Extending the Contained-Stuff Ontology with Geometry

Hyun-Kyung Kim

Qualitative Reasoning Group
Beckman Institute, University of Illinois
405 North Mathews Avenue
Urbana, Illinois, 61801, USA
email: hkim@cs.uiuc.edu

Abstract

In order to capture commonsense understanding of the physical world, it is crucial to understand how dynamics and geometries interact. This paper presents a qualitative analysis of the behaviors of fluids and their effects on fluid boundaries. The representational issue in designing intelligent systems reasoning about fluid is partitioning the fluid at an appropriate level of detail. Since the interaction of fluids and objects occurs only when they are in contact, our theory individuates fluid based on the geometry of the surface in contact with the fluid (this is called the ***bounded-stuff*** ontology). In addition, it dynamically describes bounded-stuffs as the contact configuration changes during fluid motion. Fluid motion is captured by the changes of free surfaces in the fluid, thus showing how the contact configuration changes. The motion of free surfaces is predicted by dynamically analyzing the interaction of surface geometry and pressure disturbance in fluid. Using this approach, we can derive the behaviors of fluid with complex surface geometry. This idea has been implemented and incorporated into the qualitative simulation program QPE.

1 Introduction

Understanding the interaction between dynamics and geometry is crucial to capturing commonsense physics. Without spatial reasoning, dynamics cannot fully explain the physical world. For example, applying the same force to different points on an object can cause dramatically different behaviors. Without geometric information, these behaviors would be difficult to predict.

Unfortunately, the general spatial reasoning problem is intractable. Thus, recent research has focused on more constrained problems such as motion in limited domains [DEKL75,FORB81], mechanical mechanisms [JOSK87,NIEL88] and fluid ontologies [COFO87] [HAYE85]. The studies dealing with mechanical mechanisms and motion focus only on rigid objects, ignoring the motion of fluid. In addition, the fluid ontology research is insufficient to explain fluid behavior fully. Two basic approaches to fluid ontology are *contained-stuff* ontology and *piece-of-stuff* ontology. Neither of these approaches suffices to explain all fluid motion. Suppose we want to explain the motion of the liquid in the U-tube whose left tube is connected to a gas tank and right tube is open to the air. At first, the pressure in the tank is equal to the atmospheric pressure and thus the level of liquid in both sides are the same. Next, the pressure in the tank is increasing. The most qualitative physics research dealing with the contained-stuff ontology strictly view the fluid contained in a container as an object. Thus it is impossible to consider the motion in each side of the tube since the liquid in the U-tube is treated as one object. Similarly, it appears to be impossible to consider the motion of every piece. However, the downward motion of surface in left tube and the upward motion of surface in right tube can be easily predicted by simple geometric analysis.

This paper presents a technique for reasoning about the behaviors of fluid and its subsequent effects on the surface of rigid bodies in contact with the fluid. In this paper, we focus on overall behaviors of fluids rather than the details of thermodynamics of fluid: we want to reason qualitatively about how forces are transmitted between fluid and other parts, and how their motions change in a system.

We identify the criteria in designing an intelligent system to reason about fluids based on the first principle of physics. A previous technique—the contained-stuff ontology restricted to the containment by a container—is compared with the criteria, showing its strengths and weaknesses. Since the interaction between fluids and other objects occurs only when they are in contact, our theory individuates fluid based on the the geometry of surface in contact with the fluid (this is called the *bounded-stuff* ontology). In addition, it dynamically predicts bounded-stuffs as the contact configuration changes by fluid motion. Fluid motion is captured by the changes of free surfaces in the fluid, thus showing how the contact configuration changes. During this analysis, the changes of fluid in containers are easily determined by relating the geometric structures of surfaces to containers.

Section 2 describes the nature of fluids and shows the problems and criteria in designing a reasoning system for fluids. Section 3 describes the contained-stuff ontology in terms of these criteria, showing the need for spatial reasoning based on surface contact between fluid and its neighbors. In Section 4, we describe how the interaction of pressure disturbances and surface geometry captures the behaviors of fluid in our theory. Finally, we summarize our results and discuss future plans.

