Today

- Last lecture: Basic Algorithms

- Today:
  - Time, clocks, NTP
    – Ref: CDK
  - Causality, ordering, logical clocks:
    – Ref: VG, CDK

Time

- Ordering of events are important:
  - Which happened first
- Need synchronisation between sender and receiver
- Coordination of joint activity etc..

Coordinated Universal Time

- Coordinated universal time (UTC)
  - Time maintained for civil use (on atomic clock)
  - Kept within 0.9 seconds of exact mean time for Greenwich

Clocks

- Piezoelectric effect:
  - Squeeze a quartz crystal: generates electric field
  - Apply electric field: crystal bends
- Quartz crystal clock:
  - Resonation like a tuning fork
  - Accurate to parts per million
  - Gain/lose ½ second per day

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Challenges

- Two clocks do not agree perfectly
- **Skew:** The time difference between two clocks
- Quartz oscillators vibrate at different rates
- **Drift:** The difference in rates of two clocks
- If we had two perfect clocks:
  - Skew = 0
  - Drift = 0

When we detect a clock has a skew

- Eg: it is 5 seconds behind
- Or 5 seconds ahead

- What can we do?

When we detect a clock has a skew

- e.g. it is 5 seconds behind
  - We can advance it 5 seconds to correct
  - Might skip over event scheduled in-between
- Or 5 seconds ahead
  - Pushing back 5 seconds is a bad idea
    - Message was received before it was sent
    - Document closed before it was saved etc..

  - We want **monotonicity**: time always increases
  - We want **continuity**: time doesn’t make jumps

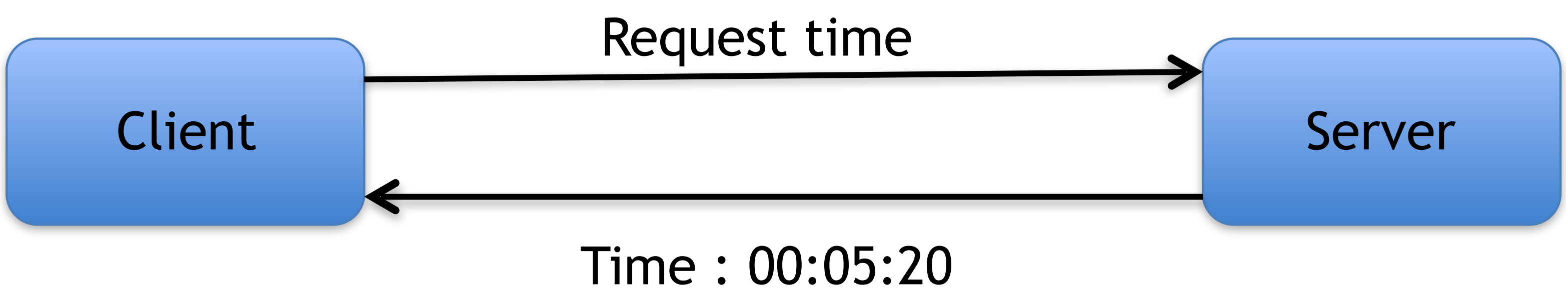
When we detect a clock has a skew

- e.g. it is behind
  - Run it faster until it catches up
- It is ahead
  - Run it slower until it catches up

- This does not guarantee correct clock in future
  - Need to check and adjust periodically

