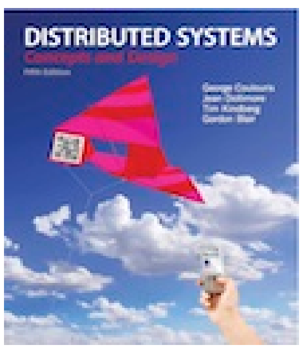
Slides for Chapter 14:
Time and Global States



From Coulouris, Dollimore, Kindberg and Blair

Distributed Systems:

Concepts and Design

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Introduction [14.1]

- We need to reason about time of events
- No perfect global clock
- Lots of work on clock synchronization, we are skipping (14.3)

Clocks, events, and process states [14.2]

- Refine the model in Chapter 2 proprocess interactions
- Consider DS a set P of N processes, p_i for i=1, …, N
- Process p_i has a state s_i that (usually) changes over time
- Process p_i takes a series of actions, from 3 choices
  - Message send
  - Message receive
  - Operation to transform its state
- **Event**≡occurrence of a single action that a process caries out as it executes
  - Totally ordered (locally) on a given host,
- **History**(p_i) ≡ h_i ≡<e_i^0, e_i^1 , e_i^2 , …> #series of events
- Note: skipping rest of 14.2 … on clocks etc and also 14.3

Logical time and logical clocks [14.4]

- (Going to teach through the VR01 slide set for most of this, then go through the examples here to reinforce)
- Also for vector clocks separate example slides

