An Introduction to Qualitative Modeling

Kenneth D. Forbus
Qualitative Reasoning Group
Northwestern University

Overview

- Why qualitative reasoning?
- Principles of qualitative representation and reasoning
  - Some successful applications
  - How qualitative modeling links to other knowledge
- Tutorial on qualitative dynamics
  - Overview of Qualitative Process theory
  - Qualitative mathematics
  - Qualitative reasoning: Overview

What is qualitative physics?

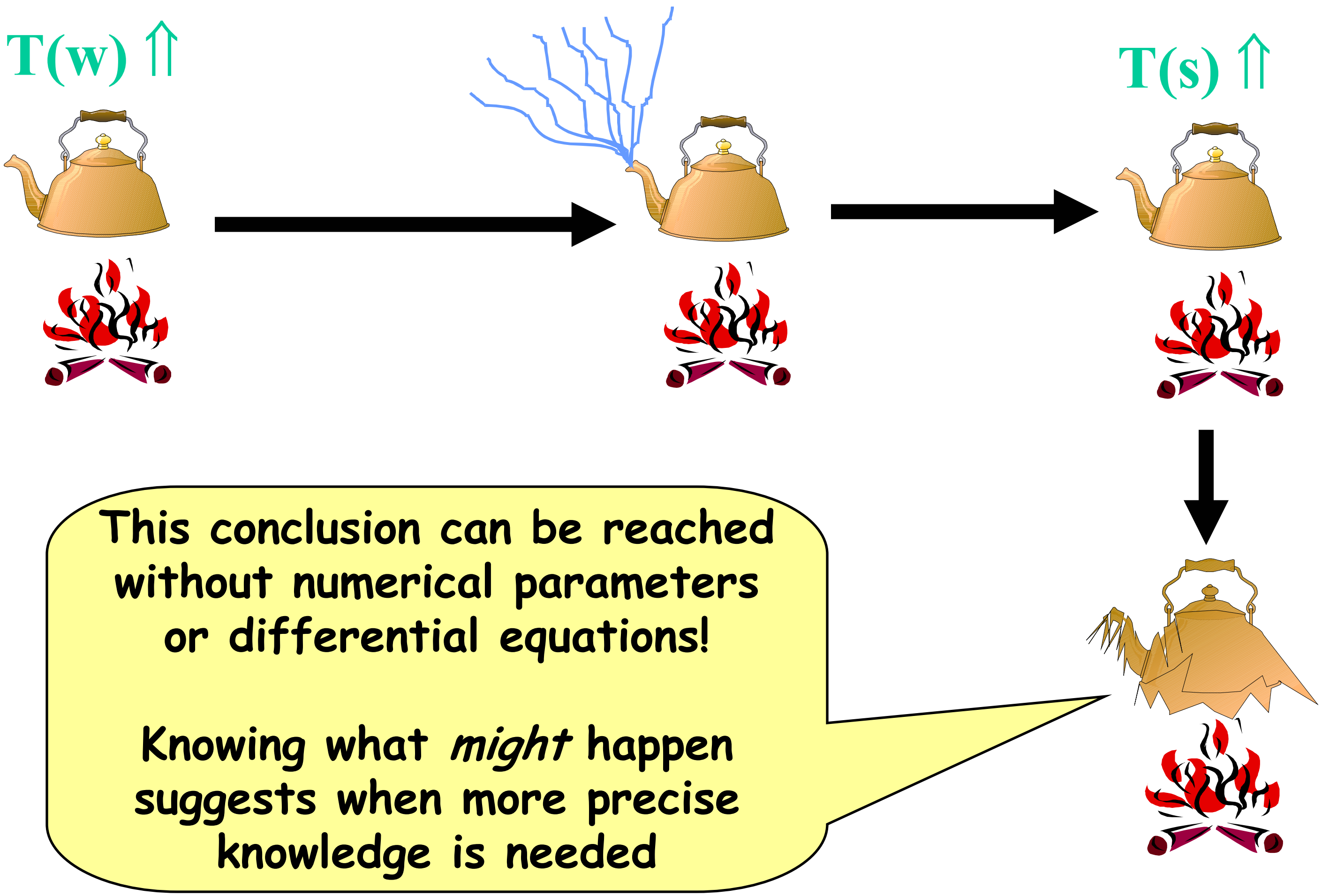
- Formalizing the intuitive knowledge of the physical world
  - From person on the street to expert scientists and engineers
- Developing reasoning methods that use such knowledge for interesting tasks.
- Developing computational models of human commonsense reasoning

Example

- What can happen when you leave a tea kettle on a stove unattended for an hour?

Example

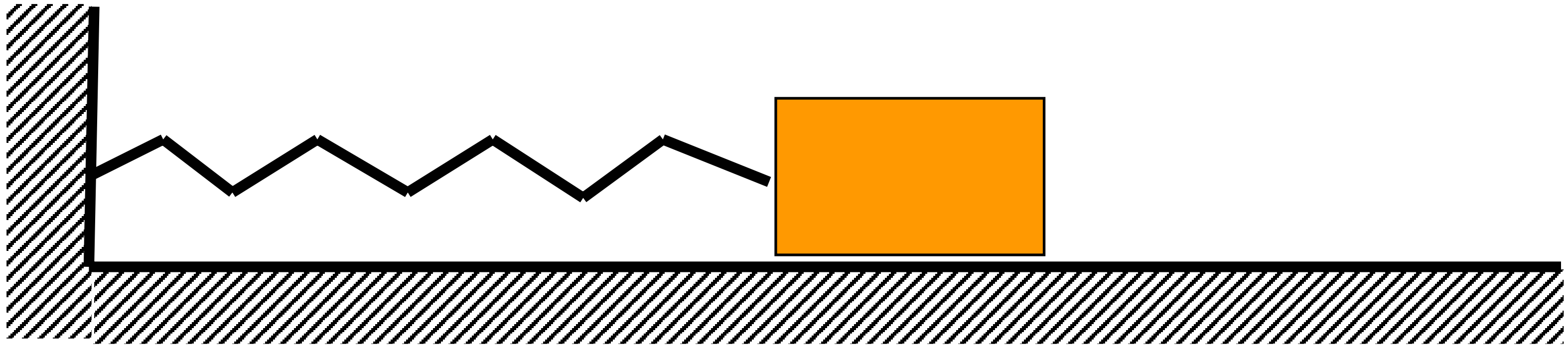
- What can happen when you leave a tea kettle on a stove unattended for an hour?



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.”

What will this system do?

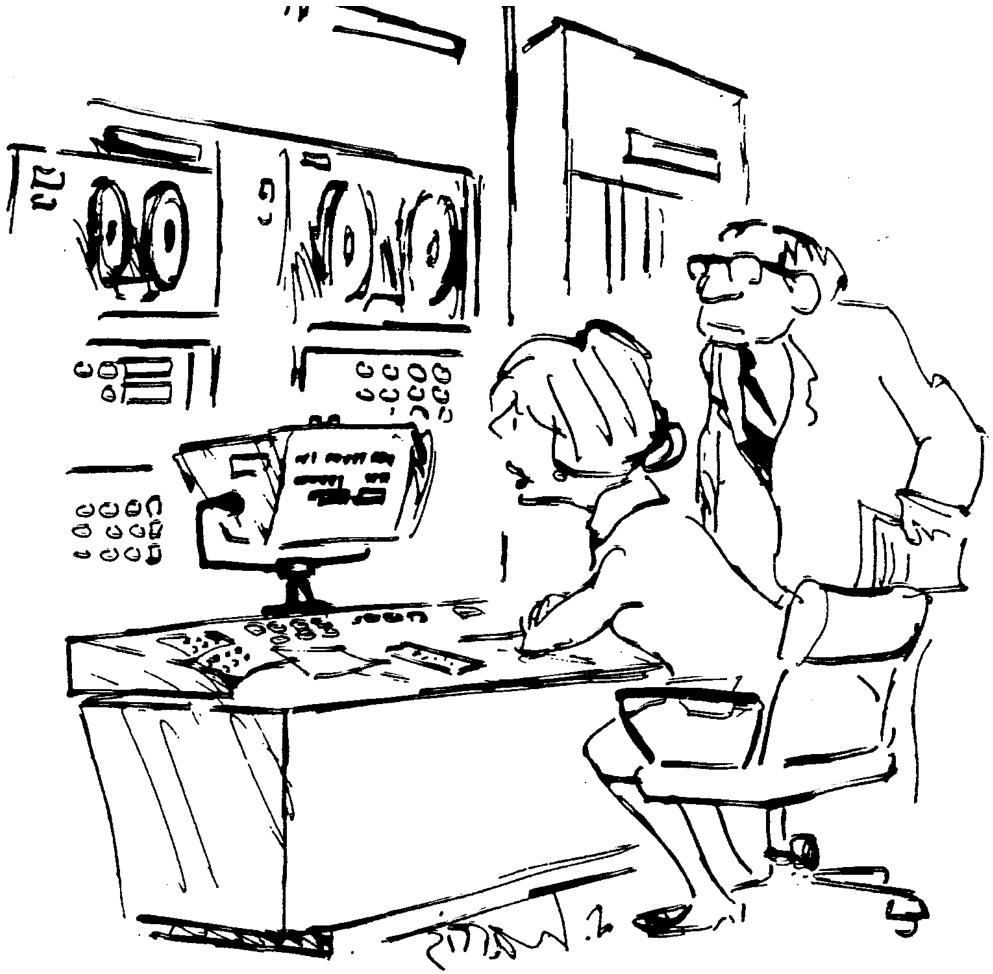


Example

- Suppose we have two identical ice cube trays.
  One tray is filled with cold tap water.
  The other tray is filled with warm tap water.
  We place both trays in a freezer at the same time.
  Q: Which will freeze first, the warmer water or the cooler water? And why?

