TDDD25
Distributed Systems

Time and State in Distributed Systems

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Agenda

TIME AND STATE IN DISTRIBUTED SYSTEMS

1. Time in Distributed Systems
2. Lamport’s Logical Clocks
3. Vector Clocks
4. Causal Ordering of Messages
5. Global States and their Consistency
6. Cuts of a Distributed Computation
7. Recording of a Global State (“Snapshot”)

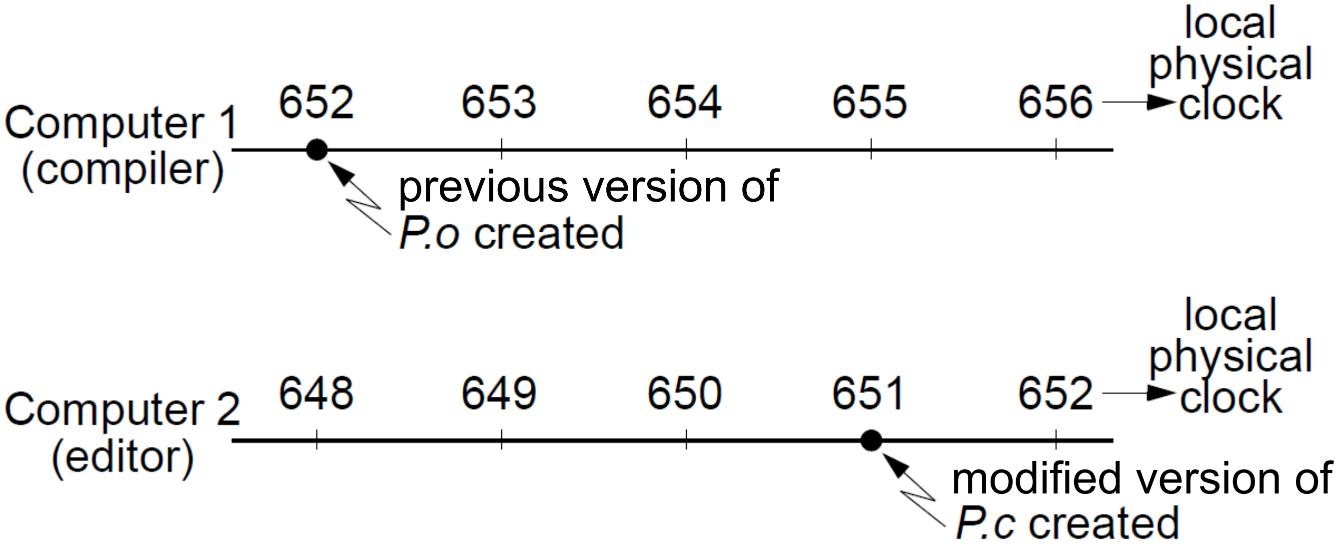
Time in Distributed Systems

- Because each machine in a distributed system has its own clock, **there is no notion of global physical time**.
  - The *n* crystals on the *n* computers will run at slightly different rates, causing the clocks gradually to get out of synchronization and give different values.
- **Problems**:
  - **Time triggered systems**: systems in which activities are scheduled to occur at predefined moments in time.
    If activities are to be coordinated over a distributed system, we need a coherent notion of time.
    - Example: time-triggered real-time systems
  - Maintaining the **consistency** of distributed data is often based on the **time** when a certain **modification** has been performed.
    - Example: a *make* program →

Time in Distributed Systems

The *make*-program example

- When the programmer has finished changing some source files, she starts *make*
  - ***make*** examines the times at which object and source files were last modified, and decides which sources have to be (re)compiled



- Although P.c is modified *after* P.o has been generated, because of the clock drift the time assigned to P.c is smaller.

  → P.c will **not** be recompiled for the new version!

Time in Distributed Systems

Solutions:

- **Synchronization of physical clocks**
  - Computer clocks are synchronized with one another to an achievable, known, degree of accuracy
    → within the bounds of this accuracy, we can coordinate activities on different computers using each computer's local clock.
  - Clock synchronization is needed for distributed real-time systems.
- **Logical clocks**
  - In many applications we are not interested in the physical time at which events occur; what is important is the ***relative* order** of events.
    - The *make*-program is such an example.
  - In such situations we do not need synchronized physical clocks.
  - Relative ordering is based on a *virtual* notion of time - **logical time**.
  - Logical time is implemented using **logical clocks**.

Lamport's Logical Clocks

- The order of events occurring at different processes is critical for many distributed applications.
  - Example: P.o_created and P.c_created in *make*-program example.

- **Ordering** can be based on two simple situations:
  1. If two events occurred in the *same* process, then they occurred in the order observed following the respective process;
  2. Whenever a message is sent between processes, the event of sending the message occurred before the event of receiving it.

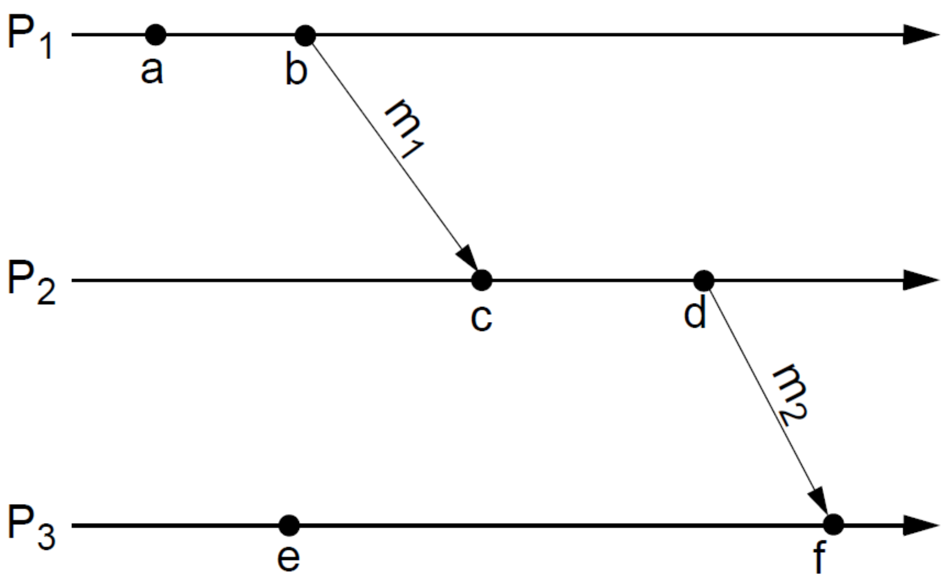
- Ordering by Lamport is based on **happened-before relation** (denoted "$\rightarrow$"):
  - $a \rightarrow b$, if *a* and *b* are events in the *same* process and *a* occurred before *b*;
  - $a \rightarrow b$, if *a* is the event of sending a message *m* in a process, and *b* is the event of the same message *m* being received by another process.

If $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$ (the relation $\rightarrow$ is **transitive**).

Lamport's Logical Clocks

- If $a \rightarrow b$, we say that event *a* **causally affects** event *b.*
  - The two events are **causally related**.
- There are events which are not related by the happened-before relation.
  - If both $a \rightarrow e$ and $e \rightarrow a$ are false, then *a* and *e* are **concurrent** events:
    - we write $a \parallel e$.

Example:



$a \rightarrow b$, $c \rightarrow d$, $e \rightarrow f$,
$b \rightarrow c$, $d \rightarrow f$

$a \rightarrow c$, $a \rightarrow d$, $a \rightarrow f$,
$b \rightarrow d$, $b \rightarrow f$, ...

$a \parallel e$, $c \parallel e$, ...

Lamport's Logical Clocks

Using physical clocks, the happened-before relation cannot be captured.

- It is possible that $b \rightarrow c$ and at the same time $T_b > T_c$ (where T_b is the physical time of event b).

Logical clocks can be used to capture the happened-before relation.

- **A logical clock is a monotonically increasing software counter**.
- There is a logical clock C_{Pi} at each process P_i in the system.
- The value of the logical clock is used to assign **timestamps** to events.
  - $C_{Pi}(a)$ is the timestamp of event a in process P_i.
- There is no relationship between a logical clock and any physical clock.

To capture the happened-before relation,
logical clocks have to be implemented so that:

- if $a \rightarrow b$, then $C(a) < C(b)$

Lamport's Logical Clocks

Implementation of logical clocks is performed using the following **rules** for updating the clocks and transmitting their values in messages:

[R1]: Each event issued at process P_i is timestamped with the value obtained after incrementing the local clock C_{Pi}: $C_{Pi} := C_{Pi} + 1$.

[R2]: a) **If** *a* is the event of sending a message *m* from process P_i, **then** the timestamp $t_m = C_{Pi}(a)$ is included in *m* ($C_{Pi}(a)$ is the logical clock value obtained after applying rule R1).

b) On **receiving** message *m* by process P_j, its logical clock C_{Pj} is updated as follows:

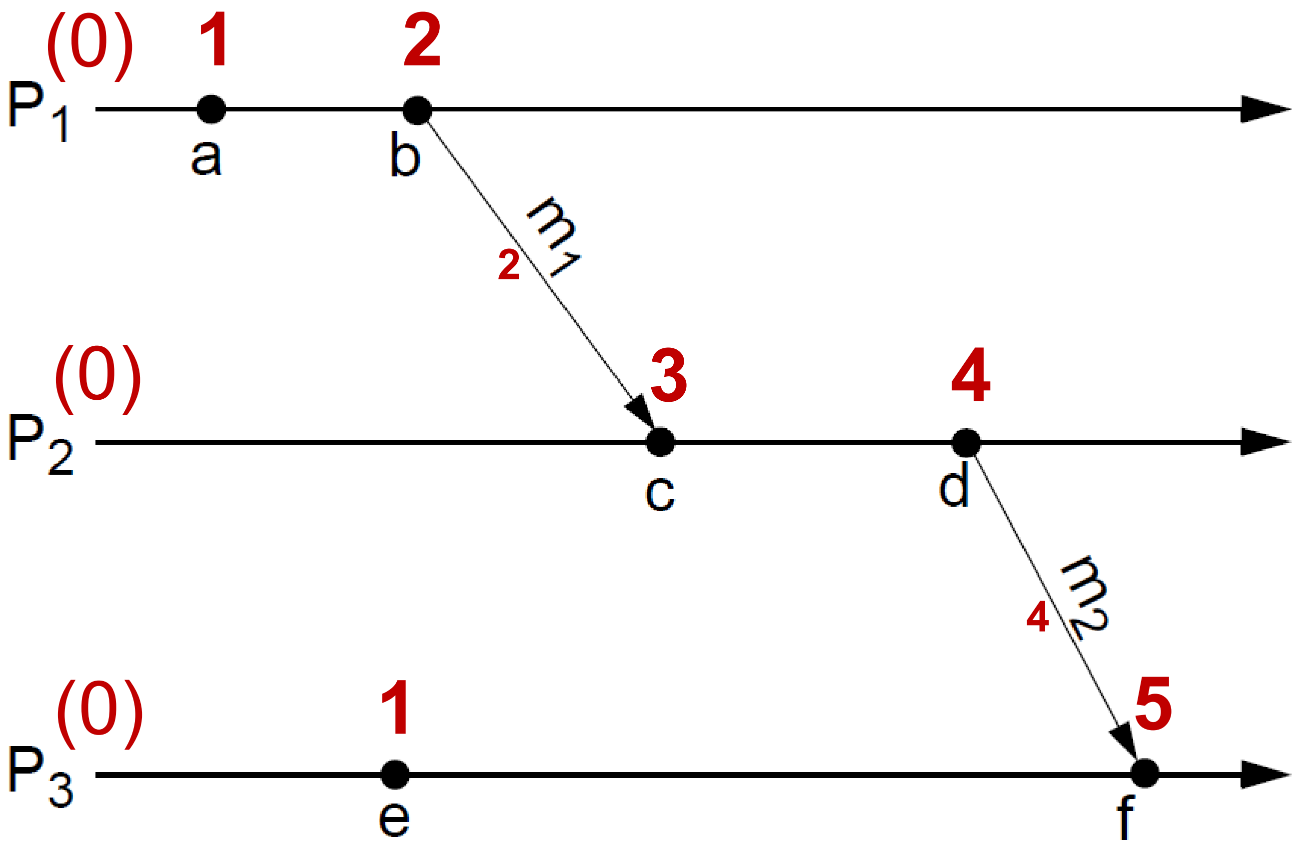
$C_{Pj} := \mathbf{max}\ (C_{Pj}, t_m)$.

c) The new value of C_{Pj} is used to timestamp the event of receiving message *m* by P_j (applying rule R1).

