Distributed Systems

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Global State & Distributed Debugging
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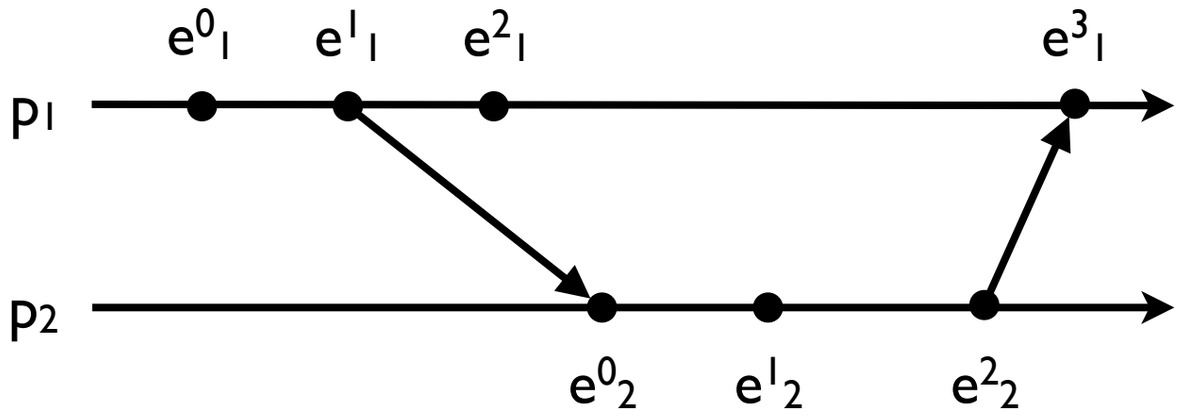
Global State: Consistent Cuts

- The global state is the combination of all process states and the states of the communication channels at an instant in time
  - So, if we had synchronized clocks, we could agree on a time for each process to record its state
- Since we cannot "stop time" to observe the *actual* global state, we attempt to find *possible* global state(s)
- A **cut** is a collection of prefix of the (combined) histories of the processes
  - partitioning all events into those occurring "before" and "after" the cut
- The goal is to assemble a meaningful global state from the the local states of processes
  - recorded at (possibly) different but concurrent times

Consistent Cuts



- A **consistent cut** is one which does not violate the happens-before relation →
- If $e_1 \rightarrow e_2$ and e_2 is in cut then e_1 is in cut. That is:
  - both e_1 and e_2 are in the cut or
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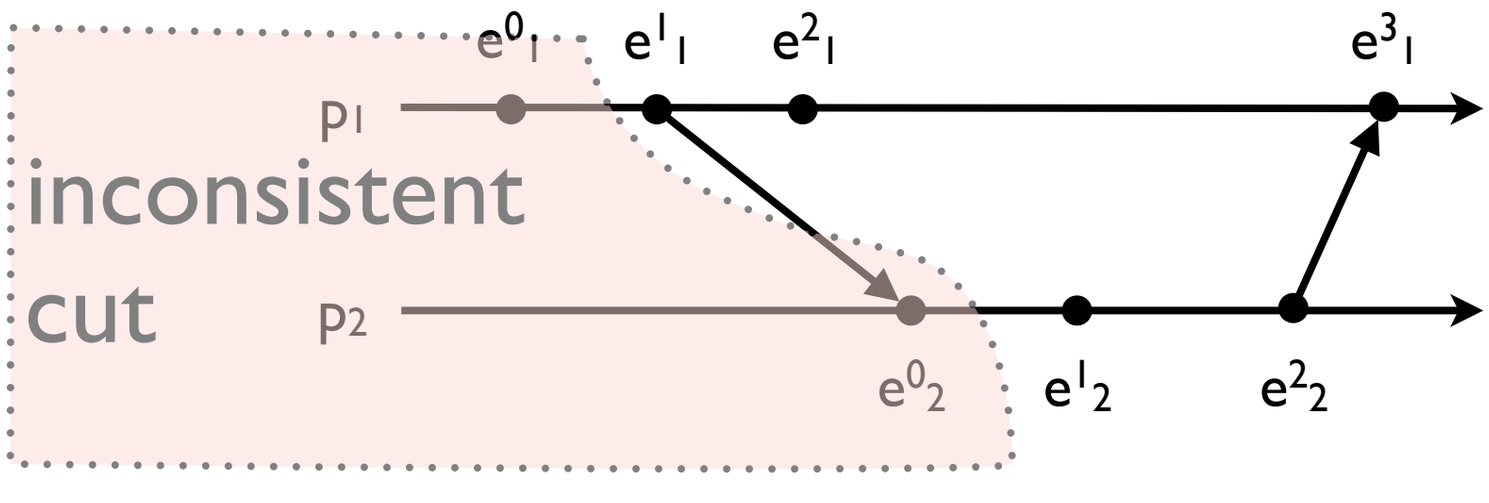

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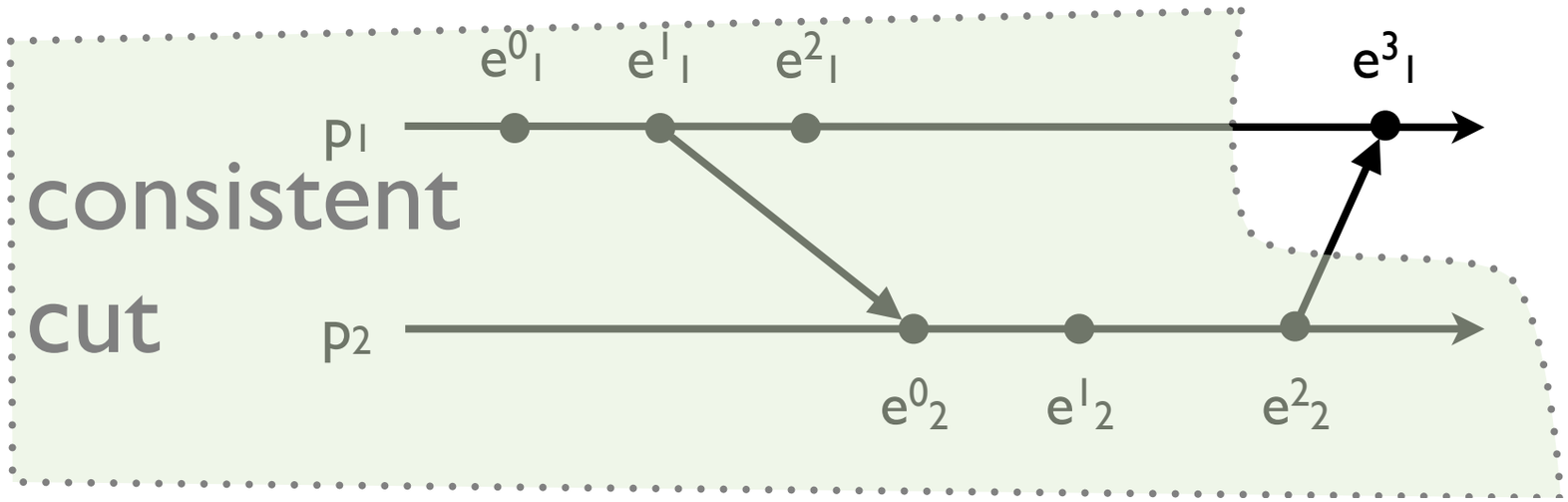

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Runs and Linearizations

- A *consistent global state* is one which corresponds to a consistent cut
  - Corresponds to a *frontier*: a set of *n* mutually concurrent events, one from each process $P_1 \ldots P_n$
  - $C = \{e_1,\ldots,e_n\}$ with $e_i \parallel e_j$ whenever $i \neq j$
- A "run" is a total ordering of all events in a global history which is consistent with the local history of each process
- A "linearization" is a total ordering of all events in the global history which is consistent with the happens-before relation →
  - So all linearizations are also runs
- Not all runs pass through consistent global states but all *linearizations* pass only through consistent global states

Global State: Safety and Liveness

- When we attempt to examine the global state, we are often concerned with whether or not a property holds
- Some properties, *B*, are "bad" properties we hope **never** hold
- and some properties, *G*, are "good" properties we hope **always** hold
- **Safety** property: a bad property *B* does not hold for any reachable state
- **Liveness** property: that a good property *G* always (eventually) holds for all reachable states

Global State: Stable and Unstable properties

- Some properties we wish to establish are **stable** properties
  - Such properties may never become true, but once they do they remain true forever
- Consider our four example problems:
  - Garbage is stable: once an object has no valid references (at a process or in transit) will never have any valid references
  - Deadlock is stable: once a set of processes are deadlocked they will always be deadlocked without external intervention
  - Termination is stable: once a set of processes have terminated they will remain terminated without external intervention
  - Debugging is not really a property but the properties we may look for whilst debugging are typically non-stable

Global State: Chandy and Lamport

- Many useful properties are stable
- Such properties may never become true, but once they do they remain true
- Our four example properties:
  - Garbage is *stable*: once an object has no valid references (at a process or in transit) will never have any valid references
  - Deadlock is *stable*: once a set of processes are deadlocked they will always be deadlocked without external intervention
  - Termination is *stable*: once a set of processes have terminated they will remain terminated without external intervention
  - Debugging is not really a property but the properties we may look for whilst debugging are likely *non-stable*

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- Any process may initiate a global snapshot at any time
- The processes may continue their execution and send/ receive normal messages whilst the snapshot takes place

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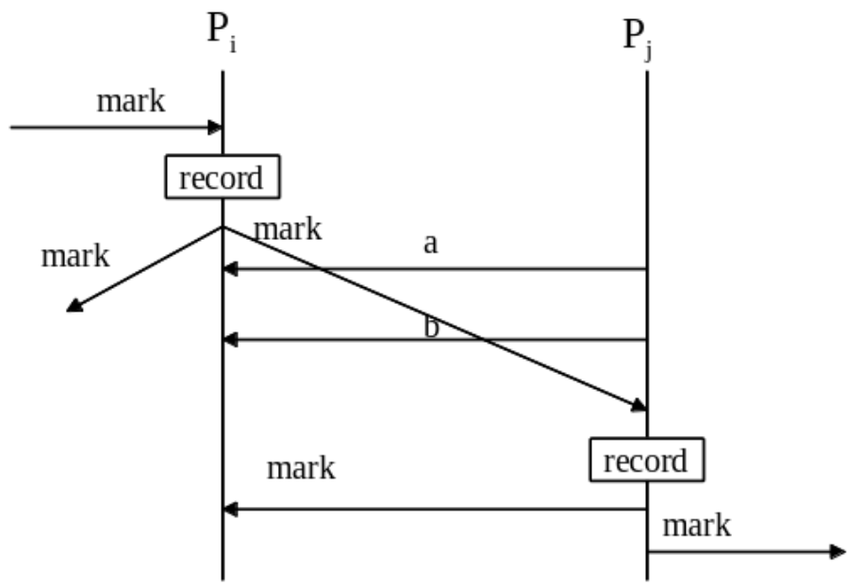
- Any process may initiate a global snapshot at any time
- The processes may continue their execution and send/ receive normal messages whilst the snapshot takes place
- Neither channels nor processes fail
- Communication is reliable: every message that is sent arrives at its destination exactly once (no repeats)
- Channels are unidirectional and provide FIFO-ordered message delivery.