Why do qualitative physics?

- Understanding how minds work
  - What do people know? Physical, social, and mental worlds.
  - Universal, but with broad ranges of expertise
    - Unlike vision, which is automatic
    - Unlike medical diagnosis

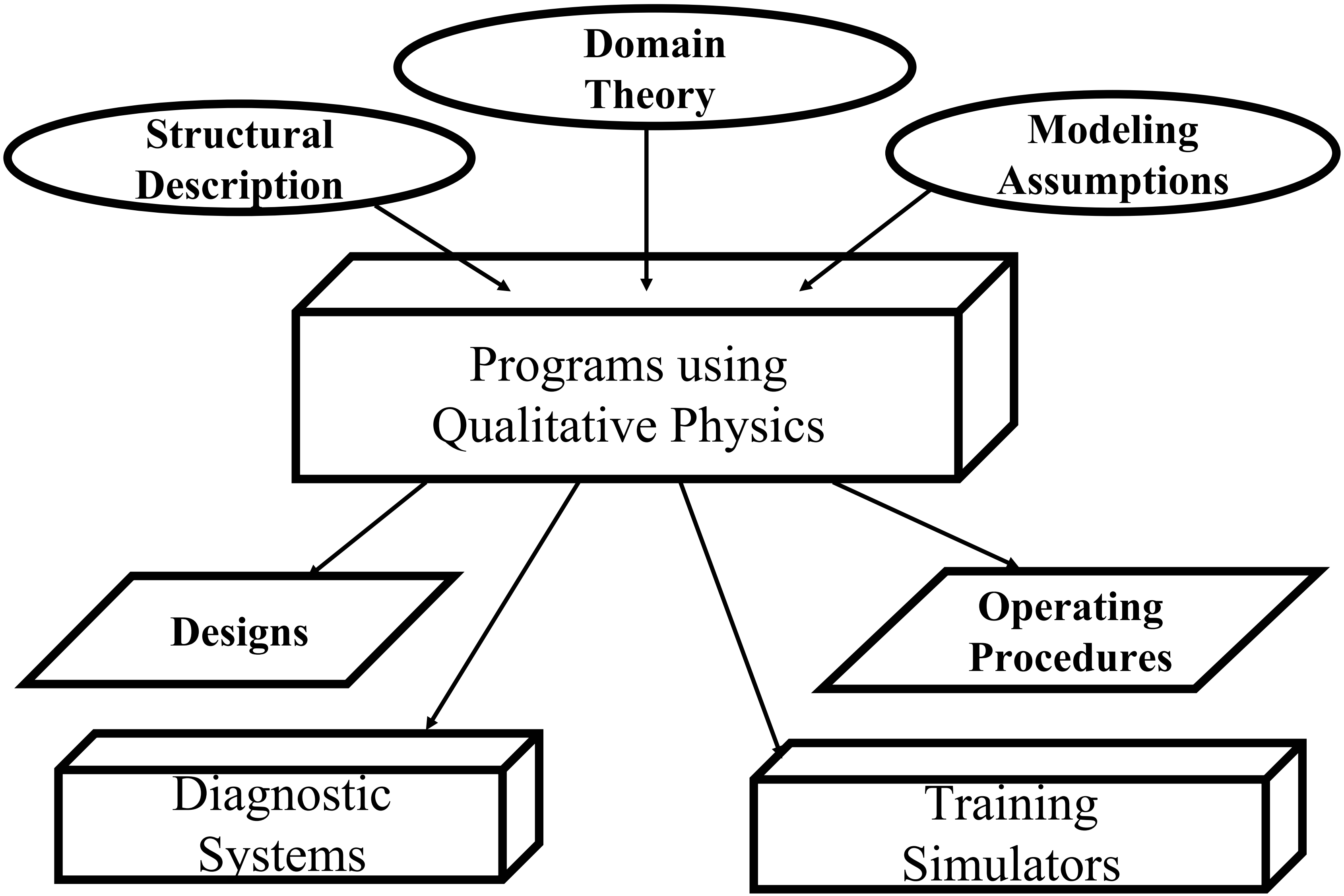


“It says it’s sick of doing things like inventories and payrolls, and it wants to make some breakthroughs in astrophysics

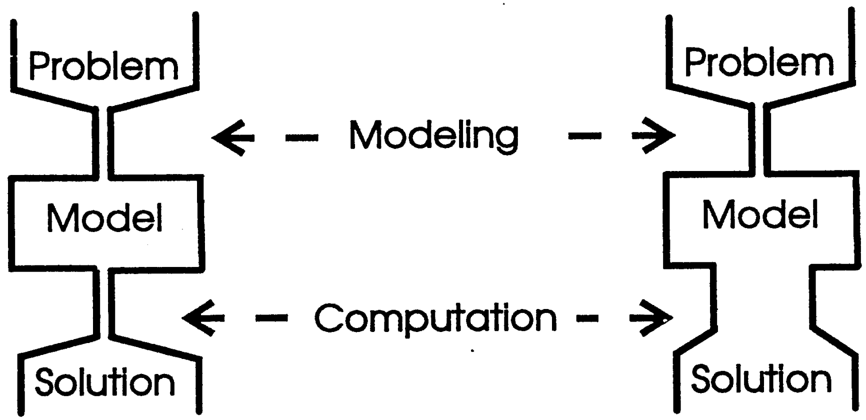
Why do qualitative physics?

- Can build useful software and systems
  - Intelligent tutoring systems and learning environments
  - Engineering Problem Solving
    - Diagnosis/Troubleshooting
    - Monitoring
    - Design
    - Failure Modes and Effects Analysis (FMEA)
  - Robots
  - Models for understanding analogies and metaphors
    - "Ricki blew up at Lucy"

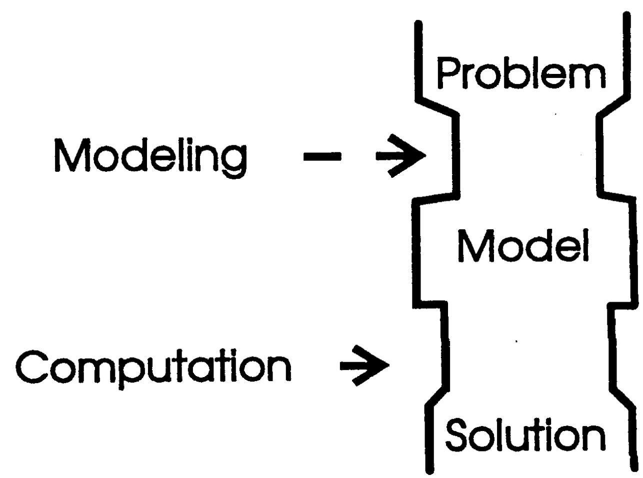
The Qualitative Physics Vision



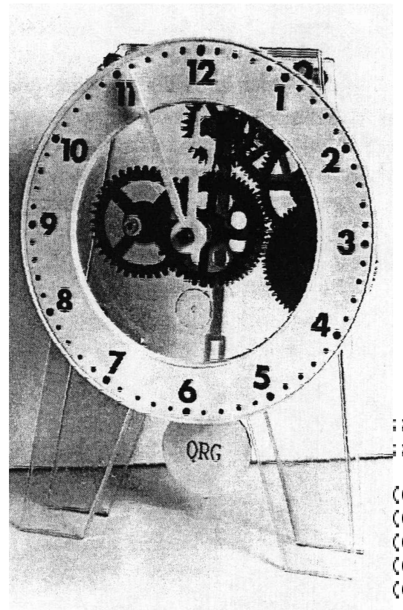
Effect of Digital Computing on Engineering Problem Solving