- If *a* and *b* are events in the *same* process and *a* occurred before *b*, then $a \rightarrow b$, and (by R1) $C(a) < C(b)$.
- If *a* is the event of sending a message *m* in a process, and *b* is the event of the same message *m* being received by another process, then $a \rightarrow b$, and (by R2) $C(a) < C(b)$.
- If $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$, and (by induction) $C(a) < C(c)$.

Lamport's Logical Clocks

Example



Problems with Lamport's Logical Clocks (1)

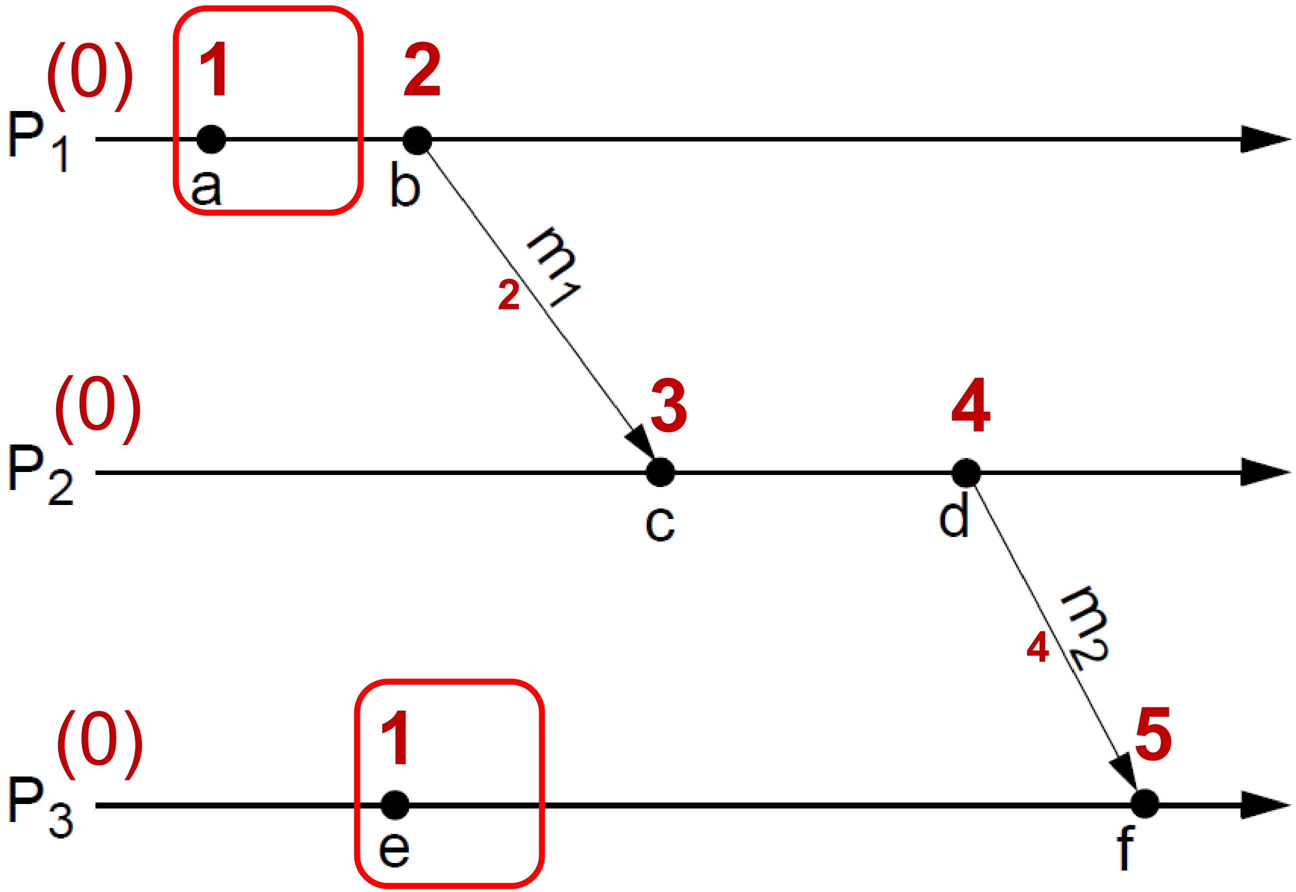
- Lamport's logical clocks impose only a **partial order** on the set of events
  - pairs of distinct events generated by different processes can have identical timestamp.
- For certain applications a **total ordering** is needed;
they consider that no two events can occur at the same time.
- In order to enforce total ordering,
a **global logical timestamp** is introduced:
  - The global logical timestamp of an event *a* occurring at process P_i, with logical timestamp $C_{Pi}(a)$, is a **pair** $(C_{Pi}(a), i)$, where *i* is an identifier of process P_i
  - We define

$$(C_{Pi}(a), i) < (C_{Pj}(b), j) \text{ if and only if } C_{Pi}(a) < C_{Pj}(b),$$
$$\text{or } C_{Pi}(a) = C_{Pj}(b) \text{ and } i < j.$$

= lexical order on pairs

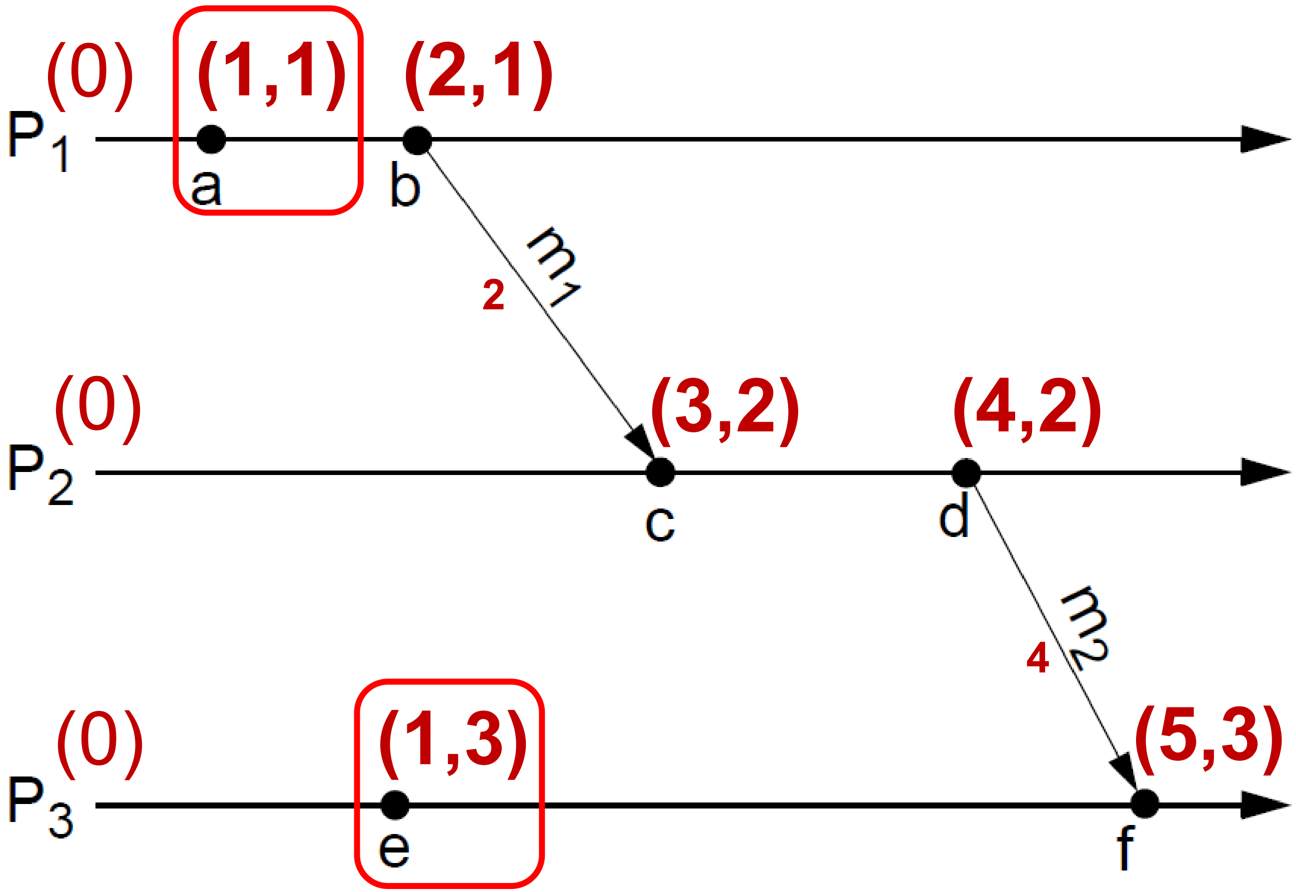
Lamport's Logical Clocks

Example



Lamport's Logical Clocks
with Global Logical Timestamps

Example



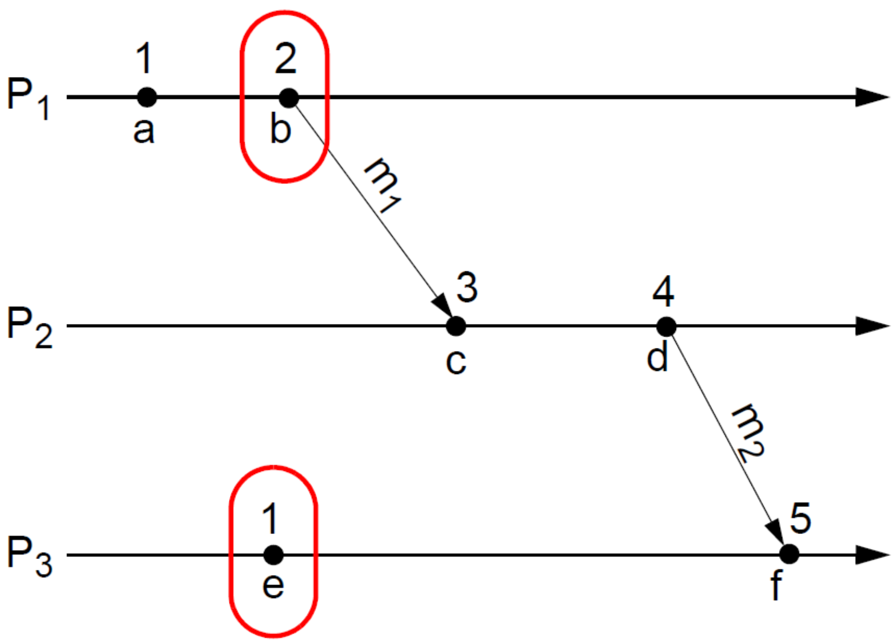
Problems with Lamport's Logical Clocks (2)

- Lamport's logical clocks are **not** powerful enough to perform a **causal ordering of events**.

  We have seen earlier:
  - if $a \rightarrow b$, then $C(a) < C(b)$.

  However, the reverse is not always true:
  - if $C(a) < C(b)$, then $a \rightarrow b$ is **not necessarily true**.