Algorithm: Sender

Sending rule for process P_i

1. After P_i receives **marker** and has recorded its state:
2. P_i sends a **marker** message for **each** outgoing channel c
   - **before** it sends any other messages over c
   - **including** the channel that P_i received mark from

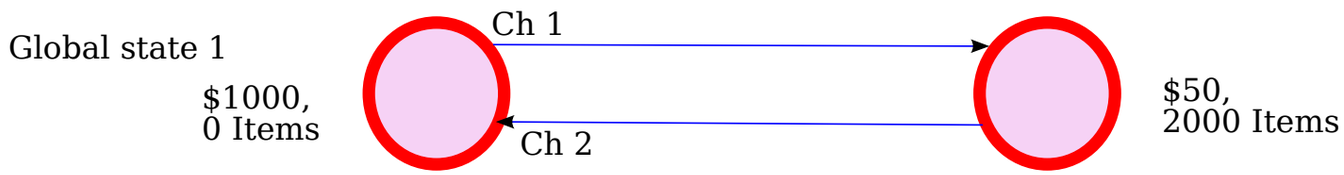


Algorithm: Receiver

Receiving rule for process P_i

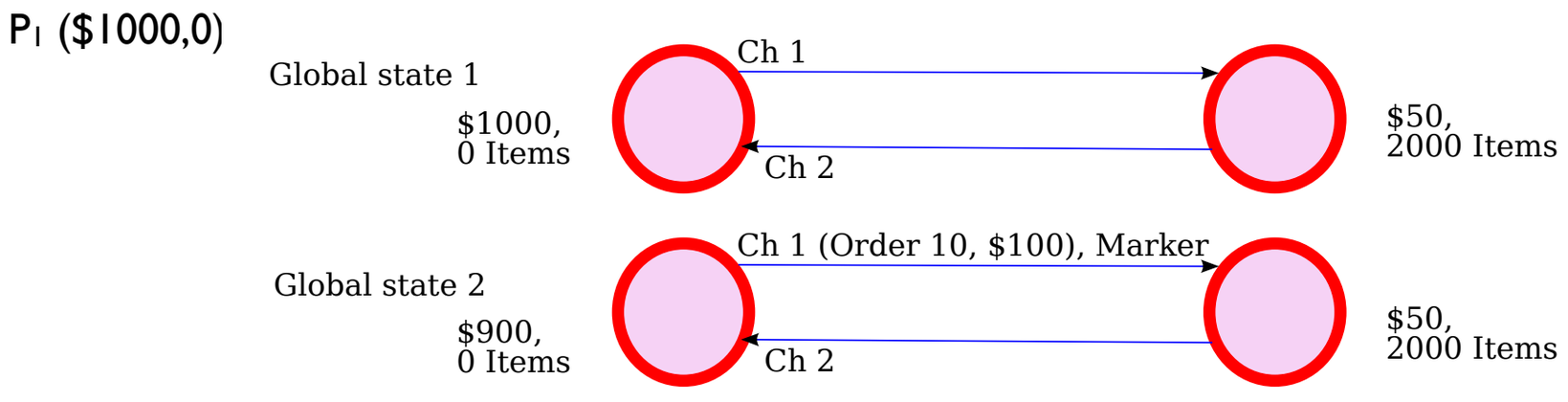
1. On receipt of a **marker** message over channel *c*:
2. **if** P_i has not yet recorded state:
   - record process state now
   - record the state of *c* as the empty set
   - turn on recording of messages arriving on all other channels
3. **else**
   - record the state of *c* as the set of messages it has recorded since P_i first recorded its state

Example



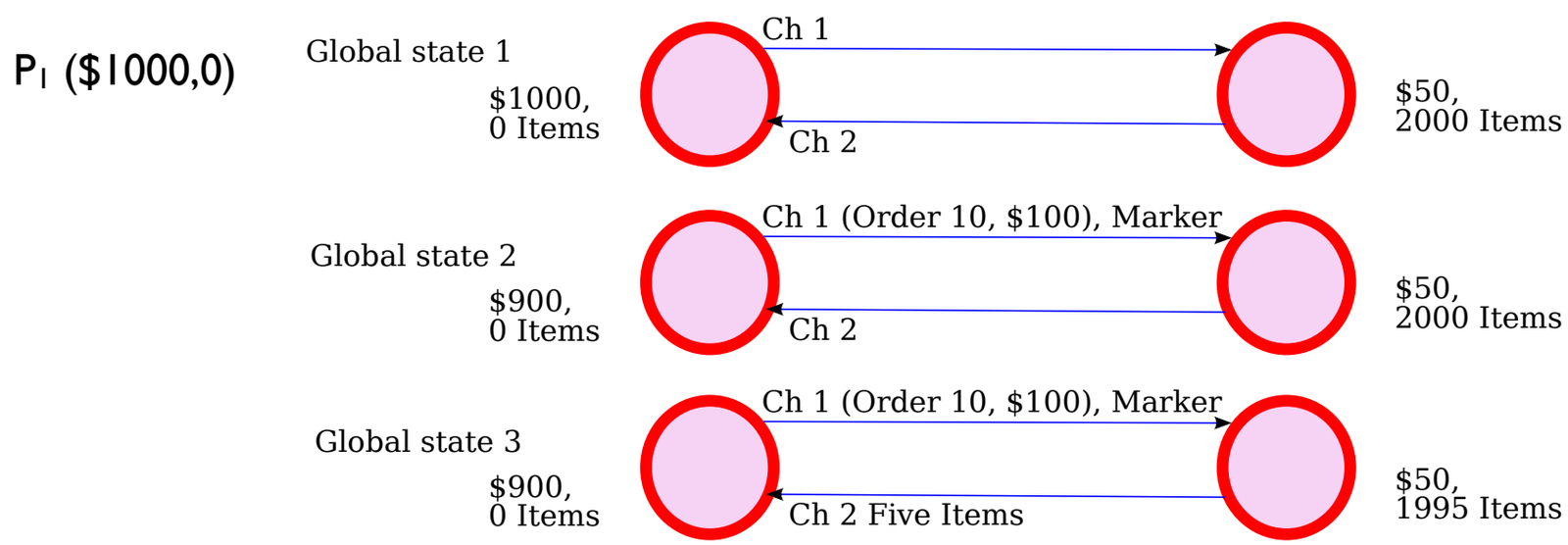
- We begin in this global state, where both channels are empty, the states of the processes are as shown, but we say nothing about what has gone before.

Example



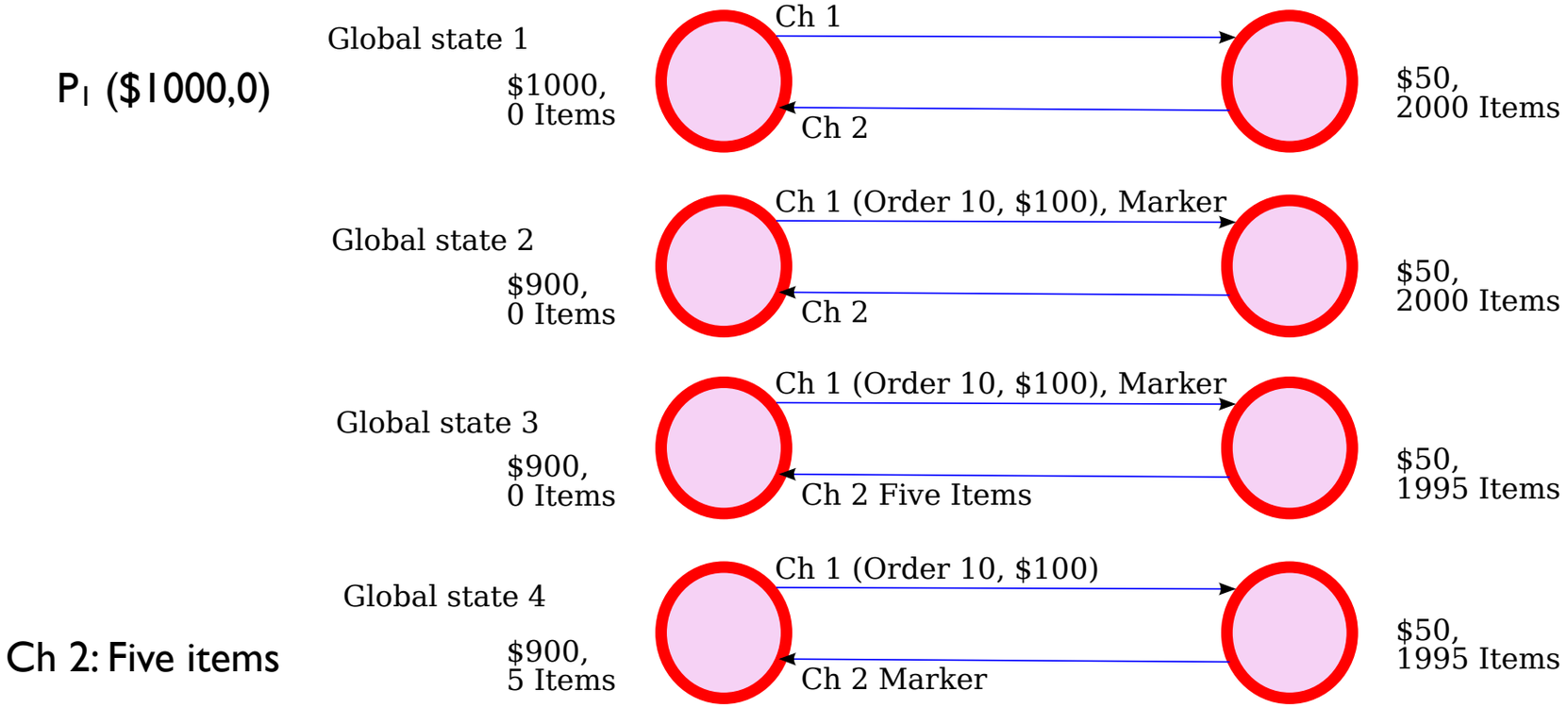
- P_1 decides to begin the snapshot algorithm and sends a Marker message over channel 1 to P_2.
- It then decides to send a request for 10 items at $10 each.

Example



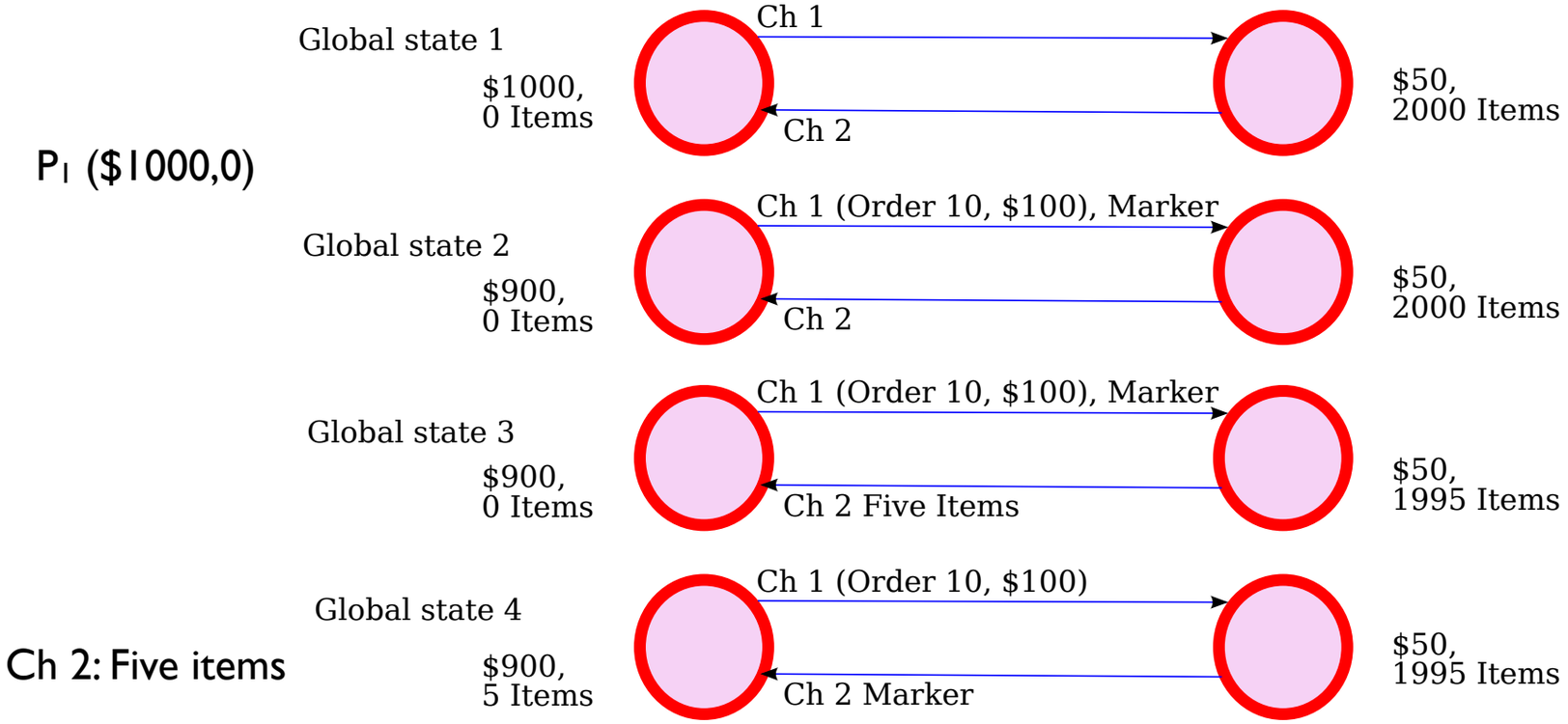
- Meanwhile, P_2 responds to an earlier request and sends 5 items to P_1 over channel 2.