Figure 14.5
Events occurring at three processes

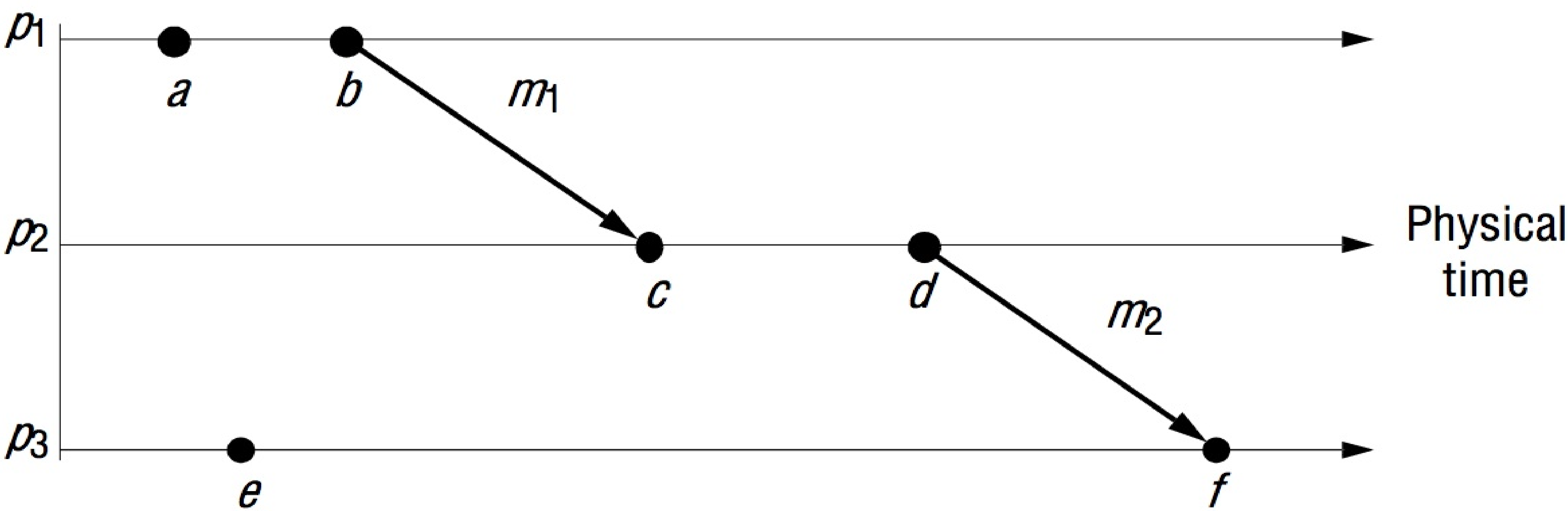

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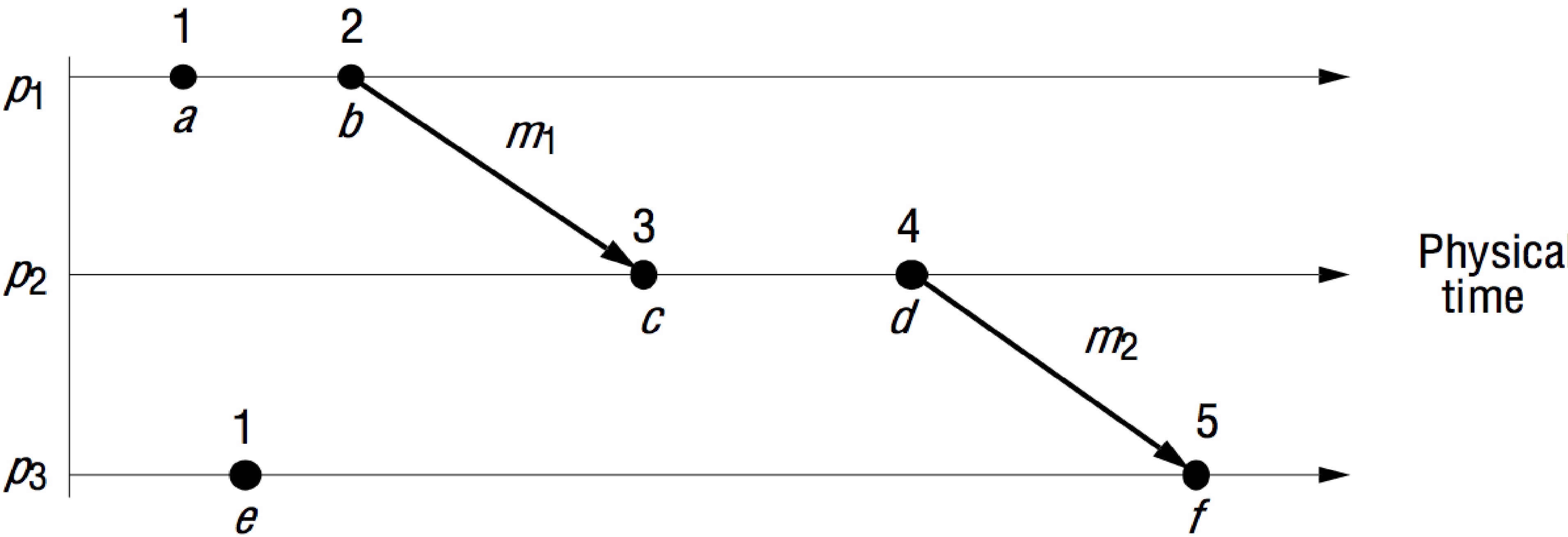
Figure 14.6
Lamport timestamps for the events shown in Figure 14.5



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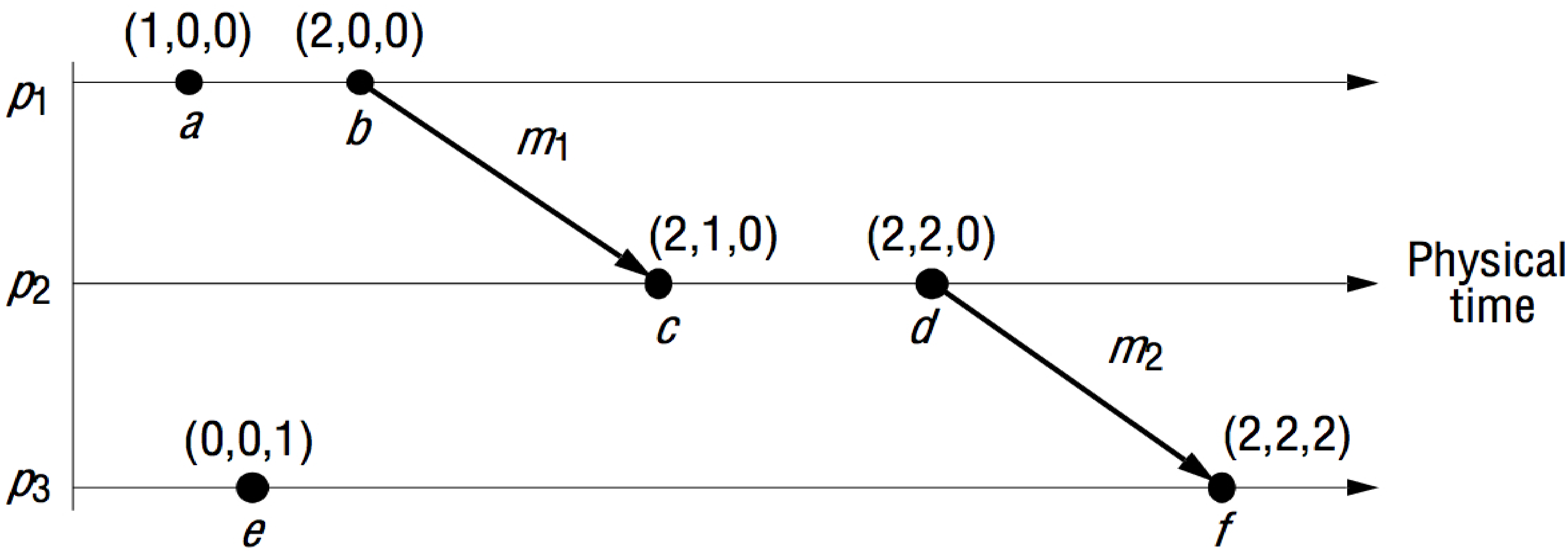
Vector clocks

- Limitation of Lamport clocks: if $L(e) < L(e')$ we can't conculde that $e \rightarrow e'$
- Solution: make the LC scalar a vector
- $V_i[i] \equiv$ number of events that p_i has timestamped
- $V_i[j]$ (for $i \neq j$) $\equiv$ #events at p_j that may have affected p_i and that p_i knows about.
- (Now see slides from the Birman book)

