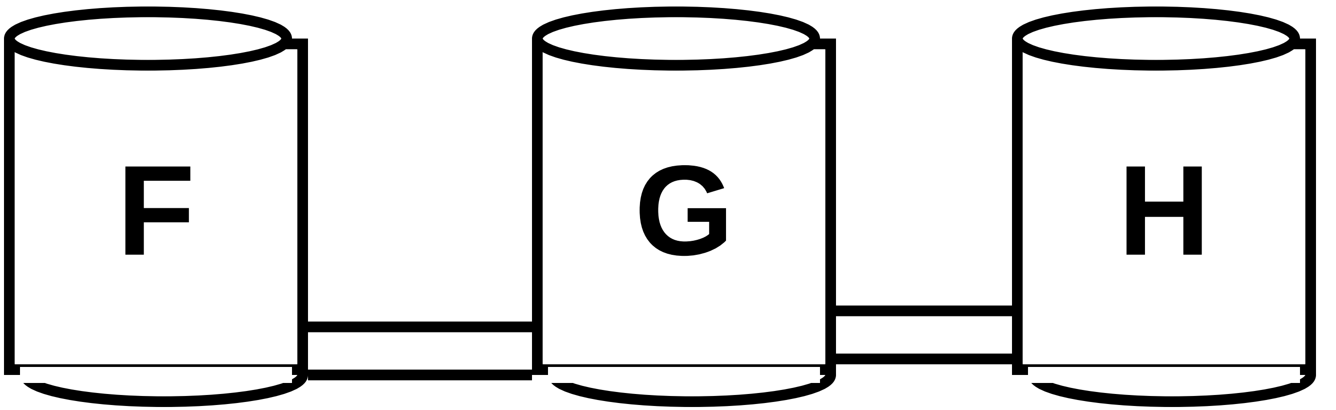
Implementing a qualitative reasoner

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.

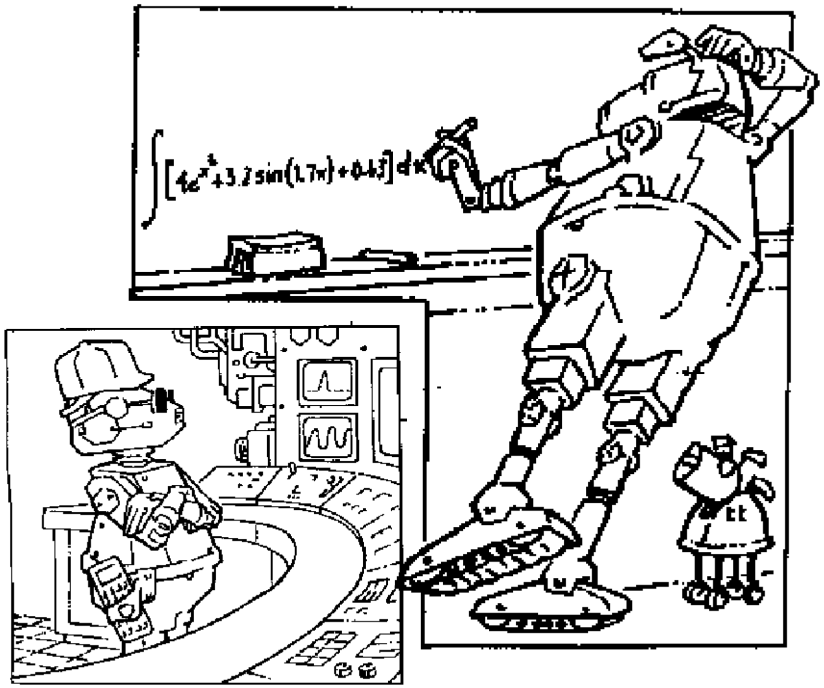
Qualitative Physics

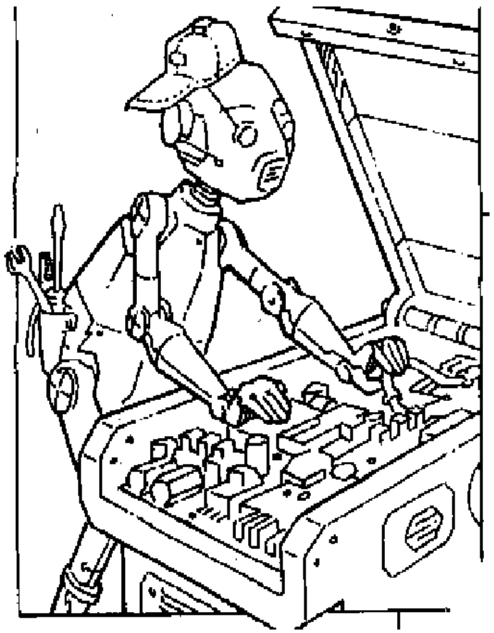
- Seeks to formalize the intuitive, common sense knowledge, ranging from the person on the street to the intuitions of scientists and engineers.