2 The Nature of Fluid

Unlike solids, fluids move and deform continuously as long as shear stresses exist. Its shape is determined by the container. These properties of fluid make it difficult to individuate fluids in a reasoning system. In physics, the following physical theory about how dynamics and geometries interact is used to capture the behaviors of fluid [HALL74].

- *Pressure transmission:* Pressure is transmitted to solid boundaries or across arbitrary sections of fluid at right angles to these boundaries or sections at every point.

- *The law of pressure change:* As elevation increases, pressure decreases.
- *Pascal's principal:* Pressure applied to an enclosed fluid is transmitted undiminished to every portion of the fluid and to the walls of the containing vessel.

To understand fluids, we first have to individuate fluids and then find the relations between the individuals : between fluid and fluid, between fluid and solid. This individuation process is difficult due to the nature of fluids. The key problem in reasoning about fluid is how to partition the fluid at an appropriate level of representation. Fluid should be divided into qualitatively different parts based on reasoning task, and unnecessary partitions should be avoided. In addition, the physical theory about fluid should be easily applied in each individuated fluid. For instance, to understand the overall behavior of fluid, the view of fluid as a collection of molecules is inappropriate: it is difficult to apply the above physical theories to each molecule. However, this view will be useful to understand the details of thermodynamic cycle of a system. We want to understand the overall behaviors of fluids rather than their microscopic behaviors. Since interaction between fluids and other parts in a system occur only when they are in contact and it is determined by how they are in contact, the individuation of fluid should be based on the geometry of surface contact with the fluid, i.e., contact configuration of the system.

As a solid part changes the configuration of the system by its motion, fluid also changes the configurations of contact by its motion. This change, whether it is caused by solid or fluid, leads to new kinematic interactions between the parts. Thus each part continuously transmits and modifies both force and motion through the system. Reasoning about fluid motion must therefore capture the subsequent change of configurations. A qualitative version of the above physical theory is used for this reasoning and should be sufficient to describe the fluids if we build the reasoning system based on deep knowledge.

Finally, it is important for the reasoning system to provide natural and easy explanations to help our understanding.

3 Problems of Contained-Stuff Ontology

The contained-stuff ontology individuates fluid using the natural boundaries provided by containment. The contained-liquid or contained-gas may disappear and reappear as the amounts of them change. This view for fluid has been used in most qualitative physics research since this provides a useful and intuitive notion for reasoning about the overall behaviors of fluids. However, this has been used in more restricted way: the fluid in a container is viewed as a single object. However, this approach is not enough to capture the fluid behavior because geometric aspects are not sufficiently considered. In this section, we describe the sources of problems and then show the problems with the lift pump example.

3.1 Sources of Problems

Two main sources of the problems of the contained-stuff ontology are:

1. The concept of a container is hard to define. Let's think about a leaky container and a channel. Hayes [HAYE85] claimed the former is a container but the latter is not. He also wrote "Unfortunately to describe these adequately requires metric ideas. (For example, a tin with a small hole in the base is a leaky tin, but a tin with the bottom missing isn't a container at all, although it could be a channel.)" However, even though we use metric information, this problem does not seem to be solved. For example, in this case, how can we define "a small hole"? Can we define a small hole as a hole whose diameter is less than half, for instance, of the diameter of the base? Can we say Figure 1a is a container but Figure 1b is not? In the case of Figure 1c, a channel is connected with a tin. In this case, the upper channel contains the liquid, which means the channel is a container. We can find more examples which confuse

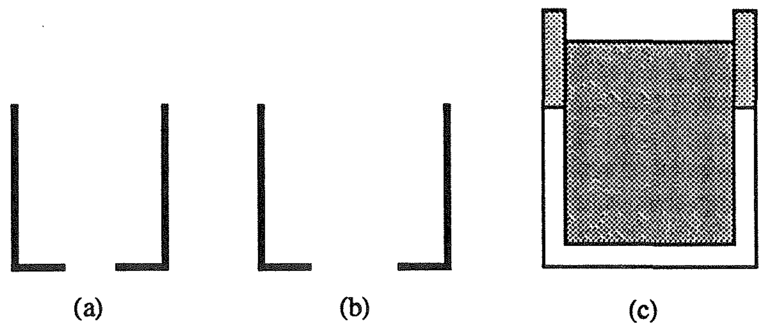

Figure 1: Container Examples

the concept of a container. These arguments show there might be no general rule to define a container upon which everyone can agree.

