Distributed Systems (5DV147)

Time and Global States

Fall 2014

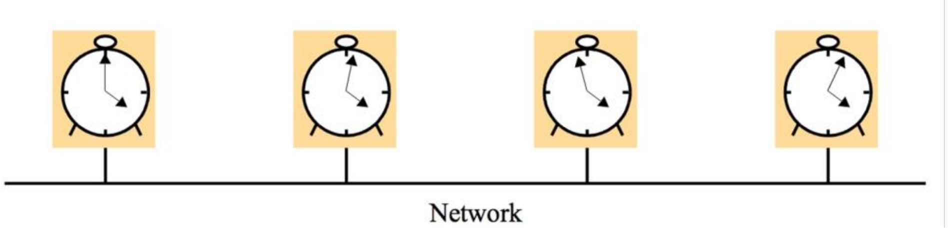
Time and the lack thereof

Motivation examples

- ❑ Replication
  - ➢ Updates applied in the same order at all sites
- ❑ Monitoring
  - ➢ all processes receive notification events in the same order
- ❑ Allocation of share resources
  - ➢ Fairness in processing requests

Why do we not have global time?

- Clocks drift, are inaccurate, may fail arbitrarily, etc.



A global notion of a correct time would be tremendously useful

Why is this a problem?

- ❑What does it mean that one event occurs after another one?
- ❑How can we know if events are concurrent if we can't compare when they happened?

… but, perhaps, all we need is that all nodes agree on a form of time

- ❑…or, at least, agree on the order in which events occur
- ❑Not a global time but a global clock

Logical time and logical clocks

Motivation

- Difficult to have a single global time
- What can we do? Let’s consider one processes:

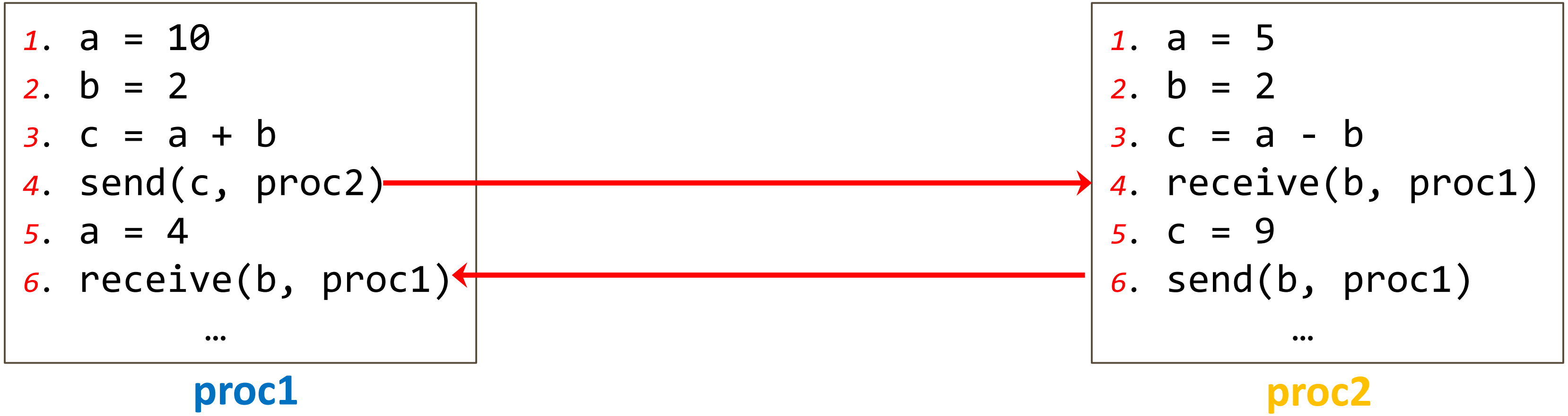
```
1. a = 10
2. b = 2
3. c = a + b
4. send(c, proc2)
5. a = 4
      …
i. receive(b, proc1)
      …
```

proc1

- What can we say about the order in which these operations are executed?

