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Synchronization

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Chapter Outline

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

- Tanenbaum, van Steen: Ch 5
- CoDoKi: Ch 10-12 (3rd ed.)



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 perfect 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

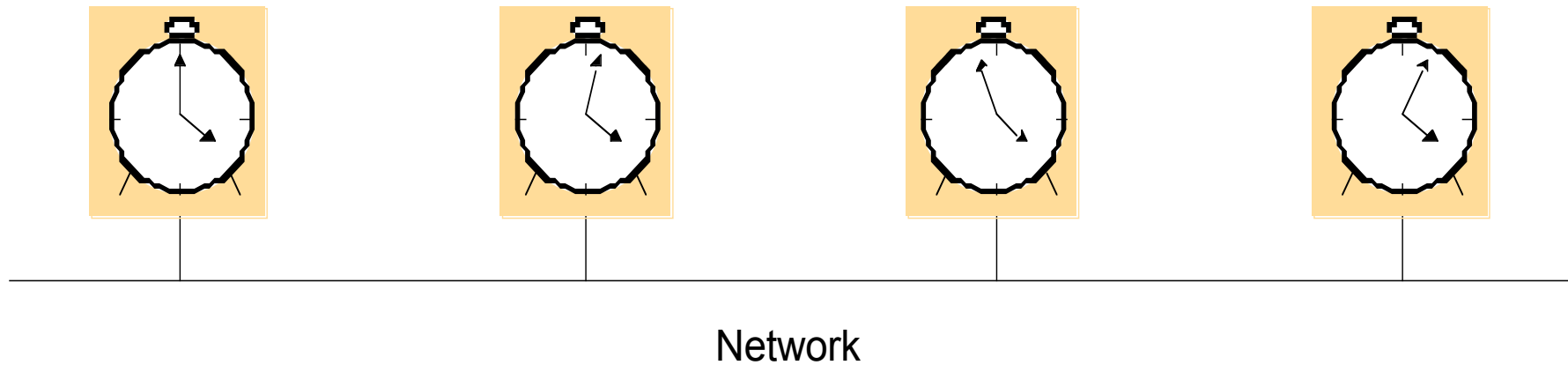
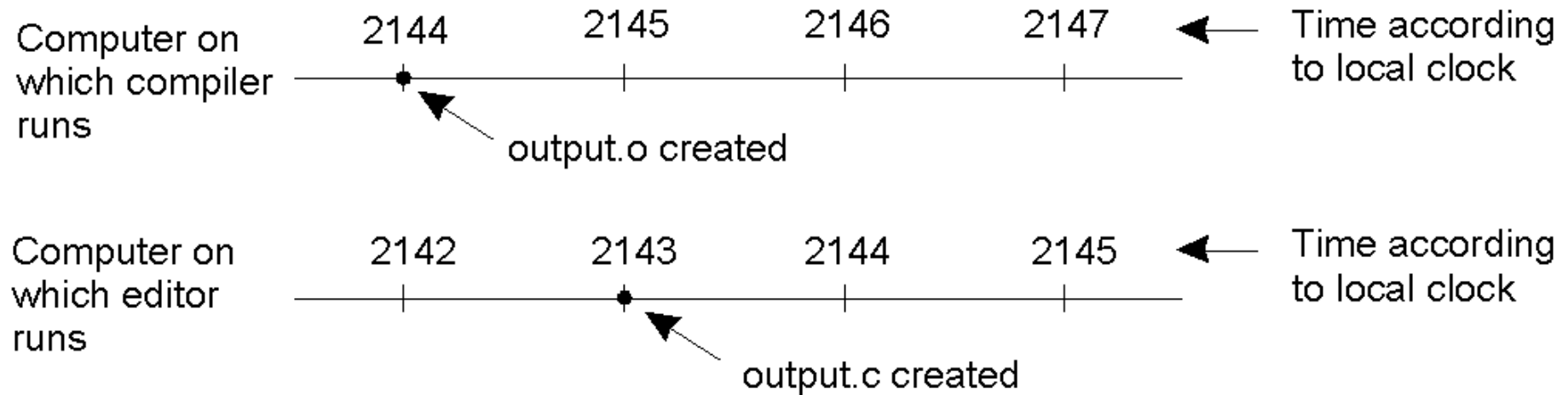


Figure 10.1



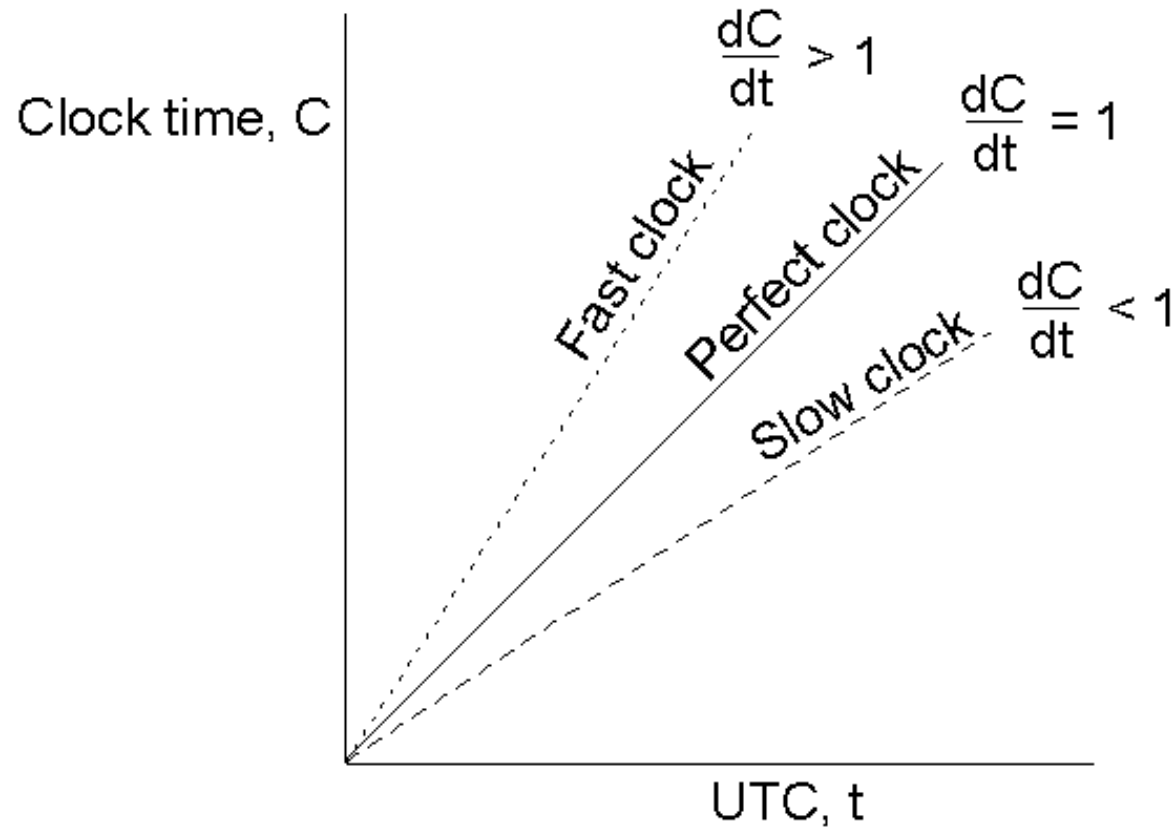
Clock Synchronization



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 \sim 17 min
1 s \sim 11.6 days

*UTC: coordinated
universal time*

accuracy:
radio 0.1 – 10 ms,
GPS 1 μ s

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

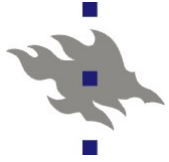
■ Obviously:

- 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)