2. Explaining fluid in terms of the contained-stuff ontology is useful and reasonable for people since this is based on the natural boundaries provided by containers. However, fluid by nature does not behave on the basis of its container. Thus this contained-stuff ontology might be inadequate to explain the fluid behavior in a container with more complex geometry. In the following subsection, the lift pump example shows this problem clearly.

3.2 Lift Pump Example

We begin with a brief description of a lift pump, and then show the problems related to the contained-stuff ontology. Figure 2 shows the abstract figure of a lift pump describing its behavior. The pump's manual explains its behavior as follows.

- (a) Lifting up the piston opens valve(A), water is also sucked up into the main chamber.
- (b) Pushing the piston down closes valve(A) by force of the water. Water is lifted up to top chamber as valve(B) opens.
- (c) Lifting the piston up again shuts valve(B) and pushes water out of the top chamber. Also water is sucked up into the main chamber as valve(A) opens.
- (d) Pushing the piston down again opens valve(B) by force of water. Also water flows into the top chamber.

As this explanation shows, the directions seemingly refer to a contained-liquid ontology to explain the behavior of the lift pump. However, we find that the strict contained-liquid ontology fails to explain the physical phenomena in this example. We explain for each case.

- (a) In our standard domain theory with the contained-stuff ontology, fluid motion is captured by fluid flow between two containers, resulting in the decrease of amount in source container and the increase in destination container. With this approach, it is difficult to fully reason how the configuration changes. Two conditions for a fluid-flow process are that two contained-stuffs meet and that there is a pressure difference between the two in the boundaries. Suppose the inlet pipe is not primed with water in the beginning, and we consider water in the inlet

