Distributed Computing

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MAPi
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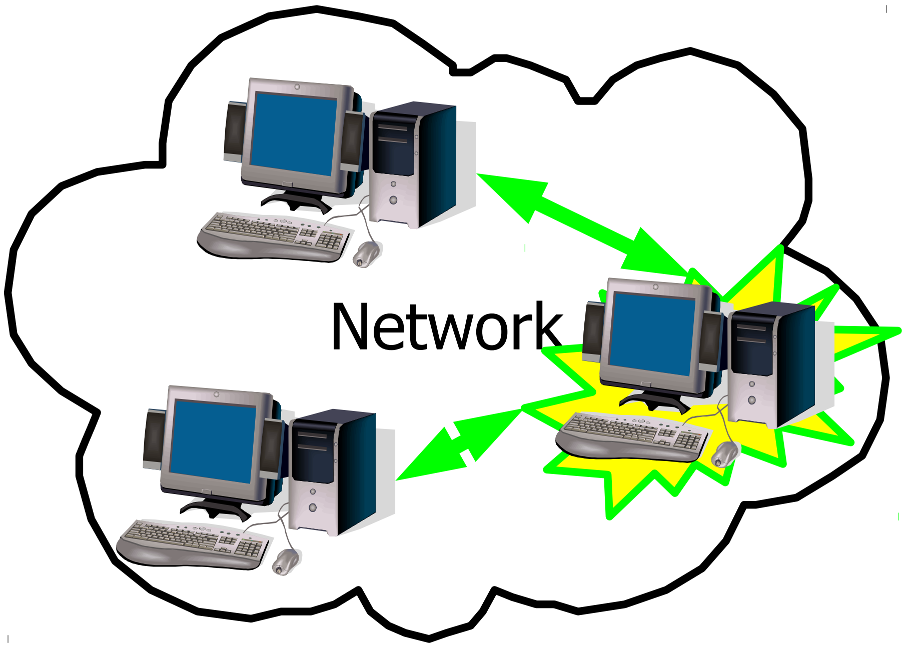
Asynchronous system model

- Avoid using a global time reference
- Assume no bounds on:
  - clock drift
  - processing time
  - message passing time
- Why?

Example: Leader election

- Select a unique leader in a distributed system
- Useful for:
  - Coordination
  - Efficiency
  - …

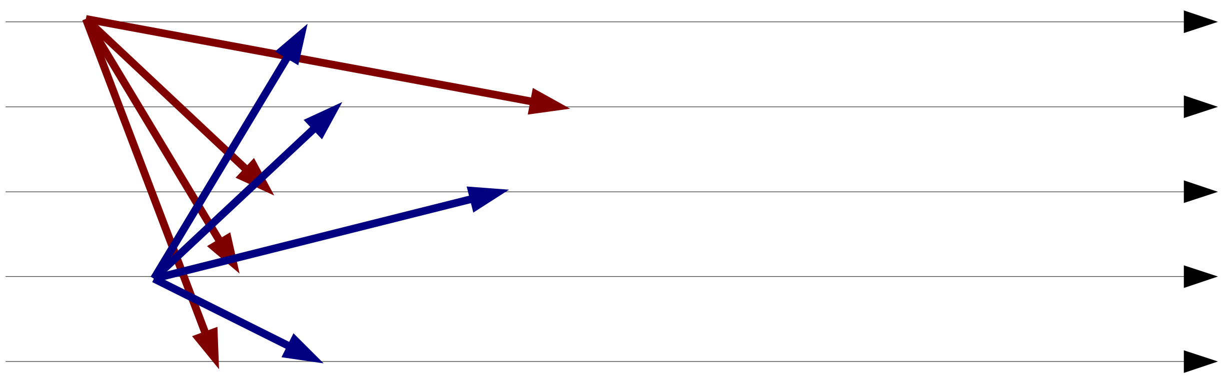


Example: Properties

- No two processes disagree about the leader
- Every process will select a leader

Example: Simple algorithm (FloodMax)

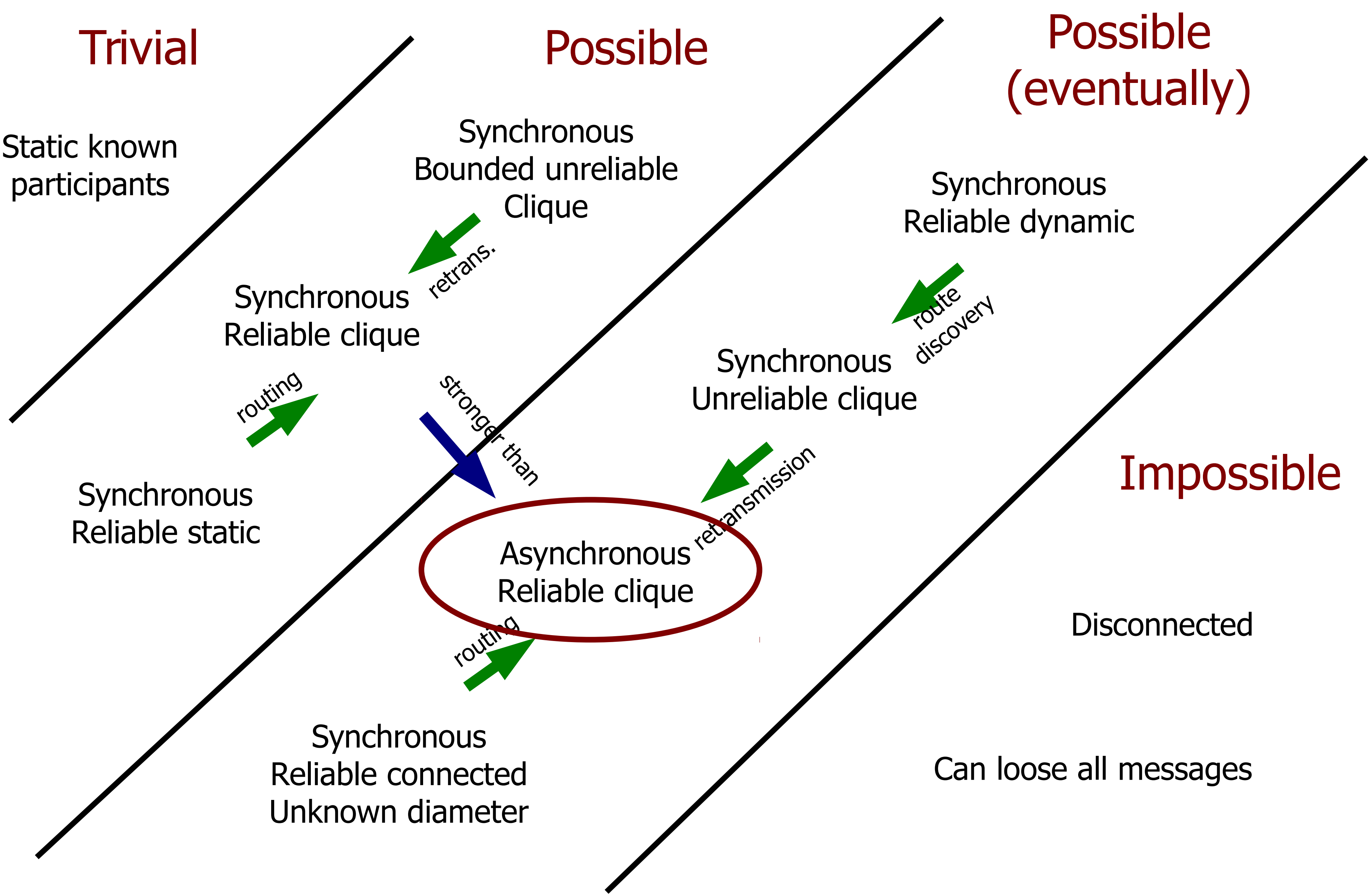
- Each process trying to be the leader sends its network address to all others
- Each process considers the process with the highest address to be the leader



Example: Approach

- Start with a synchronous reliable fully connected network
- Relax the system model:
  - Unbounded message loss
  - Large/unknown graph diameter
  - Dynamic graph
- Example: Leader election

Example: Leader election



Summary

- Asynchrony subsumes:
  - Heterogeneity
  - Dynamics
  - Uncertainty
- Much simpler than handling them explicitly
- Often considered an Universal model:
  - Widely applicable solutions

Goals

- How do we make sure that algorithms are correct?
- Why are algorithms correct?

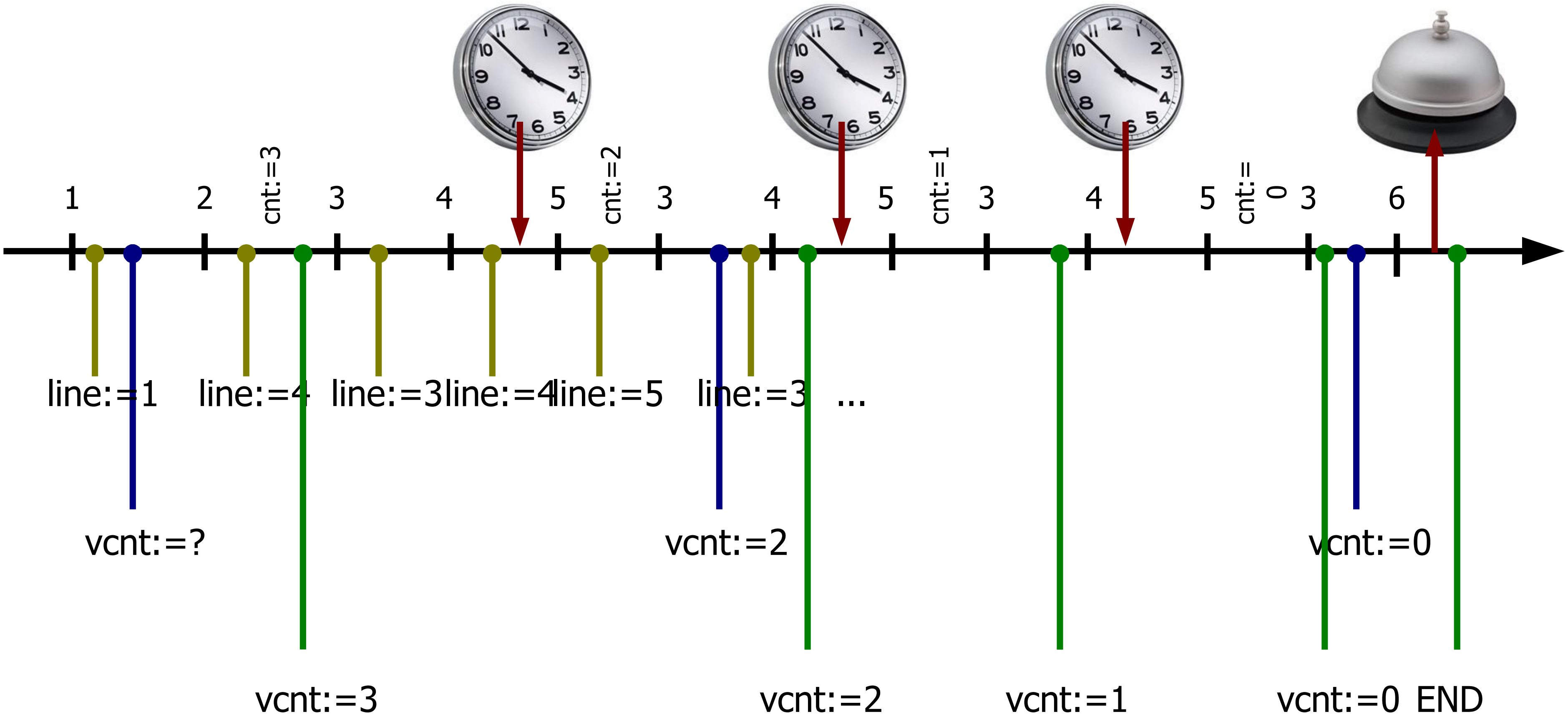
Sample computation

- An alarm clock program:

```
main:                   // line 1
    cnt:=3              // line 2
    while cnt>0:        // line 3
        sleep 1s        // line 4
        cnt := cnt-1    // line 5
    ring                // line 6
```

