Distributed Systems

Summer Term 2020

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6 Time and Global State

- Synchronization of physical clocks
- Lamport's happended before relation
- Logical clocks
- Global state

Literature

- Tanenbaum, van Steen: Kap. 5.1-5.3
- Colouris, Dollimore, Kindberg: Kap. 10
- Stallings: Kap 14.2

What is the difference between a distributed system and a single/multiprocessor system?

- Single or multiprocessor system:
  - concurrent processes: pseudo-parallel by time sharing or truely parallel
  - global time: all events in the processes can be ordered unambiguously in terms of time
  - global state: at any time a unique state of the system can be determined
- Distributed system
  - true parallelism
  - no global time
  - no unique global state

Concurrency vs. (true) parallelism

Example: 4 processes

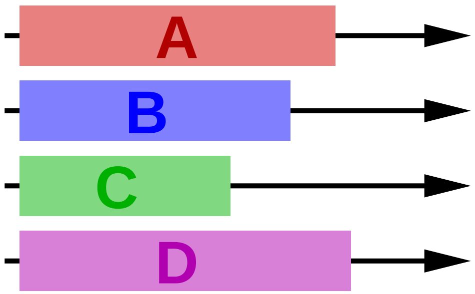
sequential

One time line, processes are not interrupted.

concurrent

One time line, processes can be interrupted by others at any time: interleaved execution.

parallel



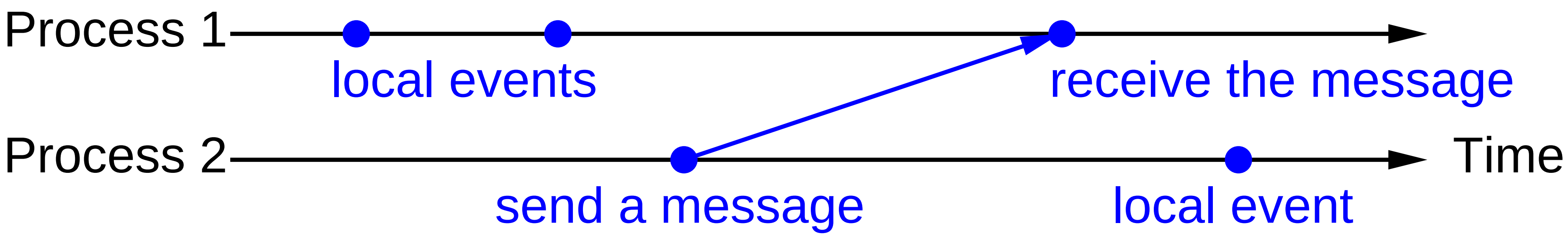
Each node / process has its own time line! Events in different processes can truely happen simultaneously.

Global Time

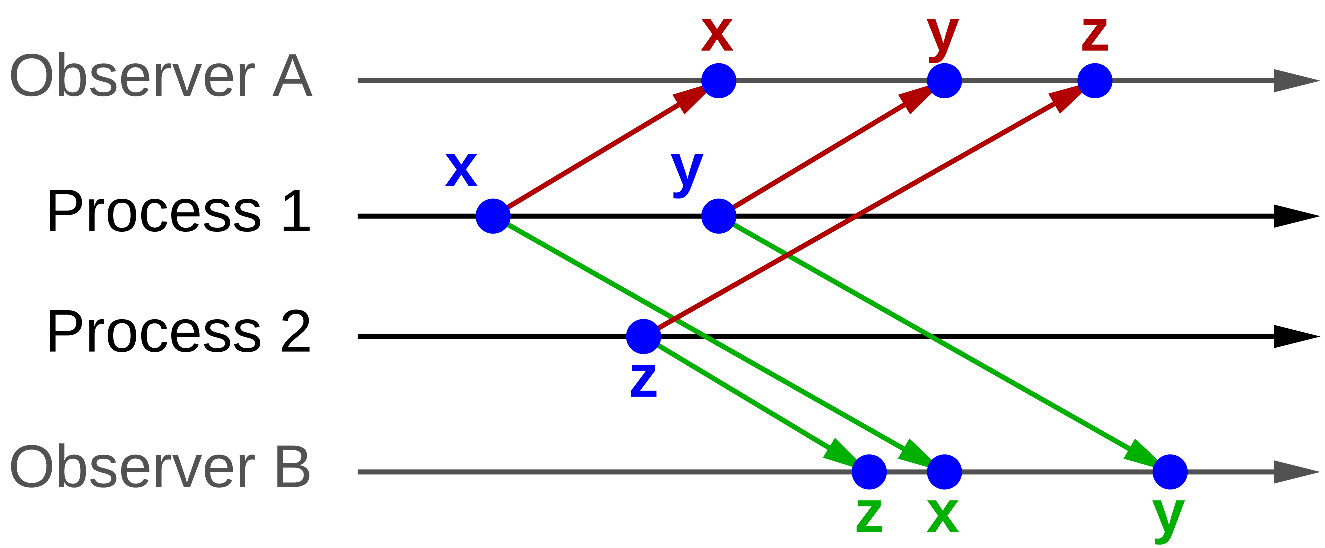
- In a single/multiprocessor system
  - each event can (at least theoretically) be assigned a unique time stamp of the same local clock
  - for multiprocessor systems: synchronization at the shared memory
- In distributed systems:
  - many local clocks (one per node)
  - exact synchronization of clocks is (on principle!) not possible
  - $\Rightarrow$ the sequence of events on different nodes can not (always) be determined uniquely
  - (cf. special theory of relativity)

An effect of distribution

- Preliminary remark: events in distributed systems



- Scenario: two processes observe two other processes



An effect of distribution ...

- The observers may see the events in different order!
- Problem e.g., if the observers are replicated databases and the events are database updates
  - replicas are no longer consistent!
- Even from time stamps of (local) clocks it is not possible to determine the order of events in a meaningful way
- Hence, in such cases:
  - events with timestamps of **logical clocks** (☞ **6.3**)
  - logical clocks allow conclusions to be made about causal order

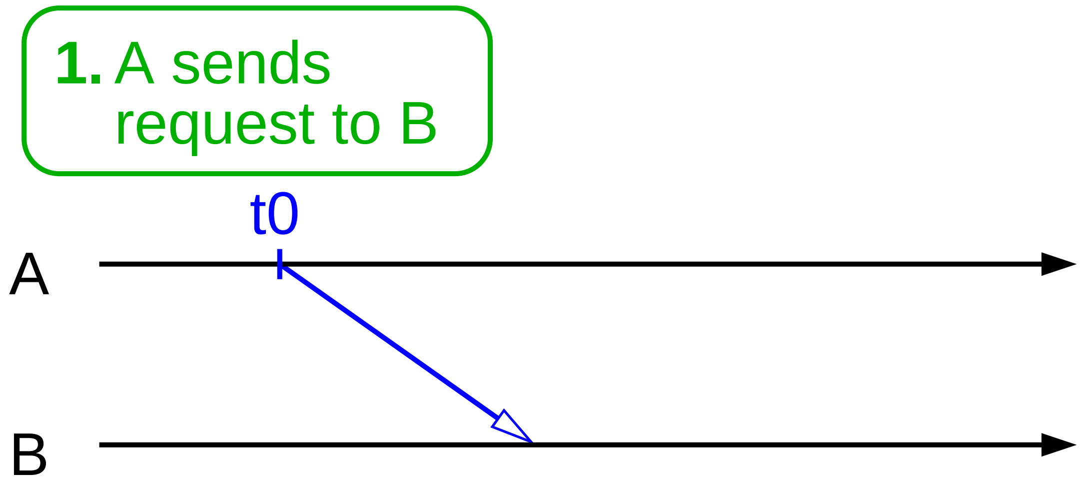
6.1 Synchronizing Physical Clocks

[Coulouris, 10.3]

- Physical clock shows 'real' time
  - based on UTC (Universal Time Coordinated)
- Each computer has its own (physical) clock
  - quartz oscillator with counter in HW and if necessary in SW
- Clocks usually differ from each other (**offset**)
  - Offset changes over time: **clock drift**
    - typ. 10^{-6} for quartz crystals, 10^{-13} for atomic clocks
- Goal of clock synchronization:
  - keep the offset of the clocks under a given limit
  - **clock skew**: maximum allowed deviation

Cristian's Method

- Assumption: A and B want to synchronize their clocks with each other
  - B can also be a time server (e.g. with GPS clock)
- Protocol:



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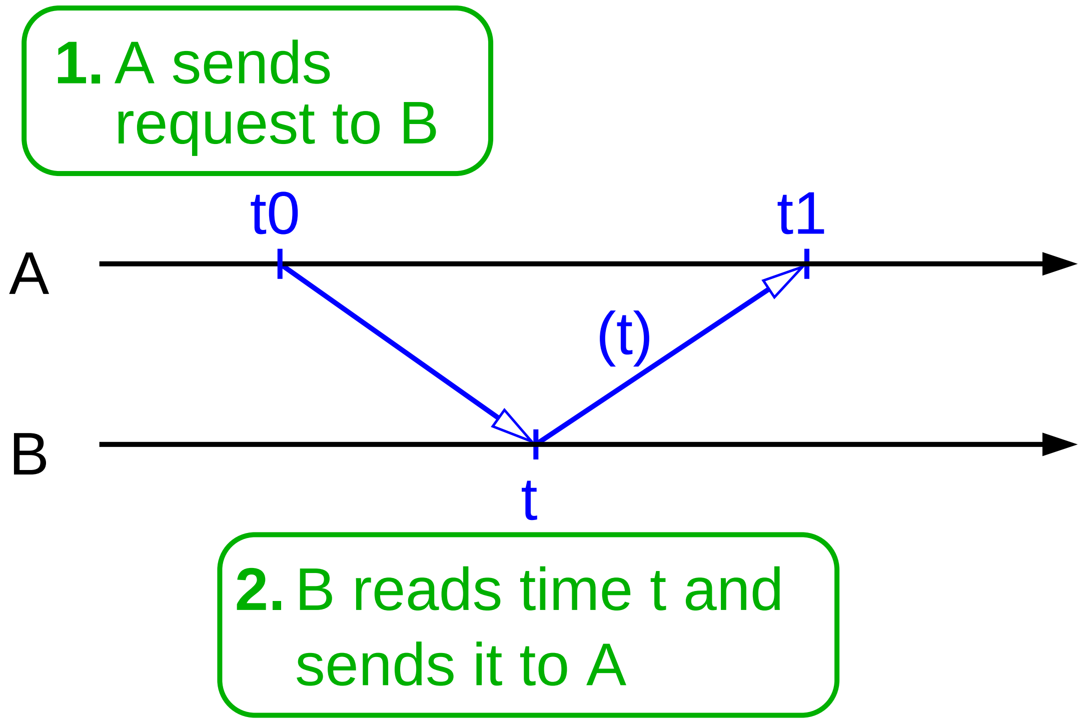