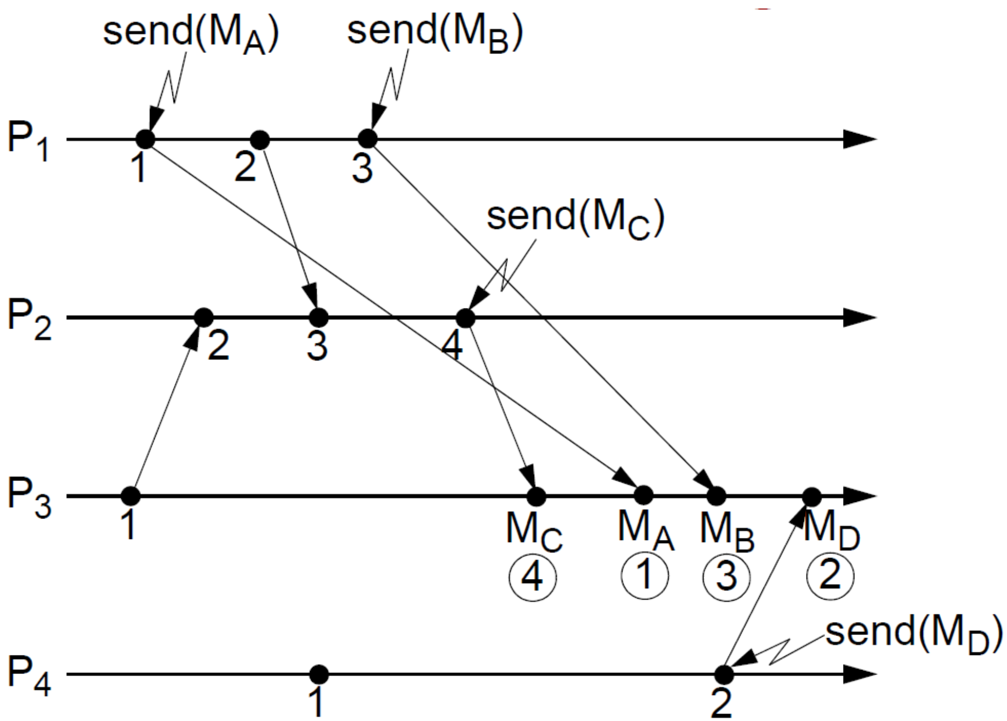
    (it is only guaranteed that $b \rightarrow a$ is not true).



$C(e) < C(b)$, however there is no causal relation from event e to event b.

By just looking at the timestamps of the events, we cannot say whether two events are causally related or not.
If $C(x) < C(y)$, it might be that $x \rightarrow y$ or $x \parallel y$

Problems with Lamport's Logical Clocks

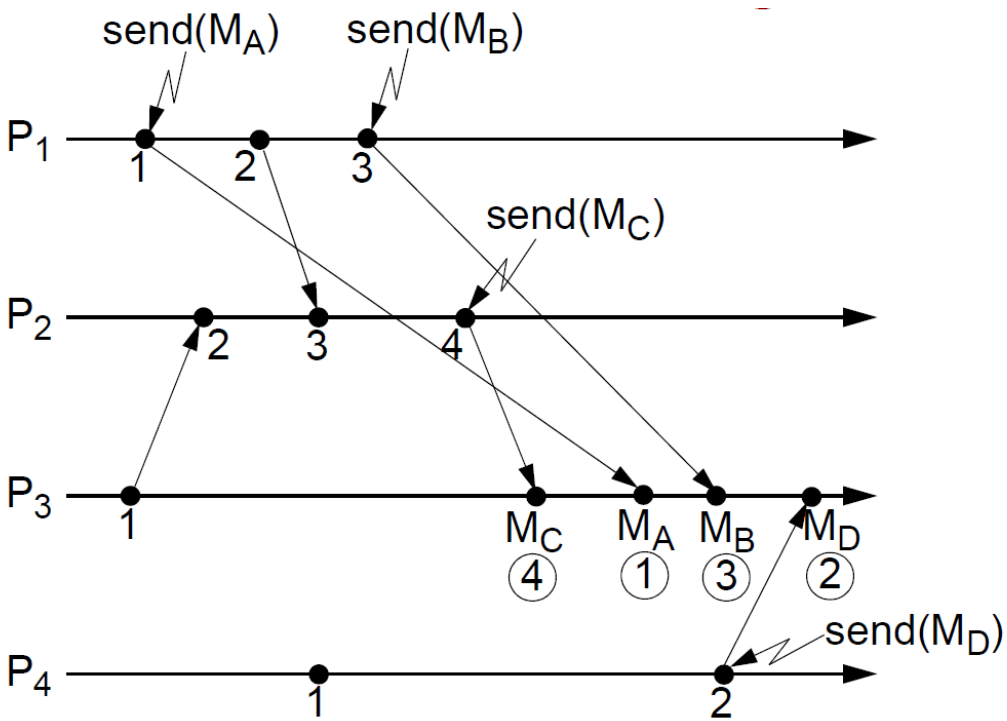


We want messages received by P_3 to be processed in their *causal* order.

Can we use the associated timestamp for this purpose?

- Process P3 receives messages M_A, M_B, M_C, and M_D.
  - send(M_A) → send(M_C), send(M_A) → send(M_B),
  - send(M_B) || send(M_C), send(M_A) || send(M_D),
  - send(M_B) || send(M_D), send(M_C) || send(M_D).

Problems with Lamport's Logical Clocks



send(M_A) → send(M_C), send(M_A) → send(M_B)
→ process M_A *before* M_C and M_B

But, P_3 needs not wait for M_B and M_D in order to process them before M_C; similarly, the delivery of M_B is not needed to be delayed after that of M_D.

By processing the messages in order of their *timestamp*, all happened-before relations will be correctly enforced, **but** additional, unneeded, delays will be introduced (due to enforcement of ordering where, in fact, not needed).

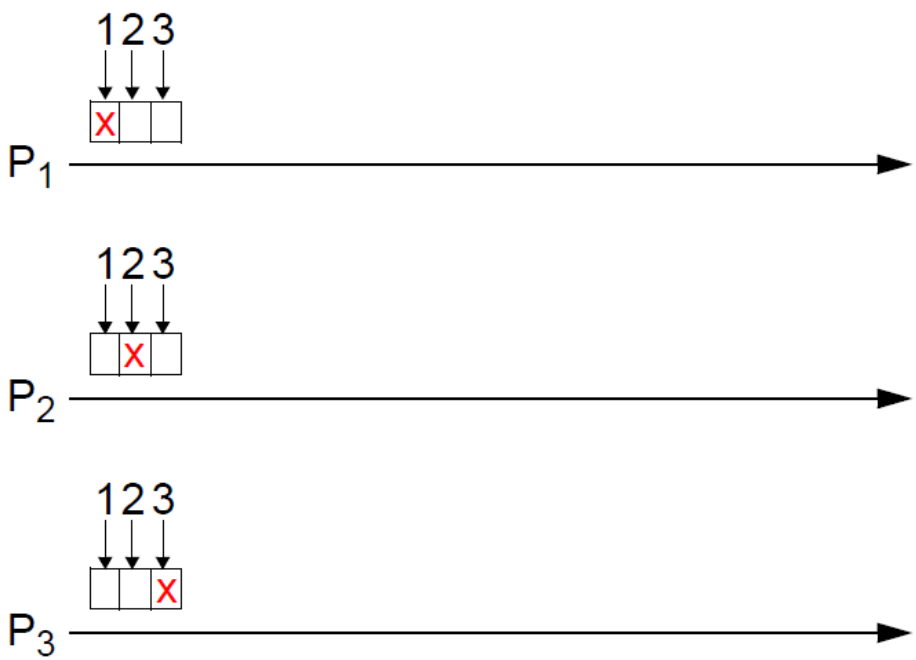
Vector Clocks

- Vector clocks give the ability to decide whether two events are **causally related** or not by simply looking at their timestamp.

- Each **process** P_i has a **clock** $C^v{}_{Pi}$
  - $C^v{}_{Pi}$ is an **integer vector** of length n
    - n is the number of processes
  - The value of $C^v{}_{Pi}$ is used to assign timestamps to events in process P_i.
    - $C^v{}_{Pi}(a)$ is the **timestamp** of event a in process P_i.
  - $C^v{}_{Pi}[i]$, the ith entry of $C^v{}_{Pi}$, corresponds to an event counter in P_i
    - simply, counts the events in P_i

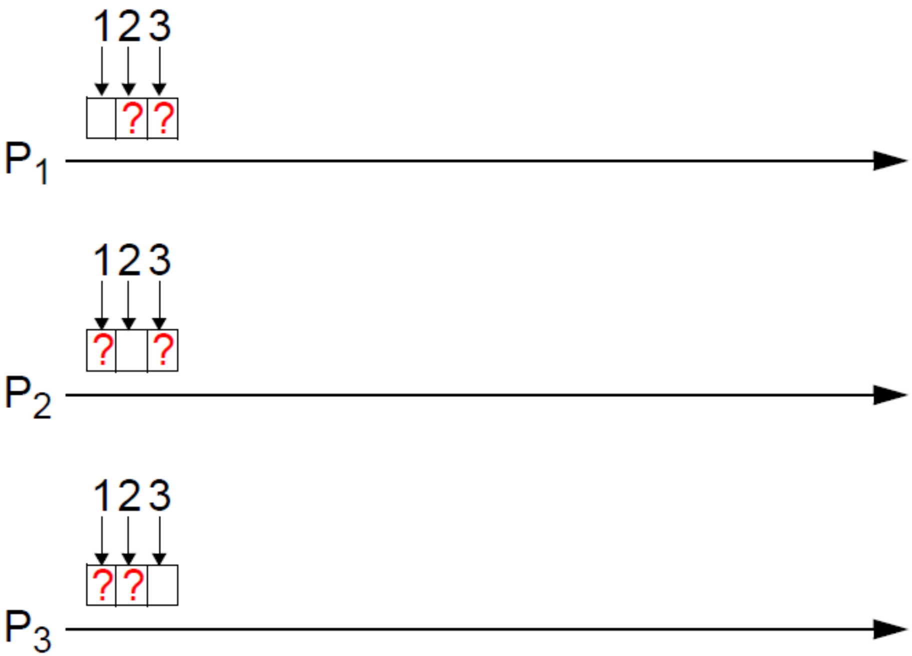
- $C^v{}_{Pi}[j]$, for $j \neq i$, is P_i's "best guess" of the local event counter at P_j
  - $C^v{}_{Pi}[j]$ indicates the value of the local event counter of P_j at the occurrence of the **last** event at P_j which is in a **happened-before** relation to the current event at P_i.

Vector Clocks Example (n=3)



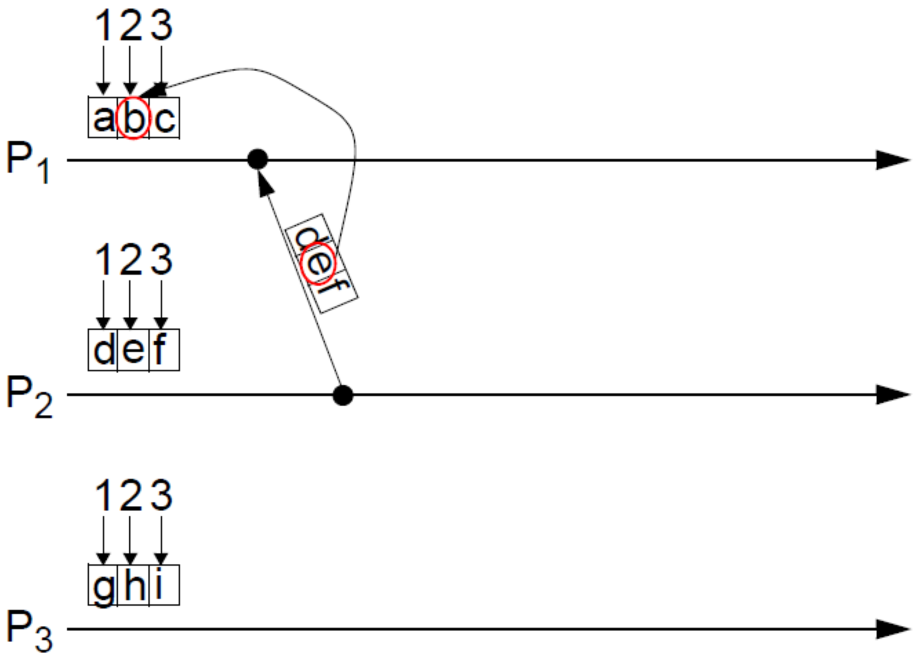
- $C^V_{P_i}[i]$, the ith entry of $C^V_{P_i}$, corresponds to an event counter in P_i (simply, counts the events in P_i).

