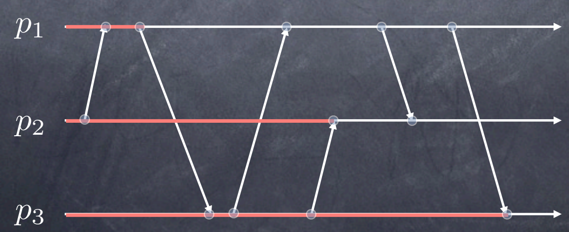
Cuts

A cut C is a subset of the global history of H

$$C = h_1^{c_1} \cup h_2^{c_2} \cup \ldots h_n^{c_n}$$



Cuts

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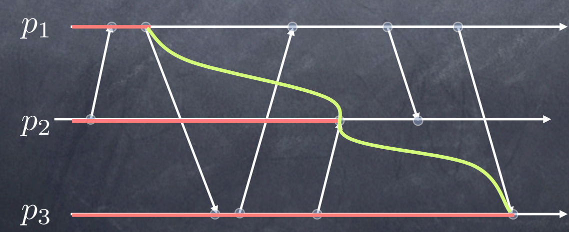
The frontier of C is the set of events

$$e_1^{c_1}, e_2^{c_2}, \ldots e_n^{c_n}$$



Global states and cuts

- The global state of a distributed computation is an n-tuple of local states

$$\Sigma = (\sigma_1, \ldots \sigma_n)$$

- To each cut $(c_1 \ldots c_n)$ corresponds a global state $(\sigma_1^{c_1}, \ldots \sigma_n^{c_n})$

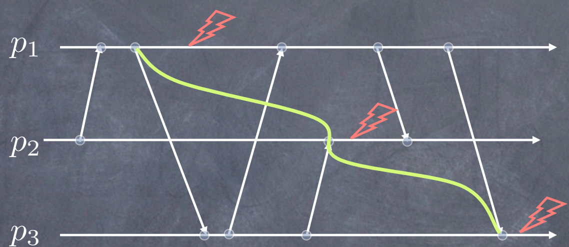
Consistent cuts and consistent global states

- A cut is consistent if

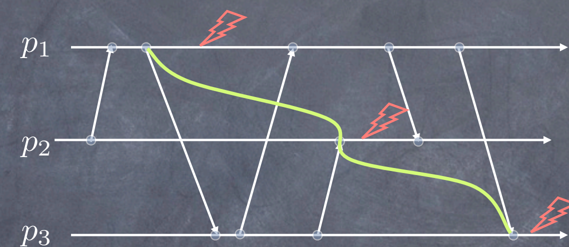
$$\forall e_i, e_j : e_j \in C \land e_i \rightarrow e_j \Rightarrow e_i \in C$$

- A consistent global state is one corresponding to a consistent cut

What p_0 sees



What p_0 sees



Not a consistent global state: the cut contains the event corresponding to the receipt of the last message by p_3 but not the corresponding send event

Our task

- Develop a protocol by which a processor can build a consistent global state
- Informally, we want to be able to take a snapshot of the computation
- Not obvious in an asynchronous system...

Our approach

- Develop a simple synchronous protocol
- Refine protocol as we relax assumptions
- Record:
  - processor states
  - channel states
- Assumptions:
  - FIFO channels
  - Each m timestamped with with $T(send(m))$

Snapshot I

i. p_0 selects t_{ss}

ii. p_0 **sends** "take a snapshot at t_{ss}" **to** all processes

iii. **when** clock of p_i reads t_{ss} **then** p

a. records its local state σ_i
b. starts recording messages received on each of incoming channels
c. stops recording a channel when it receives first message with timestamp greater than or equal to t_{ss}

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Correctness

Theorem Snapshot I produces a consistent cut

Proof Need to prove $e_j \in C \wedge e_i \rightarrow e_j \Rightarrow e_i \in C$

< Definition >
0. $e_j \in C \equiv T(e_j) < t_{ss}$

< Assumption >
1. $e_j \in C$

< Assumption >
2. $e_i \rightarrow e_j$

< 0 and 1>
3. $T(e_j) < t_{ss}$

< Property of real time>
4. $e_i \rightarrow e_j \Rightarrow T(e_i) < T(e_j)$

< 2 and 4>
5. $T(e_i) < T(e_j)$

< 5 and 3>
6. $T(e_i) < t_{ss}$

< Definition >
7. $e_i \in C$

Clock Condition

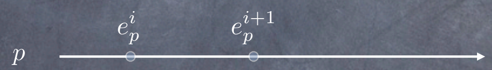
< Property of real time>
4. $e_i \rightarrow e_j \Rightarrow T(e_i) < T(e_j)$

Can the Clock Condition be implemented some other way?

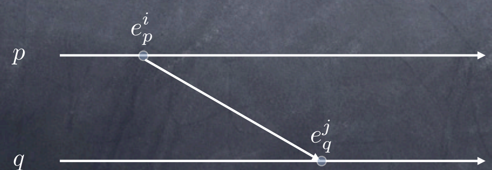
Lamport Clocks

Each process maintains a local variable LC

$LC(e) \equiv$ value of LC for event e

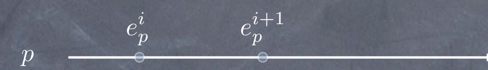


$LC(e_p^i) < LC(e_p^{i+1})$

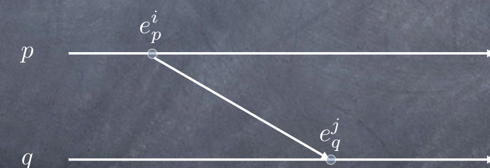


$LC(e_p^i) < LC(e_q^j)$

Increment Rules



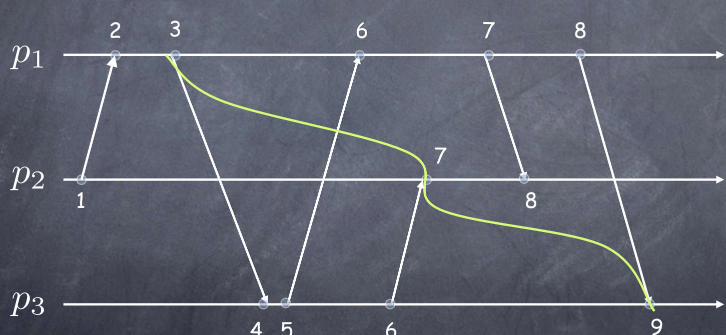
$LC(e_p^{i+1}) = LC(e_p^i) + 1$



$LC(e_q^j) = max(LC(e_q^{j-1}), LC(e_p^i)) + 1$

Timestamp m with $TS(m) = LC(send(m))$

Space-Time Diagrams and Logical Clocks



A subtle problem

when $LC = t$ do S

doesn't make sense for Lamport clocks!