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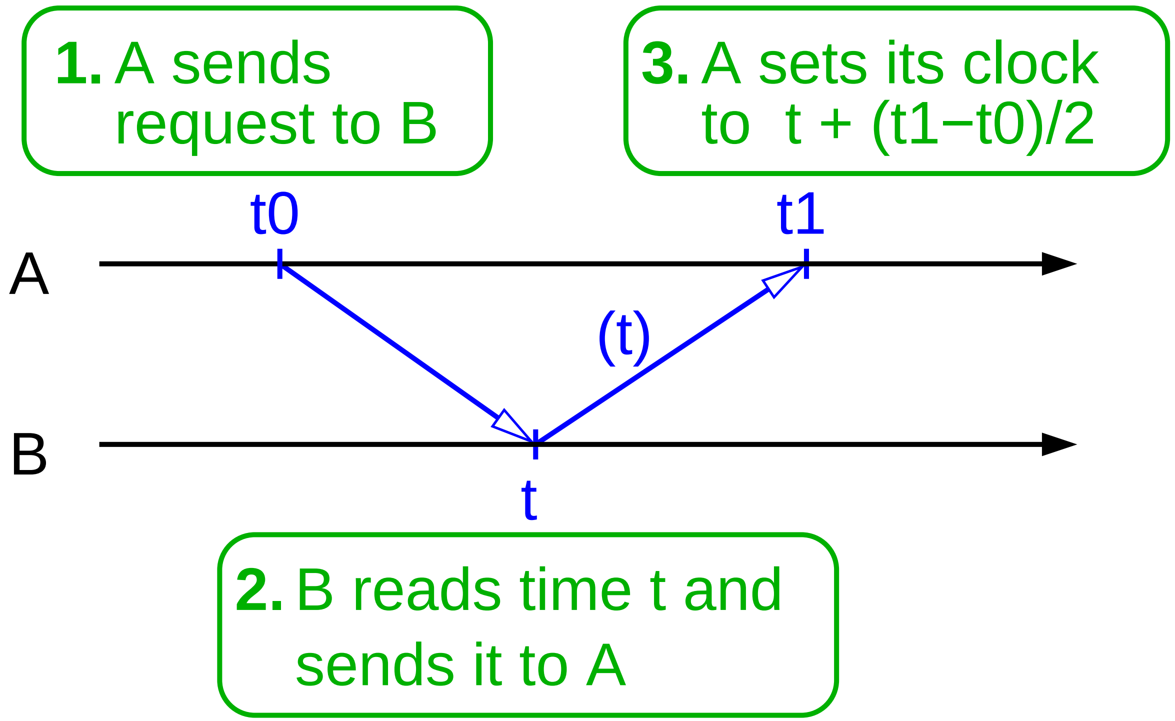

- A must take the runtime of the reply message into account
- estimate: runtime = half the round trip time = $(t1 - t0)/2$

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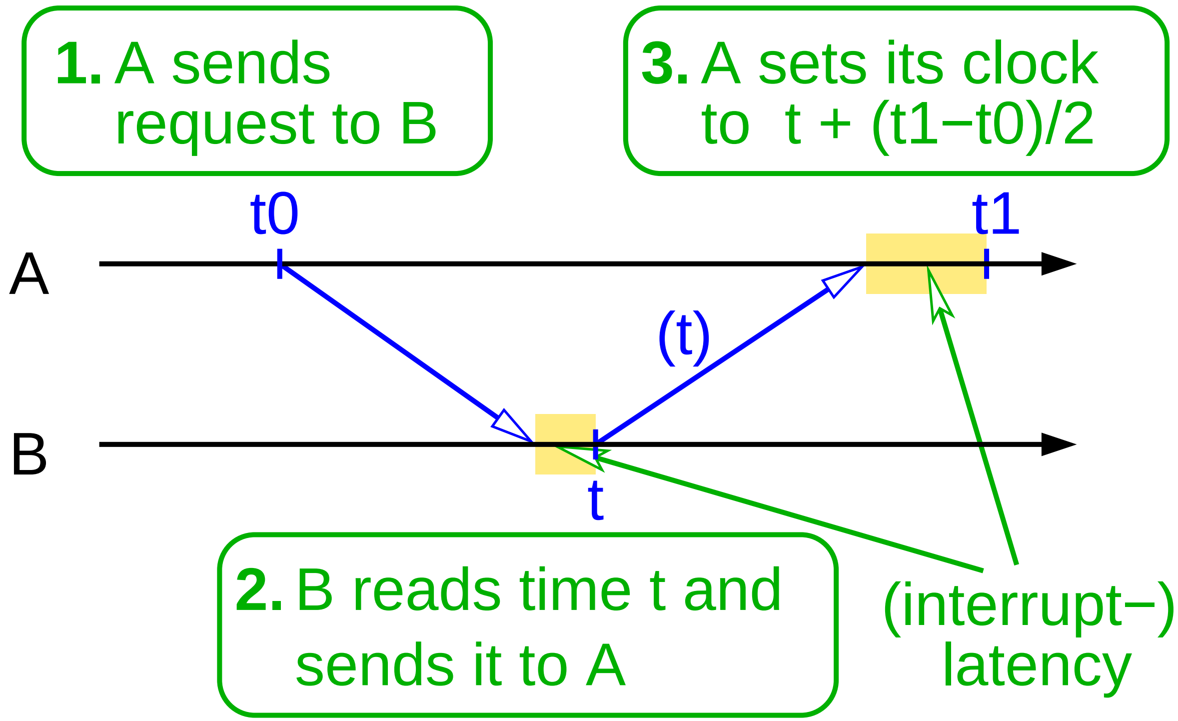

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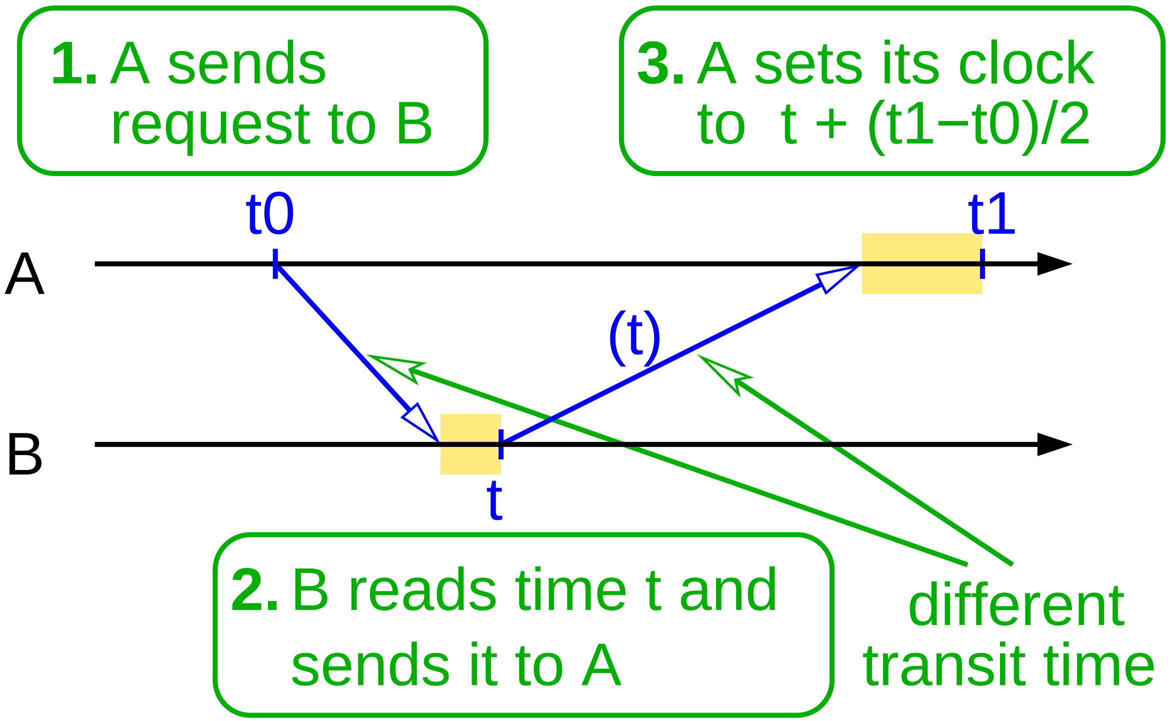

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Cristian's Method: Discussion

- Problem: runtimes of both messages may be different
  - systematic differences (different paths / latencies)
  - statistical fluctuations of the transit time
- Accuracy estimate, if minimum transit time (min) is known:
  - B can have determined t at the earliest at time $t0 + min$, at the latest at time $t1 - min$ (measured with A's clock)
  - thus accuracy $\pm \left((t1 - t0)/2 - min\right)$
- To improve accuracy:
  - execute the message exchange multiple times
  - use the one with minimum round trip time

Changing the clock

- Turning back is problematic
  - order / uniqueness of time stamps
- Non-monotonous “jumping” of the time also problematic
- Therefore: clock is generally adjusted slowly
  - runs faster / slower, until clock skew has been compensated

Further protocols

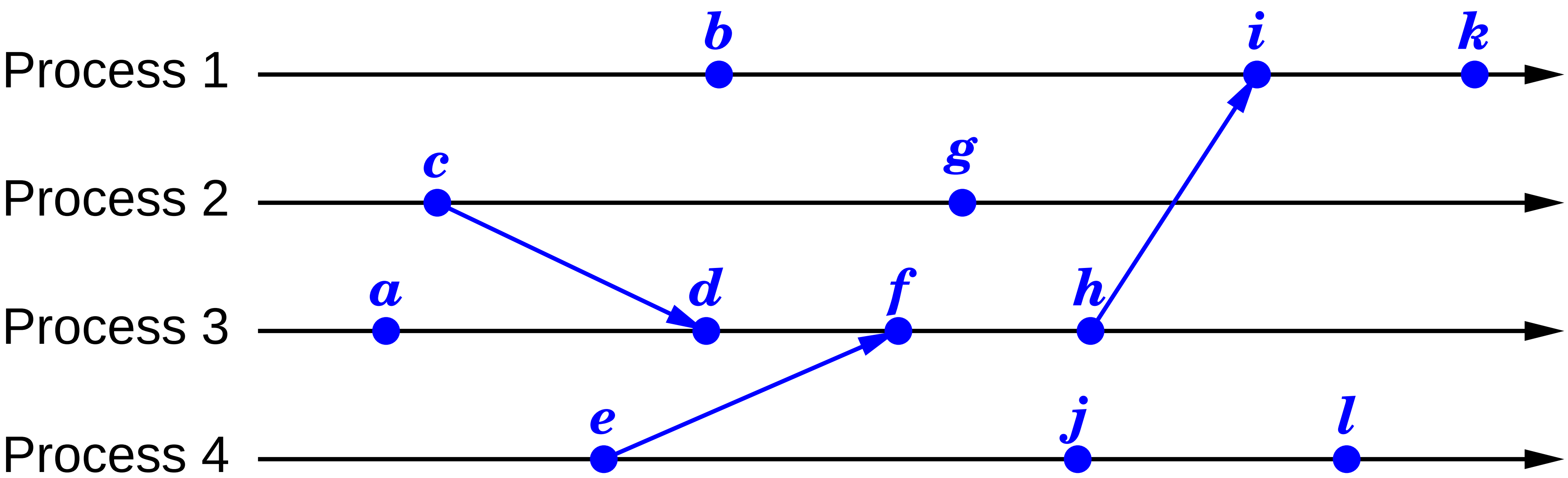
- Berkeley algorithm: server calculates mean value of all clocks
- NTP (Network Time Protocol): hierarchy of time servers in the Internet with periodic synchronization
- IEEE 1588: clock synchronization for automation systems

