# Distributed Systems

# Clocks, Ordering of events

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# Logical clocks

- Why do we need clocks?
  – To know when something happened
  – 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 synchronization, 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 $b \longrightarrow c \Longrightarrow a \longrightarrow c$

# Events

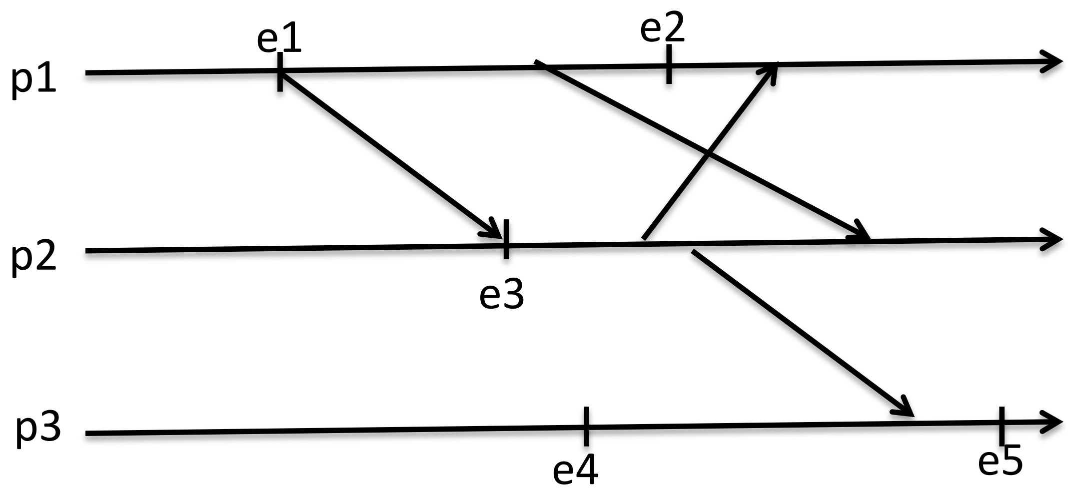
- “Happened before” can be defined between events
- Examples of event:
  - Sent message
  - Received message
  - Started/finished computation
  - Received input
  - .. Etc..
  - We can decide which events are important to us
- Events in a process are ordered by time/causality

# States

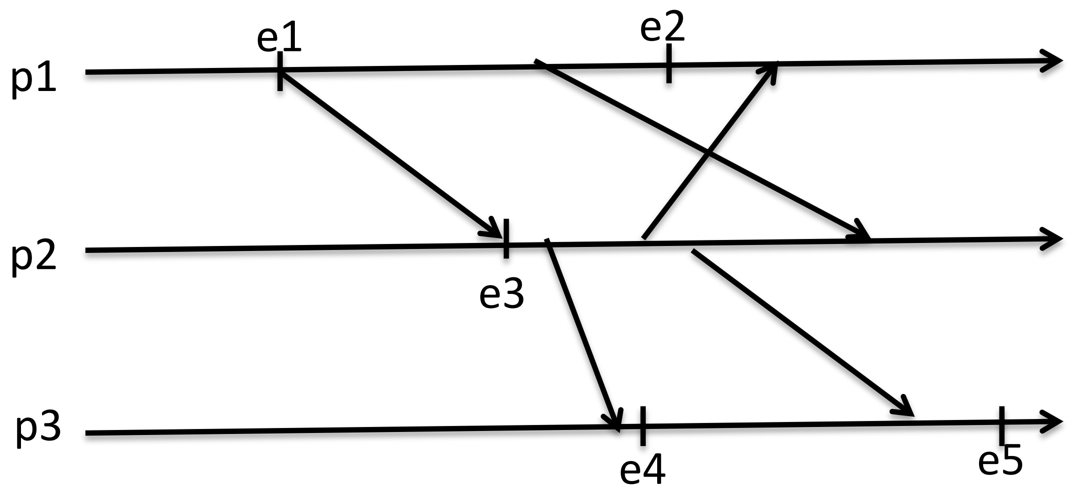
- "Happened before" can be defined between states
- A "state" can be seen as the values in all memory and registers of a computer
  - Changes all the time
- More useful: State changes when something important to us has happened
- E.g. an event we care about.
- States in a process are also ordered by time/ causality

