QUALITATIVE REASONING ABOUT PHYSICAL PROCESSES

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ABSTRACT

Common sense reasoning about the physical world must include an understanding of physical processes and the changes they cause. For example, heating a liquid causes its temperature to rise and if continued long enough may cause it to boil. A style of analysis is presented that combines deKleer's Incremental Qualitative analysis wjth the Quantity Space idea from Naive Physics to reason about the effects of physical processes and their limits. The analysis is demonstrated on an example with practical importance, and further possibilities for applications are discussed.

1. Introduction

An important component of a Naive Physics [1] is the representation of the kinds of things that can happen to an object, the processes described by the physics that act to change a situation. For example, we know that when heat flows from a flame to water in a container, the temperature of the water will rise and it may boil. We can also deduce that if the container is sealed there is some chance that the increased pressure caused by the boiling fluid can cause it to explode. These deductions are interesting both because they are so easy for us to make and because they are important for certain applications. A program that understood a steam plant in order to explain or operate it, for instance, should be able to make this particular inference. This paper introduces a new style of analysis (called Qualitative Process analysis) to be used in performing such inferences.

One part of the problem is to represent how quantities change. deKleer's Incremental Qualitative (IQ) calculus [2] can handle this. It represents the change in a quantity by one of four values (U, D, C, or ?, corresponding to "increasing", "decreasing", "constant", or "indeterminate") indicating knowledge of the sign of the derivative. While the IQ calculus is very useful for causal reasoning (see [2] and (3]). it cannot be used to deduce the limits of physical processes. This is because IQ analysis does not represent quantities, only changes in them. In the example above, we could deduce that the temperature of the water is rising, but not that It might boil This problem has appeared in studies of mental models of heat exchangers [4] as well. Qualitative Process analysis includes the IQ calculus, but also incorporates notions of rates and amounts.

The conceptualization of amounts in QP analysis comes from the notion of a quantity scale in Hayes* Naive Physics of liquids[5]. A quantity scale maP* amounts in the physics to a measure space, such as amount (whisk g, insIdeljarM to I iterate.83). In the analysis introduced here the property of real importance is the existence of an ordering among points in the scale. In determining whether or not a fluid will flow, for example, only the relative pressures need be known. The notion of a quantity space is introduced to serve as a partition of the possible values for a quantity which correspond to different processes occuring.

In the perspective of Naive Physics, Qualitative Process analysis corresponds to a cluster • a collection of knowledge and inference procedures which is sensible to consider as a module. While the axioms for liquids Hayes developed include some knowledge of process limits[1] they also include a particular choice for the representation of the effects of the processes over time and a particular geometry. I believe the kind of reasoning discussed here is independent of these particular choices and thus should be considered separately.

What follows are the basic definitions of QP analysis and an example of its use. The details have been worked out by hand on several examples; an implementation is underway.

II DEFINITIONS

A parameter of a physical system will be represented by a quantity. For purposes of QP analysis, a quantity will have three components: an amount, an IQ value, and a rfite.. Although an amount

1. Set *tot* eiamplt aitomi 52 through 62

will be assumed to take on real values, the inferences discussed here do not require quantitative values, only knowledge of the ordering between two quantities. The IQ and rate of a quantity specify how it is changing; the IQ value corresponds to the sign of the change and the rate corresponds to the amount of the change. Rates combine as do numbers and Figure 1 illustrates how IQ values combine.

The quantities in a situation which represent a particular kind of parameter are grouped together in a partial order called a quantity space. The quantity space for the levels of fluid in two tanks A and B connected by a pipe might be:

Top-of(A)
Bottom Level (A) → Level(B) → Top-of(B)

The arrow indicates that the quantity at the head is greater than the quantity at the tail. As drawn, Level (B) andTop-of(A) are unordered. We will call two points which are ordered and with no points known between them in the ordering neighboring points. In the quantity space above. Level (A) has Bottom. Top-of(A), and Level(B) as neighbors, but not Top-of (B).

Fig. 1. Combining IQ Values
This table specifies how IQ values combine across addition and multiplication. Rates and amounts are used to disambiguate cases marked by 'T in deKleer's formulation.