6.2 Lamport's Happened-Before Relation

[Coulouris, 10.4]

- In two cases, the order of events can also be determined without a global clock:
  - if the events are in the same process, local clock is sufficient
  - the sending of a message is always before its reception
- Definition of the happened-before causality relation $\rightarrow$ (*causality relation*)
  - if events a, b are in the same process i and $t_i(a) < t_i(b)$ (t_i: time stamp with i's clock), then $a \rightarrow b$
  - if a is the sending of a message and b its receipt, then $a \rightarrow b$
  - if $a \rightarrow b$ and $b \rightarrow c$, then also $a \rightarrow c$ (transitivity)
- $a \rightarrow b$ means, that b **may** causally depend on a

Examples



- Among others, we have here:
  - $b \to i$ and $a \to h$ (events in the same process)
  - $c \to d$ and $e \to f$ (sending / receiving a message)
  - $c \to k$ and $a \to i$ (transitivity)
  - $g \not\to l$ and $l \not\to g$: l and g are **concurrent** (***nebenläufig***)

6.3 Logical Clocks

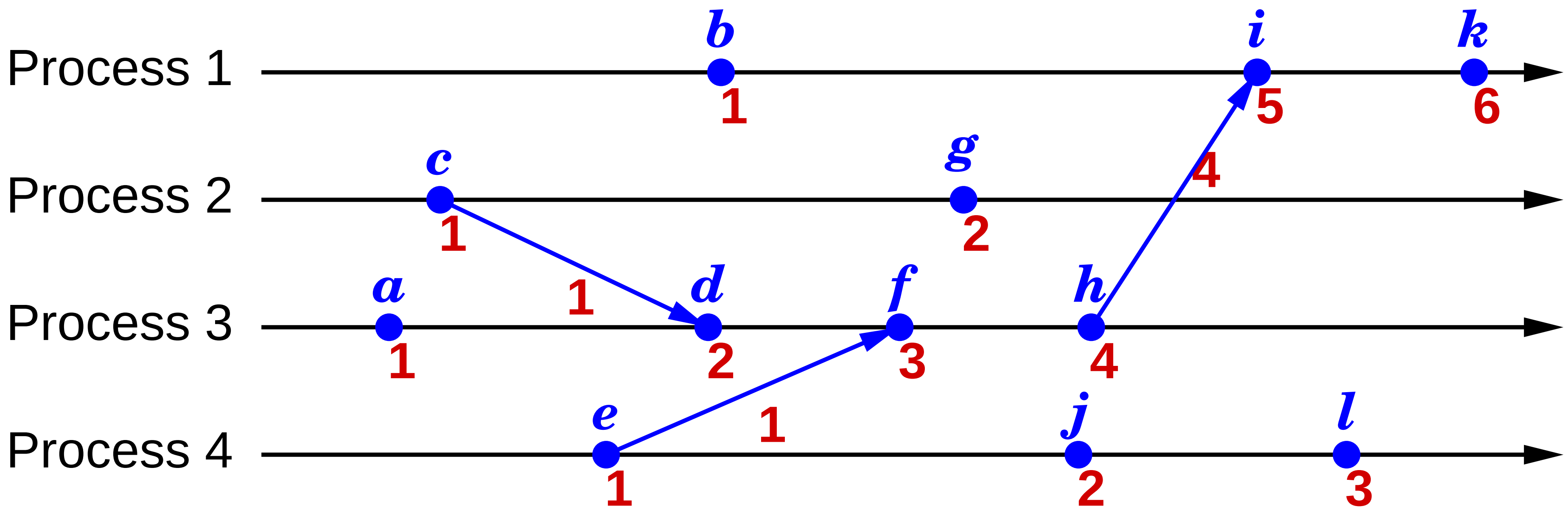
[Coulouris, 10.4]

- Physical clocks cannot be synchronized exactly
  - therefore: unsuitable for determining the **order** in which events occurred
- Logical clocks
  - refer to the causal order of events (happened-before relation)
  - no fixed relationship to real time
- In the following:
  - Lamport timestamps
    - are consistent with the happened-before relation
  - vector timestamps
    - allow sorting of events according to causality (i.e. happened-before relation)

Lamport Timestamps

- Lamport timestamps are natural numbers
- Each process i has a local counter L_i, that is updated as follows:
  - at (more precisely: before) each local event: $L_i = L_i + 1$
  - in each message, the time stamp L_i of the send event is also sent
  - at receipt of a message with time stamp t:
    $L_i = \max(L_i, t + 1)$
- Lamport time stamps are consistent with the causality:
  - $a \rightarrow b \;\Rightarrow\; L(a) < L(b)$, where L is the Lamport timestamp in the respective process
  - but the reversal does not apply!

Lamport Timestamps: Example



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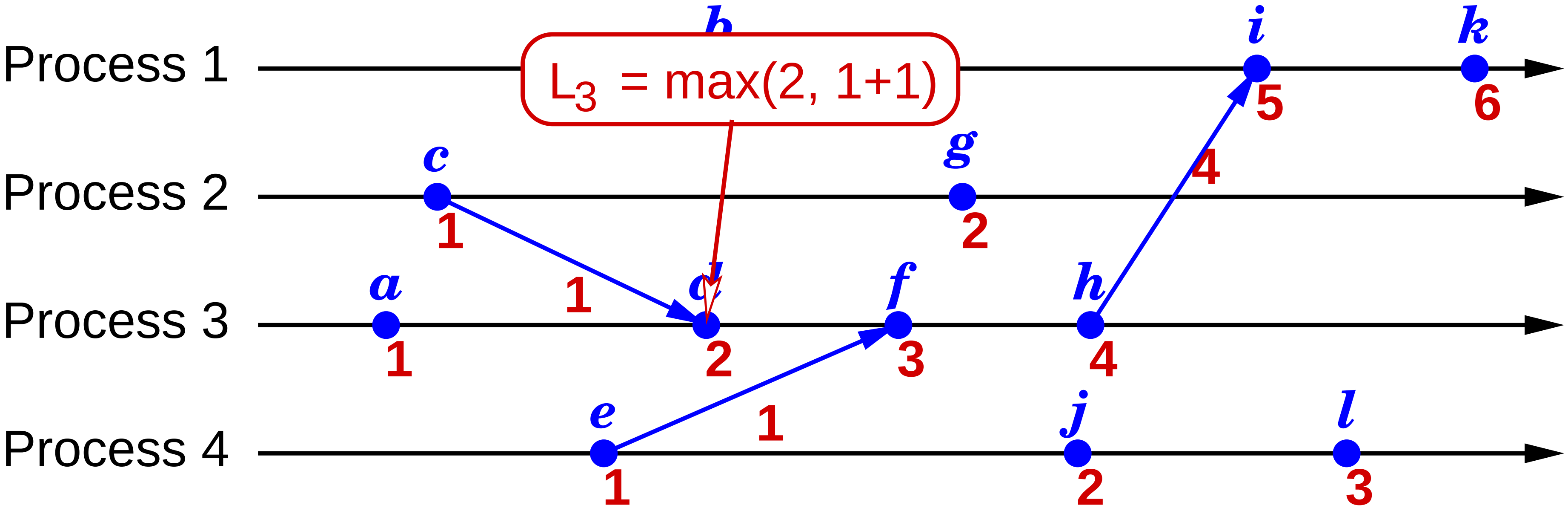

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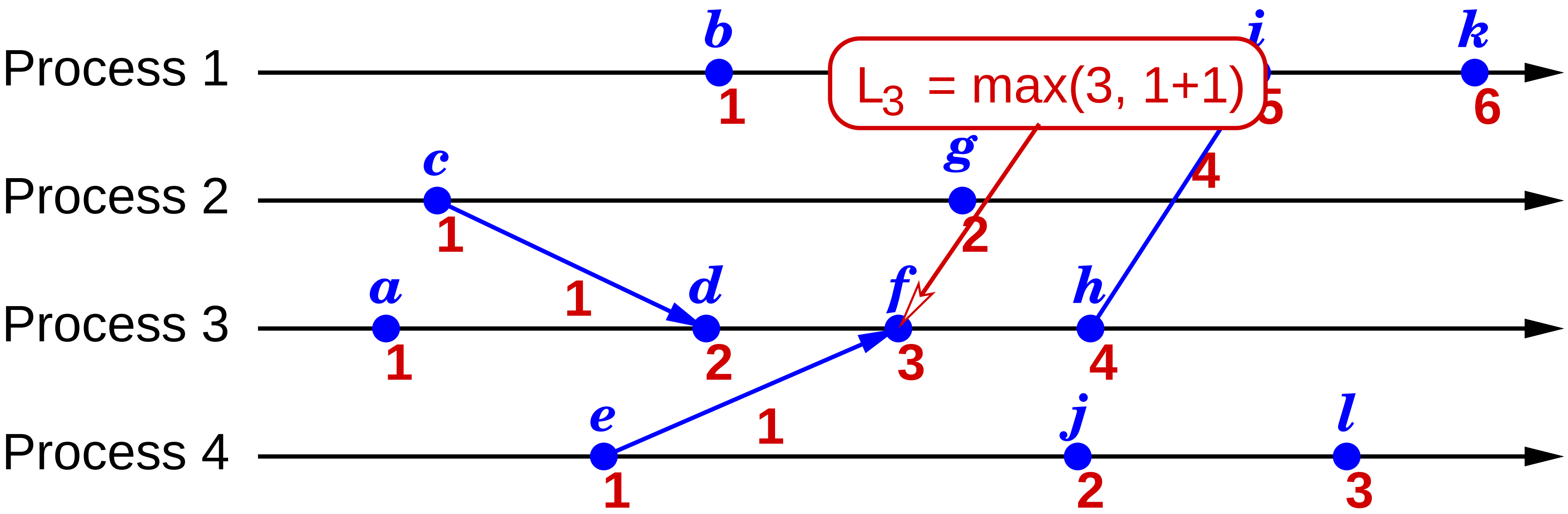