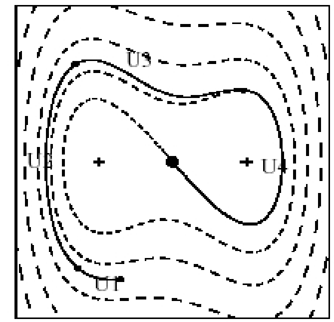


Desired effect of Qualitative Physics on Engineering Problem Solving



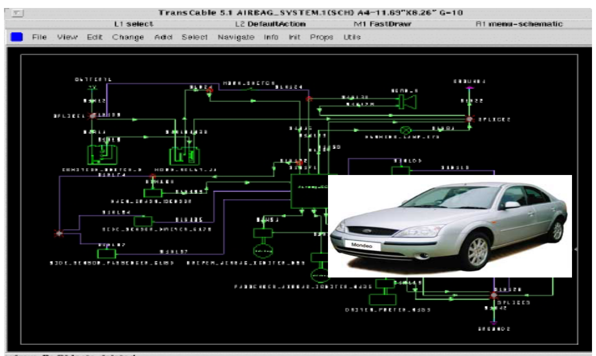
Human-like understanding of complex systems requires qualitative models



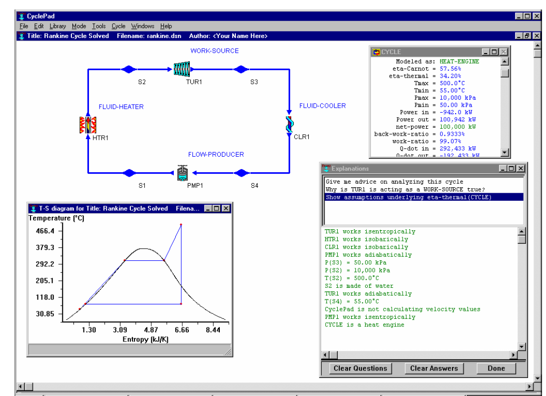



```
;; The Synthesized Control Law specifying the time instance, switching
;; state, and corresponding control value for each switching:

((time 0.) (switching-state #(-1 -3)) (control .2))
((time .284) (switching-state #(-1.82 -2.71)) (control 0.))
((time 1.06) (switching-state #(-1.86 2.49)) (control -.2))
((time 2.71) (switching-state #(1.35 1.82)) (control 0.))
((time 6.76) (switching-state #(-.0023 -.0692)) (control *local-control*))
```

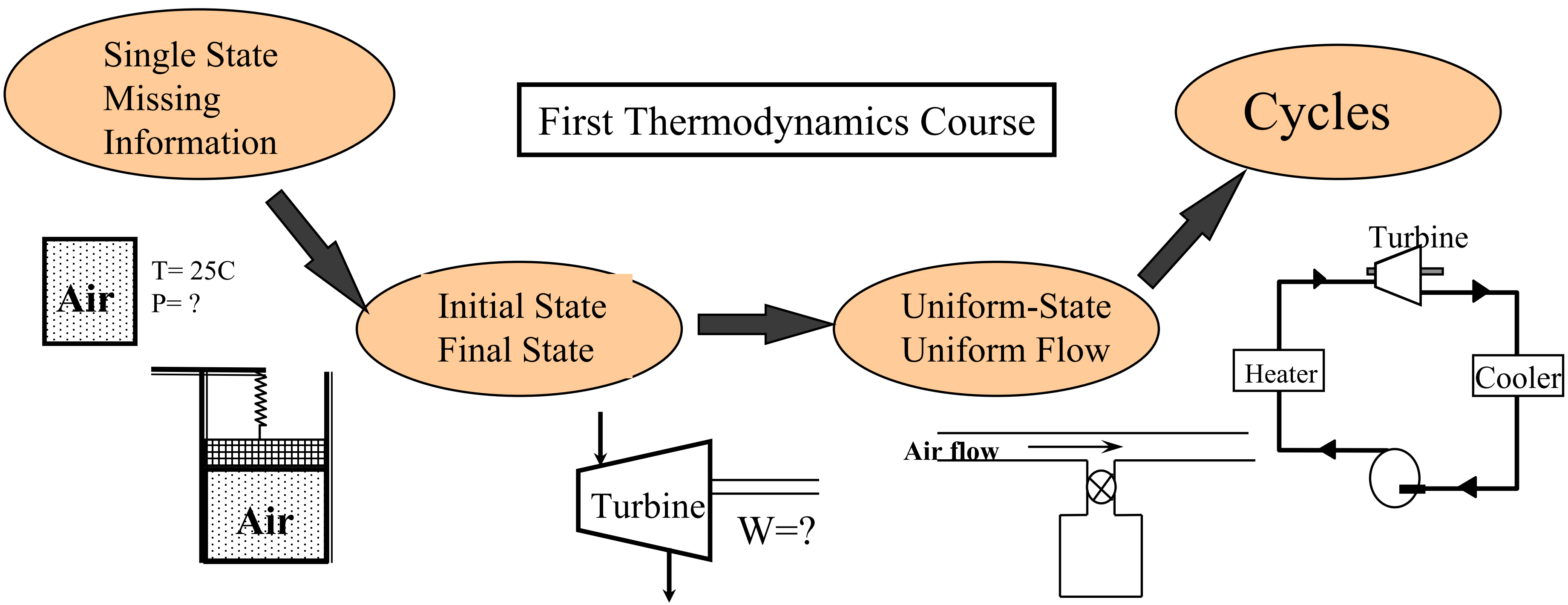


Monitoring, diagnosis,
failure modes and effects analysis,
creating control software,
explanation generation,
tutoring…



Engineering Analysis

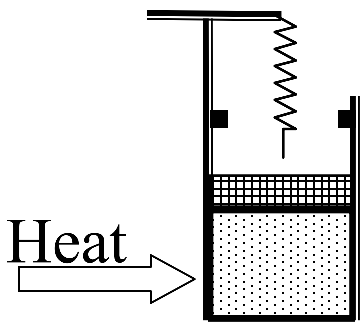
- Important in understanding engineering, scientific reasoning
- Useful model: Solving textbook problems



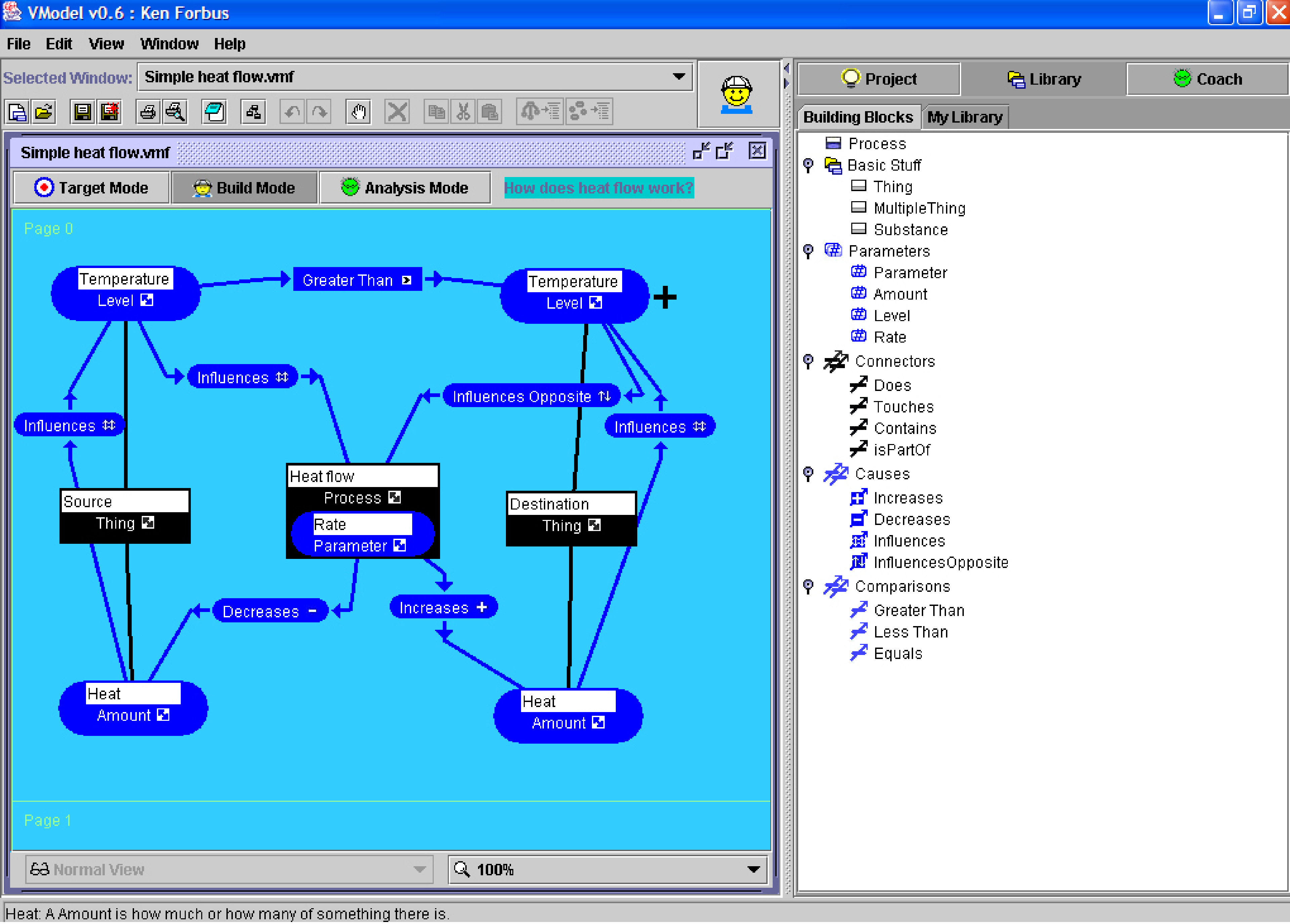
Yusuf Pisan's (1998) Thermodynamics Problem Solver

