individuals which existed before still do so.

4. When consistent, assume that the inequalities not in $\Omega$ hold.

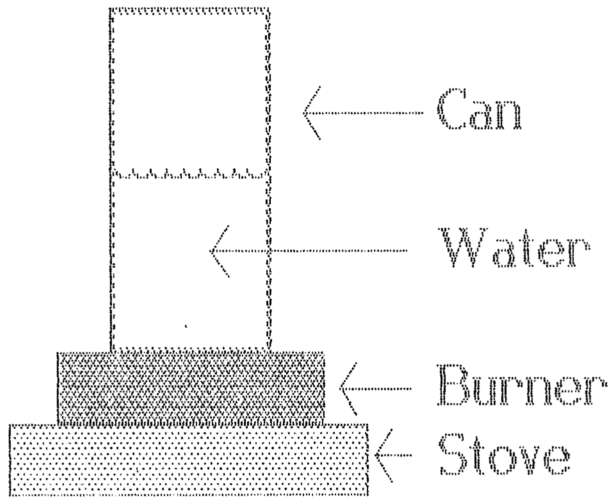
5. If any required assumption leads to a contradiction, then assert that the proposed change is inconsistent.

The algorithm is subtle, and is best understood by analyzing an example.

[5] This procedure can be easily modified to take such changes into account – in fact, the implementation does so – but we ignore this here for simplicity.

[6] Limit analysis generates possible changes by looking at quantity space information (i.e., the "current values") and the signs of derivatives for the quantities 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 described here provides one way to use this information.

**Figure 1 – Boiling water on a stove**




**4. An Example** Figure 1 depicts an example involving changes in existence. The situation consists of a can partially filled with water sitting on a stove, with the burner of the stove providing a heat path between them. We assume that initially the water is below its boiling temperature and cooler than the stove, and will ignore any possibility of the can exploding or melting. Figure 2 illustrates the possible behaviors (the envisionment) produced by **GIZMO**.[7] In the envisionment, `IS` indicates the set of quantity–conditioned individuals that exists during a situation. Situations themselves are indicated by the prefix `S`. The set of active processes in each situation is indicated by `PS`. Possible changes are indicated by the prefix `LH`. 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 (see (Forbus, 1984b) for details). To increase comprehensibility, only the most relevant information is shown.

Let us examine the envisionment step by step. In `START`, the initial state, **GIZMO** deduces that heat flow occurs, since there is assumed to be a temperature difference between the stove

[7] **GIZMO** implements the basic operations of qualitative process theory, including an envisioner for making predictions and a program for interpreting measurements taken at a single instant. See (Forbus, 1984b) for details.

and the water. It also deduces that boiling is not occurring, since we assumed no steam exists by assuming `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 `LH0` and `LH1`, respectively) or boiling will occur (if the temperature of the stove is greater than the boiling temperature, represented by change `LH2`). If boiling occurs (situation `S2`) then steam will come into existence.

We ignore flows out of the container, so the next change is that the water will vanish (`LH3`), 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 `LH4`, resulting in the final state `S4`).

We can see the role of different aspects of the temporal inheritance method by perturbing it and seeing how this description would change. Failing to distinguish between changed and inherited quantity conditions (i.e., those in $\Omega$ and those in its complement) would rule out `LH2` since we would inherit the initial assumption of no steam. Inheriting beliefs concerning quantity–conditioned individuals before updating changed inequalities would preclude `LH3`, 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, will often result in the rock breaking into several pieces, each of which can be considered a new rock. 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. We all have rough ideas about the number and shape of pieces that result from breaking certain objects consisting of different types of materials. However, we often cannot make very detailed predictions about exactly what pieces will result when we break an object. Even traditional materials science cannot predict these outcomes in full detail for an arbitrary piece of material in a closed–form solution. We must be careful not to insist that Naive Physics do better than traditional physics, especially since it starts with less information.

The centrality of geometry in the open problems above suggests that another class of good 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 we hope that this paper will inspire further work in this area.

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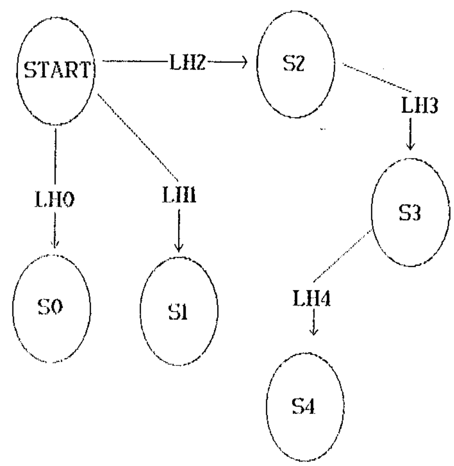
**Figure 2 – Predicted behaviors**




Abbreviations:

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

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

LH0: A[T(WC)] < A[T(ST)] becomes =.
LH1: LH0 and LH2 occur simultaneously.
LH2: A[T(WC)] < A[TB(WC)] becomes =.
LH3: A[A–of(WC)] > zero becomes =.
LH4: A[T(SC)] < A[T(ST)] becomes =.

## 6. References


de Kleer, J. & Bobrow, D. "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**, 1984a

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

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