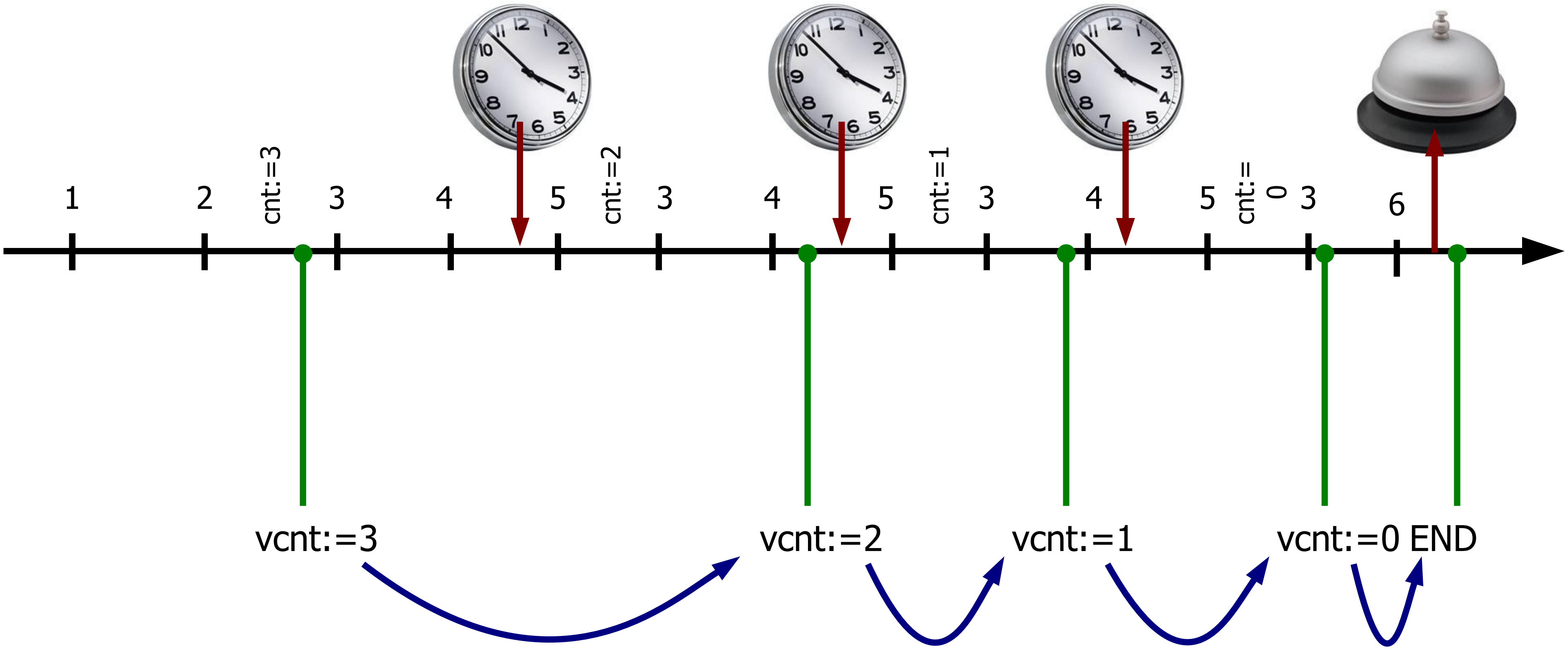
Observation

- Select model variables and periodically observe the system:



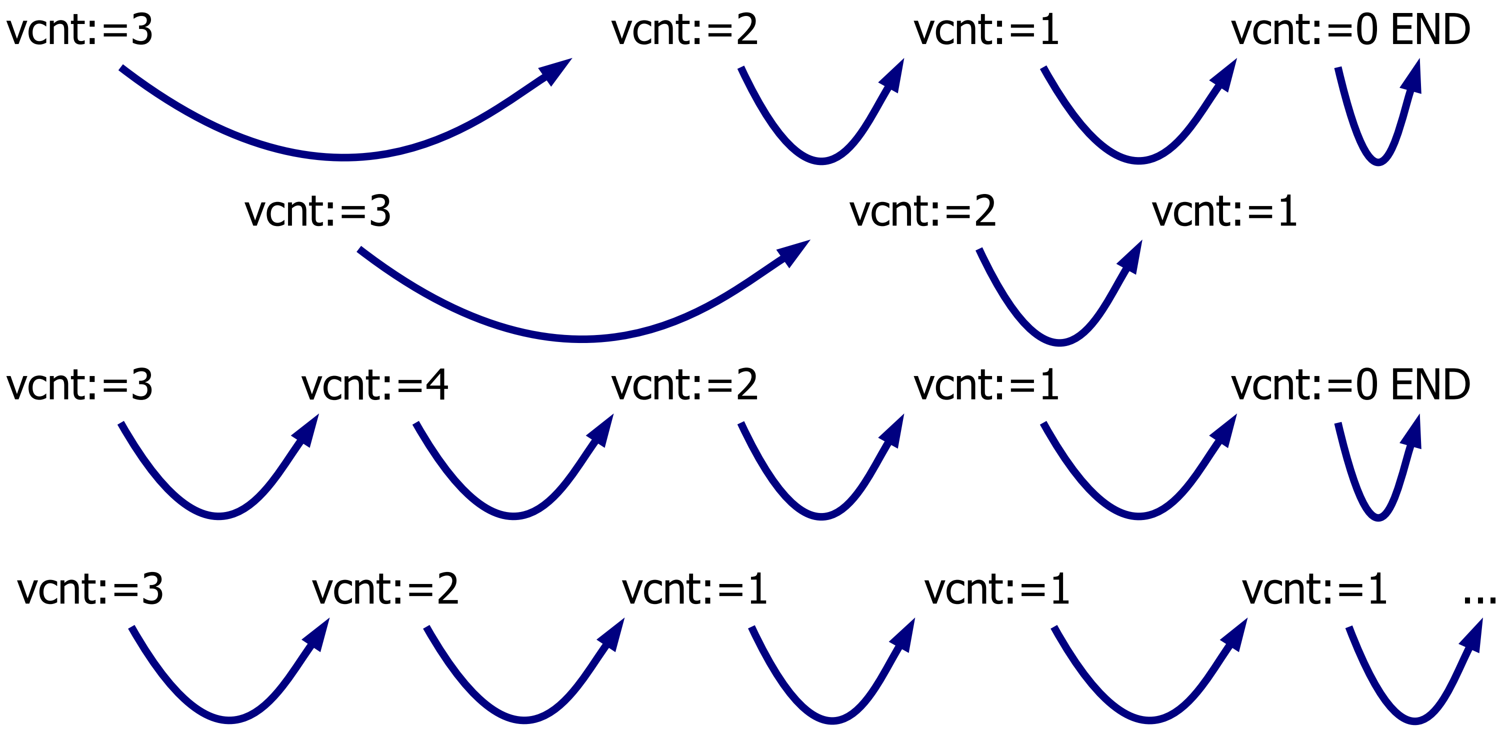
Abstraction

- Choose observation that allows reasoning on the desired properties:



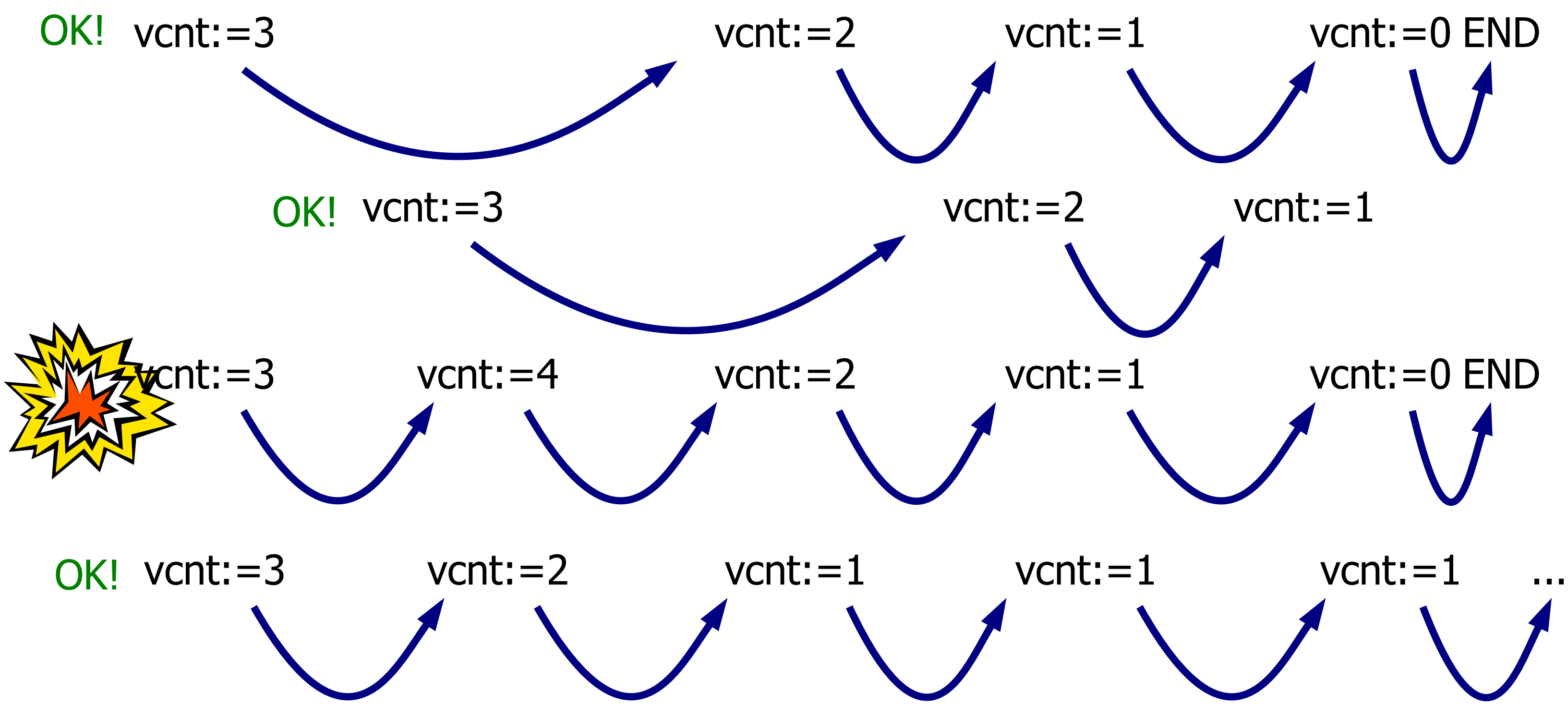
Behaviors/Executions

- Consider all possible sequences of chosen atomic actions:



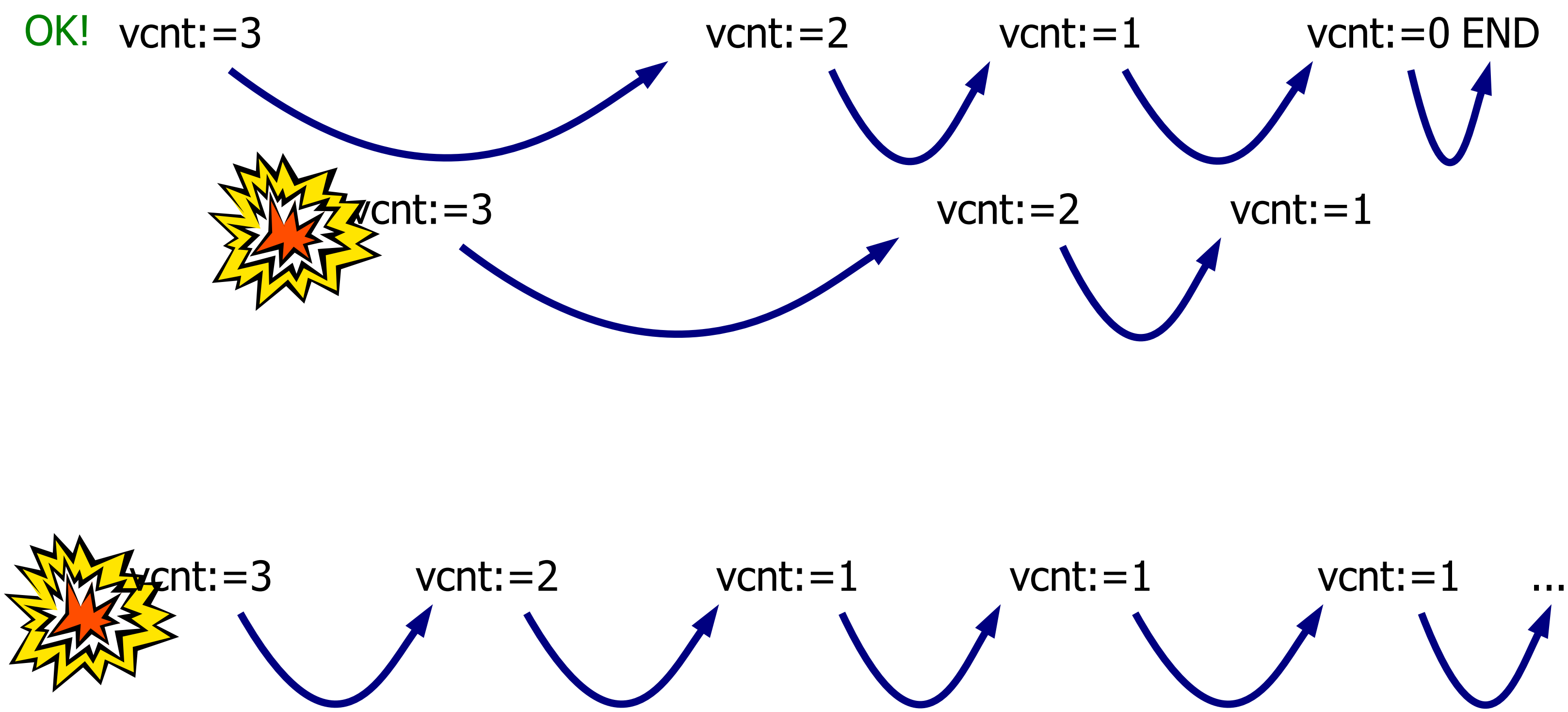
Safety properties

- Nothing bad ever happens:



Liveness properties

- Something good eventually(*) happens:



(*) eventually = inevitavelmente ≠ eventualmente

Specification

- Specification is a set of allowable behaviors:

$$S=\left\{ \text{vcnt:=3} \xrightarrow{\text{timeout}} \text{vcnt:=2} \xrightarrow{\text{timeout}} \text{vcnt:=1} \xrightarrow{\text{timeout}} \text{vcnt:=0} \xrightarrow{\text{ring}} \text{END} \right\}$$

Goal 1: Is it correct?

- Is there a convenient representation for specification sets?
  - Compact
  - Practical
- How to prove safety and liveness properties?