- there is no guarantee that LC will ever be t
- S is anyway executed after $LC = t$

Fixes:

- if e is internal/send and $LC = t - 2$
  - execute e and then S
- if $e = receive(m) \wedge (TS(m) \geq t) \wedge (LC \leq t - 1)$
  - put message back in channel
  - re-enable e ; set $LC = t - 1$; execute S

An obvious problem

- No t_{ss}!
- Choose Ω large enough that it cannot be reached by applying the update rules of logical clocks

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mmmmhhhh...

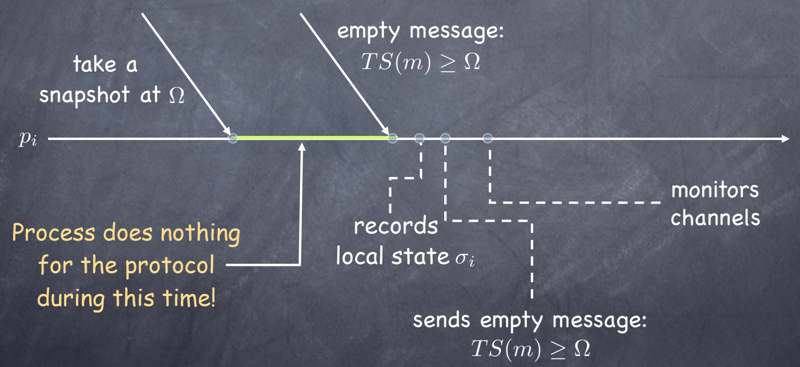
- Doing so assumes
  - upper bound on message delivery time
  - upper bound relative process speeds

We better relax it...

Snapshot II

- processor p_0 selects Ω
- p_0 sends "take a snapshot at Ω" to all processes; it waits for all of them to reply and then sets its logical clock to Ω
- when clock of p_i reads Ω then p_i
  - records its local state σ_i
  - sends an empty message along its outgoing channels
  - starts recording messages received on each incoming channel
  - stops recording a channel when receives first message with timestamp greater than or equal to Ω

Relaxing synchrony



Use empty message to announce snapshot!

Snapshot III

- processor p_0 sends itself "take a snapshot"
- when p_i receives "take a snapshot" for the first time from p_j:
  - records its local state σ_i
  - sends "take a snapshot" along its outgoing channels
  - sets channel from p_j to empty
  - starts recording messages received over each of its other incoming channels
- when p_i receives "take a snapshot" beyond the first time from p_k:
  - stops recording channel from p_k
- when p_i has received "take a snapshot" on all channels, it sends collected state to p_0 and stops.

Snapshots: a perspective

- The global state Σ^s saved by the snapshot protocol is a consistent global state

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  - many total orders (runs) are compatible with that partial order
  - all we know is that Σ^s could have occurred

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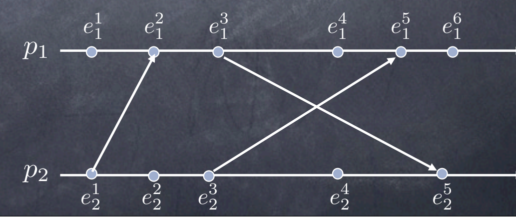
  - all we know is that Σ^s could have occurred
- We are evaluating predicates on states that may have never occurred!

An Execution and its Lattice



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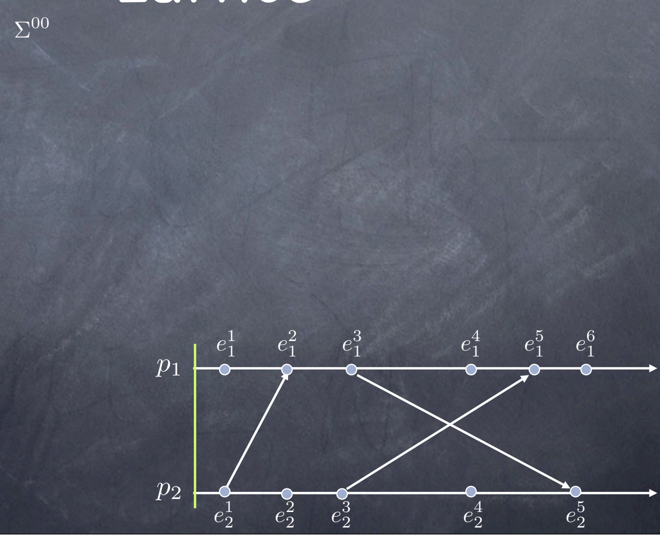