- Broad coverage: Over 100 problems, of multiple types
  - Previous systems: Isaac: ~15 Physics problems; Fermi: ~25 problems, 3 types; Cascade: ~25 Physics problems
  - Covers most types of problems found in thermodynamics texts
- Produces solutions similar to those of experts
  - Several sources of control knowledge:
    - Qualitative knowledge identifies relevant phenomena, assumptions
    - Analysis of structure of domain principles and equations identifies appropriate suggestions for use
    - Plans express domain-specific task knowledge

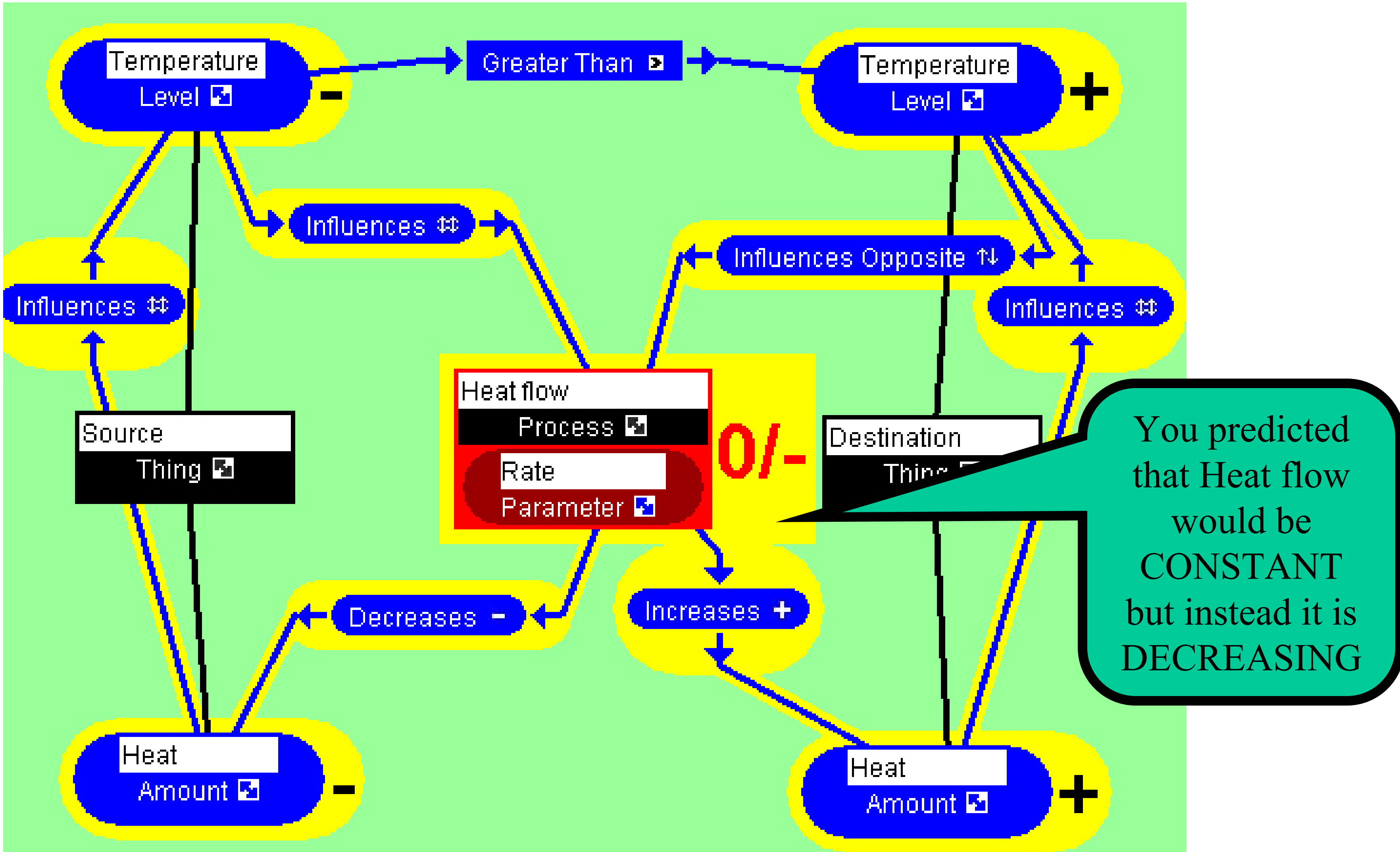
Qualitative reasoning in engineering analysis: Example



- No mass flows in or out of the system
- Volume can increase until stop is reached
- Spring force will add to air pressure when it contacts the top
- The temperature will rise, or stay the same if saturated


VModel v0.6 : Ken Forbus
File Edit View Window Help
Selected Window: Simple heat flow.vmf
Project
Library
Coach
Building Blocks
My Library
Process
Basic Stuff
Thing
MultipleThing
Substance
Parameters
Parameter
Amount
Level
Rate
Connectors
Does
Touches
Contains
isPartOf
Causes
Increases
Decreases
Influences
InfluencesOpposite
Comparisons
Greater Than
Less Than
Equals
Simple heat flow.vmf
Target Mode
Build Mode
Analysis Mode
How does heat flow work?
Page 0
Temperature
Level
Greater Than
Temperature
Level
Influences
Influences Opposite
Influences
Influences
Heat flow
Process
Rate
Parameter
Source
Thing
Destination
Thing
Decreases
Increases
Heat
Amount
Heat
Amount
Page 1
Normal View
100%
Heat: A Amount is how much or how many of something there is.

Qualitative simulation used to check student predictions

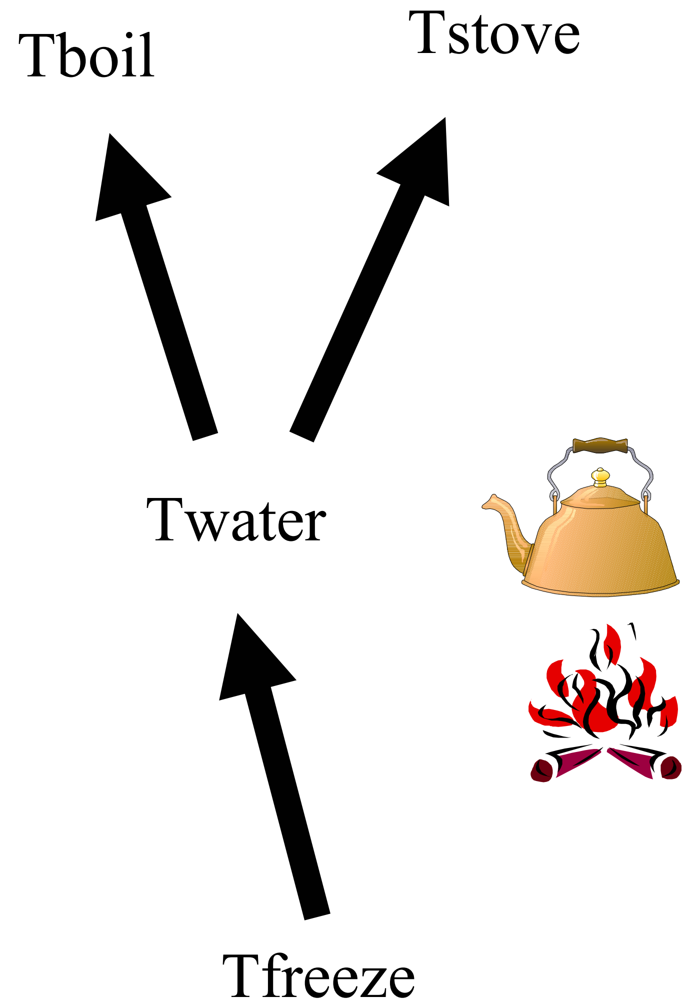


Qualitative Process Theory

- Key ideas (Forbus, 1981, 1984):
  - *Quantity space:* Representation of numerical values via ordinal relations
    "it's just above freezing"
  - *Influences:* Causal, qualitative relationships between parameters
    - *Qualitative proportionalities* ($\propto_{Q+}$, $\propto_{Q-}$): partial functions
      "the bigger the heavier"
    - *Direct influences* (**I+**, **I-**): Constraints on derivatives
      "The flow from the faucet increases the water in the tub"
  - *Physical processes:* Mechanism for physical changes.
    "Water is leaking from the radiator"