Specifications and automata

- Specification is a set of allowable behaviors:

$$S=\left\{ \text{vcnt:=3} \xrightarrow{\text{timeout}} \text{vcnt:=2} \xrightarrow{\text{timeout}} \text{vcnt:=1} \xrightarrow{\text{timeout}} \text{vcnt:=0} \xrightarrow{\text{ring}} \text{END} \right\}$$

- An automaton provides a compact and practical representation

I/O Automata

- An I/O automaton A has five components:
  - sig(A), a triplet S of disjoint sets of actions:
    - in(S), the input actions
    - out(S), the output actions
    - int(S), the internal actions
  - states(A), a (possibly infinite) set of states
  - start(A), a non-empty subset of states(A)
  - trans(A), a subset of
    states(A) x acts(sig(A)) x states(A)
  - tasks(A), a partition of local(sig(A))

Transitions

- A action is <u>enabled</u> in state s if there is some π,s' such that (s,π,s') $\in$ trans(A)
- Input transitions are required to be enabled in all reachable states of A
- A state in which only input transitions are enabled is said to be quiescent

Signature and State

- Input:
  - none
- Internal:
  - Timeout
- Output:
  - Ring

- States:
  - vcnt, integer, initially 3
  - END, boolean, initially false

Transitions

- Timeout:
  - Pre-condition:
    - ¬END and vcnt>0
  - Effect:
    - vcnt := vcnt - 1
- Ring:
  - Pre-condition:
    - ¬END and vcnt = 0
  - Effect:
    - END := True

This is an equation, not an attribution!

Effects

- Effect equation:
  - vcnt := vcnt - 1
- Read this as:
  - “vcnt-after = vcnt-before – 1 and the state otherwise unchanged”
- Could be written as:
  - vcnt-after + 1 = vcnt-before
  - vcnt-before - vcnt-after = 1
  - ...

Safe behaviors

- Enumerating safe behaviors:
  - Start with a behavior for each state s in start(A)
  - For each transition (s,a,s') in trans(A) enabled for some state s at the end of any known safe behavior:
    - Create a behavior with (a,s') appended
  - Repeat (possibly, for ever...)

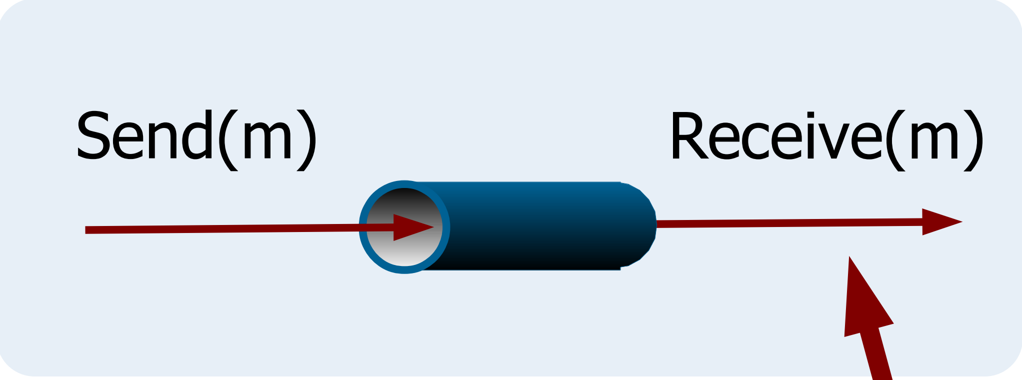
Safety properties

- Proof of safety properties:
  - Invariant proof by induction
- Strategies:
  - Strengthen the invariant
  - Include trace in state

Invariants

- Goal: Prove that always vcnt < 4 (safety!).
- Proof by induction:
  - Base step: True for all initial states?
    - 3<4: Yes!
  - Induction step: True for any next step?
    - Timeout transition:
      - vcnt-after = vcnt-before - 1
      - vcnt-before < 4
vcnt-after+1 < 4
vcnt-after < 3 < 4: Done
    - Ring transition:
      - always vcnt-after = vcnt-before = 0
      - 0<4: Done

Example: Reliable channel



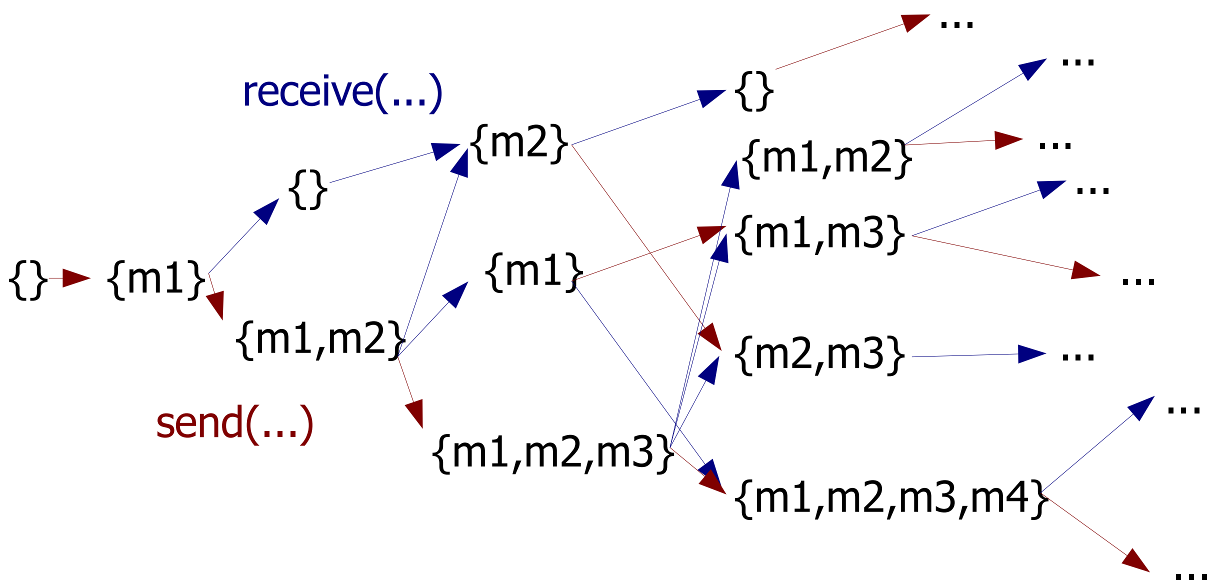
- Reliable channel:
  - Unordered
  - FIFO

Why *Receive(m)* and not *m := Receive()*?

Example: Reliable channel

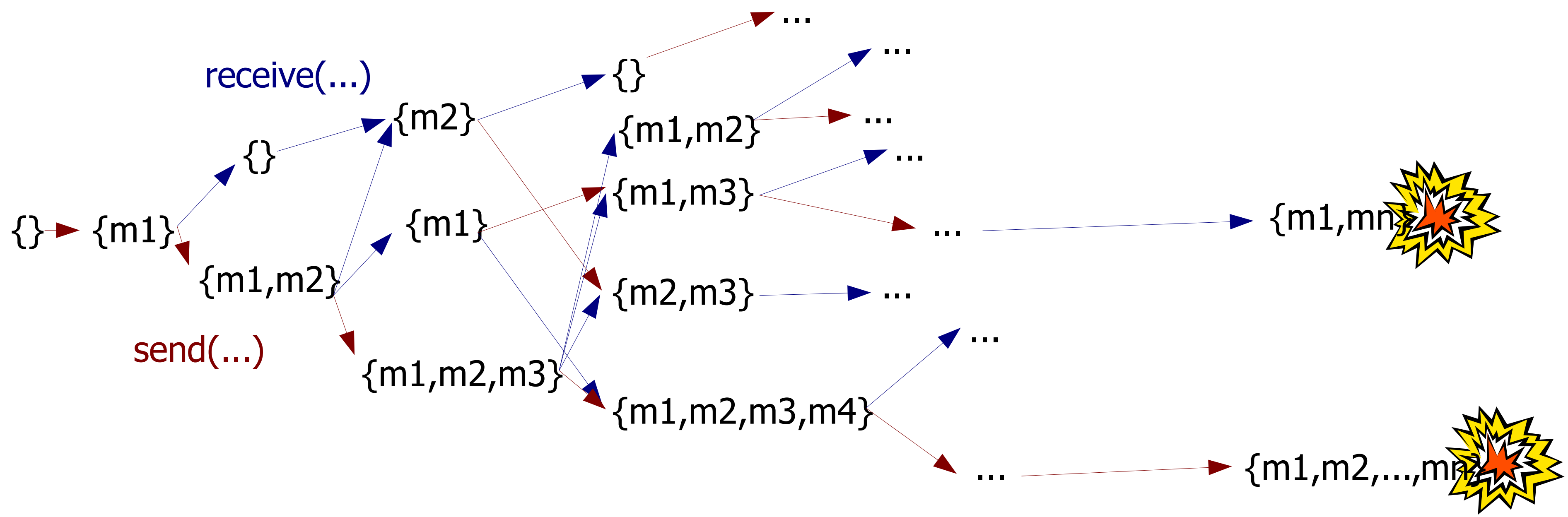
- State:
  - transit, bag of M, initially {}
- Send(m), m∈M:
  - Pre-condition:
    - True
  - Effect:
    - transit :=transit + {m}
- Receive(m), m∈M:
  - Pre-condition:
    - m in transit
  - Effect:
    - transit := transit - {m}

Behaviors of a channel



- Concurrency is modeled by alternative enabled transitions:
  - Sender and receiver
  - Within the channel (reordering)

Liveness and fairness

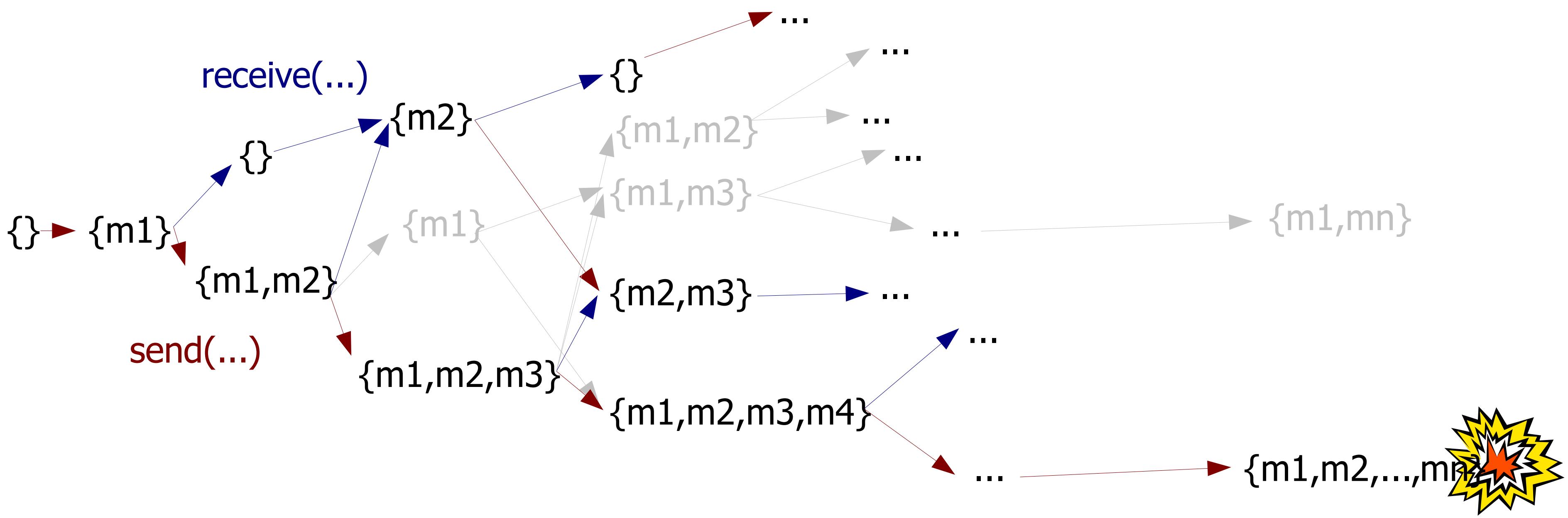


- Some behaviors do not satisfy liveness:
  - If m is sent, eventually m is received
- Some transitions don't get a fair chance to run:
  - receive(m1) and receive(m*)

Fairness

- Partition transitions in tasks:
  - Tasks:
    - For all m: {receive(m)}
- Assume that no task can be forever prevented from taking a step
- What about a FIFO reliable channel?

Liveness and fairness



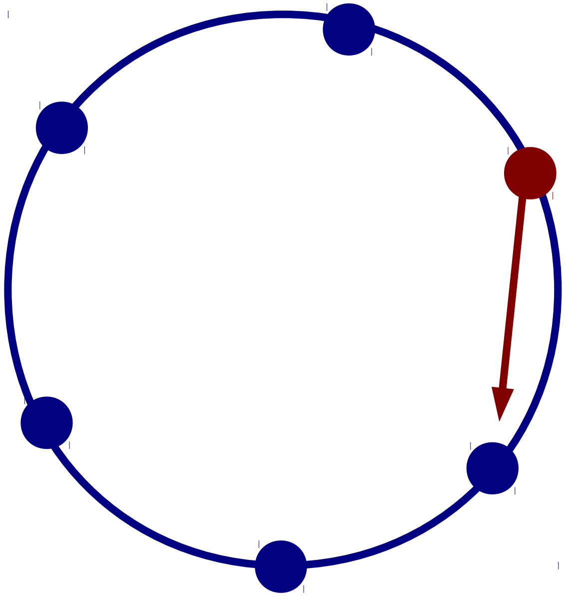
- FIFO order excludes a number of behaviors
  - Only executions with a finite number of receive(m) steps are unfair
- Fairness ensured by a single task:
  - {For all m: receive(m)}

Example: FIFO channel

- State:
  - transit, seq. of M, initially <>
- Send(m), m∈M:
  - Pre-condition:
    - True
  - Effect:
    - transit:=transit+<m>
- Receive(m), m∈M:
  - Pre-condition:
    - m=head(transit)
  - Effect:
    - transit := tail(transit)
- Tasks:
  - {For all m: receive(m)}

Example: Token ring

- Rotating token algorithm:



- Mutual exclusion?
- Deadlock freedom?