(1, 2, 3, 4, 5, …, i, …)

Now for two processes …



proc1

```
1. a = 10
2. b = 2
3. c = a + b
4. send(c, proc2)
5. a = 4
6. receive(b, proc1)
         …
```

proc2

```
1. a = 5
2. b = 2
3. c = a - b
4. receive(b, proc1)
5. c = 9
6. send(b, proc1)
         …
```

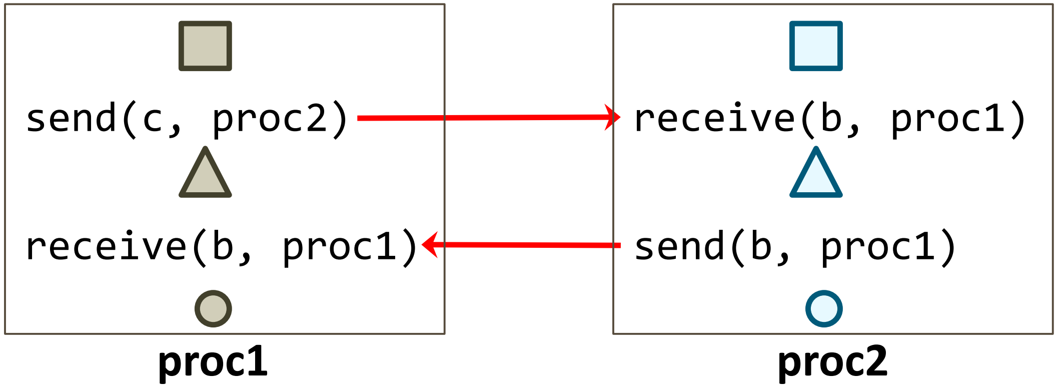
What can we say about the combined order of execution?

What can we say about **proc1**.3 and **proc2**.2?

What can we say about **proc1**.4 and **proc2**.4?

What can we say about **proc1**.6 and **proc2**.6?

Now for two processes …



send(c, proc2)

receive(b, proc1)

proc1

receive(b, proc1)

send(b, proc1)

proc2

proc1.send proc2.receive proc2.send proc1.receive

… we can say something about the order of some operations

What do we know now?

- ☐ We know the order of events occurring at the same process
- ☐ We know something about *send* and *receive* events
  - ➢ *send* causes a *receive*
  - ➢ *receive* is the effect of *send*
- ☐ Cause and effect may not be violated
  - ➢ An effect cannot be observed before the cause
  - ➢ *send* operations must always come before *receive* operations

Let’s be more formal

Let’s consider a distributed system P, of N processes:

p_i, $i = 1, 2, \ldots, N$

Each process has state s_i

Three type of events e can occur at each p_i :

Internal events, send events, receive events

Events are ordered within a process by the relation $\rightarrow_i$

$$e^0 \rightarrow_i e^1 \rightarrow_i e^2$$

Events define a history of p_i as described by $\rightarrow_i$

$$history(p_i) = h_i = \langle e_i^0, e_i^1, e_i^2, \ldots \rangle$$

Happened-before relation “→”

HB1: If there exists a process p_i: $e \rightarrow_i e'$, then $e \rightarrow e'$

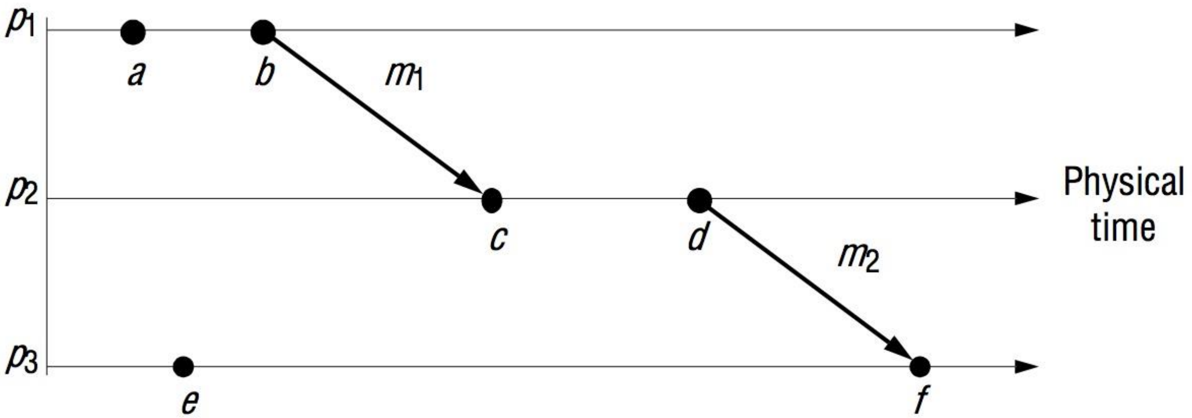
HB2: For any message m: $send(m) \rightarrow receive(m)$