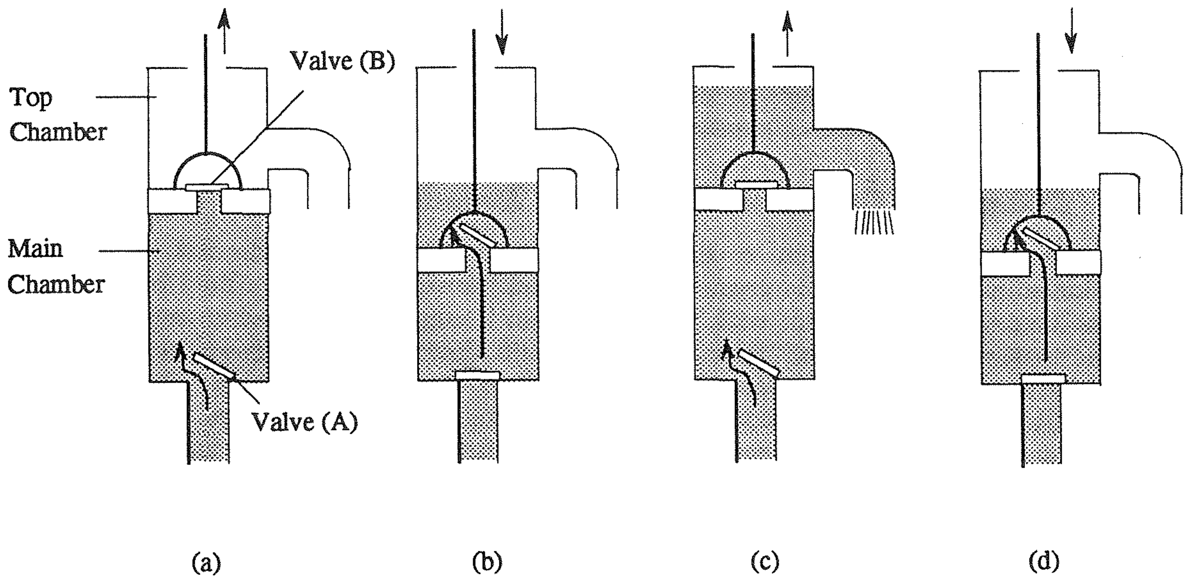

Figure 2: Lift Pump Example

pipe and the reservoir as one contained liquid. If the piston is lifted up, air in the inlet pipe flows to the main chamber as valve(A) opens. Since the pressure of the air in the pipe is less than the water pressure in the pipe, water flows up. But our liquid flow process cannot capture this since this flow happens inside of a container. If the pipe is primed and the valve is opened, fluid flow will occur. Though they happen with the same cause, the contained-stuff ontology can catch only one of them: liquid-flow which happens only on the portal of a container.

- (b) Suppose a container has a portal at the bottom and there is liquid inside. Then by applying the law of pressure change, we can make a general rule like this: the pressure at the portal is proportional to level of the contained-liquid in the container. But this is not applicable to the portal of main chamber since the pressure at the portal of the main chamber is proportional to sum of the level of contained-stuff in main chamber and the level of the top chamber. We might make specific rules for each different geometry of containers. But to keep our domain knowledge in this way seems very inefficient compared to the system to allow uniform and easy application of physical theories.
- (c) The deformation of the water, caused by the lifting piston, cannot be generally described using the current contained-stuff ontology since it is based on simple containers and thus cannot capture the changes of contact configuration of fluid.

These problems are caused by lack of geometric information as indicated during the explanation of criteria for a reasoning system about fluid: (1) The contained space by a container does not include sufficient geometry of surface contact. (2) Fluid motion does not fully capture the changes of configurations. However, it provides the ability to describe the behaviors of fluid in natural terms.

4 A Qualitative Theory of Fluid

Fluid transmits forces and motions to its neighbors through contact. These interactions are determined by the way of their contact. Thus, our theory focuses on how to reason about the configuration of fluid contact. Since, unlike solids, fluids deform while they move, our theory dynamically predicts the surface geometry of boundaries in contact with fluids in each configuration. Based on the configuration of contact and pressure change, the behaviors of fluids are determined.

4.1 Extending Contained-Space with Boundaries

We want to represent a fluid so that its behavior is inferred from the first principle of physics, mentioned in Section 2. The pressure transmission principle requires a fluid be described in terms of the boundaries in contact with the fluid. Also it suggests the need to represent the direction of the surface normal of each boundary, to find the direction of a force exerted to each boundary. To find the magnitude of the pressure at a boundary, the pressure change principle is applied. We can get the relative size of the pressure by comparing with other pressure. If $p1$ is the pressure at elevation $y1$ and $p2$ the pressure at elevation $y2$, we have (using a force balance) $p2 - p1 = -\rho g(y2 - y1)$. Thus, $p1 = p2 + \rho g(y2 - y1)$. In many cases, it is useful for $y2$ to be the elevation of a free surface in a liquid. This suggests the location and the pressure of free surfaces should be included in the theory as well as information about boundaries. Lastly, Pascal's principle suggests we view the fluid in some connected volume with contiguous boundaries as one object, since a pressure disturbance applied to any part of the fluid is transmitted to every part of the connected fluid.

Our theory is based on these requirements and thus supports inferences made from first principles. Even though the theory is useful for both gases and liquids, it is especially useful when applied to liquids. Since gas have very small density ρ, the pressure change due to height can be neglected. Thus pressure differences due to geometry can be considered insignificant. However, in the case of liquids, which have much larger densities than gases, these differences are significant. Here, we especially focus on the bounded-liquid and an implementation of our theory has been tested on this.

We extend the contained-stuff ontology from a container to include the boundaries and call our new ontology ***bounded-stuff***. A contained space which is full of fluid is treated as one object. In turn, contained-space means "some connected volume of three-dimensional-space which has a contiguous boundary (at least) below it and around it" [HAYE85]. The boundaries need not be the boundaries of a container. They might consists of the boundaries of many containers. Each boundary may be the surface of a rigid object or of other fluids.