Vector Clocks



- $C^V_{Pi}[i]$, the *i*th entry of C^V_{Pi}, corresponds to an event counter in P_i (simply, counts the events in P_i).
- What about all the other entries?

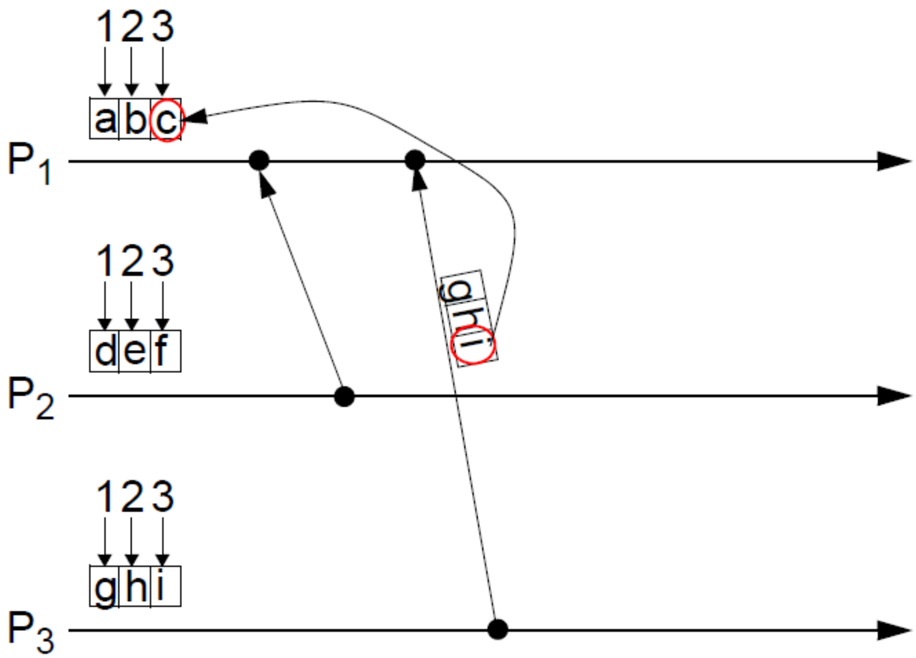
Vector Clocks



- $C^V_{P_i}[i]$, the *i*th entry of $C^V_{P_i}$, corresponds to an event counter in P_i (simply, counts the events in P_i).
- $C^V_{P_i}[j]$, $j \neq i$, is P_i's ***best guess*** of the local event counter at P_j.

  Best guess of P_i: the value of the local counter in P_j, at the moment of the most recent interaction from P_j to P_i.

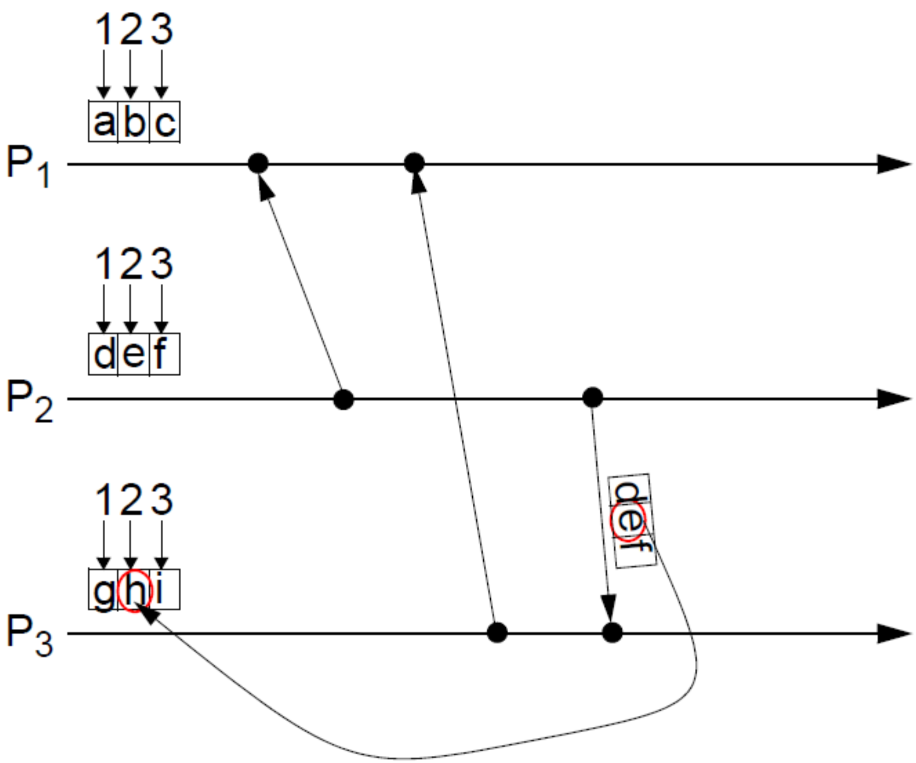
Vector Clocks



- $C^V_{P_i}[i]$, the *i*th entry of $C^V_{P_i}$, corresponds to an event counter in P_i (simply, counts the events in P_i).
- $C^V_{P_i}[j]$, $j \neq i$, is P_i's ***best guess*** of the local event counter at P_j.

  Best guess of P_i: the value of the local counter in P_j, at the moment of the most recent interaction from P_j to P_i.

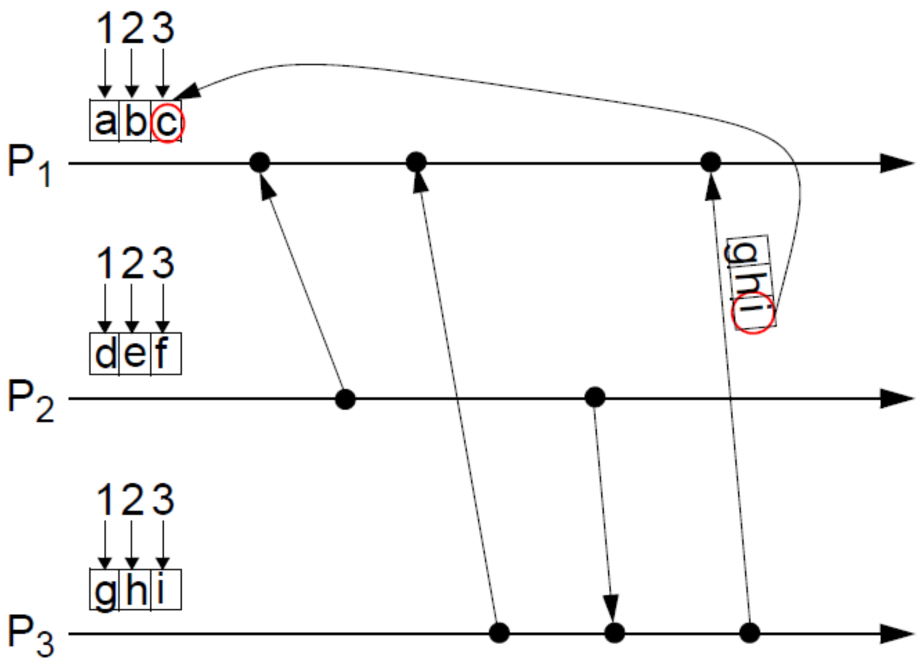
Vector Clocks



- $C^V_{Pi}[i]$, the *i*th entry of C^V_{Pi}, corresponds to an event counter in P_i (simply, counts the events in P_i).
- $C^V_{Pi}[j]$, $j \neq i$, is P_i's ***best guess*** of the local event counter at P_j.

  Best guess of P_i: the value of the local counter in P_j, at the moment of the most recent interaction from P_j to P_i.

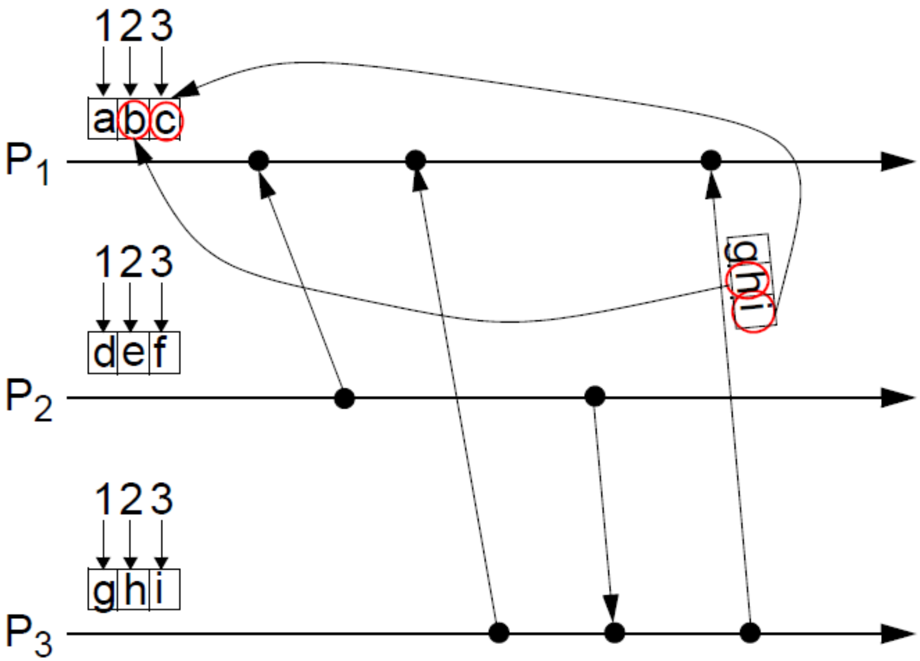
Vector Clocks



- $C^v_{Pi}[i]$, the *i*th entry of C^v_{Pi}, corresponds to an event counter in P_i (simply, counts the events in P_i).
- $C^v_{Pi}[j]$, $j \neq i$, is P_i's *best guess* of the local event counter at P_j.

  Best guess of P_i: the value of the local counter in P_j, at the moment of the most recent interaction from P_j to P_i.

Vector Clocks



- $C^V_{Pi}[i]$, the *i*th entry of C^V_{Pi}, corresponds to an event counter in P_i (simply, counts the events in P_i).

- $C^V_{Pi}[j]$, $j \neq i$, is P_i's *best guess* of the local event counter at P_j.

  Best guess of P_i: the value of the local counter in P_j, at the moment of the most recent direct or indirect interaction from P_j to P_i. $\Rightarrow$ $C^V_{Pi}[j]$ indicates the value of the local event counter of P_j at the occurrence of the last event at P_j which is in a *happened-before* relation to the current event at P_i.

Vector Clocks

Implementation of vector clocks is performed using the following **rules** for updating the clocks and transmitting their values in messages:

[R1]: Each event issued at process P_i is timestamped with the value of the vector clock $C^v{}_{Pi}$ obtained after incrementing the corresponding element $C^v{}_{Pi}[i]$: $C^v{}_{Pi}[i] := C^v{}_{Pi}[i] + 1$.