HB3: If e, e', and e'' are events such that $e \rightarrow e'$ and $e' \rightarrow e''$, then $e \rightarrow e''$

Two events are said to be concurrent if:

$$e \nrightarrow e' \text{ and } e' \nrightarrow e$$

A simple example



HB1: a ⟶ b, c ⟶ d, e ⟶ f

HB2: b ⟶ c, d ⟶ f

HB3: a ⟶ b ⟶ c ⟶ d ⟶ f

No ordering for e.g., b and e

They are concurrent, denoted b || e

Figure adapted from Instructor's Guide for Coulouris, Dollimore, Kindberg and Blair, Distributed Systems: Concepts and Design Edn. 5 © Pearson Education 2012 – **Figure 14.5**

How can we use the “→” relation when implementing systems?

Lamport’s logical clocks

Lamport's logical clocks

- Monotonically increasing counter
  - Counter serves as a timestamp
- Each process has a counter that increases when an event occurs (*send* and *receive*)
- Counter is sent with message
  - Recipient sets own clock to `max(own, received)` and then increases its own counter

Details

Denote timestamp of event e at p_i by $L_i(e)$ and globally $L(e)$

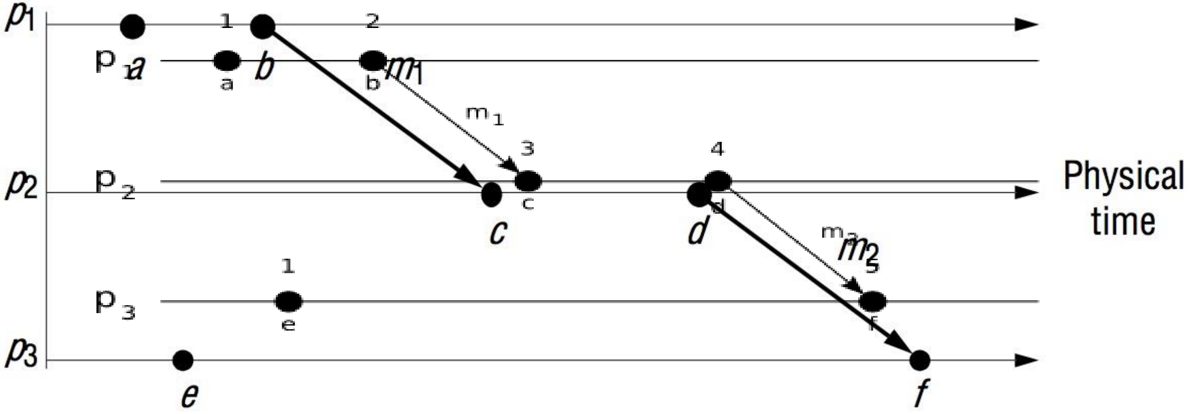
LC1: Increment L_i before each event at p_i , $L_i = L_i + 1$

LC2 : *(m* is a message, *t* is a timestamp*)*

a) When p_i sends `m`, it sends along the value $t = L_i$

b) On receiving `(m, t)`, p_j computes $L_j = \max(L_j, t)$ and then applies LC1 before time stamping the received event `receive(m)`

What can we say about our simple example



Ordering of events:

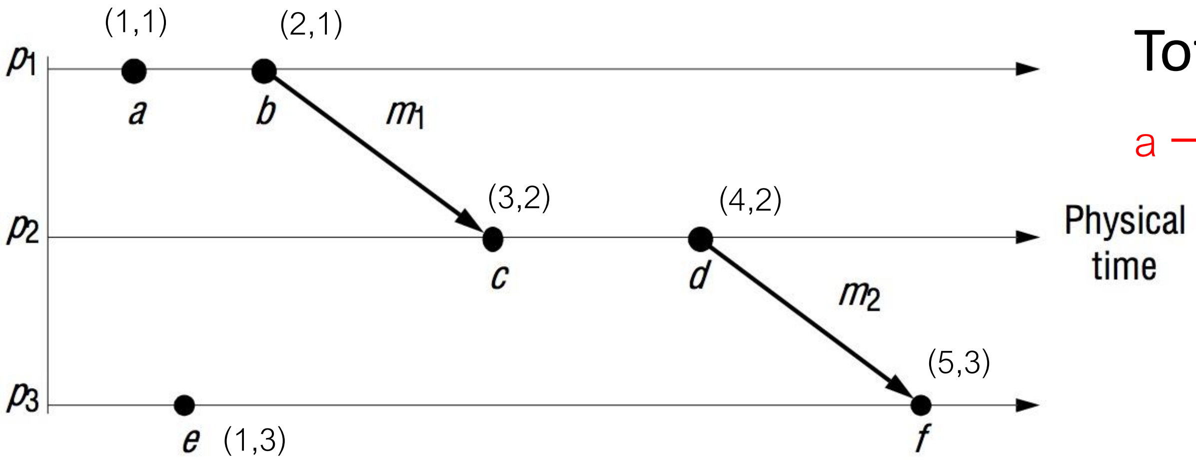
Evident that $e \rightarrow e' \Rightarrow L(e) < L(e')$

But, the opposite does not hold!

- e.g., $L(b) > L(e)$, but $b \parallel e$

Figure adapted from Instructor’s Guide for Coulouris, Dollimore, Kindberg and Blair, Distributed Systems: Concepts and Design Edn. 5 © Pearson Education 2012 – **Figure 14.6**

How can we create a total order?



Total order:

a ⟶ e ⟶ b ⟶ c ⟶ d ⟶ f

Define global timestamps for `e` and `e'` to be (T_i, i) and (T_j, j) and $(T_i, i) < (T_j, j)$ iff $T_i < T_j$, or $T_i = T_j$ and $i < j$

Figure adapted from Instructor’s Guide for Coulouris, Dollimore, Kindberg and Blair, Distributed Systems: Concepts and Design Edn. 5 © Pearson Education 2012 – **Figure 14.5**

But coming back to $L(e) < L(e') \nRightarrow e \rightarrow e'$

Vector clocks

Vector clocks

- Keep track of known events at all processes (a vector or array of timestamps)
- Each process keeps a vector clock to timestamp local events
- Send vector clock with message
  - Receiver merges clocks by setting own values to the maximum of own values and received ones

Formally

VC1: Initially, $V_i[j] = 0$, for `i, j = 1, 2, …, N`

VC2: Just before p_i timestamps `e`, it sets $V_i[i] = V_i[i] + 1$

VC3: p_i includes `timestamp =` V_i in every `send(m, timestamp)`

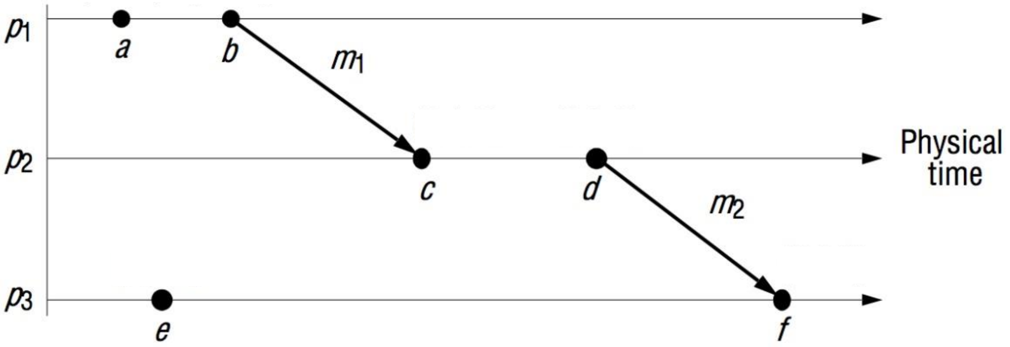
VC4: When p_i receives `timestamp` in a message, it sets

$V_i[j] = max\ (V_i[j]\ ,\ timestamp[j]\ )$, for `j = 1, 2, …, N`

Back to our simple example

$V = (L_1, L_2, L_3)$

$V_1 = (0,0,0)$
$V_2 = (0,0,0)$
$V_3 = (0,0,0)$



Vector clocks can be ordered

- V=V' if all values are the same
- V≤V' if all values in V are ≤ those in V'
- V<V' if V≤V' and V and V' are non-equal