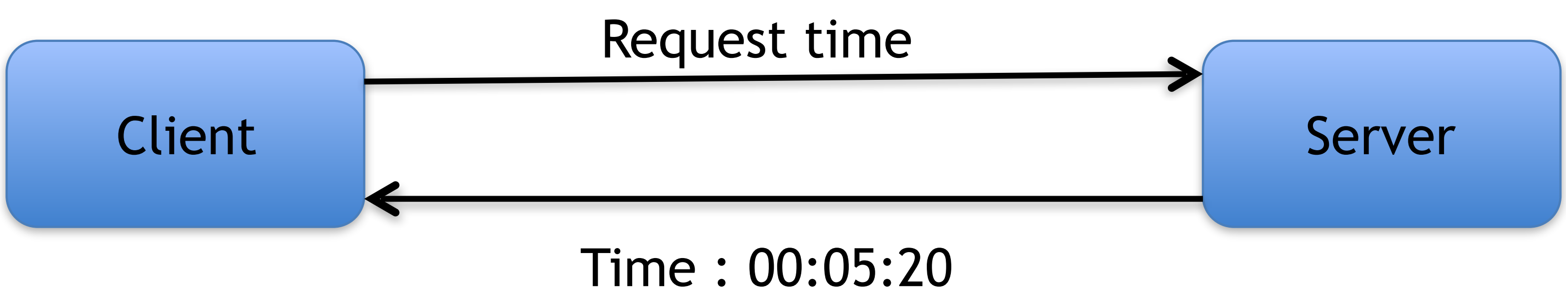
How clocks synchronise

- Obtain time from time server:



How clocks synchronise

- Obtain time from time server:



- Time is inaccurate
  - Delays in message transmission
  - Delays due to processing time
  - Server's time may be inaccurate

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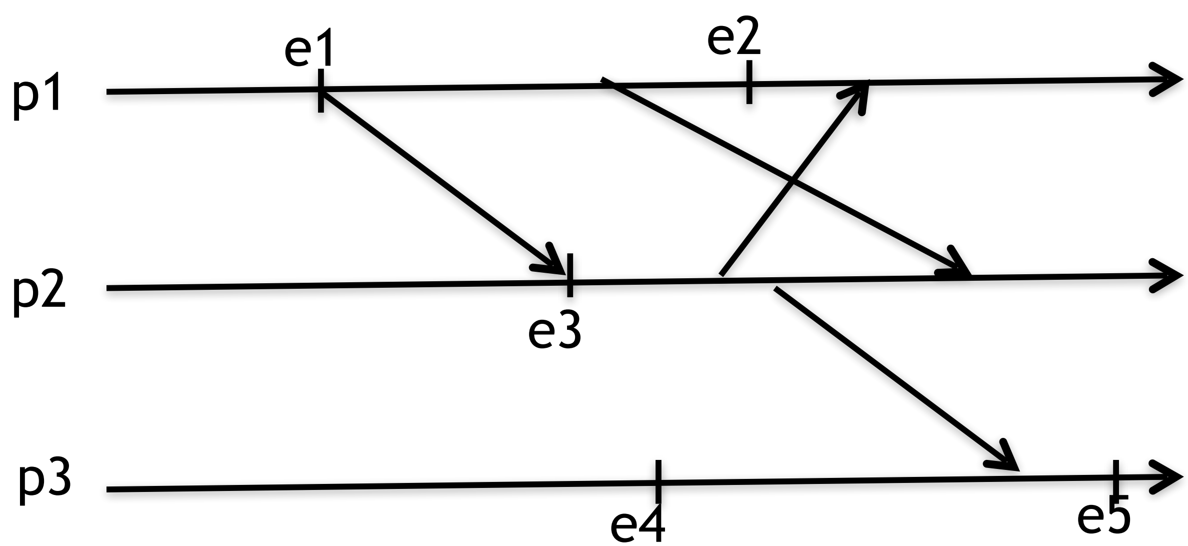
Logical clocks

- Why do we need clocks?
  – To determine when one thing happened before another
- Can we determine that without using a "clock" at all?
  – Then we don't need to worry about synchronisation, millisecond errors etc..

