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Chapter 3:
Distributed Systems: Synchronization

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Chapter Outline

- Clocks and time
- Global state
- Mutual exclusion
- Election algorithms

Time and Clocks

What we need?	How to solve?
Real time	Universal time (Network time)
Interval length	Computer clock
Order of events	Network time (Universal time)

NOTE: ***Time*** is ***monotonous***

Measuring Time

- Traditionally time measured astronomically
  - Transit of the sun (highest point in the sky)
  - Solar day and solar second
- Problem: Earth's rotation is slowing down
  - Days get longer and longer
  - 300 million years ago there were 400 days in the year ;-)
- Modern way to measure time is atomic clock
  - Based on transitions in Cesium-133 atom
  - Still need to correct for Earth's rotation
- Result: Universal Coordinated Time (UTC)
  - UTC available via radio signal, telephone line, satellite (GPS)

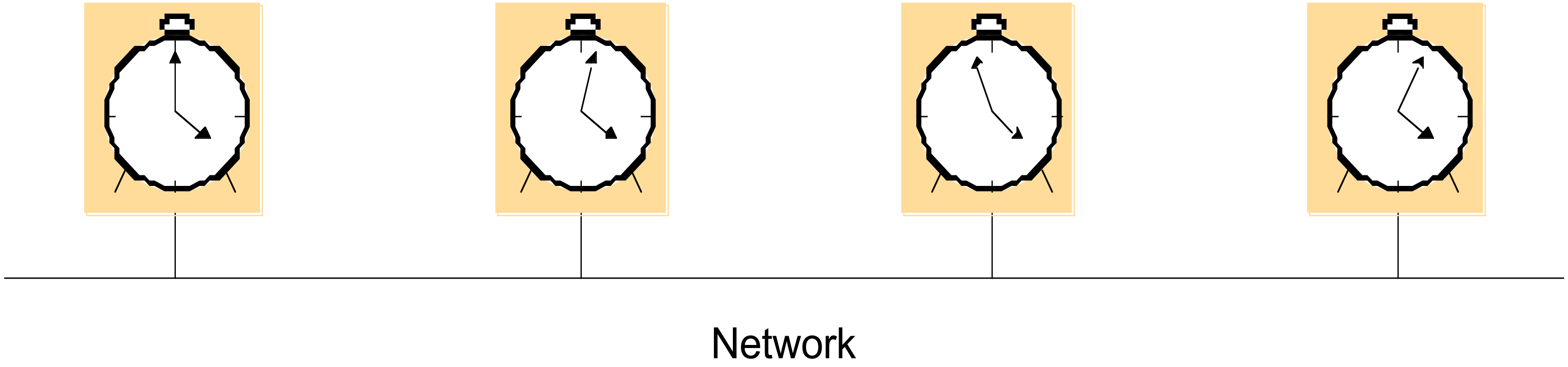
Hardware/Software Clocks

- Physical clocks in computers are realized as crystal oscillation counters at the hardware level
  - Correspond to counter register H(t)
  - Used to generate interrupts
- Usually scaled to approximate physical time t, yielding software clock C(t), $C(t) = \alpha H(t) + \beta$
  - C(t) measures time relative to some reference event, e.g., 64 bit counter for # of nanoseconds since last boot
  - Simplification: C(t) carries an approximation of real time
  - Ideally, C(t) = t (never 100% achieved)
  - Note: Values given by two consecutive clock queries will differ only if clock resolution is sufficiently smaller than processor cycle time

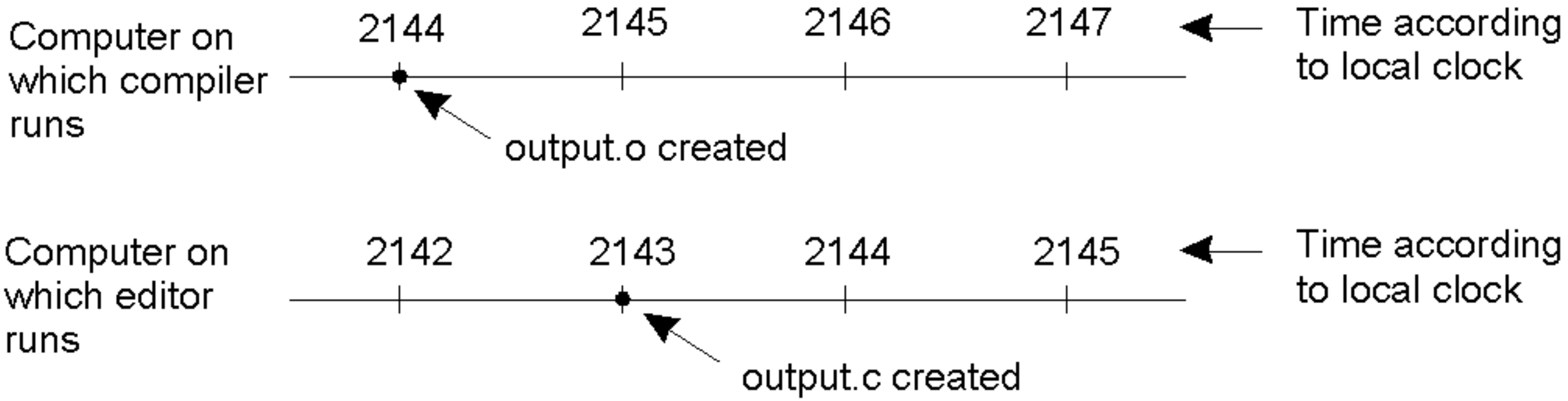
Problems with Hardware/Software Clocks

- Skew: Disagreement in the reading of two clocks
- Drift: Difference in the rate at which two clocks count the time
  - Due to physical differences in crystals, plus heat, humidity, voltage, etc.
  - Accumulated drift can lead to significant skew
- Clock drift rate: Difference in precision between a prefect reference clock and a physical clock,
  - Usually, 10^{-6} sec/sec, 10^{-7} to 10^{-8} for high precision clocks

Skew between computer clocks in a distributed system

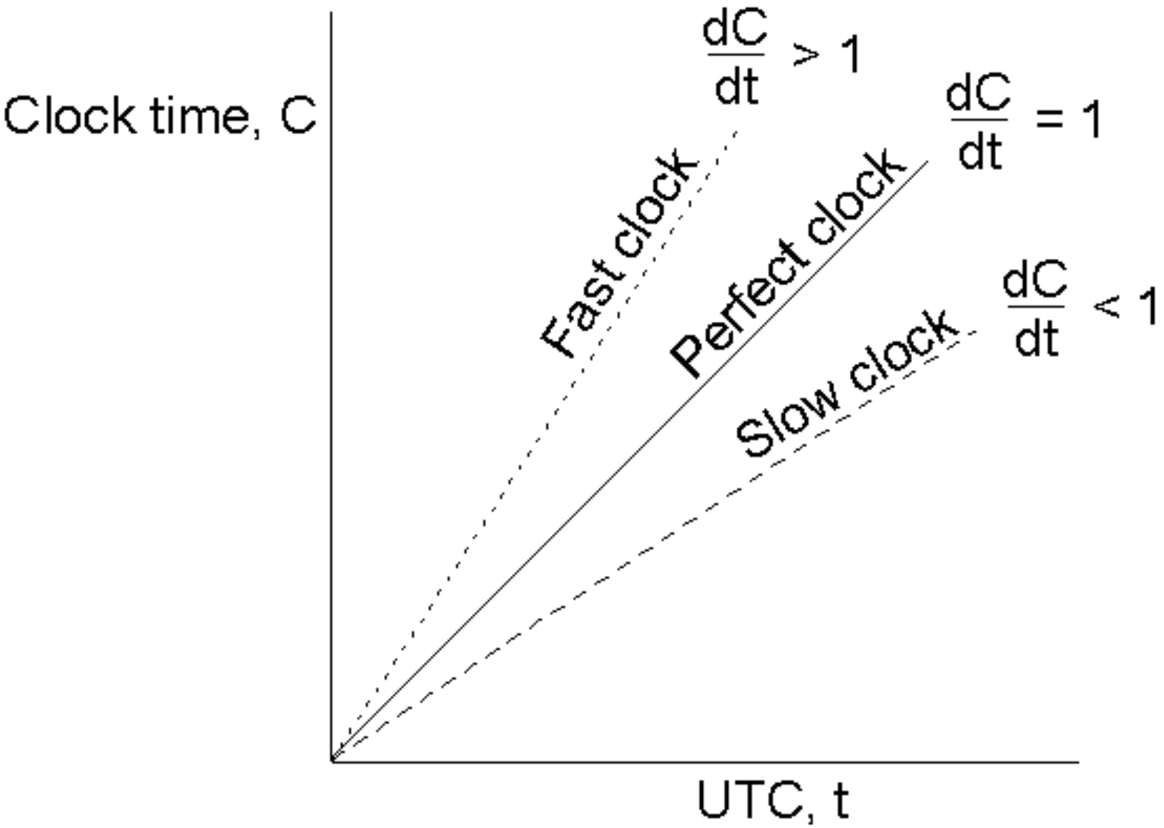


Clock Synchronization



When each machine has its own clock, an event that occurred after another event may nevertheless be assigned an earlier time.

Clock Synchronization Problem



drift rate: 10^{-6}

1 ms ~ 17 min

1 s ~ 11.6 days

UTC: coordinated universal time

accuracy:
radio 0.1 – 10 ms,
GPS 1 us

The relation between clock time and UTC when clocks tick at different rates.

Synchronizing Clocks

- External synchronization
  - Synchronize process's clock with an authoritative external reference clock $S(t)$ by limiting skew to a delay bound $D > 0$
    - $|S(t) - C_i(t)| < D$ for all t
  - For example, synchronization with a UTC source
- Internal synchronization
  - Synchronize the local clocks within a distributed system to disagree by not more than a delay bound $D > 0$, without necessarily achieving external synchronization
    - $|C_i(t) - C_j(t)| < D$ for all i, j, t
- Obviously:
  - For a system with external synchronization bound of D, the internal synchronization is bounded by 2D

Clock Correctness

- When is a clock correct?

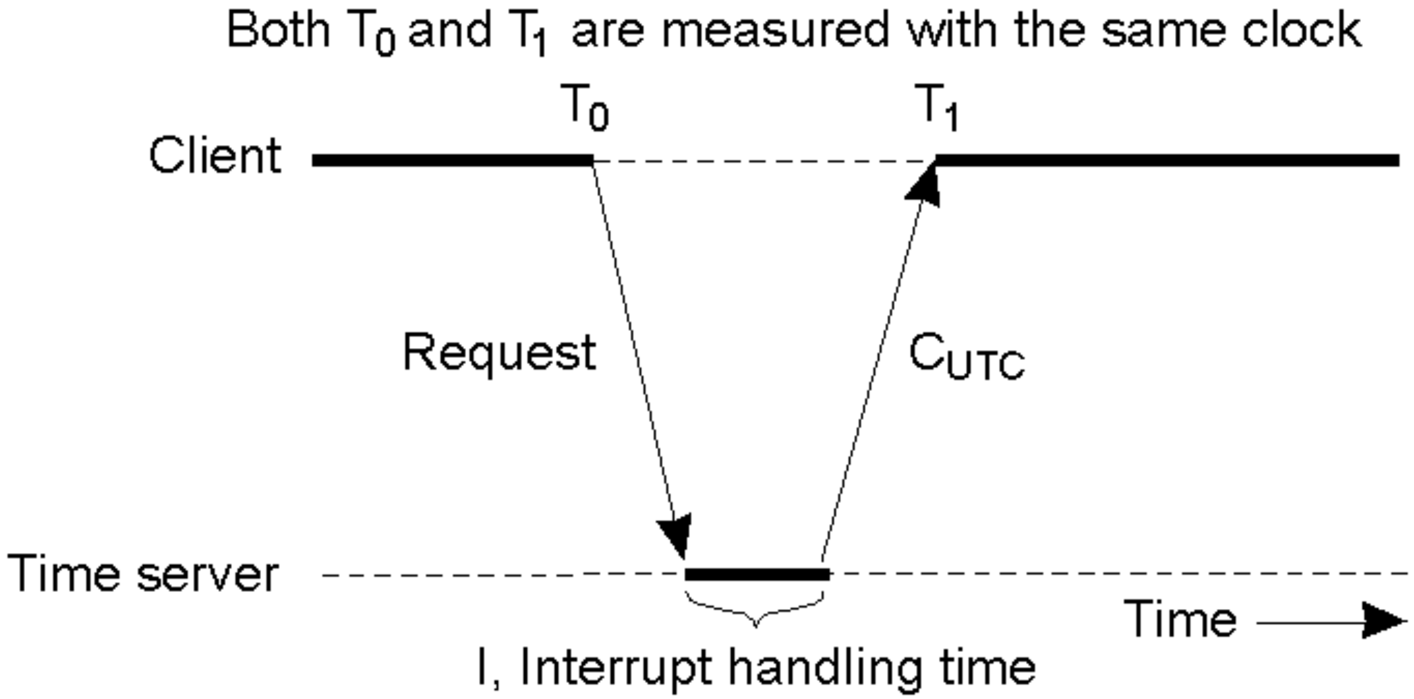
1. If drift rate falls within a bound $r > 0$, then for any t and t' with $t' > t$ the following error bound in measuring t and t' holds:
   - $(1-r)(t'-t) \leq H(t') - H(t) \leq (1+r)(t'-t)$
   - Consequence: No jumps in hardware clocks allowed
2. Sometimes monotonically increasing clock is enough:
   - $t' > t \Rightarrow C(t') > C(t)$
3. Frequently used condition:
   - Monotonically increasing
   - Drift rate bounded between synchronization points
   - Clock may jump ahead at synchronization points

