Implementing a qualitative reasoner

EECS 344
Winter 2008
Why Qualitative Physics?

• Suppose someone tells you that the level in G is rising, and you want to figure out what could be happening.
Very little information given

- No specific physical properties of the
  - containers
  - pipes
  - liquid
  - initial conditions of the system
- You may not have even seen all the parts
- You don’t have enough information to write differential equations
- You may not even know the differential equations
Yet can still say something

- Probably due to liquid flow
- If the level in F or in H is rising, then the level in the other one must be falling, since it would be the source of both changes.
- Evaporation is pretty unlikely as the cause.

These are common sense inferences, based on *qualitative reasoning* about the physical world.
Qualitative Physics

• Seeks to formalize the intuitive, common sense knowledge, ranging from the person on the street to the intuitions of scientists and engineers.
• Creates representation and reasoning schemes to use that knowledge for a variety of tasks
• Ultimate goals include building artificial engineers, accounts of human mental models, psychological models of reasoning and learning about physical domains
Key Ideas of Qualitative Physics

• Quantize the continuous for symbolic reasoning
  – Example: Represent numbers via signs or ordinal relationships
  – Example: Divide space up into meaningful regions

• Represent partial knowledge about the world
  – Example: Is the melting temperature of aluminum higher than the temperature of an electric stove?
  – Example: “We’re on Rt 66” versus “We’re at Exit 42 on Rt 66”

• Reason with partial knowledge about the world
  – Example: Pulling the kettle off before all the water boils away will prevent it from melting.
  – Example: “We just passed Exit 42, and before that was 41. We should see 43 soon.”
Tom Swift and his Artificial Engineer

Engineering applications have driven most Qualitative reasoning research.
The example, continued

- Ignore probabilities, measurement complexities
- Must know what kinds of things can happen in the world (*physical processes*)
- Must figure out how they can apply to this particular situation (*instantiating them*)
- Must figure out their consequences, to find explanations for the observation (*influence resolution*)
- Simple form of *measurement interpretation*
Qualitative Process Theory

- Ontological Assumptions
- Mathematics
- Causal Account
- Organizing Domain Theories
- Basic Inferences
Ontological Assumptions

• Focus on continuous properties of physical objects
  – mass, heat, temperature, pressure...

• Physical processes provide mechanism of change
  – fluid flow, heat flow, boiling, condensing, motion, ...

• Vocabulary of physical processes is key aspect of a domain theory
Comparing qualitative and traditional mathematics

• Traditional math provides detailed answers
  – Often more detailed than needed
  – Imposes unrealistic input requirements

• Qualitative math provides natural level of detail
  – Allows for partial knowledge
  – Expresses intuition of causality

\[ F = MA \]

*Traditional quantitative version*

\[ A \propto Q^+ F \]

*Qualitative version*
Mathematics of QP theory

• Represent numerical values by ordinal information
  – Quantity space = set of relevant numbers to compare against plus partial ordering information
  – What’s relevant determined by physical processes & similar concepts something participates in

• Key property of quantity: Its $D$s
  – Sign of its derivative indicates direction of change
  – Determines how ordinal relations can change.
Quantity Space

- Value defined in terms of ordinal relationships with other quantities
- Contents dynamically inferred based on distinctions imposed by rest of model
- Can be a partial order
- *Limit points* are values where processes change activation

![Diagram showing Tboil, Tstove, Twater, and Tffreeze]

Tboil → Tstove

Twater

Tffreeze
\[ A[\text{pressure}(W_f)] > A[\text{pressure}(W_g)] \]
\[ Ds[\text{amount-of}(W_f)] = -1 \]
\[ Ds[\text{amount-of}(W_g)] = 1 \]

**Fluid flow from F to G**

**Ends via equilibration**

\[ A[\text{pressure}(W_f)] = A[\text{pressure}(W_g)] \]
\[ Ds[\text{amount-of}(W_f)] = 0 \]
\[ Ds[\text{amount-of}(W_g)] = 0 \]
Expressing algebraic equations

(qprop accel force)
(qprop- accel mass)

• Qualitative proportionalities expresses partial information about functional dependency
• acceleration is increasing monotonic in its dependence on force
• acceleration is decreasing monotonic in its dependence on mass
• Use closed-world assumptions to define functions.
Qualitative proportionalities

• Examples
  – (qprop (T ?o) (heat ?o))
  – (qprop- (acceleration ?o) (mass ?o))

• Semantics of (qprop A B)
  – \( \exists f \text{ s.t. } A = f(\ldots, B,\ldots) \land f \text{ is increasing monotonic in } B \)
  – For qprop-, decreasing monotonic
  – B is a causal antecedent of A

• Implications
  – Weakest causal connection that can propagate sign information
  – Partial information about dependency requires closed world assumption for reasoning
Expressing Differential Equations

\[(I+ (amount-of Wg) (inflow G))\]
\[(I- (amount-of Wg) (outflow G))\]

means

\[D[(amount-of Wg)] = (inflow G) - (outflow G)\]

- \(I+, I-\) called *direct influences*
- More information than qualitative proportionalities
- Provides integration operator
Semantics of direct influences

• $I^+(A,b) \equiv D[A] = \ldots + b + \ldots$

• $I^-(A,b) \equiv D[A] = \ldots - b + \ldots$

• Direct influences combine via addition
  – Information about relative rates can disambiguate
  – Abstract nature of qprop $\Rightarrow$ no loss of generality in expressing qualitative ODE’s

