# A QUALITATIVE MODEL FOR THE BEHAVIOR OF LIQUIDS IN DAILY-LIFE CIRCUMSTANCES.*

Jo Decuyper, Didier Keymeulen
Luc Steels

V.U.B.
Artificial Intelligence Laboratory
pleinlaan 2, B-1050 Brussels,
Belgium
email: jo@arti.vub.ac.be
didier@arti.vub.ac.be
steels@arti.vub.ac.be

*Abstract*— **In this paper we analyze the behavior of liquids in daily-life situations. This behavior may be described within the qualitative physics (QP) paradigm in a way that mimics *people's common sense*. However, it may be questioned to what extend such a common sense like description can be used by *a robot* to perform liquid manipulation. We argue that the symbolic representations used in QP do not provide sufficient accuracy to solve such a control problem. The main reason for this is the critical dependence of the behavior of liquids on the spatial and temporal properties of the situation they are in. In order to deal with this dependence we propose to supplement a qualitative reasoner with an analogical simulation. In this way, the behavior of a liquid can be simulated instead of inferred. The result of a simulation can be interpreted by virtual sensors and passed to the reasoning module. We believe that this approach implements an important aspect of common sense namely the use of visual feedback to solve simple problems without reasoning.**

## 1 Introduction.

Qualitative physics addresses the problem of modeling physical systems and reasoning about their behavior given only limited knowledge and computing resources. The dominant paradigm so far is firmly rooted in the symbolic AI tradition and was shaped by the seminal papers of Hayes, De Kleer, Forbus, Kuipers, Davis and many others.[3] [6] [10] [2] [9] The basic idea is to describe a situation with qualitative descriptions and to postulate axioms that can be used by a logical or heuristic reasoner to derive new information about the situation, such as for example future world states.

We believe that there are fundamental limitations to this approach: several classes of physical phenomena that humans (and robots) encounter in daily-life situations cannot be modeled within this paradigm, at least not with the necessary predictive power to be useful for problem solving. This paper focuses on one of these classes namely the phenomena which are related with the behavior of liquids. Modeling the behavior of liquids requires a re-interpretation of three of the paradigmatic assumptions underlying the qualitative physics framework:

- The behavior-from-structure principle.
- The no-function-in-structure principle.
- The quantity space principle.

Furthermore the basic strategy which consists in qualifying the equations of physics in order to obtain a useful set of inference rules is not applicable to liquids. We elaborate on these criticisms in the next section.

The rest of this paper is divided into two parts. In section three we propose a hybrid architecture for the representation of the behavior of liquids. This architecture is composed of

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a traditional symbolic reasoning module and an analogical simulation module coupled through different interpretation and visualization routines. We also briefly comment on the kind of analogical simulation needed for the purpose of predicting *qualitatively* the behavior of liquids in a large variety of possible situations. In the fourth section we discuss the complementary aspects of analogical and symbolic representation and argue that both are needed to build powerful and accurate models of liquid behavior.

## 2 Liquids and the assumptions of qualitative physics.

The *behavior-from-structure* principle states that the overall behavior of a composite device or a complex situation [1] must be derivable solely from the behavior of each component and a structural description of the device or situation.

We argue that the symbolic structural descriptions used by qualitative physicists can never be sufficiently precise to allow inference of the behavior of liquids. There are two main reasons for this:

- First, liquids can produce an extremely versatile behavior which *changes* the structure of situations as time goes on. Therefore the structure of a situation and its evolution are intrinsically connected.
- Second, these structural changes cannot be deduced within a symbolic approach because they may depend on small spatio-temporal details of the situations. These spatio-temporal properties are beyond the power of the symbolic representations used in QP.

Consider for example the situation where an open container is moved and some of the liquid it contains gets spilled. The spill alters the structure of the situation because the topological relations between the components change. After a spill has occured there is one more component: the spilled liquid and this component may affect the structural relationships between the objects in the situation. For example, the spilled liquid may produce an electrical connection between two objects that were disconnected before. The problem is that symbolic structural descriptions are not powerful enough to derive the structural changes that may occur. These changes generally depend on the shape and motion of the containers holding the liquid. In order to figure out the consequences of this dependence a much finer resolution is needed for the representation of space and time than can be achieved with a symbolic representation.