	A	B	Result
I	C	C	C
Q	C	U	U
	C	D	D
V	U	C	U
a	U	U	U
l	U	D	(see below)
u	D	C	D
e	D	U	(see below)
	D	D	D

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When equivocable,
if + then if Rate(A)>Rate(B) then IQ(A)
          if Rate(A)<Rate(B) then IQ(B)
          otherwise C
if * then if Rate(A)*Amount(B)
             > Rate(B)*Amount(A) then IQ(A)
          if Rate(A)*Amount(B)
             < Rate(B)*Amount(A) then IQ(B)
          otherwise C
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A continuous process acts through time to vary one or more quantities/ The specification of a process has four parts: preconditions, quantity Conditions, relations, and influences. Both preconditions and quantity conditions must be true for a process to be acting. The preconditions are those factors that are external to the theory, such as someone opening or closing a valve. The quantity conditions are those limits that can be deduced within the present theory, such as requiring the temperature of two bodies to be unequal for heat flow to occur. Relations hold between quantities affected by the process, and influences are the contributions to the way a quahitity changes. Relations concern amounts and rates, while influences are assertions about the contribution to the IQ value for a quantity. To find out how a quantity is actually changing requires summing all of the influences on it, since several processes may be acting at once. Figure 2 shows the definition of two processes.

The physics of a situation determines the set of processes possible in it. The particular process(es) that are acting at some time can be determined by examining the preconditions and the orderings in the quantity spaces. Using the level quantity space above, if the pipe between A and B is unobstructed, then there will be a flow from B to A because a simple quantity condtion for fluid flow is that Level (aource) is greater than Level (destination).

Discontinuous changes in processes occur at limit points, which serve as boundary conditions. The points are chosen according to the quantity conditions of the processes that can affect that parameter. For example, the temperature quantity space for a fluid could be:

T(ice) → T(boiling)

where temperatures at T(ice) and below correspond to the solid state, temperatures of T(boiling) and above correspond to the gaseous state, and any temperature in between to being a liquid.

I. A process is not equivalent to an episode in Hayes* liquids theory. An episode includes time specifications and a geometry, while the part of a process we are considering does not. While a geometry representation is needed to set up the descriptions and a time representation to make sse of the results, the inferences themselves are nearly separable.

Fig. 2. Physical Process Definitions

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Heat-Flow(s,d)
  Precondition: ∃(p)Heat-Path(p,s,d)
  QuantityCondition: T(s)>T(d)
  Relations: rate(Heat(d))=rate(Heat(s))
  Influences: IQ(Heat(s))=D
              IQ(Heat(d))=U

Boiling (w)
  Precondition: ∃(f) AirSpace(f)
                       ∧Shared-Face(f,w)
  QuantityCondition: ∃(s)Heat-Flow(s,w)
                     T(w)=T(boil(made-of(w)))
  Creates: ∃(g)Gas(g)∧made-of(g)=made-of(w)
  Relations: rate(A(g))=rate(A(w))
             T(g)=T(w)
             rate(A(g)) α rate(Heat(w))
  Influences: IQ(T(w))=C
              IQ(A(w))=D
              IQ(A(g))=U
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A useful law for dealing with heat is

$$V(s)T(s) \propto Heat(s)$$

To model a heat source,

IQ(Heat(s))=C and so IQ(T(s))=C

Fig. 3. Linking IQ analysis with Inequalities
This table summarizes how the ordering relationship between two quantities may change as a result of their IQ values.

IQ Value	A >	B	Next Relation
I	C	C	>
Q	C	U	=
	C	D	>
V	U	C	>
a	U	U	if rate(A)>rate(B),>; < implies =, = implies >
l	U	D	>
u	D	C	=
e	D	U	=
	D	D	if rate(A)>rate(B),=; < implies >, = implies >

IQ Value	A =	B	Next Relation
I	C	C	=
Q	C	U	<
	C	D	>
V	U	C	>
a	U	U	if rate(A)>rate(B),>; < implies <, = implies =
l	U	D	>
u	D	C	<
e	D	U	<
	D	D	if rate(A)>rate(B),<; < implies >, = implies =

HI INFERENCES ABOUT PROCESSES?

The definitions of quantities and processes above provide enough formal structure to deduce. given a physics and a very general description of a situation, what processes are occuring and the changes they will cause. The preconditions and quantity conditions can be used to determine what processes are operating within the situation. This information can in turn be used to deduce changes in the properties of the situation (such as a temperature rising or an amount dropping) and the limits of the processes involved.