Figure 14.7
Vector timestamps for the events shown in Figure 14.5



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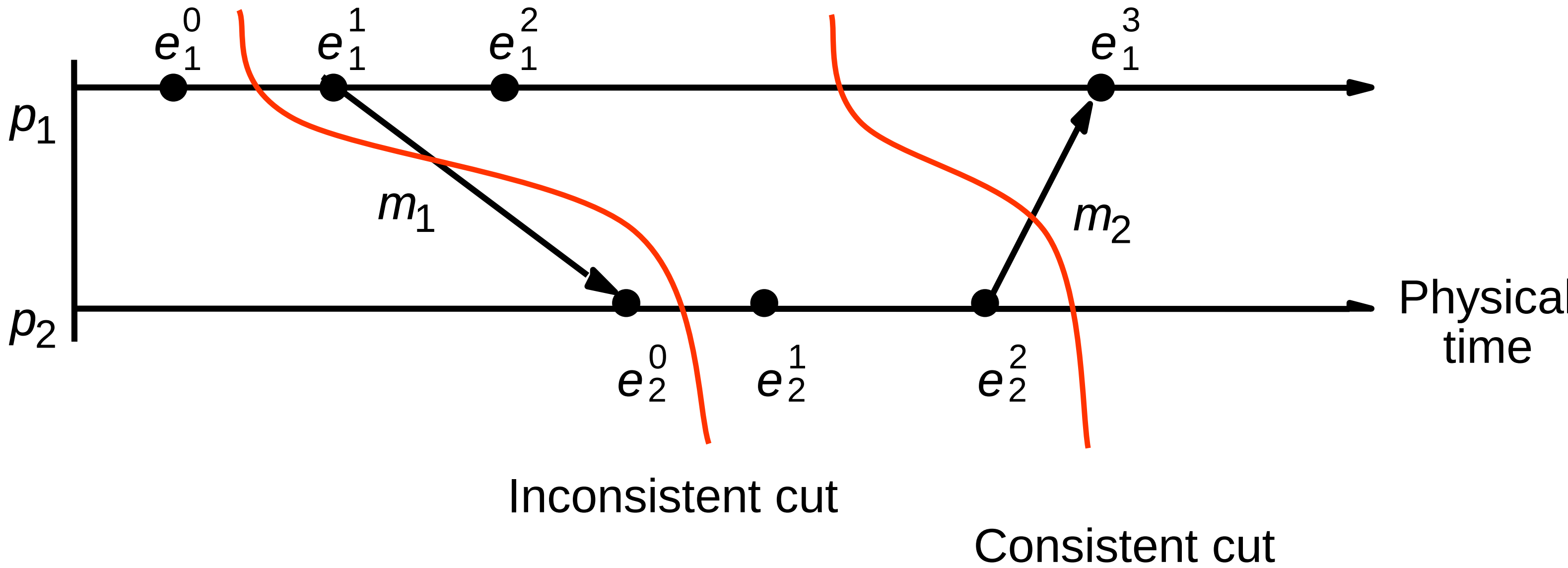
Global states [14.5]

- (See the VR01 slides for best intro to this)

Figure 14.9
Cuts



- **Cut** of a system subset of its global history: union of prefixes of process histories
  - **Frontier** of cut: last event in each process's prefix
- Cut C **consistent** if, for every event it contains, all events that "happened before" that event are also contained
  - i.e., for all events e in C, f→e ➔ f is in C

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Consistent cuts

- Recall system goes through $S_0 \rightarrow S_1 \rightarrow S_2$ ..
  - One different event at one process in $S_i \rightarrow S_{i+1}$
  - Global state then union of process states after a cut
- **Run**: a total ordering of all events in a global history that's consistent with each local history's ordering
  - Not all runs pass through consistent global states
- **Linearization** (AKA **consistent run**): ordering of events in global history consistent with happened-before relationship on the history
  - All linearizations pass only through consistent global states
- **Reachability**: state S' is **reachable** from state S if there is a linearization that passes through S and then S'.

Global state predicates, stability, safety, and liveness [14.5.2]

- Evaluate a **global state predicate** to detect deadlock, etc
  - Function mapping from global states to {True, False}
  - **Stable property**: once predicate true,stays true (opp.: **transitory**)
    - I.e., true from all states reachable from the present state
- **Safety property** (e.g., α): nothing "bad" ever happens
  - E.g., never have deadlock
  - i.e., for all states **reachable from initial state**, α is False (never True)
- **Liveness property** (e.g., β): something good eventually happens
  - E.g., distributed algorithm eventually terminates
  - I.e., **Liveness w.r.t. β**: for any linearization L starting in state S_0, β evaluates to True for some state S_L **reachable** from S_0.

Snapshot algorithm

- By Chandy and Lamport [1985]: determine global states
- Goal: record a set of process AND channel states such that it is consistent (not strongly consistent) for a set of processes p_i (i=1, 2, … N)
- Assumptions
  - Neither channels nor processes fail
  - Channels are uni-directional and FIFO ordered
  - Graph of processes and channels strongly connected (path between any 2 processes)
  - Any process may initiate the snapshot at any time
  - Processes don’t need to freeze/lock: continue normal operations

Snapshot algorithm (cont.)

- Main ideas
  - Terms: **incoming channels** and **outgoing channels** for p_i
  - Each process records its state, and for each incoming channel, set of messages sent to it
  - For each channel, process records **channel state**: messages that arrived after its last recorded state and before sender recorded state
    - I.e,. Record state at different times but account for messages transmitted but not yet received (these are part of the channel state)
  - Use distinguished **marker messages**
    - Tell receiver to save state
    - Way to determine which messages go in channel state
    - To initiate the algorithm, process acts like it received a marker message

Figure 14.10
Chandy and Lamport's 'snapshot' algorithm

Marker receiving rule for process p_i

On p_i's receipt of a *marker* message over channel c:

if (p_i has not yet recorded its state) it

records its process state now;

records the state of c as the empty set;

turns on recording of messages arriving over other incoming channels;

else

p_i records the state of c as the set of messages it has received over c

since it saved its state.

end if

Marker sending rule for process p_i

After p_i has recorded its state, for each outgoing channel c:

p_i sends one marker message over c

(before it sends any other message over c).