The *no-function-in-structure principle* states that the description of the functioning of a component should not presume the functioning of the whole of which it is a part of. In other words, that it is desirable to have context-free descriptions of the functioning of components. This principle cannot be satisfied by any model for liquids because liquids acquire most of their properties precisely through the interaction with the context. For example, the shape of a piece of liquid changes when it is put into a different container.[2]

The *quantity-space principle* states that the behavior of a physical system can be qualitatively classified with the help of qualitative variables. The different values of a qualitative variable must be relevant in the sense that if the variable changes from one value to another, the evolution of the situation it describes must also change *qualitatively*. This relevance criterion can only be satisfied by a judicious choice of landmark values.

The problem with liquids is that the determination of these relevant landmark values is not a simple straightforward procedure. Consider for example the task of pouring a cup of tea from a teapot. We recognize two qualitatively different behaviors of the tea: it stays in the pot or it flows out. This behavior depends, among other things, on the amount of tilting measured by the angle $\theta$ with the vertical. The quantity space for the qualitative variable $\theta_q$ contains two values. These values correspond to the two intervals $\theta < \theta_{limit}$ and $\theta > \theta_{limit}$. The difficulty here is the definition of the separating

[1] No fundamental distinction between situations and devices is made in the qualitative physics framework. Situations are just considered as a special kind of devices and the objects they contain as their components. In this paper we restrict ourselves to modeling situations involving liquids.

[2] This dependence on the context is also recognized in physics by the fact that the partial differential equations of continuum mechanics do not constitute by themselves a complete model for the behavior of liquids. They need to be supplemented with boundary conditions which express the influence of the context. Different boundary conditions lead to different liquid behaviors obtained by solving the same equations.

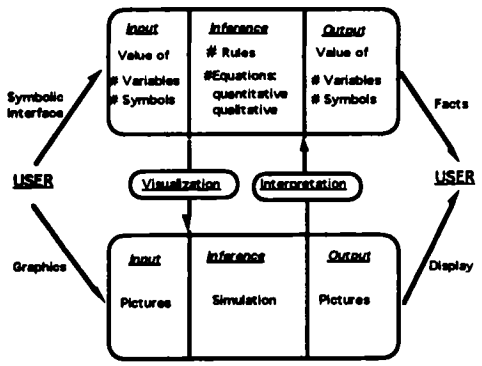


Figure 1: Hybrid architecture.

landmark value $\theta_{limit}$. This landmark depends on the shape of the teapot and the amount of tea it contains. It cannot be obtained by a simple inference procedure. In fact, for most physical situations *qualitatively* different behaviors may result from small *quantitative* changes of certain variables.

Finally, the assumption that the behavior of device or the evolution of a situation can be inferred from the qualitative counterpart of the equations of physics, does not hold for liquids. The equations of continuum mechanics that model liquid behavior concern only infinitesimally small parts of a liquid and not the liquid as a whole. The goal of qualitative physics modeling on the other hand concerns the global behavior of an amount of liquid and not the behavior of a small portion of it. For example, the fact that tea flows out of a certain teapot when it is inclined cannot be directly inferred from the physical equations, not even from the quantitave ones. These equations only describe how each small portion of the tea behaves. The global behavior can only be obtained at the expense of computing the behavior of all the small portions over a sufficient number of small time steps.

# 3 Hybrid architecture for modeling liquids.

The key question of course is how to surmount the limitations of the symbolic qualitative physics paradigm. Our approach to this problem is the following. We assume that an adequate (but still qualitative in the sense of approximate) physics modeler needs two components (figure 1) .

- *A symbolic modeling component.* This could be similar in many respects to the existing qualitative physics proposals and we will therefore not develop it further in this paper.

- *An analogical simulation component.* This second component is analogical in two ways: first it uses an analogical representation of the world and second it represents the course of time by a succession of small incremental time steps.

Analogical representations have been occasionally discussed in the AI literature but it is only recently that they have become seriously studied and applied for problem solving [12] [7] [13] [11] [8] [1] [14] [5]. They are very appropriate to represent the shape of objects and their relative position in a scene. For this purpose they provide a much finer resolution than could possibly be achieved with a symbolic representation. Because of the importance of the shape of containers for the behavior of the liquid they contain, we believe that an analogical representation is an essential part of a model for liquids.

