Unit A1.3 Model construction and simulation

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Overview

- Model fragments
  - A key constituent of domain theories
  - Will use CML syntax
- Qualitative states, transitions, and simulation
- Properties of qualitative models

Model Fragments

- Encode conditions under which domain knowledge is relevant
  - *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.

Qualitative Reasoning

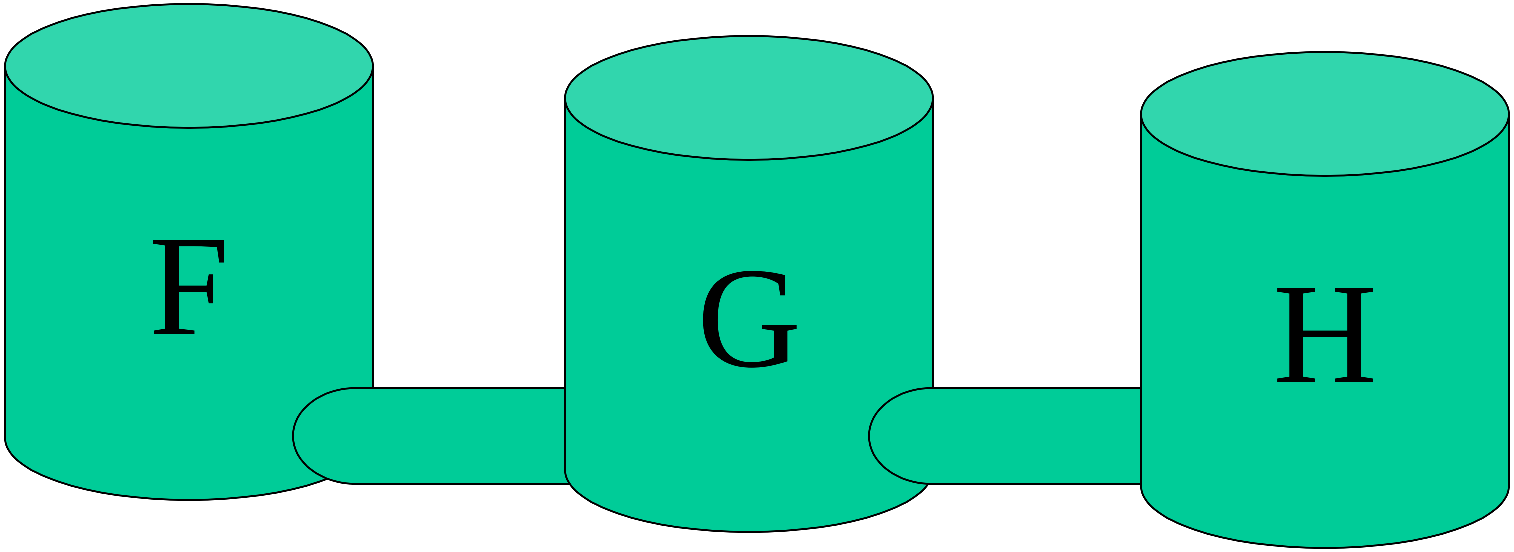
- Deriving new values from given values and qualitative constraints is one form of QR
- Qualitative simulation and envisioning are very important forms of qualitative reasoning
- There are other important types of qualitative reasoning as well:
  - Measurement interpretation
  - Simulation construction
  - …
- More complex reasoning operations can typically be defined in terms of a set of *basic inferences*

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?"

A simple example

- Might be water in each container
- Only considering flows of liquid between each
- Ignoring phase changes, evaporation, thermal properties, momentum…