- Creates representation and reasoning schemes to use that knowledge for a variety of tasks
- Ultimate goals include building artificial engineers, accounts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

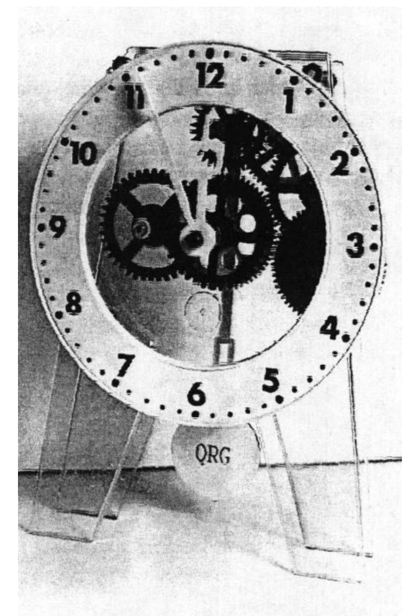
Key Ideas of Qualitative Physics

- **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."**

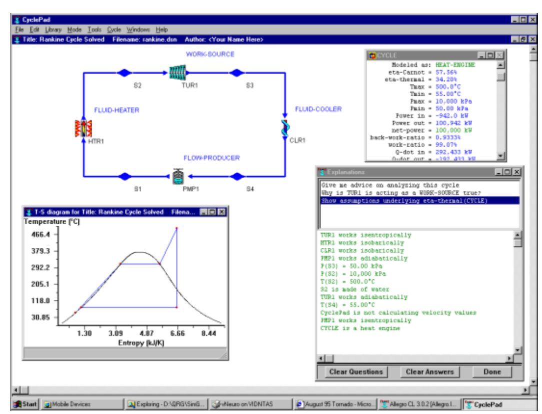
Tom Swift and his Artificial Engineer







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

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

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

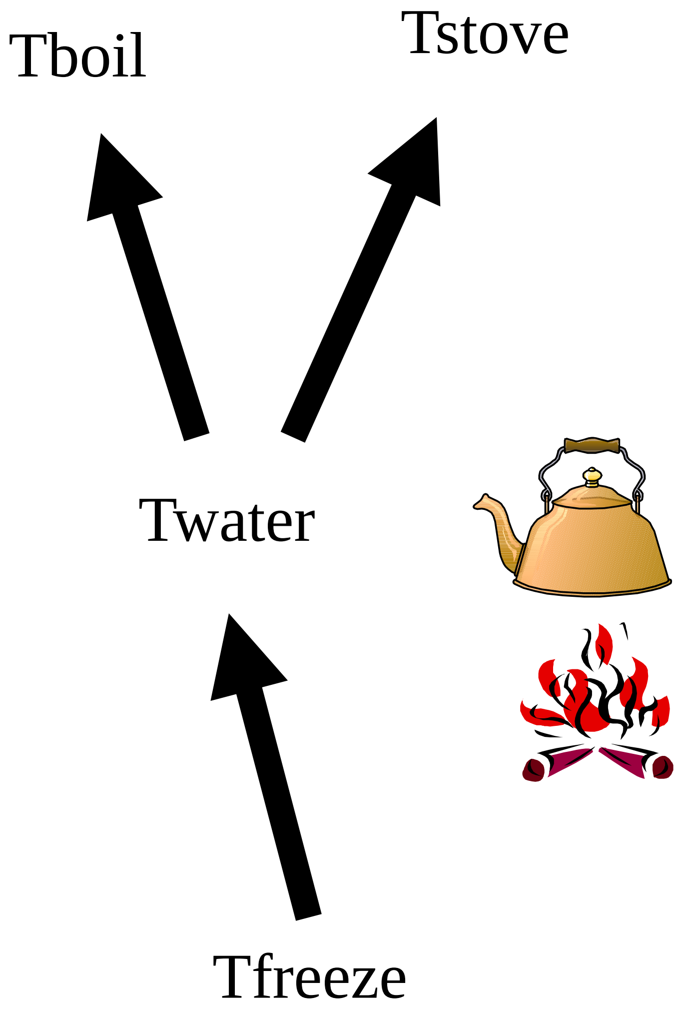