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Example of snapshot algorithm

- Two processes, trade in widgets, over two unidirectional channels
- Process p1 sends orders for widgets to p2 with its payment ($10/widget)
- Process p2 sends widget along other channel

Figure 14.11
Two processes and their initial states

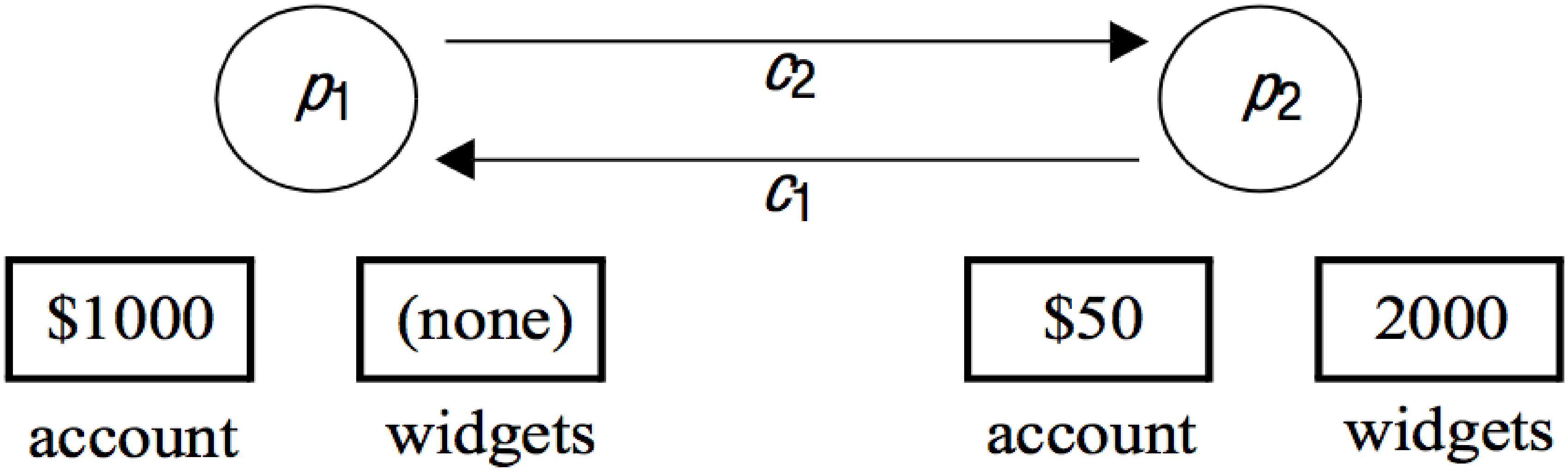

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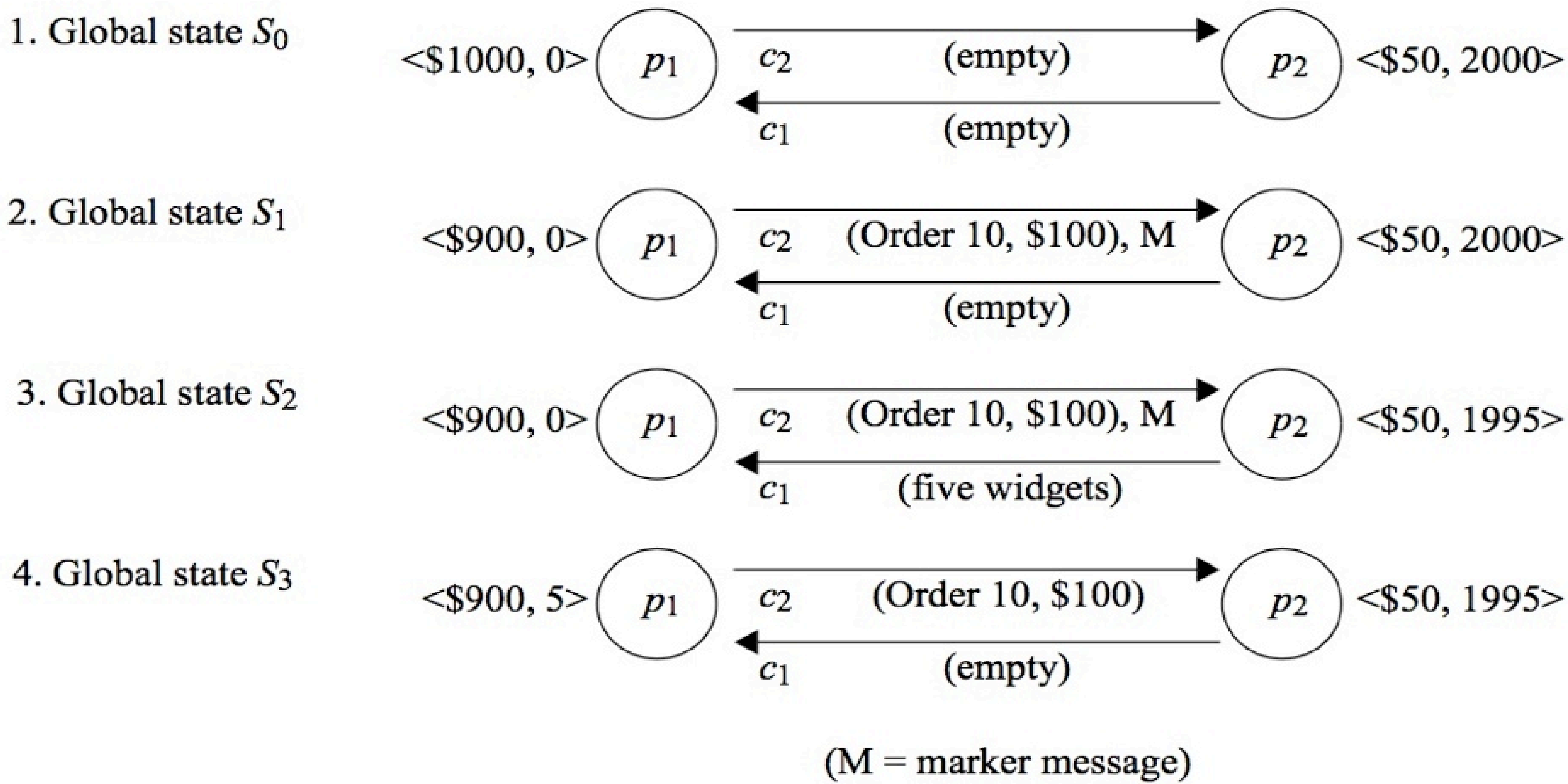
Figure 14.12
The execution of the processes in Figure 14.11