Synchronization of Clocks: Software-Based Solutions

- Techniques:
  - time stamps of real-time clocks
  - message passing
  - round-trip time (local measurement)
- Cristian’s algorithm
- Berkeley algorithm
- Network time protocol (Internet)

Christian’s Algorithm

- Observations
  - Round trip times between processes are often reasonably short in practice, yet theoretically unbounded
  - Practical estimate possible if round-trip times are sufficiently short in comparison to required accuracy
- Principle
  - Use UTC-synchronized time server S
  - Process P sends requests to S
  - Measures round-trip time T_{round}
    - In LAN, T_{round} should be around 1-10 ms
    - During this time, a clock with a 10^{-6} sec/sec drift rate varies by at most 10^{-8} sec
    - Hence the estimate of T_{round} is reasonably accurate
  - Naive estimate: Set clock to $t + \frac{1}{2}T_{round}$



Current time from a time server: UTC from radio/satellite etc
Problems:
- time must never run backward
- variable delays in message passing / delivery

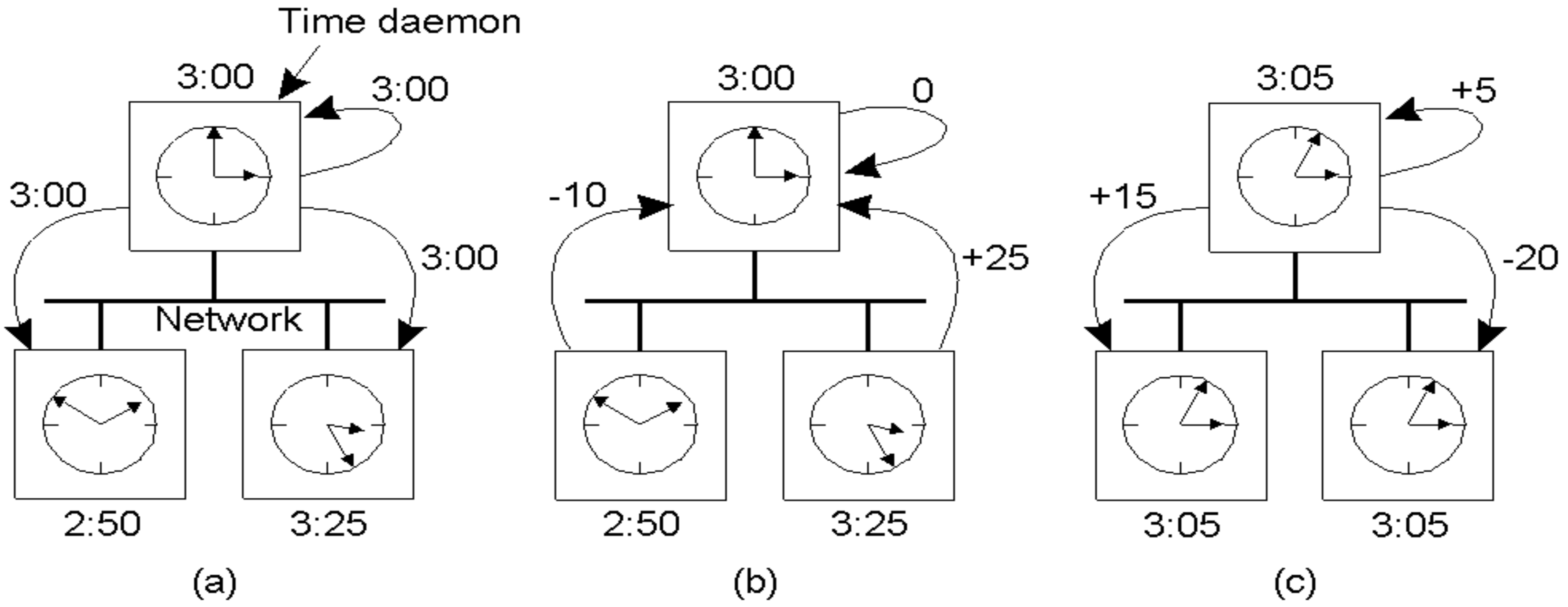
Christian’s Algorithm: Analysis

- Accuracy of estimate?
- Assumptions:
  - requests and replies via same net
  - *min* delay is either known or can be estimated conservatively
- Calculation:
  - Earliest time that S can have sent reply: $t_0 + min$
  - Latest time that S can have sent reply: $t_0 + T_{round} – min$
  - Total time range for answer: $T_{round} - 2 * min$
  - Accuracy is $\pm (½T_{round} - min)$
- Discussion
  - Really only suitable for LAN environment or Intranet
  - Problem of failure of S

Alternative Algorithm

- Berkeley algorithm (Gusella&Zatti ‘89)
  - No external synchronization, but one master server
  - Master polls slaves periodically about their clock readings
  - Estimate of local clock times using round trip estimation
  - Averages the values obtained from a group of processes
    - Cancels out individual clock’s tendencies to run fast
  - Tells slave processes by which amount of time to adjust local clock
  - Master failure: Master election algorithm (see later)
- Experiment
  - 15 computers, local drift rate $< 2x10^{-5}$, max round-trip 10 ms
  - Clocks were synchronized to within 20-25 ms
- Note: Neither algorithm is really suitable for Internet

The Berkeley Algorithm



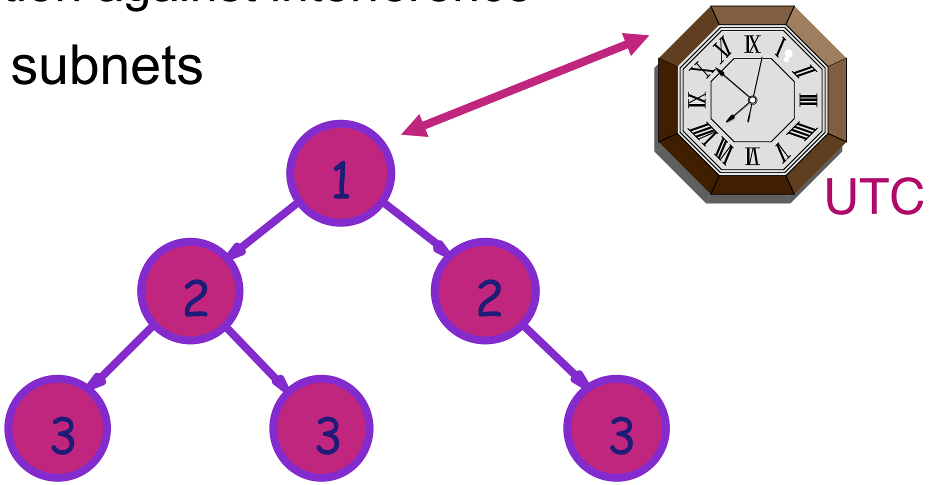
a) The **time daemon asks** all the other machines for their clock values

b) The machines answer

c) The time daemon tells everyone how to adjust their clock

Clock Synchronization: NTP

- Goals
  - ability to externally synchronize clients via Internet to UTC
  - provide reliable service tolerating lengthy losses of connectivity
  - enable clients to resynchronize sufficiently frequently to offset typical HW drift rates
  - provide protection against interference
- Synchronization subnets



strata 1

strata 2

strata 3
(user workstations)

NTP Basic Idea

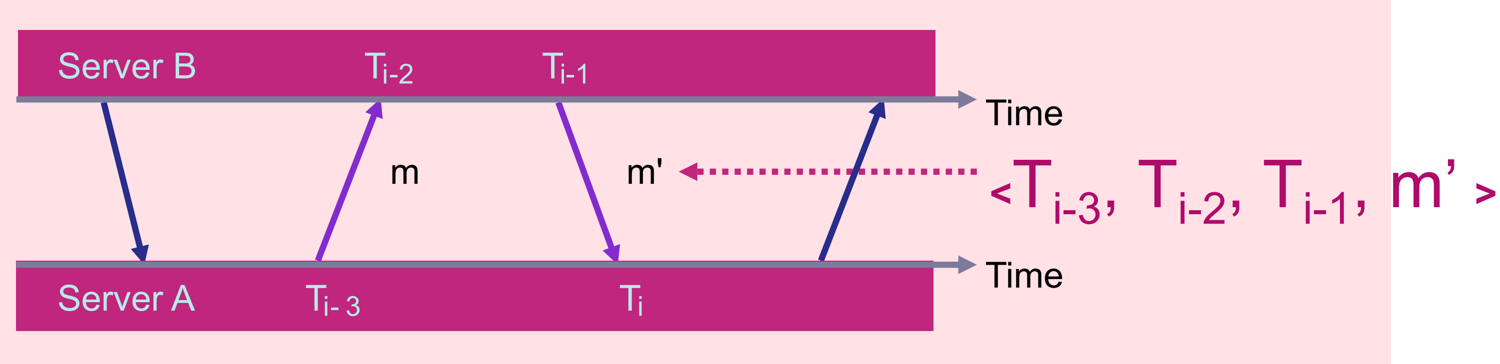
- Layered client-server architecture, based on UDP message passing
- Synchronization at clients with higher strata number less accurate due to increased latency to strata 1 time server
- Failure robustness: if a strata 1 server fails, it may become a strata 2 server that is being synchronized though another strata 1 server

NTP Modes

- Multicast:
  - One computer periodically multicasts time info to all other computers on network
  - These adjust clock assuming a very small transmission delay
  - Only suitable for high speed LANs; yields low but usually acceptable sync.
- Procedure-call: similar to Christian's protocol
  - Server accepts requests from clients
  - Applicable where higher accuracy is needed, or where multicast is not supported by the network's hard- and software
- Symmetric:
  - Used where high accuracy is needed

Procedure-Call and Symmetric Modes

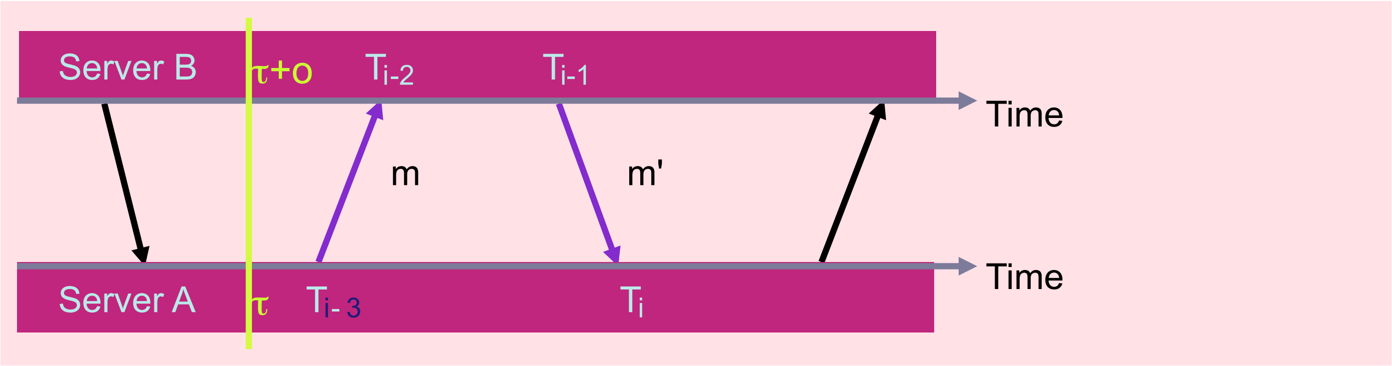
- All messages carry timing history information
  - local timestamps of send and receive of the previous NTP message
  - local timestamp of send of this message



- For each pair i of messages (m, m’) exchanged between two servers the following values are being computed

  (based on 3 values carried w/ msg and 4th value obtained via local timestamp):
  - offset o_i: estimate for the actual offset between two clocks
  - delay d_i: true total transmission time for the pair of messages

NTP: Delay and Offset



- Let o the true offset of B’s clock relative to A’s clock, and let t and t’ the true transmission times of m and m’ (T_i, T_{i-1} ... are not true time)
- Delay

  $T_{i-2} = T_{i-3} + t + o$ (1) and $T_i = T_{i-1} + t' - o$ (2) which leads to

  $d_i = t + t' = T_{i-2} - T_{i-3} + T_i - T_{i-1}$ (clock errors zeroed out → (almost) true d)
- Offset

  $o_i = ½ (T_{i-2} – T_{i-3} + T_{i-1} – T_i)$ (only an estimate)

NTP Implementation

- Statistical algorithms based on 8 most recent <o_i, d_i> pairs: → determine quality of estimates
- The value of o_i that corresponds to the minimum d_i is chosen as an estimate for o
- Time server communicates with multiple peers, eliminates peers with unreliable data, favors peers with higher strata number (e.g., for primary synchronization partner selection)
- NTP phase lock loop model: modify local clock in accordance with observed drift rate
- Experiments achieve synchronization accuracies of 10 msecs over Internet, and 1 msec on LAN using NTP

Clocks and Synchronization

Requirements:

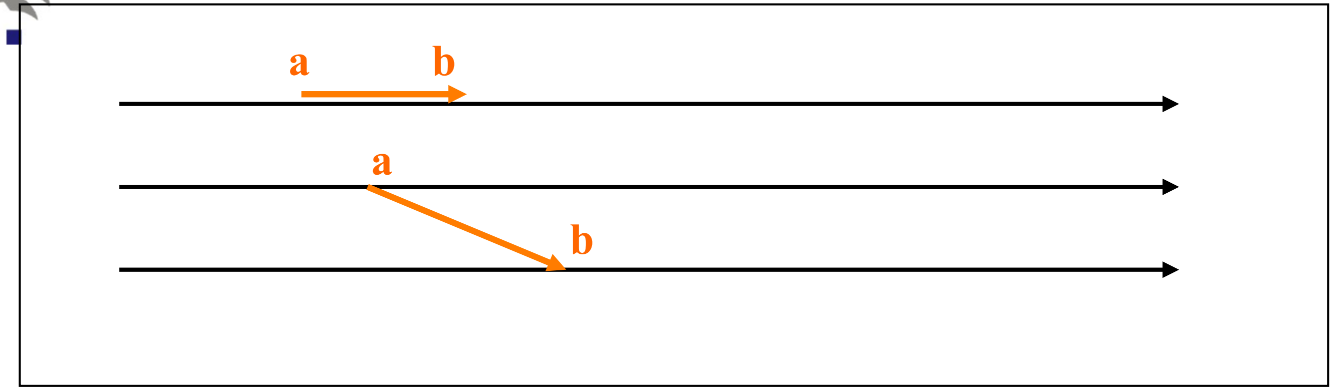
- ”*causality*”: real-time order ~ timestamp order (”behavioral correctness” – seen by the user)
- *groups* / *replicates*: all members see the events in the same order
- ”*multiple-copy-updates*”: order of updates, consistency conflicts?
- *serializability of transactions*: bases on a common understanding of transaction order

A perfect physical clock is sufficient!