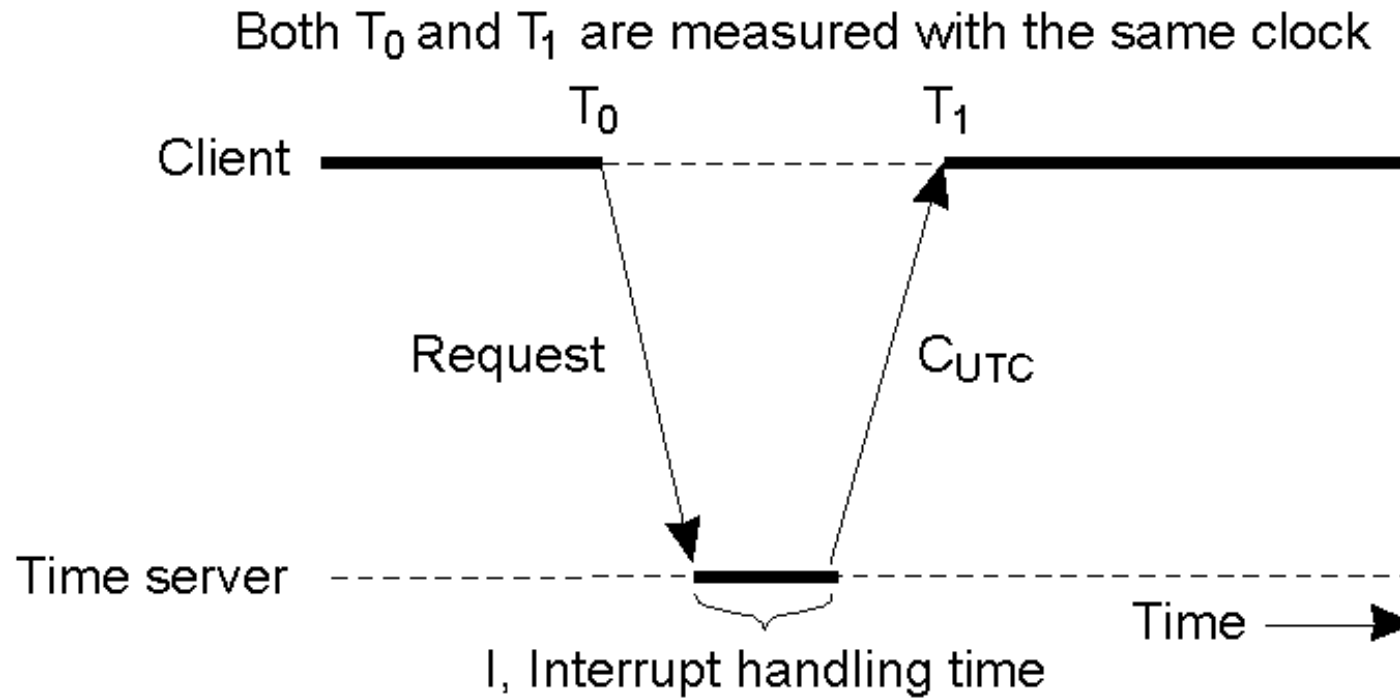
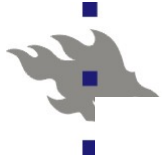
Christian's Algorithm

■ 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 $t + \frac{1}{2}T_{\text{round}}$



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 $\pm (\frac{1}{2}T_{round} - min)$

■ 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)

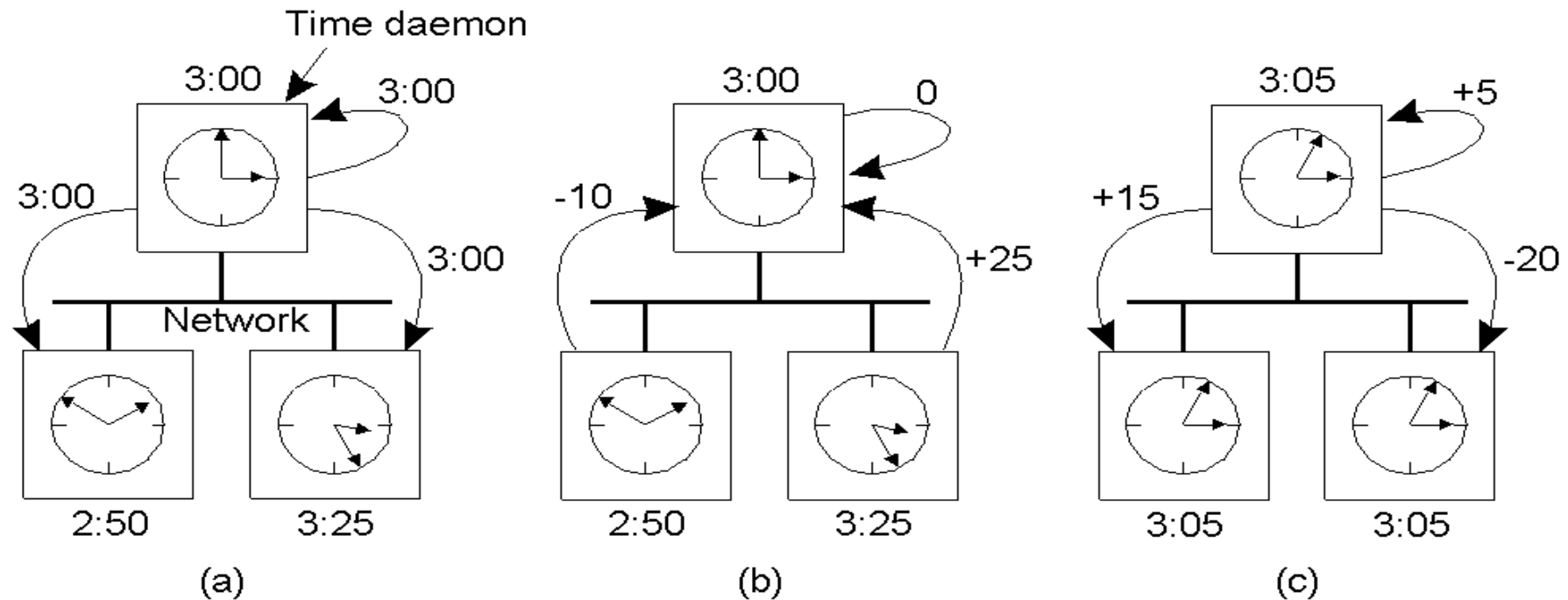
■ Experiment

- 15 computers, local drift rate $< 2 \times 10^{-5}$, 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

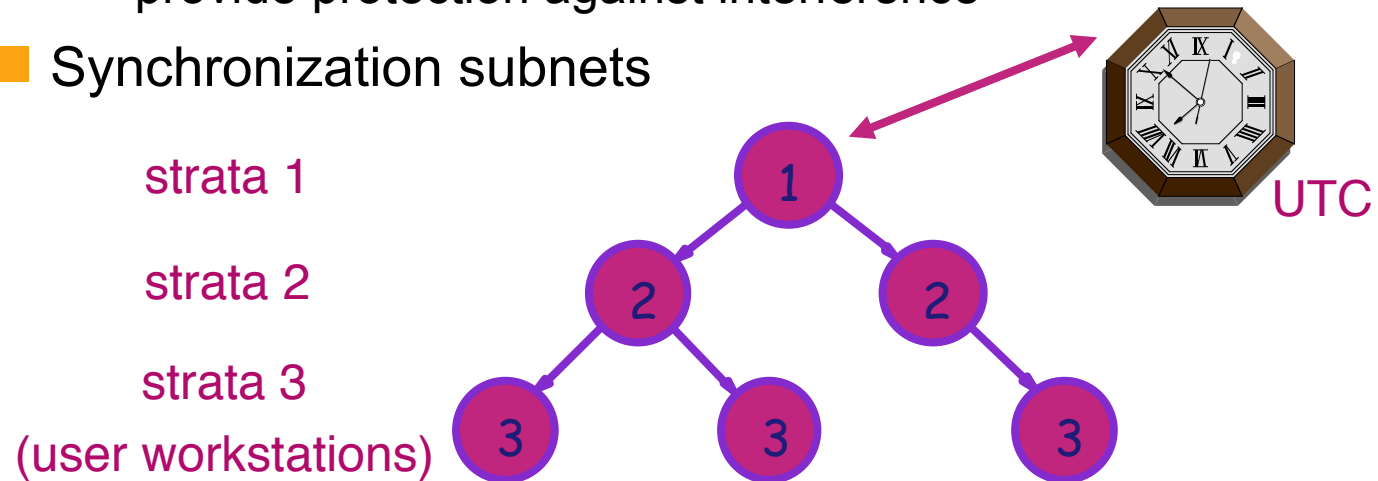


Clock Synchronization: NTP

■ 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





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 through 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

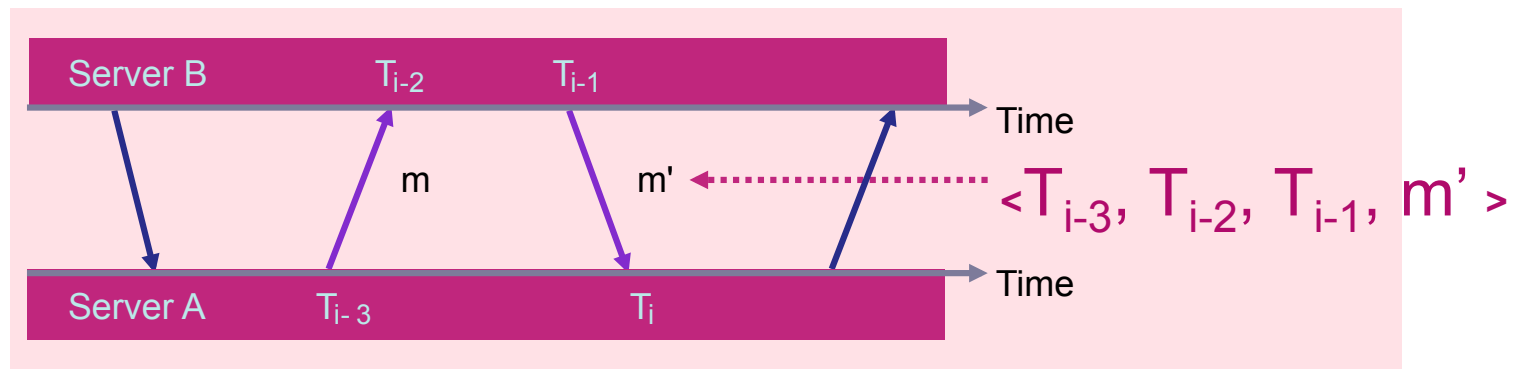
■ Symmetric:

- Used where high accuracy is needed



Procedure-Call and Symmetric Modes

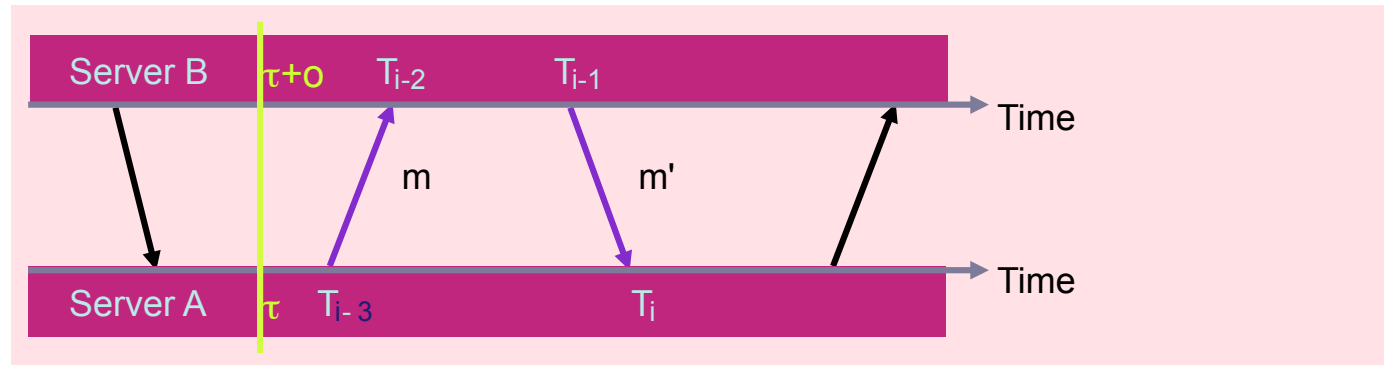
- All messages carry timing history information
 - local timestamps of send and receive of the previous NTP message
 - local timestamp of send of this message



- 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 be the **true** offset of B's clock relative to A's clock, and let t and t' be the **true** transmission times of m and m' ($T_i, T_{i-1} \dots$ 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 \rightarrow **true** d)

- Offset

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



NTP Implementation

- Statistical algorithms based on 8 most recent $\langle o_i, d_i \rangle$ pairs: \rightarrow 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:

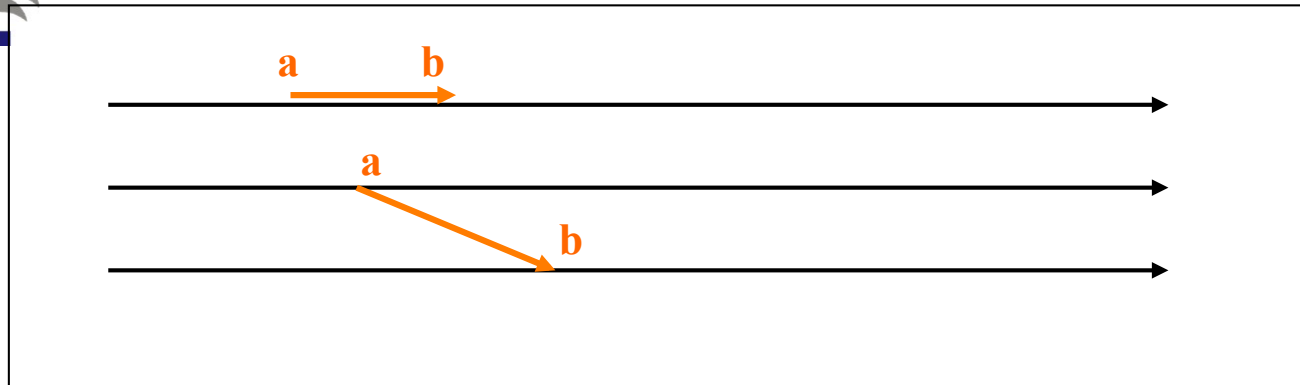
- "*causality*": real-time order \sim timestamp order ("behavioral correctness" – seen by the user)
- *groups* / *replicates*: all members see the events in the same order
- "*multiple-copy-updates*": order of updates, consistency conflicts?
- *serializability of transactions*: bases on a common understanding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

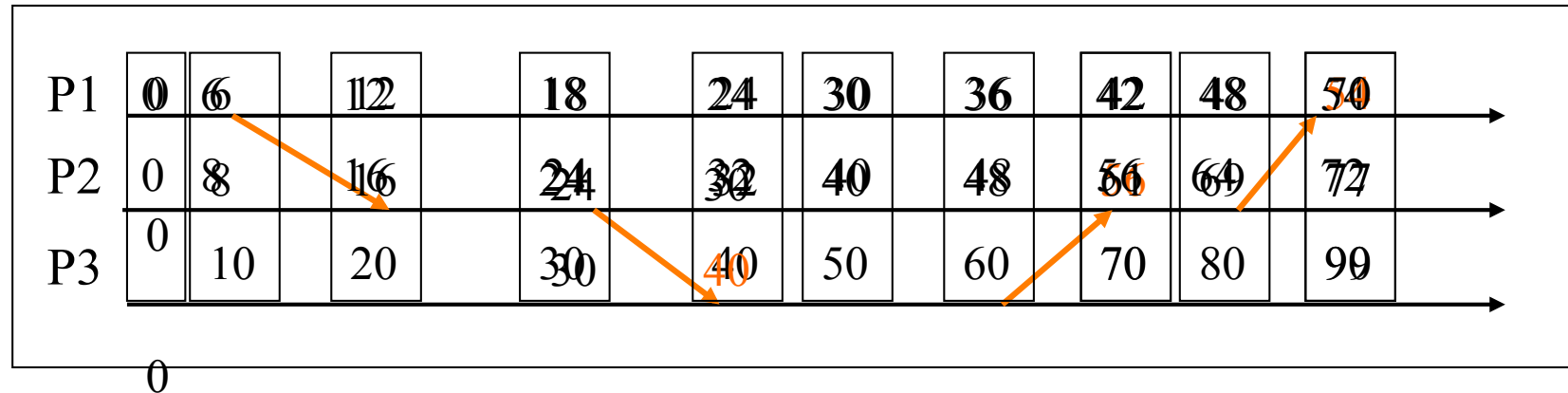


- if a, b are events in the same process, and a occurs before b , then $a \rightarrow b$
- if a is the event of a message being sent, and b is the event of the message being received, then $a \rightarrow b$
- $a \parallel b$ if neither $a \rightarrow b$ nor $b \rightarrow a$ (a and b are concurrent)

Note: if $a \rightarrow b$ and $b \rightarrow c$ then $a \rightarrow c$



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. $L_j(\text{receive event}) = L_j$;