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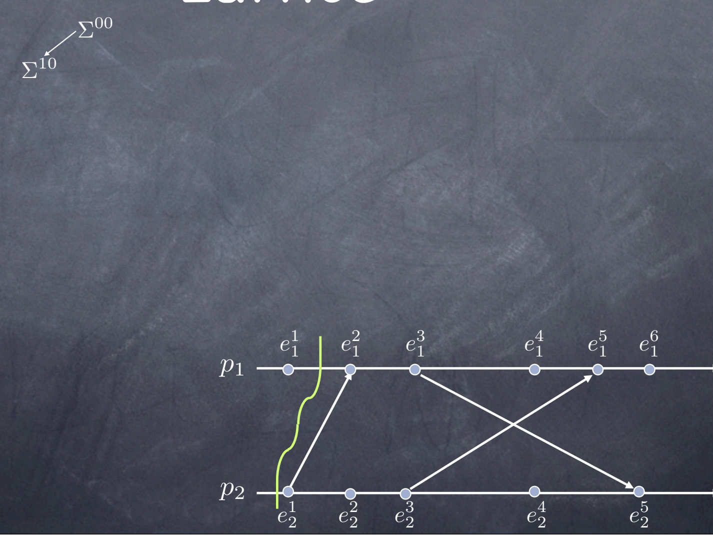
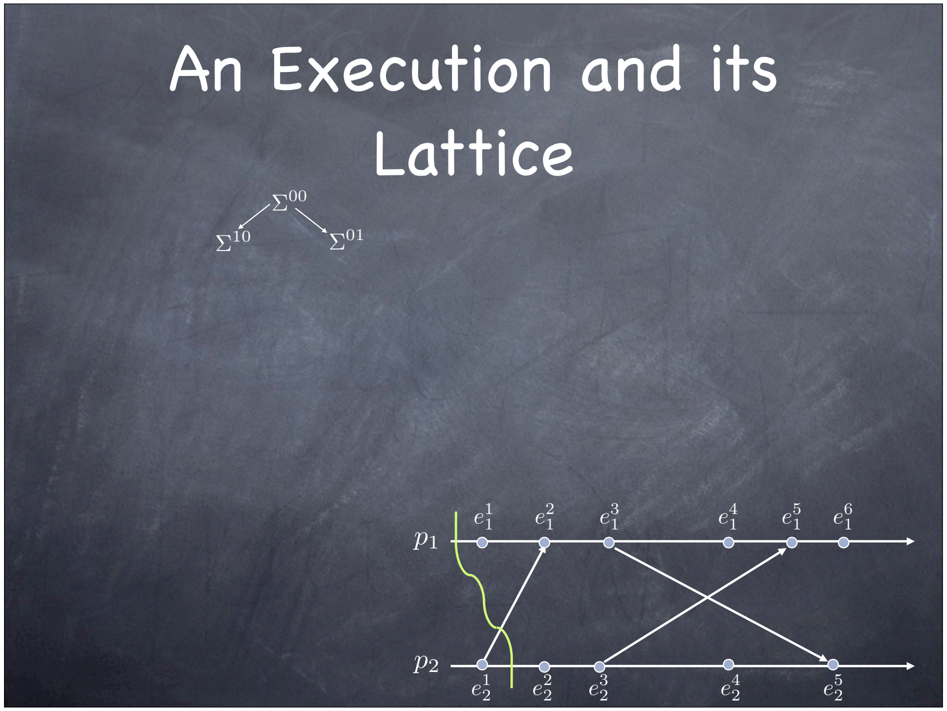
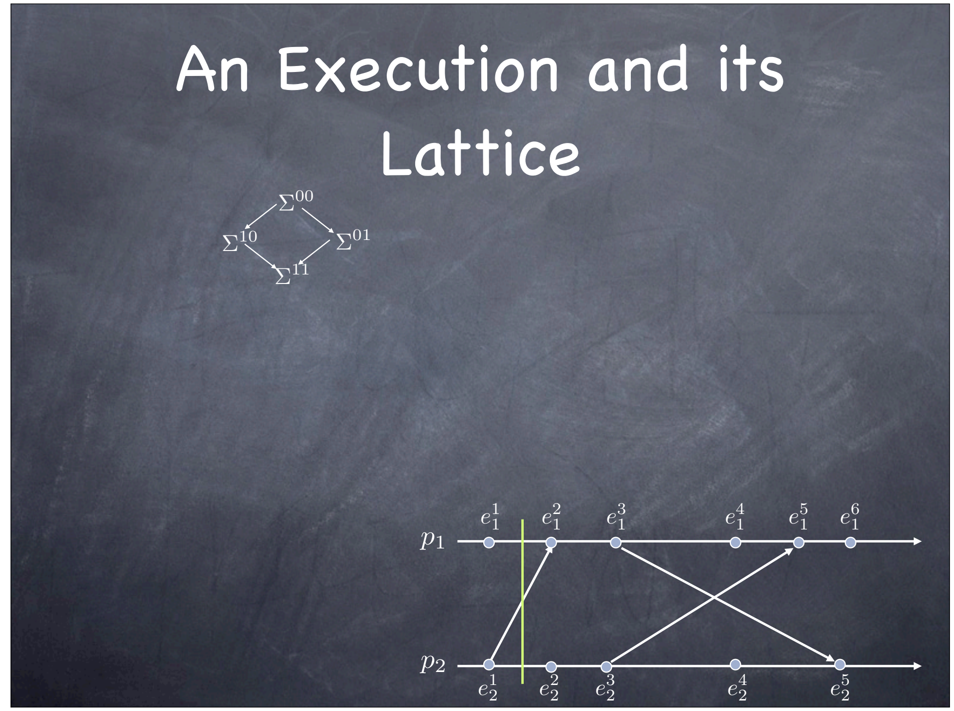