Happened before

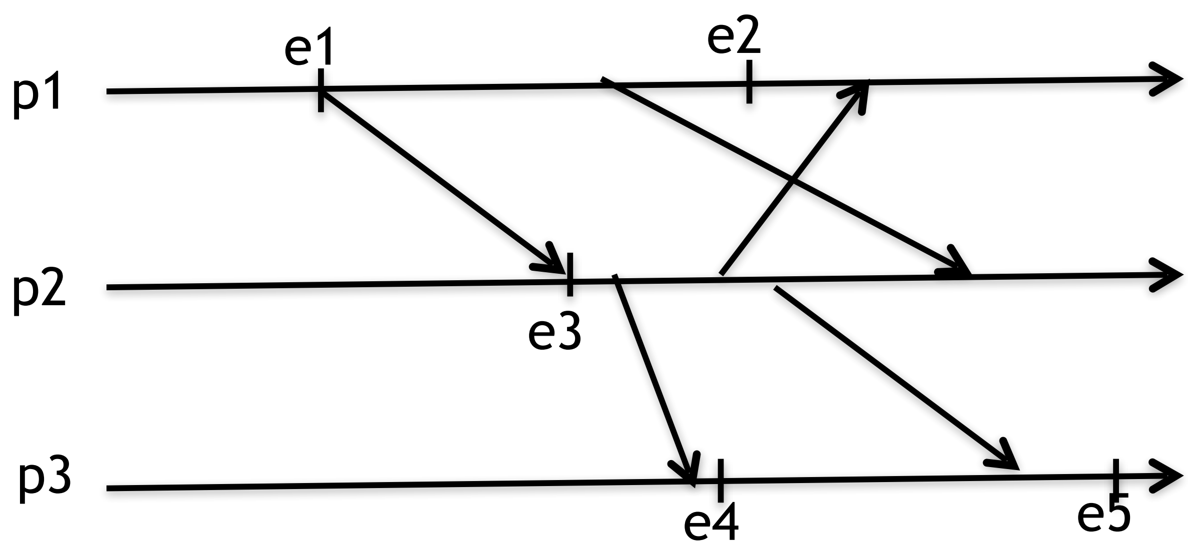
- $a \longrightarrow b$: a happened before b
  - If a and b are successive events in same process then $a \longrightarrow b$
  - Send before receive
    - If a : “send” event of message m
    - And b : “receive” event of message m
    - Then $a \longrightarrow b$
  - Transitive: $a \longrightarrow b$ and $b \longrightarrow c \implies a \longrightarrow c$

Example



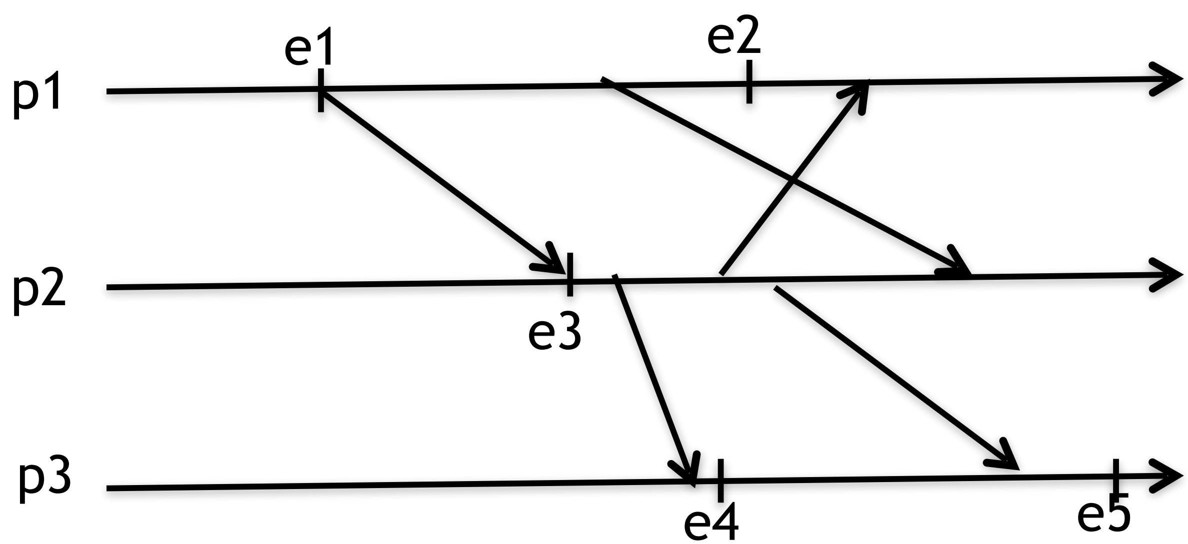
Example

- Events without a happened before relation are "concurrent"
- e1⟶e2, e3⟶e4,e1⟶e5, e5||e2