Quantity Space

- Value defined in terms of ordinal relationships
- Can be a partial order
- *Limit points* = values where processes change
- Relevant comparisons inferred dynamically



Qualitative proportionalities

- Examples
  - **`(qprop (Temperature ?o) (heat ?o))`**
  - **`(qprop- (acceleration ?o) (mass ?o))`**
- Semantics of **`(qprop A B)`**
  - $\exists$**`f`** s.t. **`A = f(`**…**`,B,`**…**`)`** $\wedge$ **`f`** is increasing monotonic in **`B`**
  - For **`qprop-`**, decreasing monotonic
  - **`B`** is a causal antecedent of **`A`**
- Properties
  - Provides partial information about dependency
  - Weakest causal connection that can propagate sign information
  - Closed world assumption used in reasoning

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

$$\mathbf{F = MA}$$

Traditional quantitative version

$$\mathbf{A \propto_{Q+} F}$$

$$\mathbf{A \propto_{Q-} M}$$

Qualitative version

Direct influences

- Examples
  - **`(I+ (amountOf bathwater) (rate inflow))`**
  - **`(I- (amountOf bathwater) (rate outflow))`**
- Semantics of direct influences
  - **I+(A,b)** ≡ **D[A]=**…**+b+**…
  - **I-(A,b)** ≡ **D[A]=**…**-b+**…
  - Information about relative rates can disambiguate conflicts
- Properties
  - Closed-world assumption needed to determine change
  - Abstract nature of qprop ⇒ no loss of generality in expressing ordinary differential equations qualitatively

Model Fragments

- Pieces of knowledge which are instantiated and assembled to form a model of a situation
- Encode conditions under which domain knowledge is relevant
- Parts of a model fragment:
  - *Participants* are the individuals and relationships that must hold before it makes sense to think about it
  - *Conditions* must be true for it to hold (i.e., be *active*)
  - *Consequences* are the direct implications of it being active.
-
```
(defmodelFragment saturated
 :participants ((am :type air-mass))
 :conditions ((= (relative-humidity am)
                 100-percent)
 :consequences ((saturated am)))
```

Example: Physical Processes

- A kind of model fragment
- But also has *direct influences*, which are constraints on derivatives
- Examples:
  - "Most water [in the air] comes from evaporation. When the sun heats the liquid water in the earth's oceans, lakes, and rivers, some of it changes into water vapor and rises into the air"
  - **`(I+ (water-vapor am) (rate evap))`**
    `(I- (amount-of water-body) (rate evap))`
  - N.B. accumulating bodies of water into an abstract entity, based on shared properties. This is a *transfer* pattern of influences.

Physical process example

```
(defModelFragment heat-flow
 :subclass-of (physical-process)
 :participants ((the-src :type thermal-physob)
                (the-dst :type thermal-physob)
                (the-path :type heat-path
                  :constraints
                   ((heat-connection
                      the-path the-src the-dst))))
 :conditions ((heat-aligned the-path)
              (> (temperature the-src)
                 (temperature the-dst)))
 :quantities ((heat-flow-rate :type heat-flow-rate))
 :consequences ((Q= heat-flow-rate
                   (- (temperature the-src)
                      (temperature the-dst)))
                (I- (heat the-src) heat-flow-rate)
                (I+ (heat the-dst) heat-flow-rate)))
```

Participants

```
:participants ((the-src :type thermal-physob)
               (the-dst :type thermal-physob)
               (the-path :type heat-path
                 :constraints
                  ((heat-connection
                     the-path the-src
                              the-dst))))
```

- Provides sufficient conditions for an instance of the process to exist
  - Computationally, enough evidence to warrant instantiation
- Constraint information customarily assumed to be true across a reasoning session
  - But reasoners should be sensitive to this assumption being violated

Conditions

```
:conditions ((heat-aligned the-path)
             (> (temperature the-src)
                (temperature the-dst)))
```

- Determines whether or not a model fragment is *active*
- Can be thought of as two types:
  - *Preconditions* involve external changes
  - *Quantity conditions* involve changes predictable from the domain theory
- Conditions can change as behavior evolves
  - Quantity conditions can change due to dynamic effects
  - Preconditions can change based on actions, other effects external to the qualitative physics

Consequences

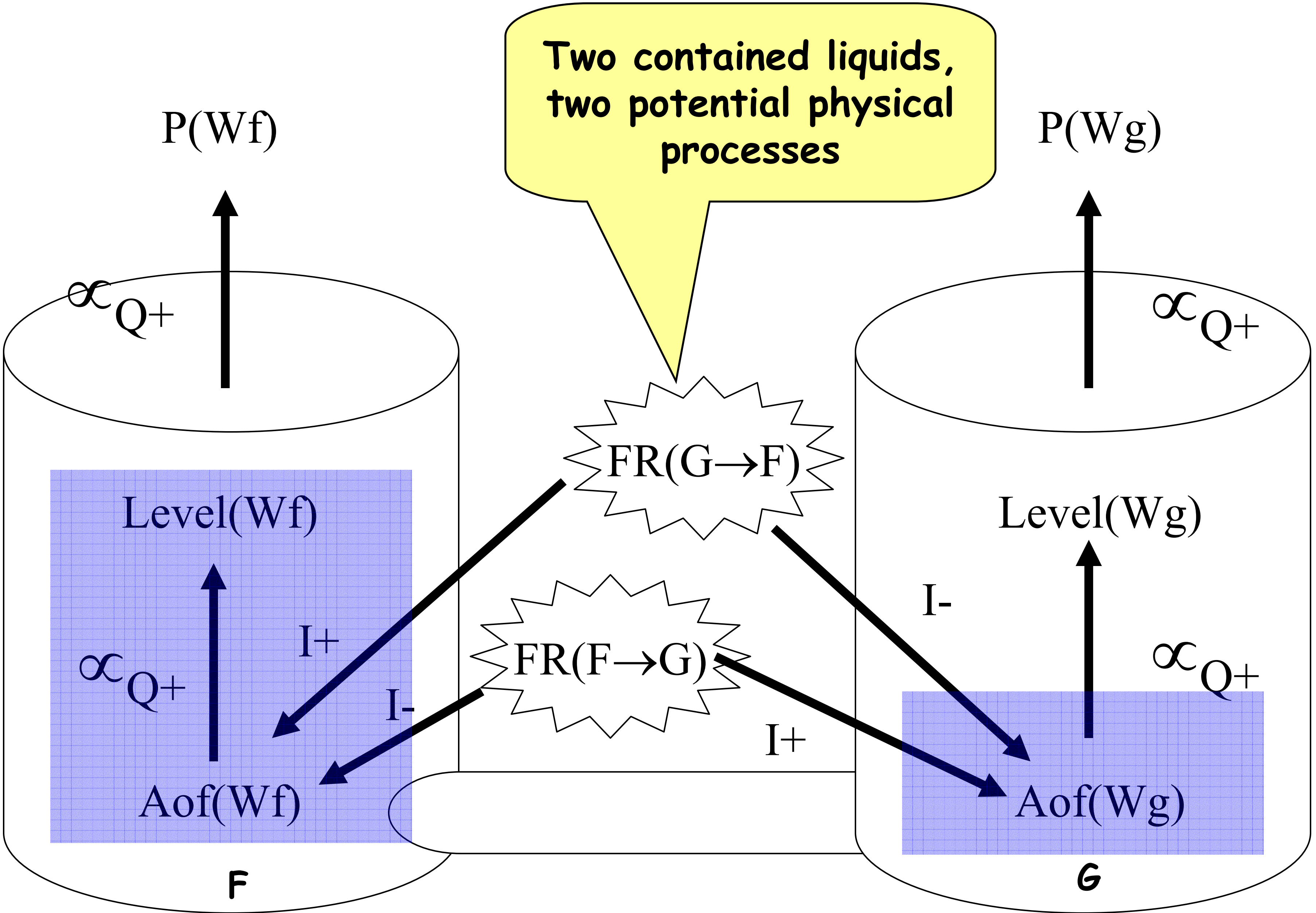
```
:quantities ((heat-flow-rate
                  :type heat-flow-rate))
:consequences ((Q= heat-flow-rate
    (- (temperature the-src)
       (temperature the-dst)))
    (I- (heat the-src) heat-flow-rate)
    (I+ (heat the-dst) heat-flow-rate)))
```

- Entities and relationships that are necessary consequences of the model fragment being active
- Provides inferential "hooks" to other theories
- Different implementations support special-purpose extensions
  - e.g., Q= ≡ appropriate qprop+, qprop-, and correspondence.