An Execution and its Lattice
Σ^{00}
Σ^{10} Σ^{01}
p_1 p_2
e_1^1 e_1^2 e_1^3 e_1^4 e_1^5 e_1^6
e_2^1 e_2^2 e_2^3 e_2^4 e_2^5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Σ^{00}
Σ^{10} Σ^{01}
Σ^{11}
p_1 p_2
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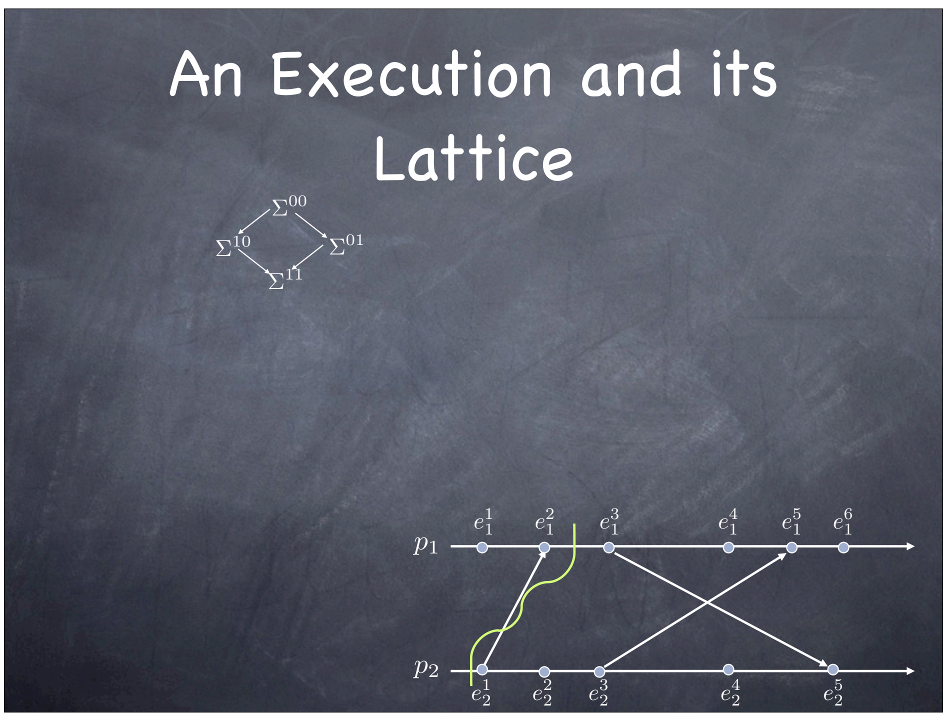
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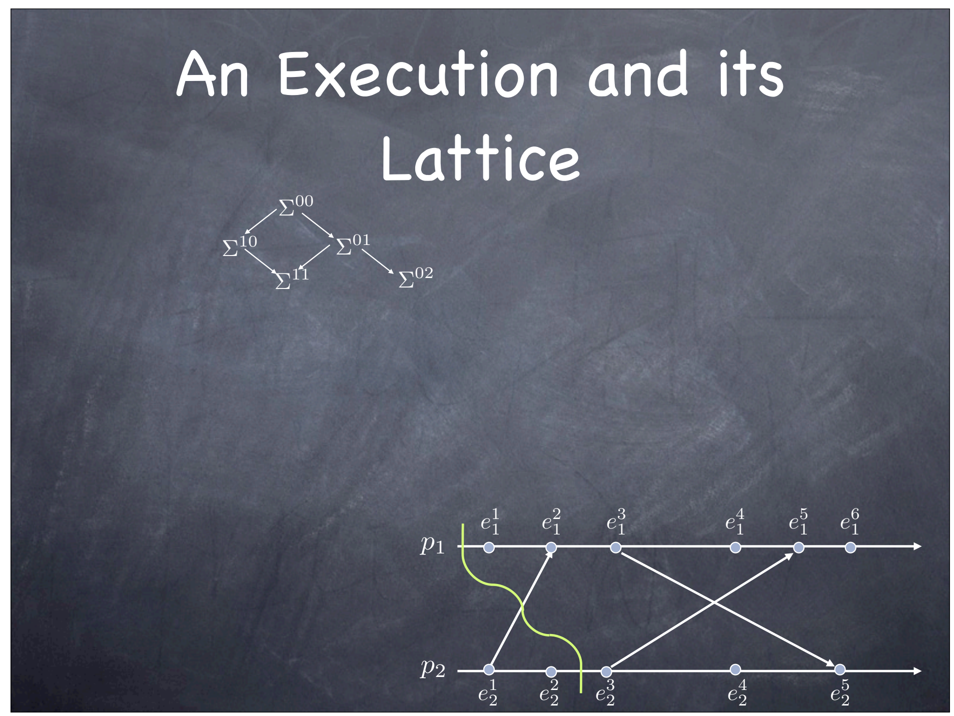
An Execution and its Lattice
Σ^{00}
Σ^{10} Σ^{01}
Σ^{11} Σ^{02}
p_1 p_2
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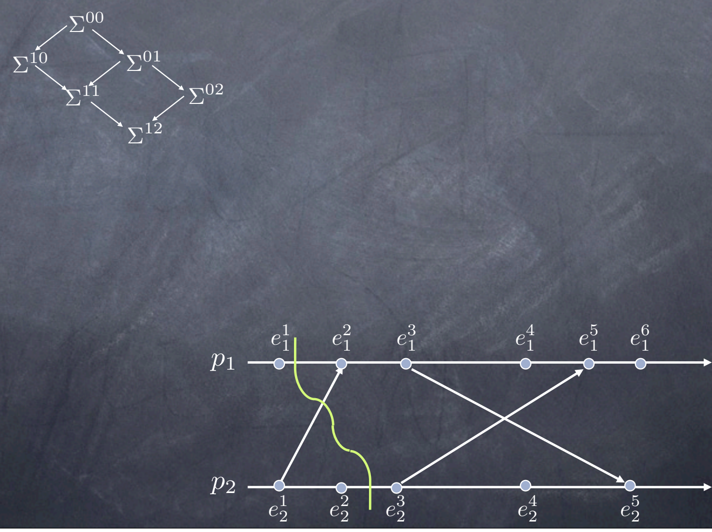

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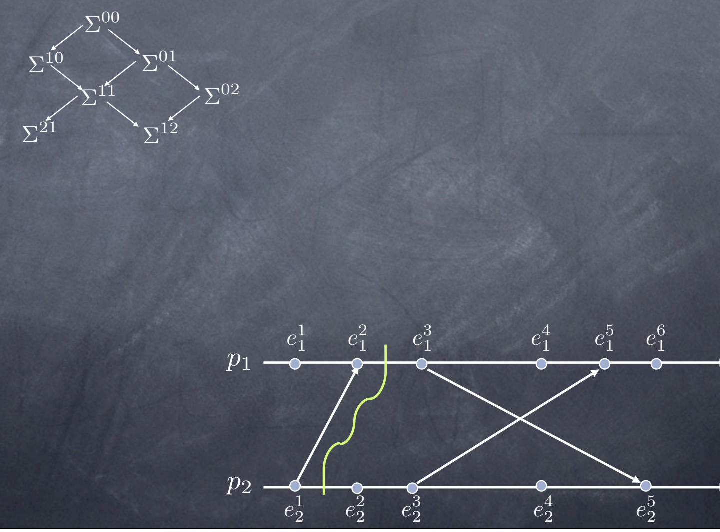