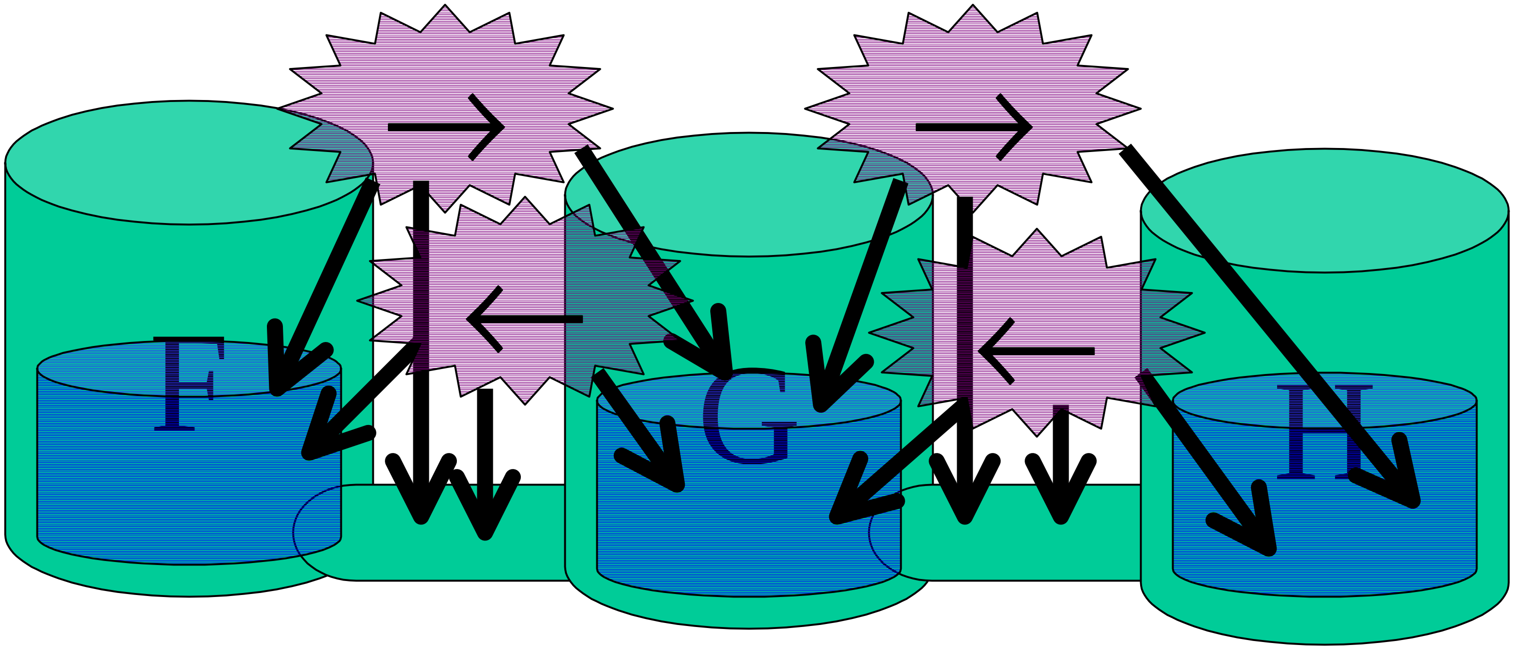
Finding model fragment instances

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

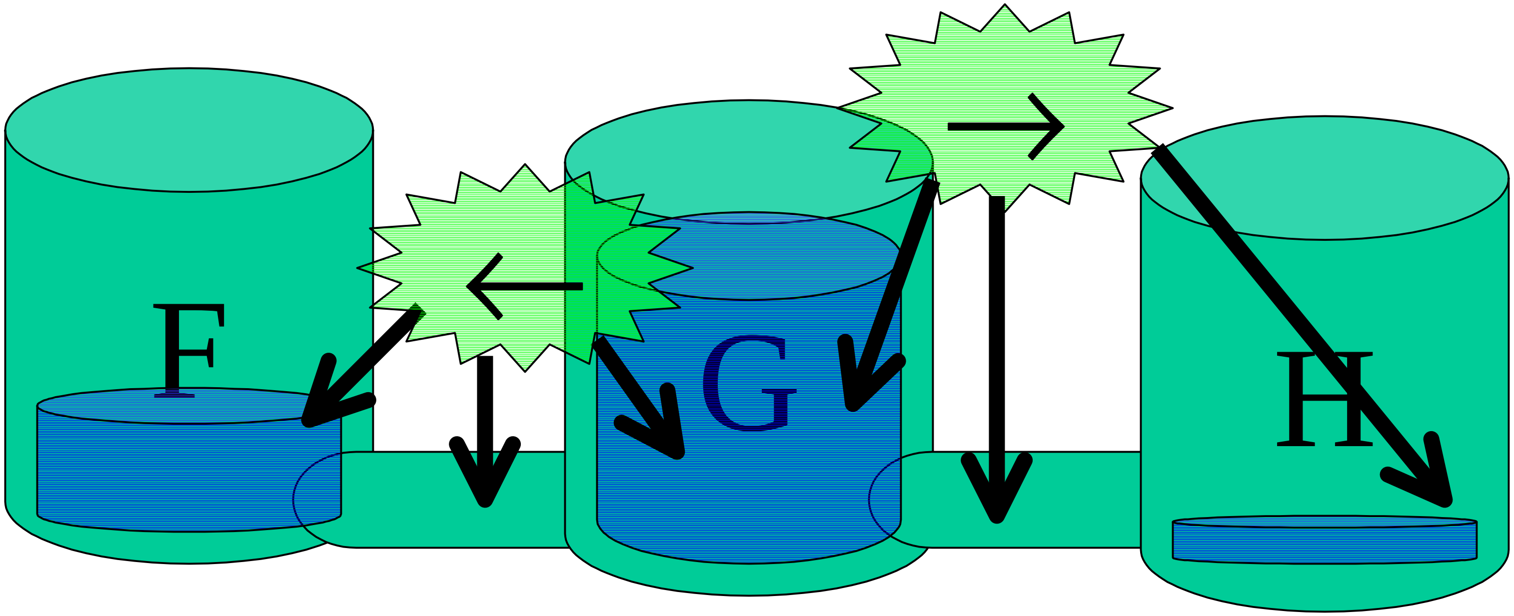


Determining Activity

- Evaluate conditions to figure out which model fragments are active.
  - Called *process structure* and *view structure* in literature, more generally, *activity structure*.
- Closed-world assumption on influences can now be made, based on
  - CWA on individuals, relationships in situation
  - CWA on domain theory
  - CWA on model fragments
- The *influence graph* that results is a set of qualitative differential equations
  - N.B. When the activity structure changes, the influence graph can change.