In our representation, rigid objects are represented by their surfaces which are in contact with the fluid. For each surface, we represent the surface normal using a qualitative vector. The pressure exerted by a fluid is applied to a boundary in the opposite direction of the surface normal. This direction of the pressure is crucial to determining the motion of the boundary. The geometry of rigid objects, such as how they are connected, and relative heights between them, is also described.

If we ignore the breakages of fixed boundaries, we can assume fixed boundaries do not move by external forces. With this assumption, we do not compute the pressure on fixed boundaries, such as the surfaces of the inlet pipe. Theoretically, this does not cost us any interesting inferences. If movable boundaries are included in the space, the kinematic interaction between the boundaries and fluid are determined by their surface normals and locations. For instance, the piston in the chamber and valves are described by the surface normals of their surfaces and relative locations.

As movable parts change their position, the configuration of a system changes, and thus the contained spaces changes. In Figure 2a, for instance, there are two contained spaces—one formed by the surfaces of the top chamber, the other formed by the surfaces of the main chamber, inlet pipe, and the reservoir. As the valve (A) is closed and the valve (B) is open, the new contained spaces are formed in Figure 2b.

4.2 Finding Bounded-stuff

Below we give some useful definitions to describe contained spaces and bounded-liquids.

Definition 1 (Connected) *Connected(pos1,c1)(pos2,c2) is true if a position pos1 of a container c1 is joined with pos2 of c2.*

Position describes the part of an object such as the bottom of the main-chamber. For instance, connected(bottom, main-chamber)(top, inlet-pipe) means that the bottom of the main-chamber is connected with the top of the inlet-pipe in the liquid pump. If two containers are connected, they can be either *aligned* or *∼aligned*. If there is a valve between them, its position determines whether or not they are aligned. Otherwise, they are always either aligned or ∼aligned. The inlet pipe and the reservoir in the pump are always aligned.

Definition 2 (Containers) *Containers(x) is the set of containers which form the boundaries of a contained space x.*

Definition 3 (Bottoms) *Bottoms(x) is a subset of Containers(x) whose bottoms are not aligned to any container in Containers(x).*

Definition 4 (Tops) *Tops(x) is a subset of Containers(x) whose tops are not aligned to any container in Containers(x).*

For instance, the main chamber belongs to Bottoms(x) while the top chamber belong to Tops(x), where x is the contained space formed by the surfaces of both chambers.

Definition 5 (Length) *Length(x) provides the number of elements in a set x.*

Definition 6 (Full) *Full(c,sub) is true if a container c is filled with liquid sub.*

Definition 7 (Empty) *Empty(c,sub) is true if there is no liquid sub in a container c.*

Suppose a system with n containers and $\{n\}$ represents the set of the n containers. Since the the system keeps changing its configuration, a number of contained spaces are possible. They are found by incremental generation as follows.

1. For all c in $\{n\}$
   - Generate $ContainedSpace(x)$, where $Containers(x)$, $Bottoms(x)$, and $Tops(x) = \{c\}$
2. For every pair of contained spaces such that $[c1 \in Containers(x1) \bigwedge c2 \in Containers(x2) \bigwedge (Connected(pos1, c1)(pos2, c2))]$ is true,
   - Generate $ContainedSpace(x3)$, where $Containers(x3) = Containers(x1) \cup Containers(x2)$ [1]

The above algorithm produces every possible contained space. As the configuration changes, some of them appear while others disappear. A contained space is *active* in a particular configuration if it exists in the configuration. Whether or not it is active is determined by the following following constraints.

[1] Tops and Bottoms are generated based on the *pos*1 and *pos*2. For instance, if both *pos*1 and *pos*2 are bottom, then Tops($x3$) = Tops($x1$) $\cup$ Tops($x2$).