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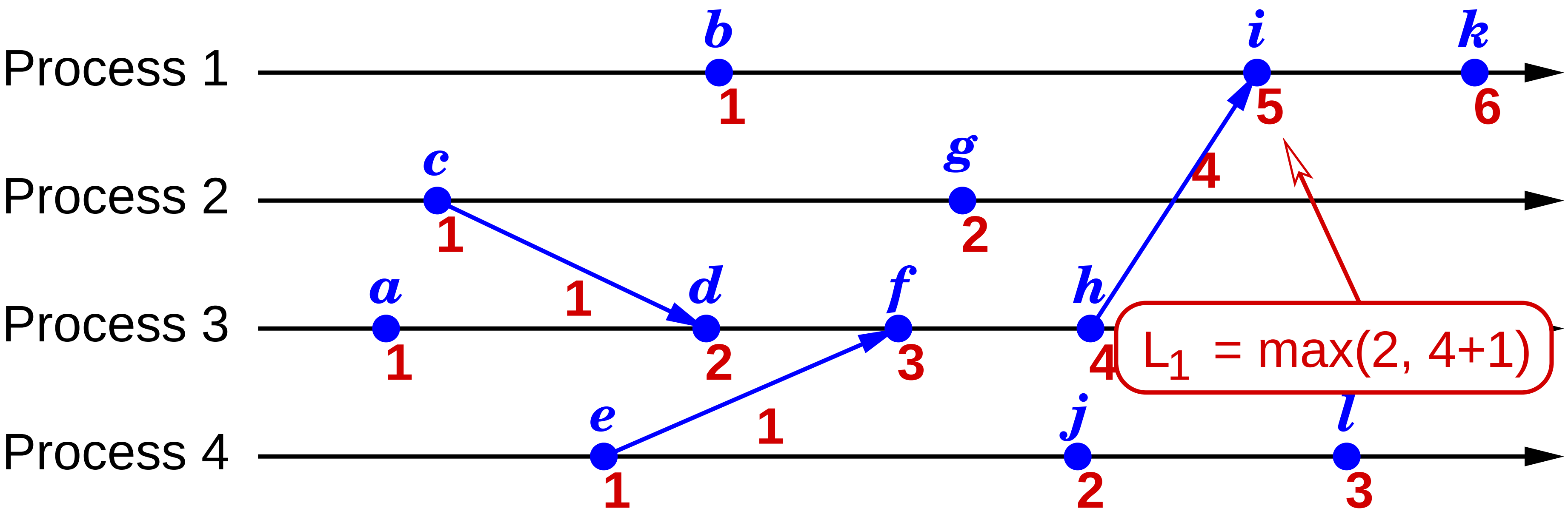

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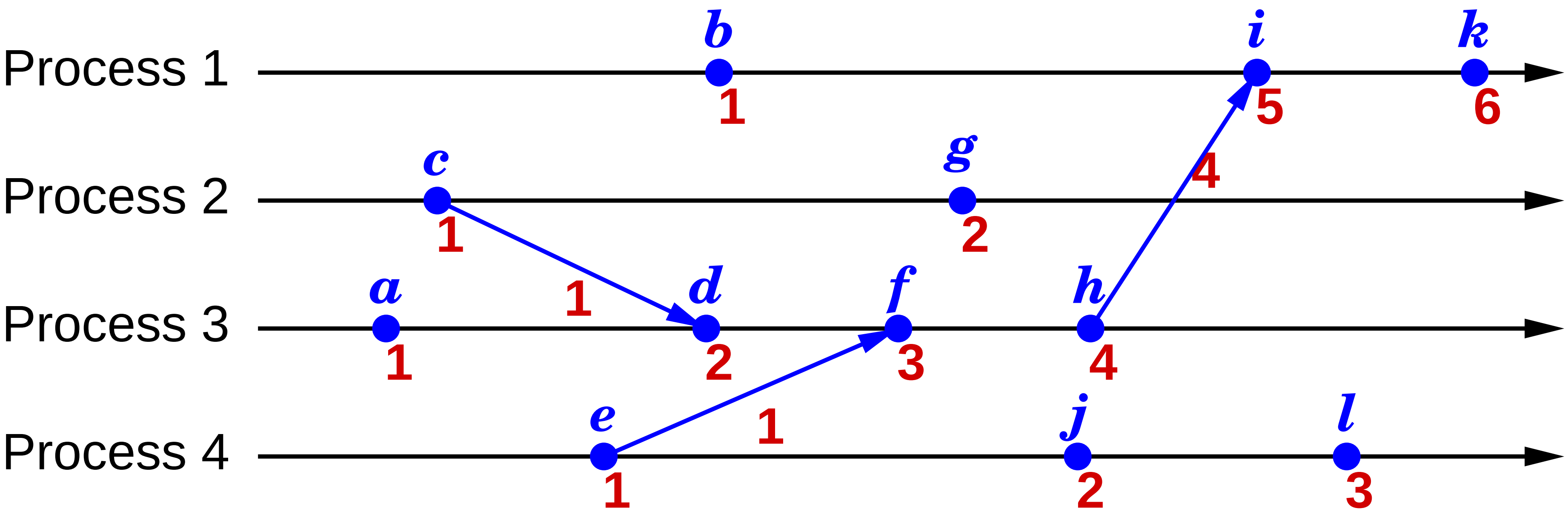


- Among others, we have here:
  - $c \to k$ and $L(c) < L(k)$
  - $g \not\to j$ and $L(g) \not< L(j)$
  - $g \not\to l$, but still $L(g) < L(l)$

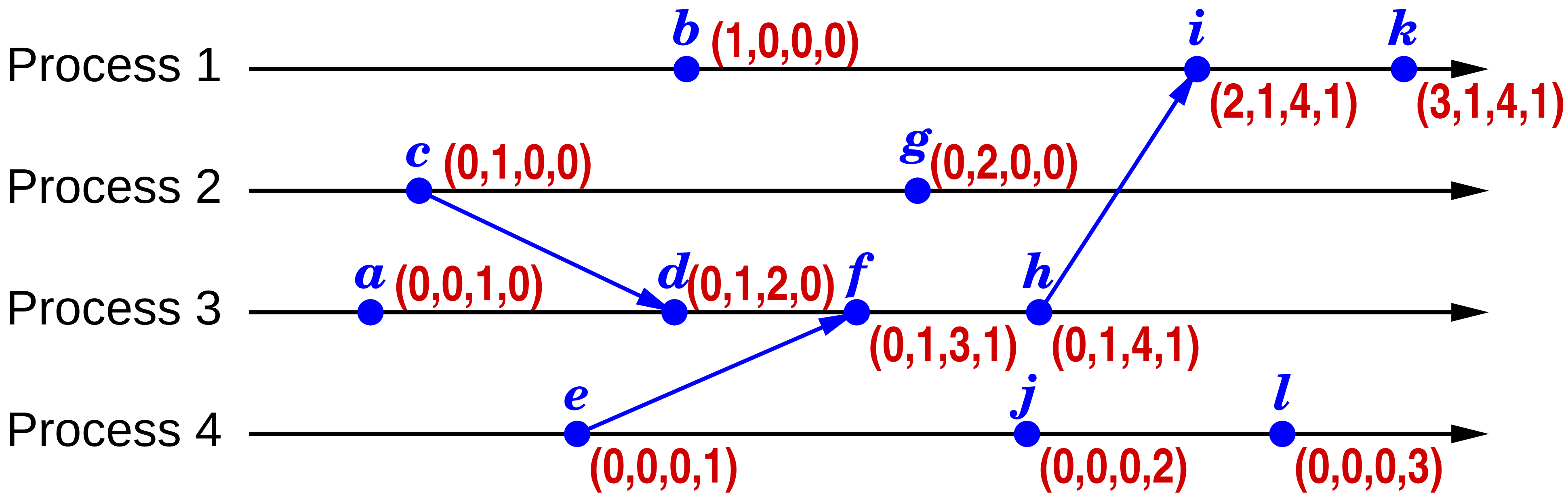
Vector Timestamps

- Objective: timestamps that characterize causality
  - $a \rightarrow b \Leftrightarrow V(a) < V(b)$, where V is the vector timestamp in the respective process
- A vector clock in a system with N processes is a vector of N integers
  - each process has its own vector V_i
  - $V_i[i]$: number of events that have occurred so far in process i
  - $V_i[j], j \neq i$: number of events in process j, of which i knows
    - i.e. by which it could have been causally influenced

Vector Timestamps ...

- Update of V_i in process i:
  - before any local event: $V_i[i] = V_i[i] + 1$
  - V_i is included in every message sent
  - when receiving a message with timestamp t:
    $V_i[j] = \max(V_i[j], t[j])$ for all $j = 1, 2, \ldots, N$
- Comparison of vector timestamps:
  - $V = V' \Leftrightarrow V[j] = V'[j]$ for all $j = 1, 2, \ldots, N$
  - $V \leq V' \Leftrightarrow V[j] \leq V'[j]$ for all $j = 1, 2, \ldots, N$
  - $V < V' \Leftrightarrow V \leq V' \wedge V \neq V'$
  - the relation $<$ defines a **partial** order

Vector Timestamps: Example



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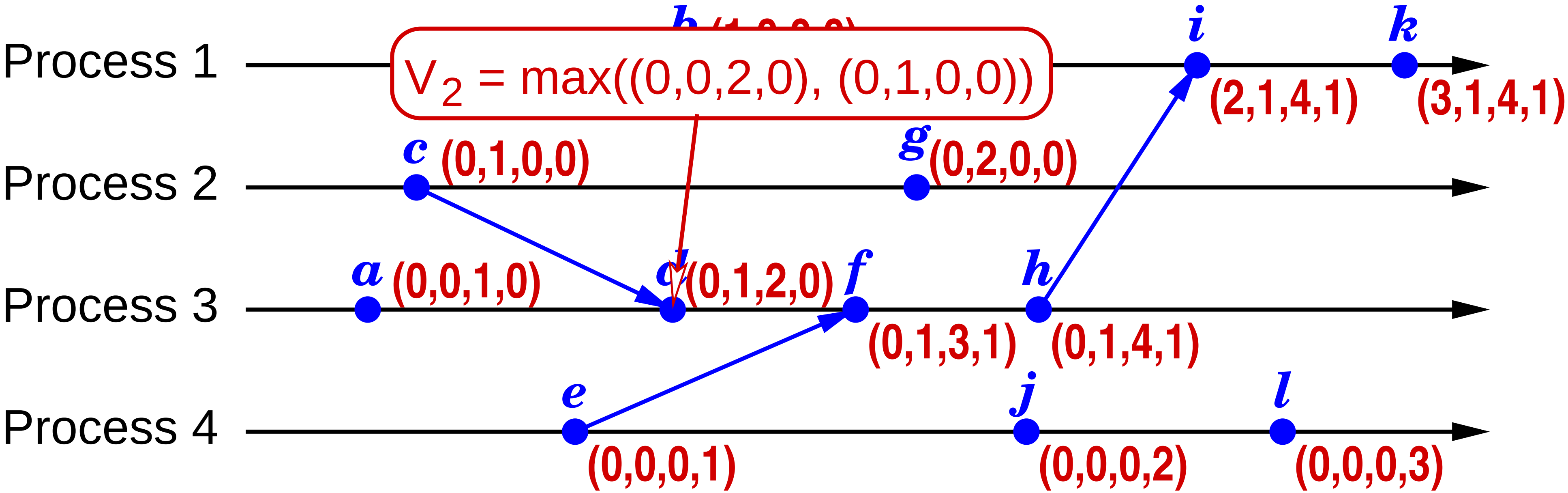