Example

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

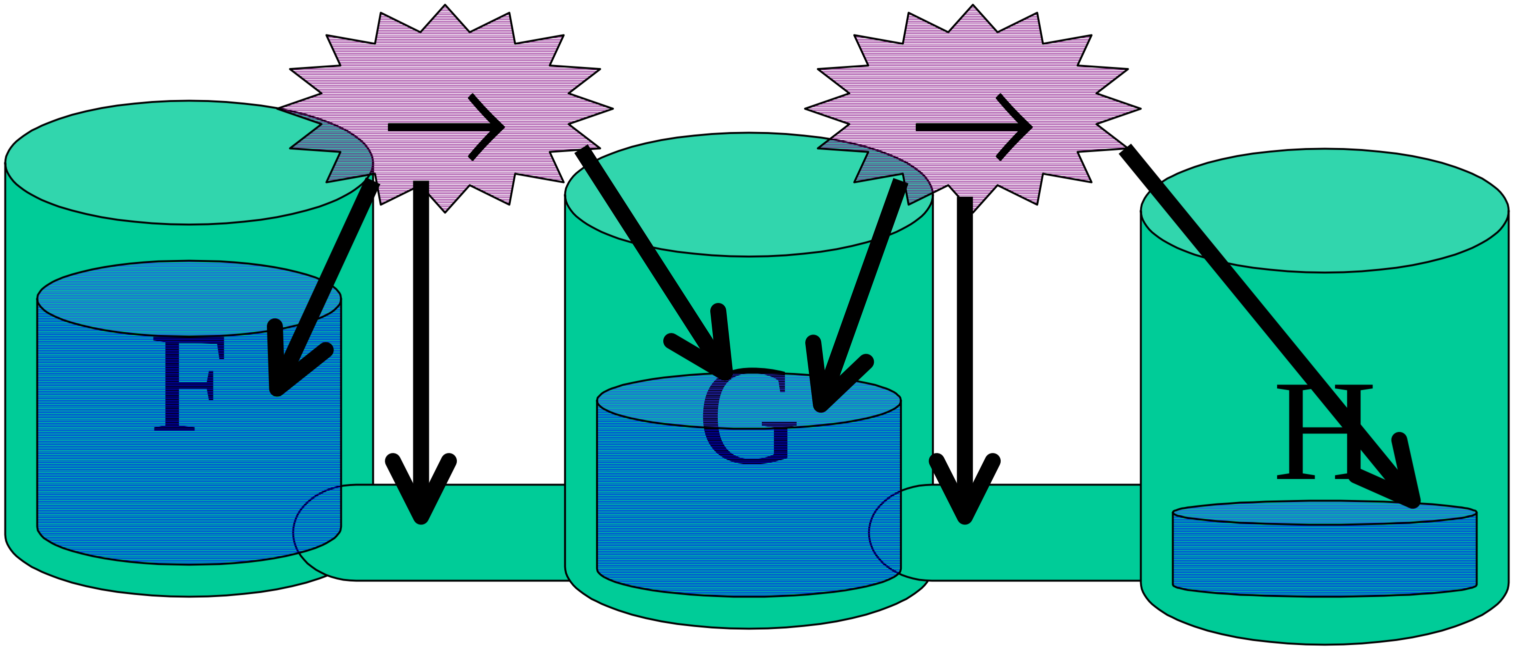


Influence Resolution

- 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
- Task determines which method of ambiguity resolution is appropriate

Example

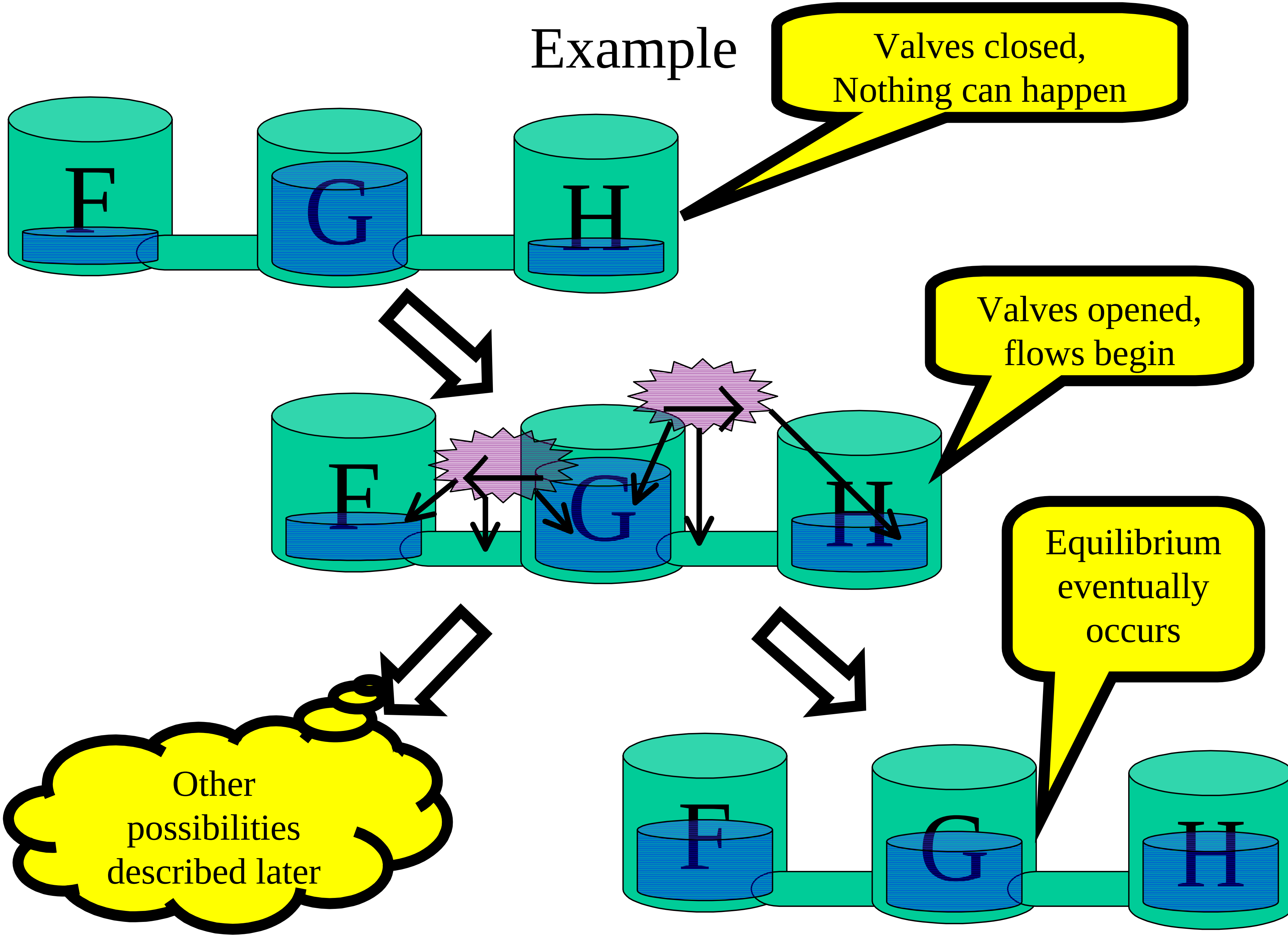
- Suppose more in F than in G than in H.
- Net effect on G unknown, unless we know or assume something about relative flow rates