Example: Token ring

- State:
  - n is the number of nodes
  - token[0]=1
  - token[i]=0, for $0<i<n$
- Move(i):
  - Pre-condition:
    - token[i]=1
  - Effect:
    - token[i]:=0
    - token[(i+1) mod n]:=1

Example: Token ring

- Mutual exclusion:
  - There is at most one token in the ring (i.e. sum of token[i]$\leq$1)
- Proof by induction:
  - Base step:
    - $\sum$token[i]=1 trivially true
  - Induction step:
    - $\sum$token-before[i]$\leq$1$\Rightarrow$$\sum$token-after[i]$\leq$1

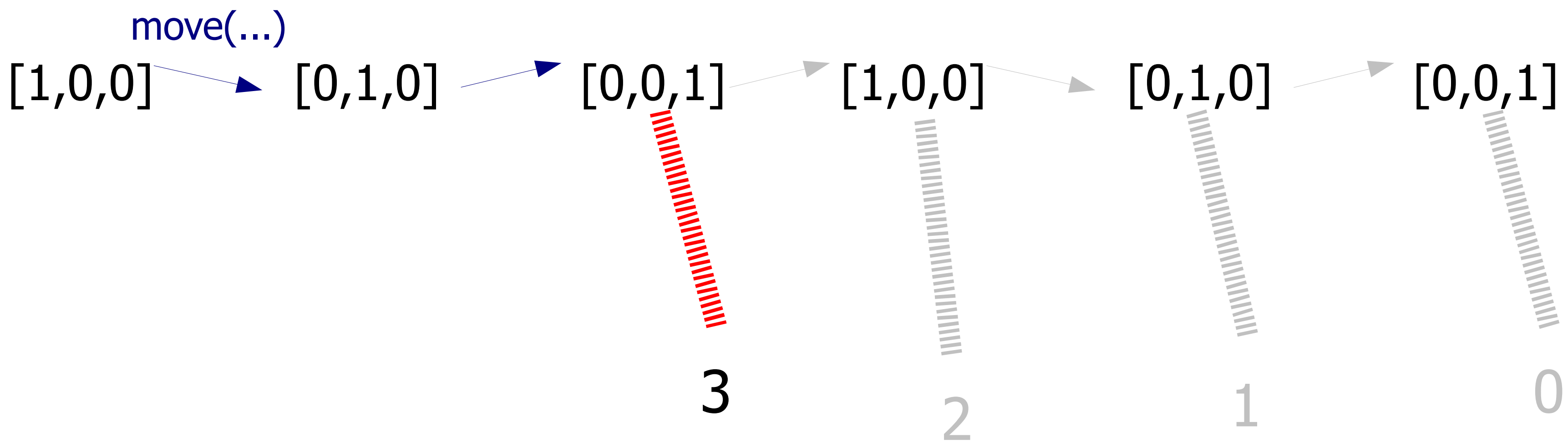
Example: Token ring

- No starvation:
  - Eventually i gets the token at least k times
- Proof with a progress function:
  - Function from state to a well-founded set
  - Helper actions decrease the value
  - Other actions do not increase the value
  - Helper actions are taken until goal is met (i.e. enabled and in separate tasks)

Invariant assertion

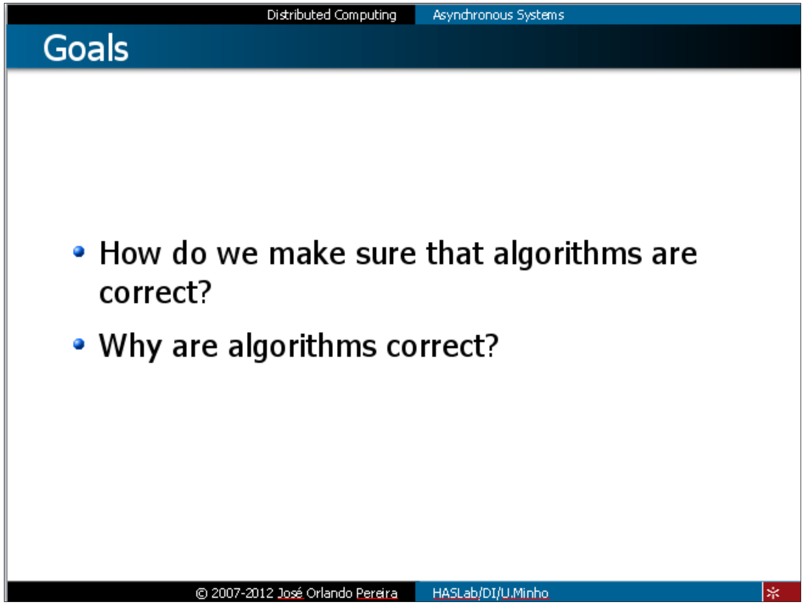
Progress function

- Define progress function f as:
  - Target is non-negative integers
  - Value is ((k-1) x n + i - 1) - length(trace)
- Example with n=3, k=2, and i=3:



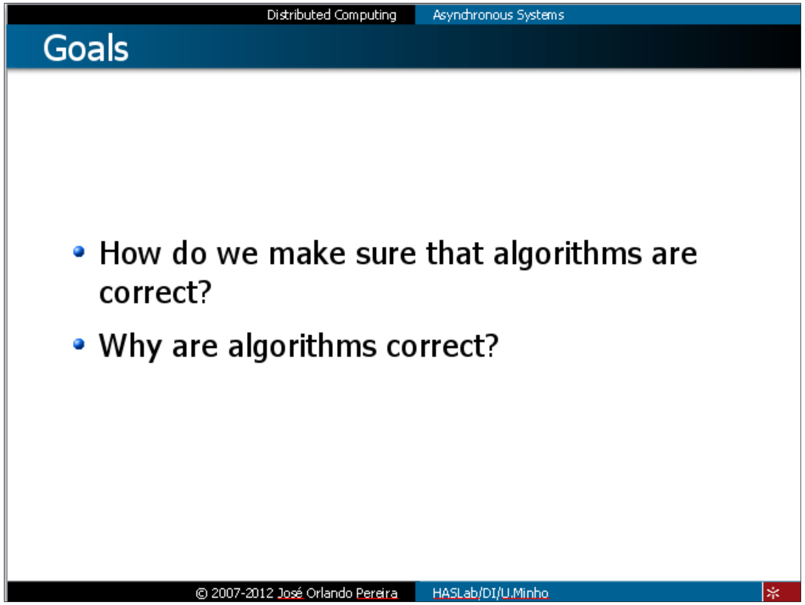
Conclusion

- First goal achieved:
  - I/O Automata
  - Safety and liveness proofs
- More:
  - Composition
  - Refinement



Goal 2: Why is it correct?

- To what extent does local state reflect global state?

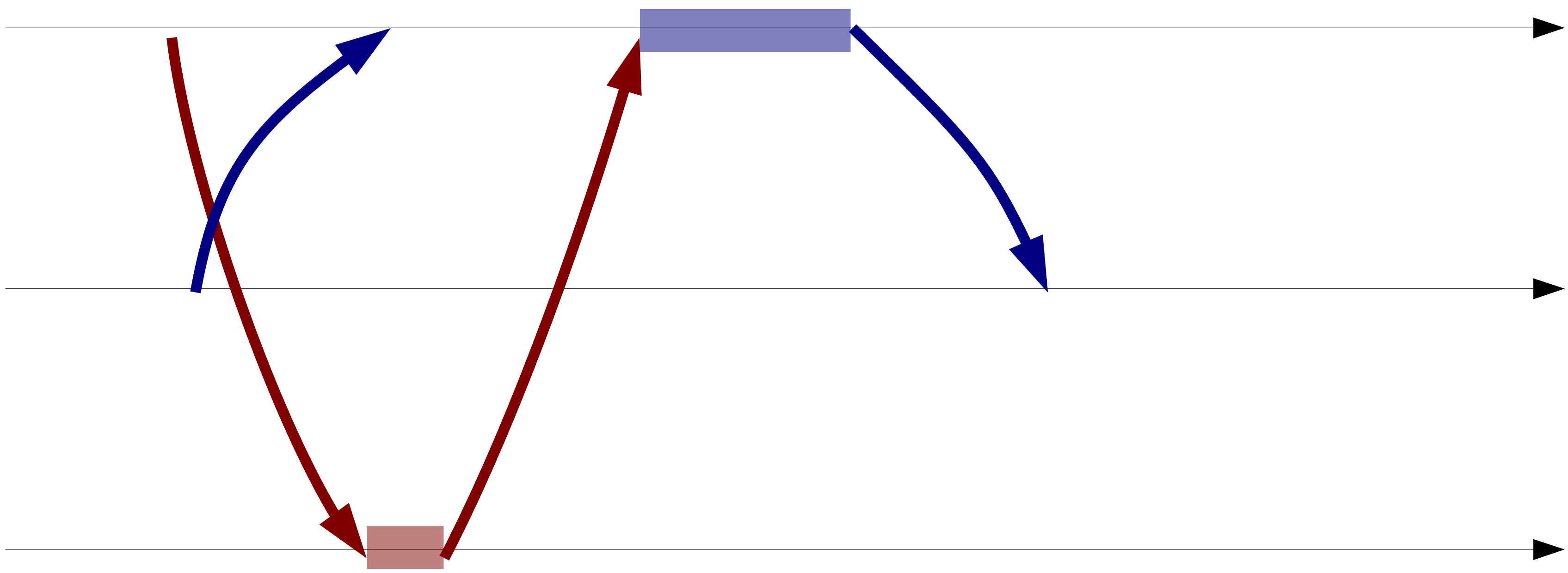


Example: Distributed deadlock

- Remote invocation
- All processes request and reply to invocations
- A mutex is held while invoking remotely or handling remote invocations
- Distributed deadlock possible when multiple processes invoke each other

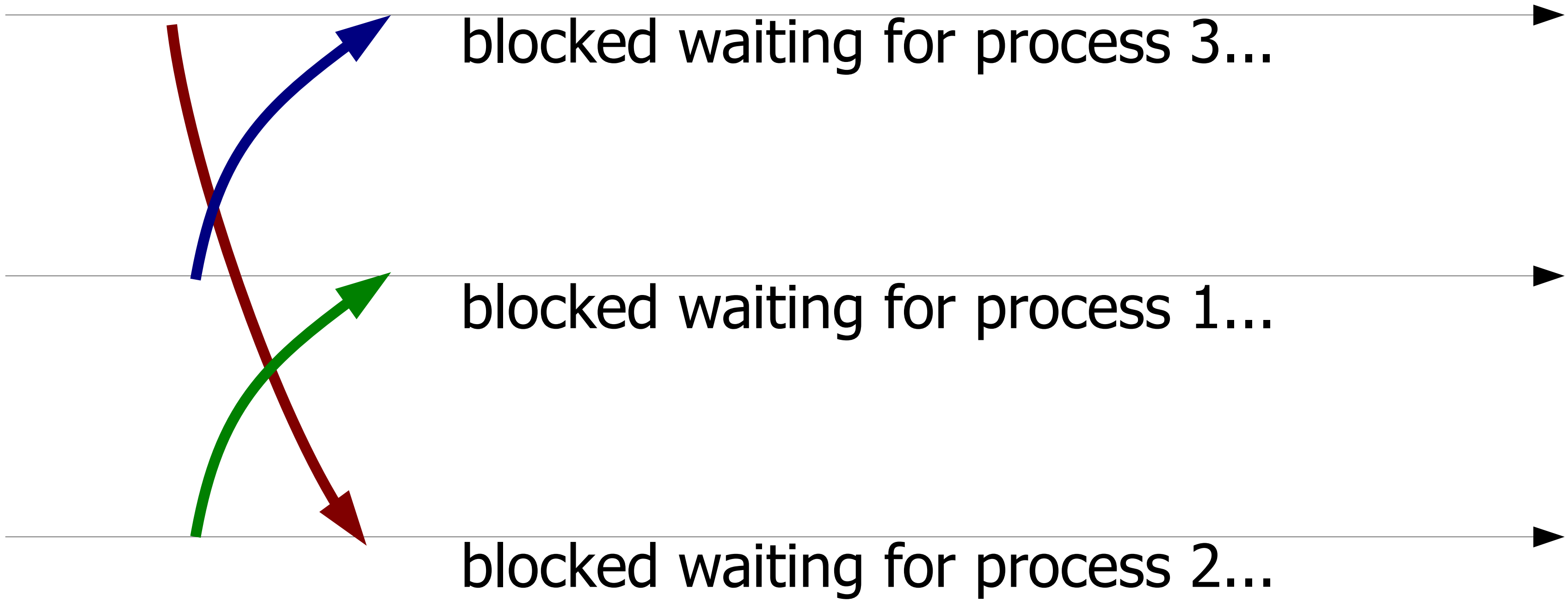
Example: Distributed deadlock

- Deadlock-free run:



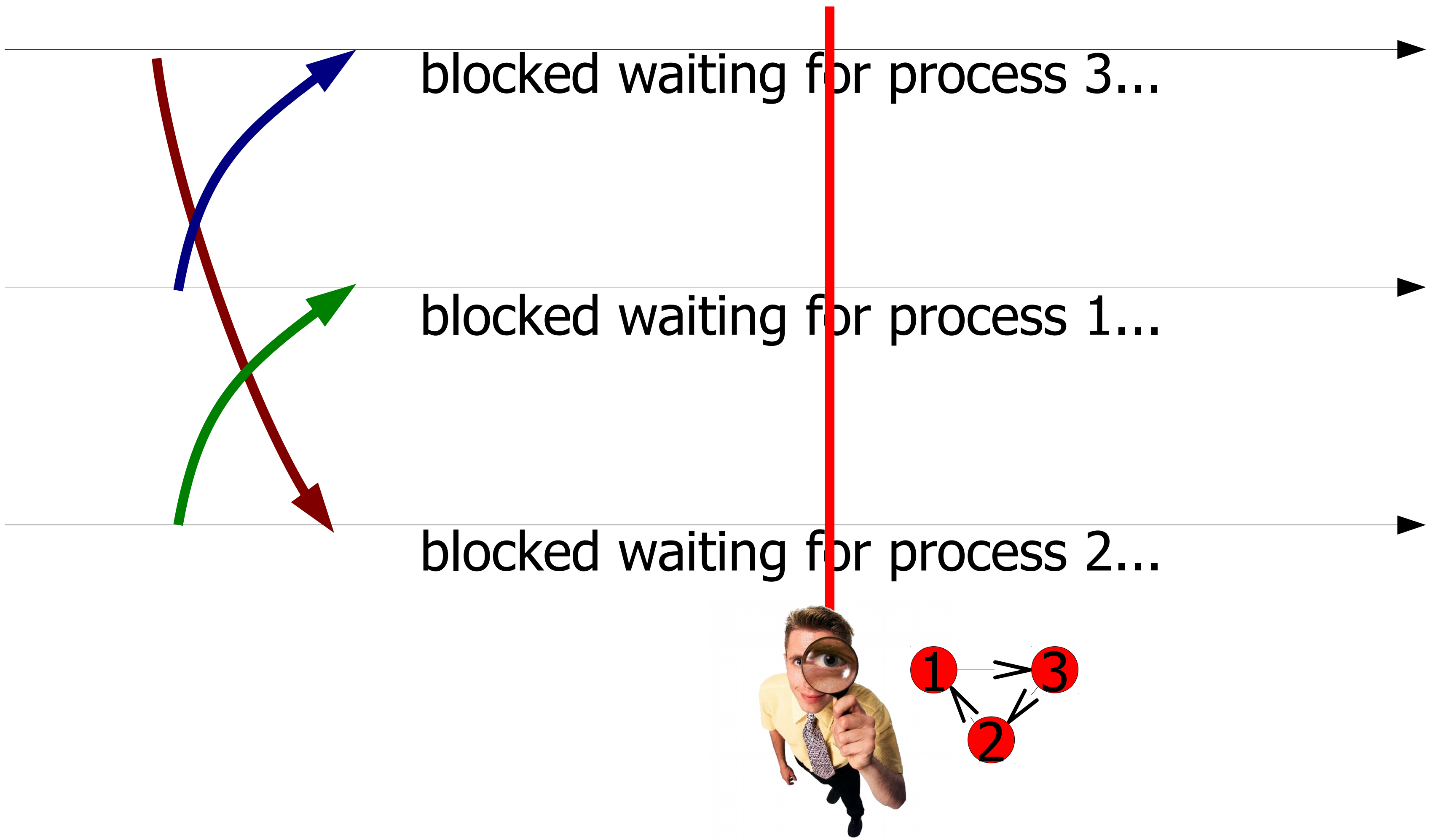
Example: Distributed deadlock

- Distributed deadlock:



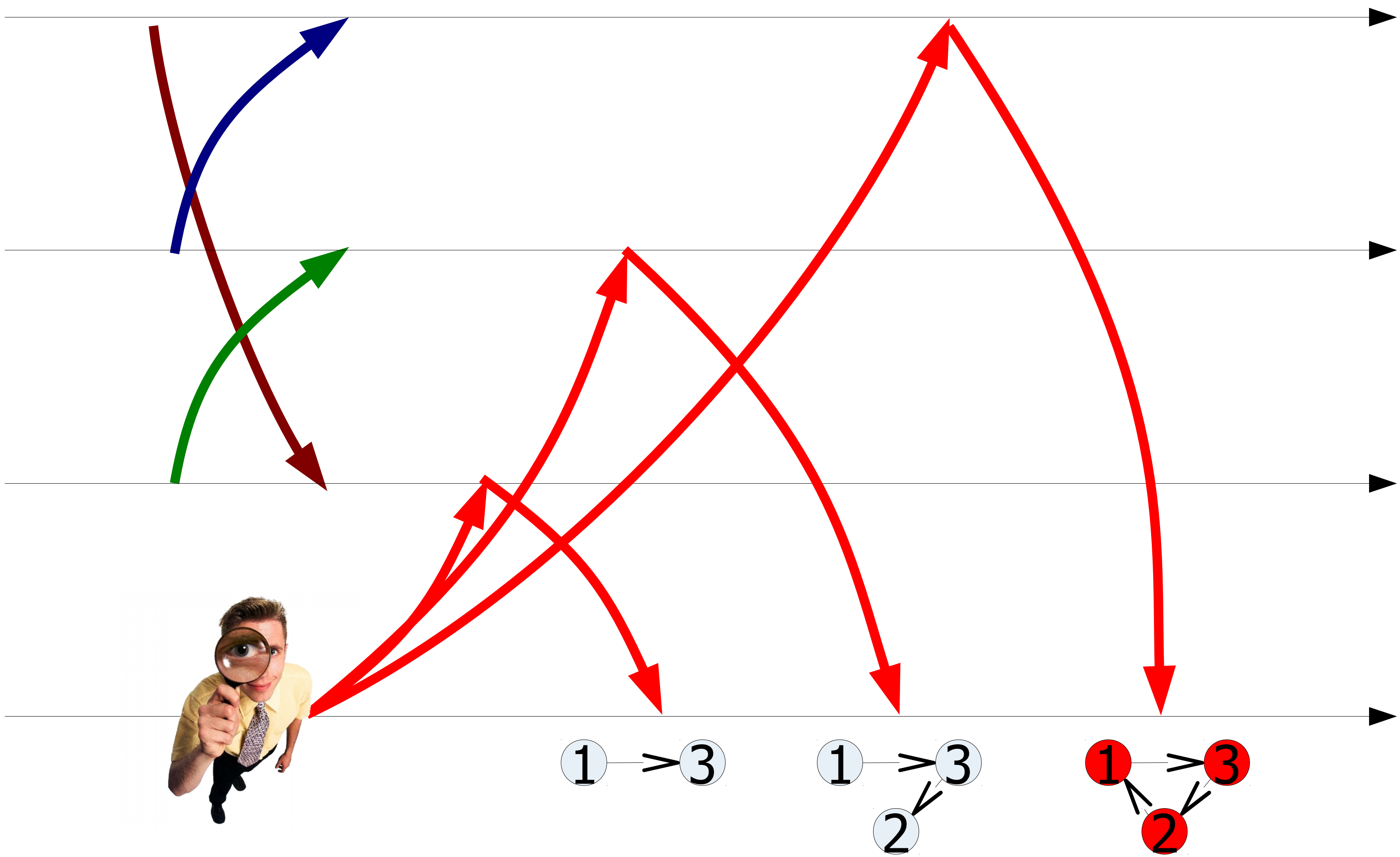
Example: Distributed deadlock

- Instant observation is impossible:



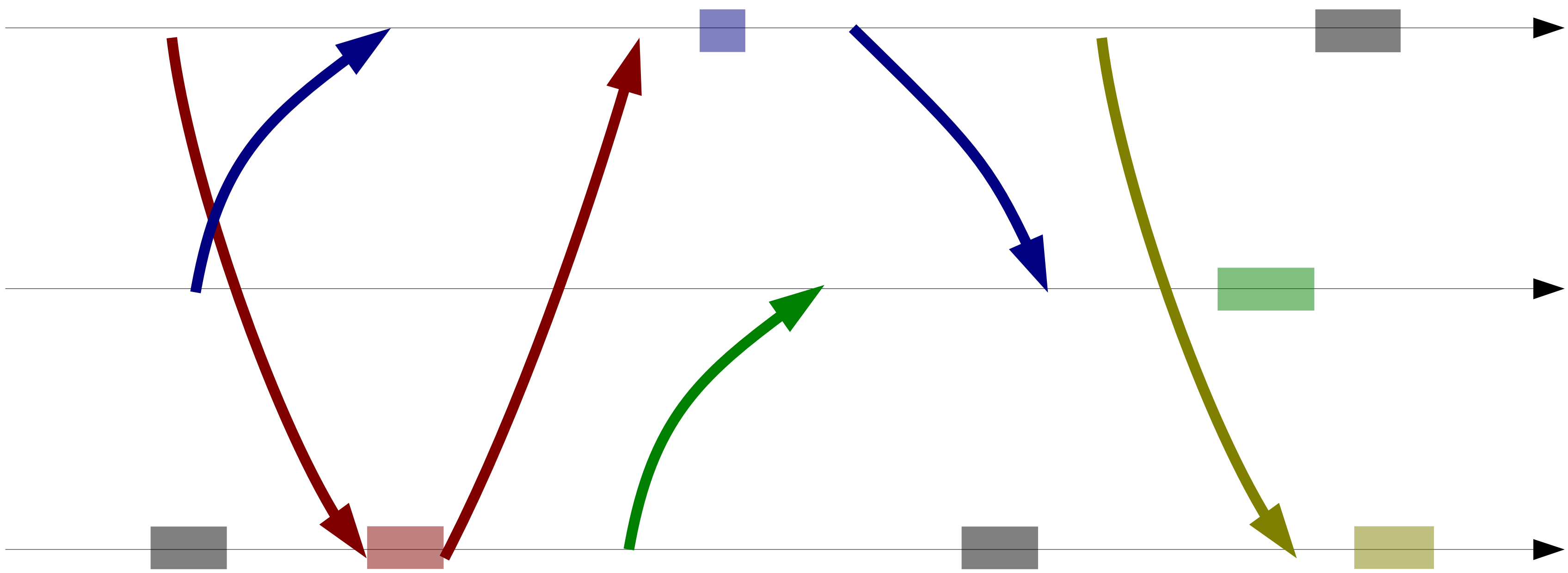
Example: Distributed deadlock

- Deadlock detection with a “wait for” graph:



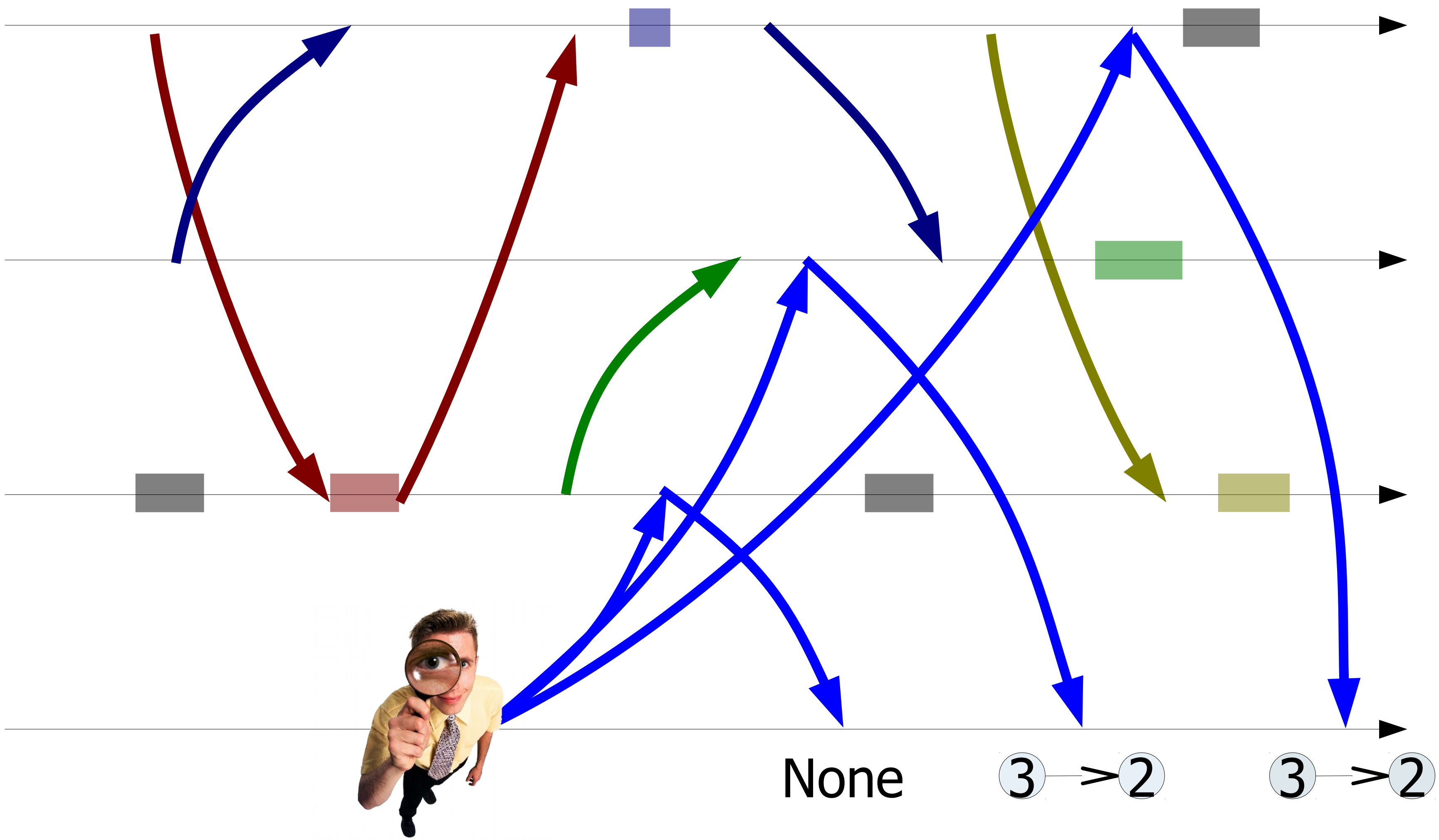
Example: Distributed deadlock

- A more complex deadlock-free run:



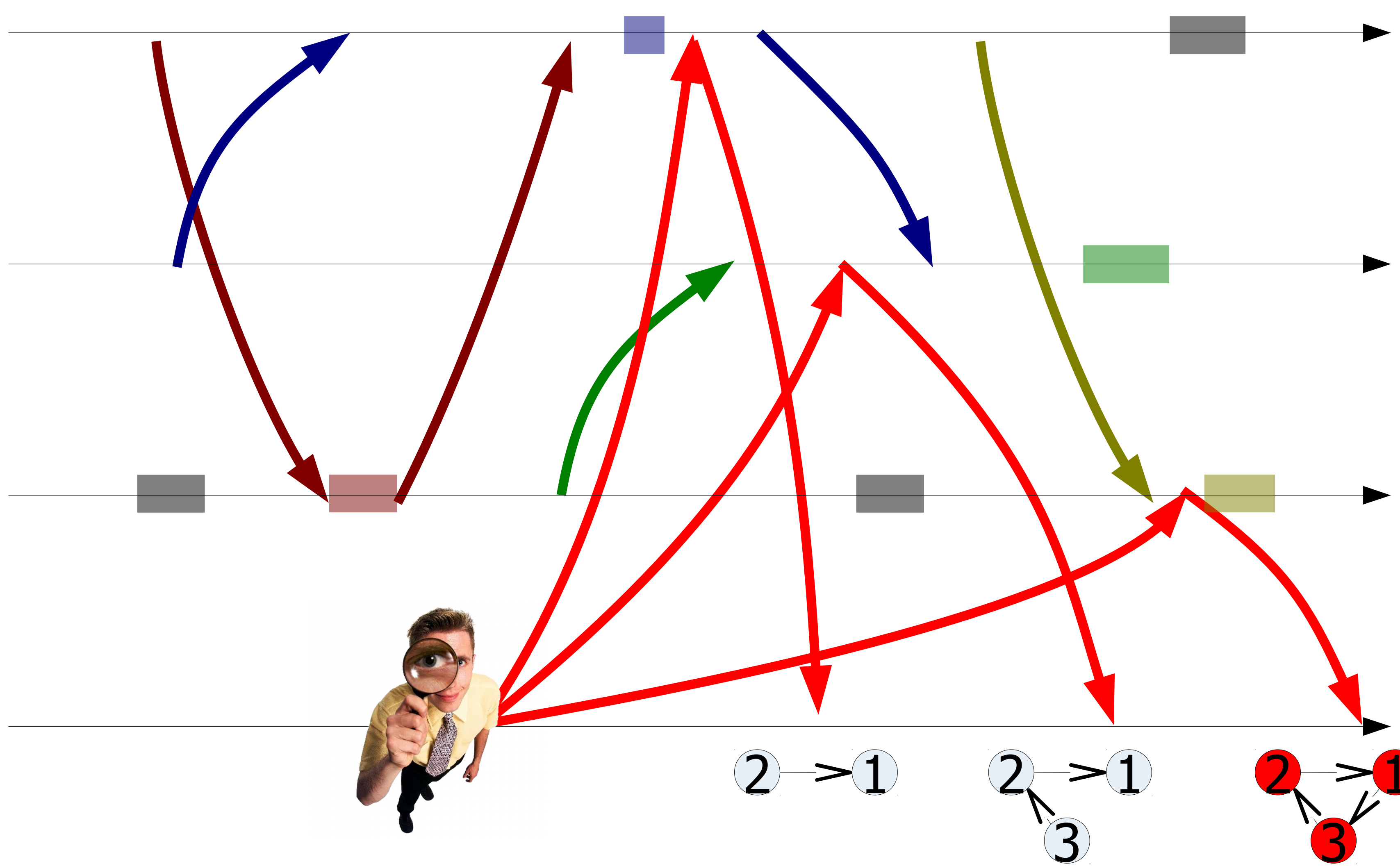
Example: Distributed deadlock

- A deadlock-free WFG:



Example: Distributed deadlock

- A WFG with a ghost deadlock:

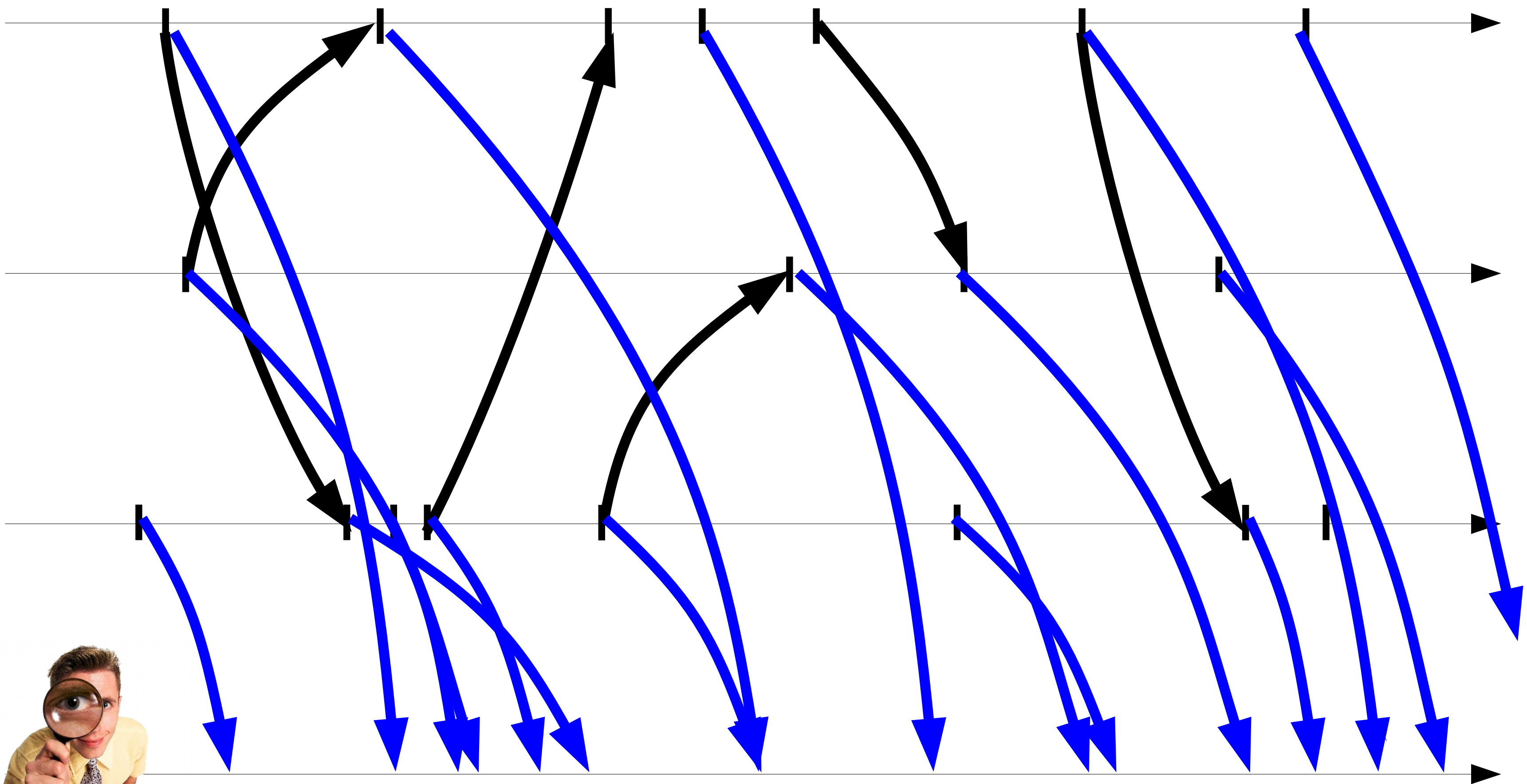


Global Property Evaluation

- All these problems are instances of the Global Property Evaluation (GPE) problem
- Can it be solved in an asynchronous system?
- Methods that can be used? Relative cost?

Passive monitor process

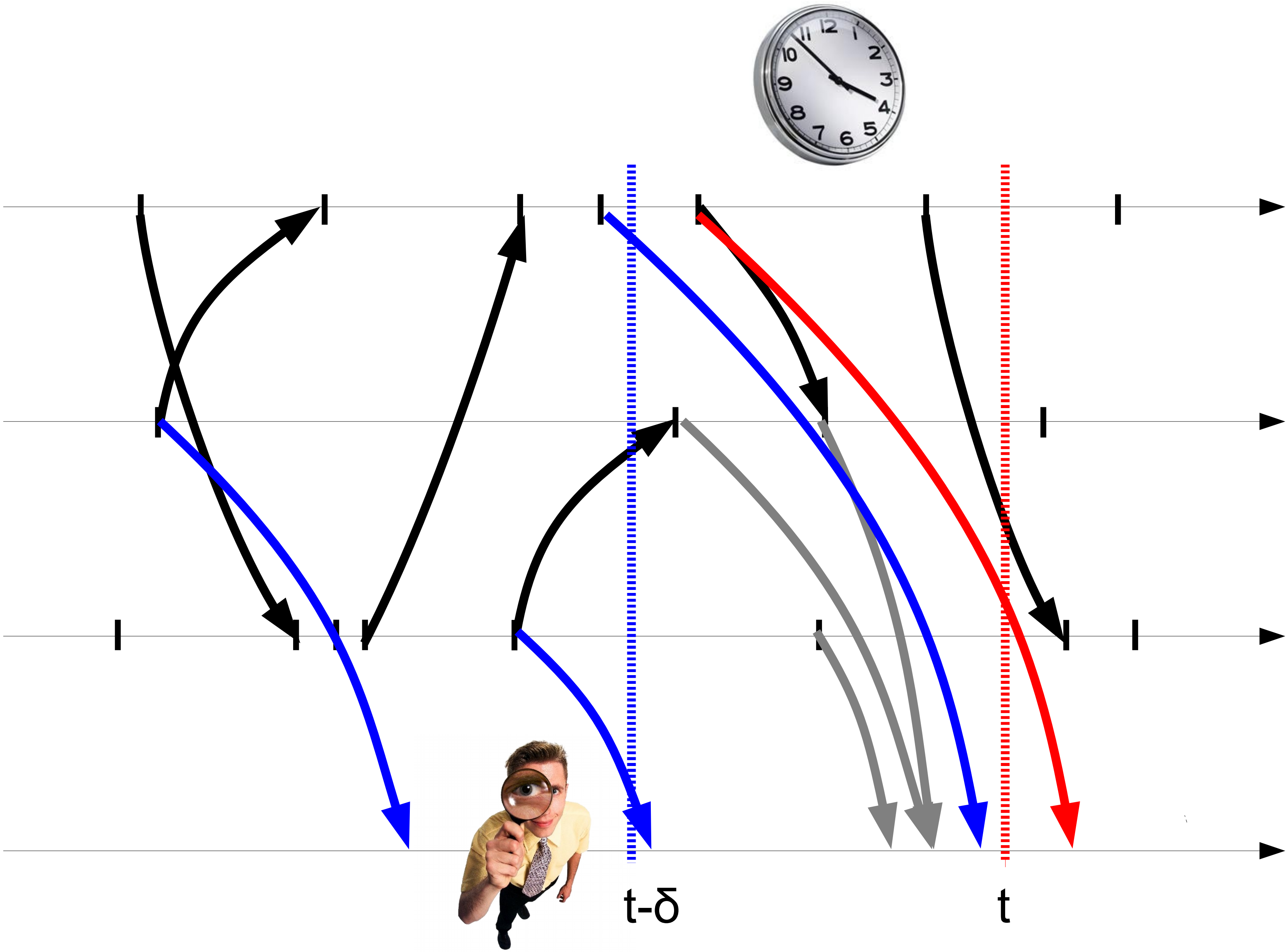
- Report all events to monitor:



First try: Synchronous system

- Global clock, δ upper bound on message delay
- Tag events with real time
- Consider events only up to t-δ
  - With synchronous rounds, this means using messages from the previous round!