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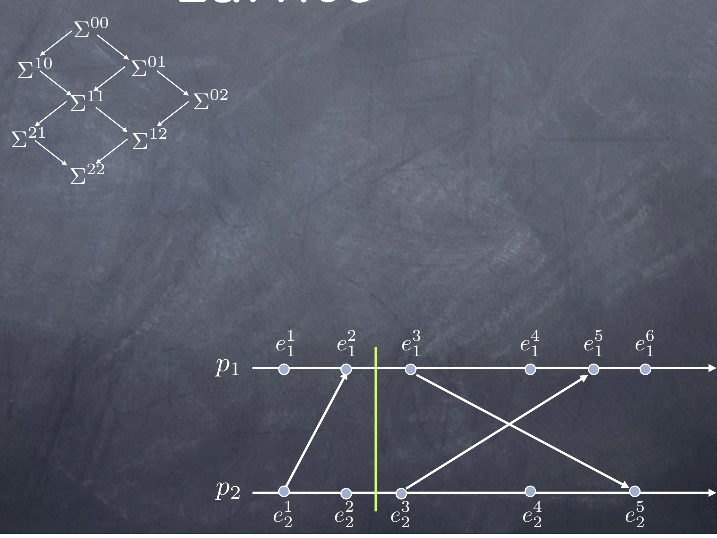

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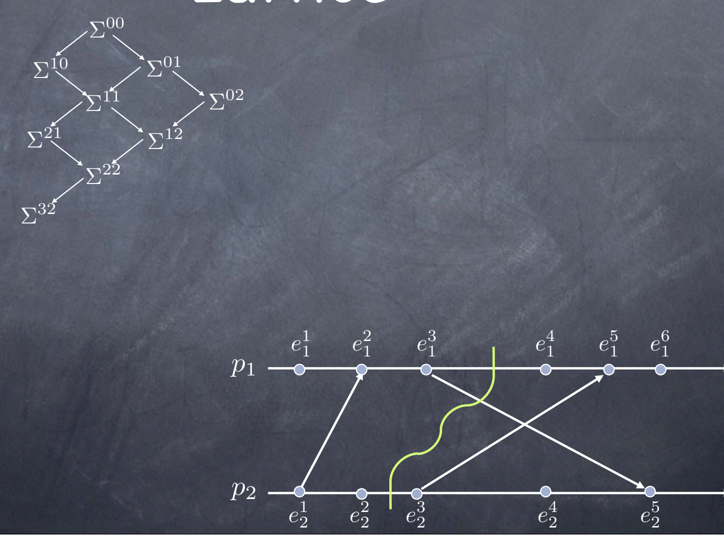

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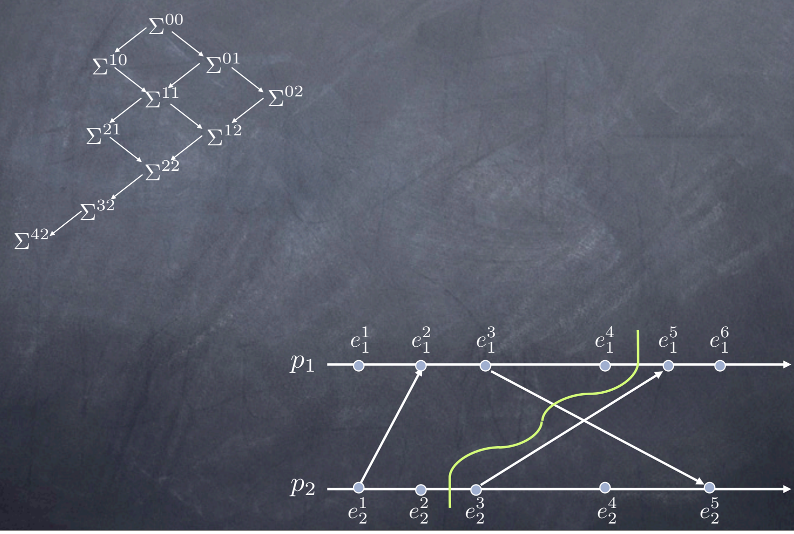

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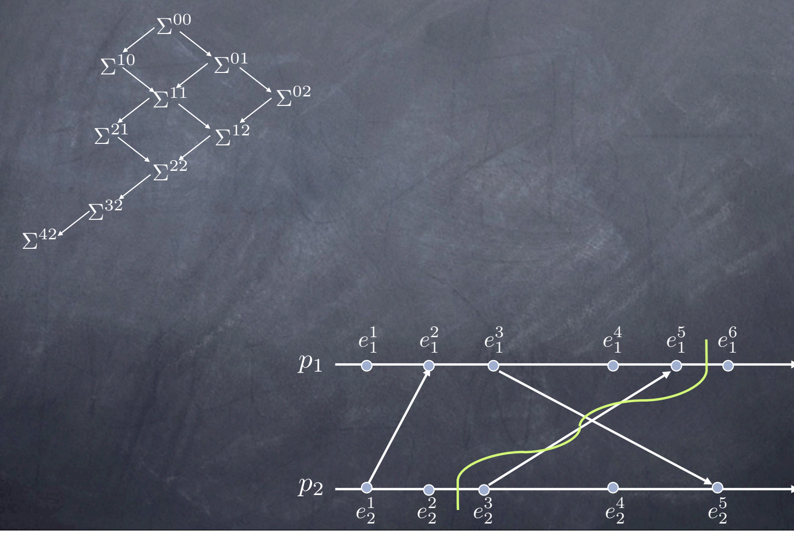