A perfect physical clock is impossible to implement!

Above requirements met with much lighter solutions!

Happened-Before Relation ”a -> b”



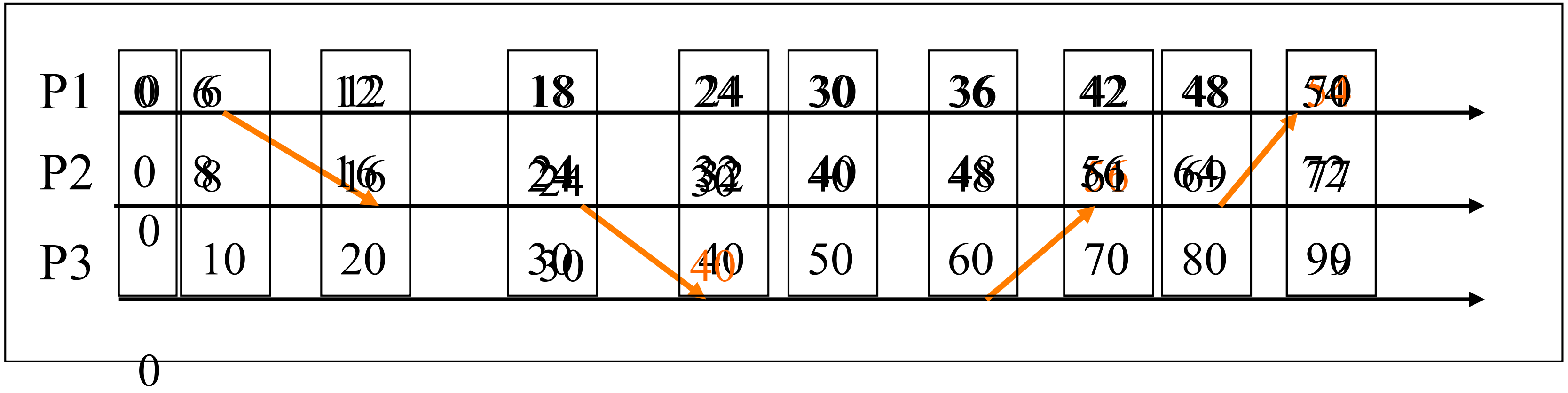
- if a, b are *events in the same process*, and a occurs before b, then a -> b

- if a is the event of a *message being sent*, and b is the event of the *message being received*, then a -> b

- a || b if neither a -> b nor b -> a (a and b are *concurrent*)

Note: if a -> b and b -> c then a -> c

Logical Clocks: Lamport Timestamps



process p_i , event e , clock L_i , timestamp $L_i(e)$

- ***at*** ***p_i*** : before each event $L_i = L_i + 1$
- when p_i sends a ***message*** m to p_j

1. p_i: ($L_i = L_i + 1$); $t = L_i$; message = (m, t) ;
2. p_j: $L_j = \max(L_j, t)$; $L_j = L_j + 1$;
3. L_j(receive event) = L_j ;

Lamport Clocks: Problems

1. Timestamps do not specify the order of events
   - e -> e' => L(e) < L(e')

   BUT

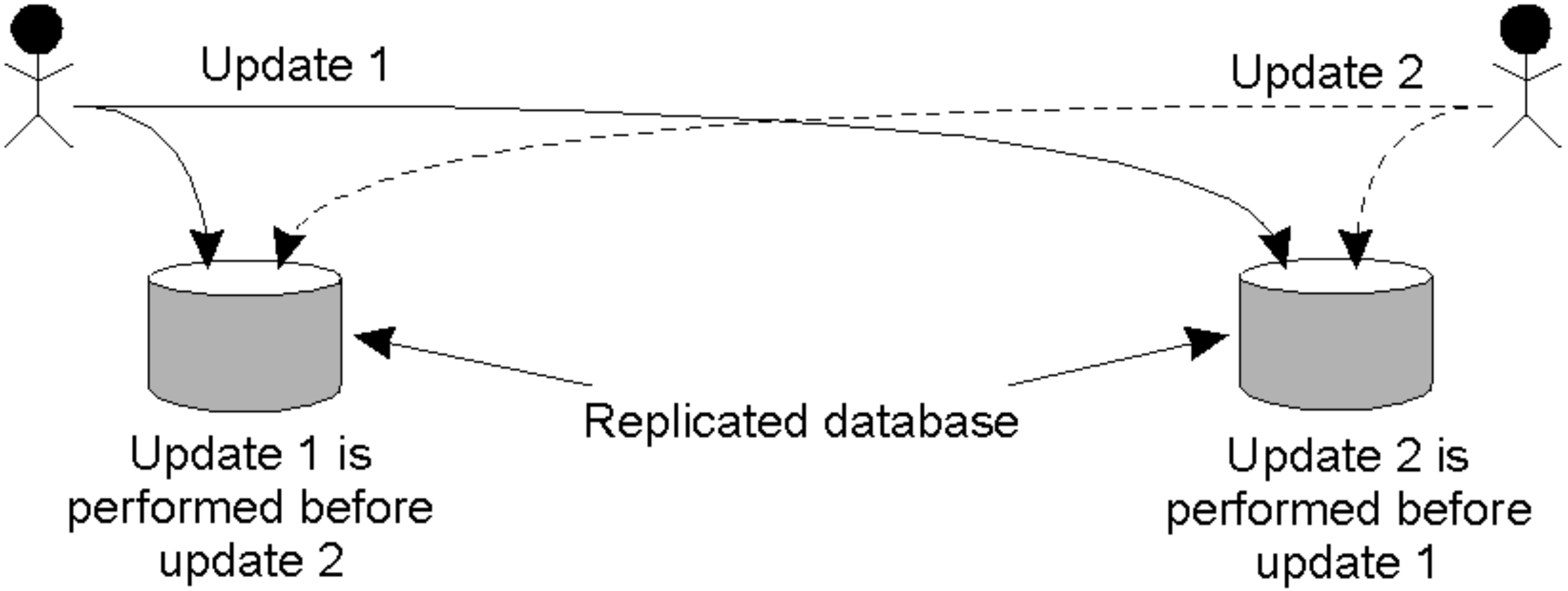
   - L(e) < L(e') does not imply that e -> e'
2. Total ordering
   - problem: define order of e, e' when L(e) = L(e')
   - solution: extended timestamp (T_i, i), where T_i is $L_i(e)$
   - definition: $(T_i, i) < (T_j, j)$

     if and only if

     either $T_i < T_j$

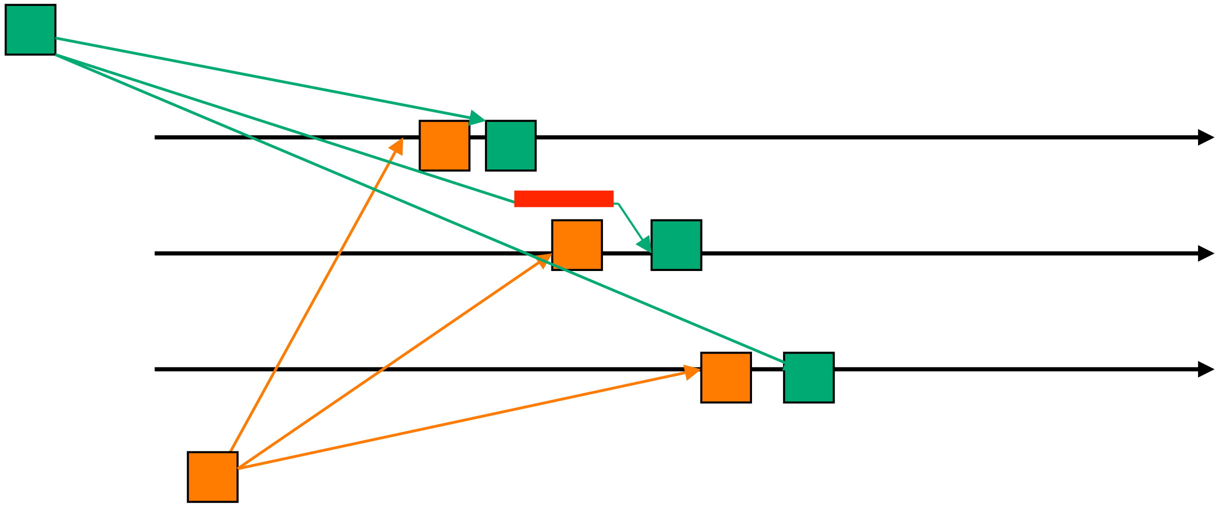
     or $T_i = T_j$ and $i < j$

Example: Totally-Ordered Multicasting (1)



Updating a replicated database and leaving it in an inconsistent state.

Example: Totally-Ordered Multicasting (2)



Total ordering:
all receivers (applications) see all messages in the same order (which is not necessarily the original sending order)

Example: multicast operations, group-update operations

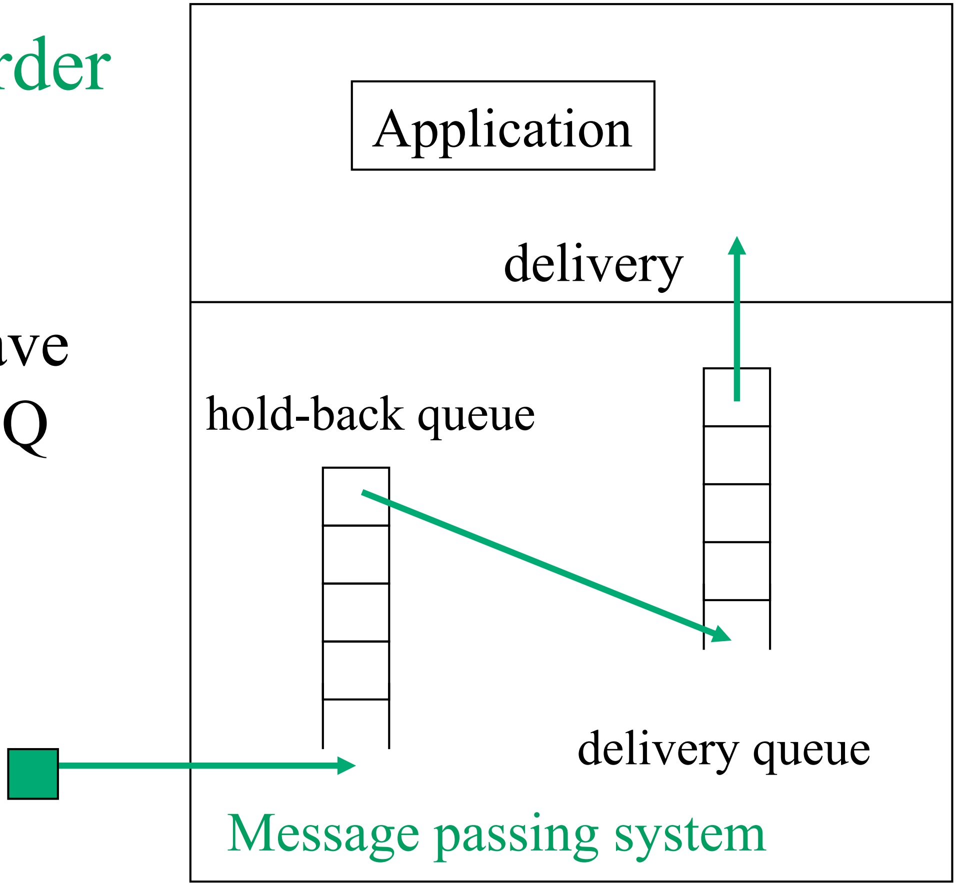
Example: Totally-Ordered Multicasting (3)