Example



- P_2 receives the Marker message, records its state and sends P_1 a Marker message over channel 2.
- When P_1 receives this Marker message it records the state of channel 2 as containing the 5 items it has received since recording its own state.

Example

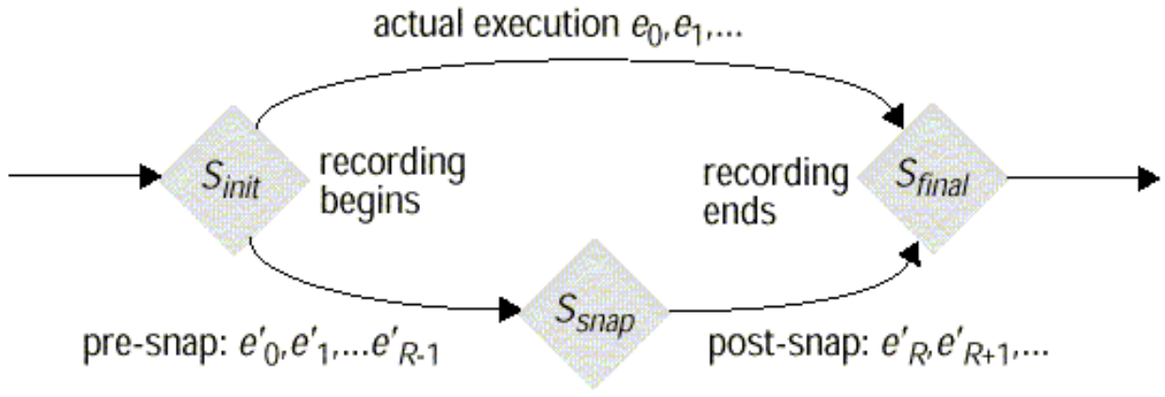


Notice that (in this story) *P2* didn't send "Five items" until **after** *P1* sent marker!
But there is no way to know this - the events are concurrent

Reachability

- The cut found by the Chandy and Lamport algorithm is always a **consistent** cut
- This means that the global state which is characterized by the algorithm is a consistent (possible) global state
  - Though it may not be one that ever "actually" occurred
- However, we can define a **reachability** relationship:
  - between the initial, observed and final global states when the algorithm is run
- Assume that the events actually occurred in a global order $H = e_1, e_2 \ldots$
  - Let S_{init} be the global state immediately before the algorithm commences and S_{final} be the global state immediately after it terminates. Finally S_{snap} is the recorded global state
  - We can find a permutation of H called H' which contains all three states: S_{init}, S_{snap} and S_{final}
- Does not break the happens-before relationship on the events in H

Chandy and Lamport: Reachability



- It may be that there are two events in H, e_n and e_{n+1} such that e_n is a post-snap event and e_{n+1} is a pre-snap event
- However we can swap the order of e_n and e_{n+1} since it cannot be that $e_n \rightarrow e_{n+1}$
- We continue to swap adjacent pairs of events until all pre-snap events are ordered before all post-snap events. This gives us the the linearization H'
- The reachability property of the snapshot algorithm is useful for recording *stable* properties
  - true in $S_{snap} \Rightarrow$ true in S_{init}; false in $S_{snap} \Rightarrow$ false in S_{init}
- However any *non-stable* predicate which is true in the snapshot may or may not be true in any other state

Chandy and Lamport: Use Cases

- No work which depends upon the global state is done until the snapshot has been gathered
- Algorithm is therefore useful for:
  - Evaluating after infrequent changes
  - Stable properties, since the property that you detect to have been true when the snapshot was taken will still be true once the snapshot has been gathered
  - Properties that have a single yes/no answer (Garbage Collection) rather than a range of increasingly appropriate answers (e.g. routing)
  - Properties that need not be acted upon immediately, again for example garbage collection.

Summary

- We looked at Chandy and Lamport's algorithm for recording a global snapshot of the system
- We defined a notion of **reachability** showing that the snapshot can be obtained by permuting concurrent events
- Thus, the snapshot is useful for detecting stable properties

Distributed debugging

- Distributed debugging was the application of our four example applications that stood out for being concerned with **unstable** properties
- This is a problem for our global snap-shot technique since its main usefulness is derived from our reachability relation which in turn means little for a non-stable property
- Distributed debugging is in a sense a combination of logical/vector clocks and global snapshots

Example Non-Stable Condition

- Suppose we are implementing an online poker game
- There is a process representing each player and one representing the pot in the centre of the table
- Players can “send chips” to the pot, and once winners have been decided the pot may send chips back to some of the players.
- We wish to make sure that the total amount of chips in the game never exceeds the initial amount
- It may be less than the initial amount since some chips may be in transit between a player and the centre pot.
- But it cannot be more than the initial amount.

Distributed debugging

- Suppose that we have a history *H* of events $e_1,...,e_n$
- $H = (e_1,...,e_n)$ is the true order of events as they actually occurred in our system
- Recall that a *run* is any ordering of those events in which each event occurs exactly once
- A *linearization* is a *consistent* run
  - A consistent run is one in which the "happens-before" relation is satisfied
  - If $e_i \rightarrow e_j$ then any linearisation (or consistent run) will order e_i before e_j.
  - So all linearisations only pass through consistent states

The possibly relation

- Any linearization *Lin* of our history of events *H* must pass through only consistent states
- A property *P* that is true in any state through which *Lin* passes, was **possibly true** at some global state through which *H* passed
- If this is the case for some property *p* and some linearisation we say *possibly(p)*
- Note: suppose we had taken a global snapshot during the set of events *H* to determine if the property *p* was true and determined that it was: *Snap(p)* evaluates to true.
  - This would imply that *p* was possible: Snap(p) ⟹ possibly(p)
- However the reverse is not true:
  - possibly(p) ⇏ Snap(p)

The definitely relation

- The sister relation to the possibly relation is the definitely relation
- This states that for any linearization Lin of *H*, *Lin* must pass through some consistent global state *S* for which the candidate property is true
- Since *H* is a linearization of itself, then the candidate property was certainly true at some point in the history of events.
  More formally:
- The statement *possibly(p)* means that there is a consistent global state *S* through which at least one linearization of *H* passes such that *S(p)* is true.
- The statement *definitely(p)* means that for all linearisations *L* of *H*, there is a consistent global state *S* through which *L* passes such that *S(p)* is true

Possibly vs Definitely

- If *p* is impossible then ¬*p* definitely holds
  - ¬*(possibly(p))* ⟹ *definitely(¬p)*
- But, from *definitely(¬p)* we cannot conclude ¬*(possibly(p))*.
  - *definitely(¬p)* means that there is at least one state in all linearizations of *H* such that *p* is not true.
  - ¬*(possibly(p))* however would require that ¬*(p)* was true in all states in all linearizations
- Also: *definitely(p)* and *definitely(¬p)* may be true simultaneously but *possibly(p)* and ¬*(possibly(p))* cannot.
  - consider blinking light, *p* = "light is on"

Distributed Debugging: Basic Outline

- The processes must all send messages recording their local state to a **master** process
  - timestamping each state with vector clock value
- The master process **collates** these and extracts the consistent global states
  - using timestamps to reconstruct happens-before order
- From this information the *possibly(p)* and *definitely(p)* relations may be computed.

Collecting the Local States

- Each process sends their initial state to the master process in a state message and thereafter periodically send their local state.
- Preparing and sending these messages may delay the normal operation of the distributed system but does not otherwise affect it
  - so debugging may be turned on and off.
- "Periodically" is better defined in terms of the predicate for which we are debugging.
  - We only need to send state messages to the master process initially and whenever our local state changes
  - We can further restrict to local state changes that affect the predicate in question.
- We can concurrently check for separate predicates as well by marking our state messages appropriately.

State Messages, Timestamps

- The individual processes send states to the master
- Each state message is timestamped with the Vector clock value at the local process sending the state message: $(s_i , V(s_i))$
- If $S = \{(s_1,V(s_1)),...(s_n,V(s_n))\}$ is a timestamped set of state messages received by the master process
- Then S is a consistent global state iff:
  - $V_i[i] \geq V_j[i] \; \forall i, j \in \{1, ..., N\}$

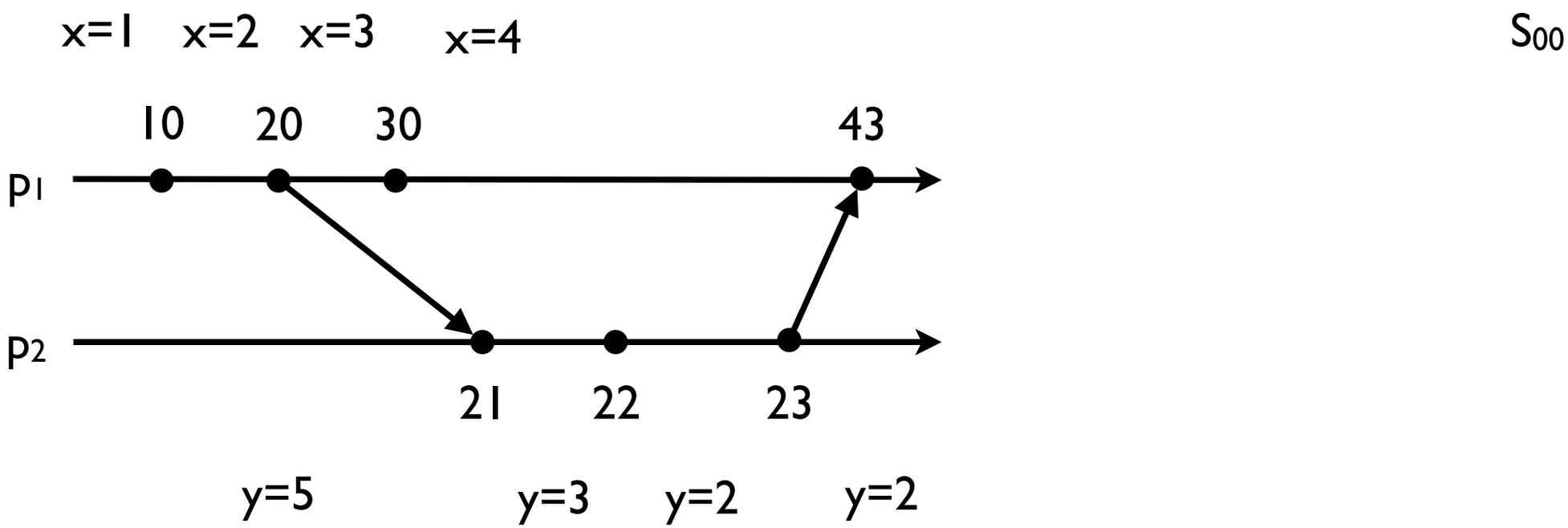
Assembled Consistent Global States

- *S* is a consistent global state iff:
  - $V_i[i] \geq V_j[i]\ \forall i, j \in \{1, \ldots, N\}$
- This says that the number of P_i's events known at P_j when it sent s_j is no more than the number of events that had occurred at P_i when it sent s_i.
- In other words:
  - if the state of one process depends upon another (according to happened-before ordering),
  - then the global state also encompasses the state upon which it depends.

