Qualitative Reasoning Experiments with the MVL Theorem Proving System

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Abstract

An experimental program, QREM, is implemented using the inference mechanism of the MVL Theorem Prover System of Ginsberg. QREM uses Forbus' *Qualitative Process Theory* for its description of physical situations and constructs the interpretations of measurements. In this paper, we mainly concentrate on the representation of process descriptions and basic deductions, and give some idea about what MVL can provide for writing qualitative physics programs.

1 Introduction

Commonsense reasoning is one of the most popular topics in Artificial Intelligence [7, 8]. Nowadays, a great deal of attention is being given to studies in qualitative physics which tries to formalize one's commonsense knowledge about the physical world [1, 11].

Our conventional physics cannot succinctly give the intuitive meaning behind the functioning of a physical system. However, qualitative physics provides this information by giving a commonsense description of the situation. This difference between the two physics mainly stems from the fact that in conventional physics we describe physical behavior in terms of quantitative values and numerical equations, whereas in qualitative physics we employ qualitative values and say, interval arithmetic.

Since in qualitative physics we only use qualitative information for reasoning, a need arises for representing the physical system in a more formal way. Fortunately, there are several formalisms for the representation of physical systems and especially Forbus' *Qualitative Process Theory* (QPT) serves as an important guide for many of the current qualitative physics programs [2, 3].

In this paper, we introduce QREM—Qualitative Reasoning Experiments with the MVL Theorem Proving System. This is an experimental qualitative physics program based on QPT. QREM serves as a simple, clear, and flexible representation language for descriptions of QPT. The reasoning tasks are accomplished using MVL's default logic, because we must be able to make inferences even in the case of incomplete information. In its current state, QREM can make inferences about simple dynamical systems consisting of a number of containers and fluid paths that allow the flow of liquid between specified containers. However, once we agree on the representation issues and code a domain model of the physical system into QREM, it must be a rather straightforward matter to carry out the basic reasoning tasks for other, more complicated systems as well.

2 Qualitative Physics

Qualitative physics deals with commonsense reasoning about the physical world [1]. The motivation primarily comes from the studies in engineering problem solving in which techniques for automating engineering practice are sought [12].

Conventional physics completely describes the behavior of a physical system using accurate quantitative values and numerical equations. However, most of the time, this description does not seem to be helpful for understanding the functioning of the system. In such cases, qualitative physics provides valuable insights into the system's functioning by giving a commonsense description and a causal explanation for the resultant behavior.

Qualitative physics, unlike the so called conventional physics, uses a symbolic and qualitative model of the physical world. The behavior of a physical system can be described using qualitative values for quantities of existing objects in the situation. This qualitative representation necessitates a quantity value to be chosen from a discrete quantity space rather than from a continuous one. The behavior of the physical system is effectively characterized by the derivatives of its quantities. Hence, a quantity may increase, decrease, or stay unchanged when its first derivative has a value of 1, -1, or 0, respectively.

In Figure 1, qualitative and conventional physics are compared. At first, both of the physics attempt to formalize the physical situation, one using complex numerical equations and the other using simple qualitative constraints. Then, both of them solve their related equations using their own methods. At the end, while qualitative physics comes up with a commonsense description of the solution, conventional physics comes up with a numerical value whose intuitive content may be null [9].

A computer program for qualitative reasoning requires a qualitative model of the physical system as input. This model must be adequate for specifying what constitutes the physical system of concern. Fortunately, there are different theories in AI that offer constraint-based, component-based, and process-based description models for physical systems [1]. The one that we apply in QREM is a process-based theory.

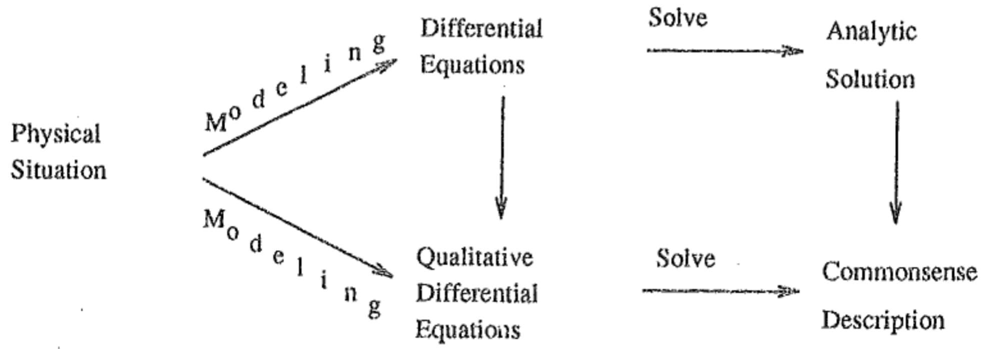

Figure 1: Comparison of qualitative and conventional physics [adapted from *Encyclopedia of AI*, Shapiro, S. C., Ed., vol. 2, p. 807].