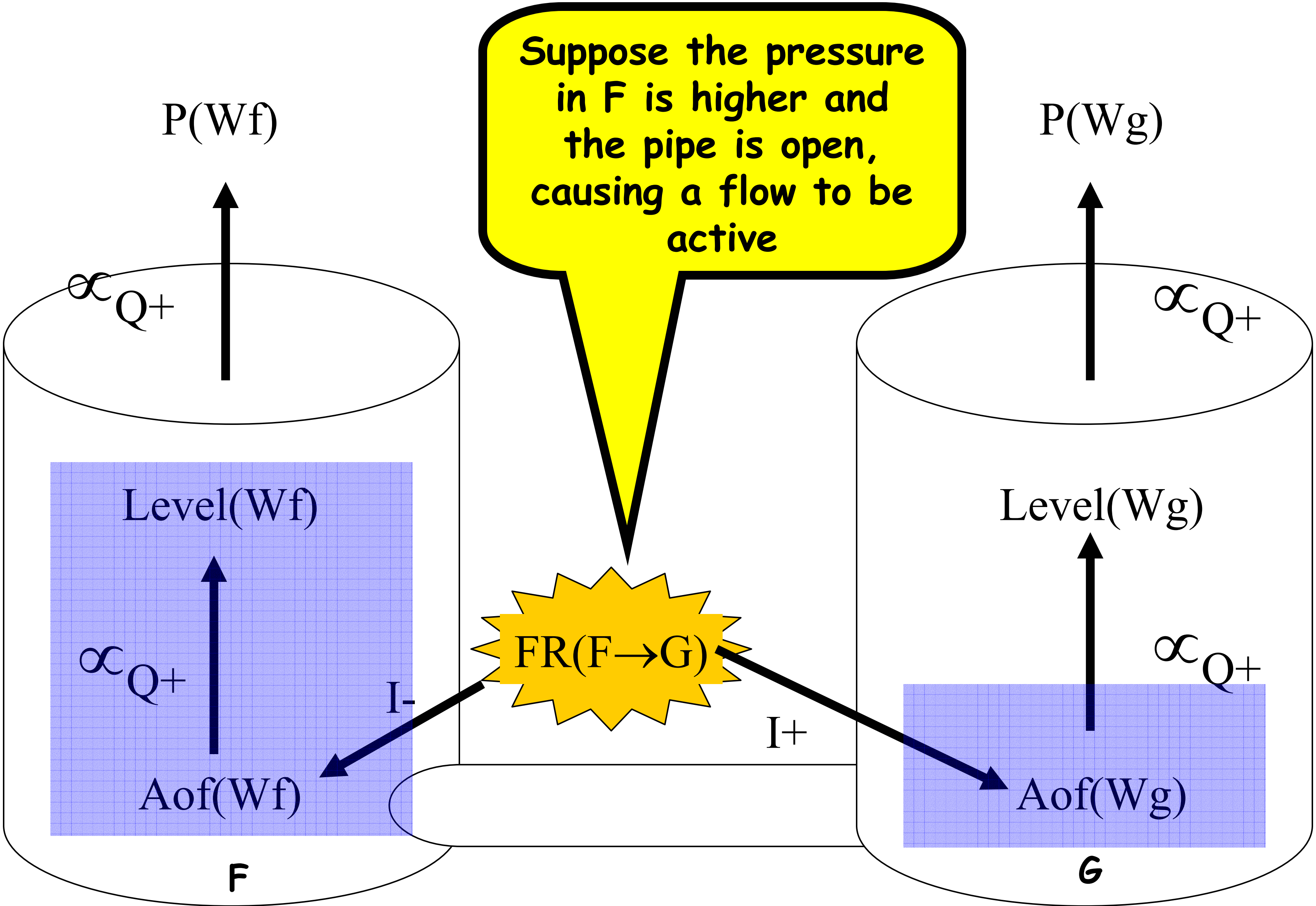
Causality in Qualitative Process theory

- All causal changes stem from *physical processes*
- Changes propagate from quantities directly influenced by processes through causal laws to other quantities
- Naturally models human causal reasoning in many domains (i.e., fluids, heat, motion…)
  - Different causal model needed for electronics (cf. Forbus & Gentner, 1986)