Example

- Events without a happened before relation are "concurrent"
- Happened before is a partial ordering



Happened before & causal order

- Happened before ==
  could have caused/influenced
- Preserves causal relations
- Implies a partial order
  - Implies time ordering between certain pairs of events
  - Does not imply anything about ordering between concurrent events

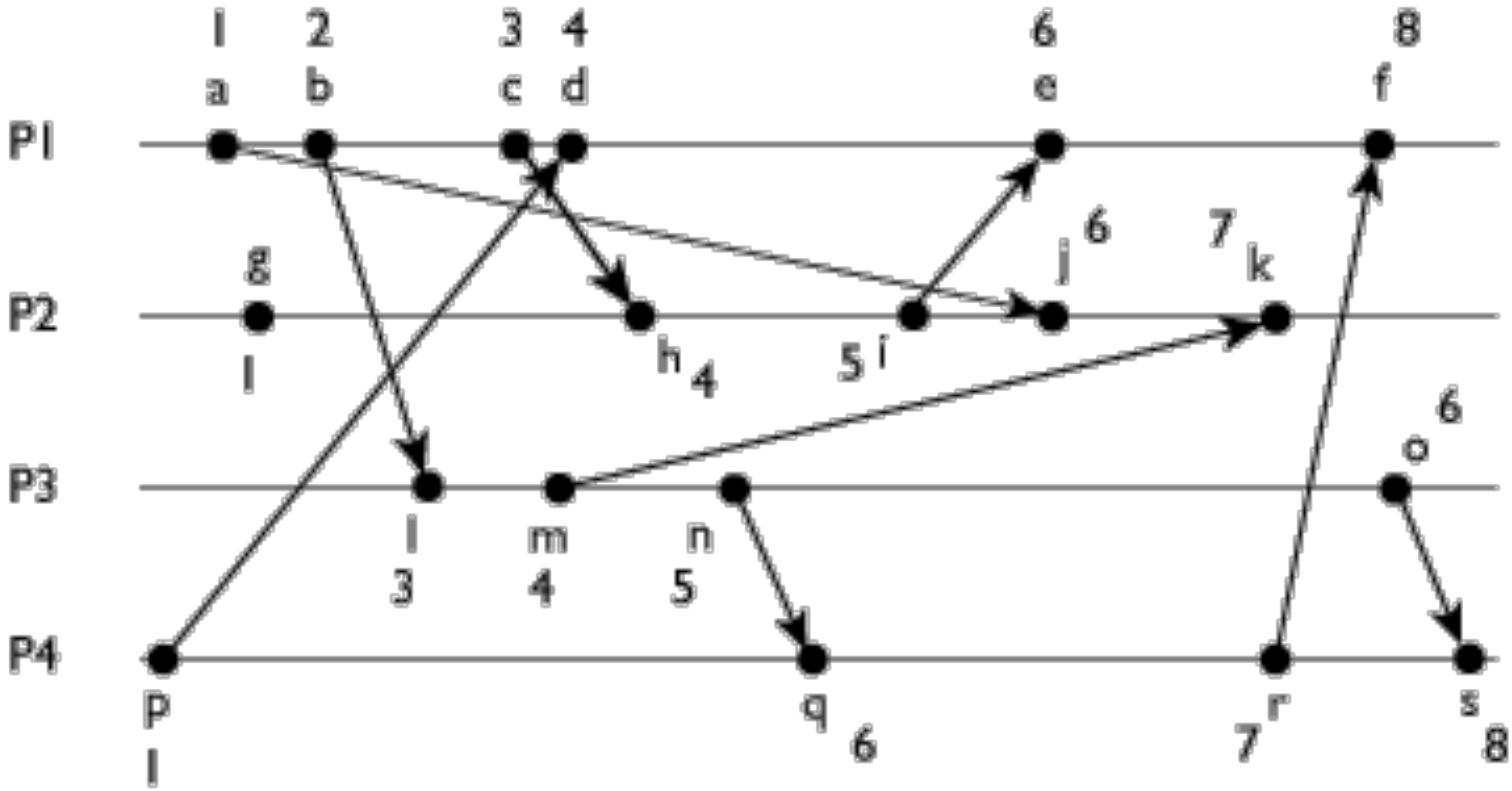
Logical clocks

- Idea: Use a counter at each process
- Increment after each event
- Can also increment when there are no events
  - Eg. A clock
- An actual clock can be thought of as such an event counter
- It counts the states of the process
- Each event has an associated time: The count of the state when the event happened