Guaranteed delivery order

- *new* message => HBQ

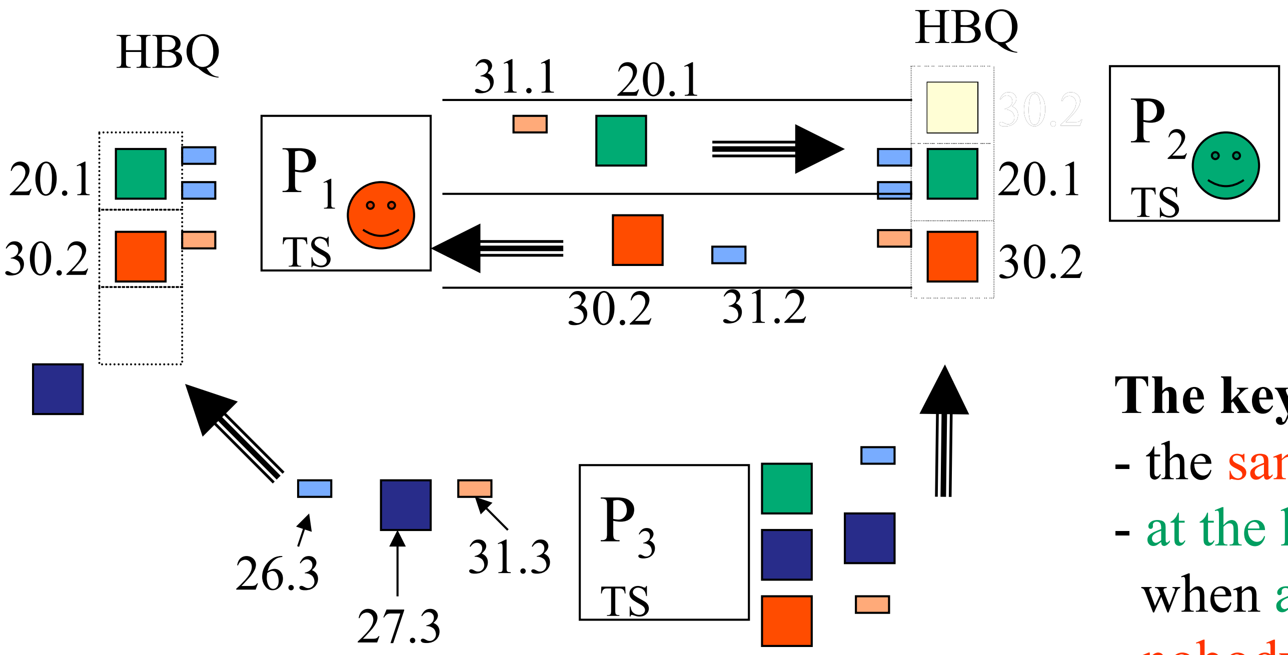
- when *all predecessors* have arrived: message => DQ

- when *at the head of DQ*: message => application (application: *receive* …)



Algorithms:
see. Defago et al ACM CS, Dec. 2004

Example: Totally-Ordered Multicasting (4)



Original timestamps

P_1 19
P_2 29
P_3 25

The key idea

- the same order in all queues
- at the head of HBQ:
  when all ack's have arrived
  nobody can pass you

Multicast:

- everybody receives the message (incl. the sender!)
- messages from one sender are received in the sending order
- no messages are lost

Various Orderings

- Total ordering
- Causal ordering
- FIFO (First In First Out)

(wrt an individual communication channel)

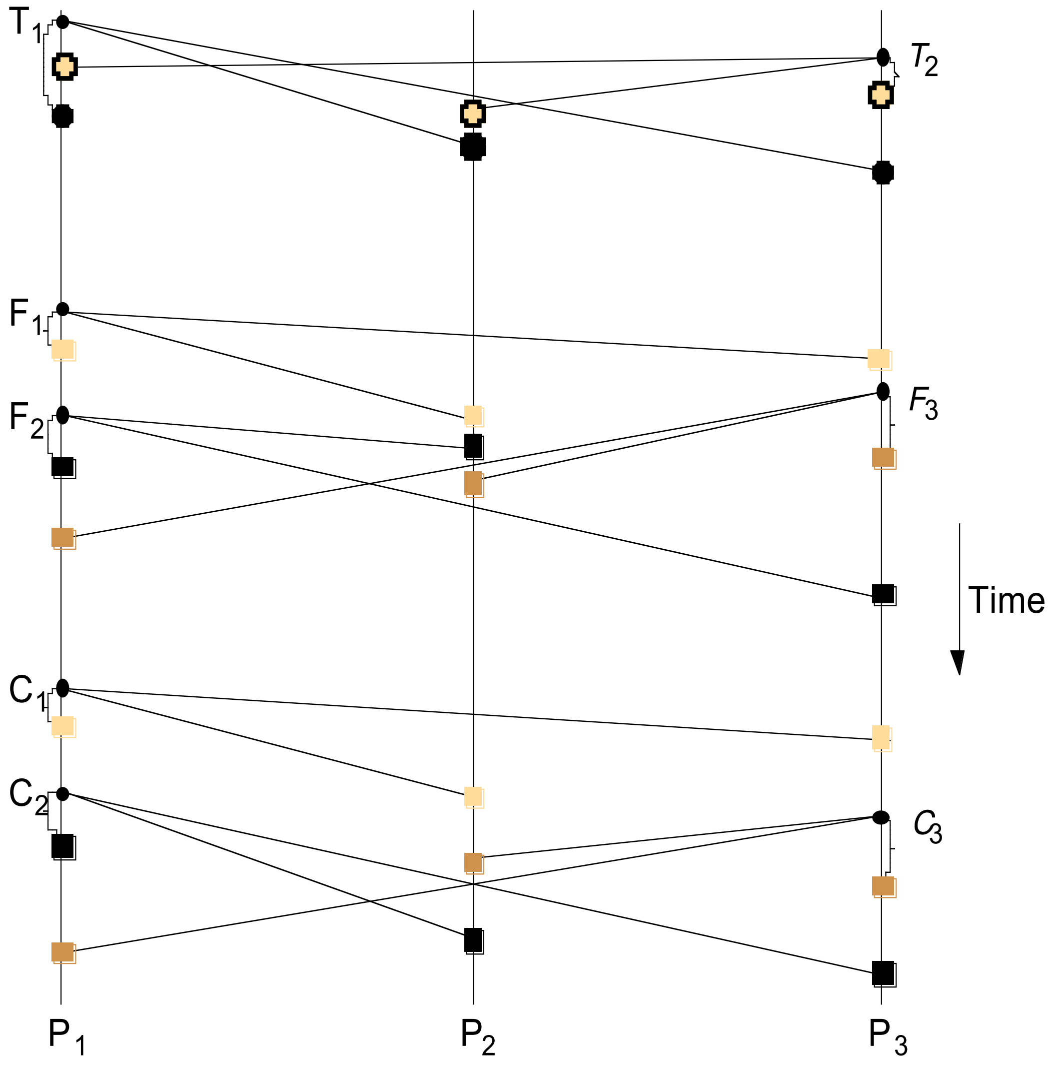
Total and causal ordering are independent:

neither induces the other;

Causal ordering induces FIFO

Total, FIFO and Causal Ordering of Multicast Messages

Notice the consistent ordering of totally ordered messages T_1 and T_2, the FIFO-related messages F_1 and F_2 and the causally related messages C_1 and C_3 – and the otherwise arbitrary delivery ordering of messages.



Vector Timestamps

Goal:

timestamps should reflect *causal ordering*

L(e) < L(e’) => “ e happened before e’ “

=>

Vector clock

each process P_i maintains a vector V_i :

1. $V_i[i]$ is the number of events that have occurred at P_i

   (the current local time at P_i)

2. if $V_i[j] = k$ then P_i knows about (the first) k events that have occurred at P_j

   (the local time at P_j was k, as P_j sent the last message that P_i has received from it)

Order of Vector Timestamps

Order of timestamps

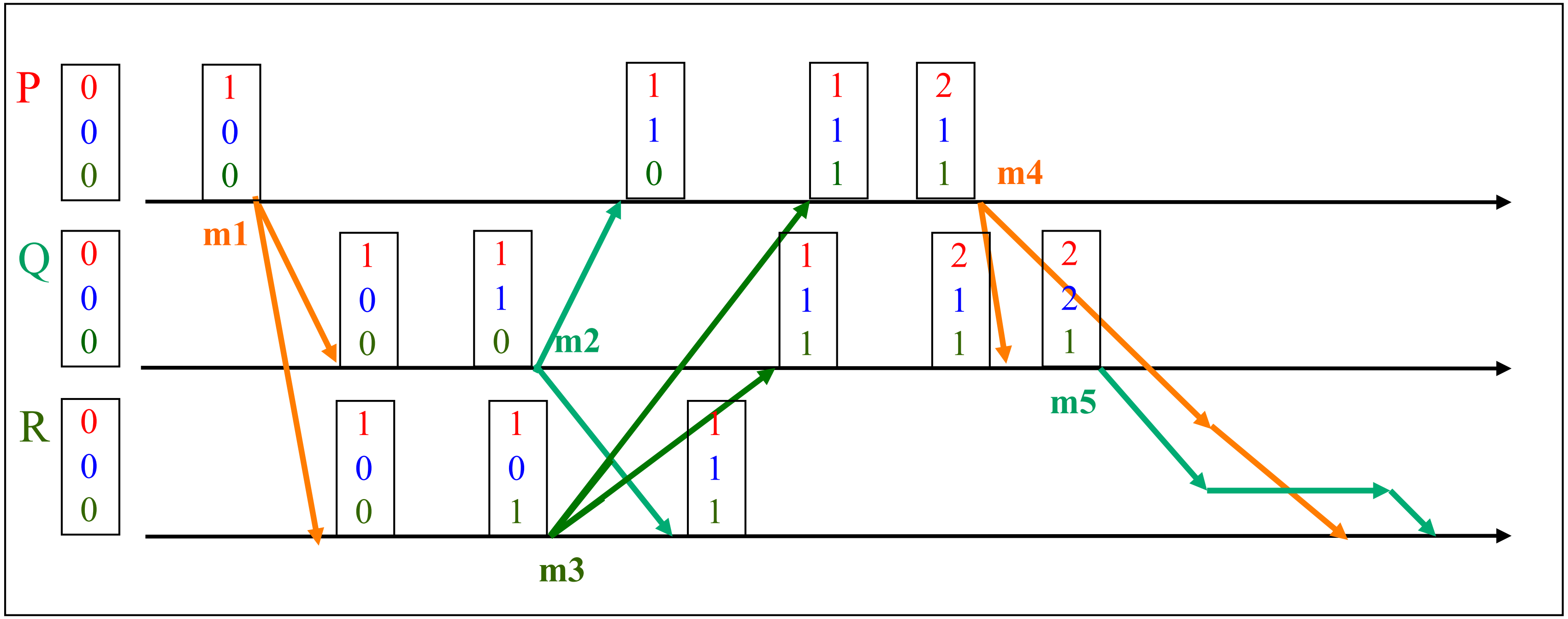
- $V = V'$ iff $V[j] = V'[j]$ for all j
- $V \le V'$ iff $V[j] \le V'[j]$ for all j
- $V < V'$ iff $V \le V'$ and $V \ne V'$

Order of events *(causal order)*

- $e \to e'$ => $V(e) < V(e')$
- $V(e) < V(e')$ => $e \to e'$
- concurrency:

e || e' if **not** $V(e) \le V(e')$
and **not** $V(e') \le V(e)$

Causal Ordering of Multicasts (1)



Event:
message sent

Timestamp [i,j,k] :

i messages sent from P

j messages sent form Q

k messages sent from R

R:	m1 [100]	m4 [211]
	m2 [110]	m5 [221]
	m3 [101]	

m4 [211] vs. 111

m5 [221] vs. 111

Causal Ordering of Multicasts (2)

Use of timestamps in causal multicasting

1) P_s multicast: $V_s[s] = V_s[s] + 1$

2) Message: include $vt = V_s[*]$

3) Each receiving P_r : the message **can be delivered when**

- **$vt[s] = V_r[s] + 1$** *(all previous messages from P_s have arrived)*
- for each component **k ($k \neq s$): $V_r[k] \geq vt[k]$**

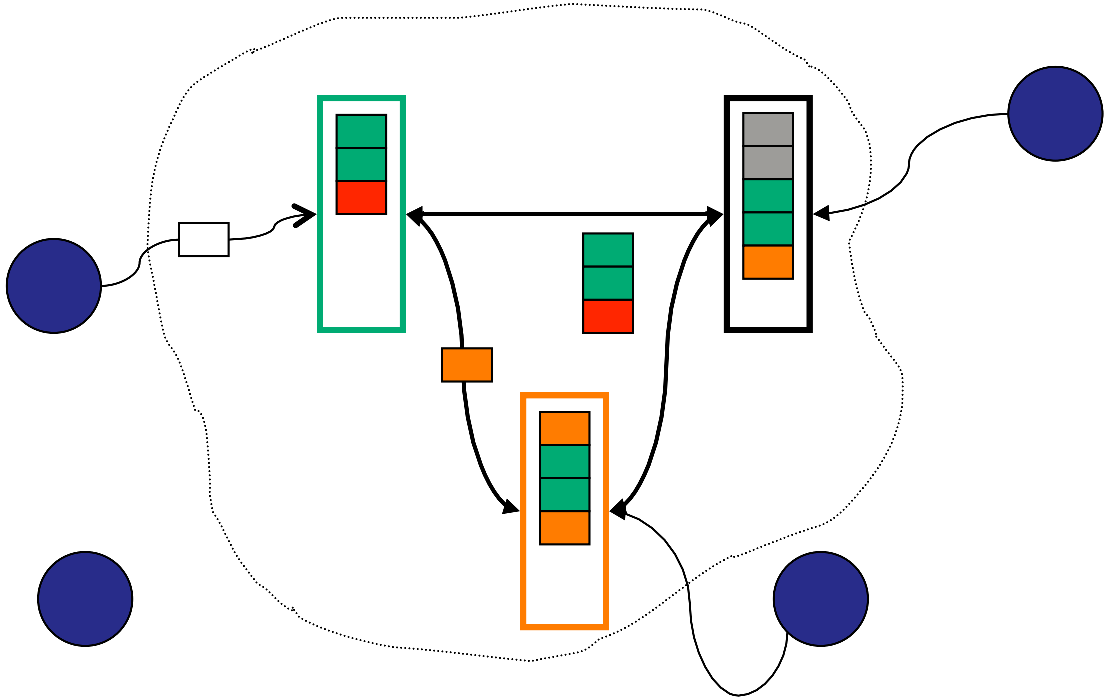
  (P_r has now seen all the messages that P_i had seen when the message was sent)