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Concurrent events

$$\mathrm{e} \rightarrow \mathrm{e}' \Rightarrow \mathrm{V(e)} < \mathrm{V(e')} \; and \; \mathrm{V(e)} < \mathrm{V(e')} \Rightarrow \mathrm{e} \rightarrow \mathrm{e}'$$

- Concurrent events (`b || e`):
  - *Neither* `V(b) < V(e)` *nor* `V(e) < V(b)`

Vector clocks have nice properties

- Causal paths can be visualized
  - Causal paths help learn updates that occurred on other processes previous to an event
- However…
  - They use more space
    - expensive in terms of memory and bandwidth (`O(N)` in both cases)
    - no upper bound on clock size
  - It is better if processes don’t change dynamically

Summary

- ✓ We don’t have universal or global time
- ✓ Logical clocks are based on events in processes and the inter-event relationships (between processes)
  - ➢ Detect causal relationships – capability of one event to affect another event either directly or transitively
  - ➢ Happened-before relation
  - ➢ Some events are concurrent

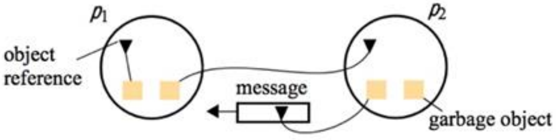
Summary (2)

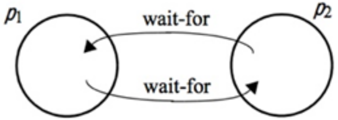
- ✓ Lamport's logical clocks are simple, but have problems with concurrent events
    - ➢ Can derive total order, but with no physical significance
    - ➢ Completely distributed
    - ➢ Fault tolerant
    - ➢ Impose minimal overhead
- ✓ Vector clocks are more powerful, but also more costly
    - ➢ Can differentiate when two events are concurrent

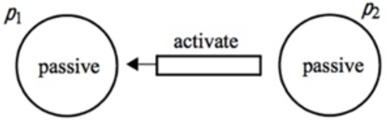
Global states

We often need to know the state of the entire distributed system of knowing if a particular property is true for the system as it executes

- Distributed garbage collection
- Stable property detection: distributed deadlocks, distributed termination detection
- Checkpointing

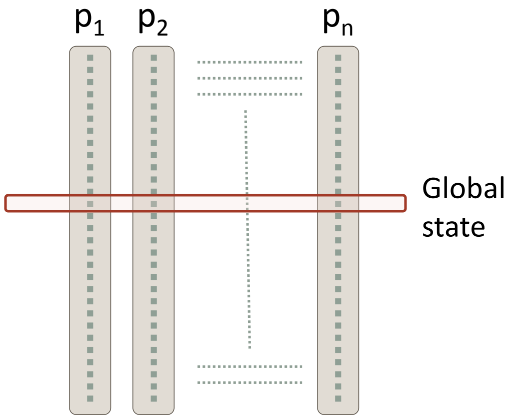






What prevents us from observing a global state in a Distributed System?

- ❑ Non-instantaneous communication
  - ➢ The view of a global state of a system depends on the observer
- ❑ Relativistic effects
  - ➢ Synchronization by time is not a reliable mechanism
- ❑ Interruptions
  - ➢ Different machines don’t react at the same time



Simple with global time!

Just issue “report state at time X”

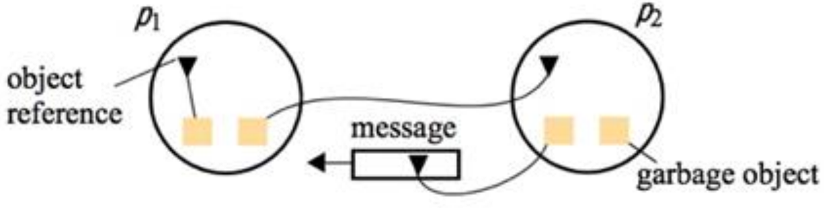
…we do not have this luxury

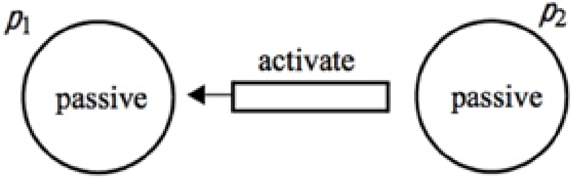
A simple approach

- Collect the state of each process one by one

Just process states are not enough!