First try: Synchronous system



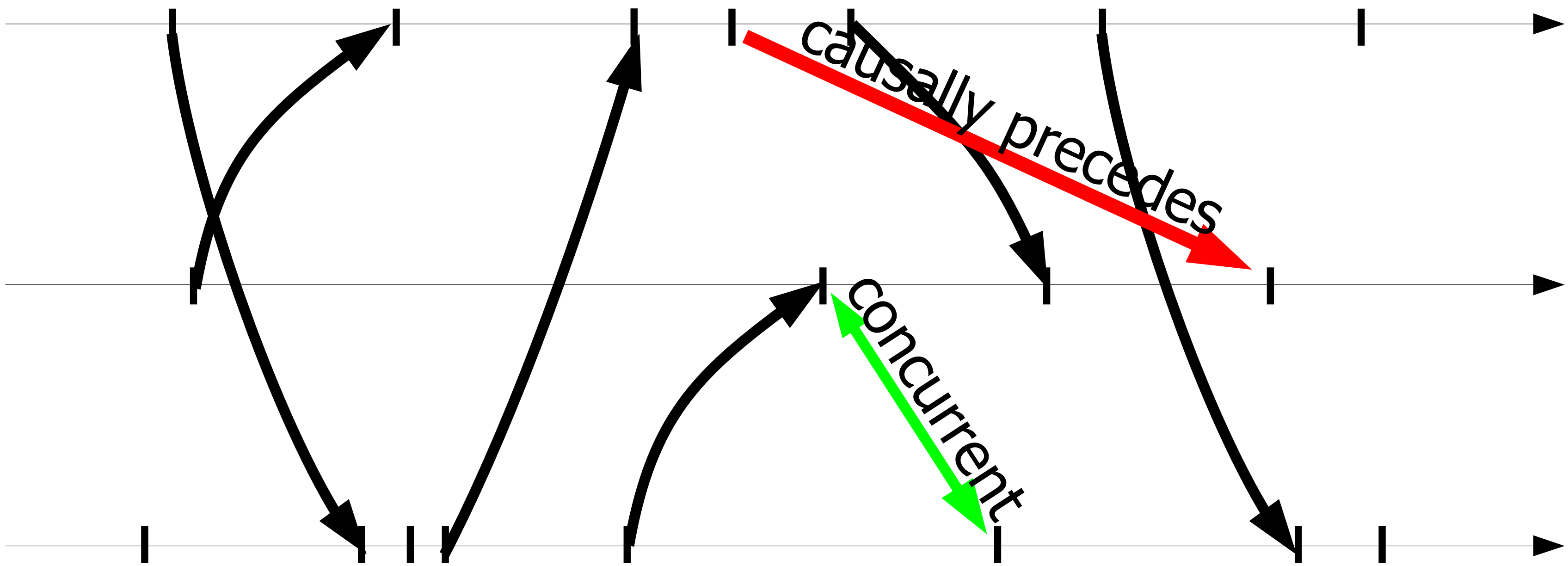
Clock properties

- What properties of a real-time clock make this approach correct?
- RC(i) the time at which i happened

Definition: Causality

- Events i and j are causally related ($i \rightarrow j$) iff:
  - i precedes j in some process p
  - for some m, i=send(m) and j=receive(m)
  - for some k, $i \rightarrow k$ and $k \rightarrow j$ (transitivity)
- Events i and j are concurrent ($i || j$) iff neither $i \rightarrow j$ or $j \rightarrow i$

Causality



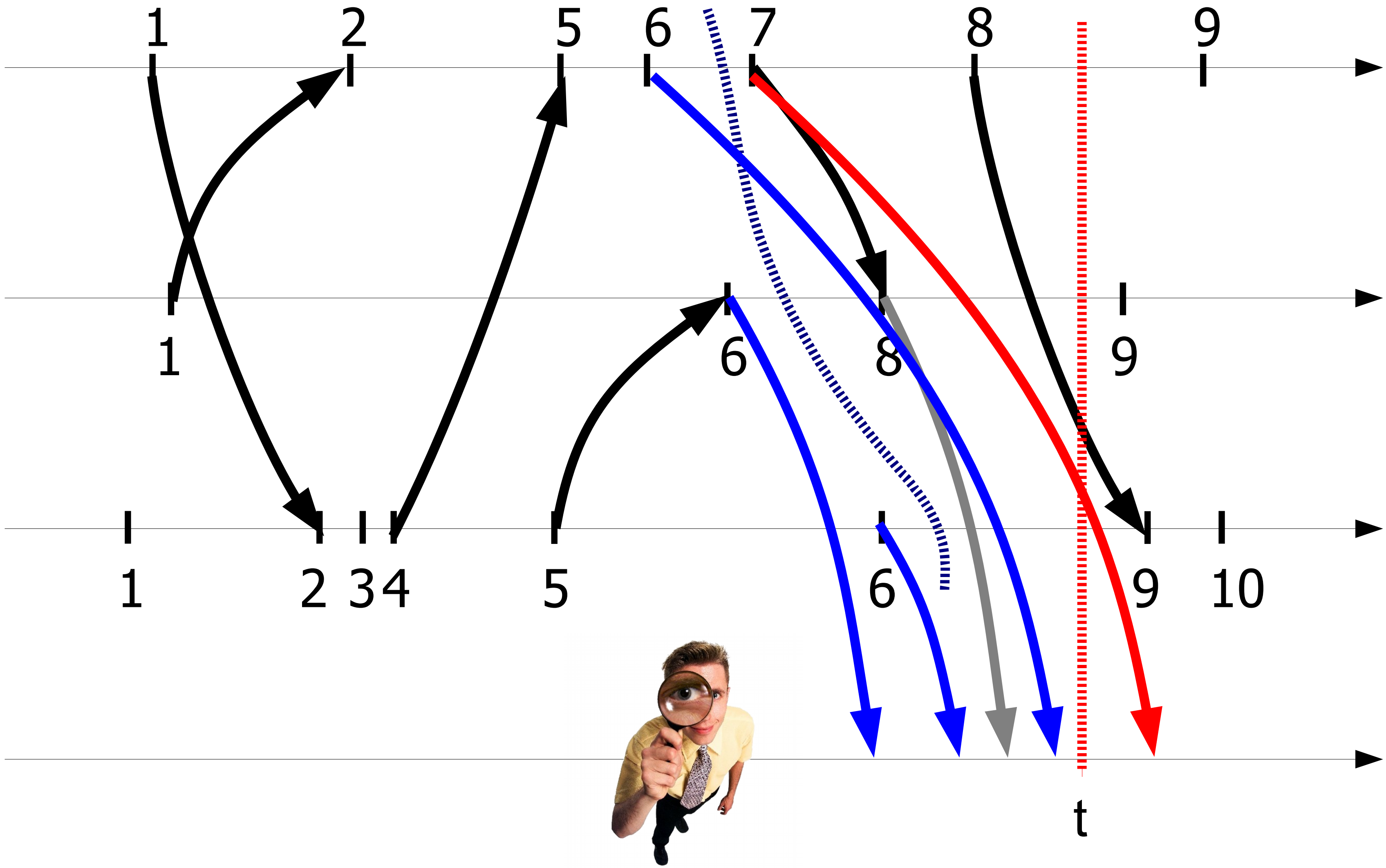
Clock properties

- If $i \rightarrow j$ then $RC(i) < RC(j)$
- For some event j:
  - When we are sure that there is no unknown i such that $RC(i) < RC(j)$
  - Then there is no i such that $i \rightarrow j$
- Can we build a logical clock with the same property?

Second try: Logical clock

- Tag events as follows:
  - Local events: increment counter
  - Send events: increment and then tag with counter
  - Receive events: update local counter to maximum and then increment
- Use FIFO channels
- Consider events only up to the minimum of maximum tags

Second try: Logical clock



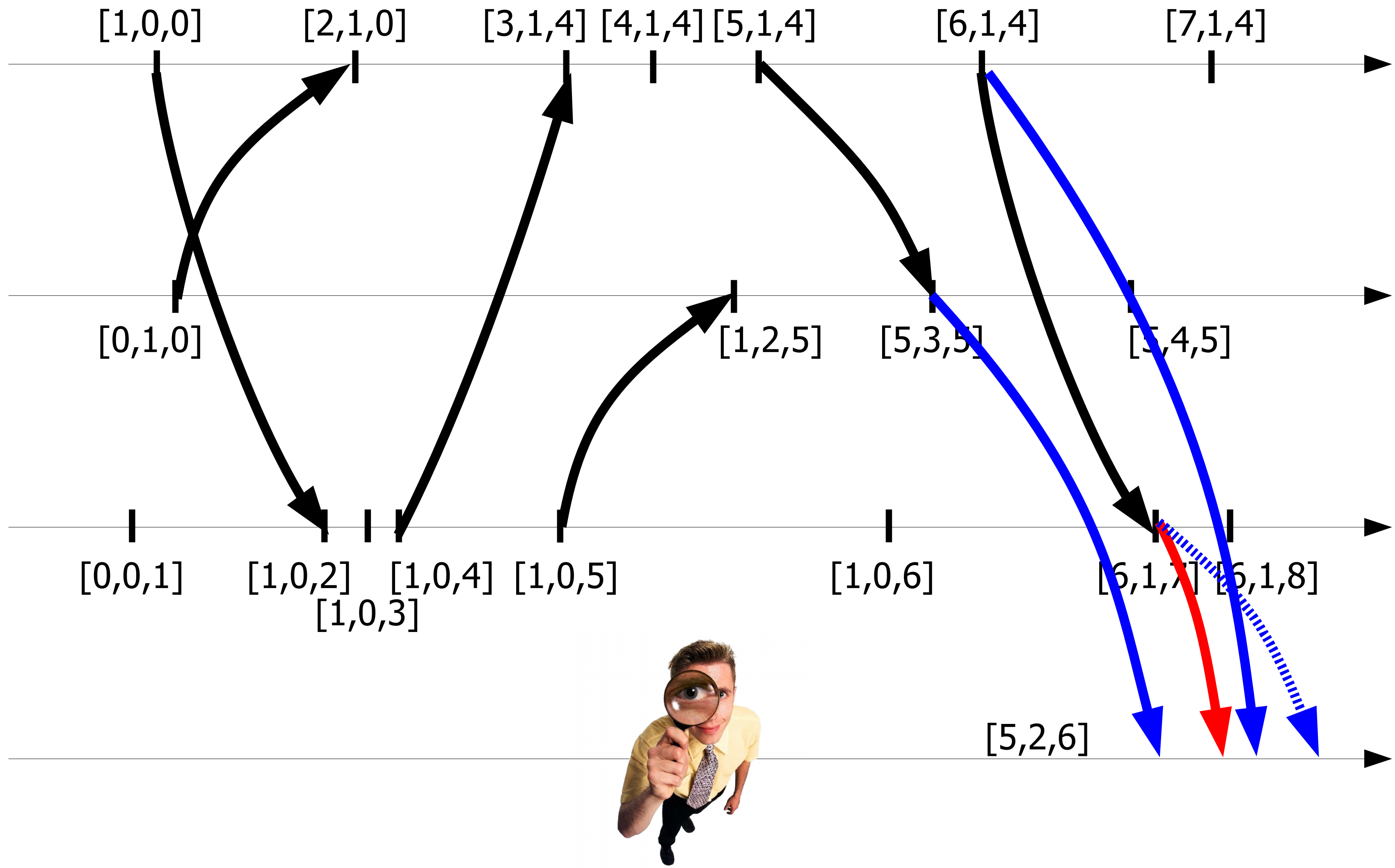
Scalar clocks

- Synchronous system (RC):
  - Delay δ to consistency
- Asynchronous system (LC):
  - Possible unbounded delay to consistency
  - Blocks if some process stops sending messages

Third try: Vector clock

- Tag events with a vector as follows:
  - Local event at i: increment counter i
  - Send event at i: increment counter i and tag with vector
  - Receive event at i: update each counter to maximum and increment counter i

Third try: Vector clock



Causal delivery

- The monitor delivers events as follows:
  - With local vector l[...]
  - For some r[...] from i
  - Wait until:
    - $l[i]+1=r[i]$
    - For all $j \neq i$: $r[i] \leq l[i]$
- The monitor is always in a consistent cut
- Blocking can be avoided by forwarding past messages

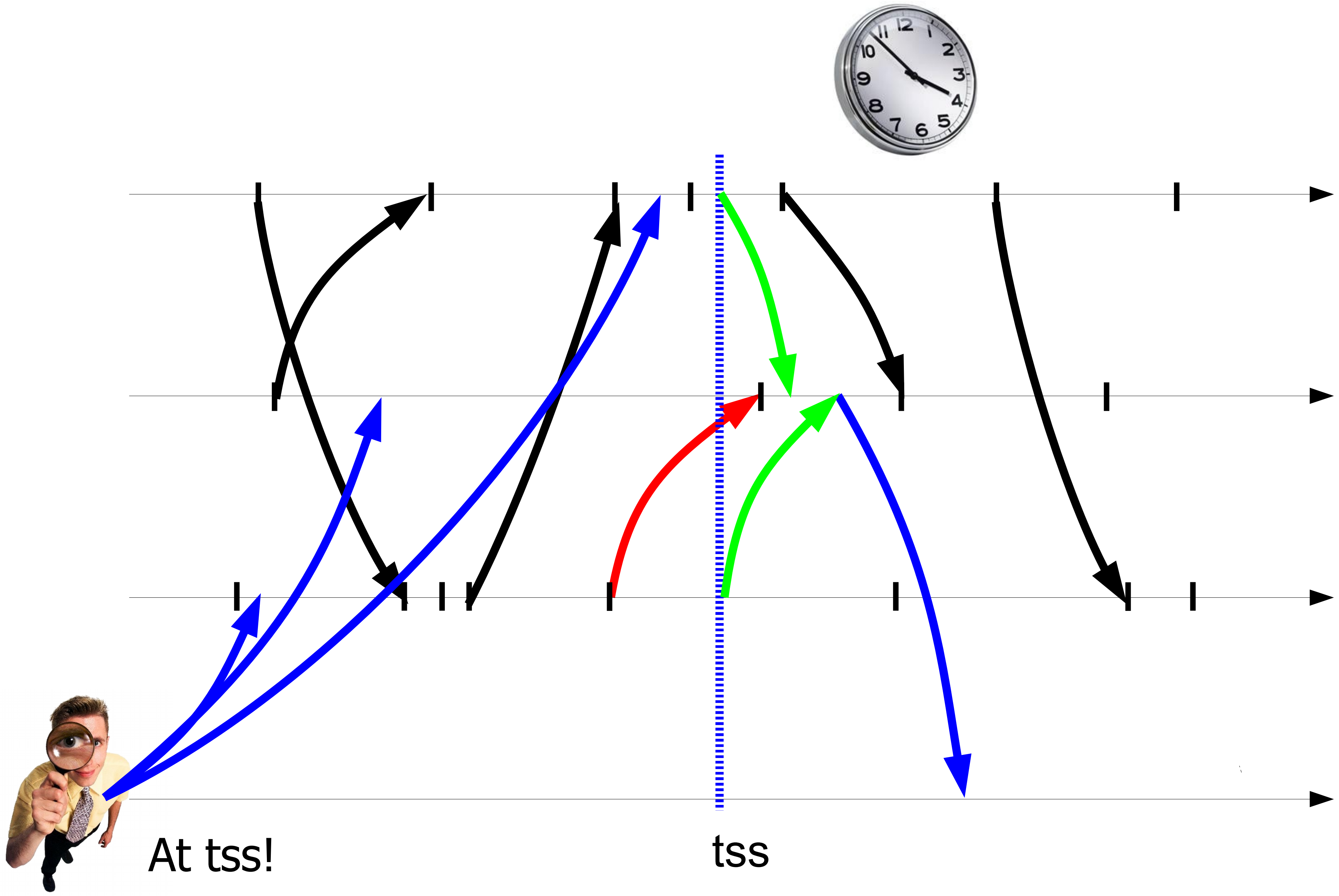
No reporting to monitor process

- Reporting all events to a monitor causes a large overhead
- Can a query be issued at some point in time?