Simple case

- Imagine the simplest case of 2 communicating processes.
- A plausible global state is S_{xy}
- The subscripts x and y refer to the number of events which have occurred at the particular process.
- The "level" of a given state is $x + y$, which is number of events which have occurred globally to give rise to the particular global state S.

Assembling consistent global states



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Suppose property *p(x,y)* = "*x* = *y*"

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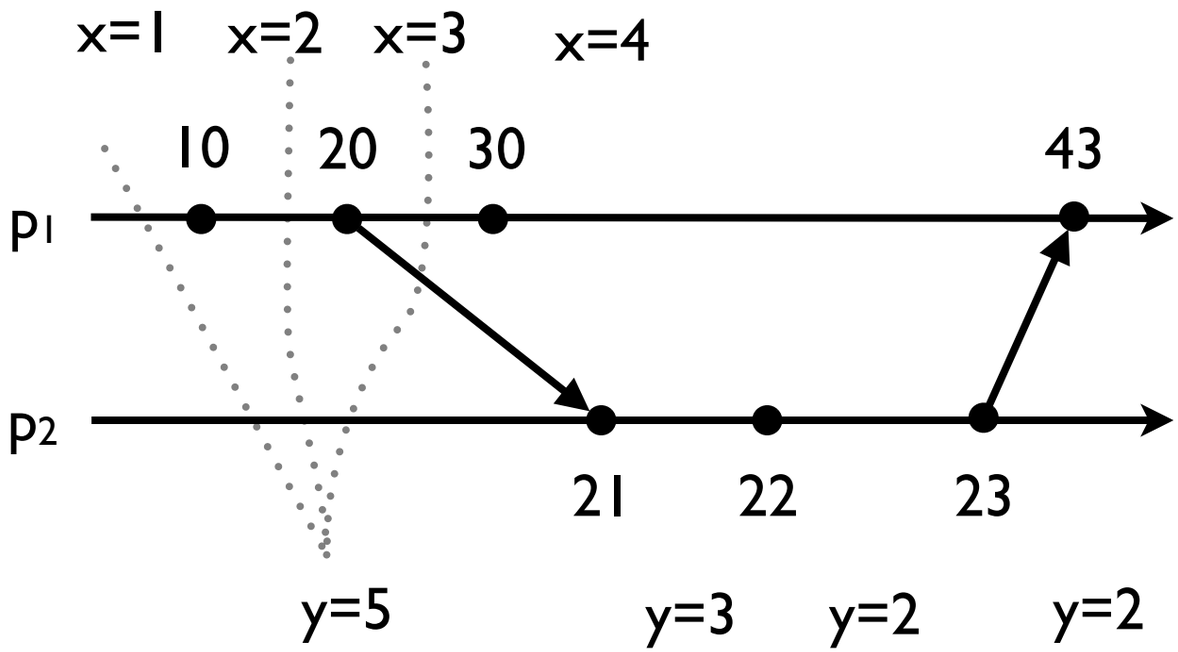

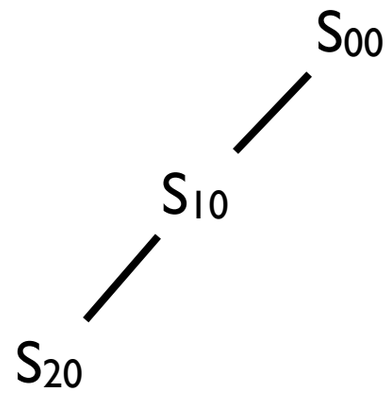

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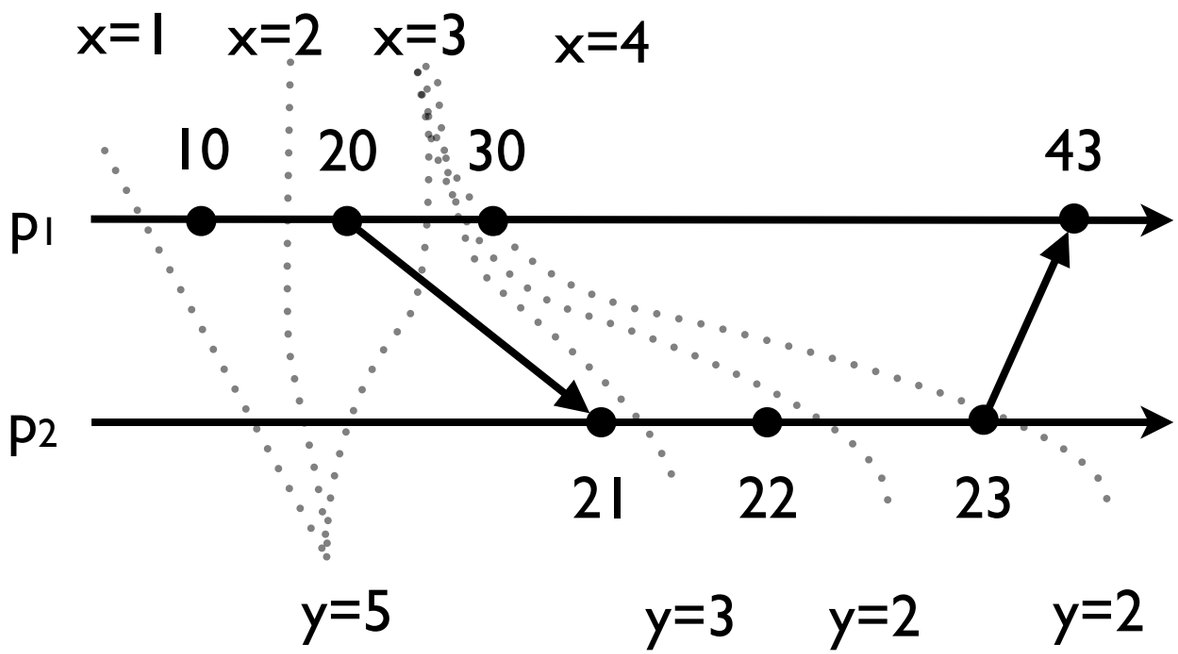

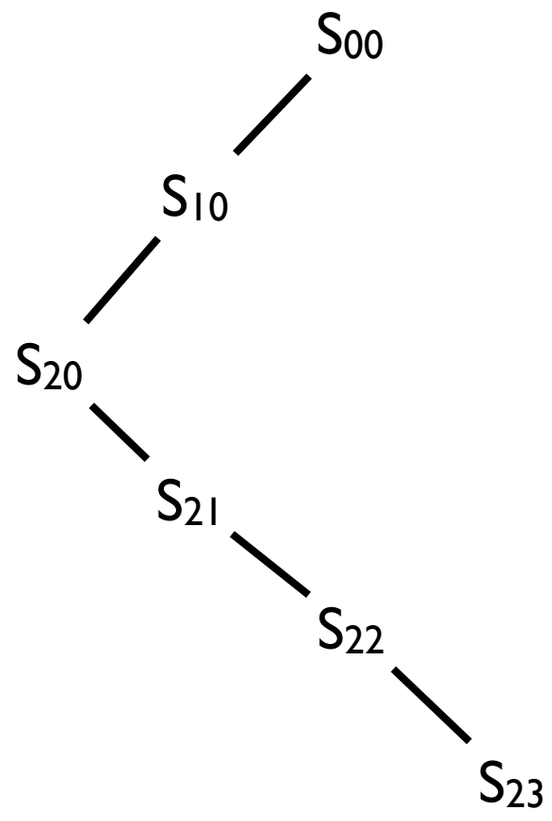

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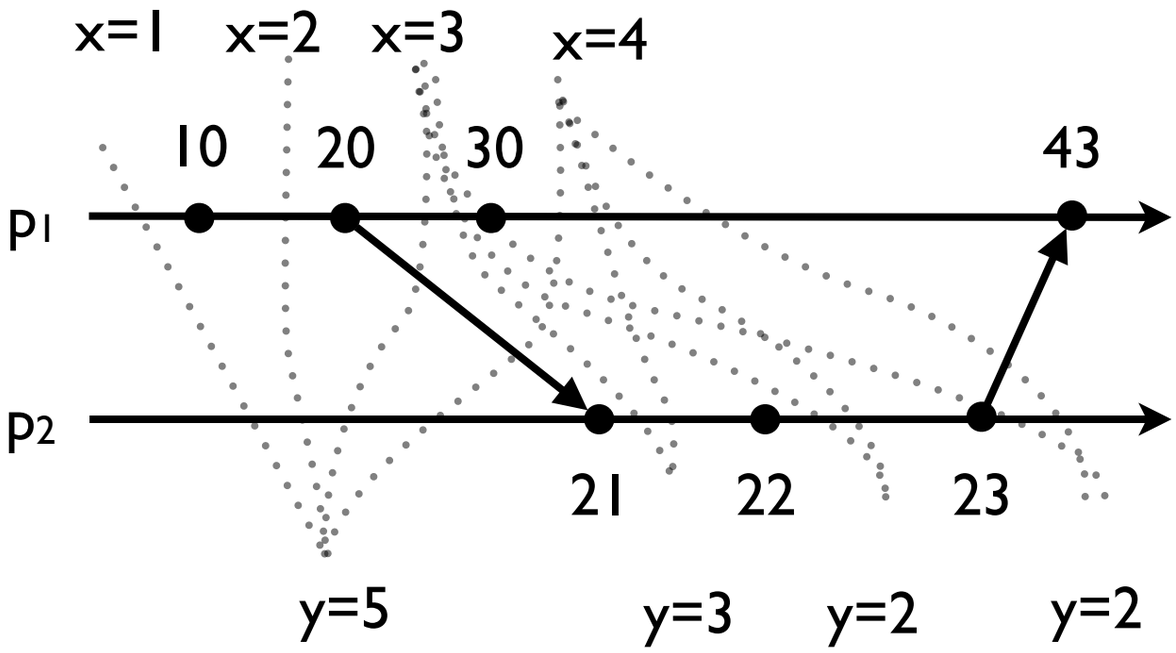