Note: (1) S_0 is when p_1 sends marker (3) p_1 had previously ordered five widgets; sent before M received by p_2 (5) After above, final recorded state includes five widgets in c_1, yet system did not go throough this state (6) Text explains how cut is consistent

Distributed debugging [14.6]

- Problem: recording system's global state to make useful statements about whether a transitory state occurred in an actual execution
  - Capture trace info and do *post hoc* analysis
- Chandy and Lamport's [1985] snapshot algorithm earlier used to collect states
  - Send to monitor process (considered outside the system)
  - Algorithm by Marzullo and Neiger [1991]

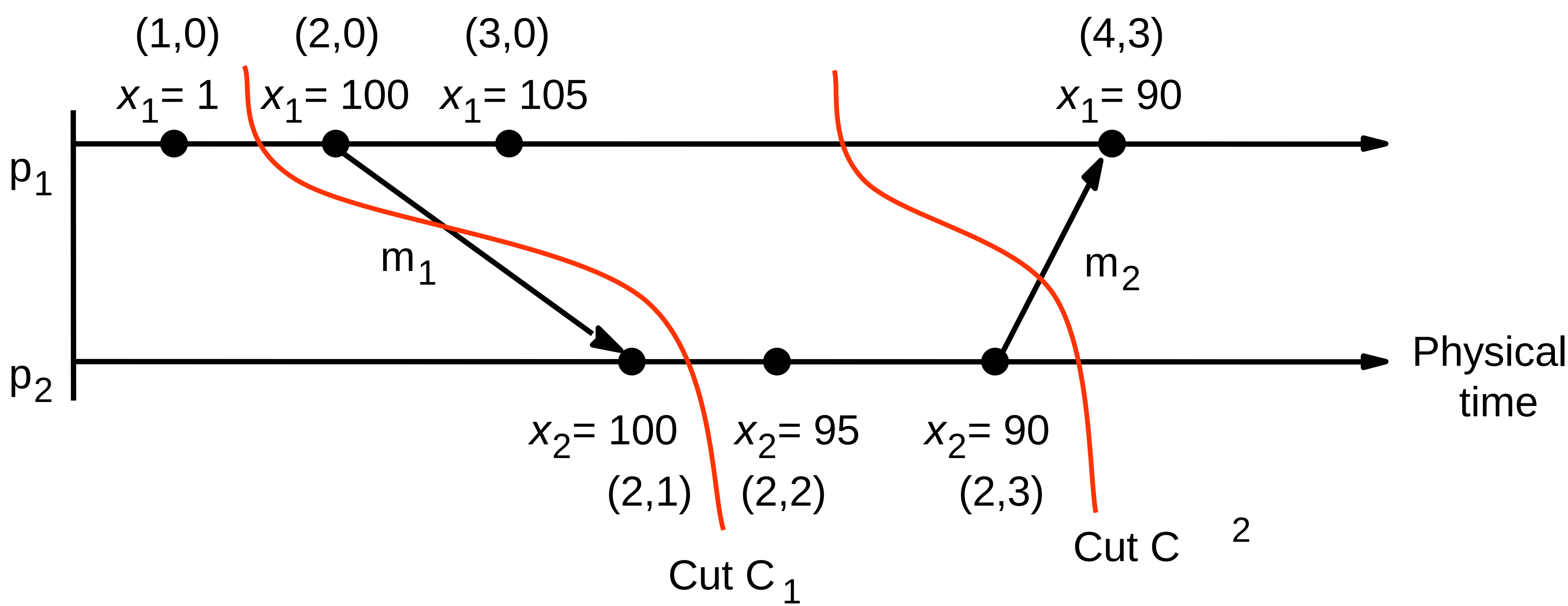
Distributed debugging (cont.)