Limit Analysis

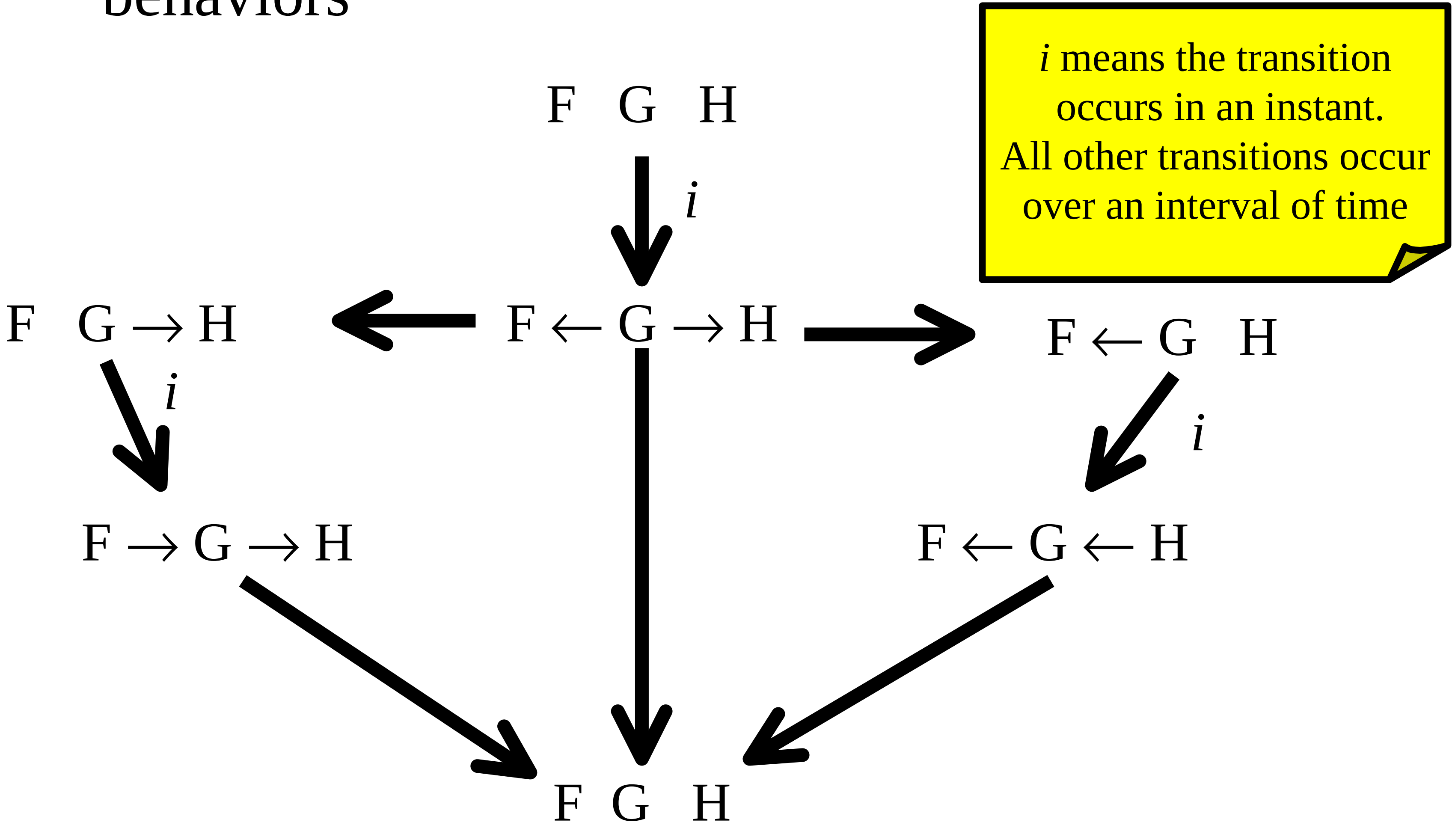
- Using derivatives, figure out how set of ordinal relations can change.
- Result are possible changes in active processes, existence of individuals
- Often ambiguous
  - multiple changes
  - relative rates/distances unknown
- Requires taking continuity into account
- Illustrates a good solution to the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