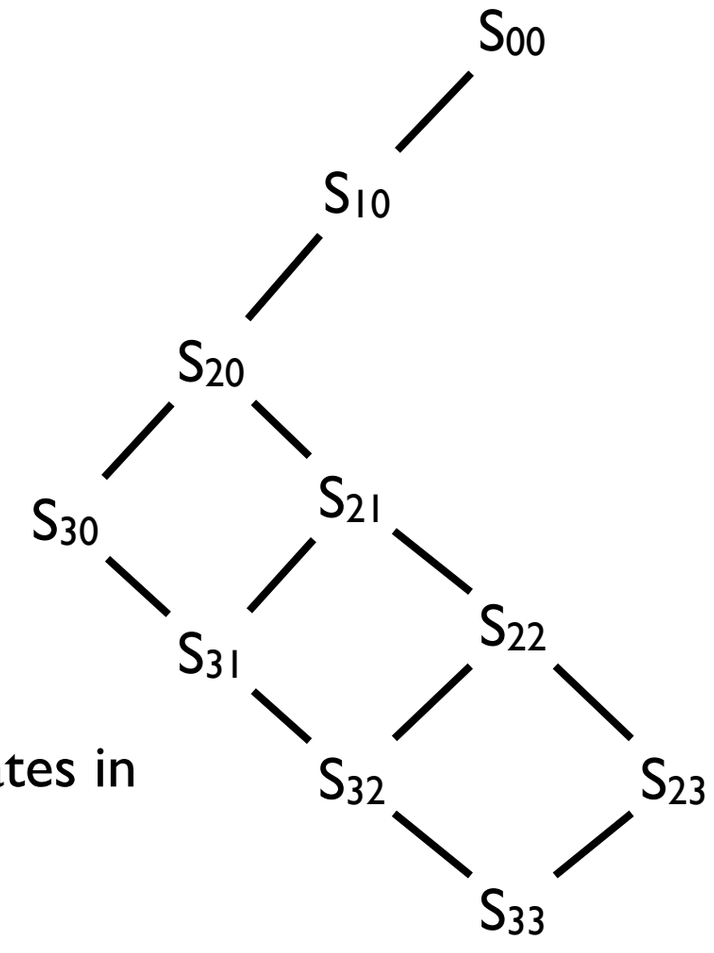

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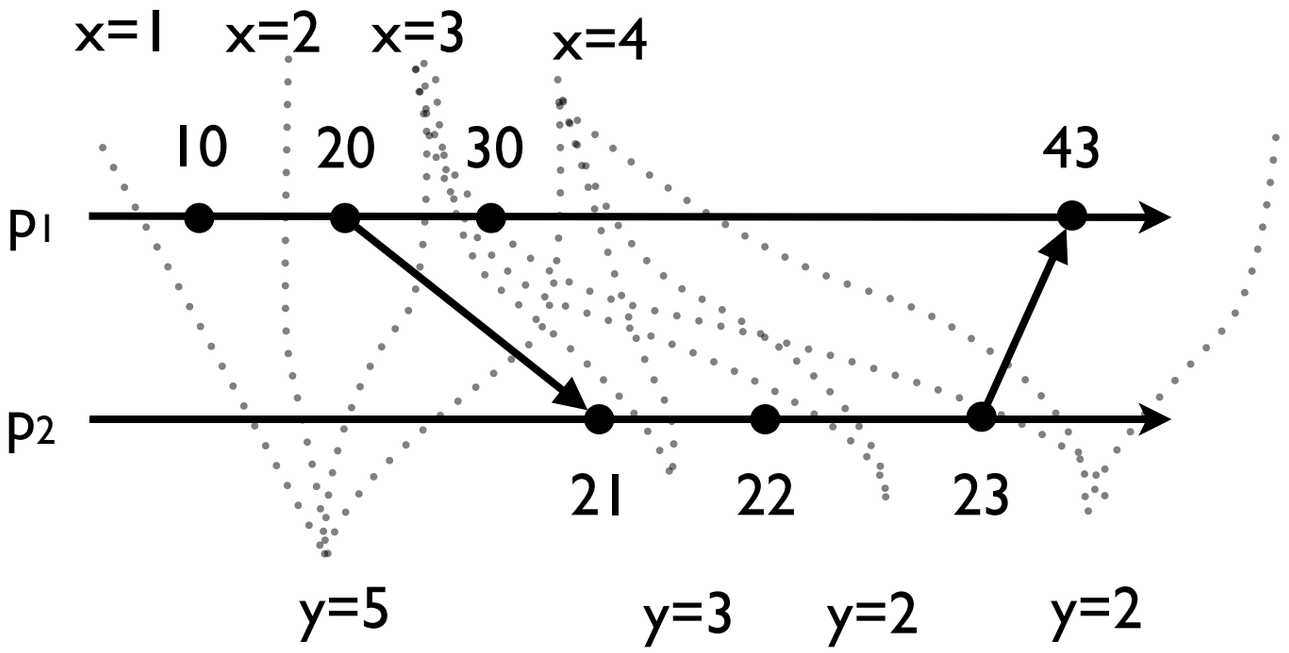

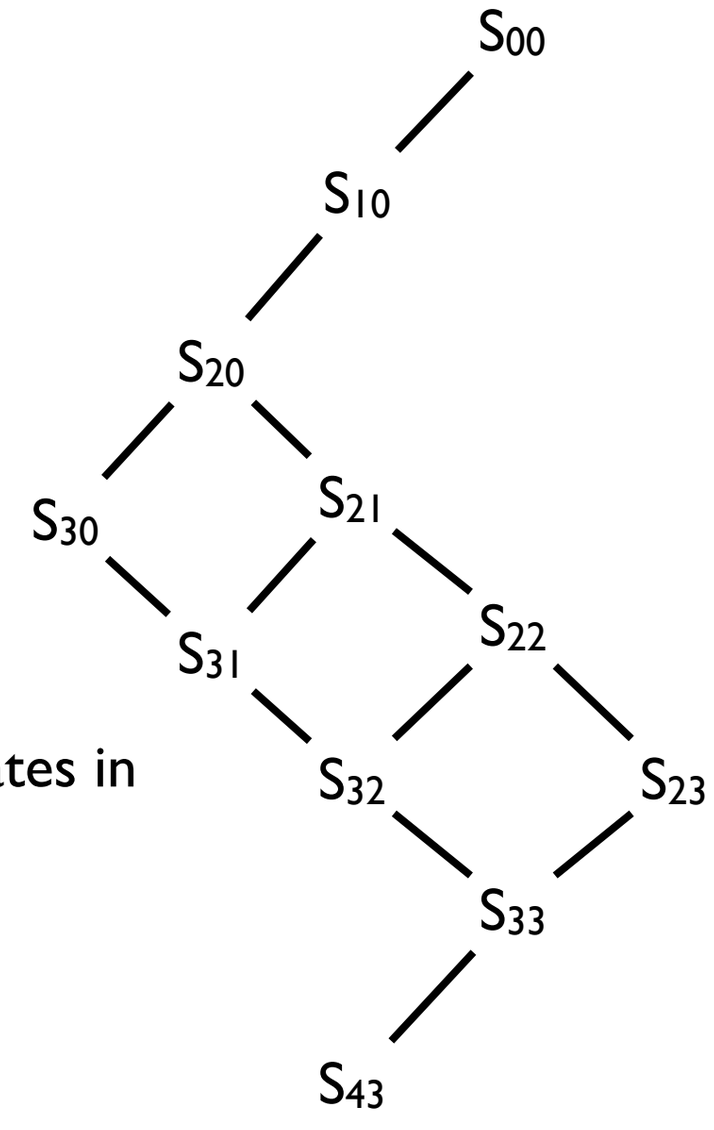

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Suppose property *p(x,y)* = "*x* = *y*"

Evaluating Possibly

A state $S' = \{s_0^{x0'}, ...s_N^{xN'}\}$ is *reachable* from a state $S = \{s^{x0}_0, ...s^{xN}_N\}$ if:

- S' is a consistent state
  - $level(S') = 1 + level(S)$ and:
  - $x_i' = x_i$ or $x_i' = 1 + x_i \quad \forall\ 0 \leq i \leq N$
- That is, S' is the result of adding exactly one possible "next" event to S
  - leading to a consistent cut/state

Evaluating Possibly

Level = 0

States = {(s^0_0,...s^0_N)}

while (*States* is not empty)

Level = Level + 1

Reachable = {}

for *S'* where *level(S') = Level*

if *S'* is reachable from some state in *States*

then if *p(S')* **then** output "*possibly(p)* is True" and **quit**

else place *S'* in *Reachable*

output "*possibly(p)* is false"

Evaluating Definitely

- Note: First check if p true in the initial state, if so output "definitely(p) is true"

  Level = 0

  States = {(s^0_0,...s^0_N)}

  while (*States* is not empty)

  Level = Level + 1

  ReachableFalse = {}

  for *S'* where *level(S') = Level*

  if *S'* is reachable from some state in *States*

  then if ¬*(p(S'))* **then** place *S'* in *ReachableFalse*

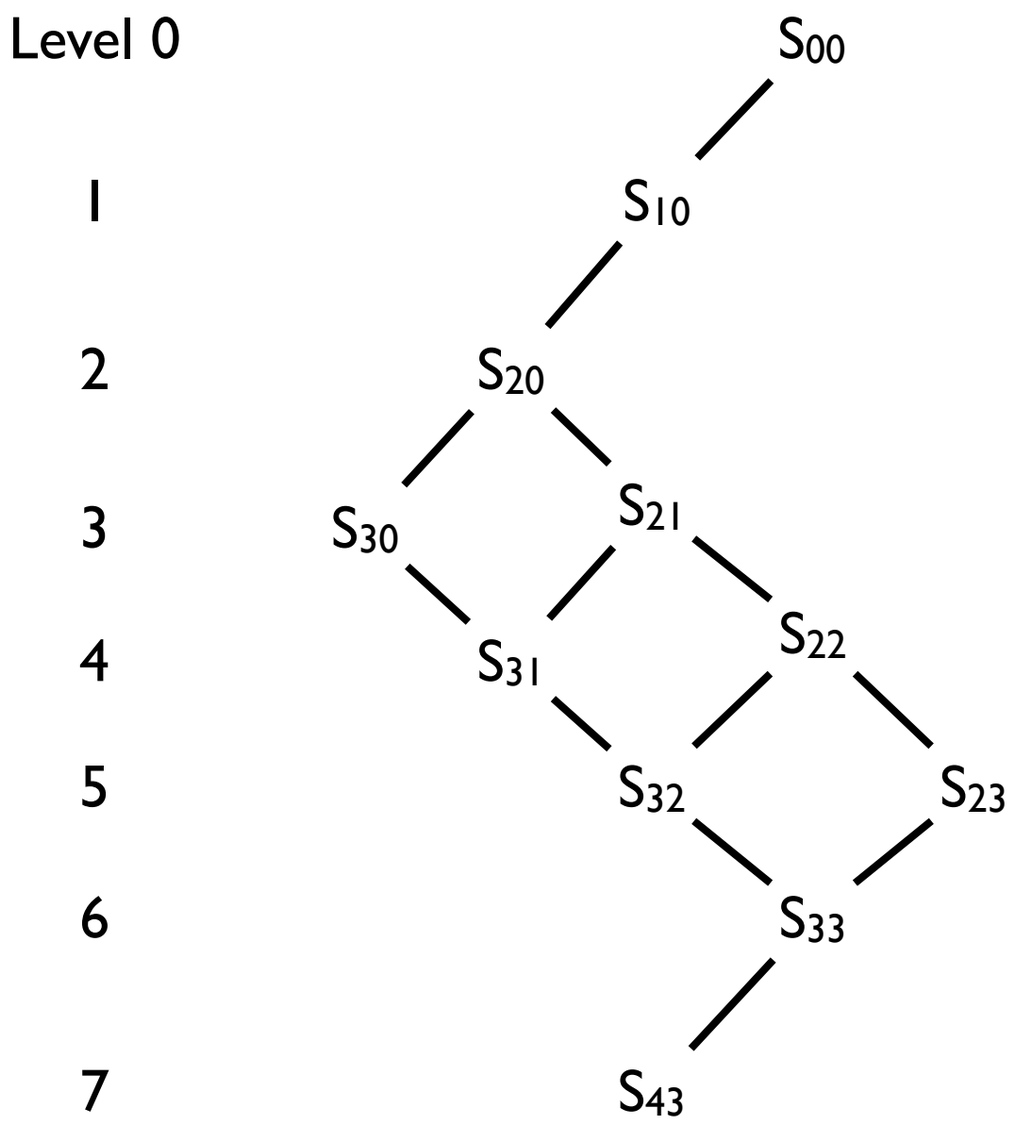
  States = ReachableFalse

  if *Level* is the maximum level recorded

  then output "*definitely(p)* is false"

  else output "*definitely(p)* is true"