4.4 The Example Problem, Revisited

Now, we show how the problems of the contained-stuff ontology are solved, using the lift pump example:

- (a) Fluid flow inside a container problem: In our approach, the fluid motion is captured by the changes of free surfaces and subsequent contact configuration between fluid and boundaries. Therefore, the upward motion in inlet pipe and the downward motion in reservoir are easily captured even though we treat the inlet pipe and the reservoir as one container.
- (b) The fluid in the main chamber and the fluid in the top chamber belong to the same bounded-stuff in Figure 2b. Since the valve(A) is at the bottom of the fluid, the downward force by the fluid is proportional to level of the fluid, i.e., the sum of the level of the main chamber and the top chamber.
- (c) Since any deformation of a fluid is explained by changes in its boundaries, the deformation when the piston is moving up can be explained by analyzing the surface structure of the lift pump.

4.5 Implementation

This analysis has been implemented and tested for several examples, including each step of the lift pump. This implementation has been incorporated into the Qualitative Process Engine (`QPE`) [FORB88b]. `QPE` is the system which implements the Qualitative Process theory using an assumption-based truth maintenance system (ATMS). Given a scenario, i.e., a particular situation being modeled, `QPE` automatically instantiates the domain model to form a scenario model. The domain model describes the physical theory in terms of processes and views. Our theory is implemented to build the domain model about fluid.

In `QPE`, contained-stuffs are treated as individual objects and thus processes related to fluids are described based on these. Since bounded-stuff are described in terms of containers and status of contained stuff, such as existence, ***full***, and ***empty***, reasonings related with contained stuff are also used for our reasoning process. However, physical theories, i.e., processes, changes, are not applied to them. Processes about fluid are applied to bounded-stuffs. To explain behavior in terms of contained-stuff helps our understanding.

Since `QPE` generates every possible configuration of a given system, we just include the constraints which determine the active contained spaces in each configuration. These are given as ***nogoods*** and applied generated contained spaces. To find the bounded-liquids in each configuration, the constraints relating them with the status of contained liquids are also given as nogoods.

Finding contained spaces is easy as described in previous subsection. If a system has n containers, `Length(Containers(`x`))` can vary from 1 to n. Then the maximum number of possible contained spaces is ${}_nC_1 + {}_nC_2 + \ldots\ {}_nC_n$, approximately 2^n. This happens when every container in a system is connected to all of the containers, which is is very hard to imagine, especially for large n. However, in many system the number of connections is linear in n. If we consider systems with $n-1$ connections, i.e., the liquid pump, the maximum number is $n + (n-1) + \ldots\ 1$, i.e, $n(n-1)/2$. If two containers are always aligned, this number reduces more. Conceptually, we can view the two as one container in counting the number of possible contained spaces, since the two always belong to same contained space.

Figure 4 shows the process for a top surface motion and the simple rule relating its motion to the change of contained-stuff. `(B-S ?sub liquid ?bnd)` express `BoundedLiquid (?bnd,?sub)`. If a container `?top` belong to `Tops(?bnd)`, then `(top-surface ?top (B-S ?sub liquid ?bnd))` is true. `Bottom-of(?top ?bnd)` provides a container which is below `?top` in `?bnd` and belongs to `Bottoms(?bnd)`.

```
(Defprocess (Surface-Up-motion ?top ?sub ?bnd)
  Individuals
    ((?top  :type container)
     (?sub  :type substance)
     (?bnd  :type contained-space
            :conditions
            (top-surface ?top (B-S ?sub liquid ?bnd)) )
     (?top2 :type container
            (top-surface ?top2 (B-S ?sub liquid ?bnd))
            (connected (bottom, (bottom-of ?top ?bnd))
               (bottom, (bottom-of ?top2 ?bnd)))) )
  PreConditions
    ((transfreedom (top-surface ?top (B-S ?sub liquid ?bnd)) up))
  QuantityConditions
    ((less-than
      (A (down-pressure (top-surface ?top (B-S ?sub liquid ?bnd))))
      (A (up-pressure (top-surface ?top (B-S ?sub liquid ?bnd)) ?top2))))
  Relations
    ((quantity flow-rate)
     (Q= flow-rate
        (- (up-pressure (top-surface ?top (B-S ?sub liquid ?bnd)) ?top2)
           (down-pressure (top-surface ?top (B-S ?sub liquid ?bnd))))) )
  Influences
    ((I+ (velocity (top-surface ?top (B-S ?sub liquid ?bnd)))
        (A flow-rate)) )


;;; Rule for relating the top-surface motion to the change
;;; in the amount of the container which include the top-surface
(Qprop (amount-of-in ?sub LIQUID ?top)
      (velocity (top-surface ?top ?B-L)))
```