Qualitative version

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 Ds**
  - 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**



```
A[pressure(Wf)] > A[pressure(Wg)]
Ds[amount-of(Wf)] = -1
Ds[amount-of(Wg)] = 1
```

Fluid flow from F to G

Ends via equilibration

```
A[pressure(Wf)] = A[pressure(Wg)]
Ds[amount-of(Wf)] = 0
Ds[amount-of(Wg)] = 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)**
  - **∃f s.t. A = f(…, B,…) ∧ f 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

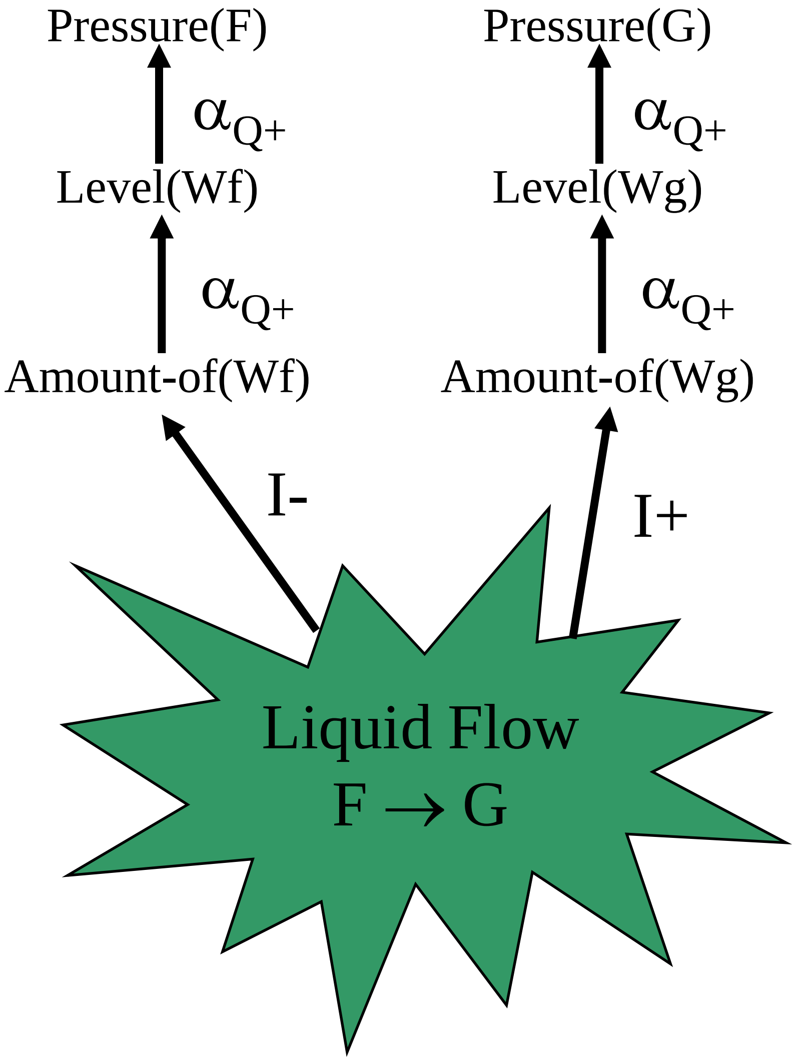
- `I+(A,b)≡ D[A]=`...`+b+`...
- `I-(A,b)≡ D[A]=`...`-b+`...