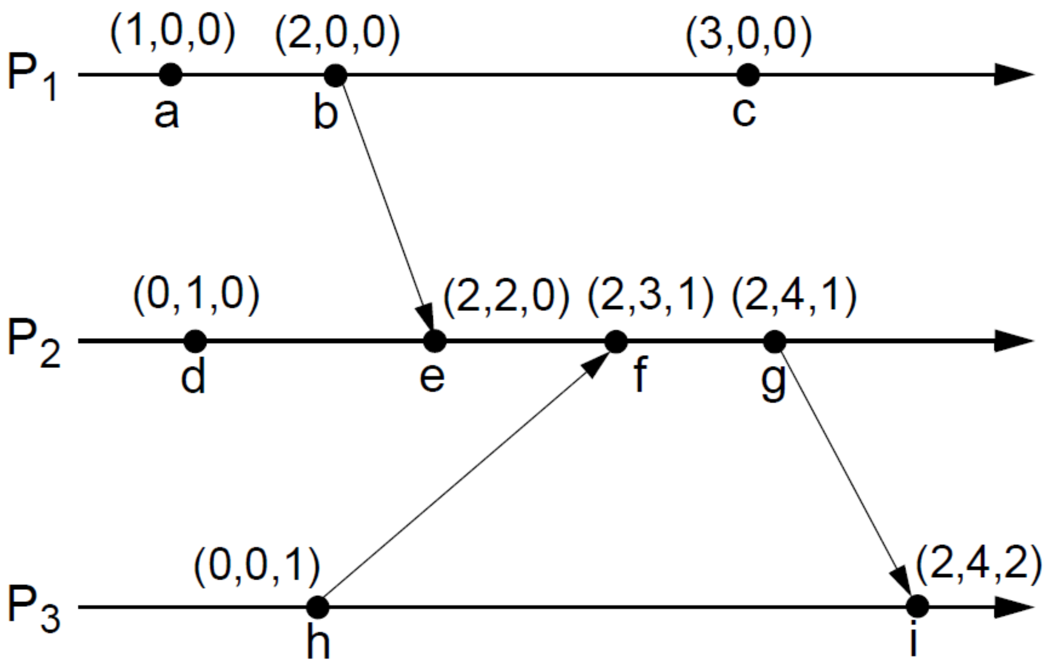
[R2]: (a) If a is the event of **sending** a message m from process P_i, then the timestamp $t_m = C^v{}_{Pi}(a)$ is included in m ($C^v{}_{Pi}(a)$ is the vector clock value obtained after applying rule R1).

(b) On **receiving** message m by process P_j, its vector clock $C^v{}_{Pj}$ is updated as follows:

$$\forall\ k \text{ in } \{ 1, 2,.., n \}, \quad C^v{}_{Pj}[k] := \mathbf{max}\ (\ C^v{}_{Pj}[k], t_m[k]\ )$$

(c) The new value of $C^v{}_{Pj}$ is used to timestamp the event of receiving message m by P_j (applying rule R1).

Vector Clocks



For any two vector timestamps *u* and *v*, we have:

- $u = v$ if and only if $\forall i,\ u[i] = v[i]$
- $u \leq v$ if and only if $\forall i,\ u[i] \leq v[i]$
- $u < v$ if and only if $u \leq v \wedge u \neq v)$
- $u \parallel v$ if and only if $\neg(u < v) \wedge \neg(v < u)$

Two events *a* and *b* are **causally related** if and only if $C^v(a) < C^v(b) \vee C^v(b) < C^v(a)$.
Otherwise, the events are **concurrent**.

Vector Clocks

Vector clocks have the property which we missed for Lamport's clocks:

- a → b   if and only if $C^v(a) < C^v(b)$.

Thus, by just looking at the timestamps of the events,
we can tell whether two events are causally related or not.

→ **Vector clocks can be used for causal ordering of events/messages.**

Global States

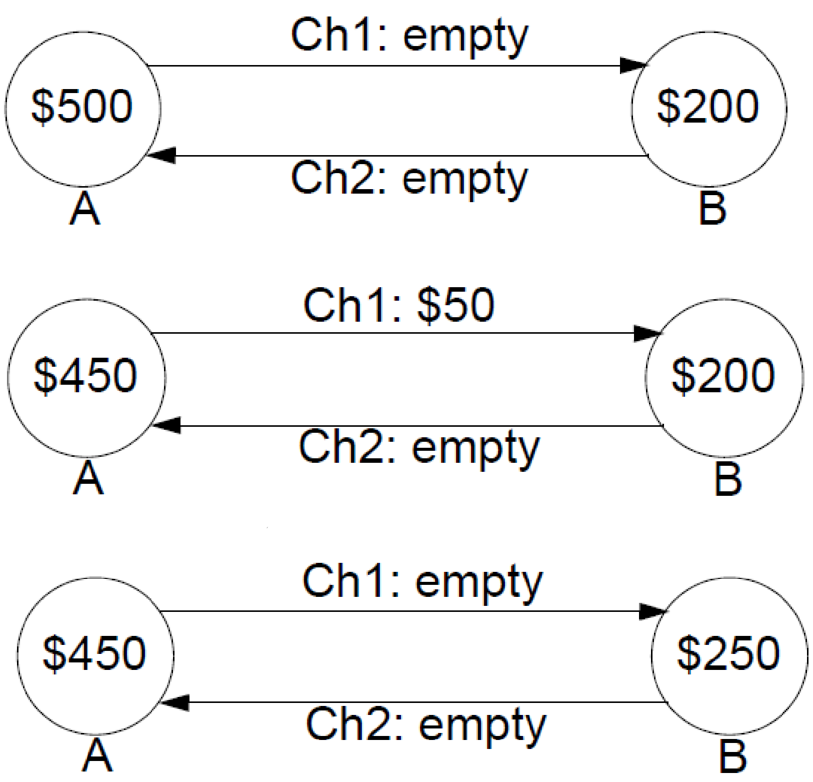
The problem is how to **collect and record a consistent global state in a distributed system**.

- "State" is application-specific
- Example use cases:
  - Monitoring of a distributed shared data structure
    - Bank account example →
  - Distributed garbage collection
  - Progress monitoring for dynamic load balancing
  - Distributed deadlock detection

- Why a problem?
  - Because there is no global clock (no coherent notion of time) and no shared memory!

Global States

Consider a bank system
with two accounts A and B at two different sites;
we transfer $50 between A and B.



A	Ch1	B	C : consistent NC: not consistent
500	empty	200	?
500	50	200	NC
450	50	200	C
450	empty	200	NC
500	50	250	NC
450	50	250	NC
450	empty	250	C
500	empty	250	NC

Global States

- In general, a **global state** consists of
  - a set of local states and
  - a set of states of the communication channels.

- The state of a communication channel in a **consistent global state** should be the sequence of messages sent along the channel before the sender's state was recorded, excluding the sequence of messages received along the channel before the receiver's state was recorded.

- It is difficult to record channel states to ensure the above rule

  → global states are very often recorded *without* using channel states.

  - This is the case in the definition below.

Formal Definition (1)

- LS_i is the **local state** of process P_i.
  - Beside other information, the local state also includes a record of all messages sent and received by the process.

- We consider the **global state** *GS* of a system as the collection of the local states of its processes:

  $$GS = (LS_1, LS_2, ..., LS_n).$$

  - A certain global state can be *consistent* or not!

Formal Definition (2)

send(m^k_{ij}) denotes the event of sending message m^k_{ij} from P_i to P_j

rec(m^k_{ij}) denotes the event of receiving message m^k_{ij} by P_j.

- $send(m^k_{ij}) \in LS_i$ if and only if the sending event occurred *before* the local state was recorded;
- $rec(m^k_{ij}) \in LS_j$ if and only if the receiving event occurred *before* the local state was recorded.

transit$(LS_i, LS_j) = \{\, m^k_{ij} \mid send(m^k_{ij}) \in LS_i \;\wedge\; rec(m^k_{ij}) \notin LS_j \,\}$

inconsistent$(LS_i, \mathrm{LS}_j) = \{\, m^k_{ij} \mid send(m^k_{ij}) \notin LS_i \;\wedge\; rec(m^k_{ij}) \in LS_j \,\}$

Formal Definition (3)

- A global state $GS = (LS_1, LS_2, ..., LS_n)$ is **consistent** if and only if:

  $\forall i, \forall j: 1 \leq i, j \leq n :: inconsistent(LS_i, LS_j) = \emptyset$

  - In a consistent global state, for every received message a corresponding send event is recorded in the global state.
  - In an inconsistent global state, there is at least one message whose receive event is recorded but its send event is not recorded.

- A global state $GS = (LS_1, LS_2, ..., LS_n)$ is **transitless** if and only if:

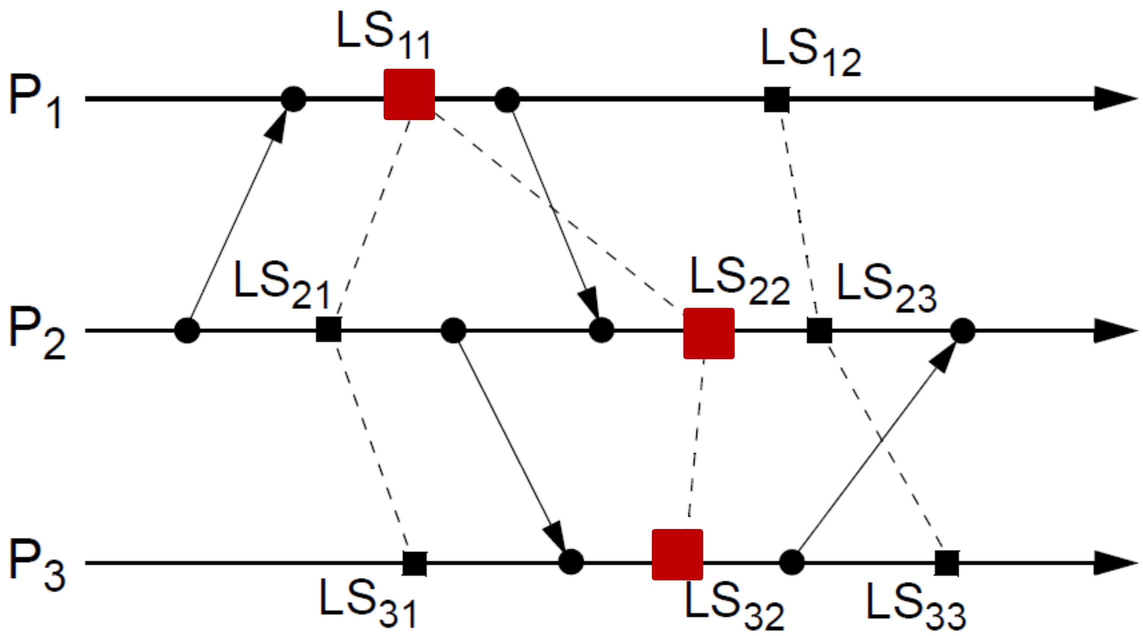
  $\forall i, \forall j: 1 \leq i, j \leq n :: transit(LS_i, LS_j) = \emptyset$

  - All messages recorded to be sent are also recorded to be received.

- A global state is **strongly consistent** if it is consistent and transitless.
  - A strongly consistent state corresponds to a consistent state in which all messages recorded as sent are also recorded as received.

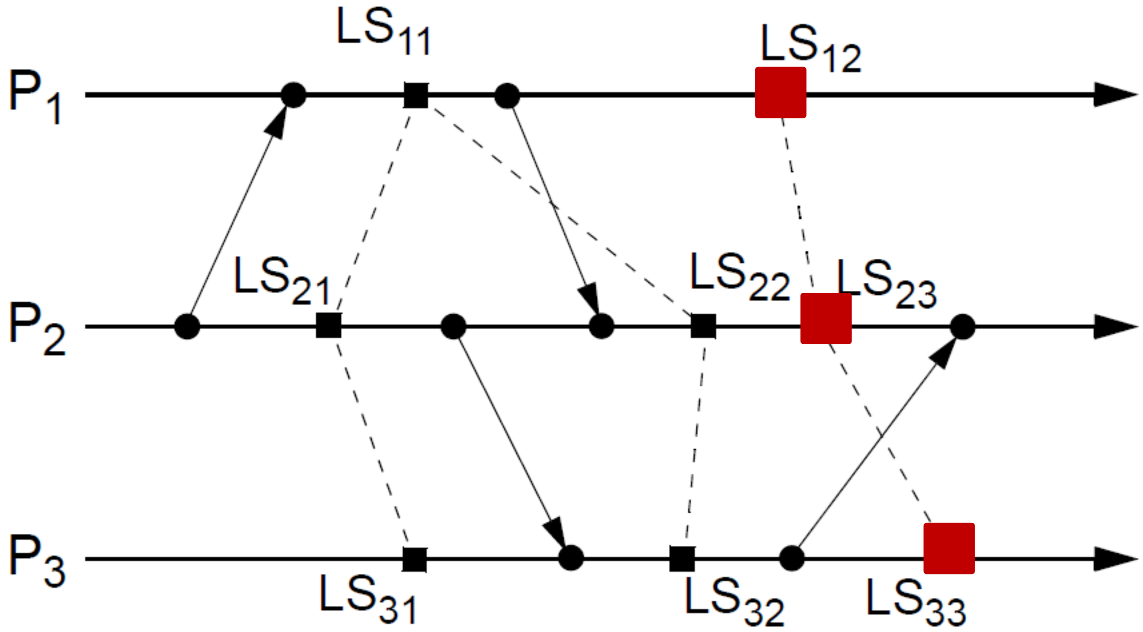
Note: the global state, as defined here, is seen as a collection of the local states, without explicitly capturing the state of the channel.