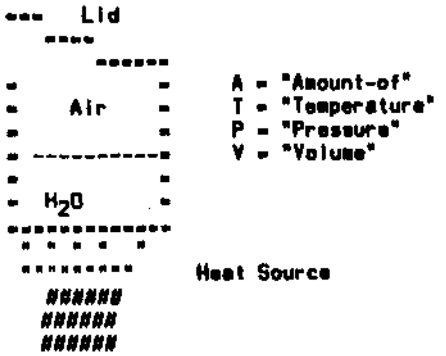
To infer the limits of a process, first find the influences on all affected quantities and determine the resulting IQ value. Then find the neighboring points within the quantity space. If there is no neighbor in a direction, then motion in that direction cannot affect the process. The ordering between each neighbor and the current amount of the quantity can be combined with the IQ values of each to determine if the relationship will change (see Figure 3). If the neighbor is a limit point, some process may end there and others begin. Thus the set of possible changes in ordering* involving limit points becomes the ways the current processes might change. This assumes that rates are non-infinitesimal, so that if a quantity is moving towards some point in its space (such as Level (A) and Level (B) above) it will actually reach that value in some finite time.

More than one change is typically possible, as will be illustrated below. There are three reasons for this. First, if the ordering within a quantity space is not total more than one neighbor can exist. Second, a process can influence more than one quantity. Finally, more than one process can be occuring at once. For some kinds of tasks just knowing the possible changes is enough (such as envisioning, in [6J). If required, knowledge outside the scope of this theory can be used to disambiguate the possibilities. Depending on the domain and the style of reasoning to be performed there are several choices: simulation (7), algebraic manipulation [6J, teleology [2], or possibly by default assumptions or observations (discussed in [8]).

IV A DEMONSTRATION OF QP ANALYSIS

To illustrate the use of this technique, let us consider the possible consequences of a situation, shown in Figure 4. The situation consists of a container partially filled with water that can be heated by a flame; the container has a lid which can be sealed and is surrounded by air. The initial amounts are assumed to be those of standard temperature and pressure, all IQ values are initially C. At some point in time the heat source is turned on. We will stipulate that if boiling occurs, the lid will be closed and sealed. Some of the physics required for this problem is contained in Figure 1. The rest of the details, and especially formalizing the geometry involved, will be ignored in this example.

Fig. 4. Situation and Quantity Spaces



When the heat source is activated, there will be a heat path between the source and the container. Assuming standard temperature and pressure in the environment, and no unstated effects, if T(source) >T (Water) there will be a heat flow from the source to the water. Being a heat source, the influence of the loss on the temperature is ignored and IQ (T(source))-C. The only influence on T (container) is that of the heat flow, so IQ(T(containter))-U. This in turn will cause a heat flow to the air surrounding the cup, the air inside the container, and the water. Most of these temperatures will be ignored. The temperature quantity space looks like:

T(ice) → T(water) → T(source)
↘ T(boil)

If T(source) >T(boH) and the process is unimpeaded, the next process that will occur is a boiling.

Before considering the boiling, we can examine what happens to the air inside the container. The relationship between the parameters of air due to its gaseous state can be expressed as:

P(air)-V(air)-A(air)*T(air)

While the water is heating,

IQ(V(air))-C and
IQ(T(air))-U
->IQ(P(air))IQ(A(air))4J

Changes in-pressure and amount of something usually result from a flow. If there is a flow then it must be either inward or outward. First assume no flow occurs. Then because the only way for Amount-of of the air to change is a flow,

IQ(A(air))-C. so IQ(P(air))-U

But initially P(air) - P(outside) so the conditions for a flow are established, contradicting the assumption. Can the flow be inward? If so, IQ(A(alr))*U. This requires IQ(P(air))-U, which enables an outward flow, again a contradiction. Finally, if there is an outward flow then IQ(A(air))-0, which is not inconsistent with what we know. By exclusion we accept it, realizing that some ambiguity still exists.[1]

Suppose the preconditions for the heat flow continue to be met and boiling occurs. The amount quantity space looks like:

NONE → A(water) → A(InitialWater)
↘ A(steam) ↗

The influence of the boiling on A(water) moves it towards NONE. So one of the ways the process might end is that all of the water is converted to steam. However, we must deduce the effects of the change in A(steam) to be sure we have all of the possibilities.