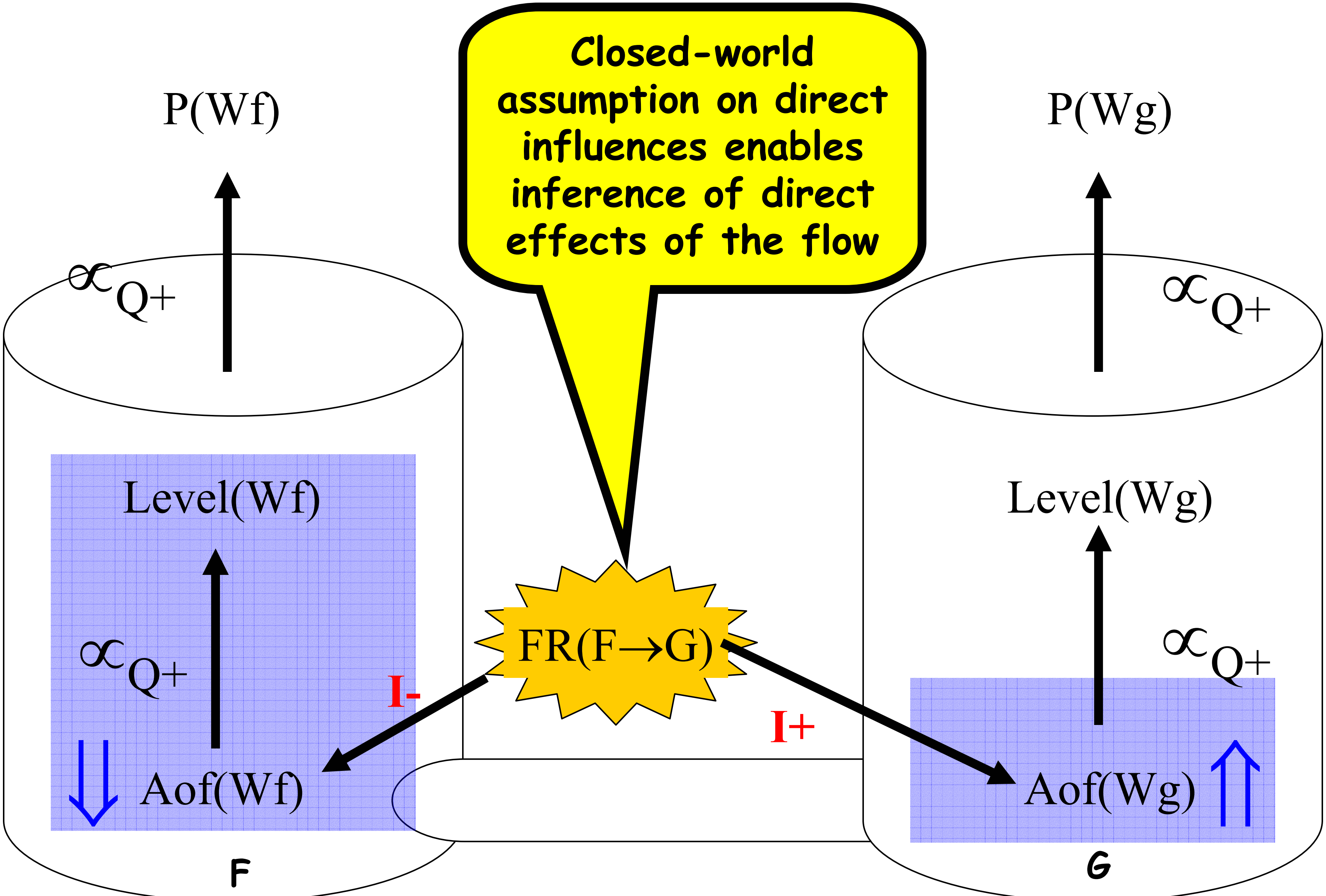
Example of causal reasoning



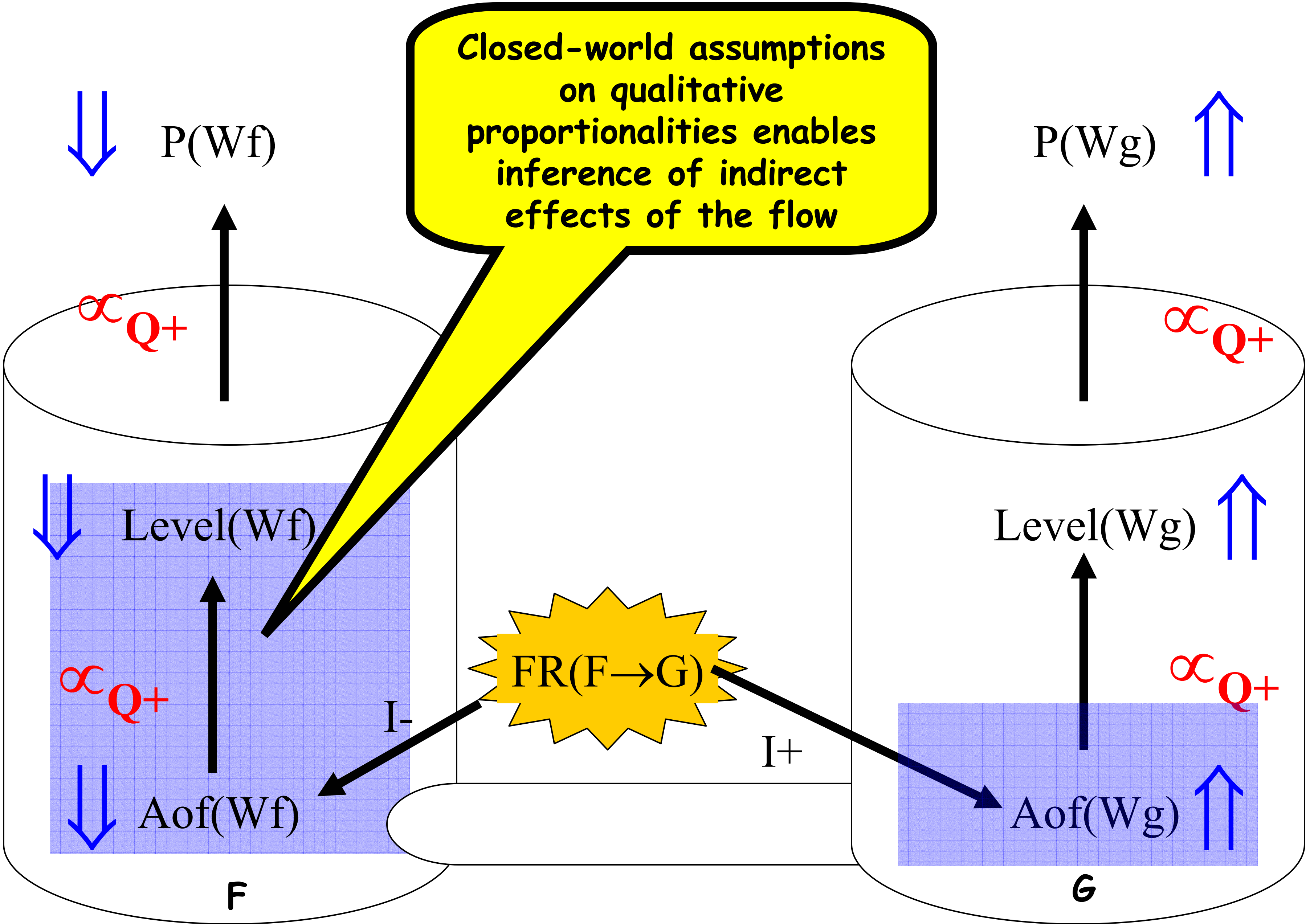
Physical processes ground causality



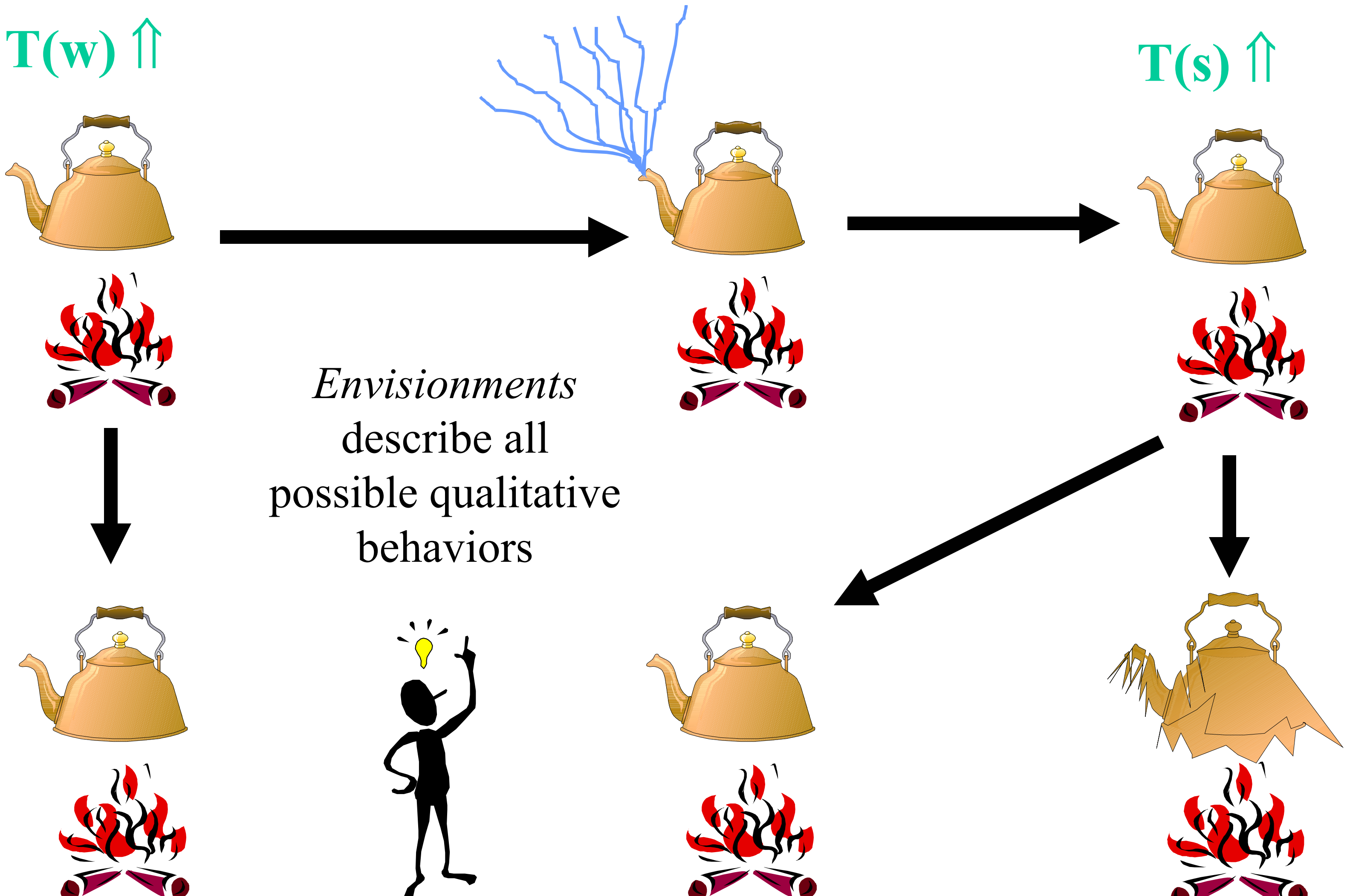
Direct influences cause changes in parameters