Example



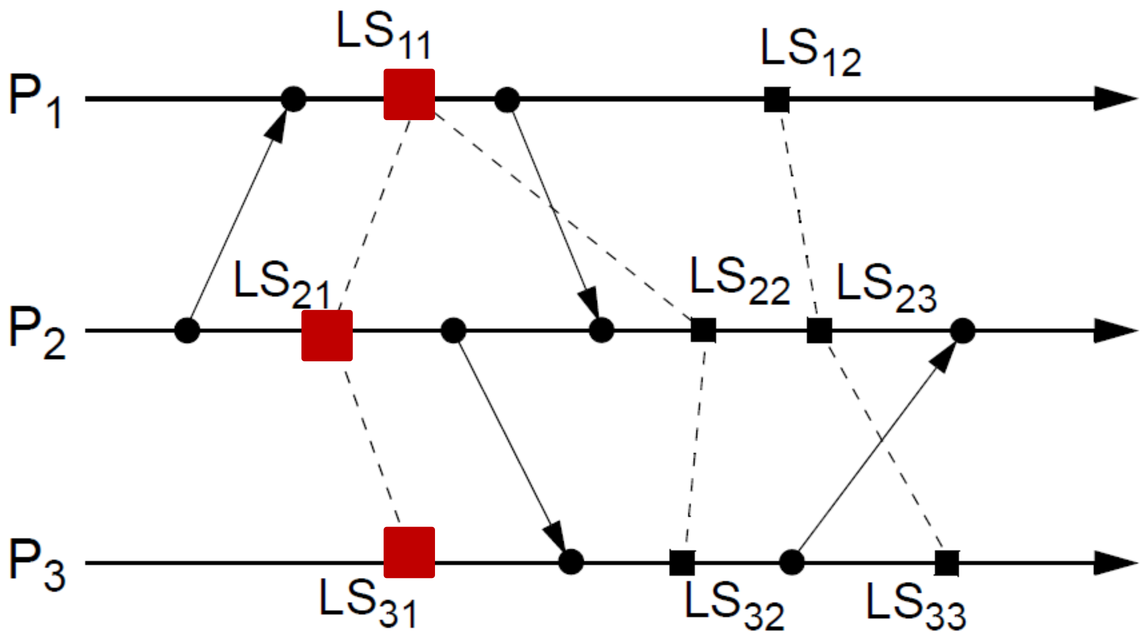
- (LS_{11}, LS_{22}, LS_{32}) is inconsistent

Example



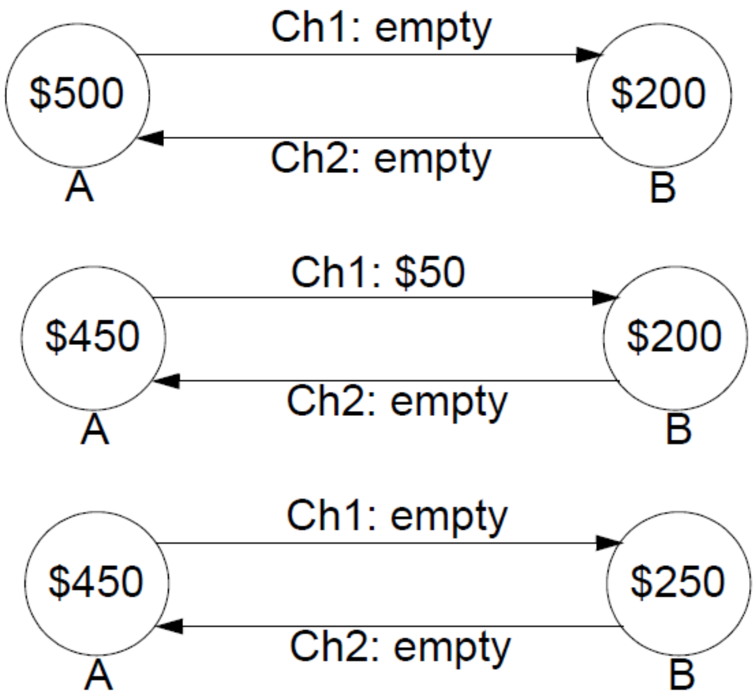
- (LS_{12}, LS_{23}, LS_{33}) is consistent

Example



- (LS_{11}, LS_{21}, LS_{31}) is strongly consistent

Example (2)



A	B	C : consistent NC: not consistent
500	200	{A,B}: strongly C
450 (mess$_1$ sent)	200	{A,B}: C
500	250 (mess$_1$ received)	{A,B}: NC
450 (mess$_1$ sent)	250 (mess$_1$ received)	{A,B}: strongly C

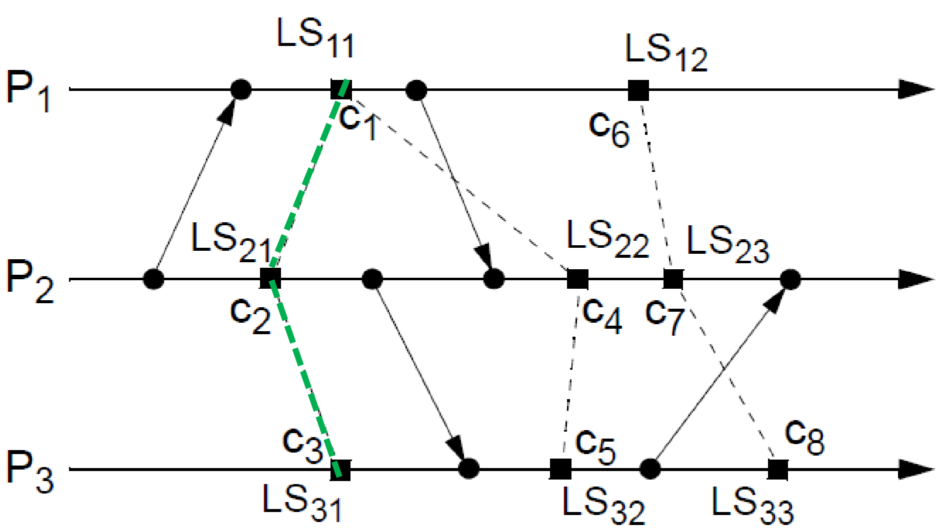
After registering of the receive event(s),
a consistent state becomes strongly consistent.

It is considered to be a normal (transient) situation.

Cuts of a Distributed Computation

- A **cut** is a graphical representation of a **global state**.
  - A consistent cut is a graphical representation of a consistent global state.
  - A **cut** of a distributed computation is a set

    $Ct = \{ c_1, c_2, ..., c_n \}$, where c_i is the *cut event* at process P_i.
  - A **cut event** is the event of recording a local state of the process.



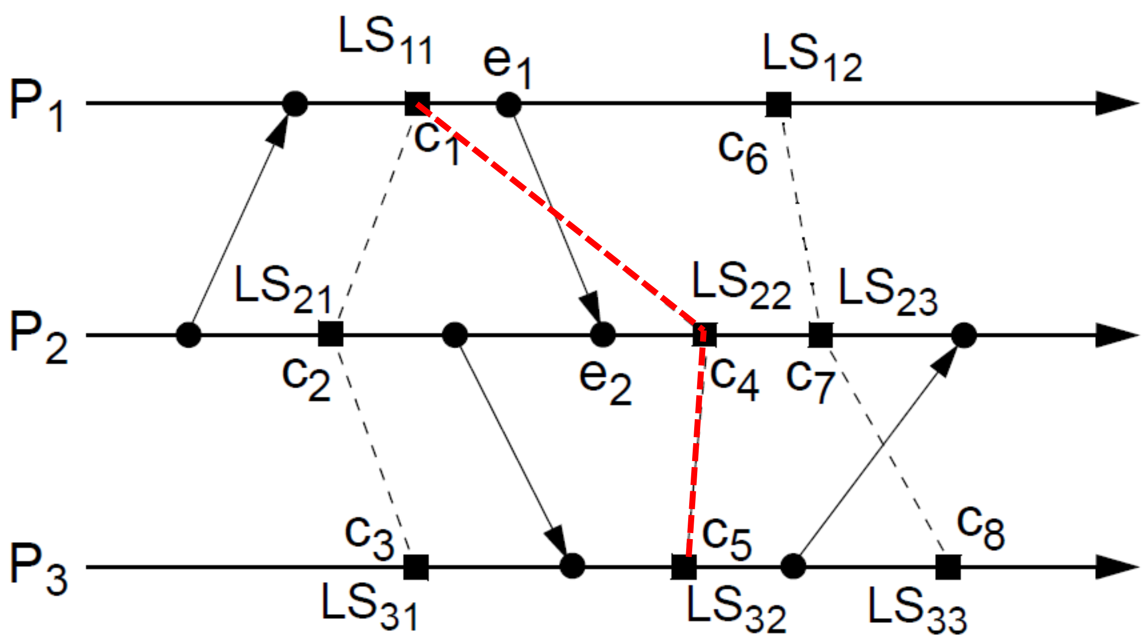
Example:
$\{ c_1, c_2, c_3 \}$ is a cut

Cuts of a Distributed Computation

- Let e_k denote an event at process P_k.
- A cut $Ct = \{ c_1, c_2, ..., c_n \}$ is a **consistent cut** if and only if

  $\forall P_i, \forall P_j$, if $\exists e_i, \exists e_j$ such that $(e_i \rightarrow e_j) \wedge (e_j \rightarrow c_j)$ then $\neg(c_i \rightarrow e_i)$

  - A cut is *consistent* if every message that was *received before* a cut event was *sent before* the cut event at the sender process.