Lamport Clocks: Problems

1. Timestamps do not specify the order of events

- $e \rightarrow e' \Rightarrow L(e) < L(e')$

BUT

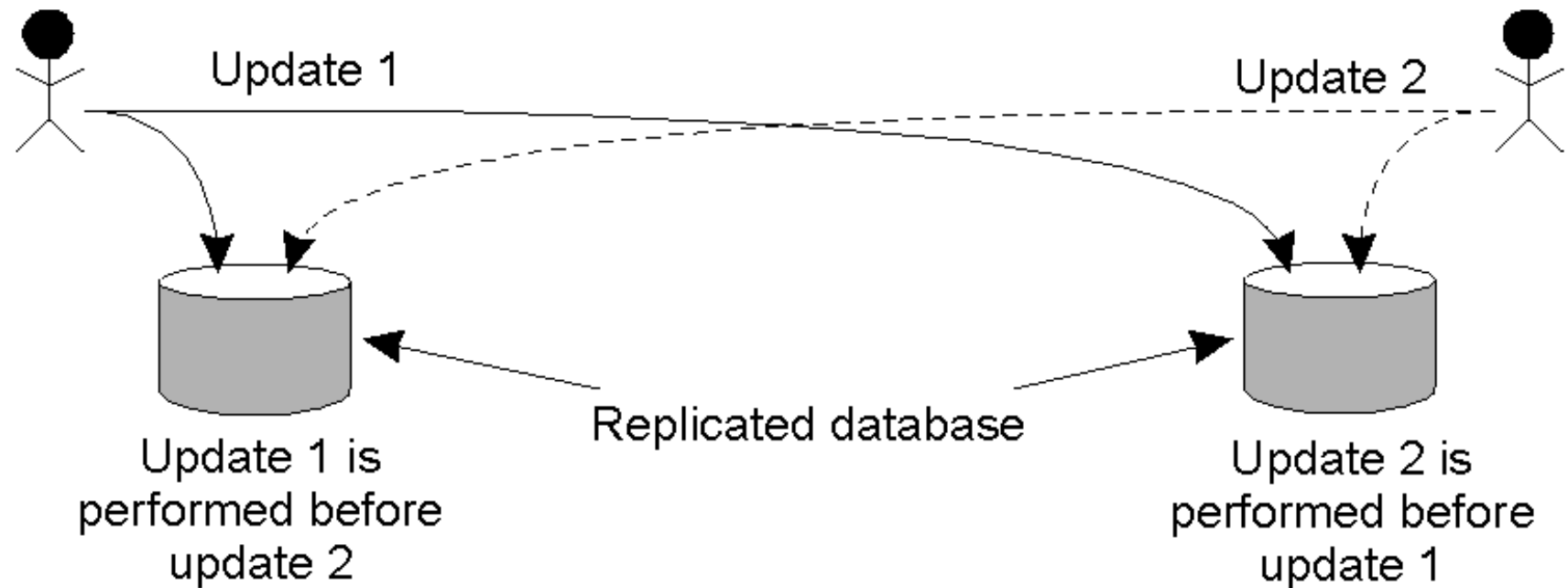
- $L(e) < L(e')$ does not imply that $e \rightarrow e'$

2. Total ordering

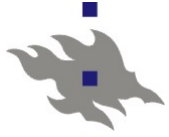
- problem: define order of e, e' when $L(e) = L(e')$
- solution: extended timestamp (T_i, i) , where T_i is $L_i(e)$
- definition: $(T_i, i) < (T_j, j)$
if and only if
either $T_i < T_j$
or $T_i = T_j$ and $i < j$



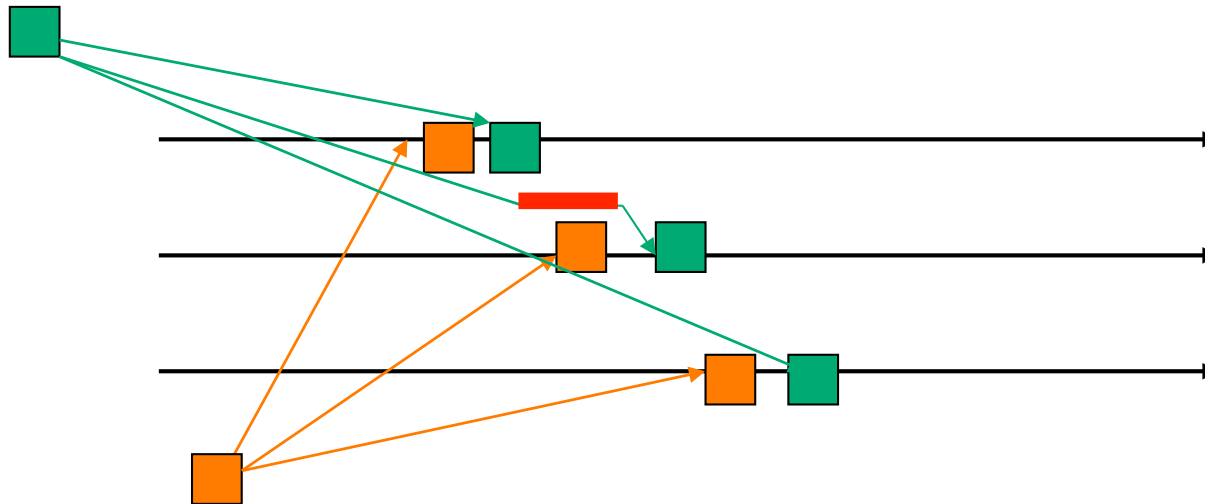
Example: Totally-Ordered Multicasting (1)



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



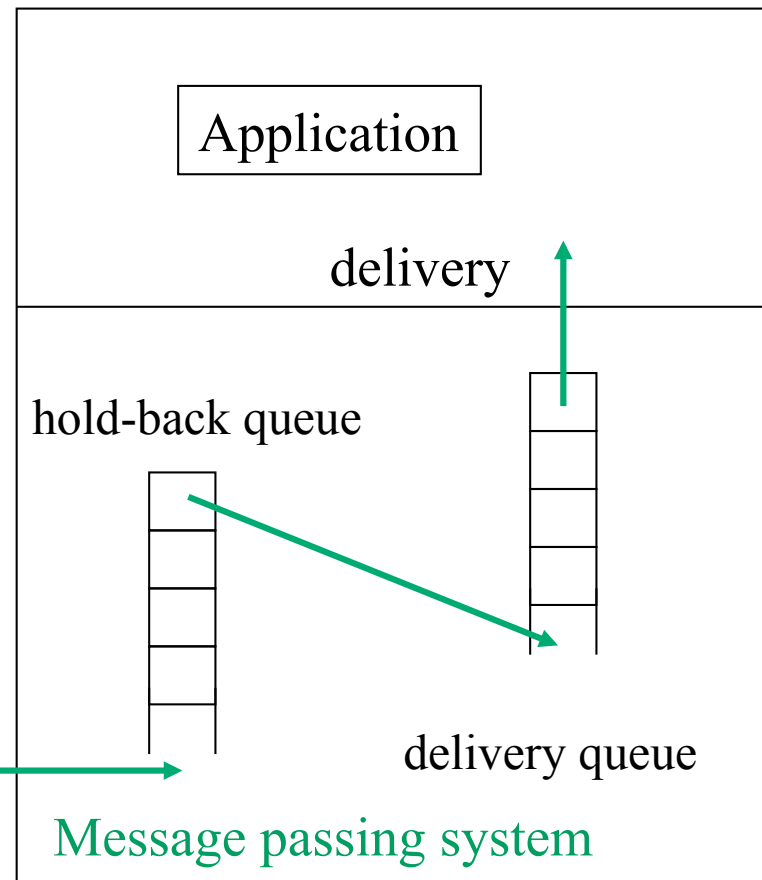
▪Example: Totally-Ordered Multicasting (3)

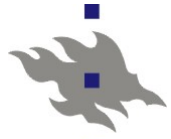
Guaranteed delivery order

- *new* message \Rightarrow HBQ
- when *all predecessors* have arrived: message \Rightarrow DQ
- when *at the head of DQ*: message \Rightarrow application (application: *receive* ...)

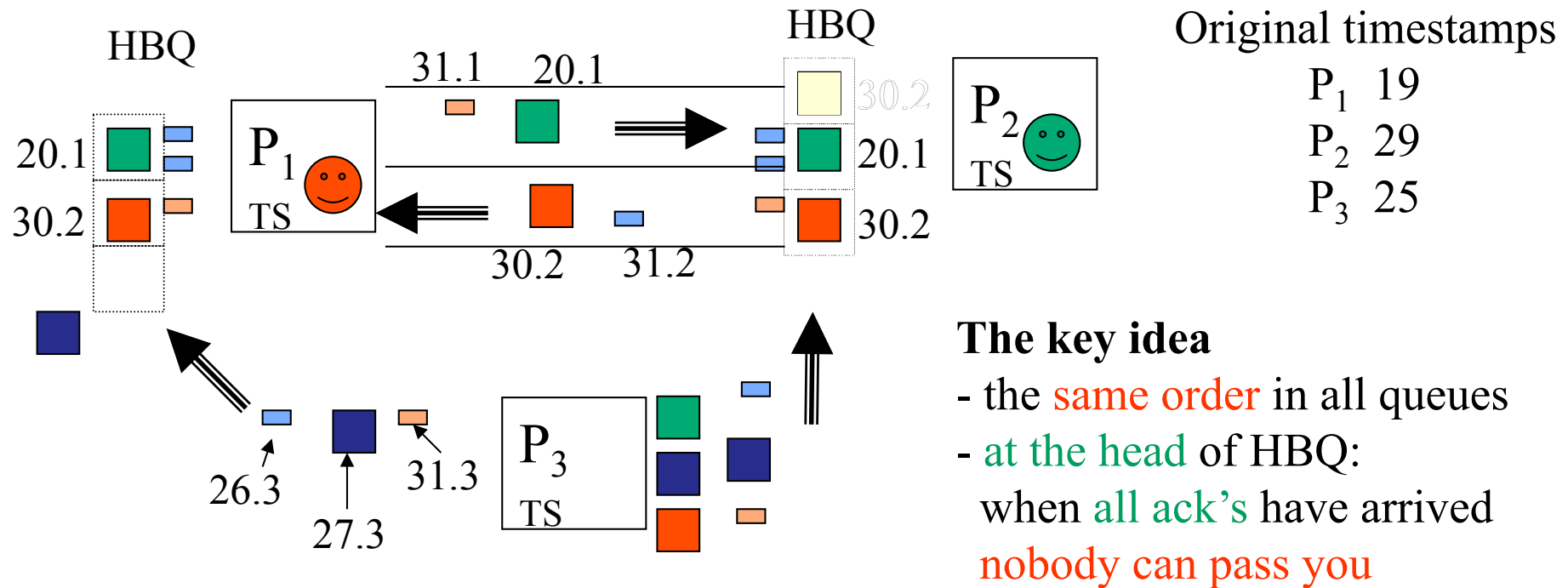
Algorithms:

see. Defago et al ACM CS, Dec. 2004





Example: Totally-Ordered Multicasting (4)



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_2 – and the otherwise arbitrary delivery ordering of messages.