# Ordering among events in different processes

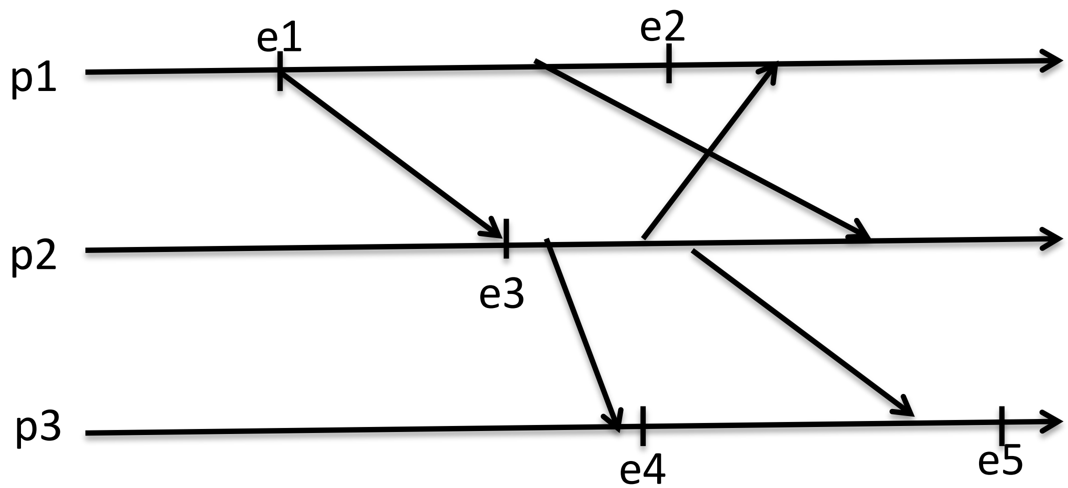
- There is a directed path:



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



- 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

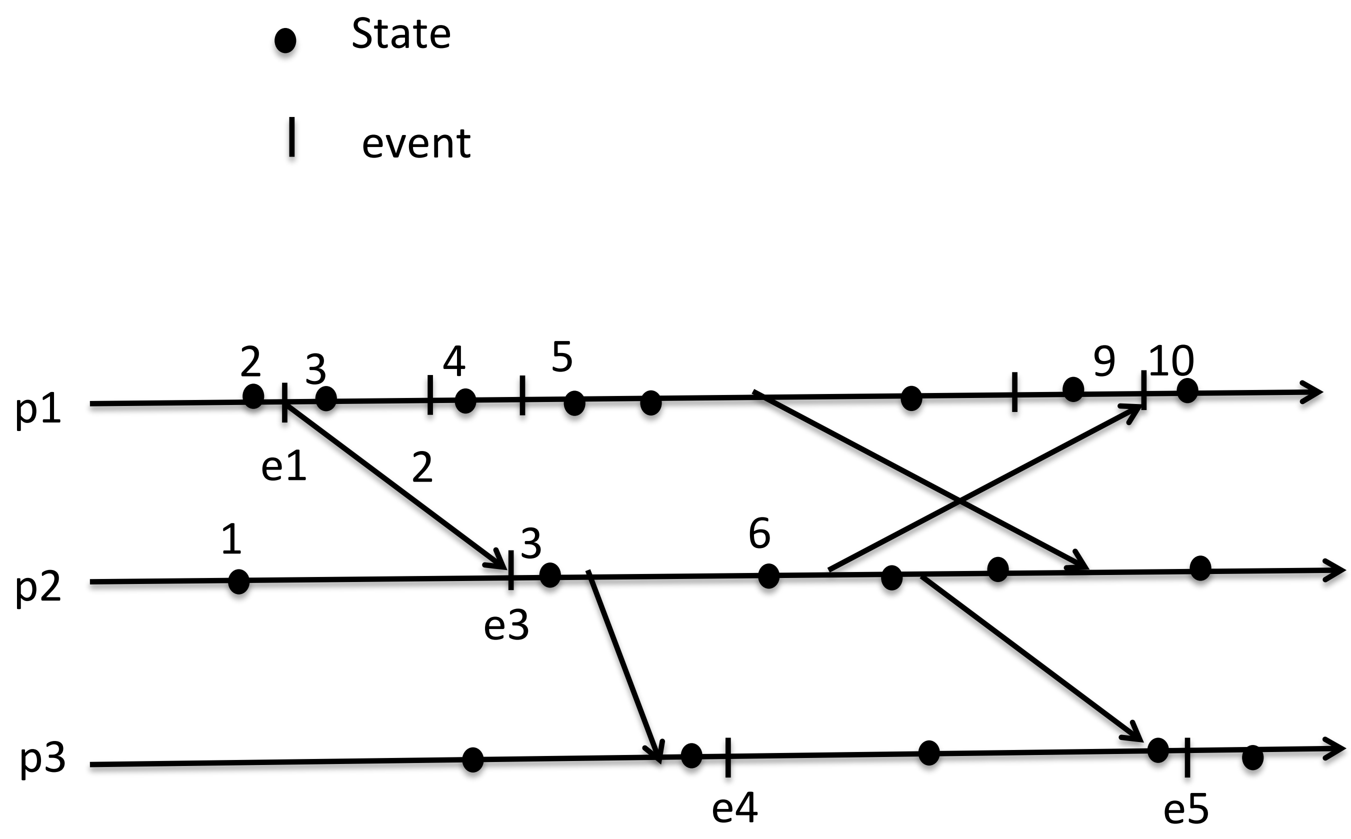
# Logical clocks

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

# Concurrency and lamport clocks

- If e1⟶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

# 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”

# 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.

# Logical clocks

- Formally, a map:
- C:S -> **N**
  - That satisfy happened before relation
  - Where S is set of states, **N** is natural numbers
  - Essentially, Assign a “number” to each state
  - Other sets (like Integers Z) work equally well. As long as the set has a total order.

- Problem:
  - Ordering preserves happened-before
  - But does not imply happened-before
  - There is no way to tell from logical clock if there can be causality.
    - The relation is not an if and only if

# Vector clocks

- We want a clock such that:
  - If a$\longrightarrow$b, then c(a) < c(b)
  - AND
  - If c(a) < c(b), then a$\longrightarrow$b