Because the steam is still in contact with the water their temperatures will be the same, and under normal conditions the boiling point of water is constant. However, we assumed that the container would be sealed when the boiling began. The only influence on A(steam) is from boiling because the geometry of the situation makes steam flow impossible. So IQ(A(steam))-U. If we think about what is happening in some particular instant of time we can first assume IQ(T(steam))-C, and since T(steam)-T(water), IQ(T(steam))-C. Steam is a gas, so its parameters are related by:

P(steam)·V(steam)-A(steam)·T(steam)

and by substitution,

IQ(P(steam))·IQ(V(steam))-U.

Since the container holds only the water and steam (ignoring the air), geometry tells us

V(Inside(container))-V(steam)+V(water)

and because the container is rigid, IQ(V(Inside(container)))-C. Also, from physics we know V(water)∝A(water) and from the process description IQ(A(water))-D. Therefore IQ(V(water))-D and IQ(V(steam))-U. Examining the combination table for IQ values reveals that for IQ(V(Inside(container)))-C to hold, it must be that

rate(V(steam)) = rate(V(water))

What does this imply about the pressure?

If IQ(P(steam))-C, then from physics we know

V(steam) >> V(water)

for some amount of water boiled off, which means

rate(V(steam)) >> rate(V(water))

which cannot be. The pressure must supply some influence on the volume, in order to make the rates equal. Suppose IQ(P(steam))-D. Then for a particular amount of steam at a particular pressure the gas law tells us the influence of pressure on volume:

IQ(P(steam))∝IQ(V(steam)) = C

1. The details of how the pressure changes with time depend on more geometry than we have here. For example, if the top is very small the pressure might build up for a while, but if it is very large then the pressure might be essentially constant. The important point is that each model for outward now is consistent.

This means the influence of the pressure change would result in IQ(V(steam))=U, which does not help. On the other hand, IQ(P(steam))=U means IQ(V(steam))=D, which can cancel the difference in rate. So IQ(P(steam))=IQ(V(steam))=U.

Because the steam touches the water and the container,
P(steam)=P(water)=P(Inside(container))
This means that IQ(P(water))=U, and because physics tells us

T(boil) $\propto$ P(water)

we conclude IQ(T(boil))=U. This means more heat can flow from the source and the boiling can continue at a higher temperature and pressure. Since the same conditions hold for the new temperature and pressure, the increase will be continuous.

How might all of this end? Unless there is some outside factor, either:
1. A(water)=NONE, boiling stops and steam heats up to T(source).
2. T(water)=T(source), boiling stops, thermal equilibrium achieved.
3. P(Inside(container))=P(burst), container explodes!

To actually determine which of these occurs requires more information, but at least we have a warning of potential disaster.

V CONCLUSIONS

In this paper it has been argued that a fairly weak formalization of quantities (partially ordered amounts, IQ values, and rates) and a simple description of physical processes are adequate for useful reasoning about the results and limits of these processes. It is evident that such inferences are a part of understanding common sense physics, so Qualitative Process analysis could be a useful component in programs that *need* to reason about the physical world. Even in programs which have access to more specific knowledge (such as numerical simulations or sensory data) than the very general sort used here might profit from the ability to easily draw conclusions about the qualitatively distinct outcomes of a situation.

A specific application for this kind of analysis is the construction of programs that understand feedback mechanisms in a sophisticated way. When using only IQ analysis (as in (2) and [3]) phenomena such as damped oscillations and stability cannot be expressed or reasoned about. For example, Within QP analysis inertia could be considered as a process spawned by matter in motion, with friction taking the form of an influence which retards the velocity.

It should be clear from the example that writing programs to perform this kind of analysis will not be trivial. While deducing the possible outcomes given a quantity space and the processes which occur is easy, setting up the quantity space and determining which parameters are indirectly affected (such as the boiling temperature being affected by the amount of steam in the example) requires fluent use of the domain physics. This is to be expected. It is hoped that separate consideration of reasoning about the limits of physical processes might make the construction of theories for specific domains easier.

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