Lamport clocks

- Keep a logical clock (counter)
- Send it with every message
- On receiving a message, set own clock to max({own counter, message counter}) + 1
- For any event e, write c(e) for the logical time
- Property:
  - If $a \longrightarrow b$, then $c(a) < c(b)$
  - If $a \,||\, b$, then no guarantees

Lamport clocks: Example



Concurrency and Lamport clocks

- If e1⟶e2
  - Then no Lamport clock C exists with C(e1)== C(e2)

Concurrency and Lamport clocks

- If $e1 \longrightarrow e2$
  - Then no Lamport clock C exists with C(e1)== C(e2)

- If e1||e2, then there exists a Lamport clock C such that C(e1)== C(e2)

The Purpose of Lamport Clocks

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The Purpose of Lamport Clocks

- If $a \longrightarrow b$, then $c(a) < c(b)$
- If we order all events by their Lamport clock times
  - We get a partial order, since some events have same time
  - The partial order satisfies "causal relations"

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The purpose of Lamport clocks

- Suppose there are events in different machines
  - Transactions, money in/out, file read, write, copy
- An ordering of events that guarantees preserving causality

Total order from Lamport clocks

- If event e occurs in process j at time C(e)
  - Give it a time (C(e), j)
  - Order events by (C, process id)
  - For events e1 in process i, e2 in process j:
    - If C(e1)<C(e2), then e1<e2
    - Else if C(e1)==C(e2) and i<j, then e1<e2

- Leslie Lamport. Time, clocks and ordering of events in a distributed system.