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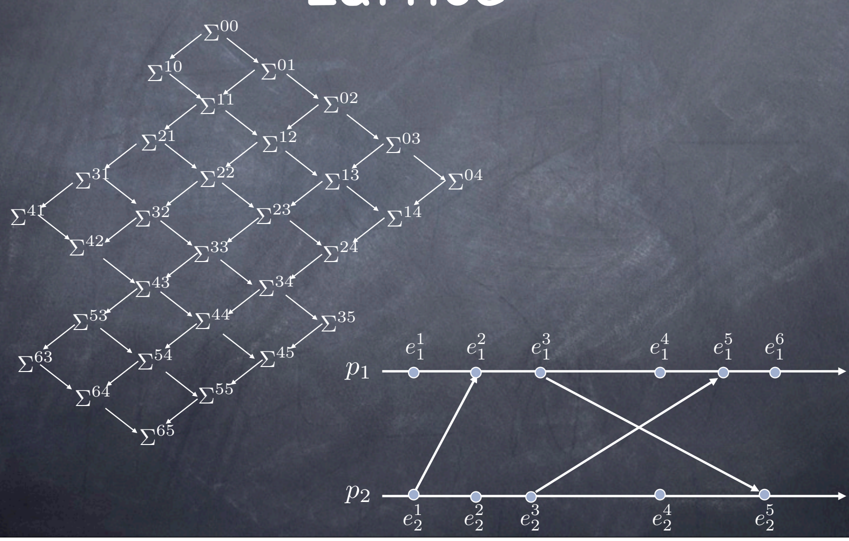
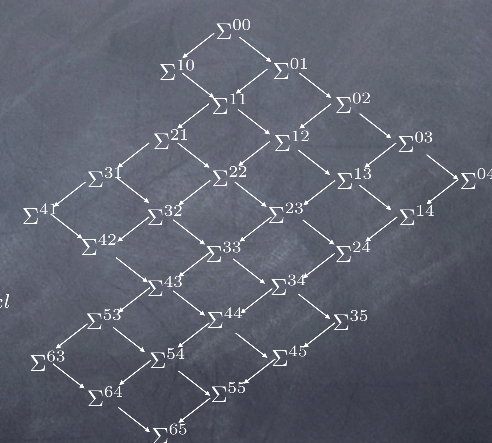


Reachability



Σ^{kl} is reachable from Σ^{ij} if there is a path from Σ^{ij} to Σ^{kl} in the lattice

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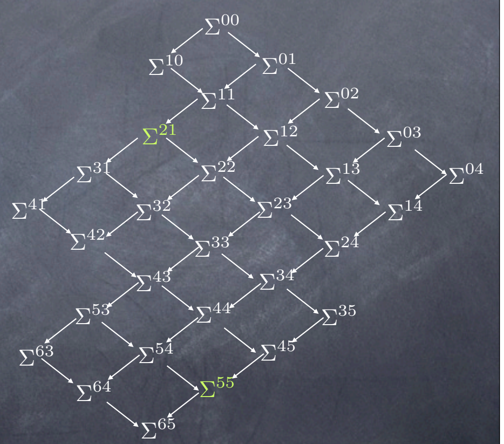

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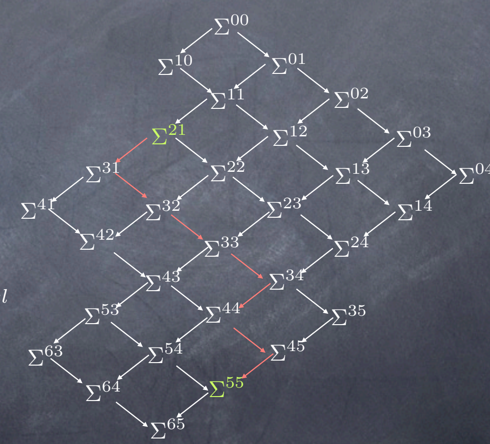

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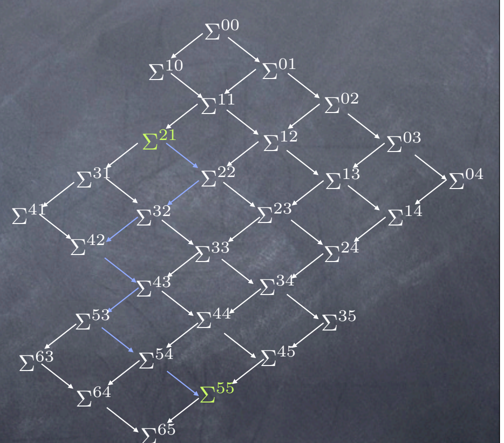

Σ^{kl} is reachable from Σ^{ij} if there is a path from Σ^{ij} to Σ^{kl} in the lattice

$$\Sigma^{ij} \rightsquigarrow \Sigma^{kl}$$

So, why do we care about Σ^s again?

- Deadlock is a stable property

  Deadlock $\Rightarrow \Box$ Deadlock

- If a run R of the snapshot protocol starts in Σ^i and terminates in Σ^f, then $\Sigma^i \rightsquigarrow_R \Sigma^f$

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- If a run R of the snapshot protocol starts in Σ^i and terminates in Σ^f, then $\Sigma^i \leadsto_R \Sigma^f$
- Deadlock in Σ^s implies deadlock in Σ^f
- No deadlock in Σ^s implies no deadlock in Σ^i

Same problem, different approach

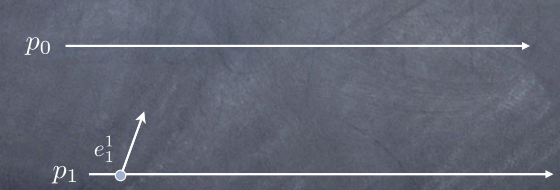
- Monitor process does not query explicitly
- Instead, it passively collects information and uses it to build an observation.

  (reactive architectures, Harel and Pnueli [1985])

An observation is an ordering of event of the distributed computation based on the order in which the receiver is notified of the events.

Observations: a few observations

- An observation puts no constraint on the order in which the monitor receives notifications



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To obtain a run, messages must be delivered to the monitor in FIFO order
What about consistent runs?