Evaluating Possibly, Definitely



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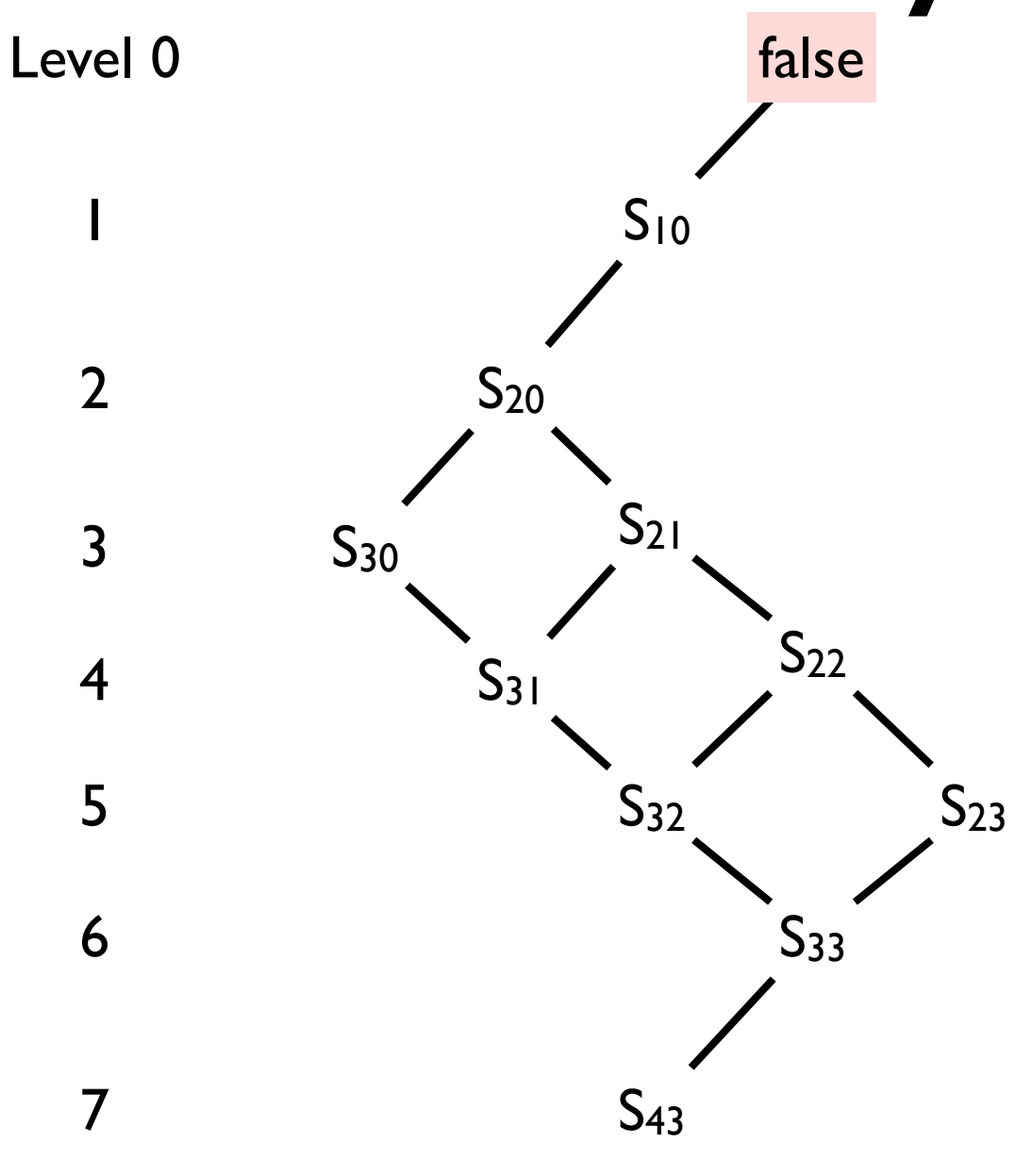

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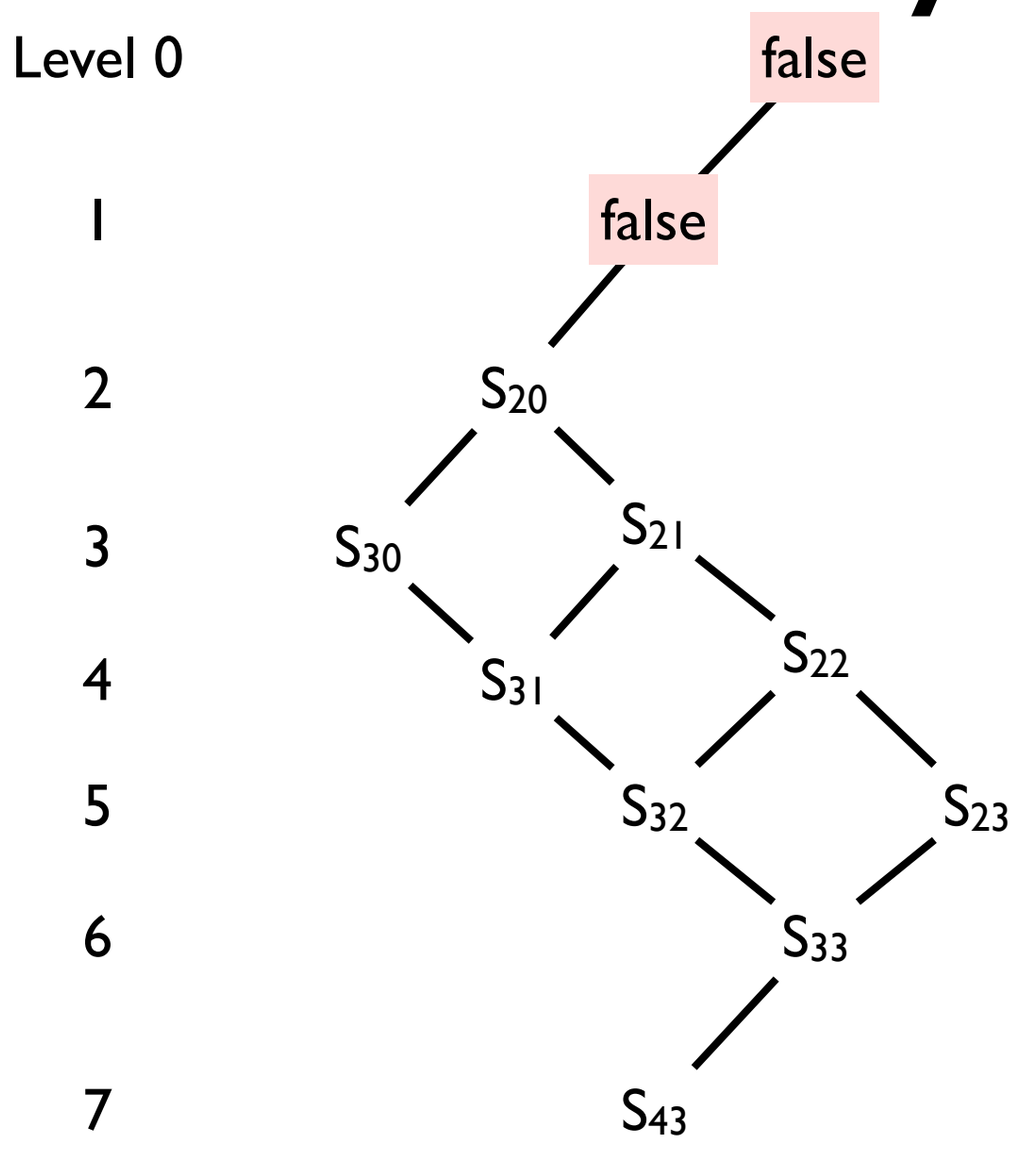

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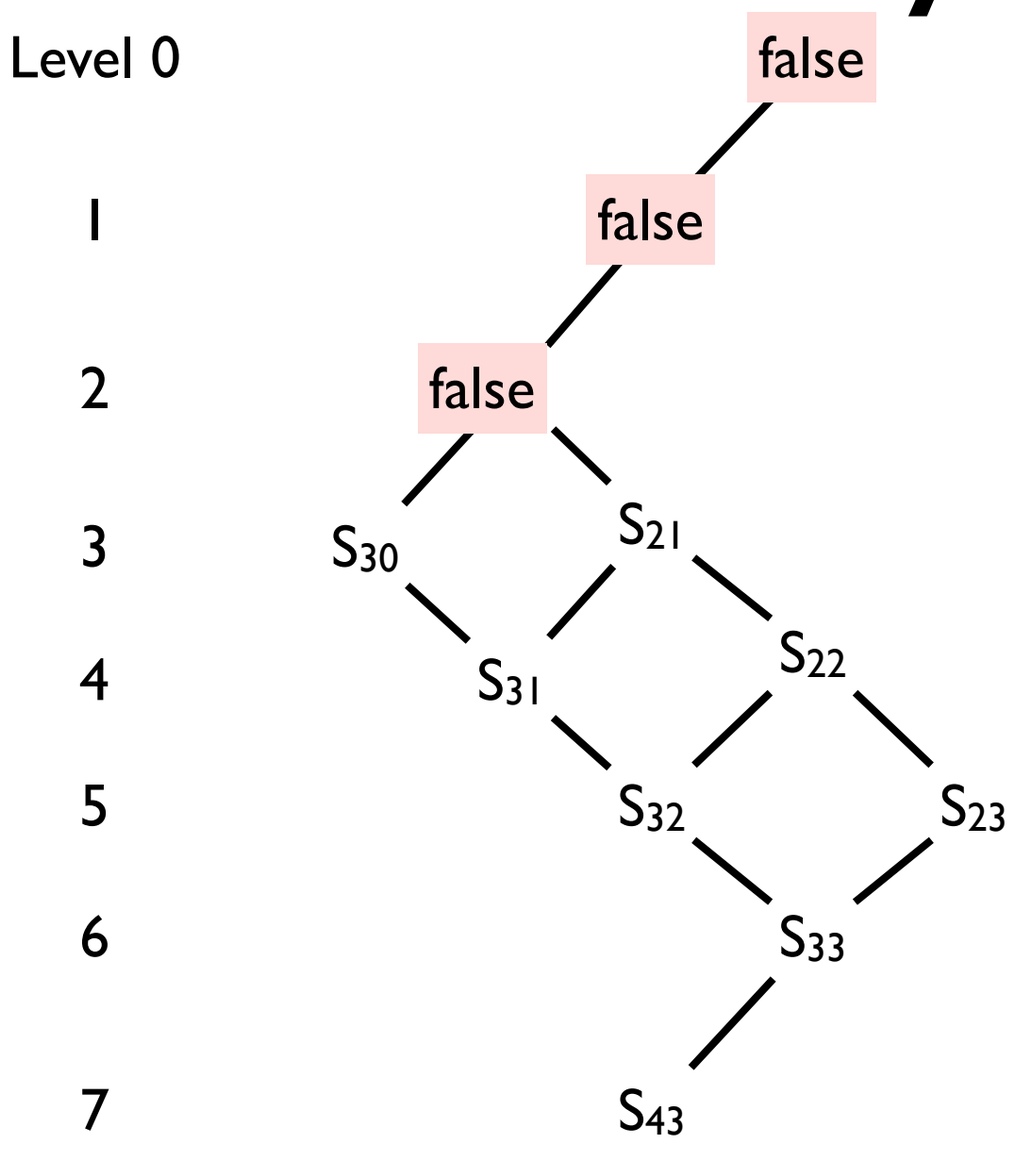