4) When the message from P_s becomes deliverable at P_r the message is inserted into the delivery queue

(note: the delivery queue preserves causal ordering)

5) **At delivery**: $V_r[s] = V_r[s] + 1$

Causal Ordering of a Bulletin Board (1)



User ⇔ BB *(“local events”)*

- read: bb <= BB_i (any BB)
- write: to a BB_j that contains all causal predecessors of all bb messages

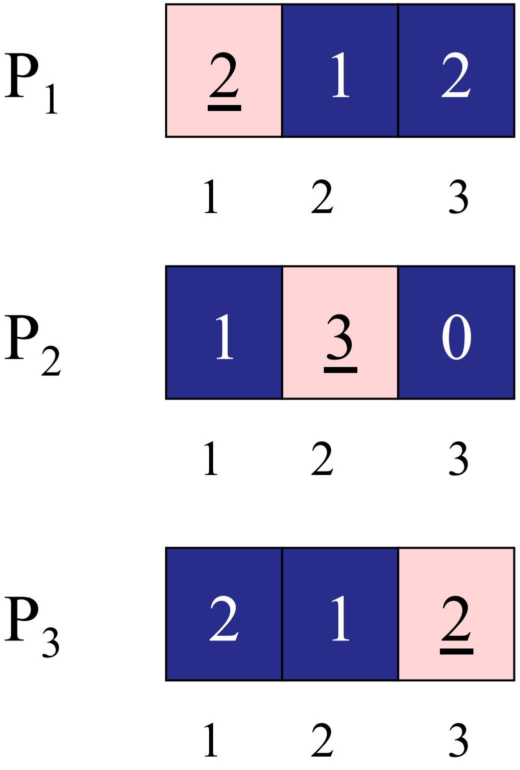
BB_i => BB_j (“messages”)

- BB_j must contain all nonlocal predecessors of all BB_i messages

Assumption:
reliable, order-preserving
BB-to-BB transport

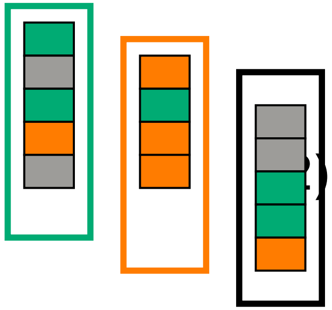
Causal Ordering of a Bulletin Board (2)

timestamps



	1	2	3
P_1	$\underline{2}$	1	2
P_2	1	$\underline{3}$	0
P_3	2	1	$\underline{2}$

Lazy propagation of messages betw. bulletin boards



1) user => P_i

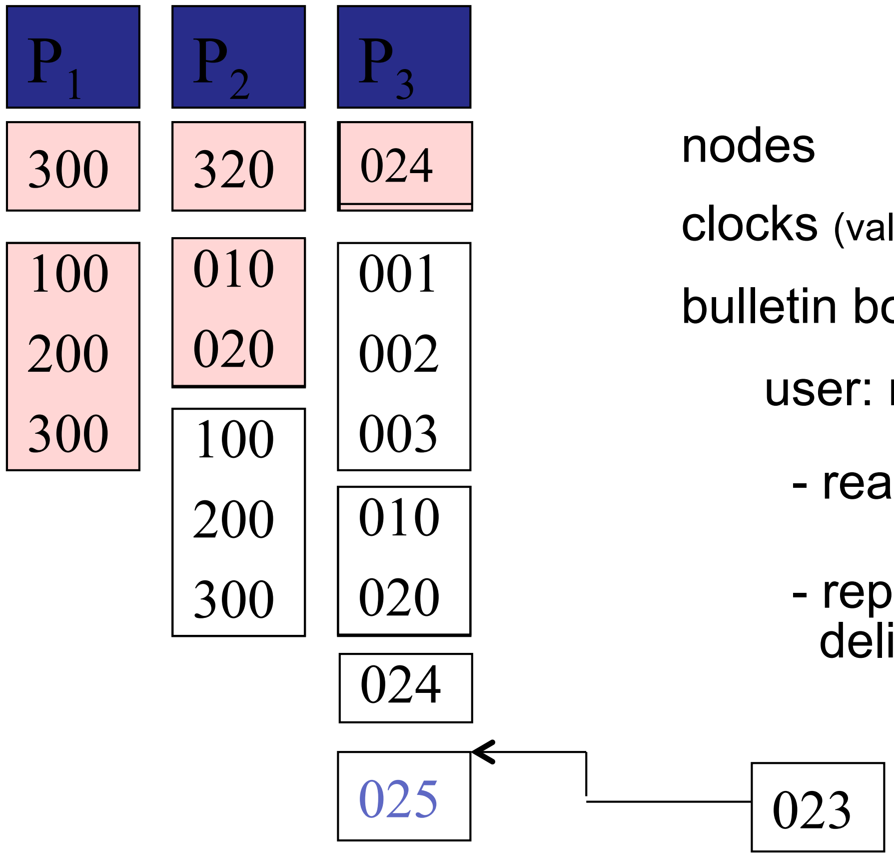
2) P_i ⇔ P_j

vector clocks: counters

$\underline{N}$ (i): messages from users to node i

N (j): messages originally received by node j

Causal Ordering of a Bulletin Board (3)



P_1	P_2	P_3
300	320	024
100	010	001
200	020	002
300	100	003
	200	010
	300	020
		024
		025

023

nodes

clocks (value: visible user messages)

bulletin boards (timestamps shown)

user: read and reply

- read stamp: 023

- reply can be delivered to: 1, 2, 3

Causal Ordering of a Bulletin Board (4)

Updating of vector clocks

Process P_i

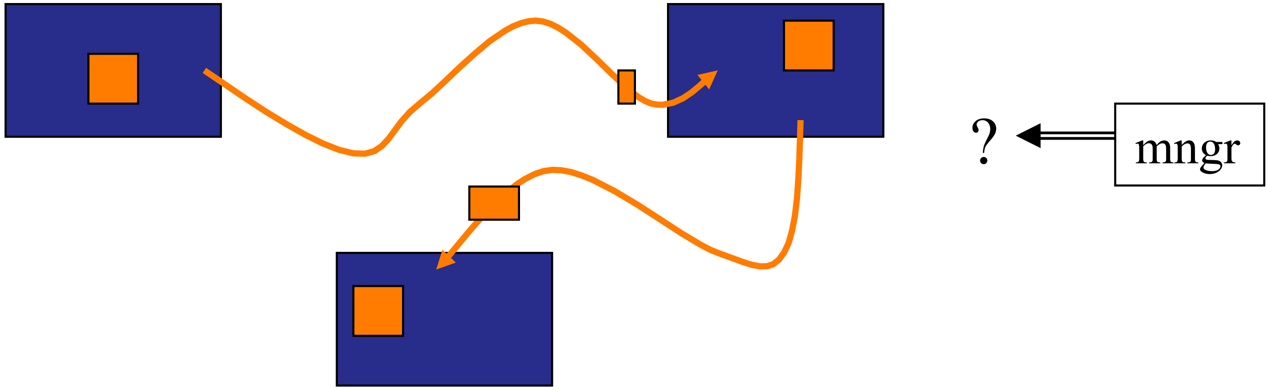
- Local vector clock V_i [∗]
- Update due to a local event: $V_i[i] = V_i[i] + 1$

  What is a “local event”? (See exercises)

- Receiving a message with the timestamp vt [∗]
  - Condition for delivery (to P_r from P_s):

    wait until for all k: k≠s: $V_r[k] \geq vt[k]$
  - Update at delivery: $V_r[s] = vt[s]$

Global State (1)

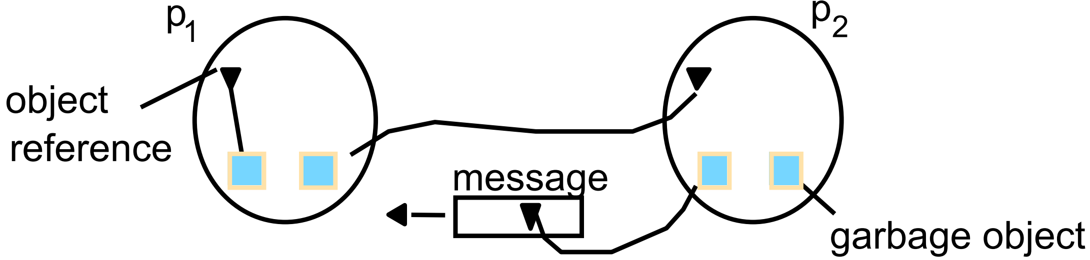


- Needs: checkpointing, garbage collection, deadlock detection, termination, testing

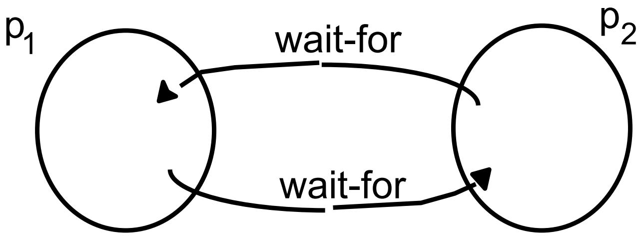
- How to observe the state
  - states of processes
  - messages in transfer

A **state**: application-dependent specification

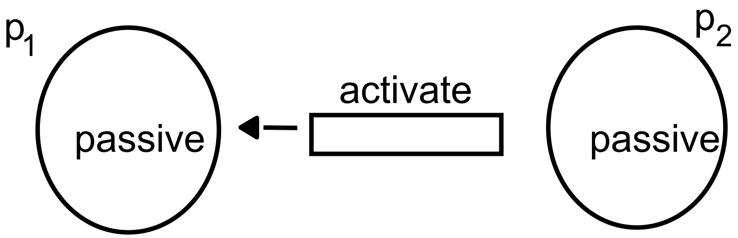
Detecting Global Properties



a. Garbage collection



b. Deadlock



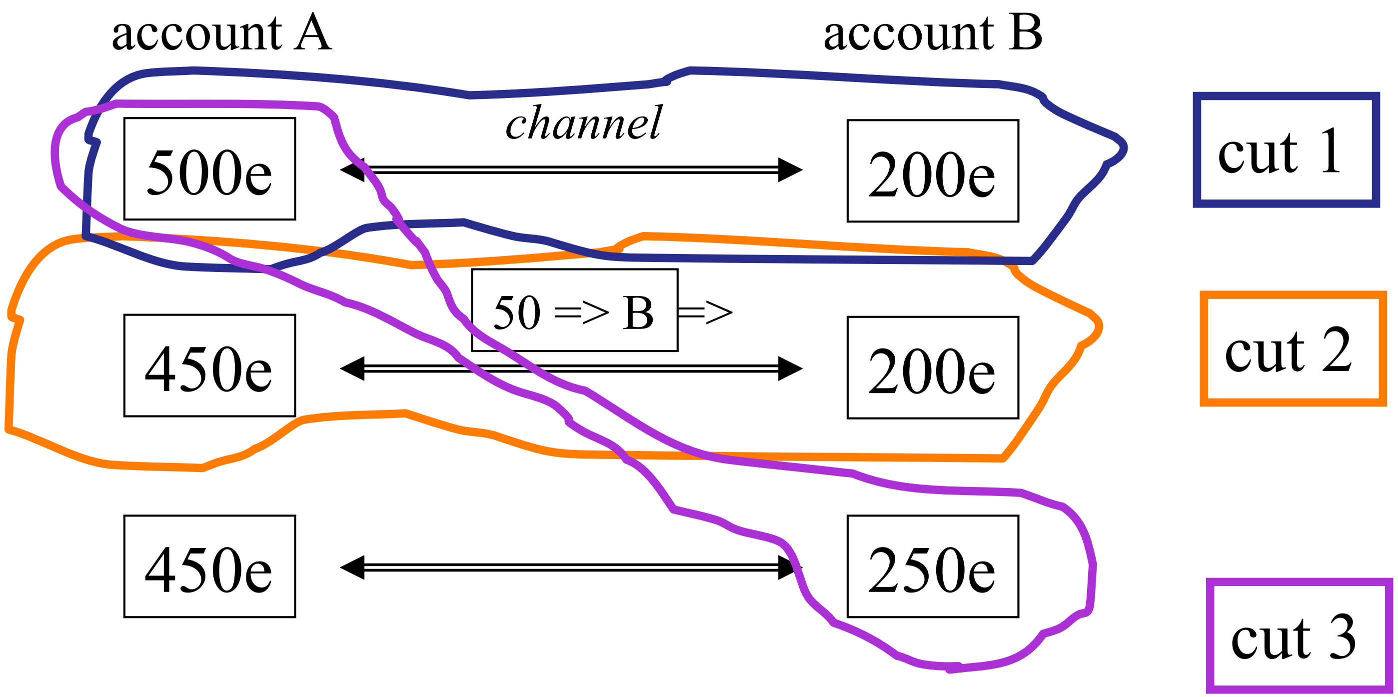
c. Termination

Distributed Snapshot

- Each node: history of important events
- Observer: at each node i
  - time: the local (logical) clock ” T_i ”
  - state S_i (history: {event, timestamp})