Causal delivery

FIFO delivery guarantees:

$send_i(m) \rightarrow send_i(m') \Rightarrow deliver_j(m) \rightarrow deliver_j(m')$

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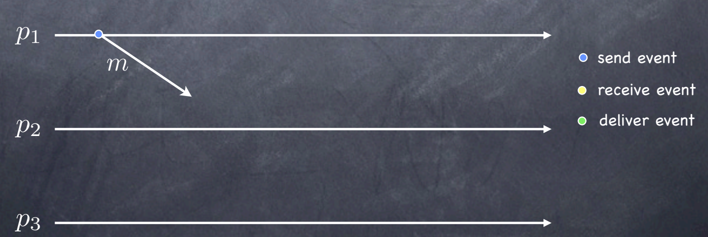

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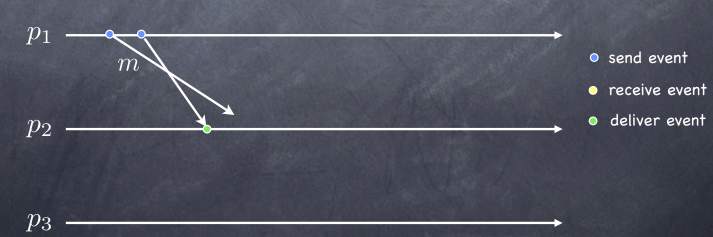

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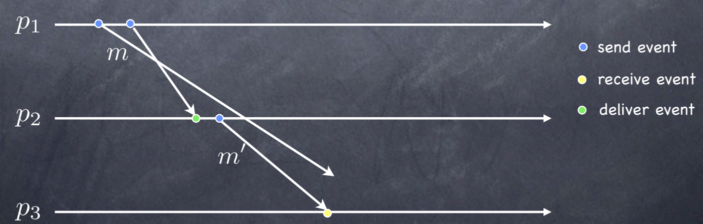

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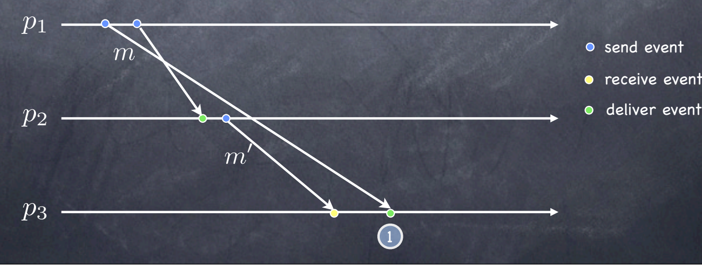

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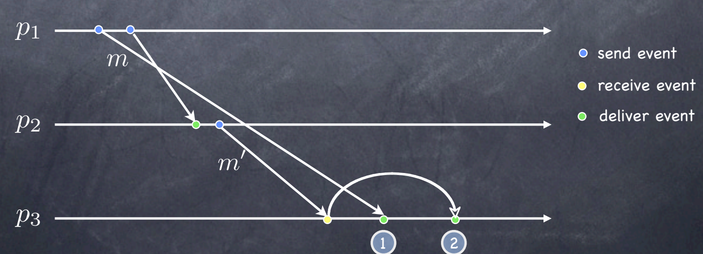

Causal Delivery in Synchronous Systems

We use the upper bound Δ on message delivery time

Causal Delivery in Synchronous Systems

We use the upper bound Δ on message delivery time

DR1: At time t, p_0 delivers all messages it received with timestamp up to $t - \Delta$ in increasing timestamp order

Causal Delivery with Lamport Clocks

DR1.1: Deliver all received messages in increasing (logical clock) timestamp order.

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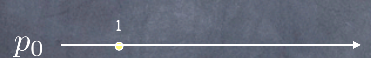

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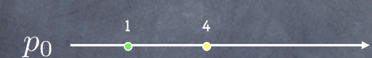

Should p_0 deliver?

Causal Delivery with Lamport Clocks

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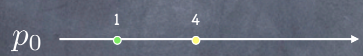

Should p_0 deliver?

Problem: Lamport Clocks don't provide gap detection

Given two events e and e' and their clock values $LC(e)$ and $LC(e')$—where $LC(e) < LC(e')$ determine whether some event e'' exists s.t.

$$LC(e) < LC(e'') < LC(e')$$

Stability

DR2: Deliver all received stable messages in increasing (logical clock) timestamp order.

A message m received by p is stable at p if p will never receive a future message m' s.t.

$$TS(m') < TS(m)$$

Implementing Stability

- Real-time clocks
  - wait for Δ time units

Implementing Stability

- Real-time clocks
  - wait for Δ time units
- Lamport clocks
  - wait on each channel for m s.t. $TS(m) > LC(e)$
- Design better clocks!

Clocks and STRONG Clocks

- Lamport clocks implement the clock condition:

$$e \rightarrow e' \Rightarrow LC(e) < LC(e')$$

- We want new clocks that implement the strong clock condition:

$$e \rightarrow e' \equiv SC(e) < SC(e')$$

Causal Histories

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$$\theta(e) = \{e' \in H \mid e' \rightarrow e\} \cup \{e\}$$

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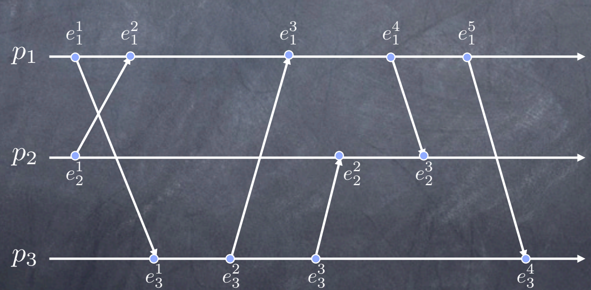
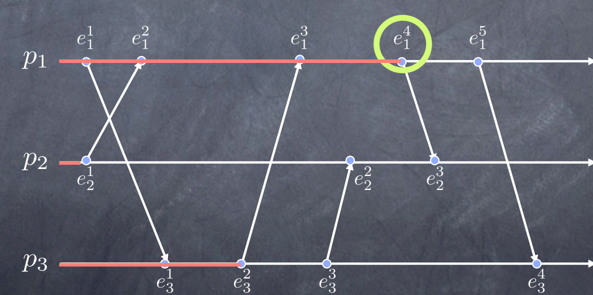