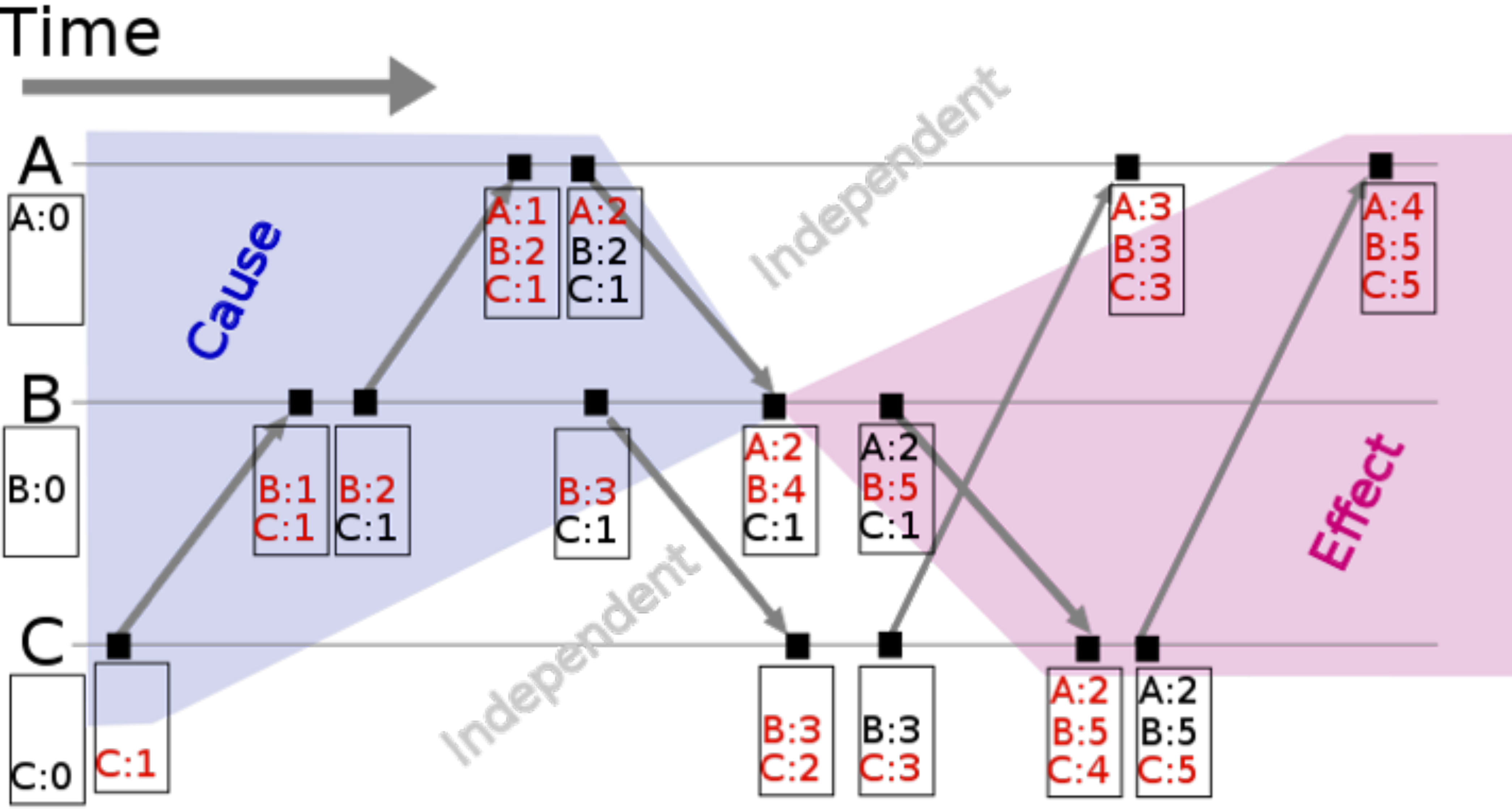
Vector Clocks

- We want a clock such that:
  - If a⟶b, then c(a) < c(b)
  - AND
  - If c(a) < c(b), then a⟶b
  - Ref: Coulouris et al., V. Garg