Figure 4: A process about free surface motion in bounded-liquid

5 Discussion

The key problem in commonsense reasoning about fluid is how to individuate the fluid at the appropriate level. In this paper, we focus on the overall behaviors of fluids rather than the details of each molecule. The bounded-stuff ontology has been built based on the first principle of physics.

The behaviors of fluid and the subsequent effects on the boundaries are predicted by analyzing the pressure and the surface geometry of boundaries. Unlike the contained-stuff ontology restricted to the confinement by a container, which views fluid motion as fluid flow between two containers, the bounded-stuff captures a fluid motion as a deformation. The latter focus on the changes in contact configuration with its boundaries. We use the bounded-stuff ontology for physics while retaining the contained-stuff ontology for complementary explanation. Since the boundaries are easily related to their containers, the changes in each container (such as increasing, decreasing of amount of a fluid, and full, etc.) could be determined during analysis of bounded-stuff.

We have only dealt with the overall behavior focusing on the pressure and motion transmission through a system by analyzing the contact configuration and subsequent effects on the the boundaries. We plan to continue expanding our theory toward a complete theory for reasoning about fluid. Reasoning about other important thermodynamic properties is left as future work. What we hope to analyze eventually is a real system, such as an internal combustion engine, which should be explained by tightly integrating dynamics and kinematics of rigid bodies and fluid. Our bounded-stuff ontology is one step toward that goal.

6 Acknowledgements

I would like to thank Ken Forbus for his guidance. Thanks to Gordon Skorstad for proofreading and comments. This research was supported by the Office of Naval Research, Contract No. N00014-85-K-0225.

References

[COFO87] **J. Collins, K. Forbus**: "Reasoning About Fluids Via Molecular Collections", Proceedings of AAAI-87, July, 1987

[DEKL75] **J. deKleer**: "Qualitative and Quantitative Knowledge in Classical Mechanics", TR-352,MIT AI Lab, Cambridge,MA., 1975

[FALT90] **B. Faltings**: "Qualitative Kinematics in Mechanisms", *Artificial Intelligence*, **44**, 1990

[FORB81] **K. Forbus**: "A Study of Qualitative and Geometric Knowledge in Reasoning about Motion", TR-615,MIT AI Lab, Cambridge,MA, 1981

[FORB84] **K. Forbus**: "Qualitative Process Theory," *Artificial Intelligence*, **24**, 1984

[FFN87] **K. Forbus, B. Faltings, P. Nielsen**: "Qualitative Mechanics: A Framework", *Artificial Intelligence*, **24**, 1991

[FORB88b] **K. Forbus**: "Qualitative Process Engine," *International Journal of AI in Engineering*, 1988

[HALL74] **D. Halliday,R. Resnick**: *Fundamentals of Physics*, John Wiley Sons, Inc., 1974

[HAYE85] **P. Hayes**: "Naive Physics 1: Ontology for Liquid" in Hobbs, J. and Moore, B. (Eds.), *Formal Theories of the Commonsense World.* Ablex Publishing Corporation, 1985

[JOSK87] **L. Joskowicz**: "Shape and Function in Mechanical Devices" Proceedings of AAAI-87, July, 1987

[KIM90] **H. Kim**: "Qualitative Reasoning about the Geometry of Fluid Flow," Proceedings of CogSci, August, 1990

[NIEL88] **P. Nielsen**: "A Qualitative Approach to Mechanical Constraint" Proceedings of AAAI-88, August, 1988

[WHIT79] **F. White**: *Fluid Mechanics*, McGraw-Hill Book Co., 1979