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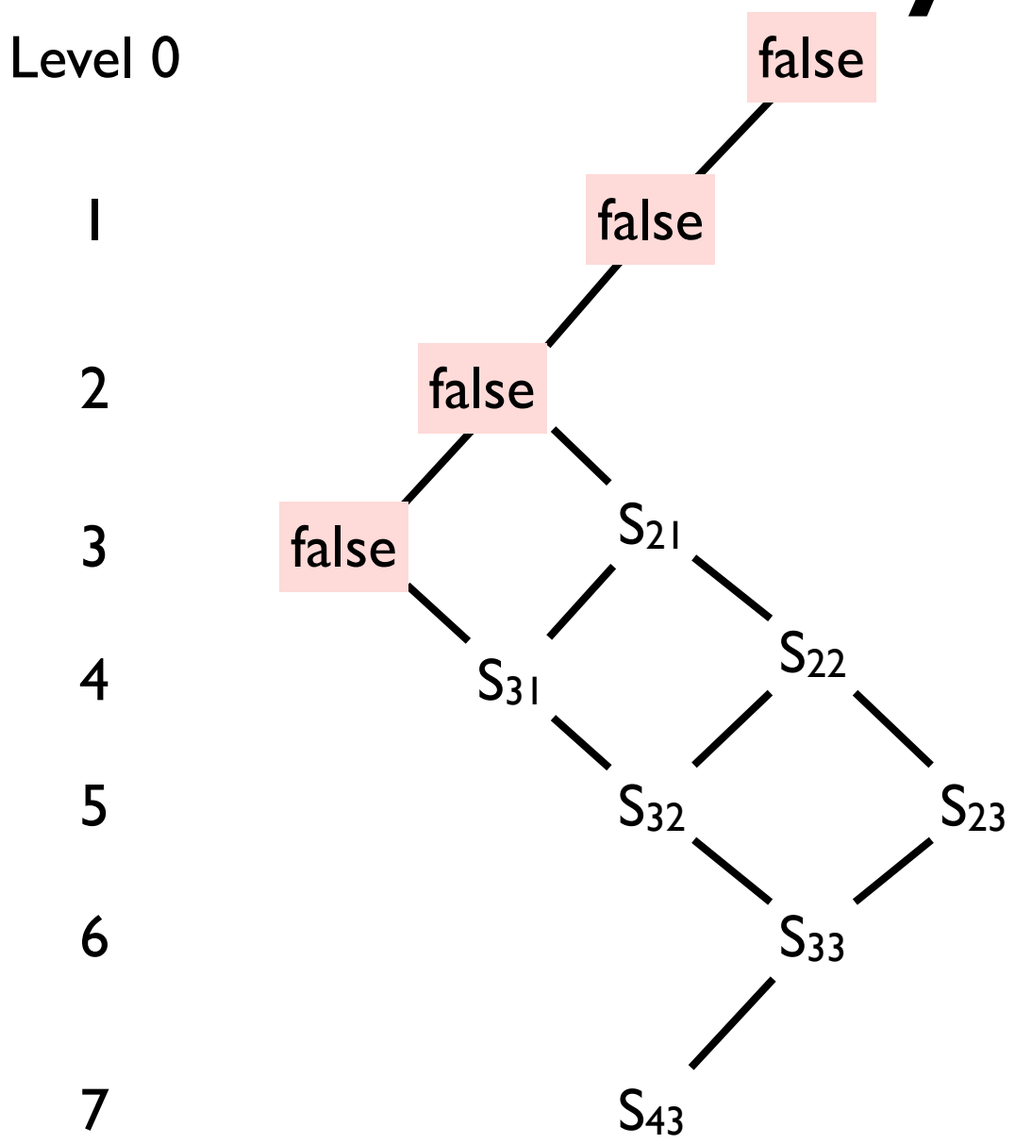

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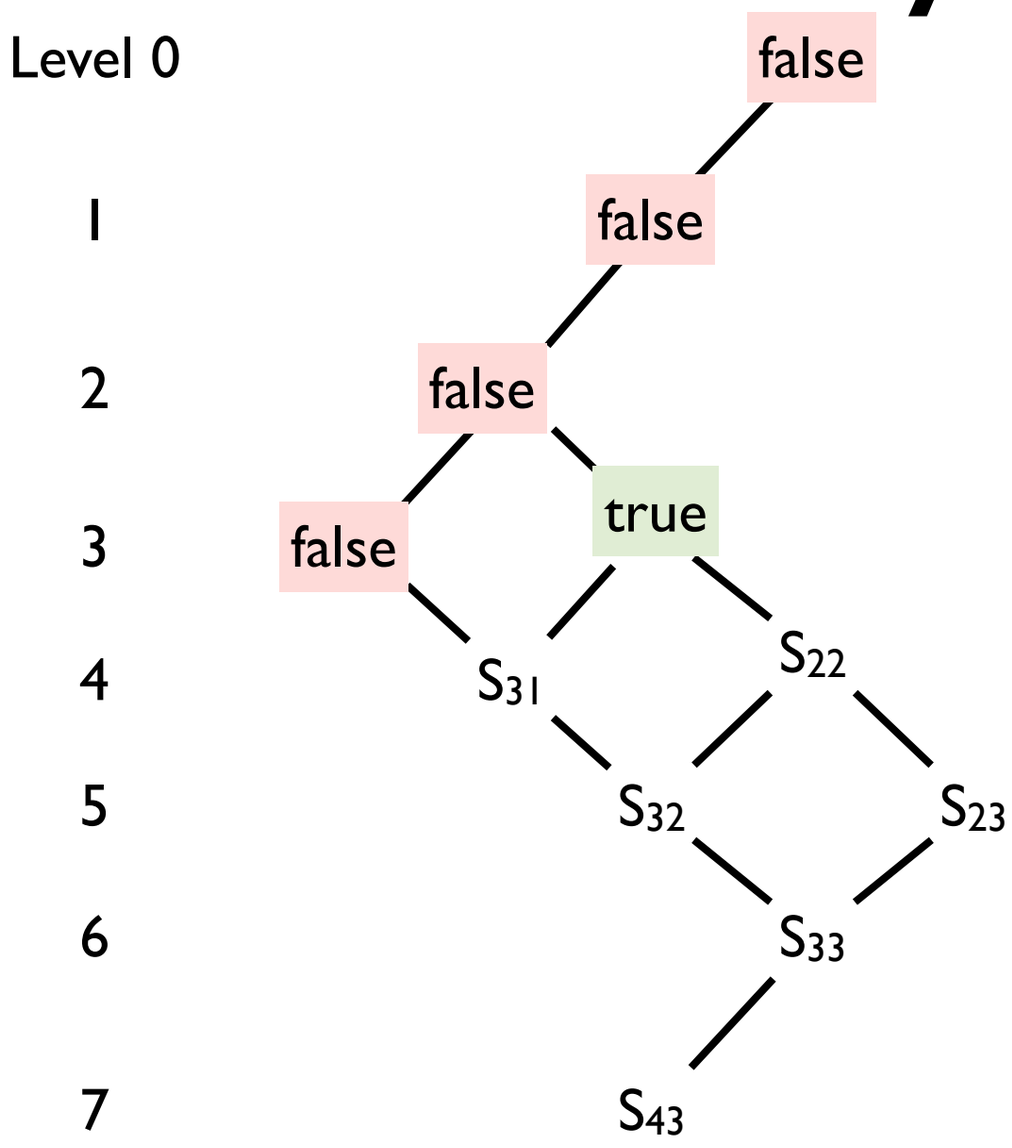