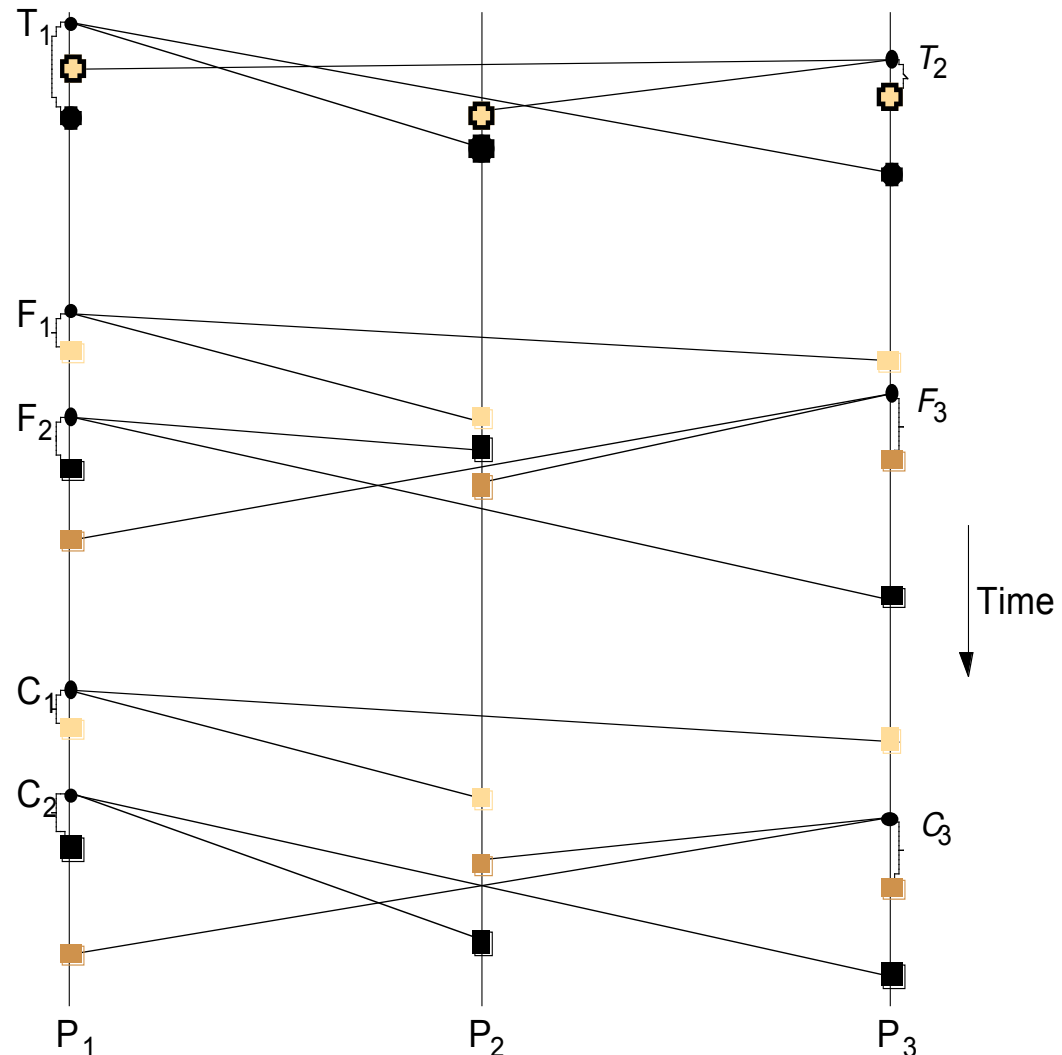


Figure 11.12



Vector Timestamps

Goal:

timestamps should reflect *causal ordering*

$L(e) < L(e') \Rightarrow$ “ e happened before e’ “

\Rightarrow

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

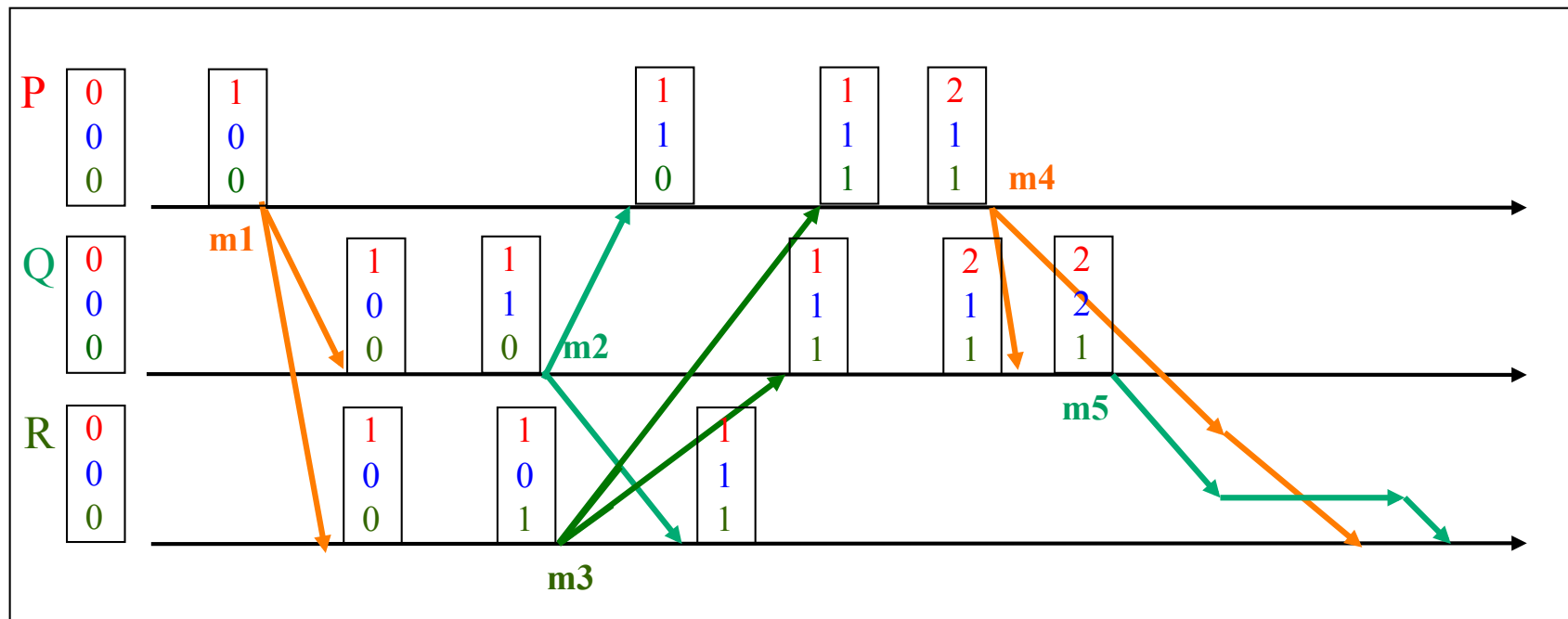
- $V = V'$ iff $V[j] = V'[j]$ for all j
- $V \leq V'$ iff $V[j] \leq V'[j]$ for all j
- $V < V'$ iff $V \leq V'$ and $V \neq V'$

Order of events (*causal order*)

- $e \rightarrow e' \Rightarrow V(e) < V(e')$
- $V(e) < V(e') \Rightarrow e \rightarrow e'$
- concurrency:
 $e \parallel e'$ if **not** $V(e) \leq V(e')$
and **not** $V(e') \leq V(e)$



Causal Ordering of Multicasts (1)



Event:
message sent

Timestamp [i,j,k] :
 i messages sent from P
 j messages sent from Q
 k messages sent from R