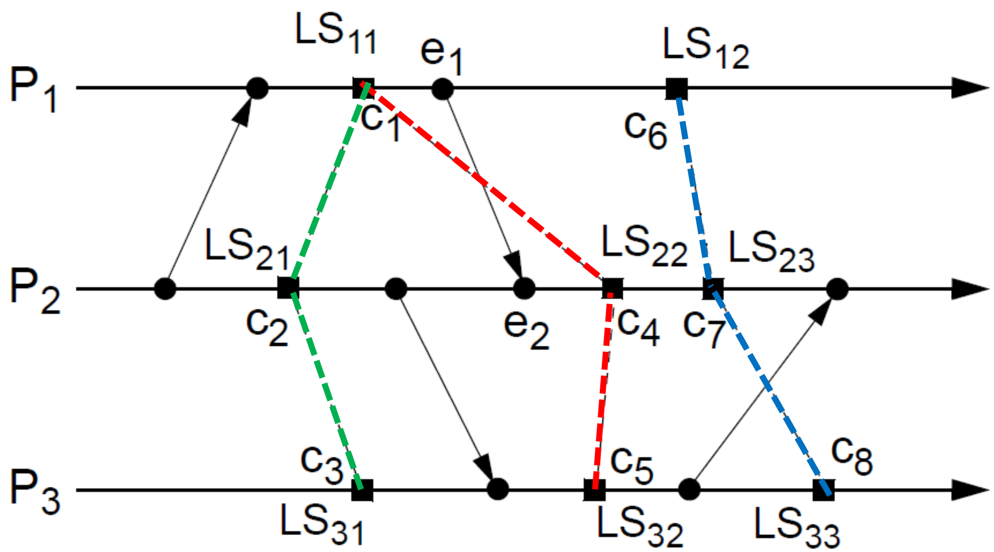
$\{ c_1, c_4, c_5 \}$ is not consistent, as $(e_1 \rightarrow e_2) \wedge (e_2 \rightarrow c_4) \wedge (c_1 \rightarrow e_1)$

Cuts of a Distributed Computation

Theorem

A cut $Ct = \{ c_1, c_2, ..., c_n \}$ **is a consistent cut**
if and only if no two cut events are causally related,
that is, $\forall c_i, \forall c_j \in Ct: \quad \neg(c_i \rightarrow c_j) \wedge \neg(c_j \rightarrow c_i)$

- **A set of concurrent cut events forms a consistent cut.**



- $\{ c_1, c_2, c_3 \}$ strongly consistent (no communication line is crossed)
- $\{ c_6, c_7, c_8 \}$ consistent (comm. line crossed, but no causal relation)
- $\{ c_1, c_4, c_5 \}$ not consistent $(c_1 \rightarrow c_4)$

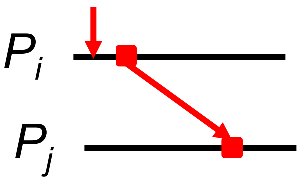
Global State Recording

(Chandy-Lamport Algorithm)

- The algorithm records:
  - a collection of local states,
    which give a consistent global state of the system, and
  - the state of the channels,
    which is consistent with the collected global state.
- Such a recorded "view" of the system is called a **snapshot**.
- We assume here that
  - processes are connected through one-directional channels and message delivery is FIFO.
  - the graph of processes and channels is strongly connected (there exists a path between any two processes).
- The algorithm is based on the use of a special message, the **snapshot token**, in order to control the state collection process.

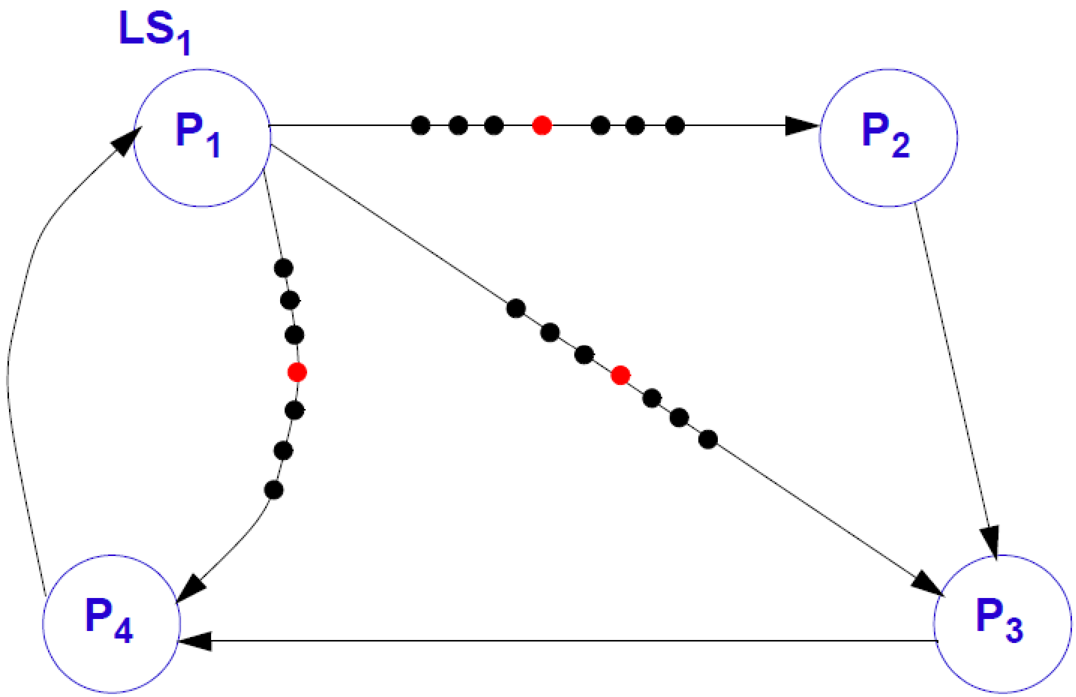
Global State Recording

How to collect a global state?



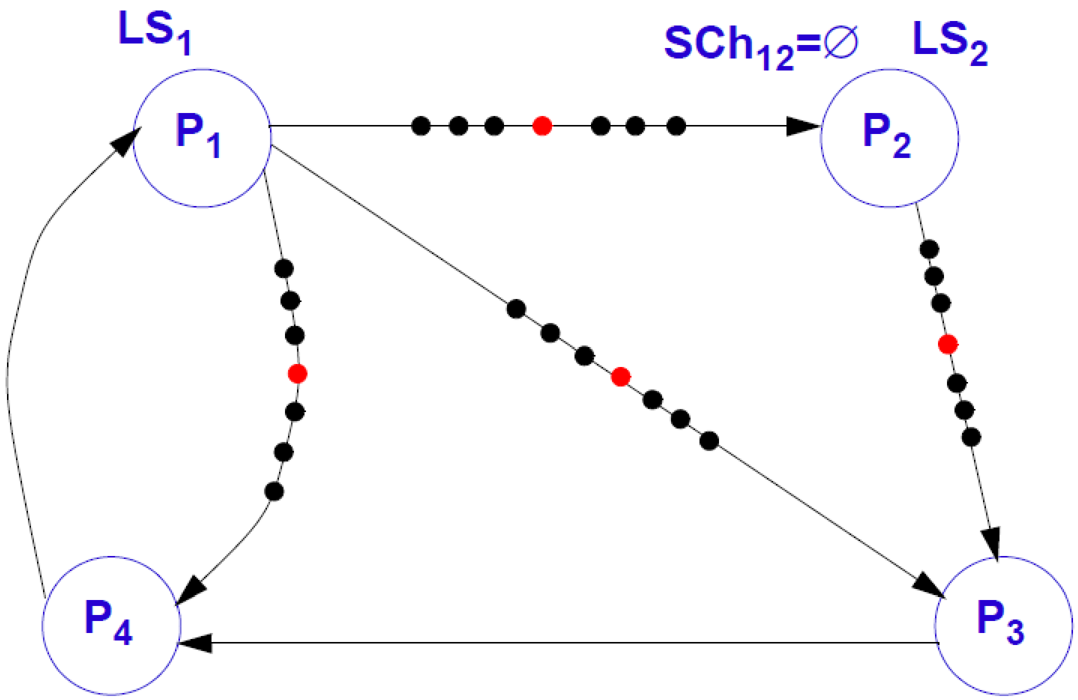
- A process P_i records its **local state** LS_i and later sends a message m to P_j
  - LS_j at P_j has to be recorded *before* P_j has received m.
- The **channel state** Sch_{ij} of the channel Ch_{ij} consists of all messages that process P_i *sent before* recording LS_i and which have not been *received* by P_j when recording LS_j.
- A **snapshot** is started at the request of a particular process P_i, for example, when P_i suspects a deadlock because of long delay in accessing a resource.
  P_i then records its state LS_i and, before sending any other message, it **sends** a **token** to every P_j that P_i communicates with.
- When P_j **receives** a **token** from P_i, and this is the first time it received a token, it must record its state before it receives the next message from P_i.
  After recording its state, P_j sends a token to every process it communicates with, before sending them any other message.

Global State Recording



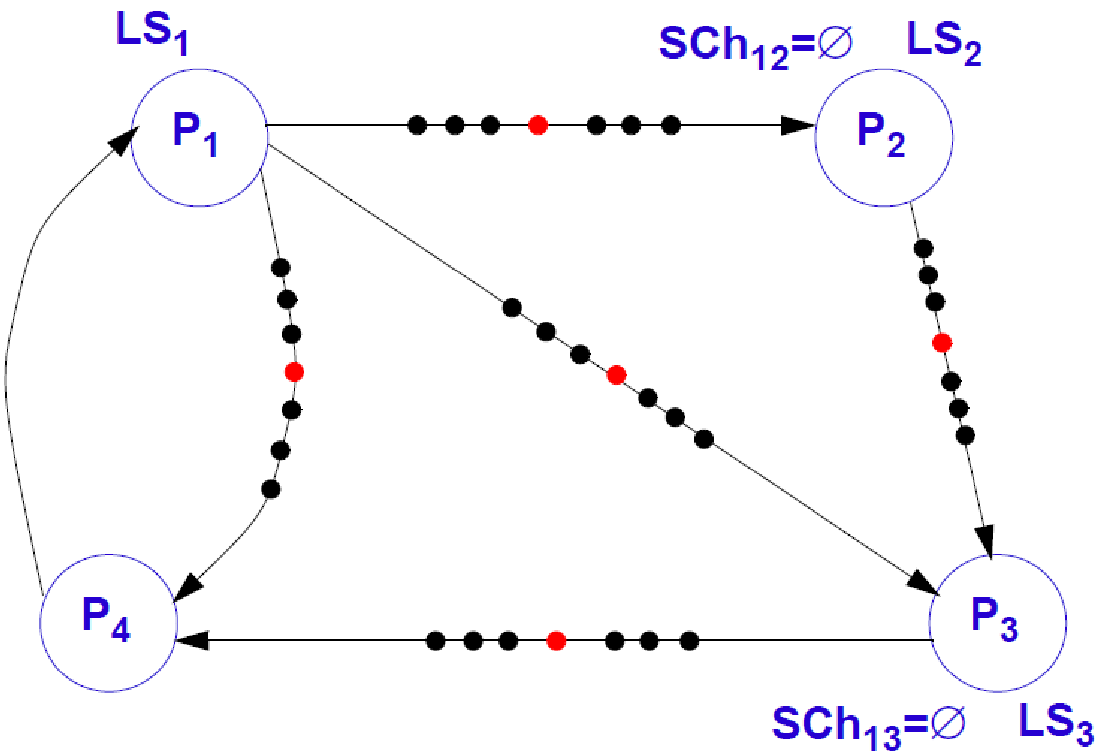
- P_1 initiates the global state recording: it saves its local state and send out the snapshot token on all its output channels.

Global State Recording



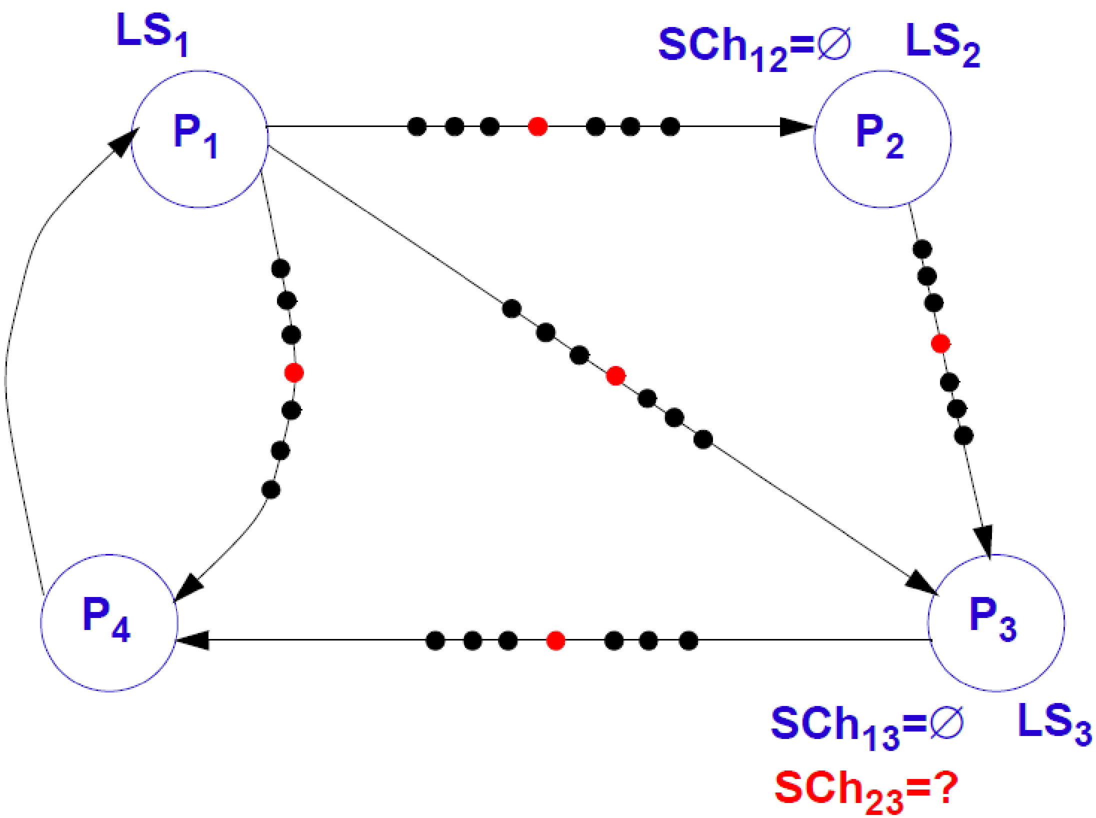
- P_2 receives the snapshot token from P_1: it saves its local state and the state of the channel $P_1 \rightarrow P_2$; It sends the snapshot token on all its output channels.