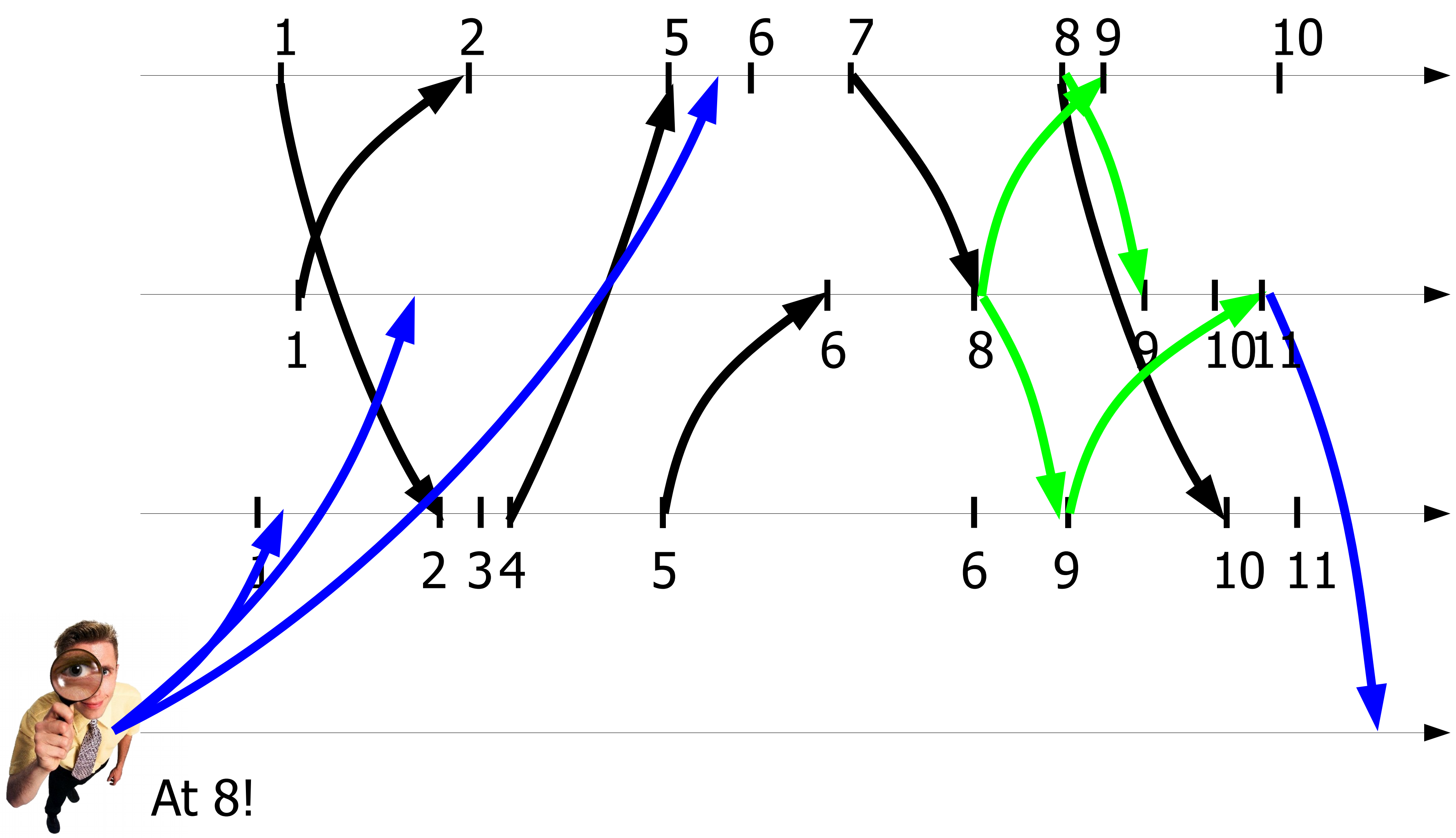
Fourth try: No reporting, synchronous

- Monitor broadcasts tss in the future
- At tss, each process:
  - Records state
  - Sends messages to all others
  - Starts recording messages until receiving a message with RC > tss
- After stopping, sends all data to monitor

Fourth try: No reporting, synchronous



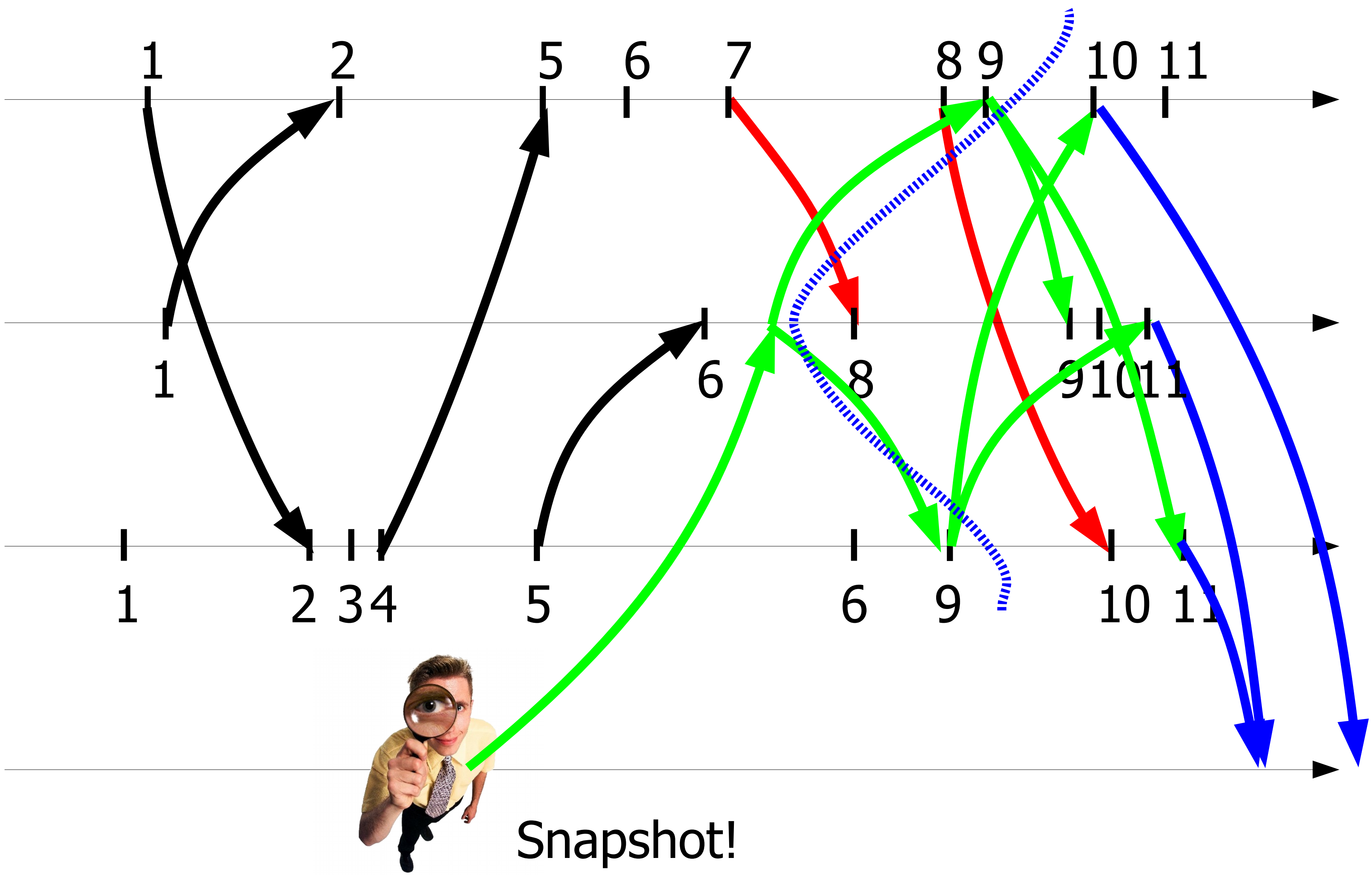
Fifth try: No reporting, logical clock



Chandy and Lamport

- Send a "Snapshot" message to some process
- Upon receiving for the first time:
  - Records state
  - Relays "Snapshot" to all others
  - Starts recording on each channel until receiving "Snapshot"
- Send all data to monitor

Chandy and Lamport



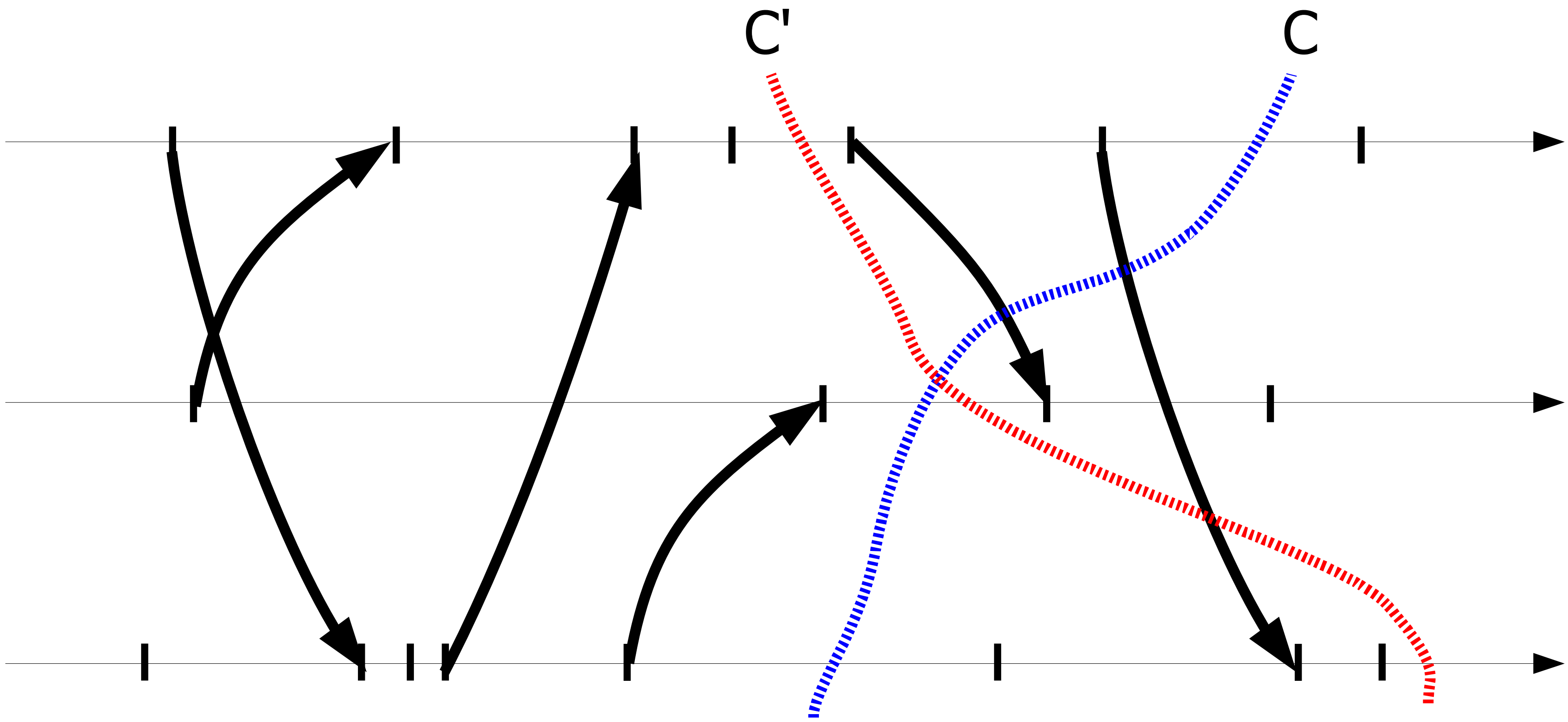
Global Property Evaluation

- GPE requires no gaps in observed history, regarding causality
- What properties can be evaluated?

Cuts and consistency

- A cut is the union of prefixes of process history
- A consistent cut includes all causal predecessors of all events in the cut
- Intuitive methods:
  - If a cut is an instant, there are no messages from the future
  - In the diagram, no arrows enter the cut
  - All events in the frontier are concurrent

Consistent cuts



Conclusion

- Second goal achieved:
  - Causality
  - Consistent cuts