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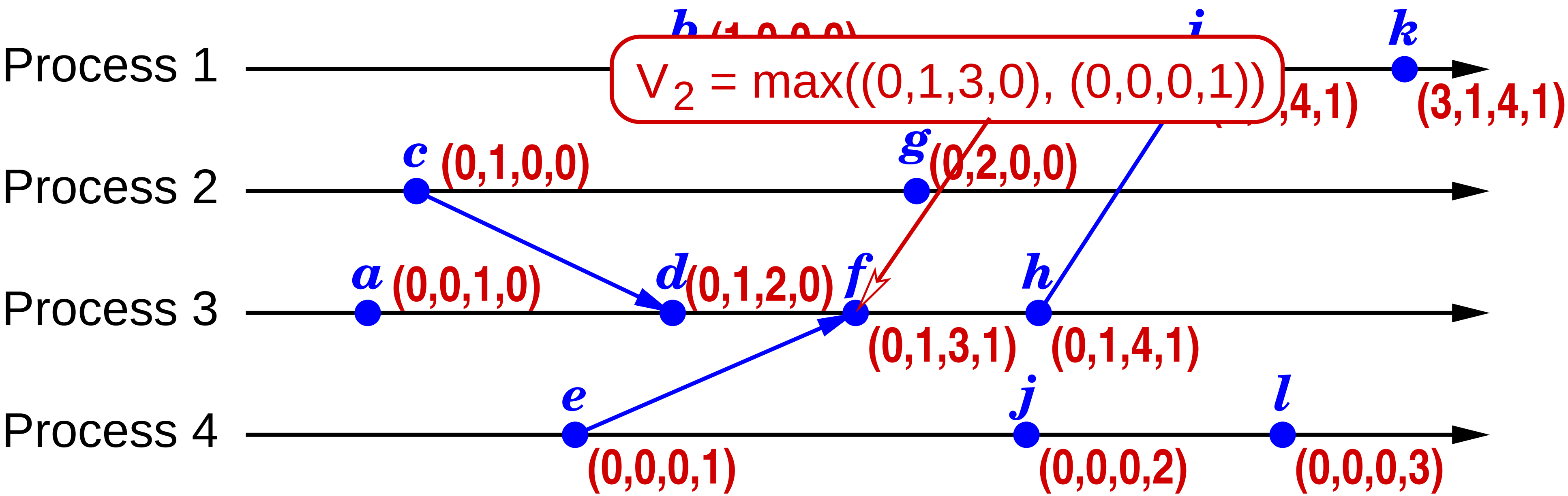

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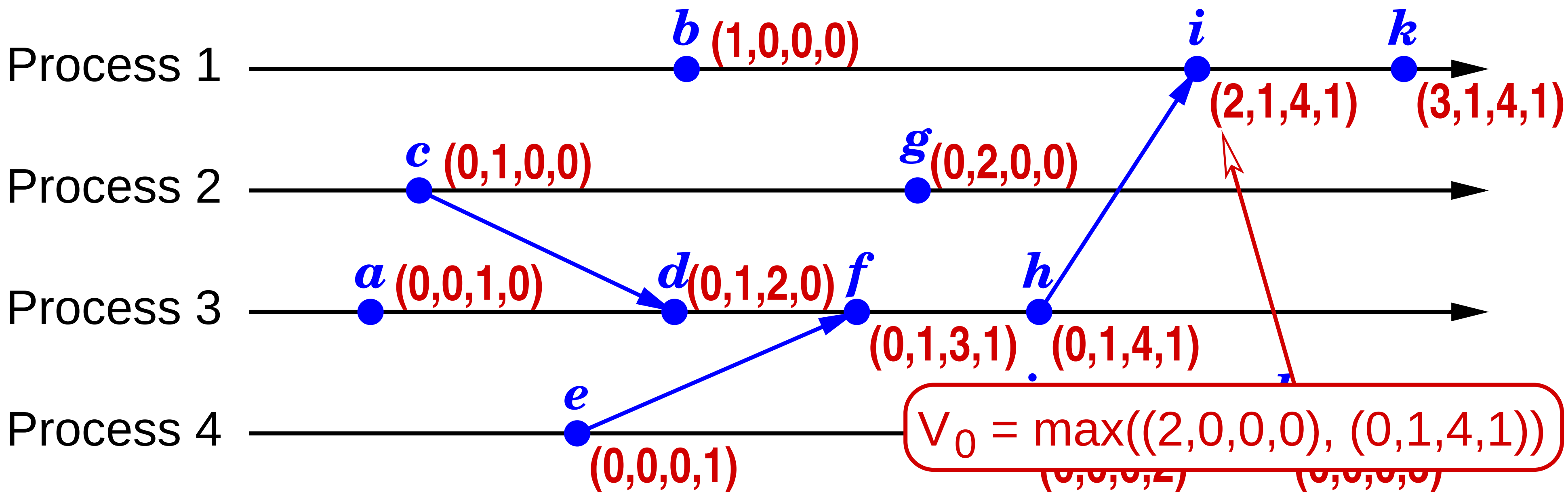

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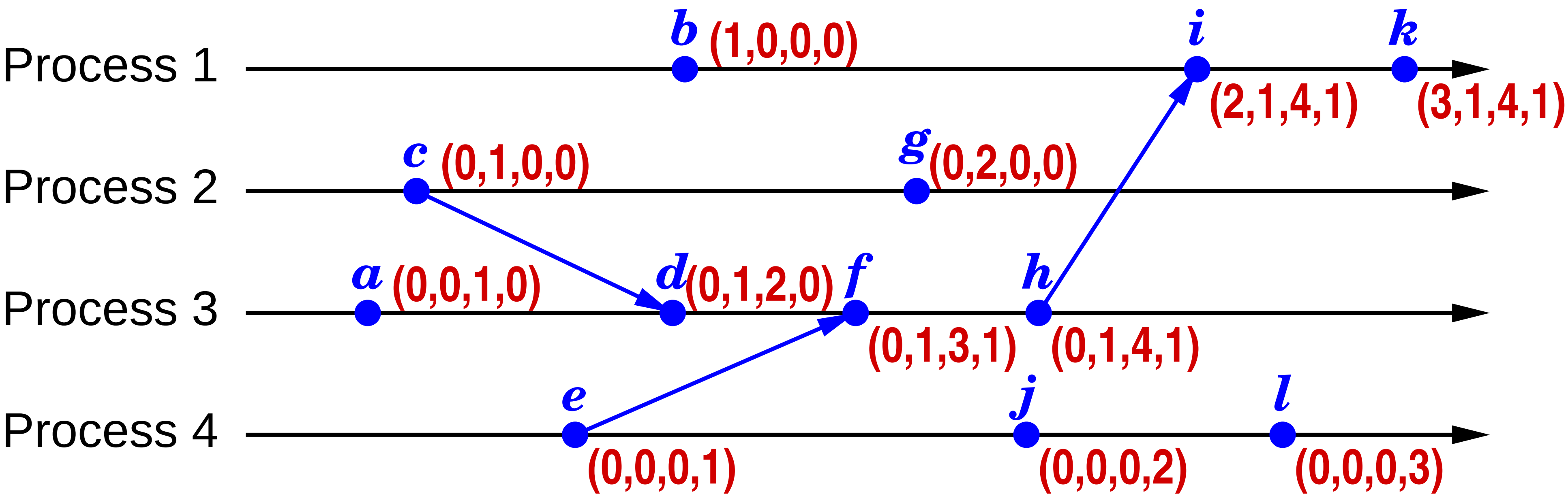


- Among others, we have here:
  - $c \rightarrow k$ and $V(c) < V(k)$
  - $g \not\rightarrow l$ and $V(g) \not< V(l)$, as well as $l \not\rightarrow g$ and $V(l) \not< V(g)$
    - $V(l)$ and $V(g)$ not comparable $\Leftrightarrow$ l and g concurrent

A Motivating Example

- Scenario: peer-to-peer application, processes send requests to each other
- Question: when can the application terminate?
- Answer: when no process is processing a request

A Motivating Example

- Scenario: peer-to-peer application, processes send requests to each other
- Question: when can the application terminate?
- **Wrong** answer: when no process is processing a request
  - reason: requests can still be on the way in messages!

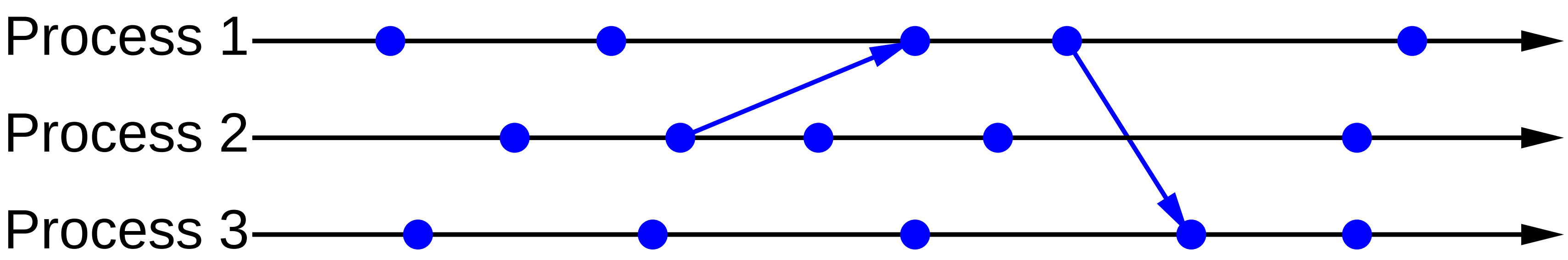
- Other applications: distributed garbage collection, distributed deadlock detection, ...

6.4 Global State ...

- How can we determine the overall state of a distributed process system?
  - naïvely: union of the states of all processes (**wrong!**)
- Two aspects have to be considered:
  - messages that are still in transit
    - must be included in the state
  - lack of global time
    - a global state at time t cannot be defined!
    - process states always refer to local (and thus different) times
    - question: condition on local times? $\Rightarrow$ **consistent cuts**

Consistent Cuts

- Objective: build a meaningful global state from local states (which are not determined simultaneously)
- Processes are modeled by sequences of events:



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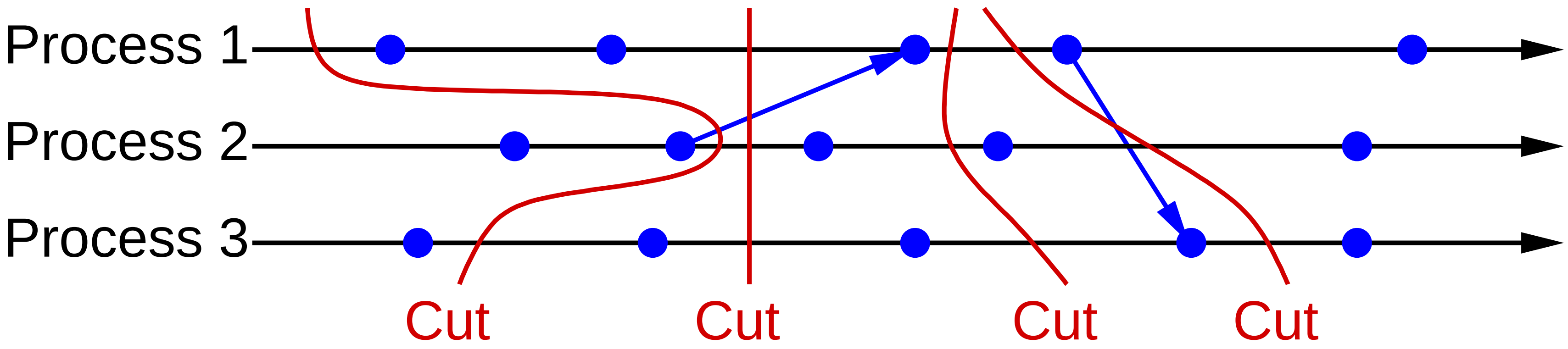