- Goal: determine cases where global state predicate ϕ
  - Was **definitely True** at some point in the execution
  - Was **possibly True** at some point in the execution
- "Definitely" applies to actual execution, not run extrapolated from it
  - Basically, we want to know if a **transitory state** actually occurred in an actual execution
    - Why not worry if a **stable state** did?
  - Can consider all linearizations H of the observed events
  - **Possibly ϕ** : **exists** a consistent global state S through which a linearization of H passes such that ϕ(S) is True
  - **Definitely ϕ**: **for all** linearizations L of H, exists a consistent global state S through which L passes such that ϕ(S) is True

Collecting the state [14.6.1]

- Procs p_i send in initial state, then periodically later ones
  - Does not interfere with execution, only delays a bit (!!)
  - Only need to send updates when change in variable used in ϕ
  - Monitor proc records state msgs from each p_i in queue Q_i

Figure 14.14 Vector timestamps and variable values for the execution of Figure 14.9



Example : safety property $|x_i - x_j| \leq \delta$ for all i, j in [1,N]

E.g. δ = 50 & send only "large adjustments" next slides..

Inconsistent cut C_1 show violation that never happened... but C_2 did

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Observing consistent global states [14.6.2]

- Recall a cut C **consistent** if, for every event it contains, all events that "happened before" that event are also contained
  - i.e., $\forall$ events $e \in C$, $f \rightarrow e$ implies that $f \in C$
- Fig 14.14 & only send when adjustments "large enough"
  - Upon receipt, process updates its value to that of sender
- To know of cut is consistent, processes also send vector clocks with (changed) state

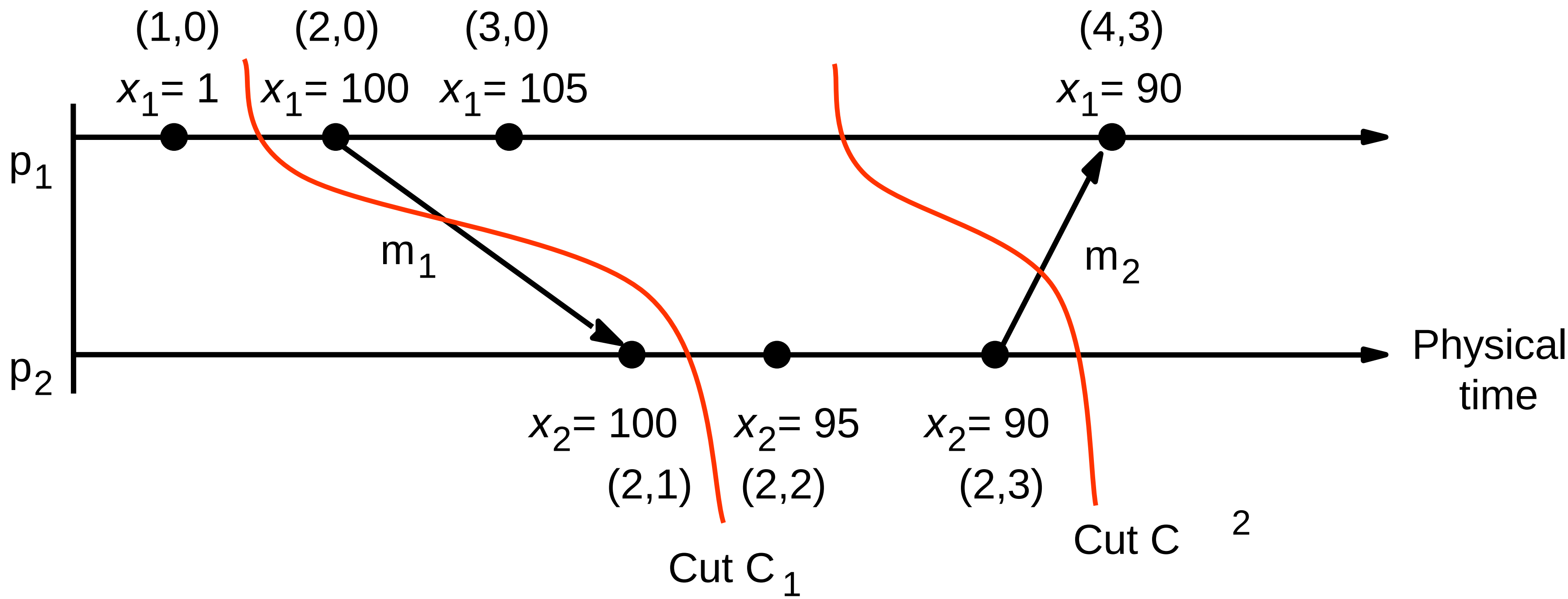
Observing consistent global states (cont.)

- Let
  - $S=\{s_1, s_2, \ldots ,s_N\}$ be a global state at monitor, from the state msgs
  - $V(s_i)$ vector timestamp of state s_i received from process p_i
- Then S is a consistent global state iff

  $V(s_i)[i] \geq V(s_j)[i]$ for i,j in [1,N]

  - I.e., # of p_i's events known at p_j when it sent s_j is no more than then number of events that had occurred at p_i when it sent s_i.
  - I.e., if one proc's state depends on another (by happened-to), then global state also encompasses state upon which it depends
  - How to represent? Lattices (2 slides away)
  - Condition depicted next…

Figure 14.14 REDUX Vector timestamps and variable values for the execution of Figure 14.9



- Consistent cut iff **$V(s_i)[i] \geq V(s_j)[i]$ for i,j in [1,N]**
  - I.e., # of p_i's events known at p_j when it sent s_j is no more than then number of events that had occurred at p_i when it sent s_i.
  - I.e., if one proc's state depends on another (by happened-to), then global state also encompasses state upon which it depends