3 Essence of QREM

3.1 Descriptions in QREM: QPT

QPT is a process-based theory for describing physical situations. Forbus characterizes his theory as one in which reasoning about dynamical systems can be made easily and effectively. He mentions this in [2]: "Qualitative Process Theory defines a simple notion of physical process that appears useful as a language in which to write dynamical theories."

According to QPT, a dynamical system changes its state as a result of active processes in the situation. In QPT, a *process* is described as something that causes changes in objects over time [2]. Motion, colliding, fluid flow, and boiling are examples of processes acting on objects. In Figure 2, a potentially existing process, namely fluid flow, is represented in the framework of a dynamical system consisting of two containers and a fluid path.

A domain model of a dynamical system consists of descriptions of existing objects in the system, relationships between those objects, and the processes that can occur in some physical situation. A specific situation occurs when all of its conditions hold. Particularly, active processes in each situation need not be given individually; they can be inferred using the process specifications in the domain model.

QPT describes a process using the following components:

- **Individuals** Objects that the process acts on.
- **Preconditions** Conditions that are imposed by the external world.
- **Quantity Conditions** Conditions that are necessary for the process to become active.
- **Relations** Relations between quantity values and process variables (i.e., what holds when the process is active)
- **Influences** Direct effects of a process. Each process has at least one direct influence.

Now, we have some idea about how to describe a physical system using processes, but how are we going to perform reasoning tasks using those processes? QPT's reasoning goes through the following basic deductions:

- **Finding Possible Processes** Processes whose preconditions hold are potential processes that can occur in some situation.
- **Determining Activity** A process instance is *Active*, if its preconditions and quantity

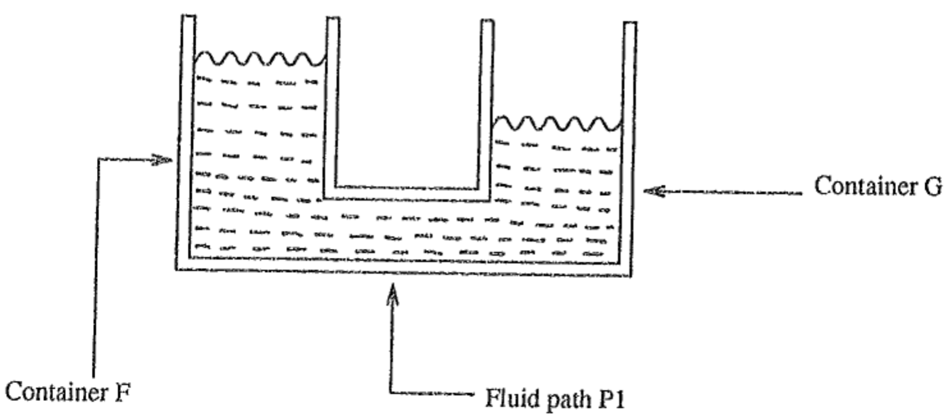

Figure 1: A physical system where a liquid flow process can be *Active*.

conditions hold. Otherwise, it is *Inactive.*

- **Determining Change** Direct and indirect influences of a process are resolved in order to find the changes in the system.
- **Limit Analysis** Changes in quantities may change some process instances. Limit analysis is used to determine those.

Using QPT's basic deductions we can perform *predictions*, *measurement interpretation*, and *causal reasoning* about dynamical systems.

3.2 Inference in QREM: MVL

The MVL theorem proving system written in Common Lisp is an implementation of theoretical work done at Stanford University [4]. The core of the system relies on the "multivalued logics" paradigm of Ginsberg [5].