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

m4 [~~2~~11] vs. 111



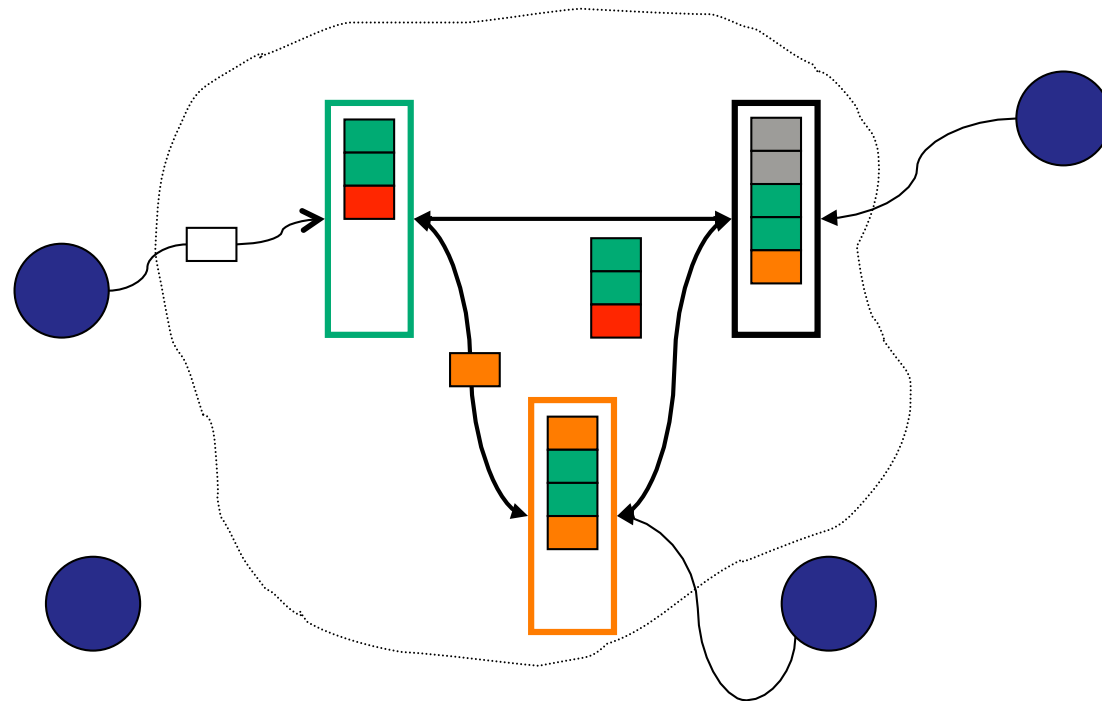
Causal Ordering of Multicasts (2)

Use of timestamps in causal multicasting

- 1) P_i multicast: $V_i[i] = V_i[i] + 1$
- 2) Message: include $vt = V_i[*]$
- 3) Each receiving P_j : the message **can be delivered when**
 - $vt[i] = V_j[i] + 1$ (*all previous messages from P_i have arrived*)
 - for each component k ($k \neq i$): $V_j[k] \geq vt[k]$
(*P_j has now seen all the messages that P_i had seen when the message was sent*)
- 4) When the message from P_i becomes deliverable at P_j the message is inserted into the delivery queue
(*note: the delivery queue preserves causal ordering*)
- 5) **At delivery:** $V_j[i] = V_j[i] + 1$



Causal Ordering of a Bulletin Board (1)



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

User \Leftrightarrow **BB** ("*local events*")

■ read: $bb \leq BB_i$ (any BB)

■ write: to a BB_j that
contains all causal
predecessors of all bb
messages

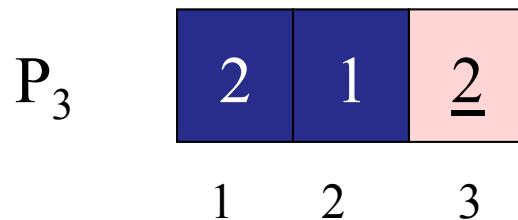
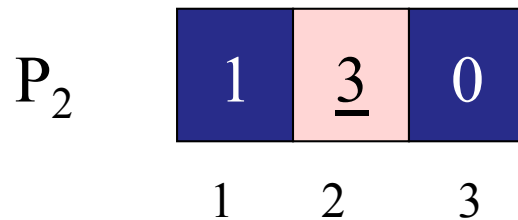
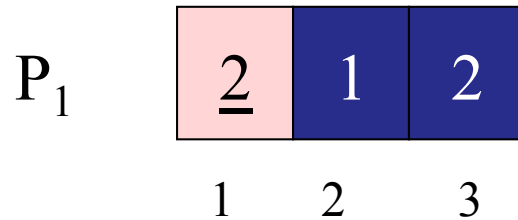
$BB_i \Rightarrow BB_j$ ("*messages*")

■ BB_j must contain all
nonlocal predecessors of
all BB_i messages

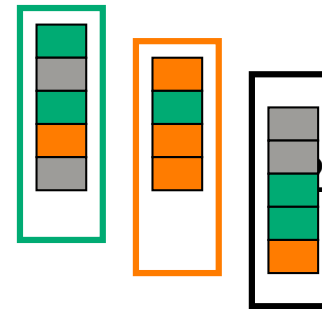


Causal Ordering of a Bulletin Board (2)

timestamps



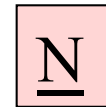
Lazy propagation of messages betw.
bulletin boards



1) user $\Rightarrow P_i$

$P_i \Leftrightarrow P_j$

vector clocks: counters



i

messages from
users to node i

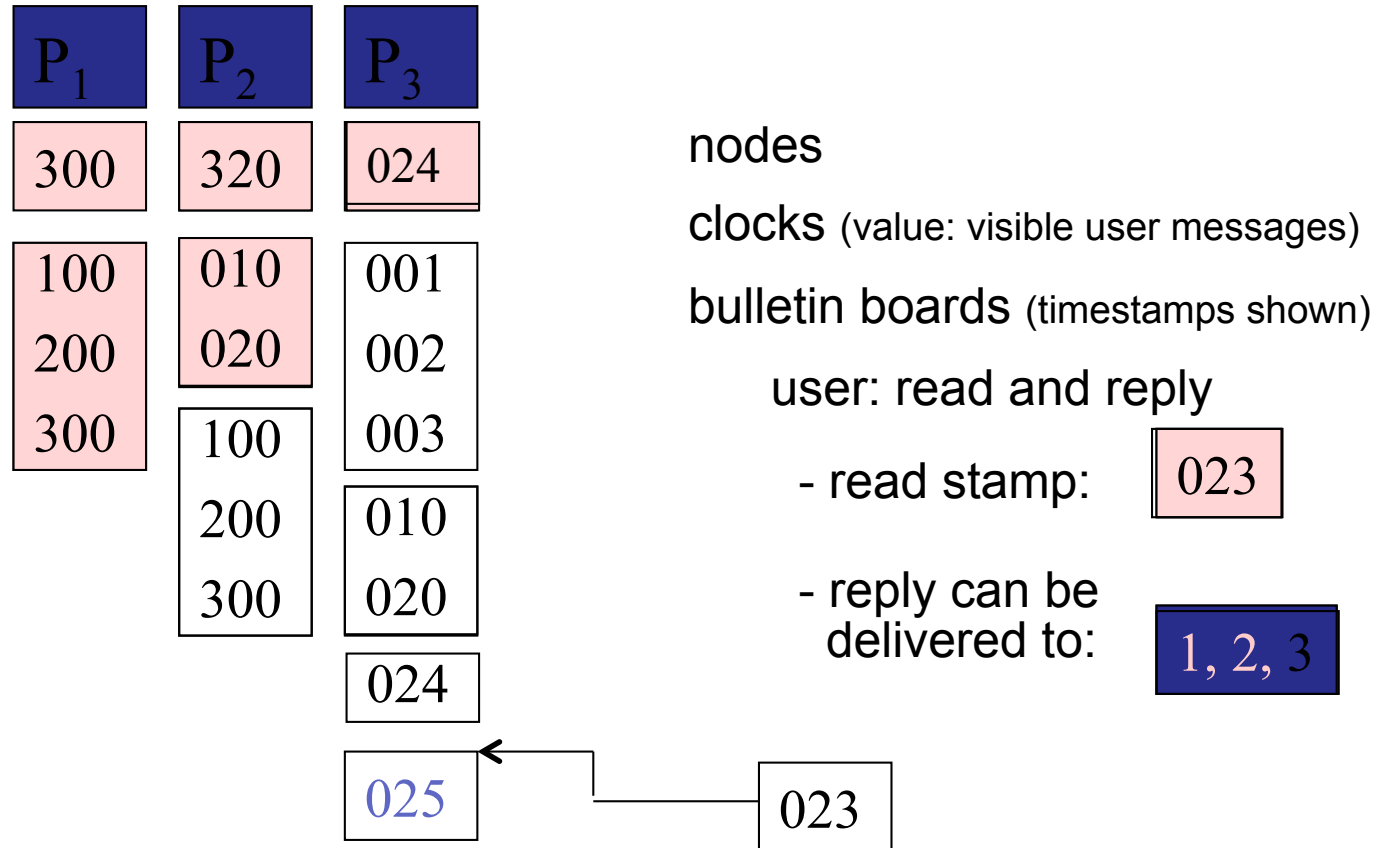


j

messages originally
received by node j



Causal Ordering of a Bulletin Board (3)