- **Cut**: consider a **prefix** of the event sequence in each process

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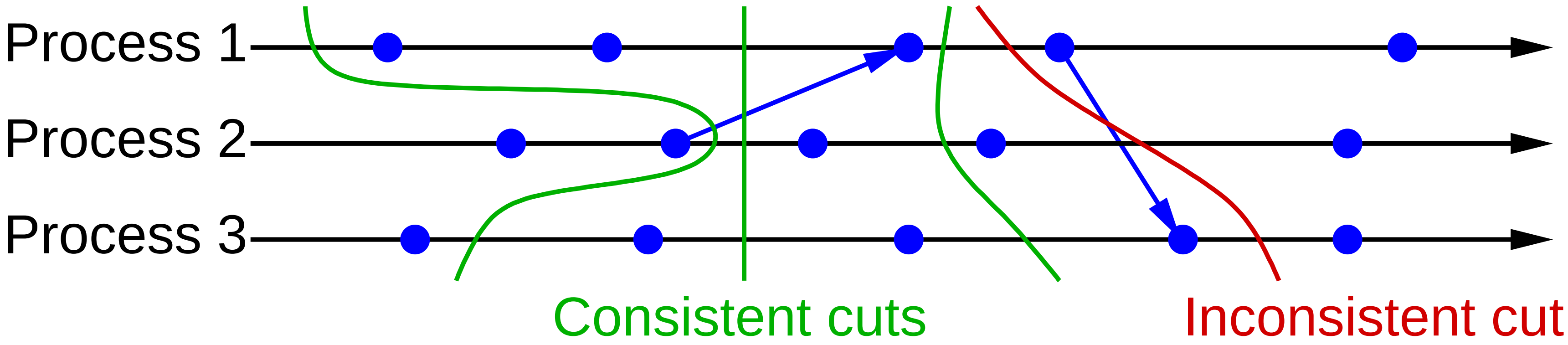


- **Cut**: consider a **prefix** of the event sequence in each process
- **Consistent cut**:
  - if the cut contains the reception of a message, it also contains the sending of this message

The Snapshot Algorithm of Chandy and Lamport

- Determines online a “snapshot” of the global state
  - i.e.: a consistent cut
- The global state consists of:
  - the local states of all processes
  - the status of all communication connections
    - i.e. the messages in transmission
- Assumptions / properties:
  - reliable message channels with sequence retention
  - process graph is strongly connected
  - each process can trigger a snapshot at any time
  - the processes are not blocked during the algorithm

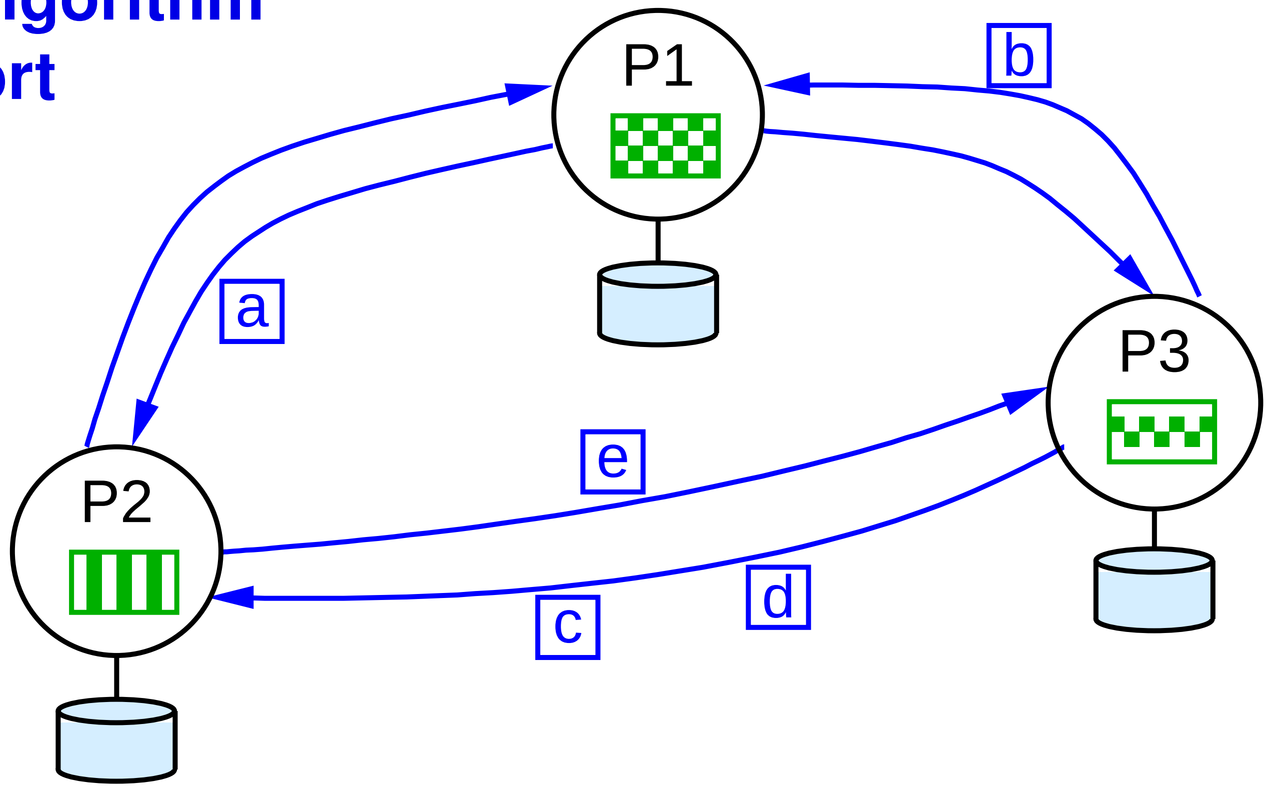
The Snapshot Algorithm of Chandy and Lamport ...

- When a process wants to initiate a snapshot:
  - process first saves its local state
  - then it sends a marker message over each outgoing channel
- When a process receives a marker message:
  - if it has not yet saved its local state:
    - it saves its local state
    - and sends a marker over each outgoing channel
  - else:
    - for the channel where the marker was received, it saves all messages that have been received since the local state was saved
    - i.e., it records the status of the channel

The Snapshot Algorithm of Chandy and Lamport ...

- The algorithm terminates when each process has received a marker message on each channel
  - the determined consistent section is then (initially) stored in a distributed way

Example for the algorithm of Chandy/Lamport



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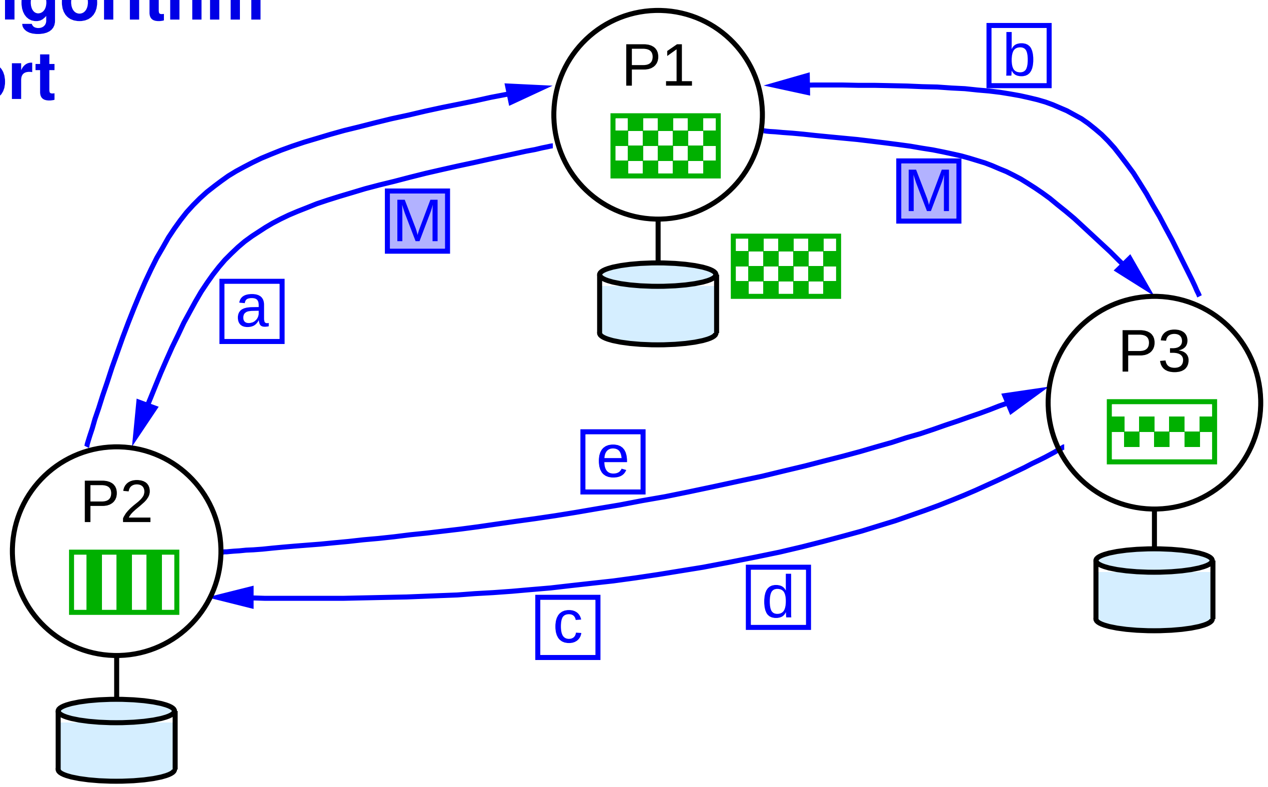

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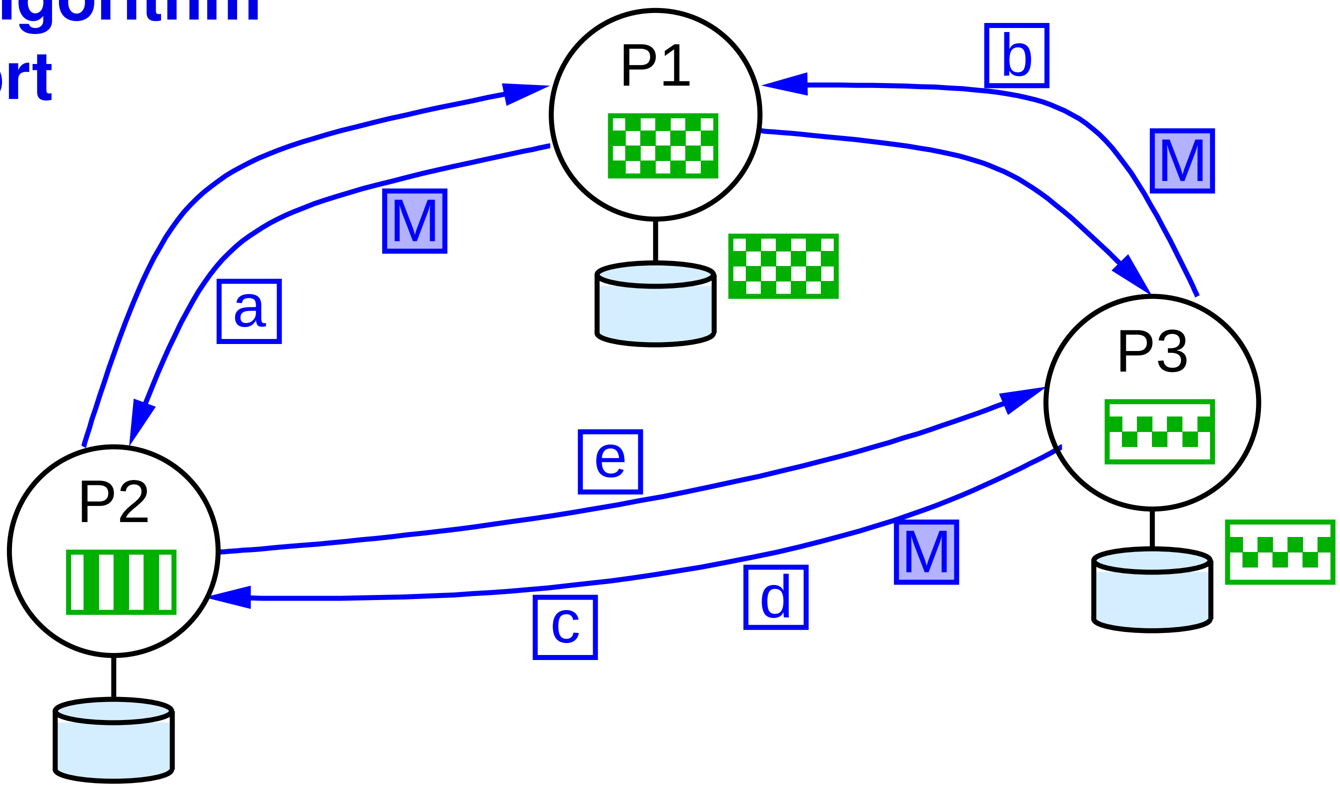