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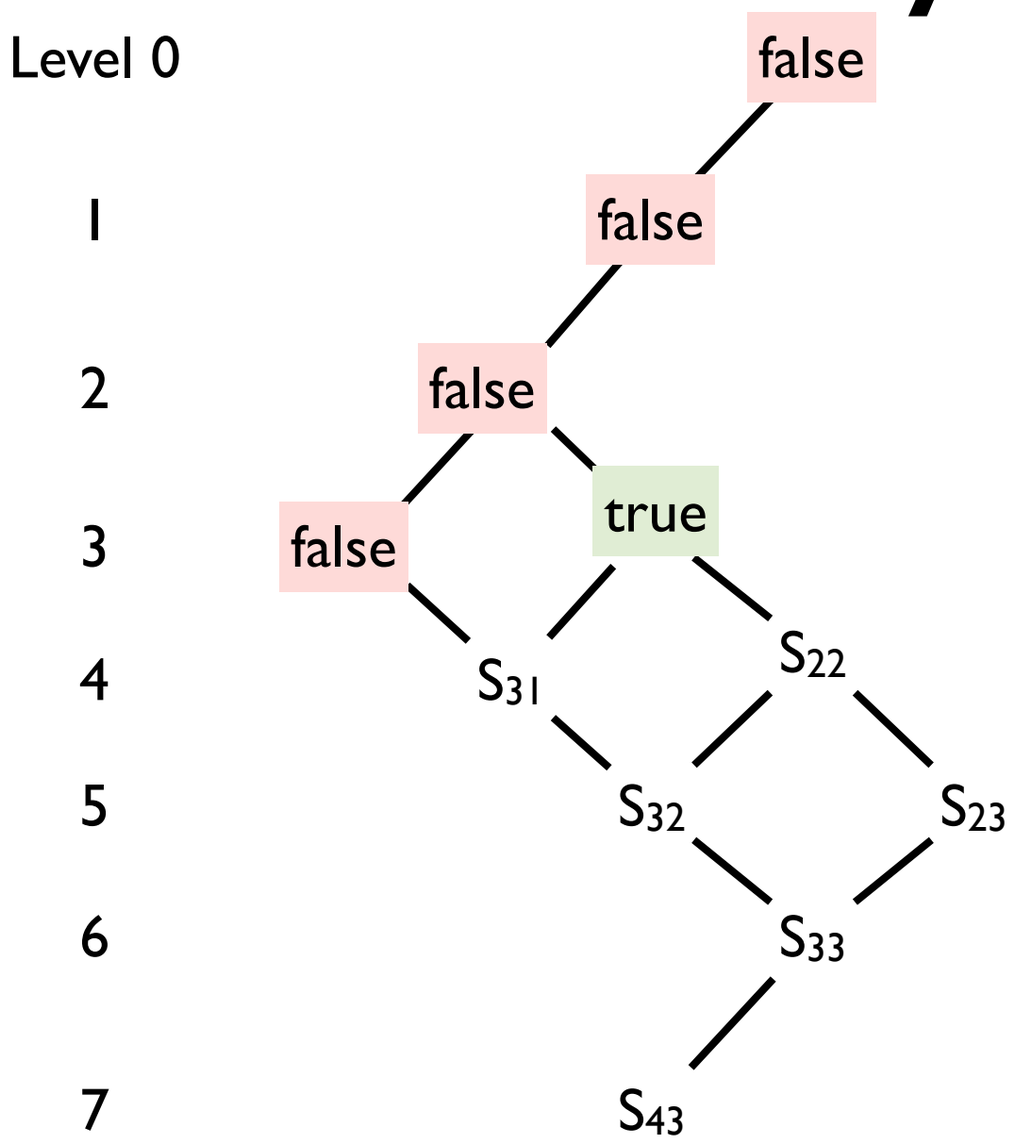
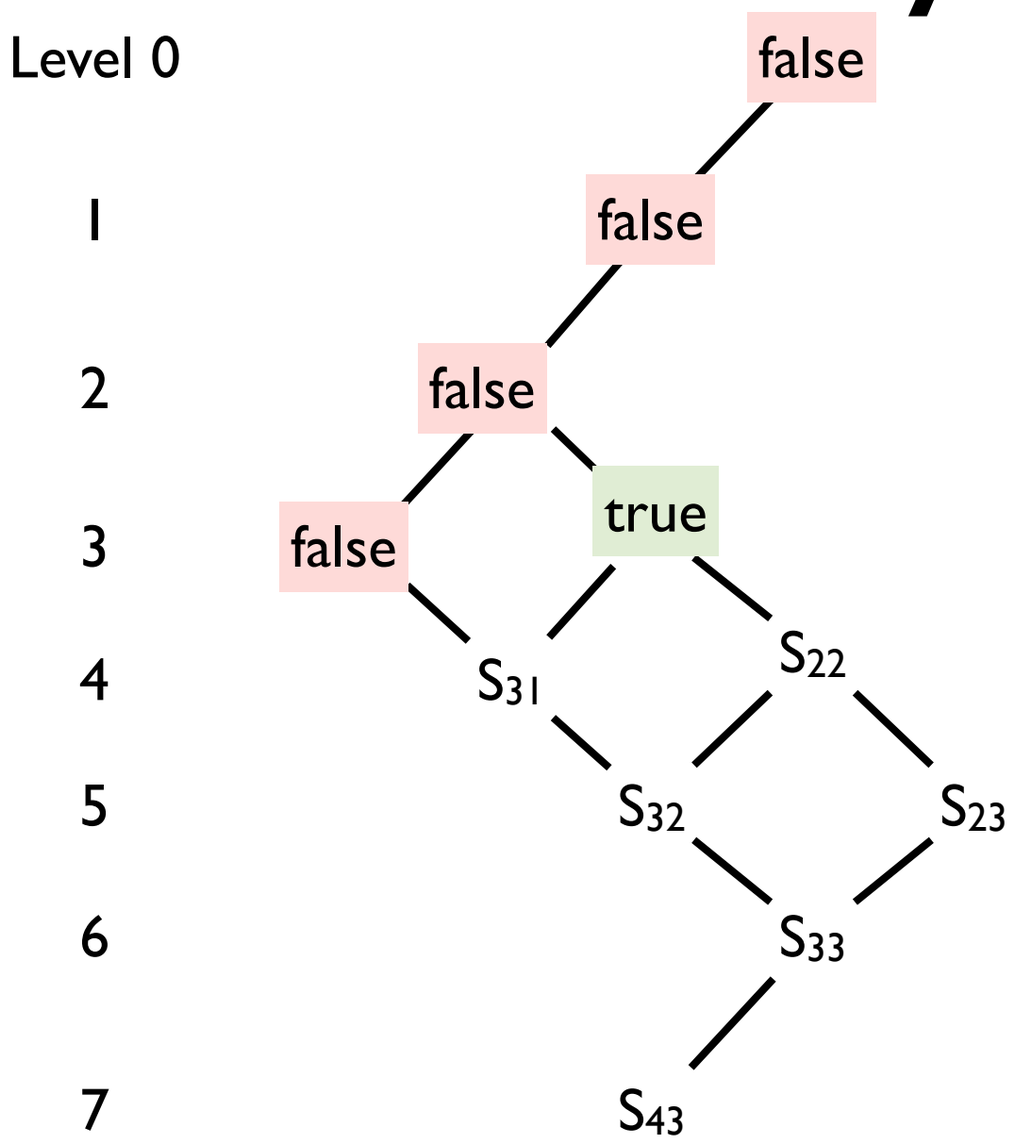
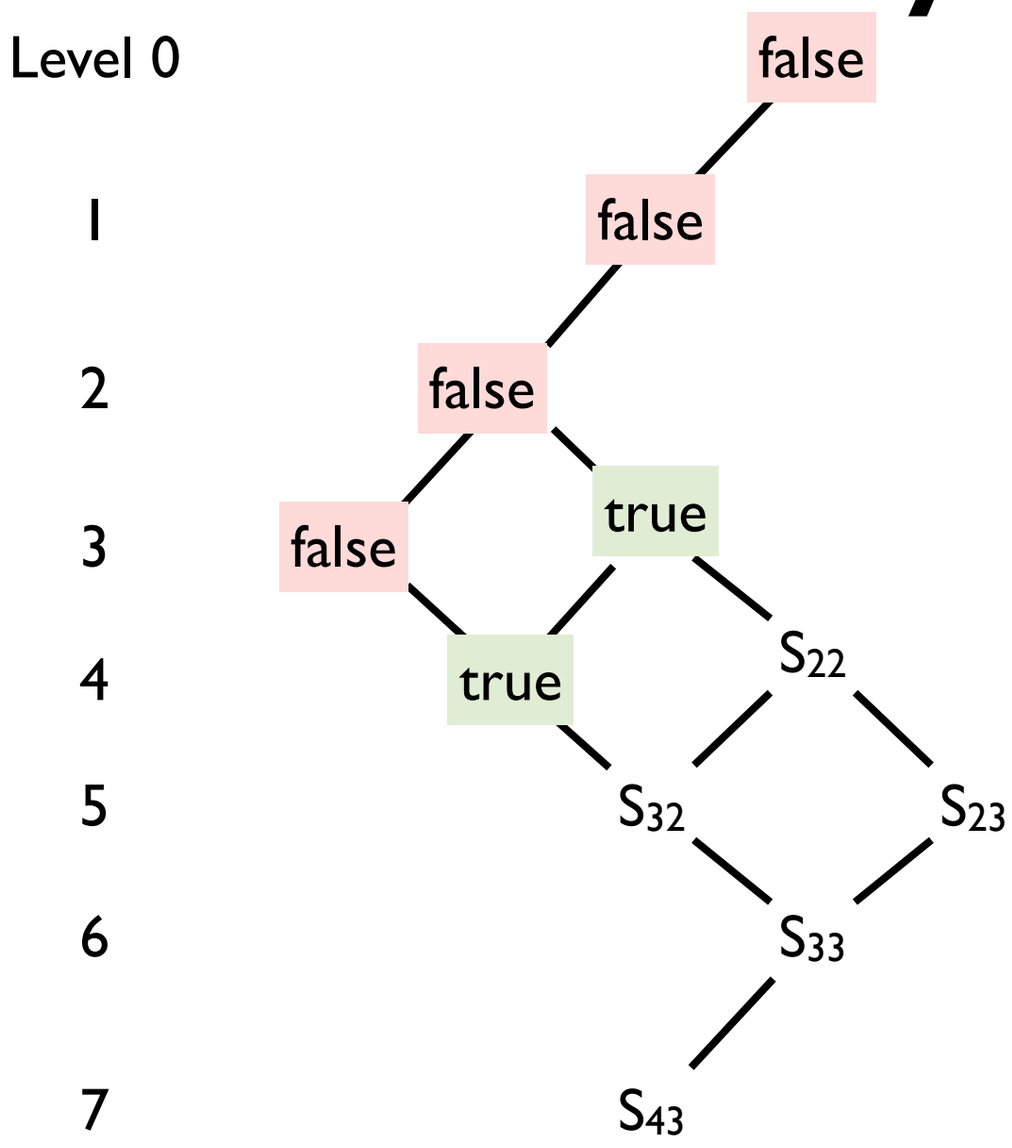


Possibly(p) is True

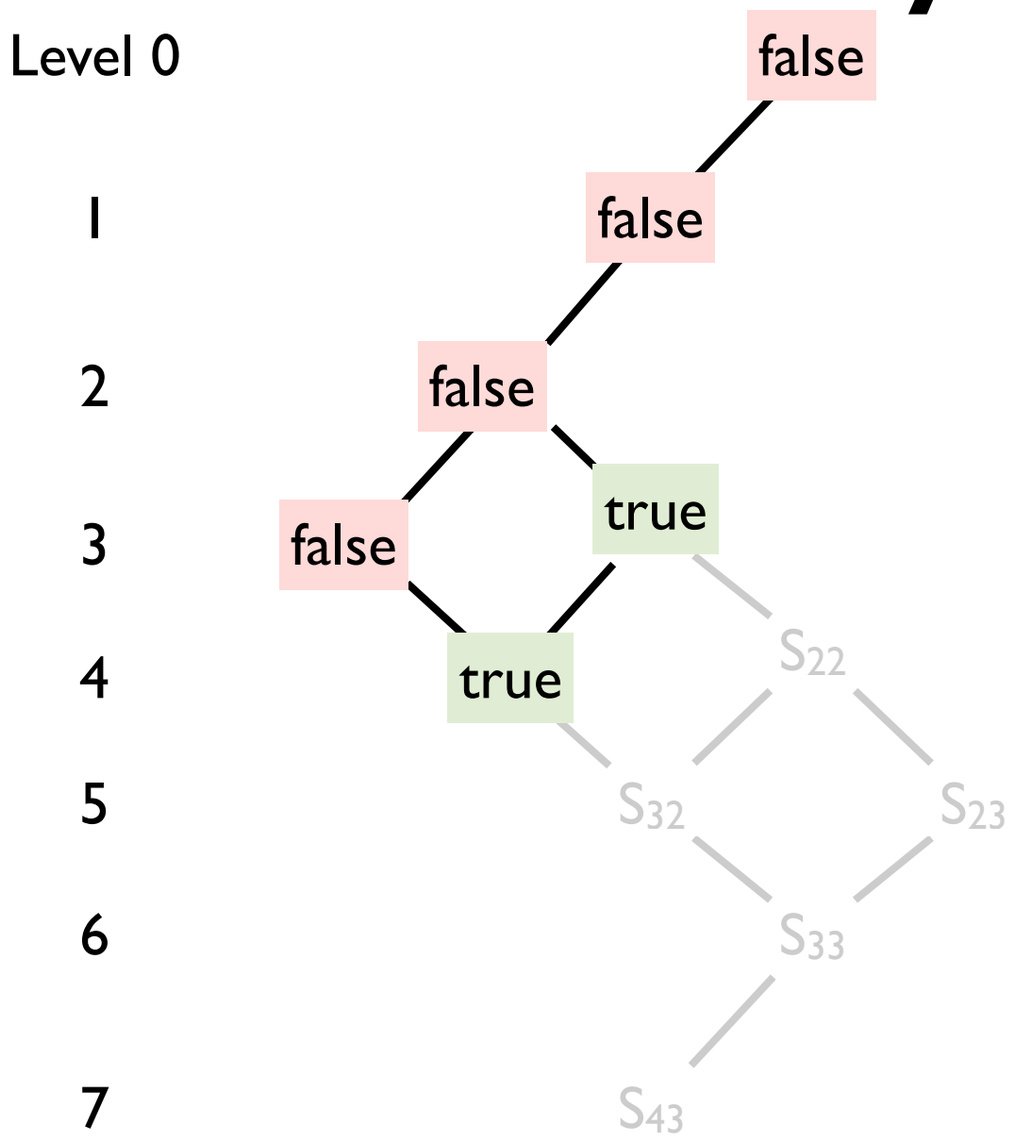
Evaluating Possibly, Definitely



Evaluating Possibly, Definitely



Evaluating Possibly, Definitely



Definitely(p) is True

Evaluating Possibly and Definitely

- Note that the number of states that must be evaluated is potentially huge
- In the worst case, there is no communication between processes, and the property is False for all states
- We must evaluate all **permutations** of states in which each local history is preserved
  - worst-case exponential time (NP-complete in general)
- This system therefore works better if there is a lot of communication and few local updates (which affect the predicate under investigation)

Distributed Debugging (Synchronous case)

- We have so far considered debugging within an **asynchronous** system
- Our notion of a consistent global state is one which could potentially have occurred
- In a synchronous system we have a little more information to make that judgement
- Suppose each process has a clock internally synchronized with the each other to a bound of D.
- With each state message, each process additionally time stamps the message with their local time at which the state was observed.
- For a single process with two state messages (s^x_i, V_i, t_i) and (s^{x+1}_i, V'_i, t'_i) we know that the local state s^x_i was valid between the time interval:
  - $t_i - D$ to $t'_i + D$

Distributed Debugging (Synchronous case)

- Recall our condition for a consistent global state:
  - $V_i[i] \geq V_j[i]\ \forall i, j \in \{1, ..., N\}$
- We can add to that:
  - $t_i - D \leq t_j \leq t'_i + D$ and vice versa forall i,j
- This can help eliminate impossible global states
  - improving performance and making "possibly" more precise
- But if there is a lot of communication (or D is large) then we may not prune the number of states very much

Summary

- Each process sends state update messages to a monitor process whenever a significant event occurs.
- From this the monitor can build up a set of consistent global states which may have occurred in the true history of events
- This can be used to evaluate whether some predicate was possibly true at some point, or definitely true at some point
- This can lead to a combinatorial explosion if there is a lot of concurrency
  - synchronized clocks can be used to decrease the number of concurrent states to consider