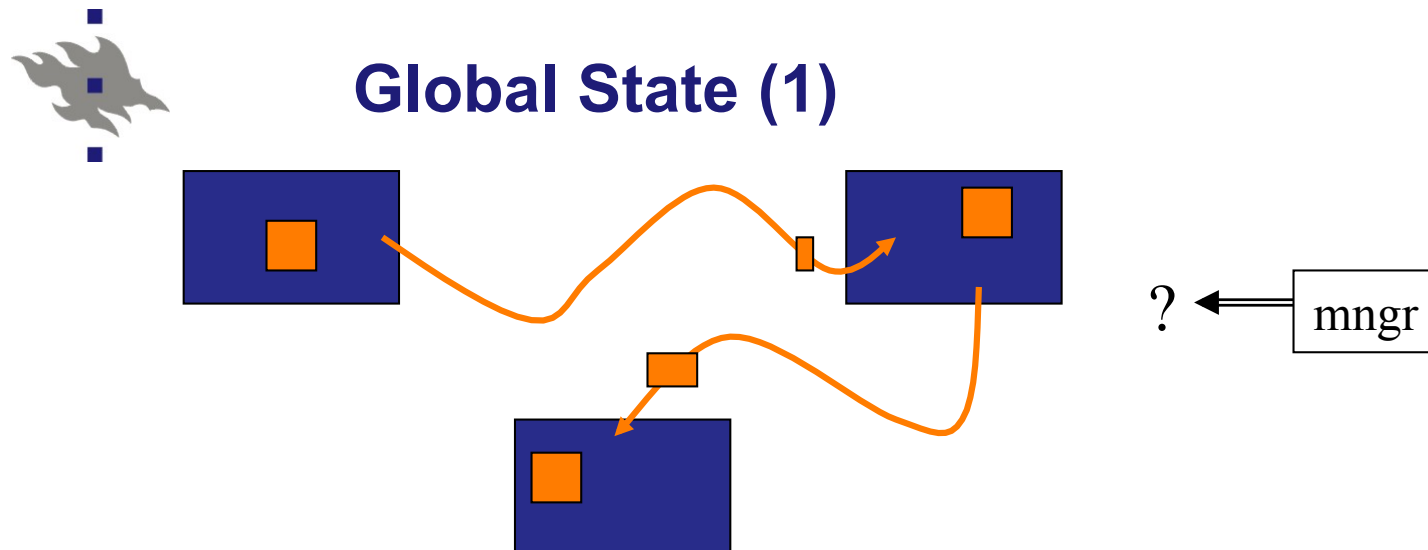
Causal Ordering of a Bulletin Board (4)

Updating of vector clocks

Process P_i

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

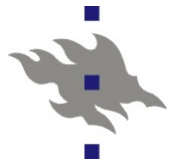
- Receiving a message with the timestamp $vt[*]$
 - Condition for delivery (to P_i from P_j):
wait until for all $k: k \neq j: V_i[k] \geq vt[k]$
 - Update at the delivery: $V_i[j] = vt[j]$