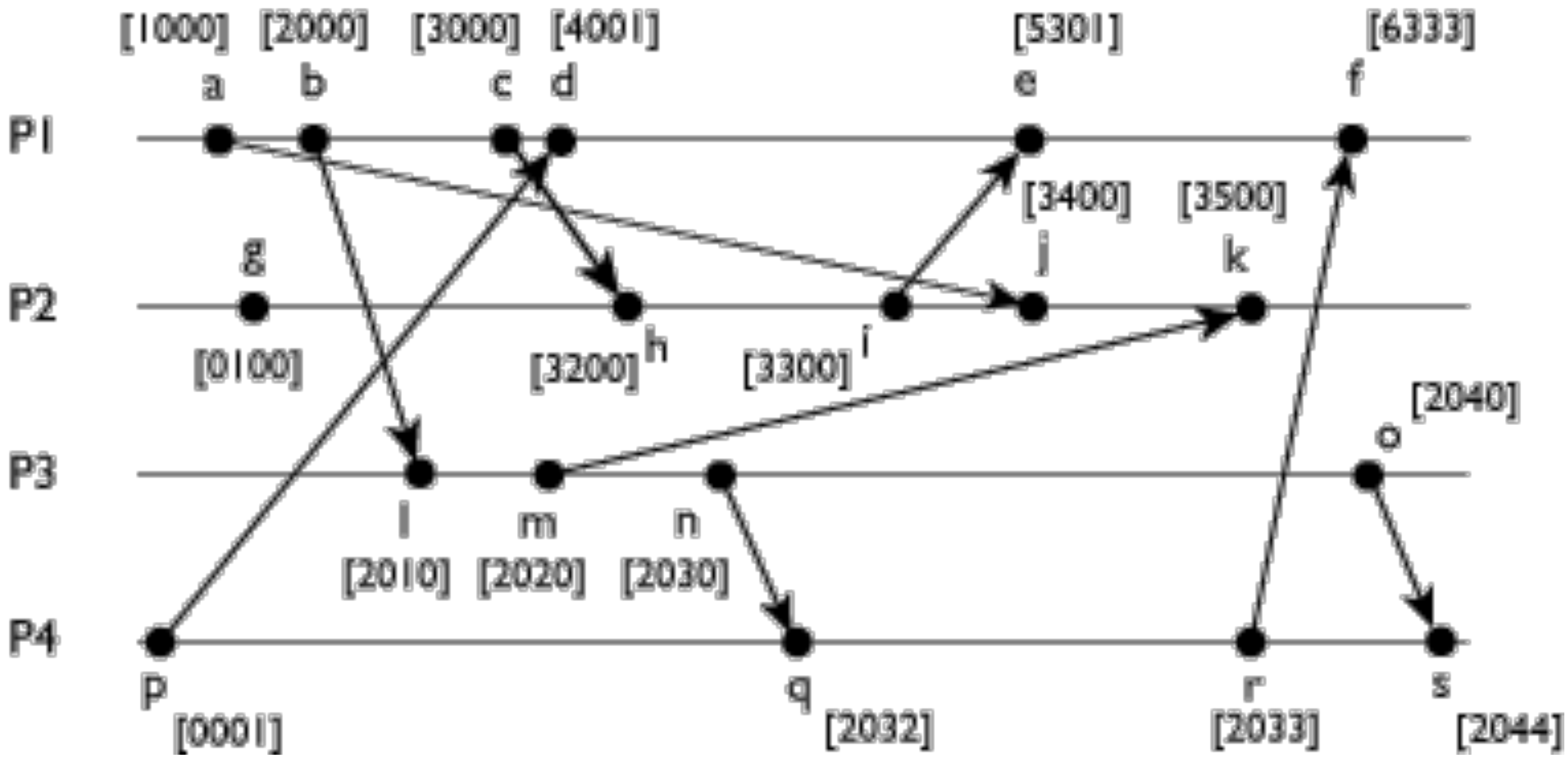
Vector Clocks

- Each process i maintains a vector V_i
- V_i has n elements
  - keeps clock $V_i[j]$ for every other process j
  - On every local event: $V_i[i] = V_i[i]+1$
  - On sending a message, i sends entire V_i
  - On receiving a message at process j:
    - Takes max element by element
    - $V_j[k] = \max(V_j[k], V_i[k])$, for k = 1,2,…,n
    - And adds 1 to $V_j[j]$

Example


Time
A
A:0
B
B:0
C
C:0
Cause
Independent
Independent
Effect
C:1
B:1 C:1
B:2 C:1
A:1 B:2 C:1
A:2 B:2 C:1
B:3 C:1
A:2 B:4 C:1
A:2 B:5 C:1
B:3 C:2
B:3 C:3
A:3 B:3 C:3
A:2 B:5 C:4
A:2 B:5 C:5
A:4 B:5 C:5

Another Example



Comparing Timestamps

- V = V' iff V[i] == V'[i] for i=1,2,…,n
- V < V' iff V[i] < V'[i] for i=1,2,…,n

Comparing Timestamps

- V = V' iff V[i] == V'[i] for i=1,2,…,n
- V < V' iff V[i] < V'[i] for i=1,2,…,n

- For events a, b and vector clock V
  - $a \longrightarrow b$ iff V(a) < V(b)

- Is this a total order?

Comparing Timestamps

- V = V' iff V[i] == V'[i] for i=1,2,…,n
- V ≤ V' iff V[i] ≤ V'[i] for i=1,2,…,n

- For events a, b and vector clock V
  - a⟶b iff V(a) ≤ V(b)

- Two events are concurrent if
  - Neither V(a) ≤ V(b) nor V(b) ≤ V(a)

Vector Clock Examples

- $(1,2,1) \leq (3,2,1)$ but $(1,2,1) \nleq (3,1,2)$

- Also $(3,1,2) \nleq (1,2,1)$
- No ordering exists

Vector Clocks

- What are the drawbacks?
- What is the communication complexity?