- **Direct influences combine via addition**
  - **Information about relative rates can disambiguate**
  - **Abstract nature of qprop ⇒ no loss of generality in expressing qualitative ODE's**
- **Direct influences only occur in physical processes (*sole mechanism assumption*)**
- **Closed-world assumption needed to determine change**

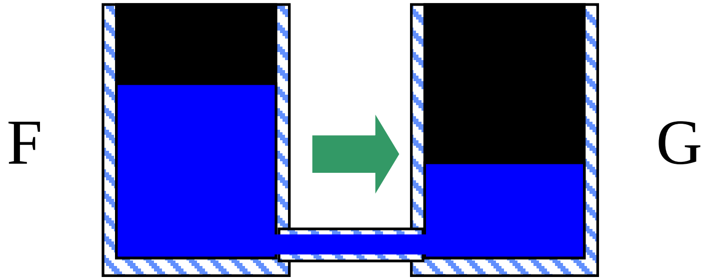
Qualitative Mathematics

- 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

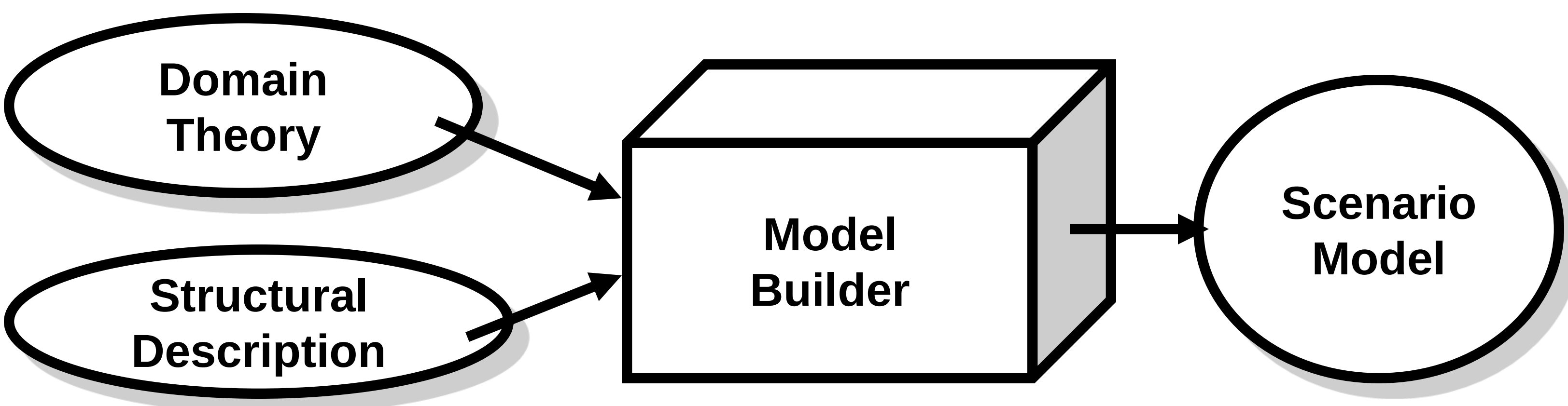
- **All causal changes stem from *physical processes***
- **Changes propagate from quantities directly influenced by processes through causal laws to indirectly influenced quantities**
- **Naturally models human reasoning in many domains (i.e., fluids, heat, motion…)**





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?"