The use of analogical representations by themselves is not sufficient to predict the behavior of liquids. Prediction requires an account of the time evolution of the variables or pictures used in the representation. In the case of analogical representations also an analogical inference method is needed: a simulation. A simulation is based on a discretization of time into a succession of small discrete time steps similar to the ticks of an imaginary clock. These time steps are chosen small enough such that only direct interactions between elements have to be considered.[3] The next section elaborates on the construction of an analogical simulation.[4]

## 3.1 The grain-size of analogical simulation.

The crucial difference between an analogical simulation and a symbolic qualitative reasoner concerns the scale at which phenomena are represented. A qualitative reasoner manipulates symbols which represent distinct physical objects and formal rules which represent the behavior of these physical objects *as observed by*

[3] This amounts to assuming that interactions can only happen between any element and its nearest neighbors.

[4] We use the term analogical simulation to differentiate it from qualitative simulations a la QSIM

*a human.* The inference processes that are performed over these symbols mimic the way a person reasons about the objects they represent. In an analogical simulation on the contrary, objects are represented as collections of small identical elements. These elements represent only tiny parts of objects, which are not recognized separately in a symbolic approach. For this reason they are called subsymbolic. The rules which govern the behavior of these subsymbolic elements do not correspond to a person's reasoning about objects. They correspond to fundamental physical principles governing the interaction between small parts of physical objects.

The behavior-from-structure principle as well as the no-function-in-structure principle are both satisfied by the analogical simulation of liquids. The description of the behavior of a subsymbolic liquid element does not need to presume much about the context. The rules simply express how it is going to evolve during a small timestep according to the laws of physics. The point here is that only very few rules are necessary to describe the behavior of a subsymbolic element because there are only few physical principles and these are valid in many different situations.

The behavior of a sizable amount of liquid, such as the tea in a cup for example, can be "inferred" from this small set of rules and the structural organization of the liquid elements as captured in the analogical representation. The price to pay for such a simple and powerful representation is the computational burden of the simulation of large numbers of subsymbolic elements during many short timesteps. In this sense analogical simulation is closer to the physical processes occuring in real liquids while symbolic qualitative physics is closer to the way people reason about physical processes.

## 3.2 Analogical simulation and Commonsense.

We believe that a carefully designed analogical simulation can provide a useful substitute for symbolic commonsense knowledge, given that the phenomena it generates correspond qualitatively to their real world counterparts and that there is a way to interpret the analogical representation in terms of the symbols used by a qualitative reasoner. The general idea is to replace the large set of rules, required to deal with a substantial subset of possible situations, by a smaller set of rules about more general classes of situations. In a first approximation a qualitative reasoner uses the symbolic descriptions to infer knowledge about a situation. Whenever more precise knowledge depending on spatio-temporal aspects of the situation is needed, an analogical simulation is run. The result of this simulation is then interpreted and passed as symbolic knowledge to the qualitative reasoner.

Interpreting the analogical simulation is done by means of virtual sensors: they are placed directly in the analogical representation and obtain the desired information by interacting with the subsymbolic elements in their neighborhood. A simple example is a flow sensor. In order to detect whether tea is flowing out of a simulated teapot a flow sensor is put at the end of the spout. Its functioning is very simple: it becomes true whenever it gets wet by tea. More complicated sensors can be constructed as combinations of elementary ones for practically any type of information.

It could be argued that the analogical approach requires much more resources than the symbolic one and thus that it does not comply with the parsimony idea of QP. We belief that this must be relativated with respect to the problem that must be solved. Suppose the problem consists in pouring a glass of wine. A symbolic reasoner may come up with a plan to do. However, it is tacitly assumed in QP that this plan will be executed by a human. This human then will use his or her common sense knowledge to fill in the missing details and to execute the plan properly. In doing so he or she will automatically take into account the different shapes of bottles and glasses and the level of the wine in them.

Matters are entirely different when a robot must execute the same plan. It can not be expected that it will show the same abilities in interpreting the high level instructions and carrying them out. At this point we believe that an analogical simulation may be called in. By running such a simulation the robot may find out how far it can incline the bottle before the wine starts to flow. This simulation indeed requires a lot of computation but the point is: there is no other way to obtain that information. Furthermore, the analogical representation with the bottle and the glasses may be obtained directly from a camera input without much processing. Also the simulation may run on a parallel machine thus providing fast response.