  => system state { S_i }
- A *cut:* the system state { S_i } ”at time T”
- Requirement:
  - {Si} might have existed ⇔ consistent with respect to some criterion
  - one possibility: consistent wrt ” happened-before relation ”

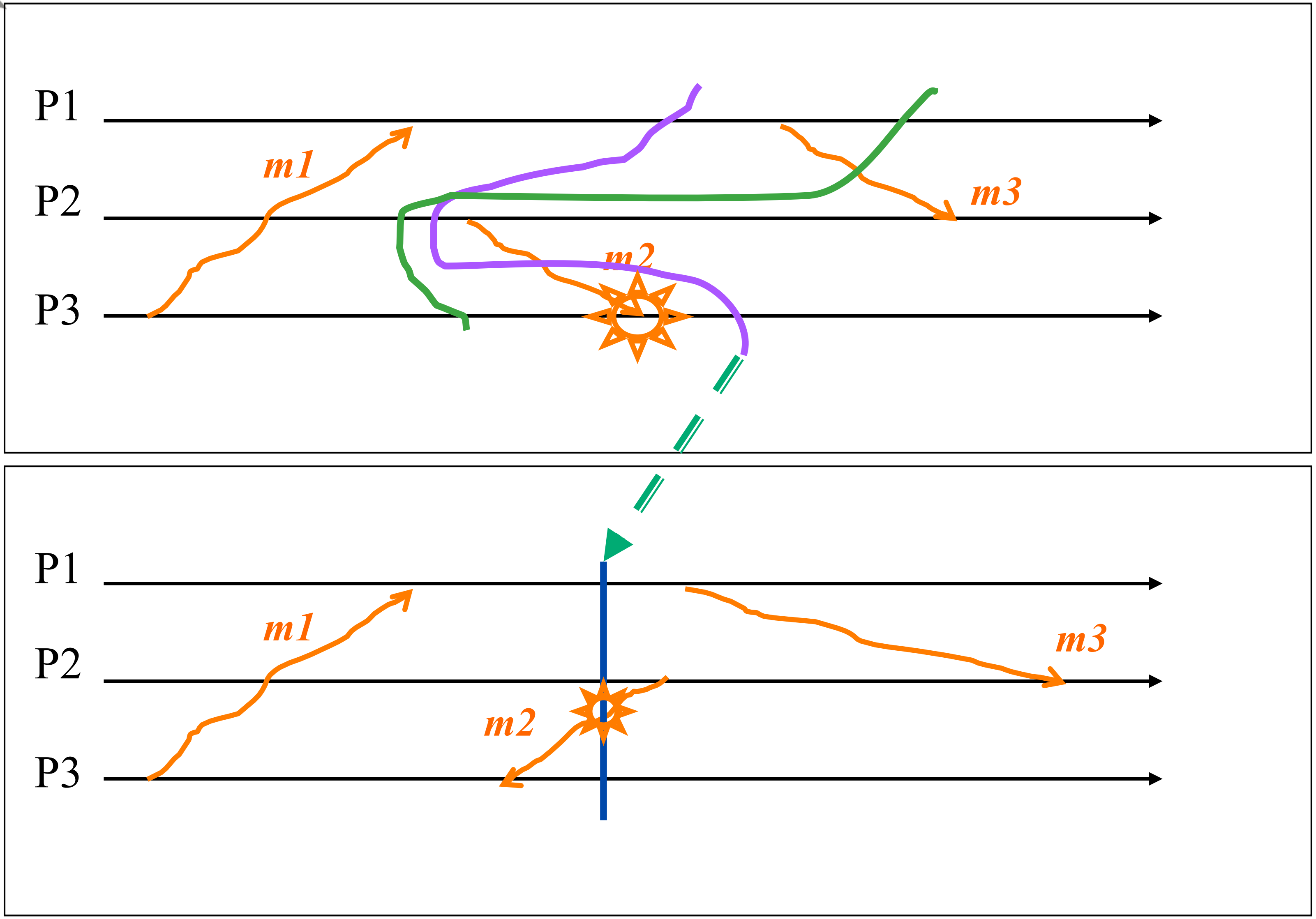
Ad-hoc State Snaphots



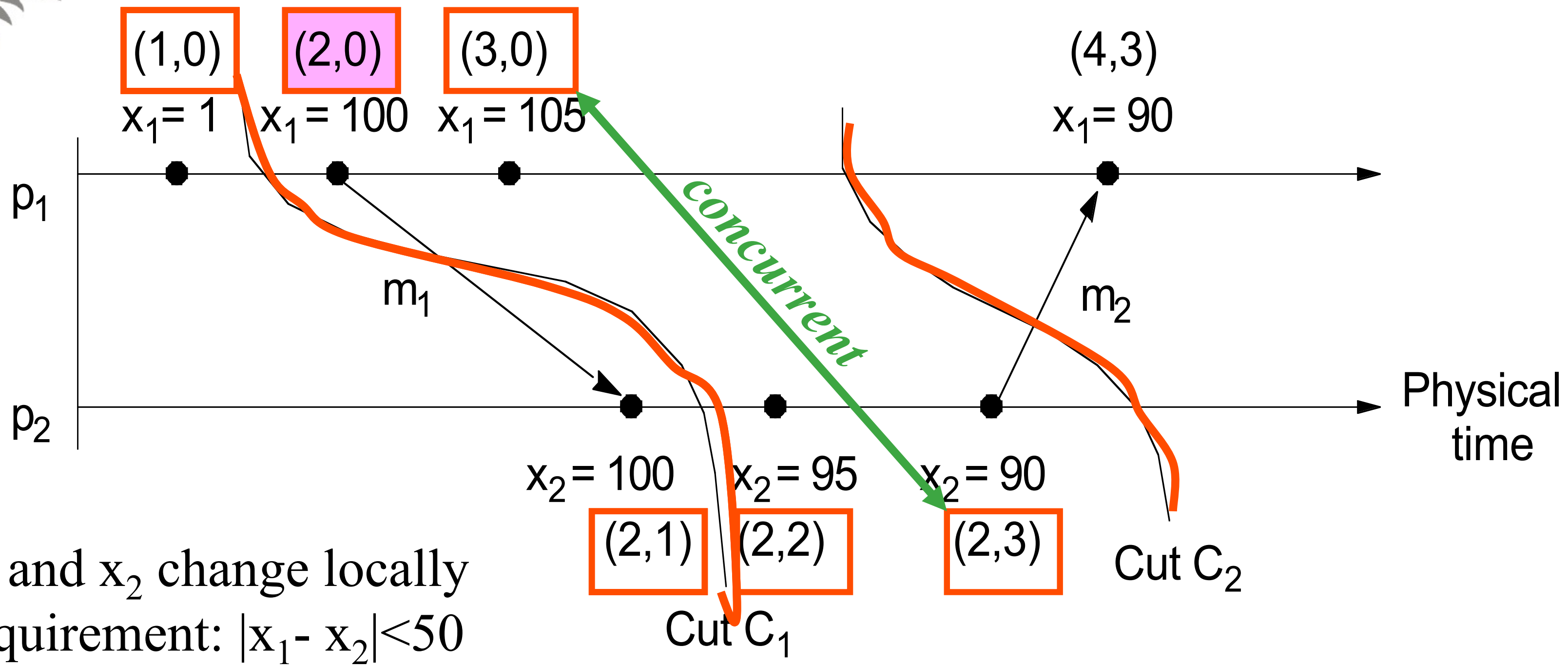
(inconsistent or)
inconsistent
strongly consistent
weakly

state changes: money transfers A ⇔ B
invariant: A+B = 700

Consistent and Inconsistent Cuts



Cuts and Vector Timestamps



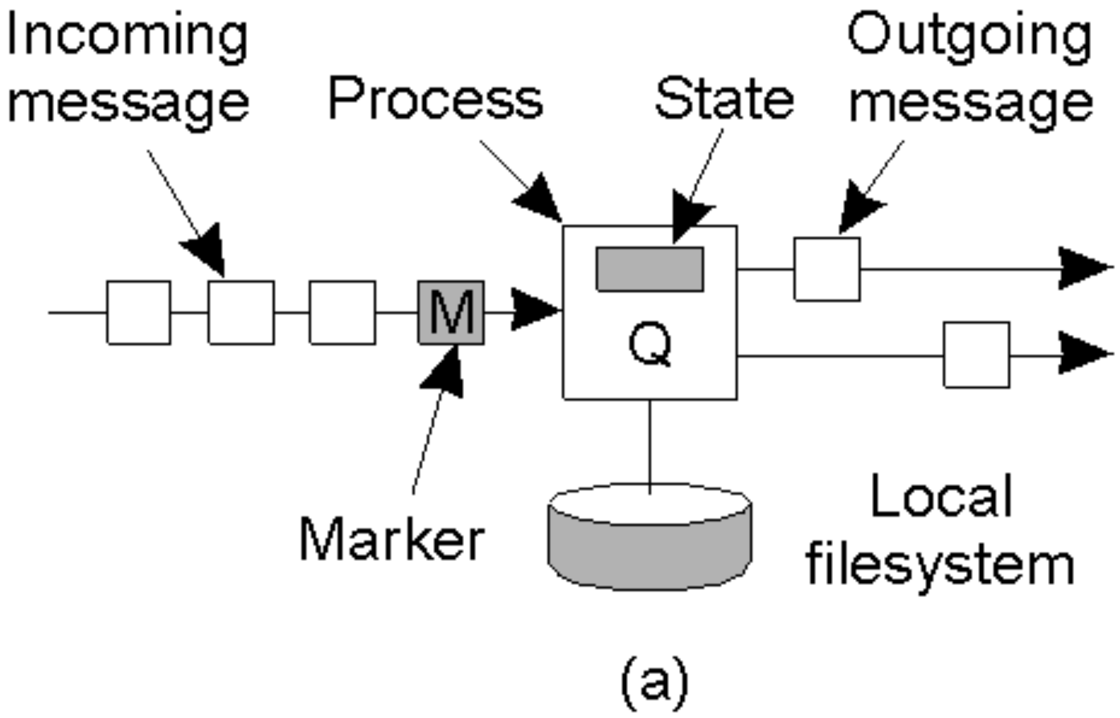
x_1 and x_2 change locally
requirement: $|x_1 - x_2| < 50$
a ”large” change (”>9”) =>
send the new value to the other process

event: a change of the local x
=> increase the vector clock

{S_i} system state history: all events
Cut: all events before the ”cut time”

A cut is consistent if, for each event, it also contains all the events that ”happened-before”.

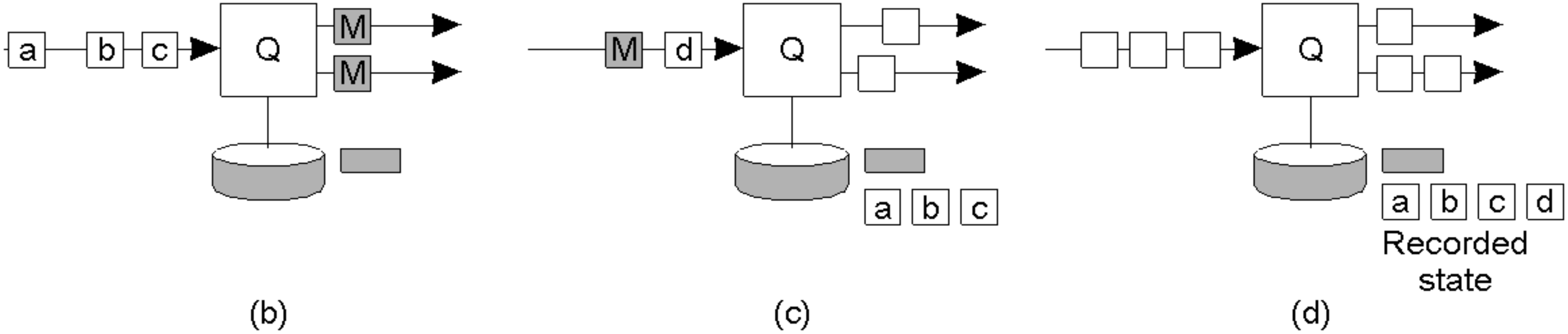
Chandy Lamport (1)



The snapshot algorithm of Chandy and Lamport

a) Organization of a process and channels for a distributed snapshot

Chandy Lamport (2)

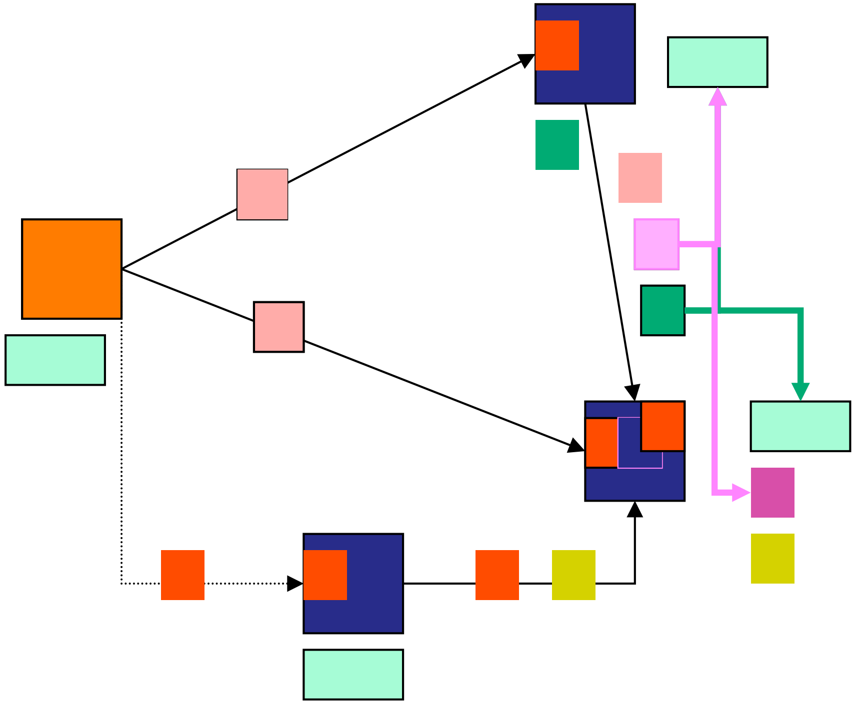


b) Process Q receives a marker for the first time and records its local state
c) Q records all incoming messages
d) Q receives a marker for its incoming channel and finishes recording the state of this incoming channel