Example


Valves closed,
Nothing can happen
F
G
H
Valves opened,
flows begin
F
G
H
Equilibrium
eventually
occurs
F
G
H
Other
possibilities
described later

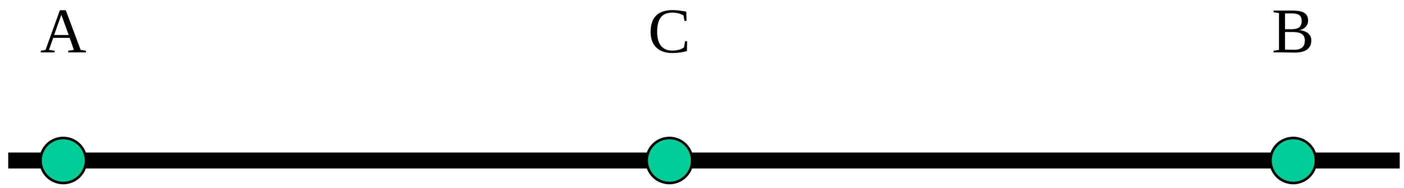
Partial knowledge ⇒ Ambiguity

- In general, limit analysis can predict multiple behaviors



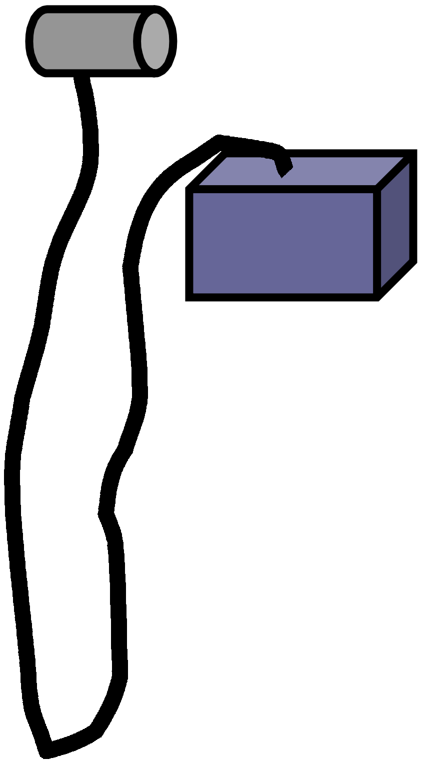
Continuity and Change

- You can’t get from A to B without going through C.
- Holds for qualitative values, too
  - Ds[foo] = -1 → Ds[foo] = 1? No, must be Ds[foo] = 0 first
  - foo < bar → foo > bar? No, must be foo = bar first
- Key constraint for pruning state transitions in qualitative simulation



Continuity has surprising consequences

- Suppose the string is unbreakable and perfectly inelastic. What can happen in the situation below when the block is released?



Putting the basic inferences to work

- Measurement Interpretation
- Qualitative simulation
- Envisioning

Measurement Interpretation

Given a set of measurements at a single time:

1. Find possible model fragments
2. Perform a dependency-directed search over possible activation structures
   - Resolve influences for each combination.
   - If ambiguous influences, search all possibilities.
   - If state satisfies measurements, record
3. Return as answer the set of recorded states