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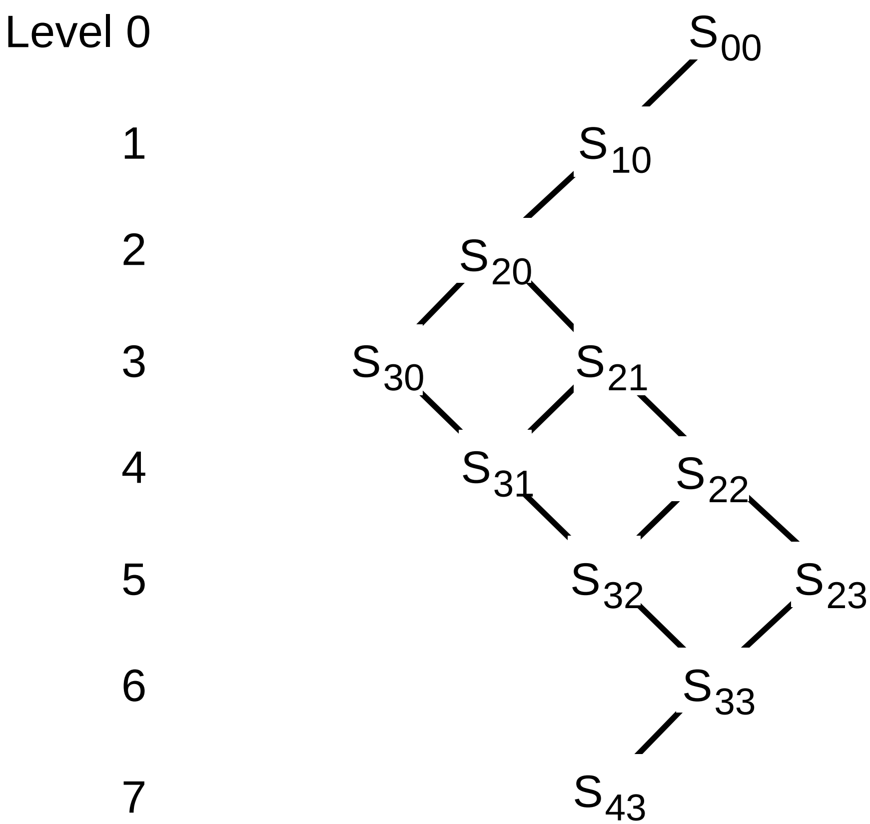
Figure 14.15
The lattice of global states for the execution of Figure 14.14



Sij = global state after *i* events at process 1 and *j* events at process 2

- **<u>Lattice</u>**: a partially ordered set represented graphically (loose defn)
- Captures reachability between consistent global states
- A linearizations traverses from top to bottom, one level down only.
- Eg. Above is all consistent global states in the history

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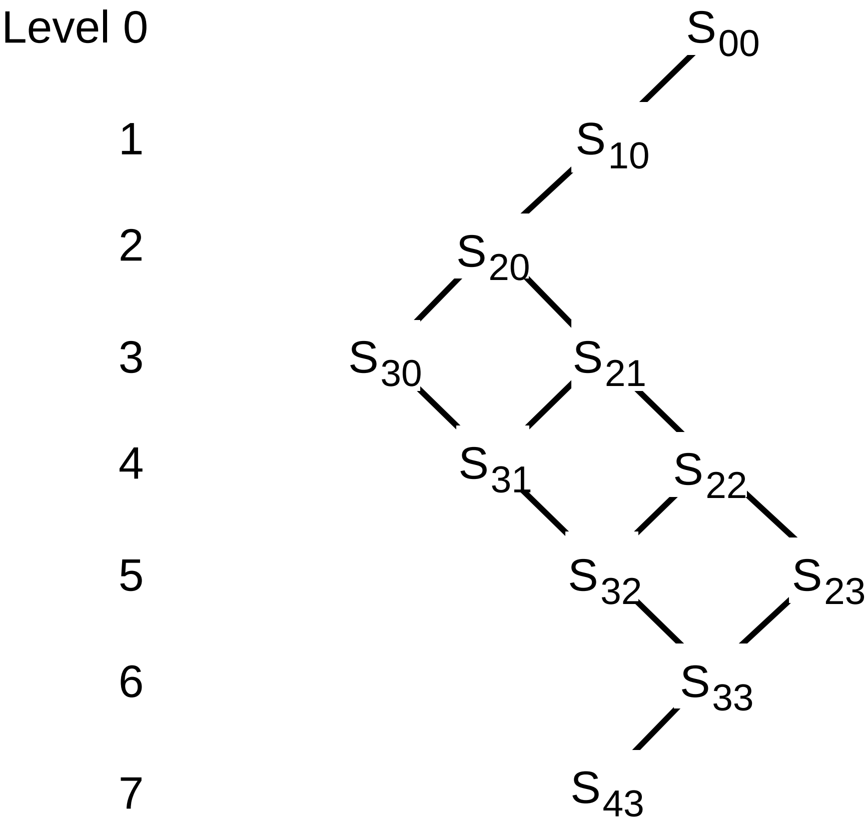
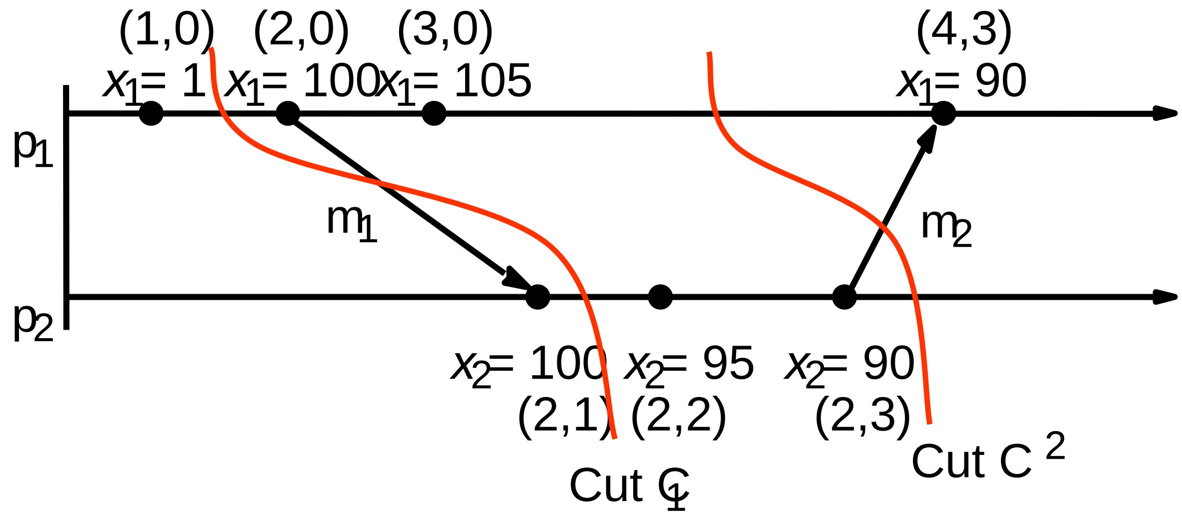
Figure 14.15 Redux
The lattice of global states for the execution of Figure 14.14