### 3.3 Physics and analogical simulation.

The analogical simulation that we have built differs from the usual physical models studied in continuum mechanics in two ways:

- It combines the continuum view with the particle view instead of adopting only one of them.

- It is based on fundamental physical principles rather than on a discretization of the Navier Stokes equation.[5]

The continuum view corresponds to the "contained stuff" approach introduced by P. Hayes while the particle view corresponds to his "liquid individuals".[9] Because of the representation of both the continuous and the discrete aspects of liquids we call our model the dac-model. Each view in the dac-model addresses a different class of phenomena. The particle view is very appropriate for expressing conservation laws and their implications on the behavior of liquids. It can however not cope very well with the interactions between different parts of a continuum. The continuum view on the contrary is very appropriate for expressing these interactions. The hydrostatic pressure, such as exerted by water on a dam for example, can easily be modeled in the continuum view. By combining both views in a judicious way it is possible to overcome the limitations of both and to construct a fairly general model for the behavior of liquids in daily-life situations. We want to emphasize that this combination is more than just having both views available and deciding for every situation which view is going to be appropriate. Rather, every liquid in a given situation is *at the same time* represented in both views. For the technical details about this model we refer to [4]. There we also discuss its implementation on a DAP computer [6].

[5]The Navier Stokes equation is the most important differential equation of continuum mechanics. It is derived from Newton's law of motion under the specific assumption of continuity. The model we use here does not make the same assumption, therefore Navier Stokes equation is not sufficiently general for the situations we want to model.

[6]DAP is a trademark of AMT

## 4 Interpreting an analogical simulation.

Complex situations involving fluid components can be simulated with the dac-model. The result is always a state of the analogical representation characterized by the position of the particles and the velocity and pressure of the cells. A qualitative reasoner for the control of a robot cannot use such information directly. It needs to know whether there is liquid in a certain place or whether liquid is spilled if a particular container is moved in a particular way. We propose to extract such knowledge by means of virtual sensors which are placed in the analogical representation and which are specificaly designed. We illustrate the use of sensors for the task of filling a bottle from a tap. The following assumptions are made:

- Bottles of different shapes and heights are allowed.

- Bottles are placed on a horizontal table and can be moved left or right by a simulated robot.

- The tap is either open or closed. When it is open it releases liquid at a constant rate.

- A bottle must be filled up to a predefined level: one inch from the top.

- Spilling has to be avoided.

Two subtasks are considered separately: positioning a bottle with its opening underneath the valve and filling a correctly positioned bottle. In order to execute these subtasks a robot needs two instructions: move the bottle to the left or to the right *over a certain distance* and open the valve *for a certain time*. These instructions clearly show the importance of spatio-temporal knowledge and therefore also the advantage of analogical simulation for the execution of tasks in the real world.

Consider the problem of positioning a bottle with its opening underneath the tap. This task can be solved by using appropriately placed sensors which detect whether liquid is flowing through them or not. The basic idea is that if a real bottle is correctly positioned under a tap, no liquid will end up on the floor. We carry over this idea to the analogical simulation and install a left and right flow sensor. If the simulated bottle is correctly positioned, both the left and right sensor will stay dry when liquid

is released from the tap. If on the contrary the bottle is too much to the left, the right sensor will get wet. In that case the bottle is slowly moved to the right until no more liquid flows by the right sensor. The total distance over which the simulated bottle is moved is accumulated and returned, together with the direction, to the qualitative reasoner which can use this to issue controls to the robot. We believe that this way of proceeding implements some of the visual capabilities that people use to manipulate objects without much reasoning at all.

# 5 Conclusion.

In this paper we argued that analogical simulations can be used in conjunction with symbolic qualitative reasoners to deal with the spatio-temporal aspects of physical processes. One of the major advantages of such a hybrid physics modeler is the increased precision of predictions about the evolution of physical systems. Situations or devices involving liquid components are particularly sensitive to spatial and temporal factors. They form a class of systems that can potentially benefit from a hybrid physics modeler.

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