Messages currently in the channels





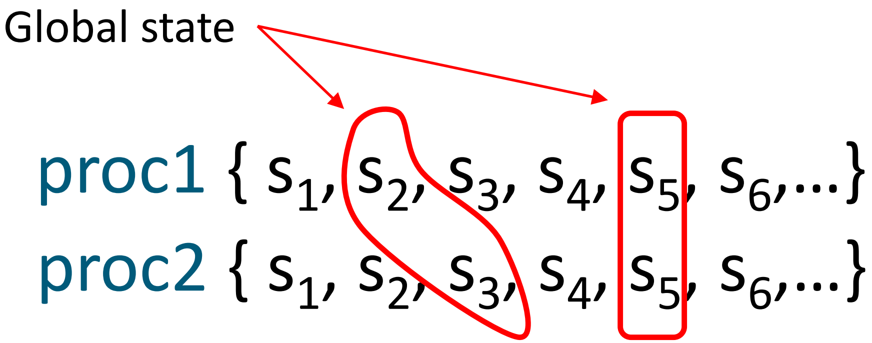
Motivation

```
a = 10                S1
b = 2                 S2
c = a + b             S3
send(c, proc2)        S4
a = 4                 S5
receive(b, proc1)     S6
      …               …
```

proc1

```
a = 5                 S1
b = 2                 S2
c = a - b             S3
receive(b, proc1)     S4
c = 9                 S5
send(b, proc1)        S6
      …               …
```

proc2



Each process maintains own history

- ☐ We could create global history by just taking union of all local histories

We only want to consider such global states *S* that may have occurred at some point in time

We can be more formal

Let’s remember that events at p_i defined a *history*

$history(p_i) = h_i = <e_i^0, e_i^1, e_i^2, ...>$

each process changes state accordingly

$s_i = <s_i^0, s_i^1, s_i^2, ...>$

The global history is the union of processes histories:

$$H = h_0 \bigcup h_1 \bigcup \dots$$

Let’s consider a prefix (first κ events) of a process histories

$h_i^k = <e_i^0, e_i^1, ..., e_i^k>$

Cuts

A *cut* is a union of prefixes of process histories:

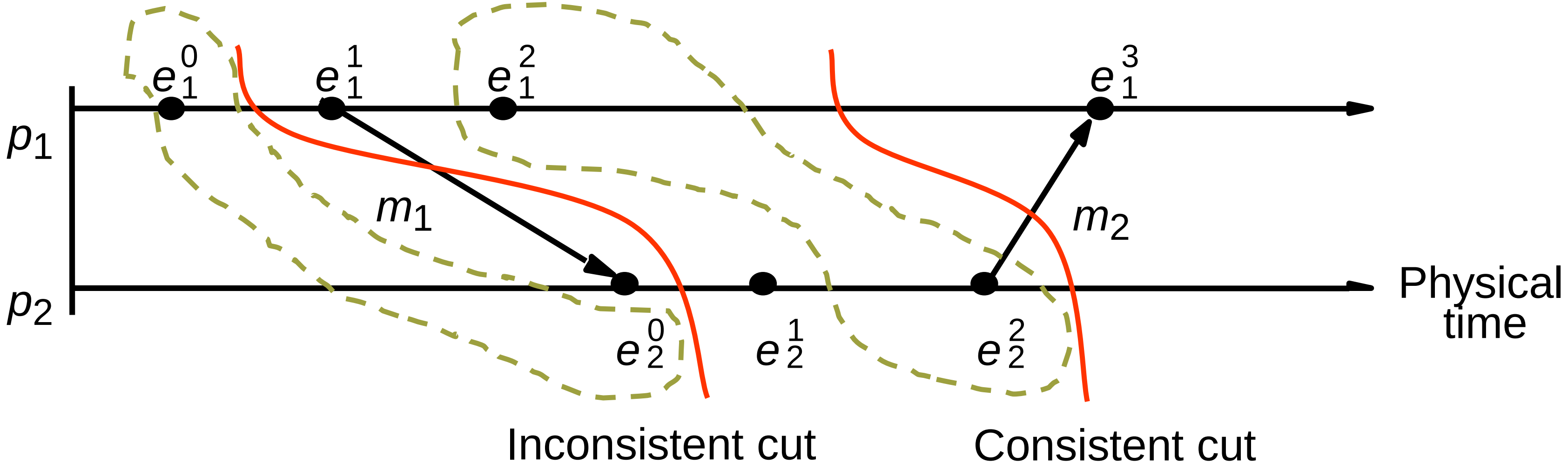
$$C = h_1^{c_1} \bigcup h_2^{c_2} \bigcup \dots \bigcup h_N^{c_N}$$

Frontier of the cut

States in which each process is after processing the last event in the cut:

$$\{e_i^{c_i} : i = 1,2, \dots , N\}$$

A simple example



According to the definition, we can make any cut that we want, including ones that make no sense!