Sij = global state after *i* events at process 1 and *j* events at process 2



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Evaluating with the lattice

- Lattice shows us all linearizations corresponding to a history
- Evaluating possibly ϕ
  - Start at initial stage & step through all consistent states
  - Evaluate ϕ at each stage, stop when it evaluates to True
- Evaluating definitely ϕ
  - Try to find a set of states through which all linearizations must pass
  - Then check if the set's states all evaluate ϕ to True; done if find
  - E.g., $\phi(S_{30})$ and $\phi(S_{21})$ both true, and one or other must be passed through for all executions

Figure 14.16: Algorithms to eval. *possibly* ϕ and *definitely* ϕ
NOTE: infinite depth

1. *Evaluating possibly ϕ for global history H of N processes*

$L := 0;$
$States := \{ (s_1^0, s_2^0, \ldots, s_N^0) \};$
while $(\phi(S) = False$ for all $S \in$ States$)$
    $L := L + 1;$
    $Reachable := \{ S' : S'$ reachable in H from some $S \in$ States $\wedge$ level$(S') = L \};$
    $States := Reachable$
end while
output "*possibly* ϕ";

S' set where one event diff. from S
Reachable iff $V(s_j)[j] \geq V(s'_i)[j]$ for i≠j in [1,N]
Can find all states: traverse state queue messages Q_{i1}

2. *Evaluating definitely ϕ for global history H of N processes*

$L := 0;$
if $(\phi(s_1^0, s_2^0, \ldots, s_N^0))$ *then* $States := \{\}$ *else* $States := \{ (s_1^0, s_2^0, \ldots, s_N^0) \};$
while $(States \neq \{\})$
    $L := L + 1;$
    $Reachable := \{ S' : S'$ reachable in H from some $S \in$ States $\wedge$ level$(S') = L \};$
    $States := \{ S \in Reachable : \phi(S) = False \}$
end while
output "*definitely* ϕ";

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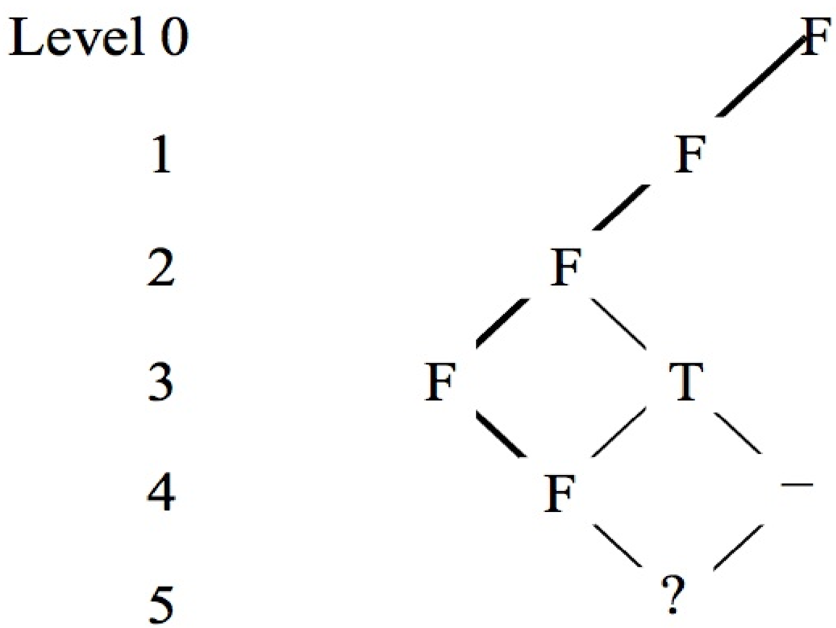
Figure 14.17
Evaluating *definitely* ϕ



F = (ϕ(*S*) = False); T = (ϕ(*S*) = True)

Only traverse states eval F
E.g., Level 3 only one (bold lines)
E.g., Level 4 only one, right one not reachable from F
If ϕ(?) is True then definitely ϕ holds

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