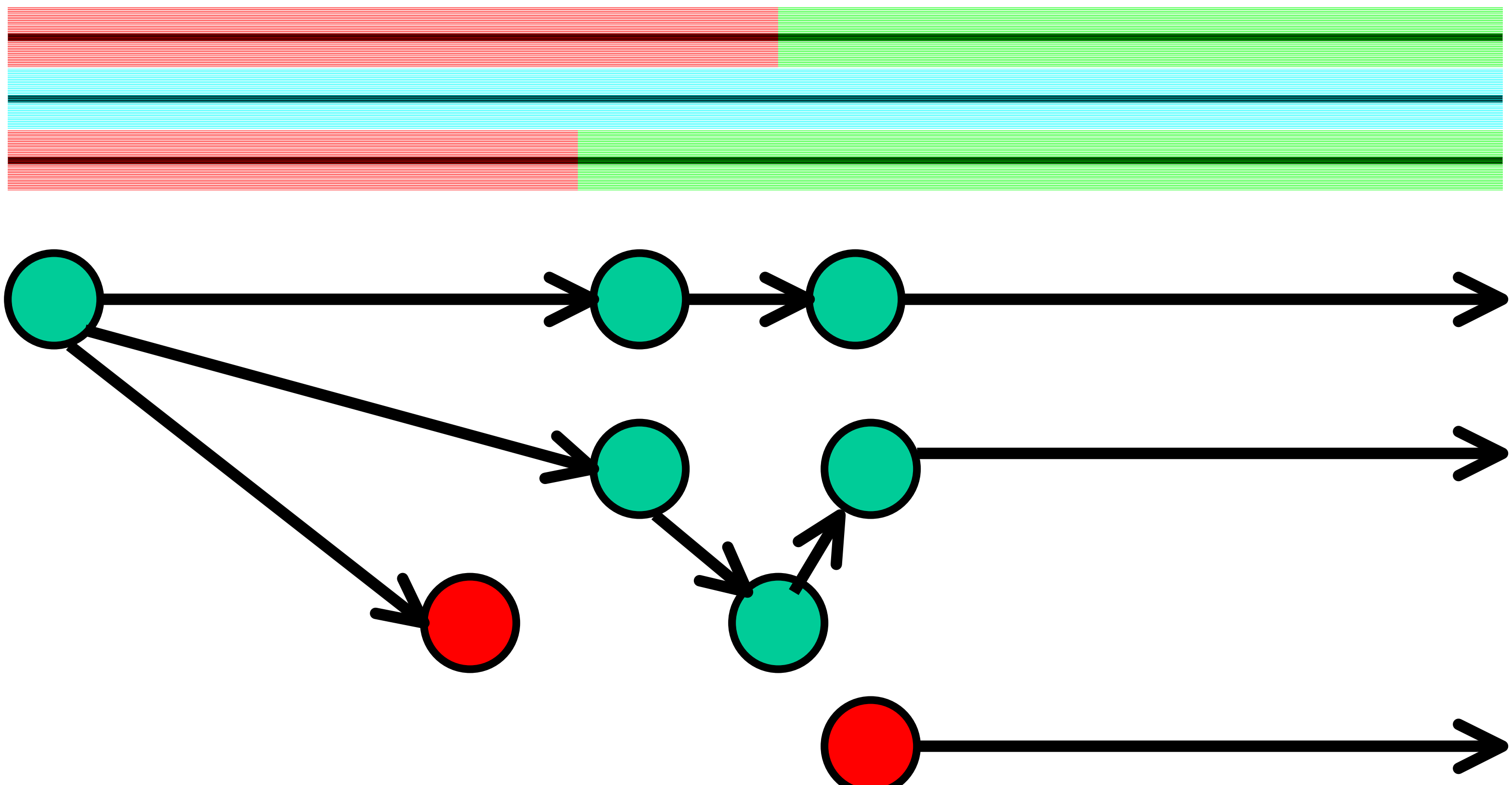
Example

	$F \rightarrow G \quad H$	$F \quad G \rightarrow H$	★
★	$F \leftarrow G \quad H$	$F \quad G \leftarrow H$	
★	$F \rightarrow G \rightarrow H$	$F \leftarrow G \leftarrow H$	★
★	$F \leftarrow G \rightarrow H$	$F \rightarrow G \leftarrow H$	

$F \quad G \quad H$

Interpreting measurements across time

- Find best explanation in terms of qualitative behaviors
- Use transitions as *compatibility constraints* to prune