Global State Recording



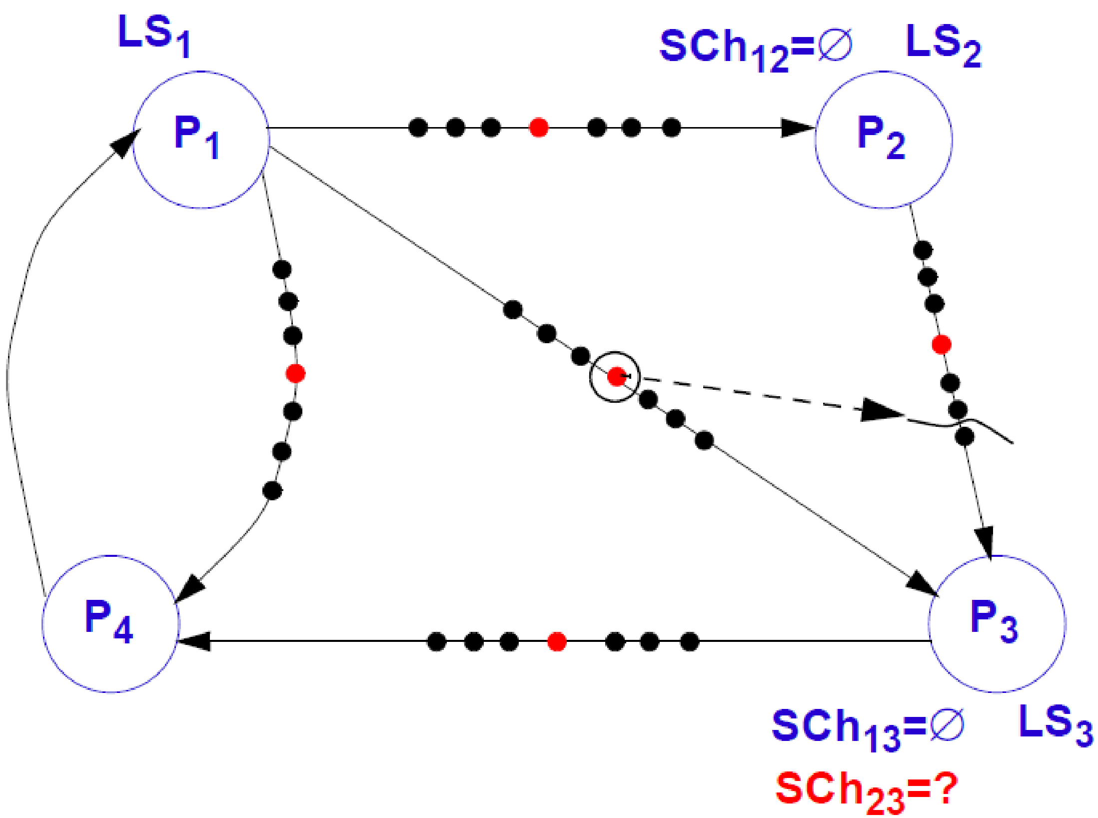
- P_3 receives the snapshot token from P_1: it saves its local state and the state of the channel $P_1 \rightarrow P_3$; It sends the snapshot token on all its output channels.

Global State Recording



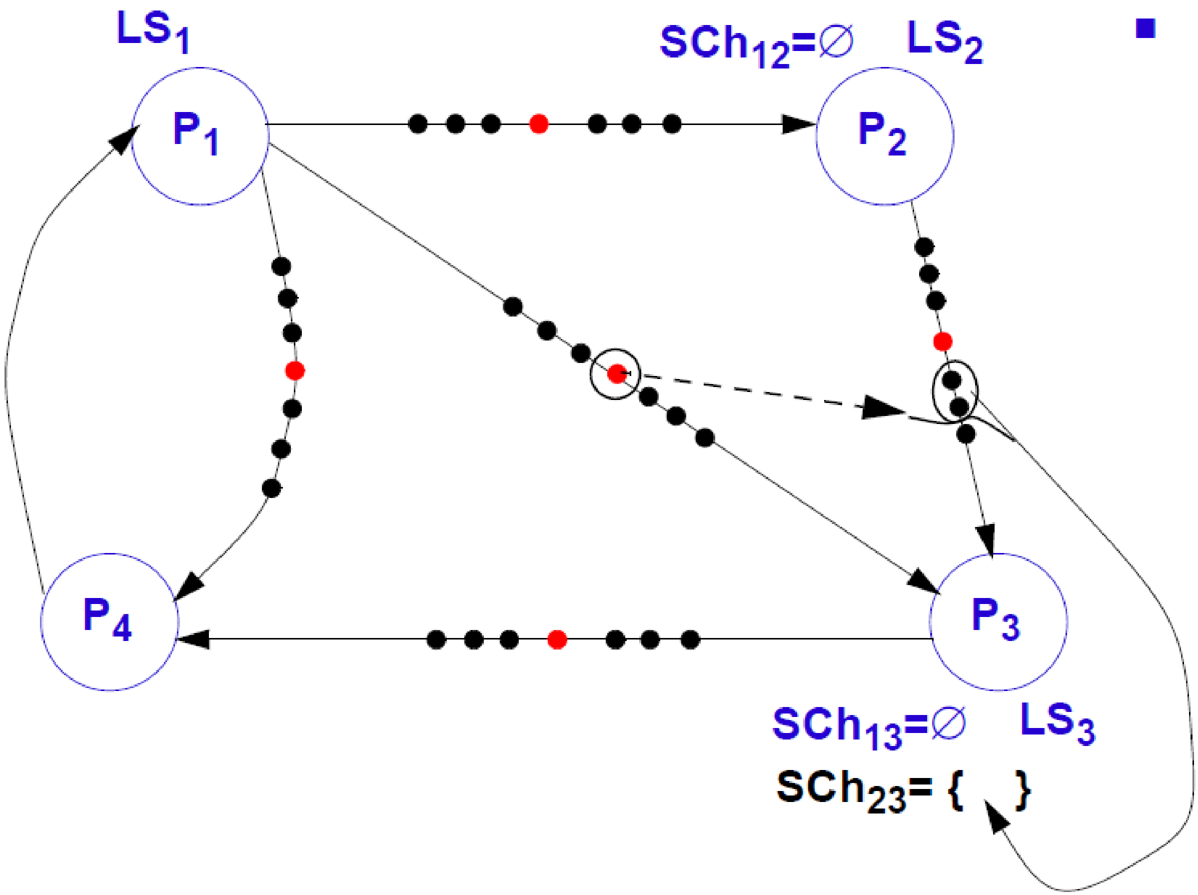
- P_3 receives the snapshot token from P_2: the local state LS_3 is already saved! It saves the state of channel $P_2 \rightarrow P_3$ so that it is consistent with states LS_2 and LS_3 (that already are saved)! (Snapshot token on its output channel is already sent!)

Global State Recording



- P_3 receives the snapshot token from P_2: the local state LS_3 is already saved! It saves the state of channel $P_2 \rightarrow P_3$ so that it is consistent with states LS_2 and LS_3 (that already are saved)! (Snapshot token on its output channel is already sent!)

Global State Recording



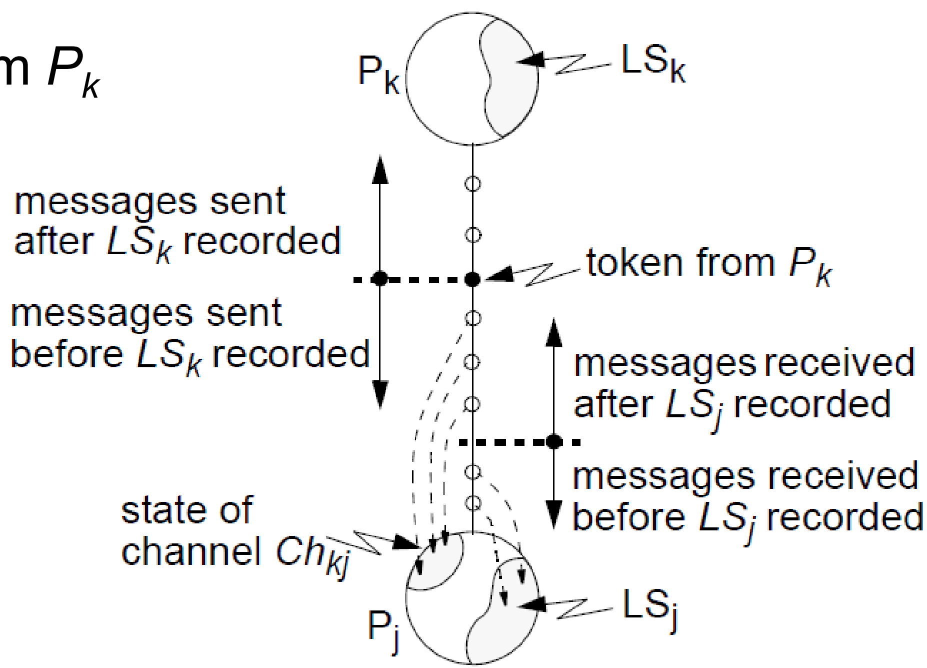
- P_3 receives the snapshot token from P_2: the local state LS_3 is already saved! It saves the state of channel $P_2 \rightarrow P_3$ so that it is consistent with states LS_2 and LS_3 (that already are saved)! (Snapshot token on its output channel is already sent!)

Global State Recording

Channel states?

- P_i sends a token to P_j and this is the first time P_j received a token
  → P_j immediately records its state.
  All messages sent by P_i *before* sending the token have been received at P_j
  → $SCh_{ij} := \emptyset$.

- P_j receives a token from P_k, but P_j already recorded its state.
  - M is the set of messages that P_j received from P_k after P_j recorded its state and before P_j received the token from P_k
    → $SCh_{kj} := M$.



- The algorithm terminates when all processes have received tokens on all their input channels.

- The process that initiated the snapshot should be informed; it can collect the global snapshot.

Global State Recording

- **Rule for sender P_i:**

  /* performed by the initiating process
  and by any other process at the reception of the first token */

  [SR1]: P_i records its state.

  [SR2]: P_i sends a token on each of its outgoing channels.

- **Rule for receiver P_j:**

  /* executed whenever P_j receives a token from another process P_i
  on channel Ch_{ij} */

  [RR1]: **if** P_j has not yet recorded its state then

  Record the state of the channel: SCh_{ij} := Ø.

  Follow the "Rule for sender".

  else

  Record the state of the channel: $SCh_{ij} := M$,
  where M is the set of messages that P_j received from P_i
  after P_j recorded its state and
  before P_j received the token on Ch_{ij}.

  end if.

Acknowledgments

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