• Direct influences only occur in physical processes (sole mechanism assumption)

• Closed-world assumption needed to determine change
Qualitative Mathematics

• Any ordinary differential equation can be expressed by combinations of qualitative proportionalities and direct influences
  – Including non-linear equations!
• Each qualitative equation stands for a large class of quantitative equations
• Can reason with partial knowledge
  – don’t need to know specific equations
  – don’t need to know everything a parameter depends on
• There are costs
  – Often qualitative reasoning is ambiguous
  – Ambiguities indicate where more precise knowledge is required
Causality in QP theory

- All causal changes stem from physical processes
- Changes propagate from quantities directly influenced by processes through causal laws to indirectly influenced quantities
- Naturally models human reasoning in many domains (i.e., fluids, heat, motion...)

Liquid Flow

\[ F \rightarrow G \]
Organizing Domain Theories

• Domain theory = collection of general knowledge about some area that can be used to model a wide variety of systems for multiple tasks.

• Scenario model = a model of a particular situation, built for a particular purpose, out of fragments from the domain model.
Model fragments contain applicability information

(defview (Contained-Stuff (C-S ?sub ?st ?can)))
 :individuals ((?can (container ?can)
 (substance ?sub)
 (phase ?st)))
 :quantity-conditions
  ((> (A (amount-of ?sub ?st ?can)) ZERO))
 :relations
  ((only-during (exists (C-S ?sub ?st ?can)))
   (quantity (TBoil (C-S ?sub ?st ?can)))
   (> (A (Tboil (C-S ?sub ?st ?can))) ZERO)))
A Physical Process

(defprocess (heat-flow ?src ?path ?dst)
  :individuals ((?src (quantity (heat ?src)))
                 (?path (heat-connection ?path ?src ?dst))
                 (?dst (quantity (heat ?dst))))
  :preconditions ((heat-aligned ?path))
  :quantity-conditions
  ((> (A (temperature ?src)) (A (temperature ?dst))))
  :relations
  ((quantity (flow-rate ?self))
   (> (A (flow-rate ?self)) ZERO)
   (qprop (flow-rate ?self) (temperature ?src))
   (qprop- (flow-rate ?self) (temperature ?dst)))
  :influences ((I- (heat ?src) (flow-rate ?self))
               (I+ (heat ?dst) (flow-rate ?self))))
Compositional Modeling

(defview (heat-flow-thermal-conductance ?hf)
  :individuals ((?hf (process-instance
                      (heat-flow ?src ?path ?dst))
                     (consider
                      (thermal-conductance ?path))))
  :quantity-conditions ((active ?hf))
  :relations ((Qprop (flow-rate ?hf)
                     (thermal-conductance ?path))))

• Add detail as necessary by composing simple model fragments
• Automate model building by including explicit modeling assumptions
Basic inferences of QP theory

1. Finding process and view instances
   - “What phenomena might be relevant?”

2. Determining activity
   - “What’s happening?”

3. Influence resolution
   - “What’s changing?”

4. Limit Analysis
   - “What might happen next?”
Finding process and view instances

Figure out how the model fragments in the domain theory can be instantiated given the structural description

• Introduces new conceptual entities
• New entities can themselves participate in other entities
Example

Three possible contained stuffs, four potential fluid flows

F — G — H
Determining Activity

- Evaluate preconditions and quantity conditions to figure out which processes and views are active.
- All changes are ultimately caused by active processes
Example

If pressure in G is higher than in F and H, and both paths are aligned, water will flow out of G.
Influence Resolution

• Combine effects of direct influences to figure out net change
• Propagate through qualitative proportionalities
• Can be ambiguous
• Resolve ambiguities by
  – adding extra information
  – exploring all possibilities
  – adding assumptions
Example

Net effect on G unknown, unless we assume something about relative flow rates.
Time and change

- Time individuated by changes in qualitative state

- Qualitative states differentiated by
  - Set of active physical processes
  - What dynamic relationships hold
  - Quantity space values

Spring state

Block velocity
Limit Analysis

• Using derivatives, figure out how set of ordinal relations can change.
• Result are possible changes in active processes, existence of individuals
• Often ambiguous
  – multiple changes
  – relative rates/distances unknown
• Requires taking continuity into account
• Illustrates a good solution to the frame problem
Qualitative Simulation

• For initial state
  – Find view and process instances
  – Determine activity
  – Resolve influences
  – Perform limit analysis

• For each next state, treat as initial state
• Continue until no new states

*Envisioning:* Qualitative simulation from each possible initial state
Qualitative states and transitions

Many dynamical properties of systems can be reasoned about based on topological properties of qualitative state graphs.
Measurement Interpretation

Find possible views and processes
Perform a dependency-directed search over possible process structures
  – Resolve influences for each combination.
  – If ambiguous influences, search all possibilities.
  – If state satisfies measurements, record

Return as answer the set of recorded states
Example

```
F  G  H  F  G  H  F  G  H  F  G  H  F  G  H  F  G  H

F  G  H  F  G  H

F  G  H  F  G  H

F  G  H  F  G  H
```

Stars: ✪ ✪
TGIZMO: A partial implementation of QP theory

• Doesn’t do limit analysis
• Does everything else
• Includes “one look” measurement interpretation algorithm
• Most complex system in the book
Organization of TGIZMO

Next time!