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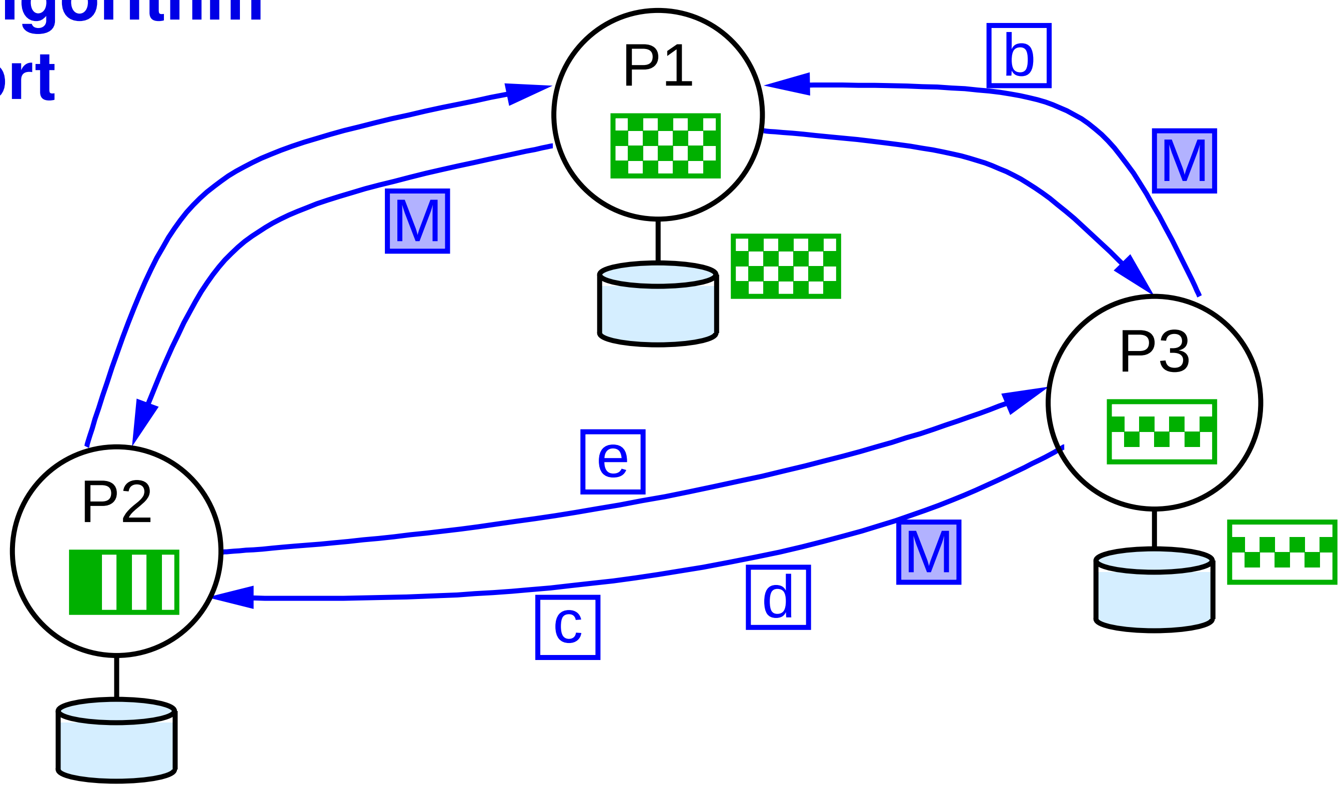

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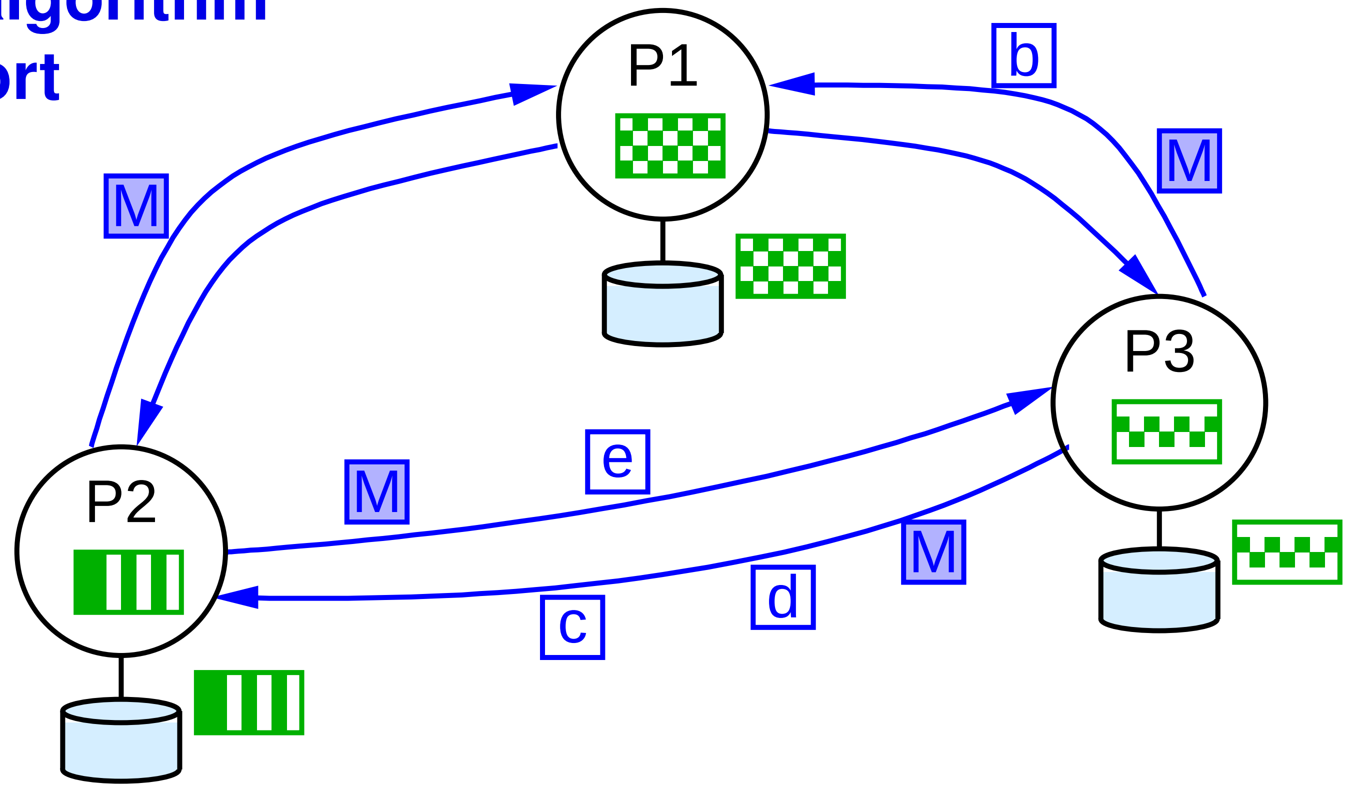

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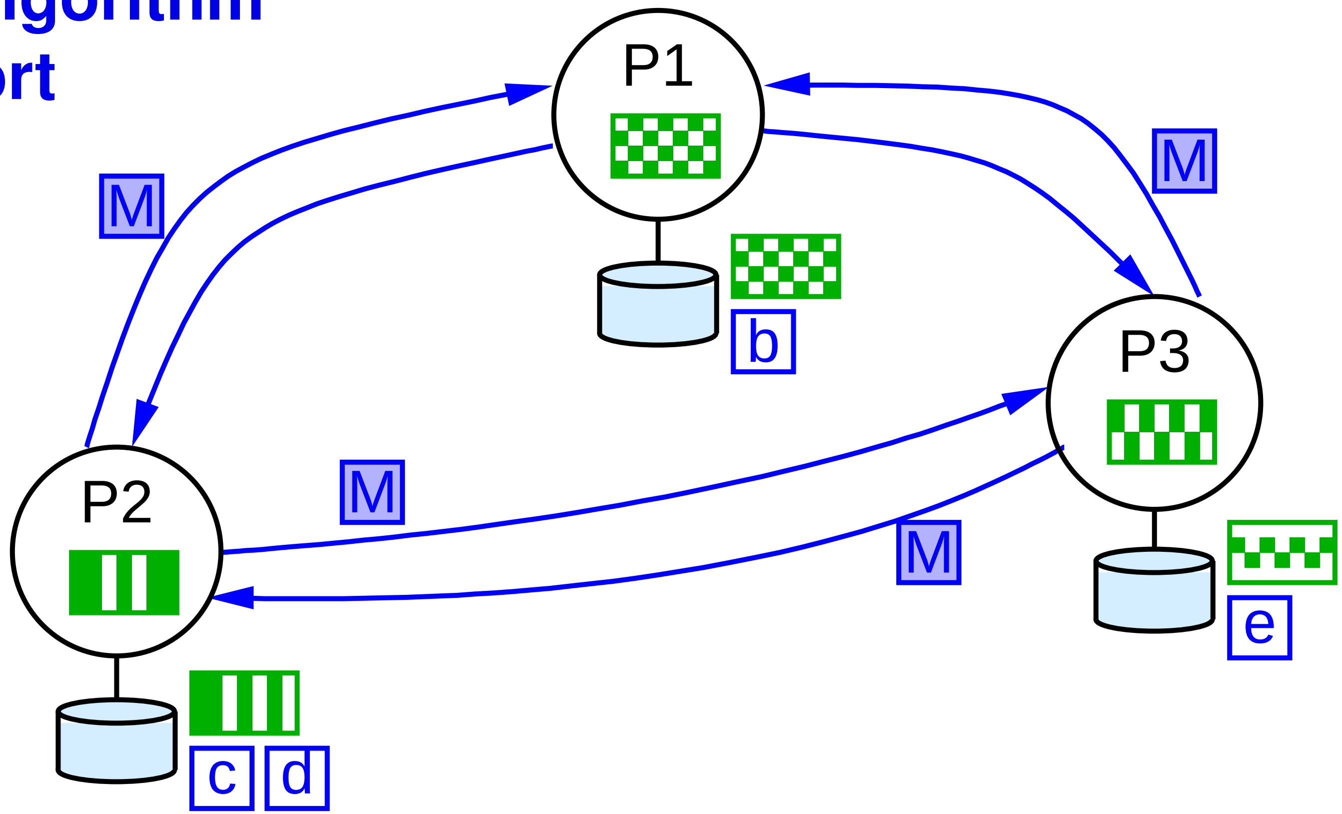