MVL provides facilities for making satisfactory inferences in various logics—default logic, circumscription, probabilistic logic are some of these—and allows one to define new logics. The most important feature of MVL is its use of multiple truth values for logical statements. Unlike Prolog, MVL does not simply label a statement to be true; it also considers "true by default," "true by some assumption," "false," "false by default" as bona fide truth values and uses these when determining the answer for a query [6].

The MVL database consists of sentences that are represented as LISP *s*-expressions and labeled with truth values. The logical connectives NOT, OR, and AND are used for constructing MVL statements.

For inference tasks there are two types of connectives: "=>" and "<=". The connective "<=" is used for backward chaining and " =>" is used for forward chaining. The form of backward- and forward-chaining rules are as follows [6]:

(<= *Conclusion* $Premise_1$ $Premise_2$ ... $Premise_n$)
(=> $Premise_1$ $Premise_2$ ... $Premise_n$ *Conclusion*)

4 Implementation

4.1 Representational Aspects of QPT

Individuals and Quantities Individuals in a physical system are characterized by their existence. If an individual may exist in a situation it must have the quantity property. Hence, we represent any object that has a quantity as an individual, e.g.,

```
(<= (and (individual ?x) (?q ?x))
    (quantity-type ?q)
    (has-quantity ?p ?q)
    (?p ?x))
```

Here, `(has-quantity ?p ?q)` means `?q` is a quantity for individual `?p` whereas `?x` in `(?p ?x)` is a particular instance of `?p`. The expression `(?q ?x)` instantiates quantity `?q` for `?x`.

Some individuals in QPT can be defined by making the existing ones more specific. One example would be `contained-stuff` if we already have an individual called piece-of-stuff. Here, contained-stuff is a piece-of-stuff contained in a place and contained-liquid is a contained-stuff:

```
(<= (contained-stuff (?substance ?state ?place))
    (piece-of-stuff ?substance)
    (state ?substance ?state)
    (contains ?place ?substance ?state))
(<= (contained-liquid (?substance ?place))
    (contained-stuff (?substance LIQUID ?place)))
```

In QPT, relationships between quantities are basically indicated by qualitative proportionalities, correspondences, and inequalities. A qualitative proportionality $Q_1 \alpha_Q Q_2$ means "there exists a function that determines Q_1 and is monotonic in its dependence on Q_2." Correspondences are used for mapping value information from one quantity space to another via α_Q [2, 3]. Those are written in MVL with the same notational considerations as in QPT. Below ?x is a contained-liquid:

```
(qprop+ (pressure ?x) (amount-of ?x))
```

Here, qprop+ denotes that the pressure of ?x is qualitatively proportional ('+' denotes increasing) to its amount. Inequalities can either be given directly or inferred depending on whether numeric values of those quantities are known. For this purpose greater, less, equal-to, and some algebraic manipulations are defined in MVL.

Domain Models A domain model of QPT can be specified by defining quantities, individuals, and processes that exist in the domain. The types of quantities in the domain are defined as (quantity-type < *type* >), e.g.,(quantity-type pressure).

Until now, we gave only the basic components of a domain model that can easily be described by using predicates. With those predicates in the database, we can make some simple inferences [10], e.g., "What kind of individuals exist in the domain?" However, we need more complex inferences for QPT's basic deductions. For this purpose, we are going to represent processes and some other related concepts in the form of rules.

In QREM, a process description is given in three parts, i.e., we have three rules for each process. One rule defines a process along with its individuals. If individuals exist in the situation, the process is considered to be potentially *Active*. The other two rules are related to a process as being *Active* in the situation.

Status of a process can be inferred using the following rule which says that a process is *Active* when all the conditions imposed on it hold:

```
(<= (status (process ?process ?individuals) ACTIVE)
    (hold-conditions (process ?process ?individuals)))
```

A sample process description for liquid-flow captures all necessary conditions (preconditions and quantity conditions) and individual specifications for that process:

```
(<= (process liquid-flow (individuals ?source ?destination ?path))
    (contained-liquid ?source)
    (contained-liquid ?destination)
    (not (equal ?source ?destination))
    (fluid-path ?path)
    (fluid-connection ?path ?source ?destination))
```

Individuals for liquid-flow process are contained-liquids—one source, one destination—and a fluid-path between source and destination, e.g., there is a fluid-connection between source and destination.

```
(<= (hold-conditions
        (process liquid-flow (individuals ?source ?destination ?path)))
    (process liquid-flow (individuals ?source ?destination ?path))
    (aligned ?path)
    (greater (a (pressure ?source)) (a (pressure ?destination)))
    (status (view liquid-flow-support
                 (individuals ?source ?destination ?path)) ACTIVE))
```