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Consistent cuts and global states

- A cut is *consistent* if for each event in the cut
  - all events that happened before are also in the cut

$$e \in C,\ f \rightarrow e \Rightarrow f \in C$$

- We want to only consider *consistent cuts*
- Consistent global states correspond to consistent global cuts
  - We only move between consistent global states during execution: $S_0 \rightarrow S_1 \rightarrow S_2 \rightarrow \dots$

Linearization and runs

- Total orderings of all events in the global history
  - A *run* is only consistent with the ordering of each process' own local history
  - A *linearization* is consistent with the (global) happened-before relation
- Runs do not have to pass through consistent global states, but all linearizations do
  - `s'` is *reachable* from `s` if ∃ a linearization from `s` to `s'`

Snapshot algorithm (Chandy-Lamport algorithm)

Snapshot algorithm

- ❑ Chandy and Lamport, distributed algorithm for determining global states of a distributed system
- ❑ Constructs a snapshot of the global state (both processes and channels)
  - ➢ Ensures that the global state is *consistent*
  - ➢ Makes **no guarantee** that the system was actually in the recorded state!

Assumptions

- ❑ Neither channel nor processes fail
  - ➢ Communication is reliable
- ❑ There’s a communication path between any two processes
  - ➢ Unidirectional channels with FIFO message delivery
- ❑ Any process may initiate a global snapshot at any time
- ❑ Algorithm does not interfere with the normal execution of the processes

How does the algorithm works?

- Each process records its local state and the state of the incoming channels
- The algorithm works by using markers for two purposes:
  - As a signal for saving a process state
  - As a means of determining which messages belong to the channel state
- State is recorded at each process,
  - Global state is formed by collecting states from all processes

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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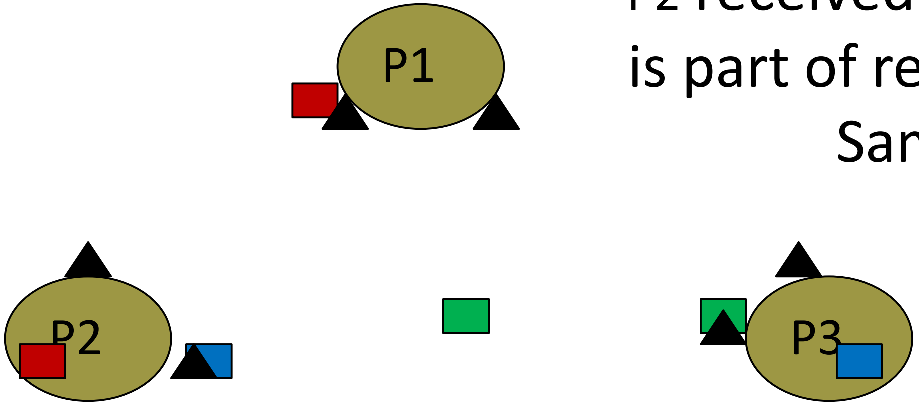
Snapshot example



P2 received marker on P1→P2 after 🟥, so it is part of recorded state

Same for P3 and 🟦

However, P3 sent out 🟩 before the marker, and P2’s state snapshot does not include it

Note that 🟩 is neither part of the state of P3 nor of P2 at this point!

Algorithm concludes that 🟩 was in transit between P3 and P2

Summary

- ✓ There are some cases where it is necessary to know the global state of a system
  - ➢ Lacking a global clock makes this difficult
- ✓ Global state encompasses both processes and channels states
- ✓ We Introduced the concept of cuts and consistent cuts
- ✓ We learned how to captured consistent global states corresponding to consistent cuts
  - ➢ Snapshot algorithm (Chandy & Lamport)

Next Lecture

Mutual exclusion and Elections