Causal Delivery in Synchronous Systems

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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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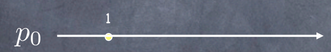

Causal Delivery with Lamport Clocks

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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

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- 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

- The causal history of an event e in $(H, \rightarrow)$ is the set

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

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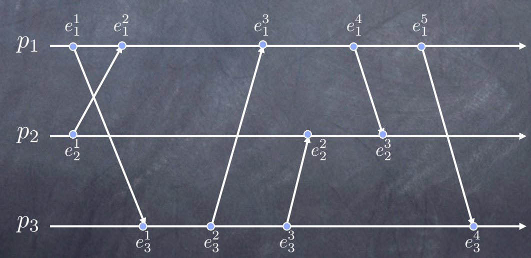

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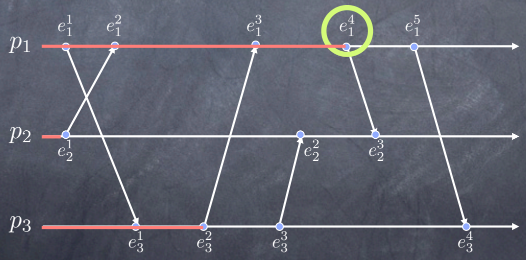


$$e \rightarrow e' \equiv \theta(e) \subset \theta(e')$$

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 $\theta(e)$

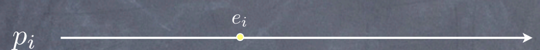
Vector Clocks

- 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 $k_1, k_2, \ldots, k_n$

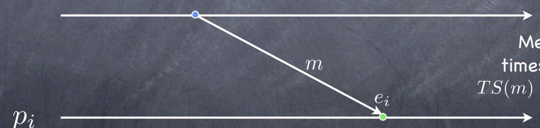
Represent θ using an n-vector VC such that

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

Update rules



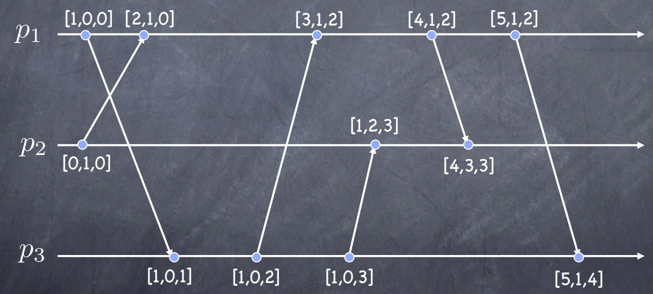
$VC(e_i)[i] := VC[i] + 1$



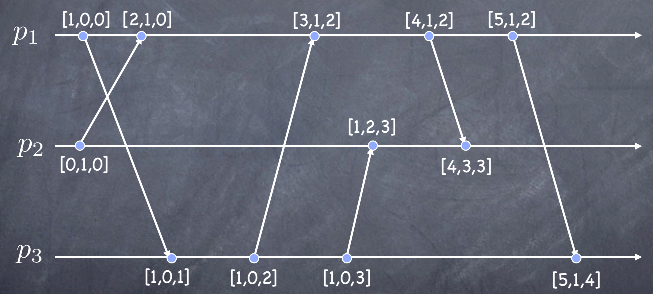
Message m is timestamped with $TS(m) = VC(send(m))$

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

Example



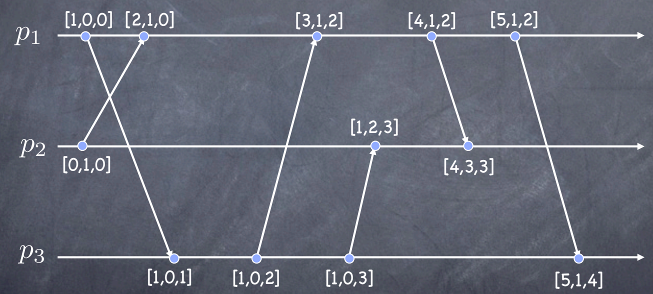
Operational interpretation



$VC(e_i)[i]$ =

$VC(e_i)[j]$ =

Operational interpretation



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

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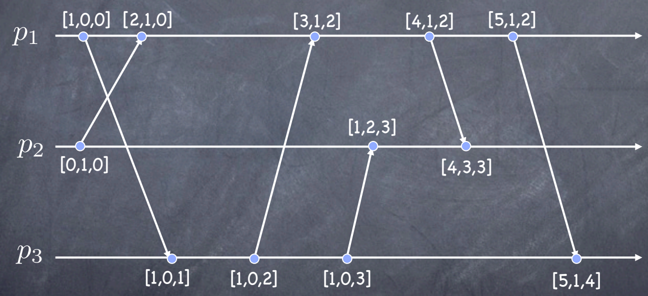
Operational interpretation



$VC(e_i)[i]$ = 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

VC properties: event ordering

Given two vectors V and V', less than is defined as:

$$V < V' \equiv (V \neq V') \wedge (\forall k : 1 \leq k \leq n : V[k] \leq V'[k])$$

- Strong Clock Condition: $e \rightarrow e' \equiv VC(e) < VC(e')$
- Simple Strong Clock Condition:
  Given e_i of p_i and e_j of p_j, where $i \neq j$
  $$e_i \rightarrow e_j \equiv VC(e_i)[i] \leq VC(e_j)[i]$$
- Concurrency
  Given e_i of p_i and e_j of p_j, where $i \neq j$
  $$e_i \parallel e_j \equiv (VC(e_i)[i] > VC(e_j)[i]) \wedge (VC(e_j)[j] > VC(e_i)[j])$$

VC properties: consistency

- Pairwise inconsistency
  Events e_i of p_i and e_j of p_j $(i \neq j)$ are pairwise inconsistent (i.e. can't be on the frontier of the same consistent cut) if and only if
  $$(VC(e_i)[i] < VC(e_j)[i]) \vee (VC(e_j)[j] < VC(e_i)[j])$$
- Consistent Cut
  A cut defined by $(c_1, \ldots, c_n)$ is consistent if and only if
  $$\forall i, j : 1 \leq i \leq n, 1 \leq j \leq n : (VC(e_i^{c_i})[i] \geq VC(e_j^{c_j})[i])$$