Direct effects propagated via qualitative proportionalities

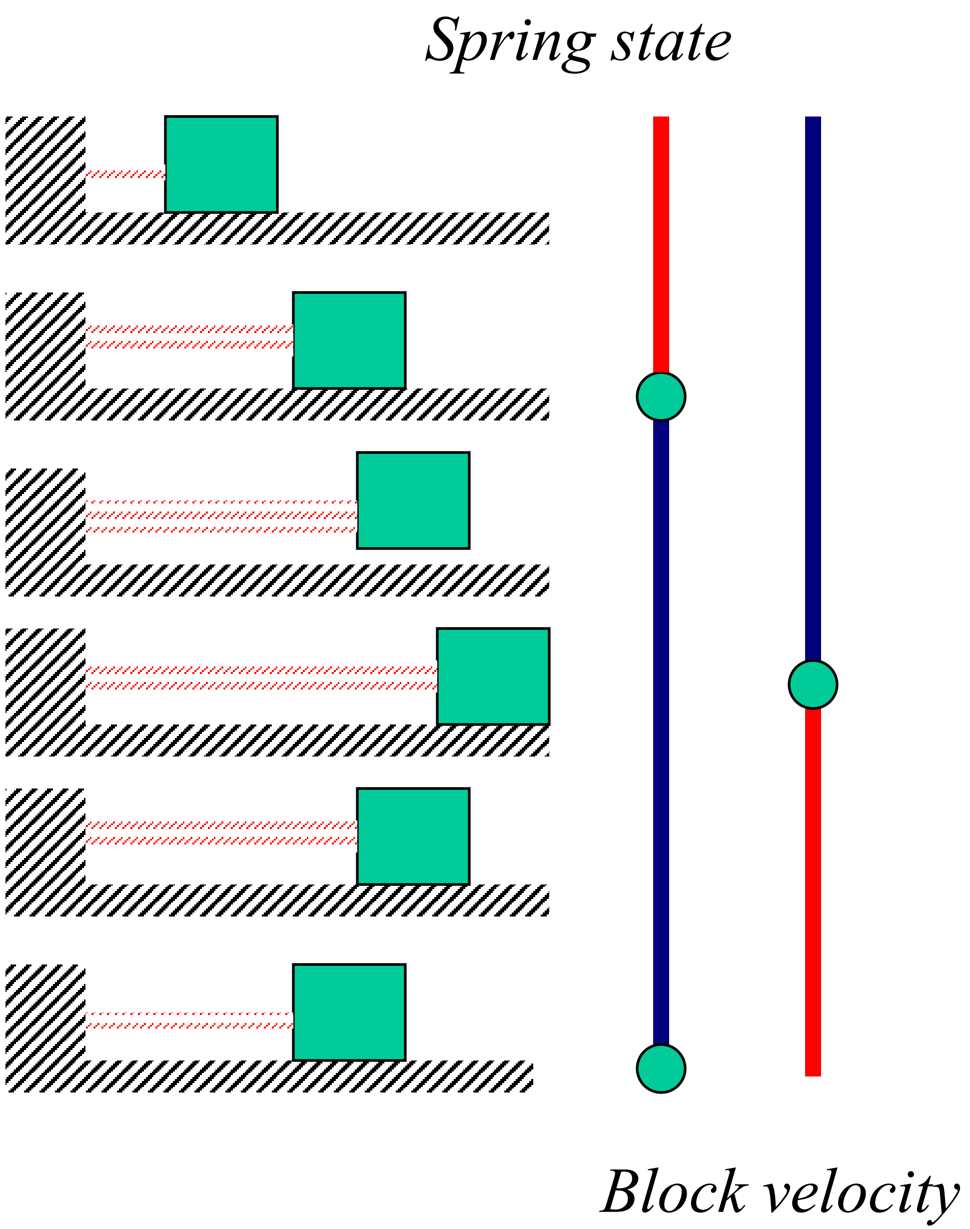


Partial knowledge ⇒ Ambiguity



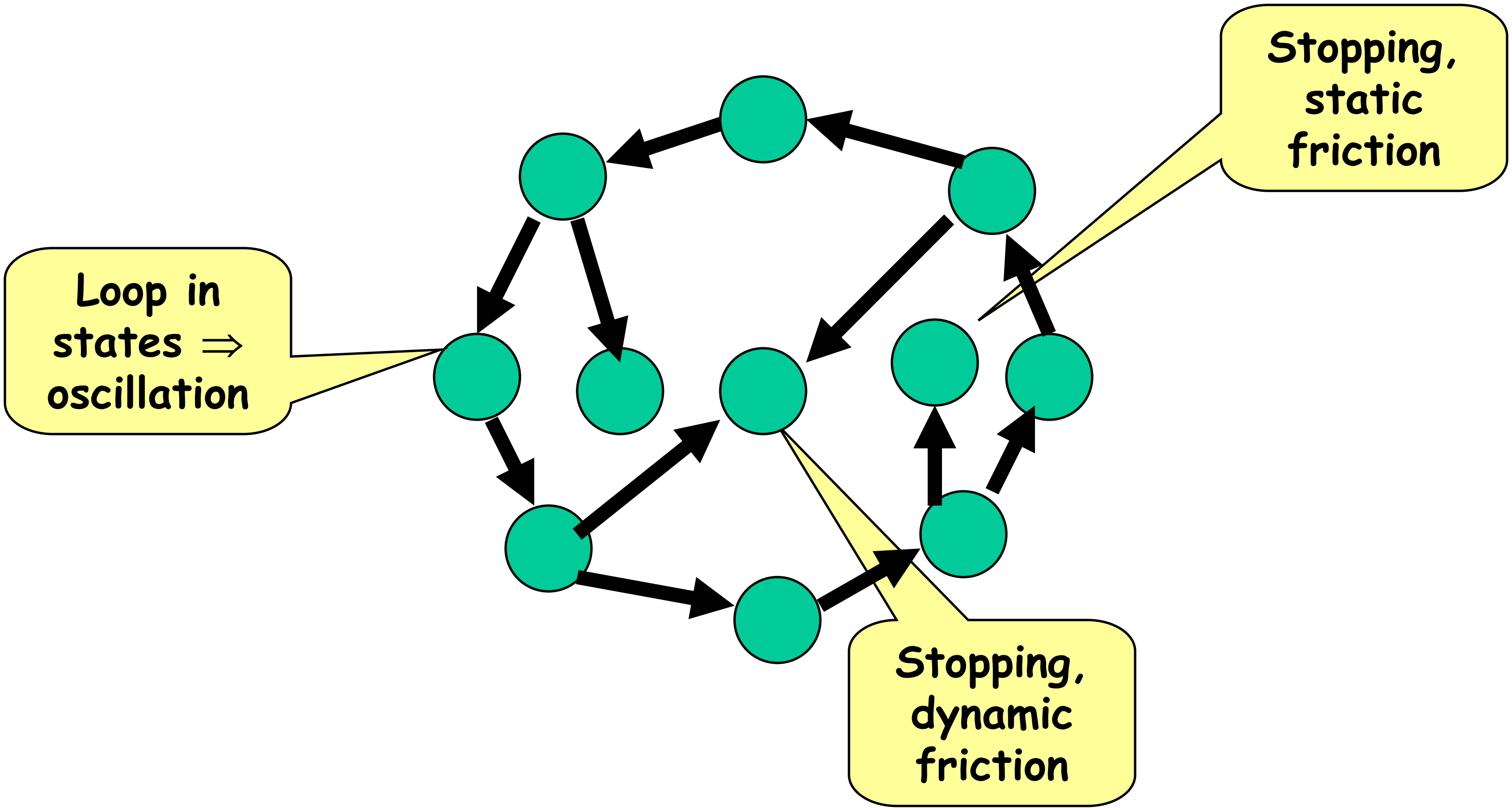
Time and change

- Time individuated by changes in qualitative state
- Qualitative states differentiated by
  - Set of active physical processes
  - What dynamic relationships hold
  - Quantity space values
- Similar to event structure in language
  - Both carve continuous change into symbolic, meaningful chunks
  - QR suggests fine-grained decomposition on physical grounds
  - NL includes non-physical decompositions



Qualitative states and transitions

Many dynamical properties of systems
can be reasoned about based on
graph properties of envisionments

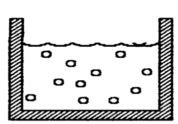


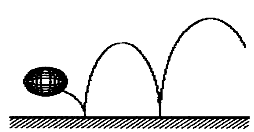
Other approaches to Qualitative Modeling

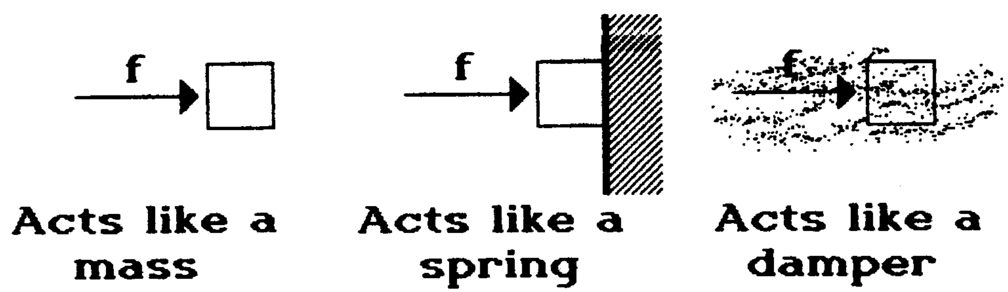
- Use qualitative mathematics directly
  - e.g., Kuiper's QSIM
  - Advantages:
    - Simple
    - Can build exactly the right model for the situation
  - Drawbacks
    - Models can be ad hoc, each task requires a new model
    - None of the skill of model-building is captured in the formalism

Other Approaches, continued

- Component-based ontology
  - e.g., de Kleer & Brown's *confluence* based qualitative physics, Price *et al* models of automobile electronics
  - Advantages
    - Natural for some domains, e.g., analog electronics
    - Direct mapping from structural description to parts of the model
  - Drawbacks
    - Unnatural for many domains
    - Still relies on human skill in model formulation







Summary

- Qualitative representations provide formalisms for conceptual knowledge
  - Qualitative mathematics expresses partial knowledge
  - Supports causal reasoning
- Qualitative reasoning captures important aspects of human reasoning
  - Can use partial, incomplete information
  - Orchestrates the use of other kinds of knowledge
- Qualitative Process theory
  - Changes are caused by physical processes
  - Influences provide a qualitative mathematics that is compositional and captures causal intuitions