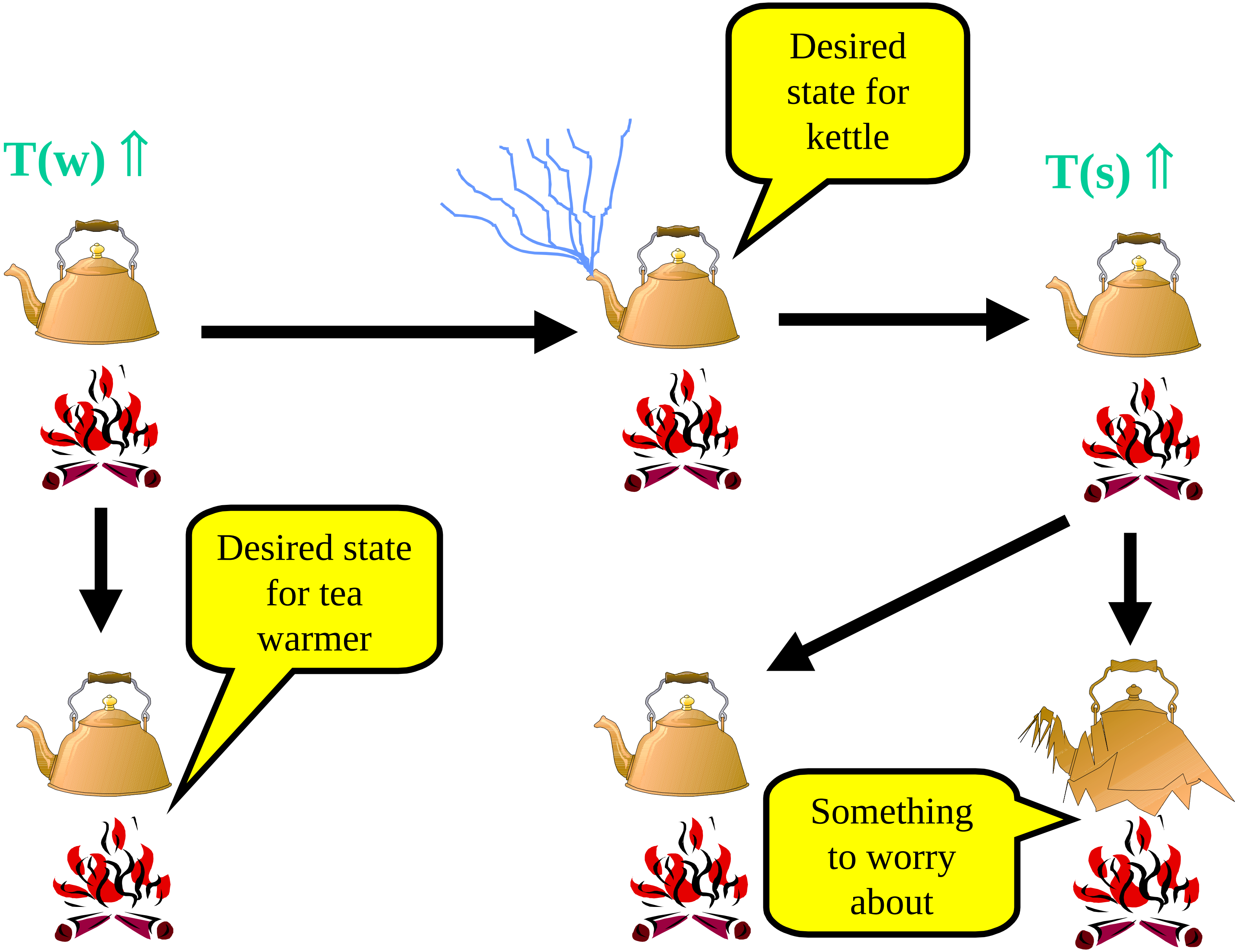
Qualitative Simulation

- For initial state
  - Find view and process instances
  - Determine activity
  - Resolve influences
  - Perform limit analysis
- For each next state, treat as initial state
- Continue as desired
  - Some desired/undesired behavior found
  - Resource limits

Envisioning

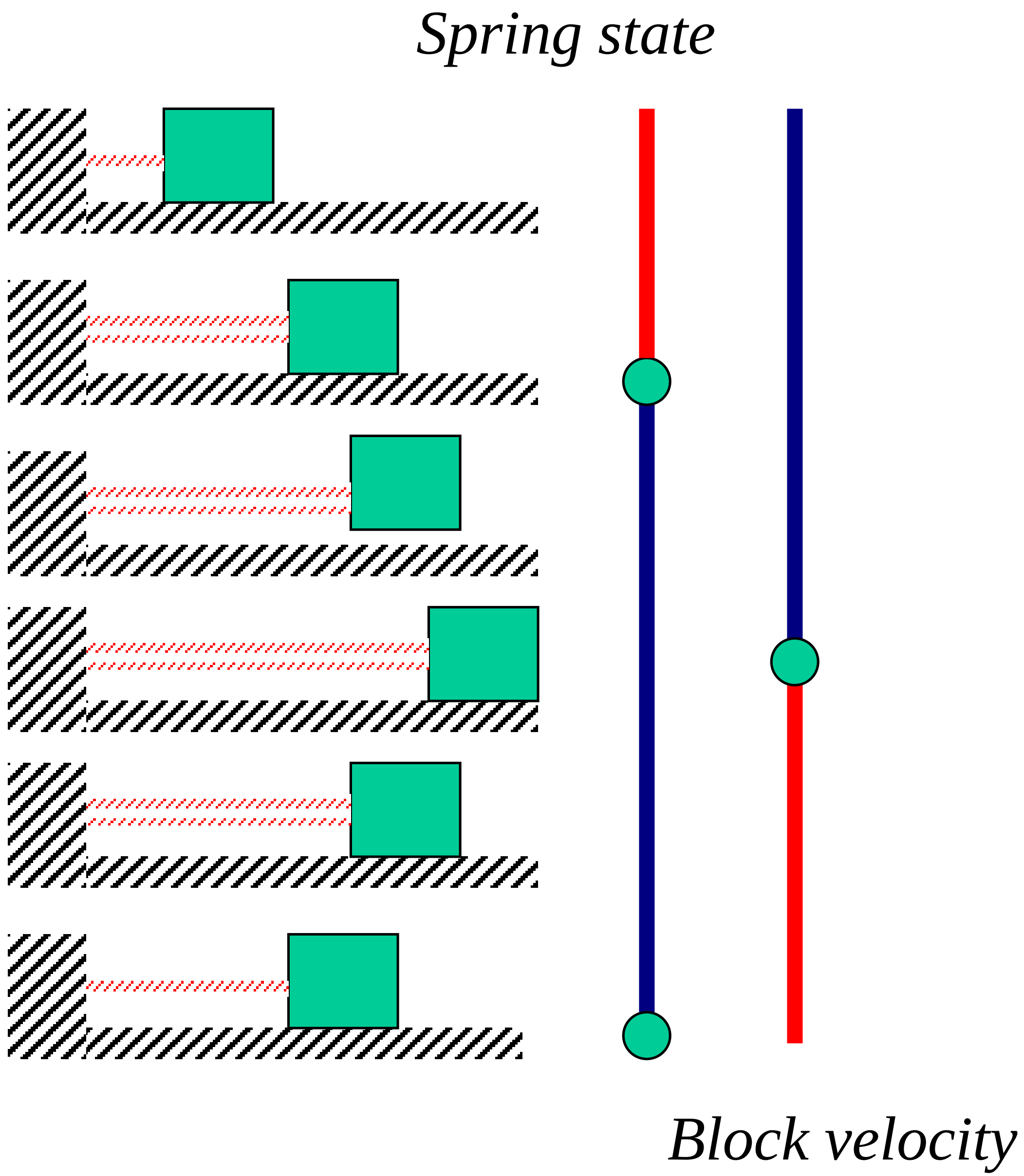
- Envisioning = complete qualitative simulation
  - *Attainable envisionment* = all states that might be reached from a given initial state
  - *Total envisionment* = all possible states of the system and all possible transitions between them
- Envisionments provide finite characterization of system behavior
  - Can be useful for FMEA, design
- Caution: Finite $\neq$ small
  - Can be exponential in size of system
  - With landmark introduction, no longer finite