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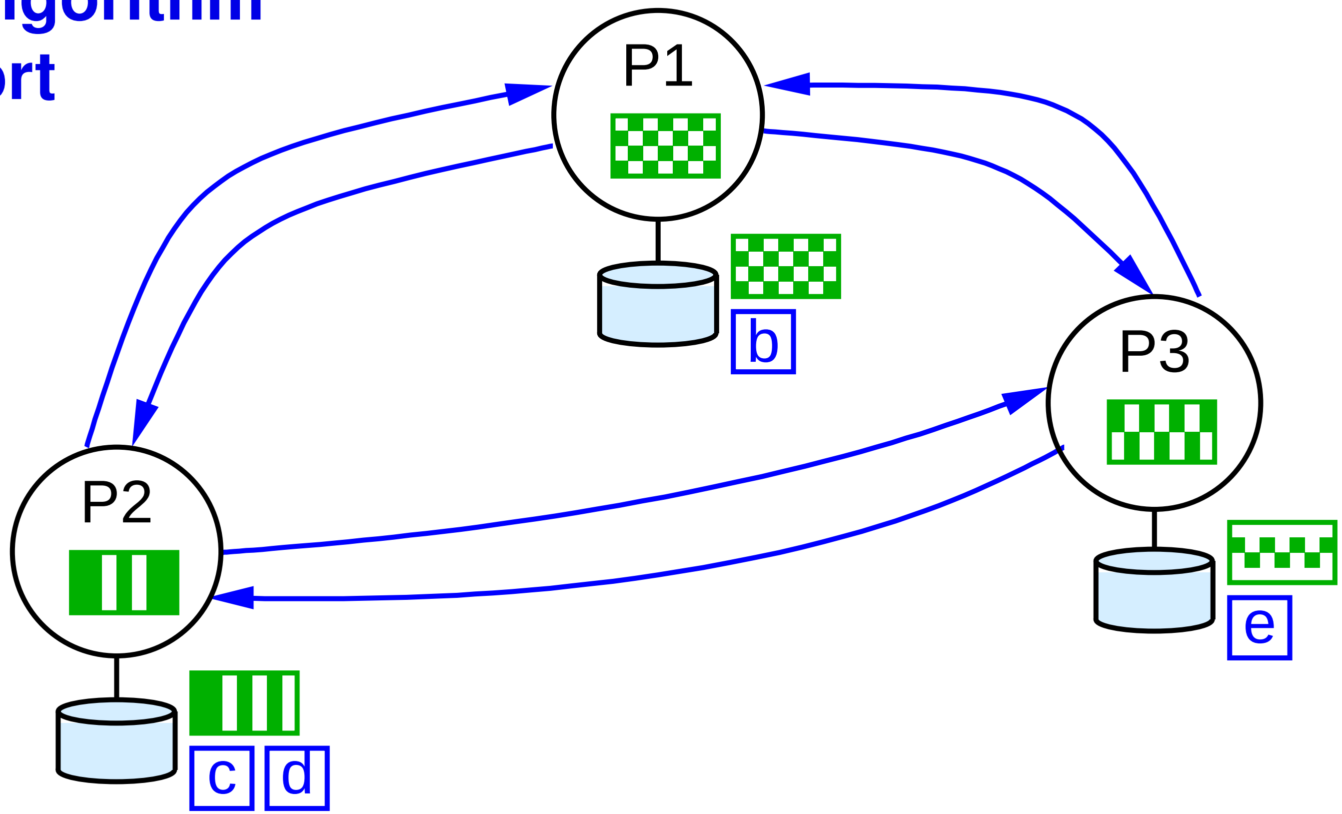

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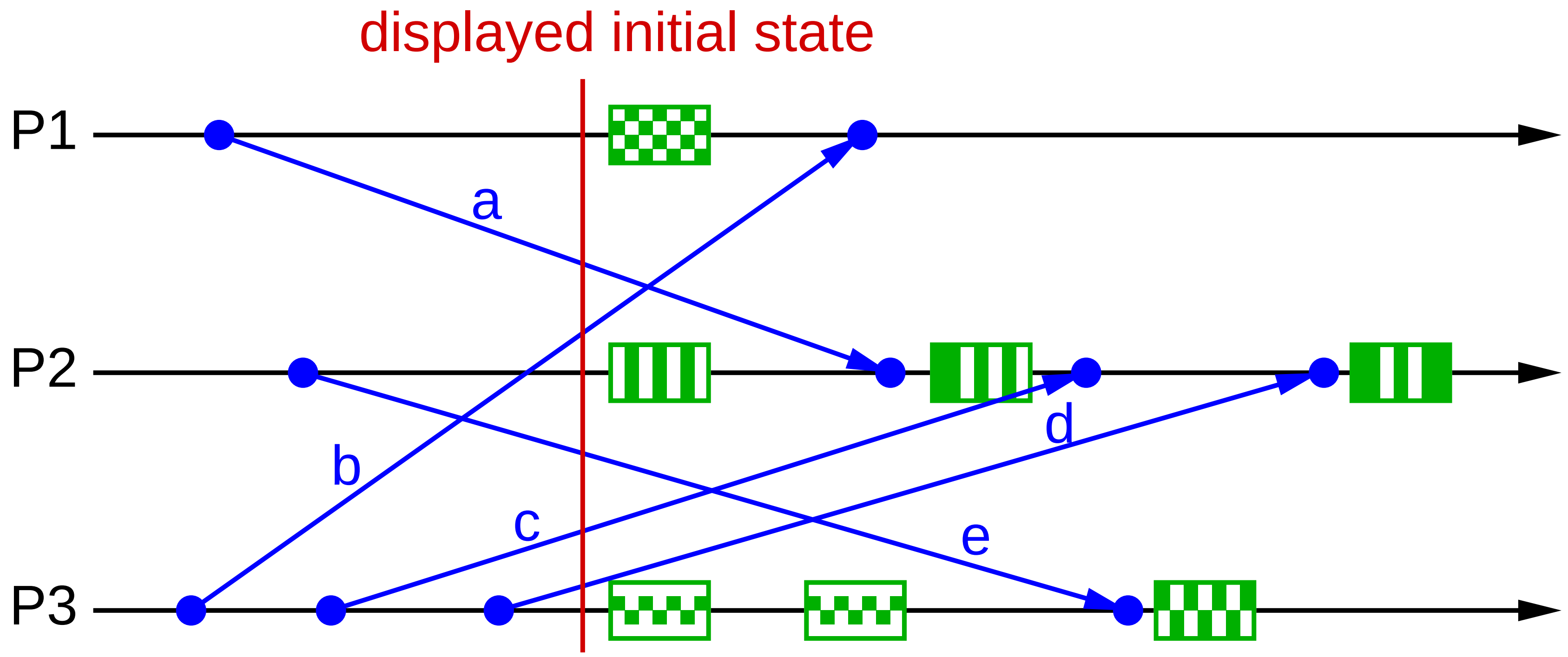
Sequence in the Example and Selected Cut



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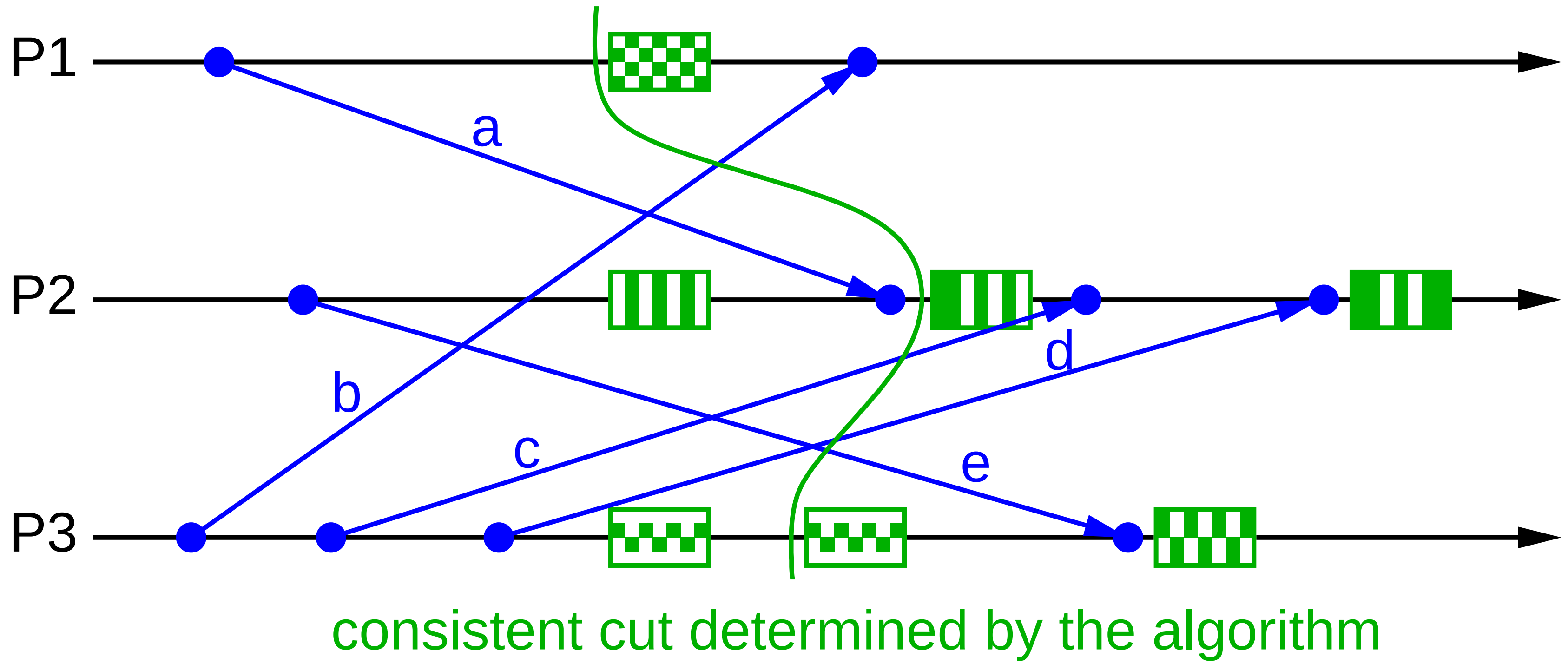

- The cut consists of the local states of P1, P2, P3 and the messages b, c, d, e