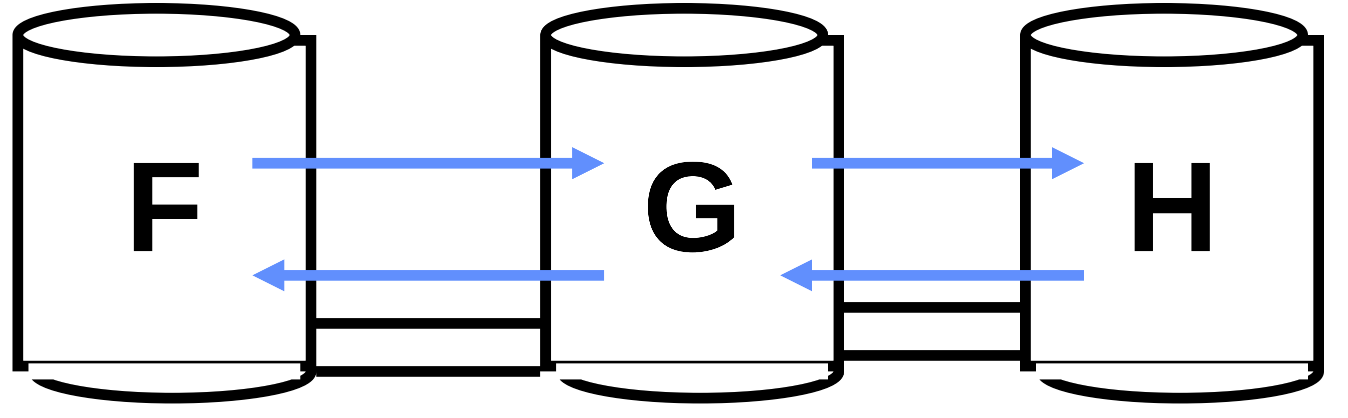
Finding process and view instances

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

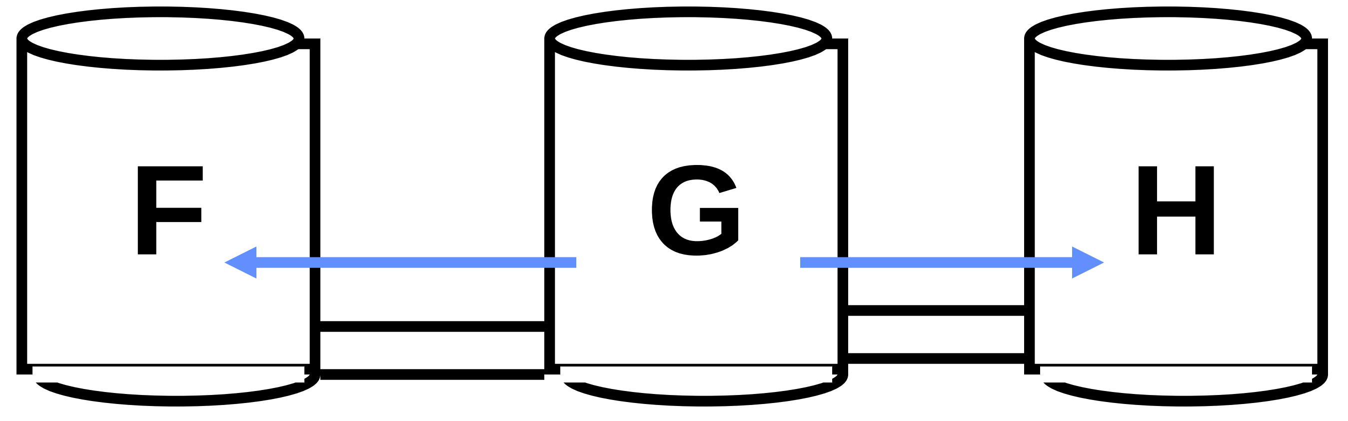


Determining Activity

- **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

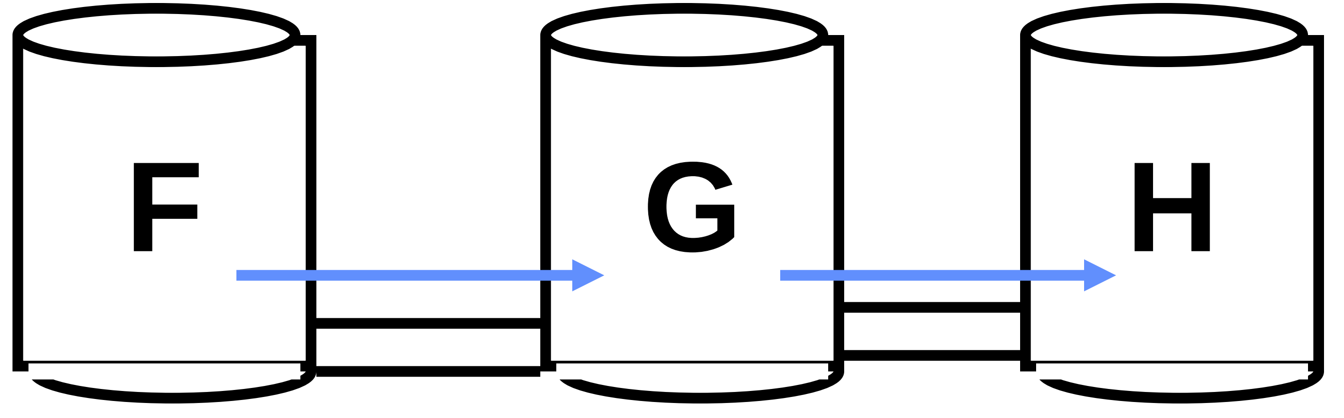


Influence Resolution

- **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**

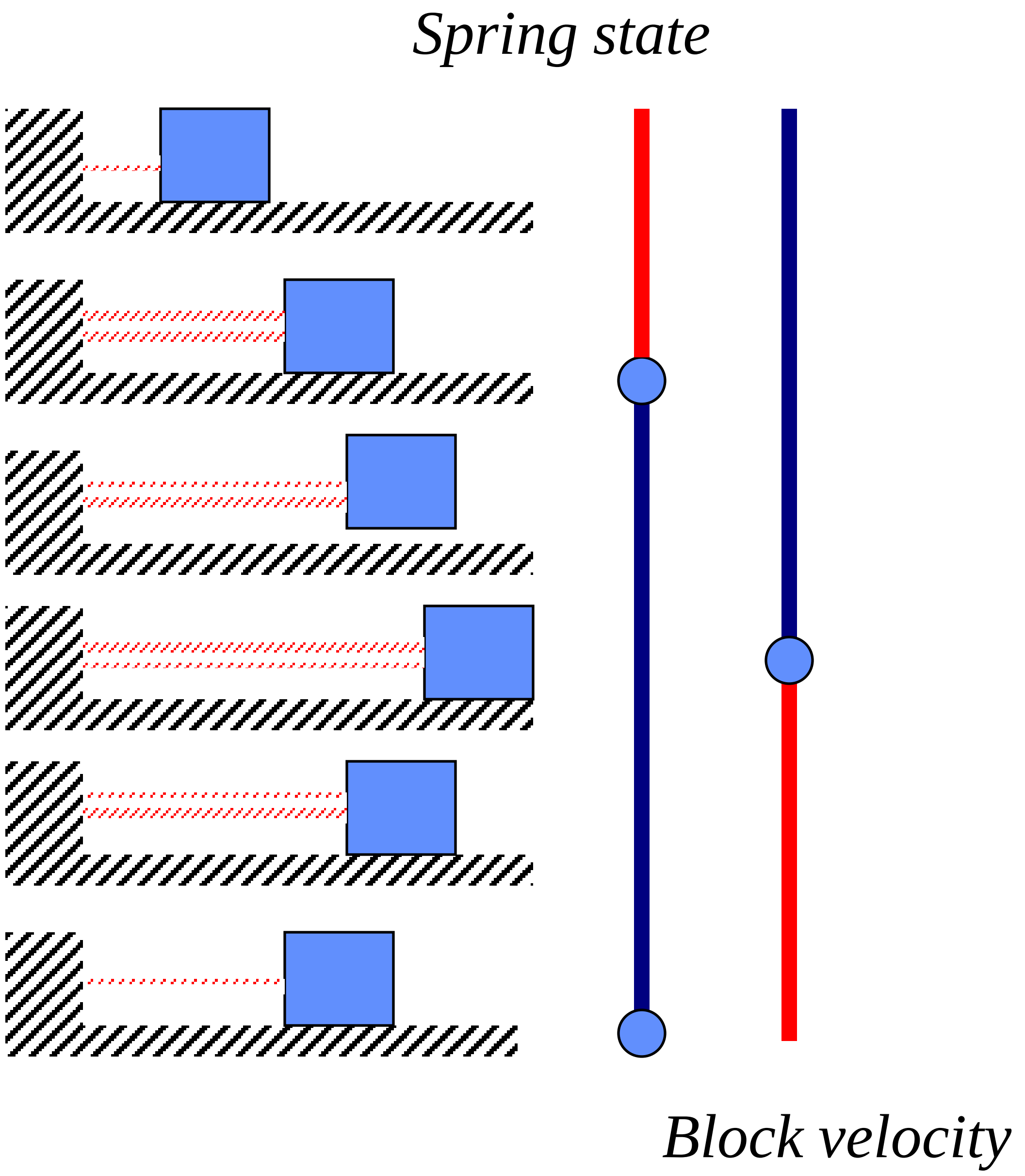