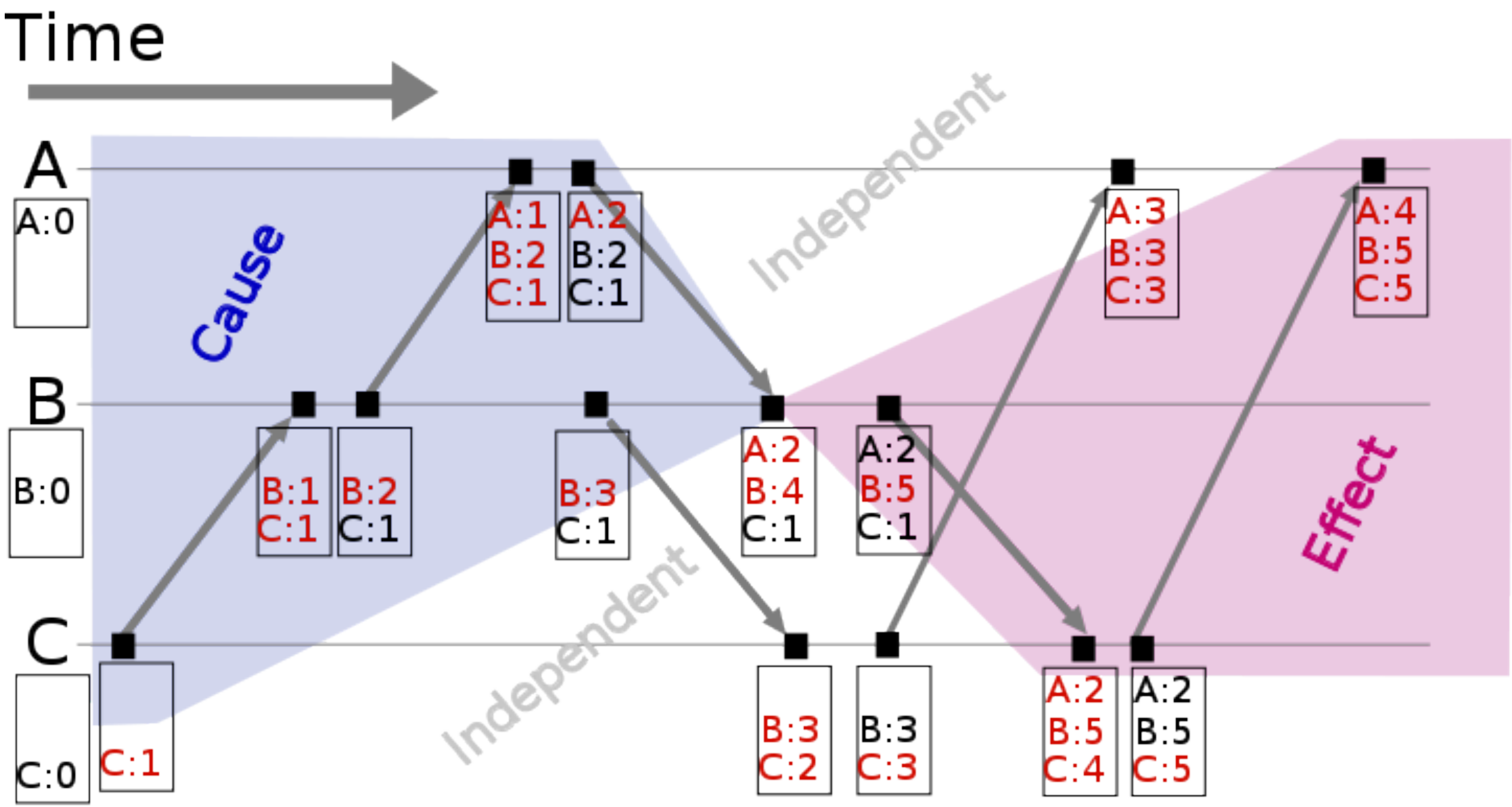
  - Ref: Coulouris et al., V. Garg

# Vector clocks

- V: S -> $\mathbf{N}^n$
  - Where n is the number of processes
- And:
  - For states x and y
  - $V_x \leq V_y$ iff for each i in {1,2,…n}, $V_x[i] \leq V_y[i]$
  - The strict inequality is defined as:
    - $V_x < V_y$ iff for each i in {1,2,…n}, $V_x[i] \leq V_y[i]$
    - And there is a j such that $V_x[j] < V_y[j]$
- That satisfy that
  - $V_x < V_y$ iff $x \longrightarrow y$

# Vector clock algorithm

- 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 $k = 1,2,\ldots,n$
    - And adds 1 to $V_j[j]$



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

# 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
- V < V' iff V[i] ≤ V'[i] for i=1,2,…,n
  - And there is an i such that V[i] < V'[i]

# 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 $i=1,2,\ldots,n$
- $V \leq V'$ iff $V[i] \leq V'[i]$ for $i=1,2,\ldots,n$

- For events a, b and vector clock V
  - $a \longrightarrow b$ 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 $(1,2,1) \not\leq (3,1,2)$

- Also $(3,1,2) \not\leq (1,2,1)$
- 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?
  - $\Omega(n)$ *per message*

# Logical and vector 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