Chandy and Lamport’s ‘Snapshot’ 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 $c$).
```

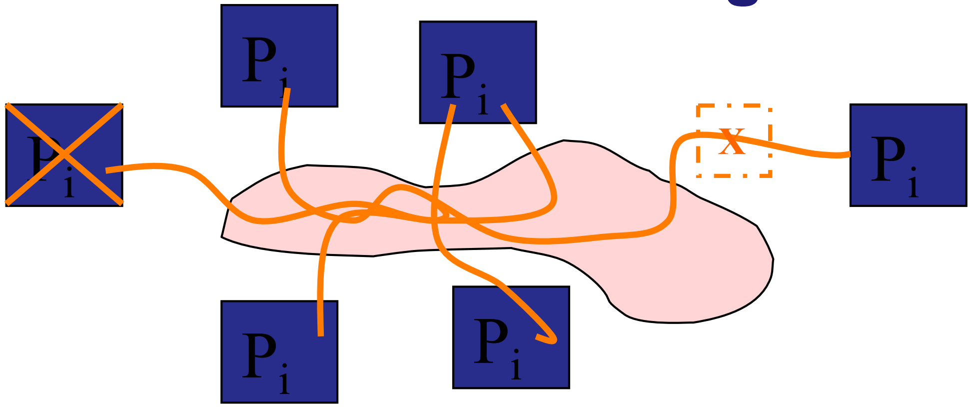
Implementation of Snapshot



Chandy, Lamport

point-to-point, order-preserving connections

Coordination and Agreement



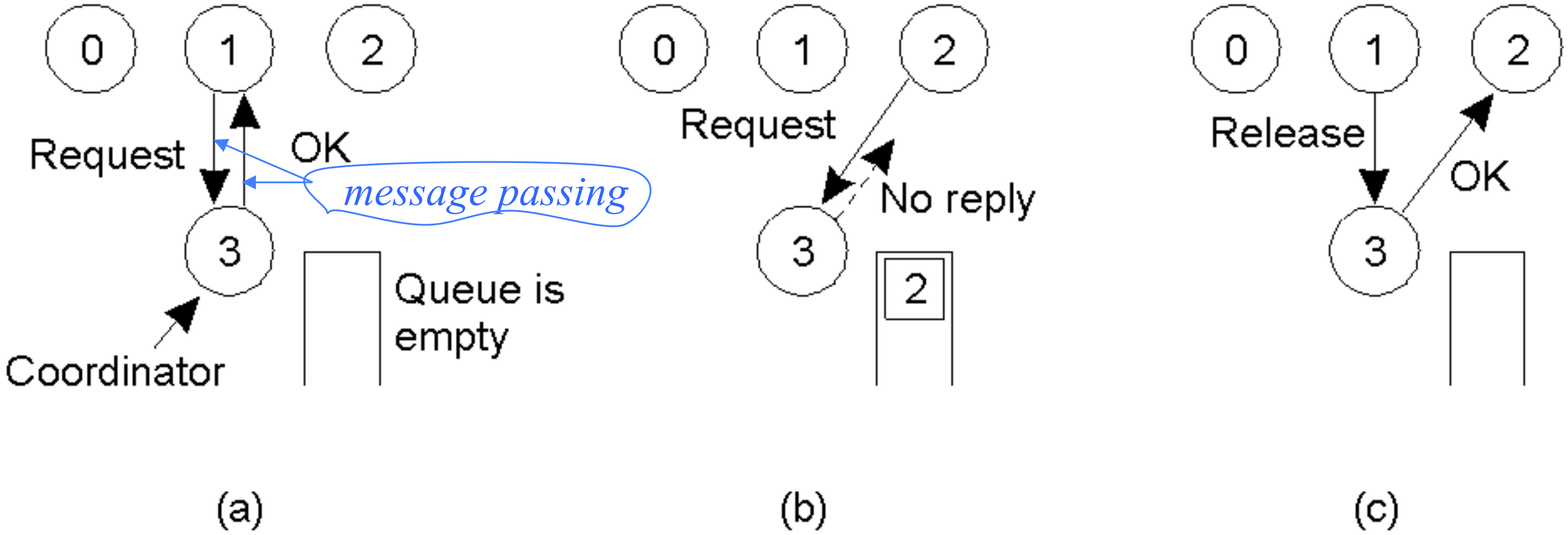
Coordination of functionality

- reservation of resources *(distributed mutual exclusion)*
- elections (coordinator, initiator)
- multicasting
- distributed transactions

Decision Making

- Centralized: one coordinator (decision maker)
  - algorithms are simple
  - no fault tolerance *(if the coordinator fails)*
- Distributed decision making
  - algorithms tend to become complex
  - may be extremely fault tolerant
  - behaviour, correctness ?
  - assumptions about failure behaviour of the platform !
- Centralized role, changing “population of the role”
  - easy: one decision maker at a time
  - challenge: management of the “role population”

Mutual Exclusion: A Centralized Algorithm (1)



a) Process 1 asks the coordinator for permission to enter a critical region. Permission is granted

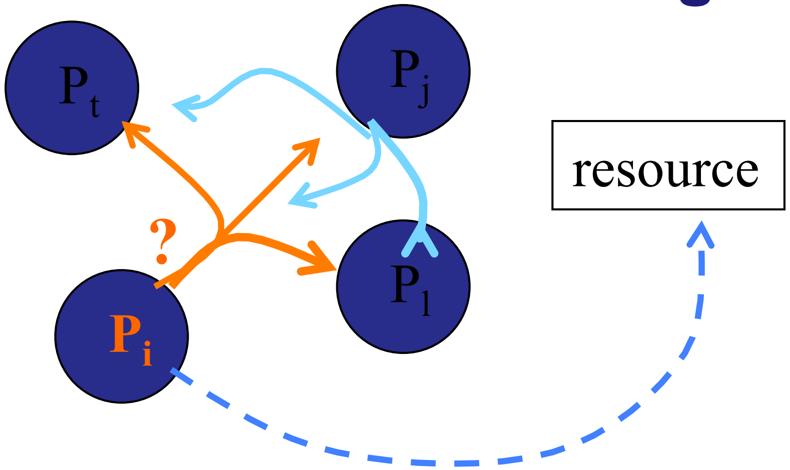
b) Process 2 then asks permission to enter the same critical region. The coordinator does not reply.

c) When process 1 exits the critical region, it tells the coordinator, which then replies to 2

Mutual Exclusion: A Centralized Algorithm (2)

- **Examples** of usage
  - a stateless server (e.g., Network File Server)
  - a separate lock server
- General **requirements** for mutual exclusion
  1. **safety**: at most one process may execute in the critical section at a time
  2. **liveness**: requests (enter, exit) eventually succeed *(no deadlock, no starvation)*
  3. **fairness** (ordering): if the request A *happens before* the request B then A is honored before B
- **Problems**: fault tolerance, performance

A Distributed Algorithm (1)



Ricart – Agrawala

- The general idea:
  - ask everybody
  - wait for permission from everybody

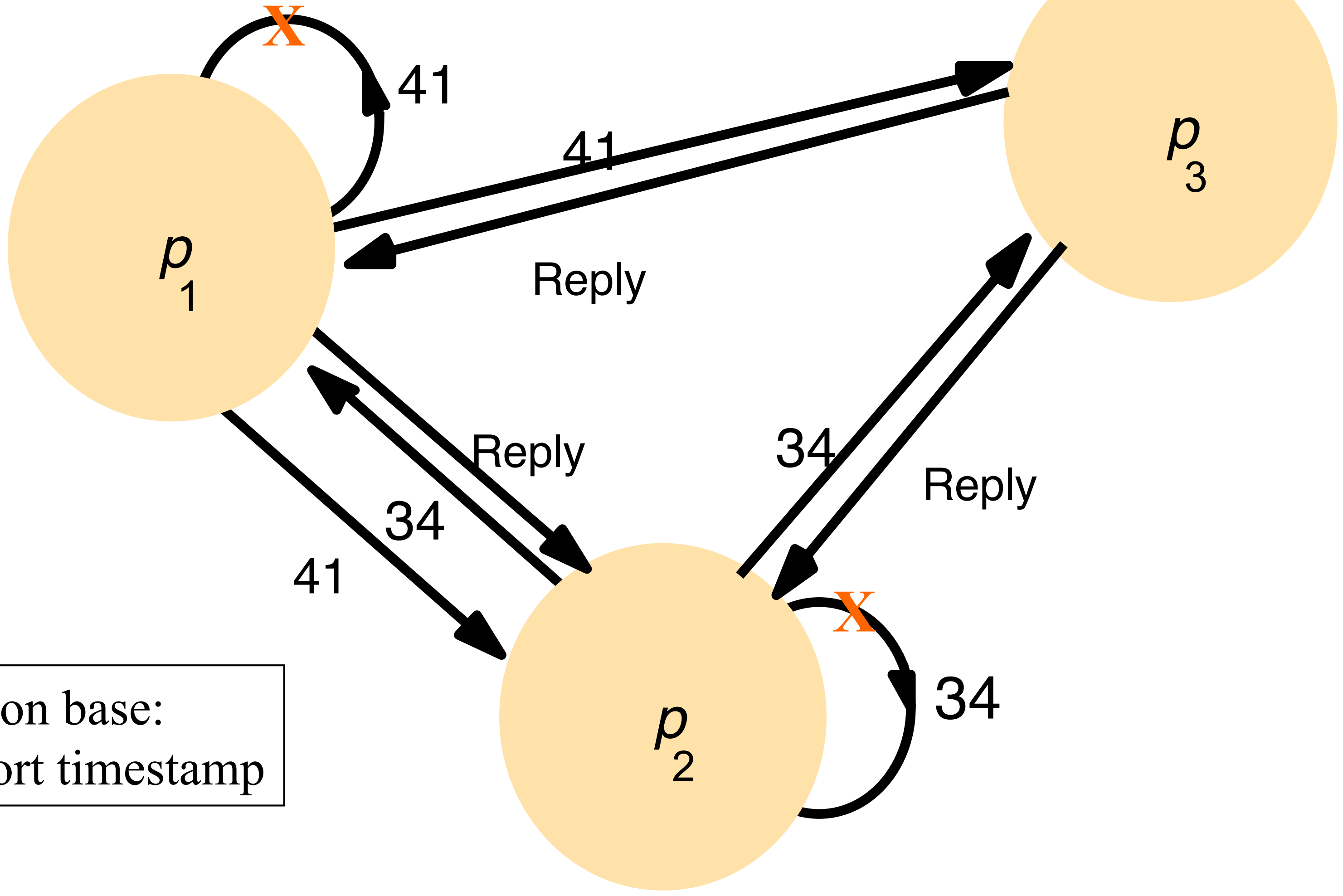
The problem:

- several simultaneous requests (e.g., P_i and P_j)
- all members have to agree (*everybody*: "first P_i then P_j")

A Distributed Algorithm (2)

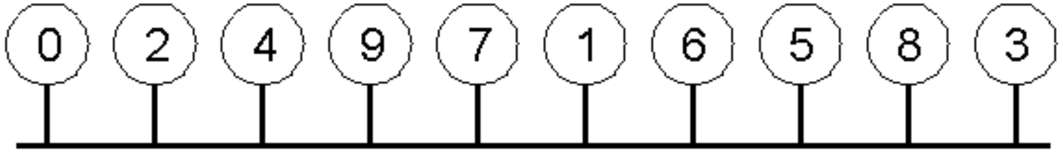
```
On initialization
    state := RELEASED;
To enter the section
    state := WANTED;                                }
    T := request's timestamp;                       }   request processing deferred here
    Multicast request to all processes;             }
    Wait until (number of replies received = (N-1) );
    state := HELD;