Causal Histories

- The causal history of an event e in $(H, \rightarrow)$ is the set
$$\theta(e) = \{e' \in H \mid e' \rightarrow e\} \cup \{e\}$$



$$e \rightarrow e' \equiv \theta(e) \subset \theta(e')$$

How to build $\theta(e)$

Each process p_i:

- initializes θ: $\theta := \emptyset$
- if e_i^k is an internal or send event, then
  $$\theta(e_i^k) := \{e_i^k\} \cup \theta(e_i^{k-1})$$
- if e_i^k is a receive event for message m, then
  $$\theta(e_i^k) := \{e_i^k\} \cup \theta(e_i^{k-1}) \cup \theta(send(m))$$

Pruning causal histories

- Prune segments of history that are known to all processes (Peterson, Bucholz and Schlichting)
- Use a more clever way to encode $\theta(e)$

Vector Clocks

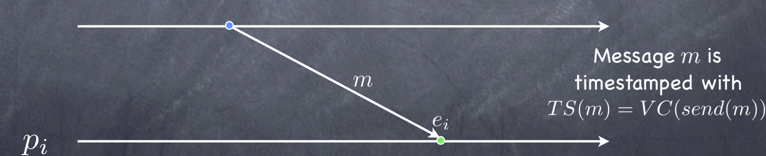
- Consider $\theta_i(e)$, the projection of $\theta(e)$ on p_i
- $\theta_i(e)$ is a prefix of h^i: $\theta_i(e) = h_i^{k_i}$ – it can be encoded using k_i
- $\theta(e) = \theta_1(e) \cup \theta_2(e) \cup \ldots \cup \theta_n(e)$ can be encoded using $k_1, k_2, \ldots, k_n$

Represent θ using an n-vector VC such that

$$VC(e)[i] = k \Leftrightarrow \theta_i(e) = h_i^{k_i}$$

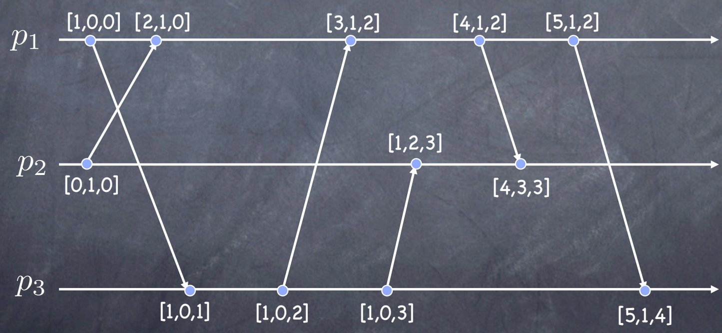
Update rules

$$VC(e_i)[i] := VC[i] + 1$$

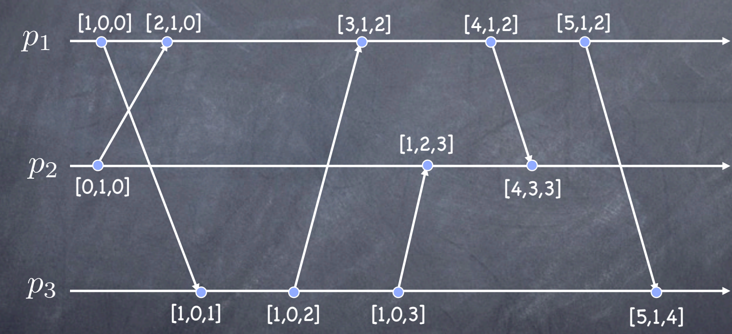


$$VC(e_i) := max(VC, TS(m))$$
$$VC(e_i)[i] := VC[i] + 1$$

Example



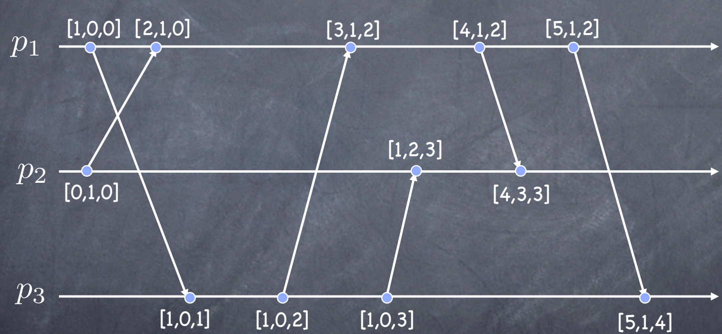
Operational interpretation



$VC(e_i)[i]$ =

$VC(e_i)[j]$ =

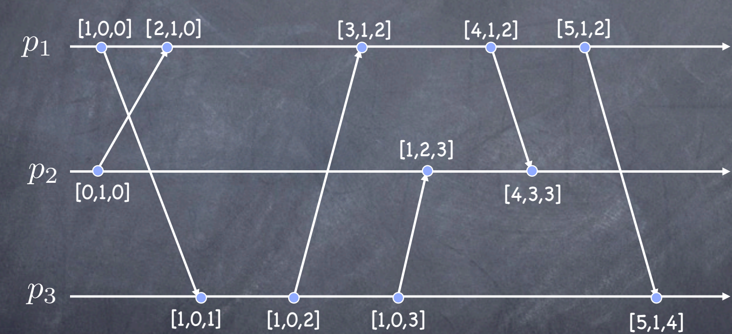
Operational interpretation



$VC(e_i)[i]$ = no. of events executed by p_i up to and including e_i

$VC(e_i)[j]$ =

Operational interpretation



$VC(e_i)[i]$ = no. of events executed by p_i up to and including e_i

$VC(e_i)[j]$ = no. of events executed by p_j that happen before e_i of p_i