How qualitative simulation can be used in design

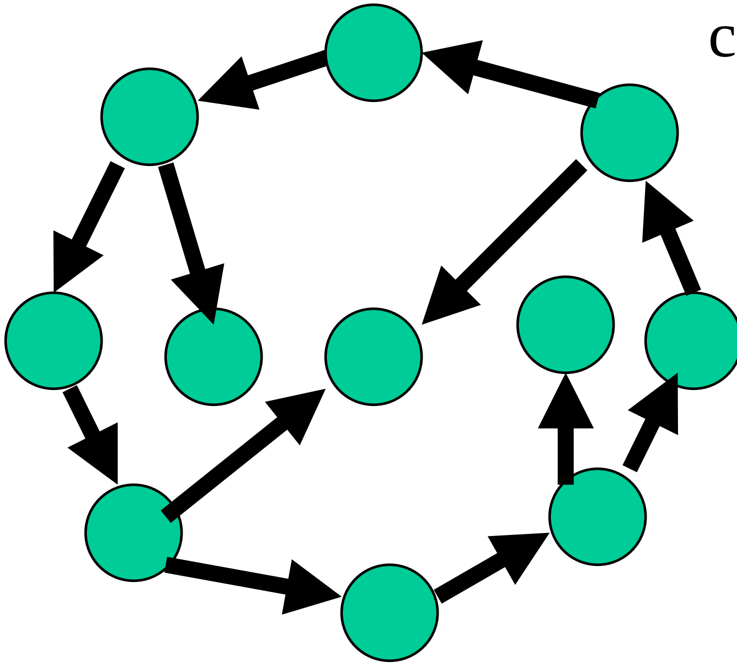


Time and change

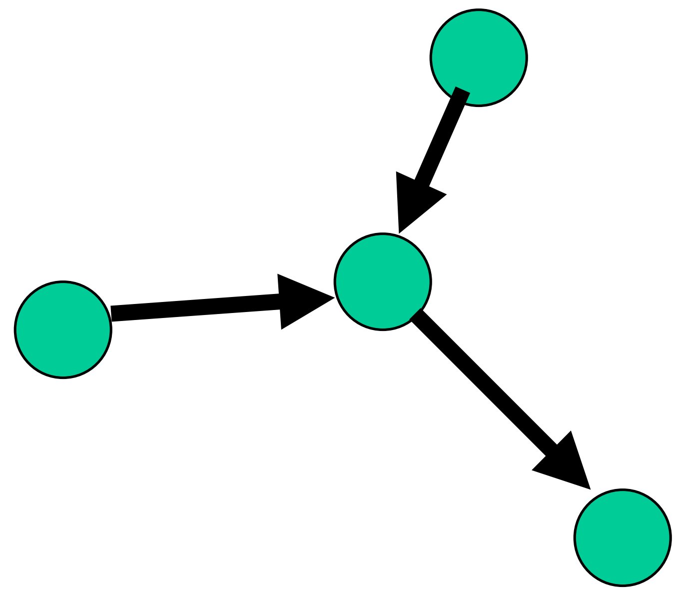
- Time individuated by changes in qualitative state
- Qualitative states differentiated by
  - Set of active model fragments
  - Qualitative values of system parameters
- Constrast with notion of time used in numerical simulators



Qualitative states and transitions



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

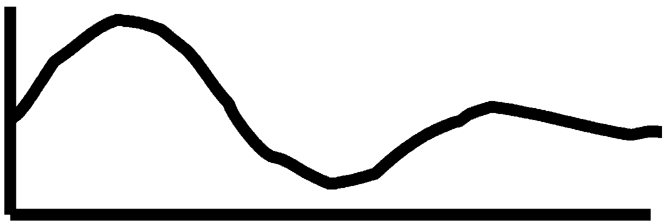


Judging correctness of qualitative reasoning

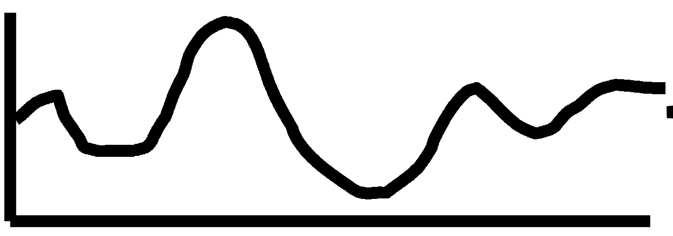
- Several “gold standards” possible
  - Physical world
  - Mathematical models
  - Psychological plausibility
- Example: What does it mean for a qualitative simulation to be correct?
  - Envisionment = quantized phase space for physical system
  - Every state = some real behavior
  - Every transition = some transition that could occur between real states as part of a real behavior
  - Not quite enough…

Paths = possible behaviors?

- Ideally, all paths through envisionment should correspond to physically possible behaviors
- Not always true!



Physically possible for a spring/block oscillator with dynamic friction



Not physically possible due to energy considerations

Properties of qualitative simulation

- *Soundness*: If it is in the envisionment, it is possible
- *Completeness*: If it is physically possible, there is something corresponding to it in the envisionment
- Qualitative simulation is *unsound* but *complete*
- Interesting question:
  - Is there some minimal level of information, less detailed than say numerical values, that would make qualitative simulation sound?