On receipt of a request <$T_i$, $p_i$> at $p_j$ ($i \neq j$)
    if (state = HELD or (state = WANTED and ($T$, $p_j$) < ($T_i$, $p_i$)))
    then
        queue request from $p_i$ without replying;
    else
        reply immediately to $p_i$;
    end if;
To exit the critical section
    state := RELEASED;
    reply to all queued requests;
```

Multicast Synchronization



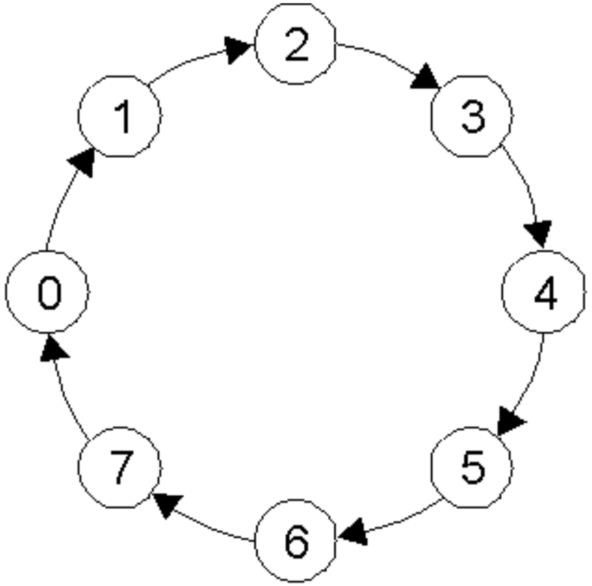
Decision base:
Lamport timestamp

A Token Ring Algorithm



An unordered group of processes on a network.

(a)



(b)

A logical ring constructed in software.

Algorithm:

- token passing: straightforward
- lost token: 1) detection? 2) recovery?

Comparison

Algorithm	**Messages per entry/ exit**	**Delay before entry (in message times)**	**Problems**
Centralized	3	2	Coordinator crash
Distributed	2 (n – 1)	2 (n – 1)	Crash of any process
Token ring	1 to ∞	0 to n – 1	Lost token, process crash

A comparison of three mutual exclusion algorithms.

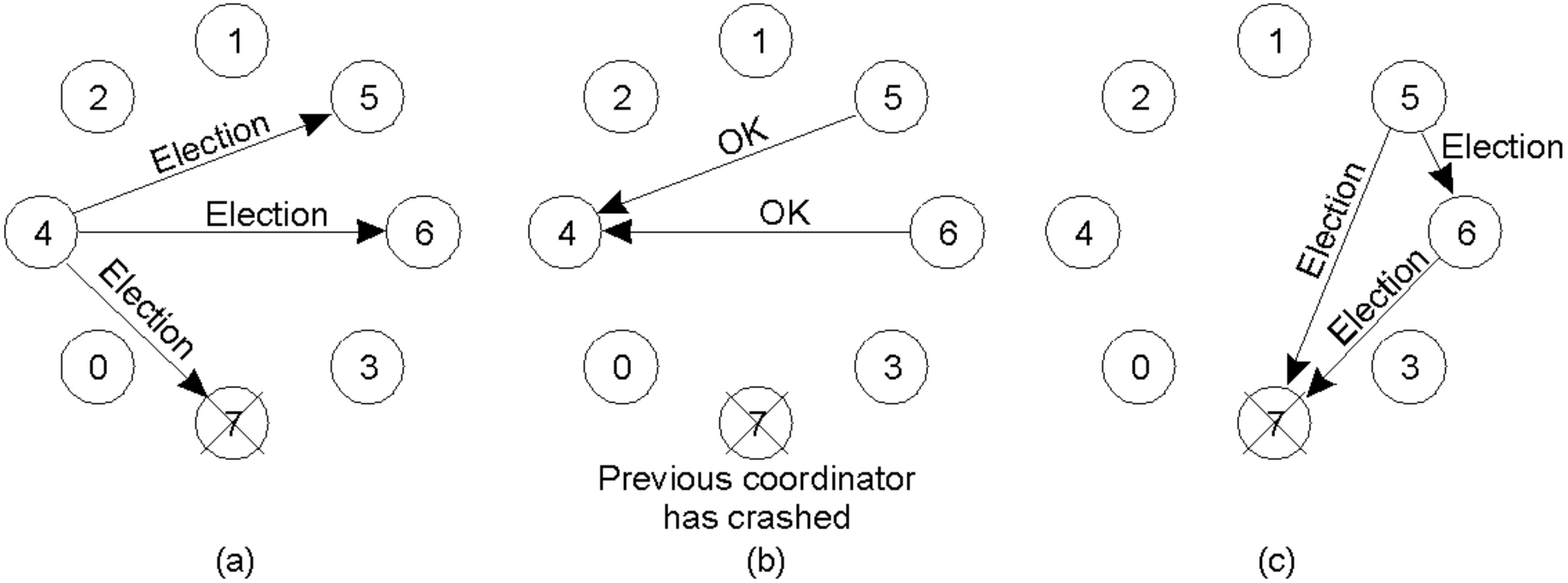
Election Algorithms

- Need:
  - computation: a group of concurrent actors
  - algorithms based on the activity of a special role (coordinator, initiator)
  - election of a coordinator: initially / after some special event (e.g., the previous coordinator has disappeared)
- Premises:
  - each member of the group {Pi}
    - knows the identities of all other members
    - does not know who is up and who is down
  - all electors use the same algorithm
  - election rule: the member with the highest Pi
- Several algorithms exist

The Bully Algorithm (1)

- P_i notices: coordinator lost
    1. Pi to {all Pj st Pj>Pi}: ELECTION!
    2. if no one responds => Pi is the coordinator
    3. some Pj responds => Pj takes over, Pi's job is done
- P_i gets an ELECTION! message:
    1. reply OK to the sender
    2. if Pi does not yet participate in an ongoing election: hold an election
- The new coordinator P_k to everybody: " P_k COORDINATOR"
- P_i: ongoing election & no "P_k COORDINATOR": hold an election
- P_j recovers: hold an election

The Bully Algorithm (2)

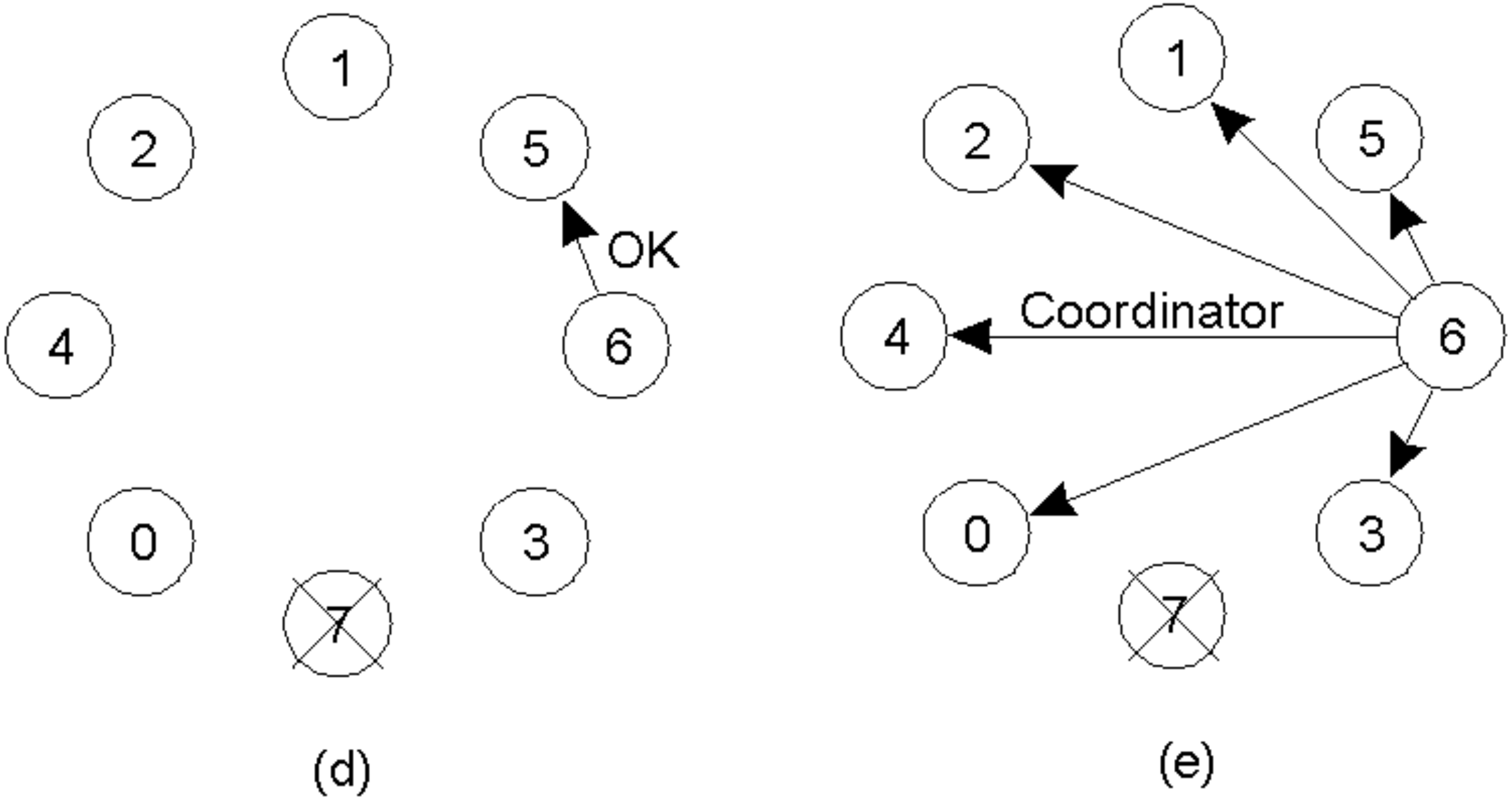


The bully election algorithm

a) Process 4 holds an election

b) Process 5 and 6 respond, telling 4 to stop

c) Now 5 and 6 each hold an election



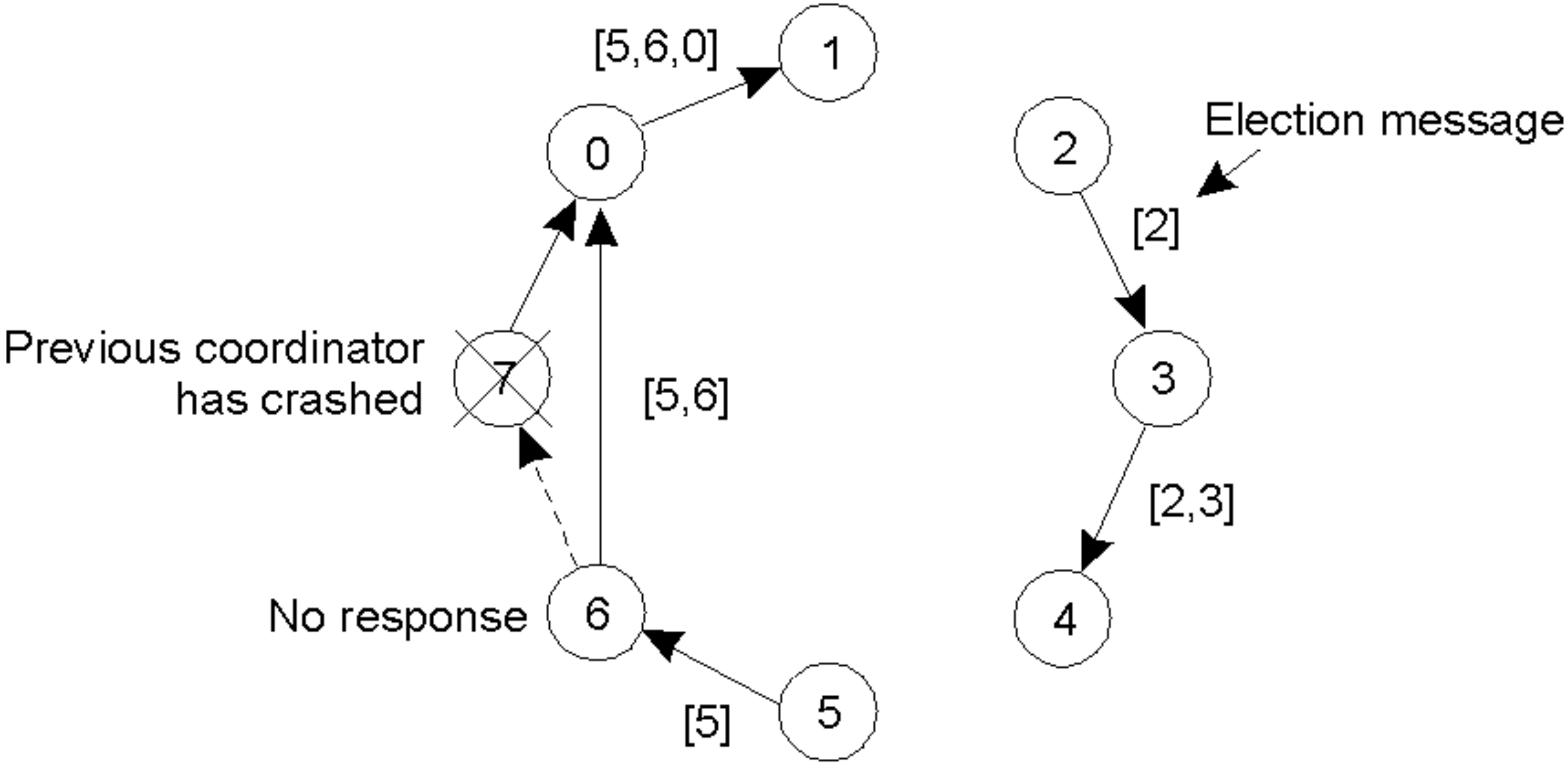
d) Process 6 tells 5 to stop

e) Process 6 wins and tells everyone

A Ring Algorithm (1)

- Group {Pi} ”fully connected”; election: ring
- Pi notices: coordinator lost
  - send ELECTION(Pi) to the next P
- Pj receives ELECTION(Pi)
  - send ELECTION(Pi, Pj) to successor
- . . .
- Pi receives ELECTION(..., Pi, ...)
  - active_list = {collect from the message}
  - NC = max {active_list}
  - send COORDINATOR(NC; active_list) to the next P
- …

A Ring Algorithm (2)



Election algorithm using a ring.

Chapter Summary

- Synchronization
- Clocks
- Logical and vector clocks
- Coordination, elections