When preconditions and quantity conditions hold, a process becomes *Active*. For the liquid-flow process, (aligned ?path) is a precondition indicating that the fluid path is isolated from any other external effect. If the pressure of the source is greater than the pressure of the destination and the geometric properties of the fluid path allow it, then there will be a flow of liquid from the source to the destination:

```
(<= (and (I+ (amount-of ?destination) (flow-rate ?path))
         (I- (amount-of ?source) (flow-rate ?path)))
    (status (process liquid-flow
                     (individuals ?source ?destination ?path)) ACTIVE))
```

In QPT, processes are the only source of direct influences [2, 3]. I+ and I- represent direct influences of flow-rate on the amount of source and destination ('+' positive influence, '-' negative influence) when the liquid-flow process is *Active*. If flow rate is increasing, then the " amount of destination" will also increase whereas the "amount of source" will decrease.

4.2 Basic Deductions

Finding Possible Processes Possible processes are simply characterized by their individuals. All processes that have their individuals exist in the situation are potentially *Active* and can be found them using a simple inference on the rules of process descriptions.

The following MVL query searches for all possible process instances in the domain:

```
;; Backward search for all processes
   (bcs '(process ?process ?individuals))
```

The binding list of this query is passed to a Lisp function which makes status assumptions about process instances. Inconsistent process instances (process instances that cannot be *Active* together in the same situation) are thrown away. This procedure is called *Elaboration*.

Determining Activity Process instances found by *Elaboration* can be *Active* if they satisfy their conditions. To find which process instances are *Active*, we invoke the following query that tries to prove whether a potential process is *Active*:

```
;; Backward search for all processes and
;; try to prove that a potential process is Active.
;; Take all processes that are proved to be Active.
   (bcs '(status (process ?process ?individuals) ACTIVE))
```

Determining Change In QPT, changes are imposed by *Active* processes; processes are the only source of direct influences [2, 3]. Quantities may change either because of some direct or indirect influences (expressed by qualitative proportionalities) on them. A quantity is said to be *directly influenced* if there exists at least one process directly influencing it at some particular time. On the other hand, a quantity is *indirectly influenced* if it is a function of some other quantity that is changing.

The derivative of a directly influenced quantity equals the sum of all of the direct influences on it. In QREM, an *influence adder* is used for finding this derivative just as described in QPT [2, 3].

4.3 Measurement Interpretation

The importance of measurement interpretation is emphasized in [12]: "The problem of interpreting observations of a system over time is fundamental to intelligent reasoning about the physical world. We view interpretation as the task of determining which possible behaviors predicted by the current model are consistent with the sensory data, including which are most plausible."

Measurement interpretation through time is more difficult than interpretation at a given time. Although QPT mentions the notion of time, there is no satisfactory temporal representation that can be easily embedded in an implementation. Hence, for experimentation we only use interpretation at a time instant. The algorithm used for measurement interpretation is given in Figure 3.

```
MEASUREMENT-INTERPRETATION

1. find process instances PROCESS-INS
2. make status assignments about PROCESS-INS
   2.1. find all combinations of process instances
   2.2. throw away inconsistent combinations
3. for each combination do
   3.1. resolve influences of quantities
   3.2. if measurement of a given quantity is
        equal to the one found in resolving influences, then
        this combination is a possible situation at that time,
        hence give it as a cause of the measurement
```

Figure 3: Algorithm for measurement interpretation.

5 Conclusion and Future Work

We introduced an experimental program called QREM for qualitative reasoning about dynamical systems. In general, representation of physical systems plays an important role in qualitative physics. A clear representation of physical system descriptions proves to be useful when writing domain models.

In QREM, we make use of a flexible representation tool, viz. the MVL theorem proving system that provides multivalued inference. When reasoning qualitatively, we may lack some information about the situation, and some assumptions need to be made. In these cases, the default logic of MVL allows us to make some default assumptions.

In QREM, measurement interpretation of an observed quantity value is implemented. In the future, other important reasoning tasks such as limit analysis and prediction may be implemented. Yet another project may be to concentrate on the ATMS part of MVL in order to make the inferences more efficient.

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