Example

Net effect on G unknown, unless we assume something about relative flow rates



Time and change

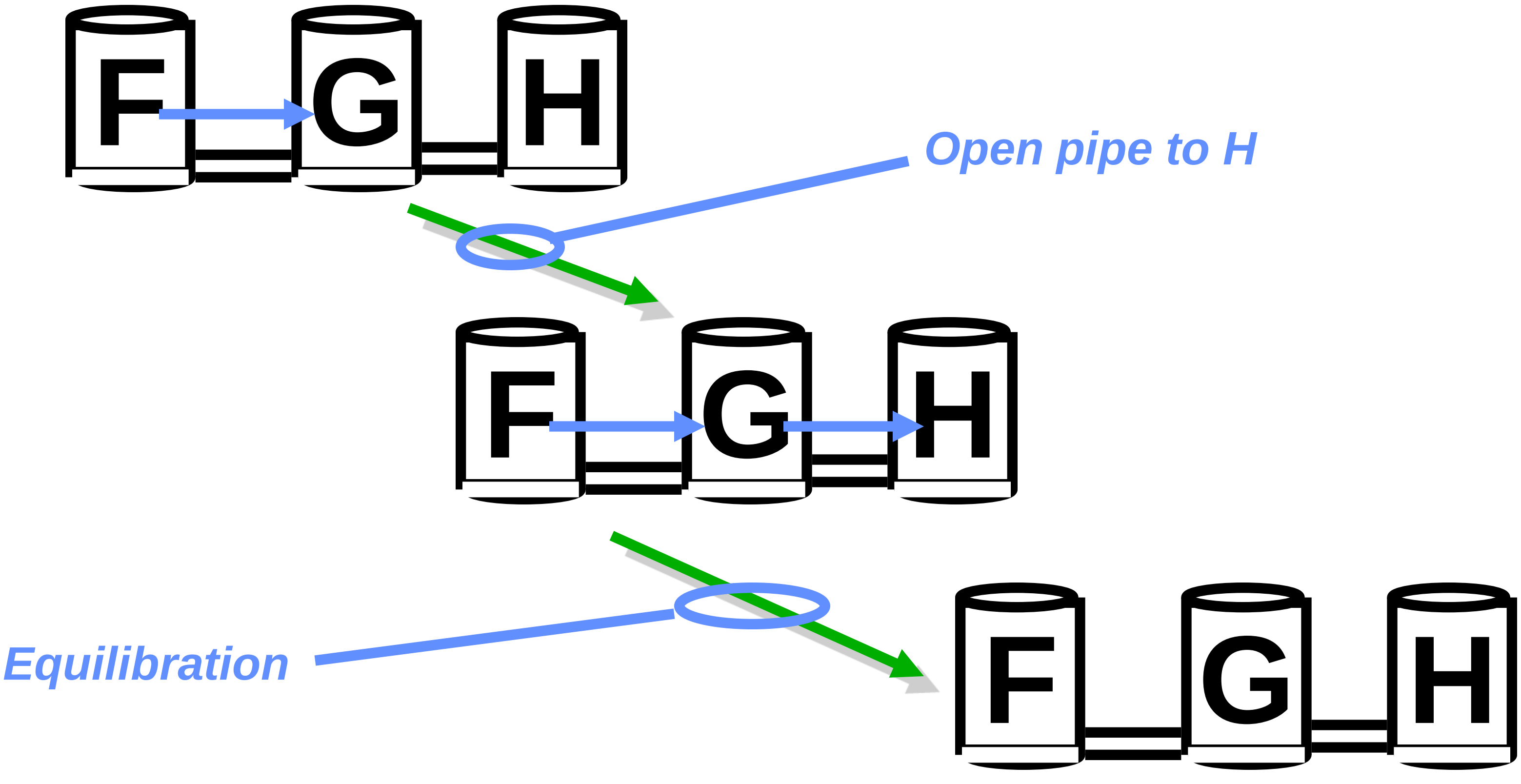
- **Time individuated by changes in qualitative state**
- **Qualitative states differentiated by**
  - **Set of active physical processes**
  - **What dynamic relationships hold**
  - **Quantity space values**



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