Vector Clocks

- What are the drawbacks?
  - Entire vector is sent with message
  - All vector elements (n) have to be checked on every message
- What is the communication complexity?
  - Ω(n) *per message*
  - Increases with time

Logical Clocks

- There is no way to have perfect knowledge on ordering of events
  - A “true” ordering may not exist..
  - Logical and vector clocks give us a way to have ordering consistent with causality

Distributed Snapshots

- Take a “snapshot” of a system
- E.g. for backup: If system fails, it can start up from a meaningful state

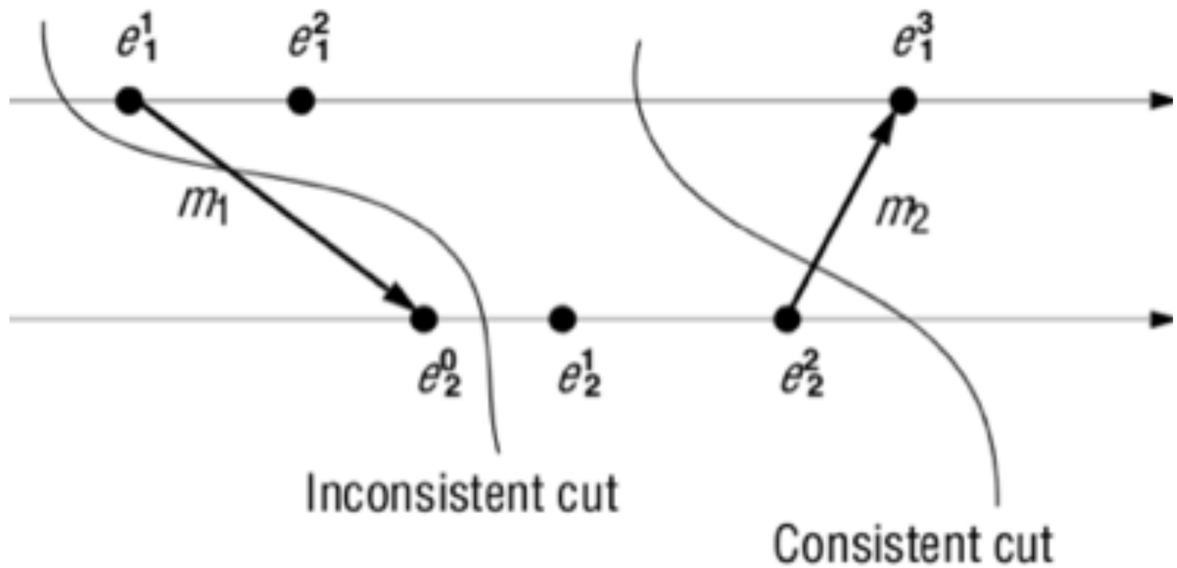
- Problem:
  - Imagine a sky filled with birds. The sky is too large to cover in a single picture.
  - We want to take multiple pictures that are consistent in a suitable sense
    - Eg. We can correctly count the number of birds from the snapshot

Distributed Snapshots

- Global state:
  - State of all processes and communication channels
- Consistent cuts:
  - A set of states of all processes is a consistent cut if:
  - For any states s, t in the cut, s||t

- If a⟶b, then the following is not allowed:
  - b is before the cut, a is after the cut

Consistent Cut



Distributed Snapshot Algorithm

- Ask each process to record its state
- The set of states must be a consistent cut

- Assumptions:
  - Communication channels are FIFO
  - Processes communicate only with neighbours
    - We assume for now that everyone is neighbour of everyone
  - Processes do not fail

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Global Snapshot
Chandy and Lamport Algorithm

- One process initiates snapshot and sends a **marker**
- Marker is the boundary between “before” and “after” snapshot

Global snapshot
Chandy and Lamport algorithm

- **Marker send rule** (Process i)
  1. Process i records its state
  2. On every outgoing channel where a marker has not been sent:
     - i sends a marker on the channel
     - before sending any other message
- **Marker receive rule**
  (Process i receives marker on channel C)
  – If i has not received the marker before
     - Record state of i
     - Record state of C as empty
     - Follow marker send rule
  – Else:
     - Record the state of C as the set of messages received on C since recording i's state and before receiving marker on C
- Algorithm stops when all processes have received marker on all incoming channels

Complexity

- Message?
- Time?