Example

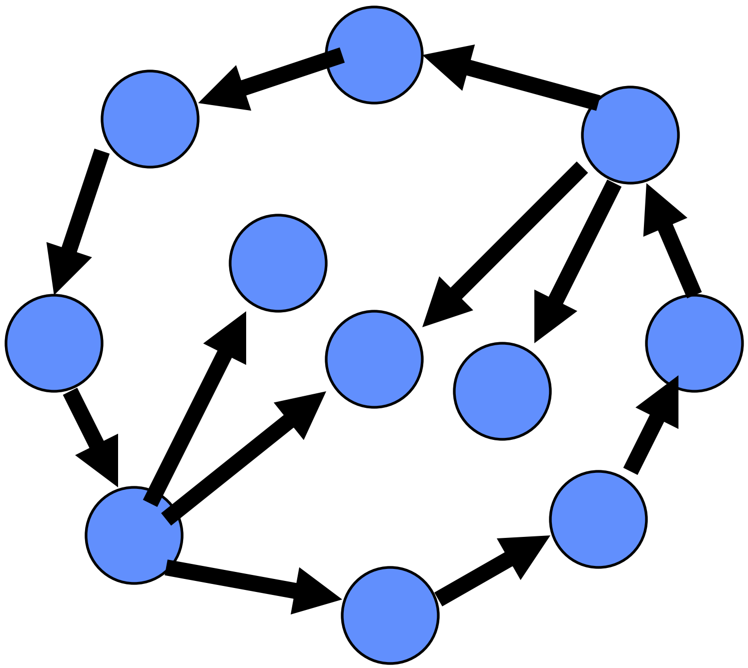


Qualitative Simulation

- **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

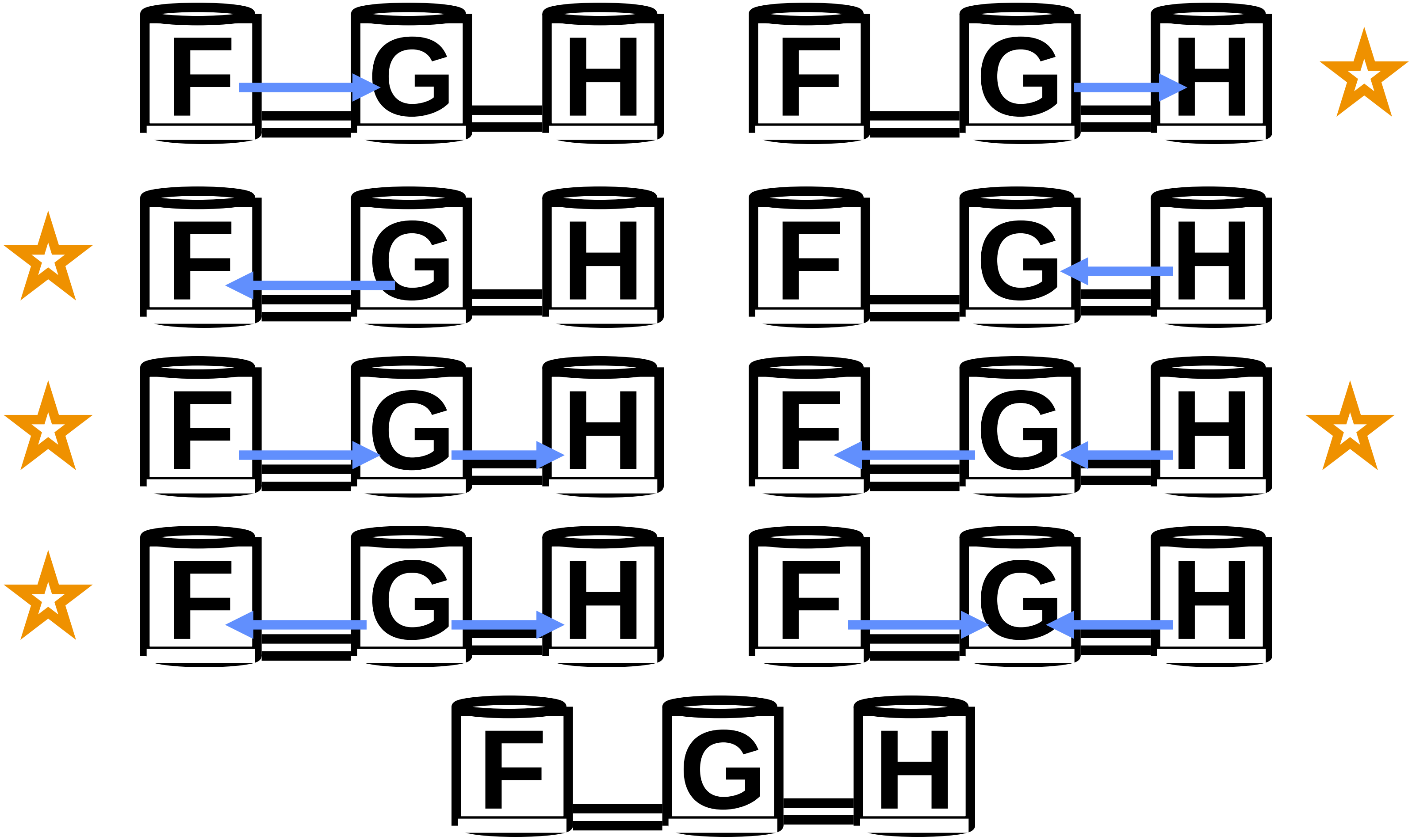


Many dynamical properties of systems can be reasoned about based on topological properties of qualitative state graphs

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



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!