■ 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

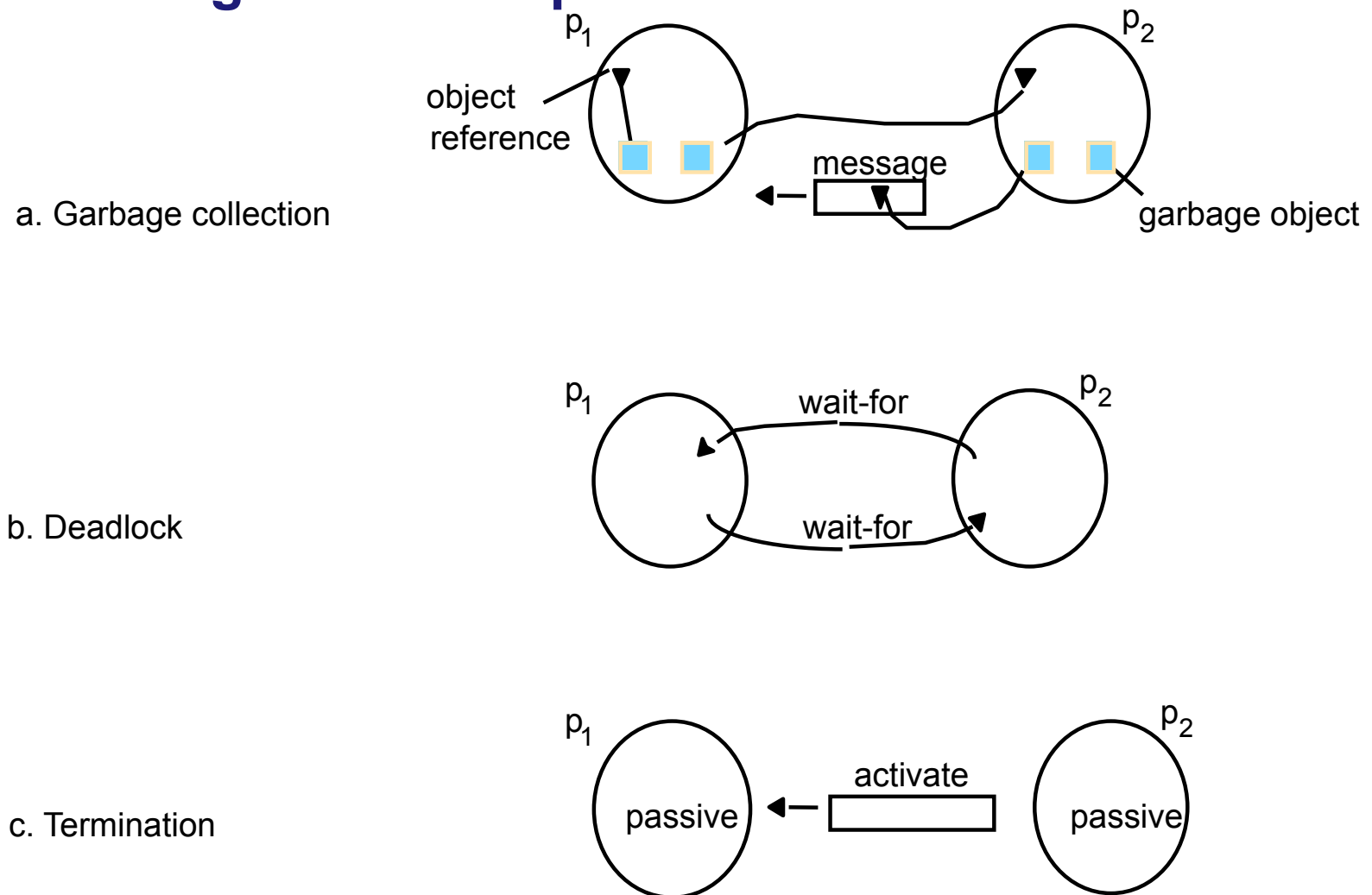


Figure 10.8



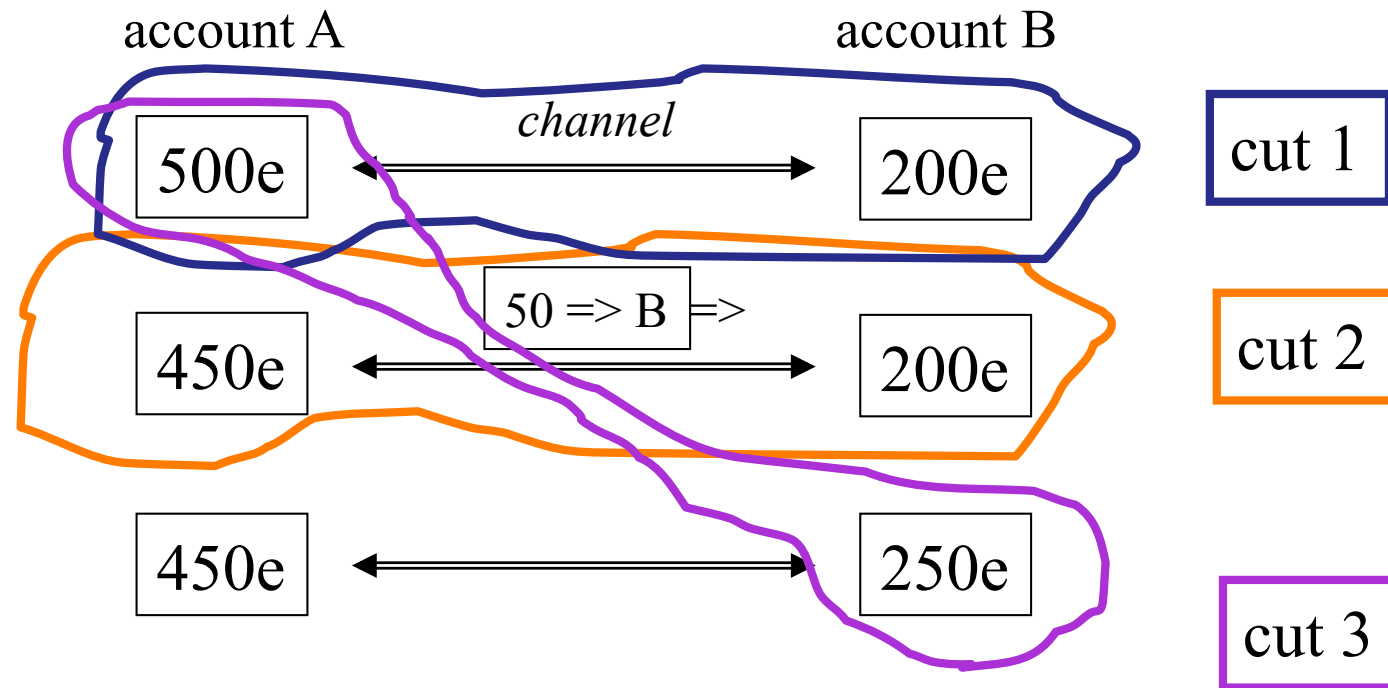
Distributed Snapshot

- 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:
 - $\{S_i\}$ might have existed \Leftrightarrow consistent with respect to some criterion
 - one possibility: consistent wrt "happened-before relation"



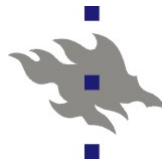
Ad-hoc State Snapshots



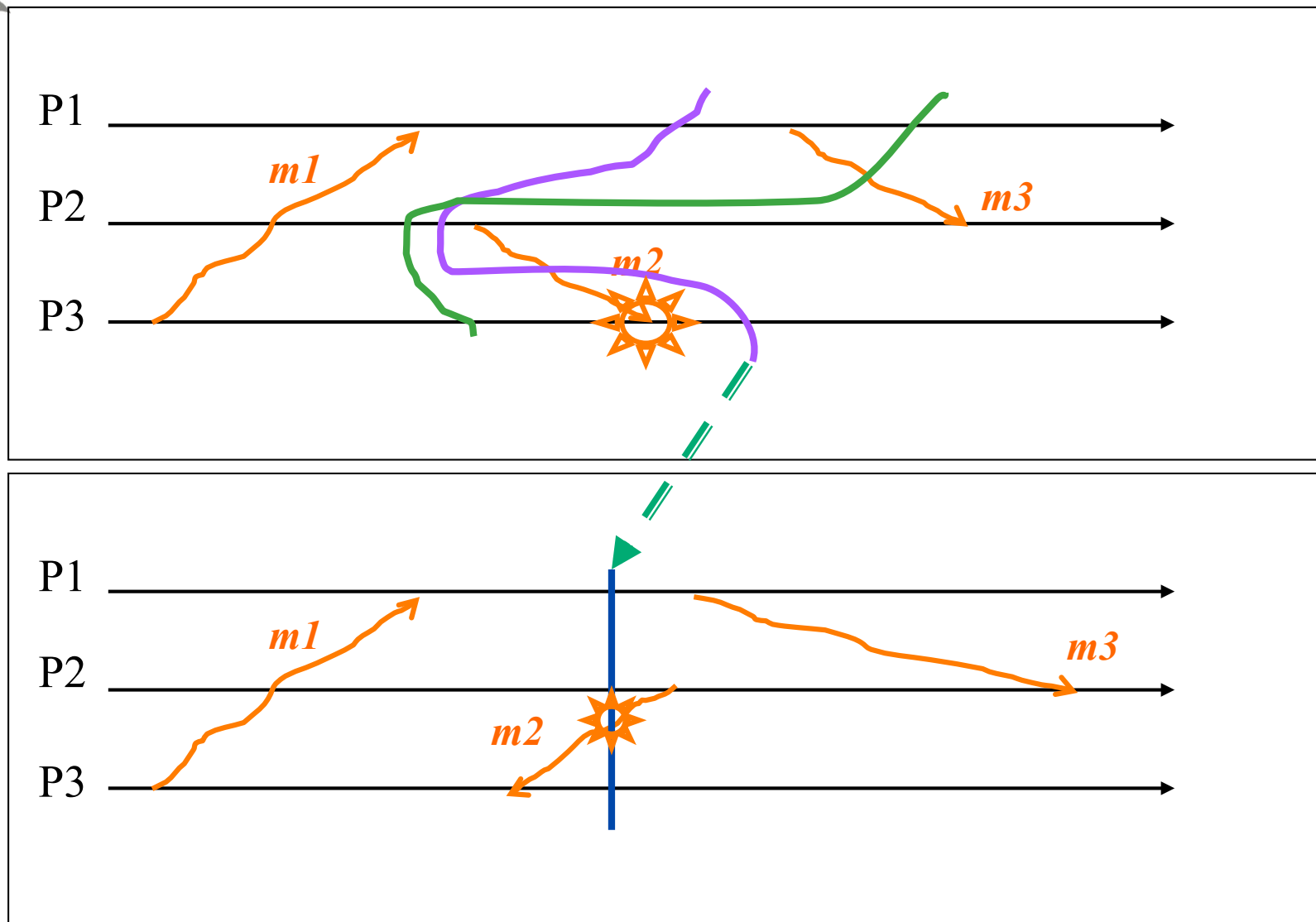
(*inconsistent or*)
strongly consistent

state changes: money transfers $A \Leftrightarrow B$

invariant: $A+B = 700$

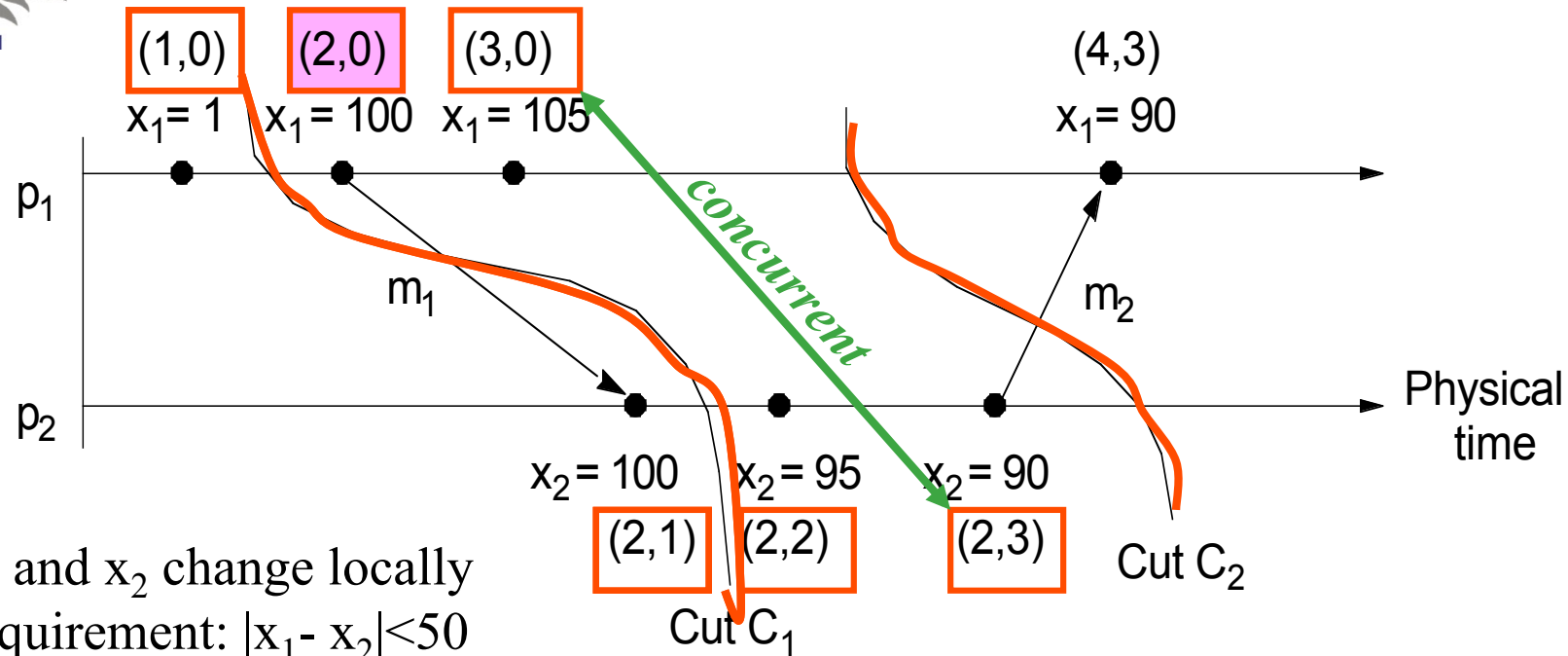


Consistent and Inconsistent Cuts





Cuts and Vector Timestamps



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

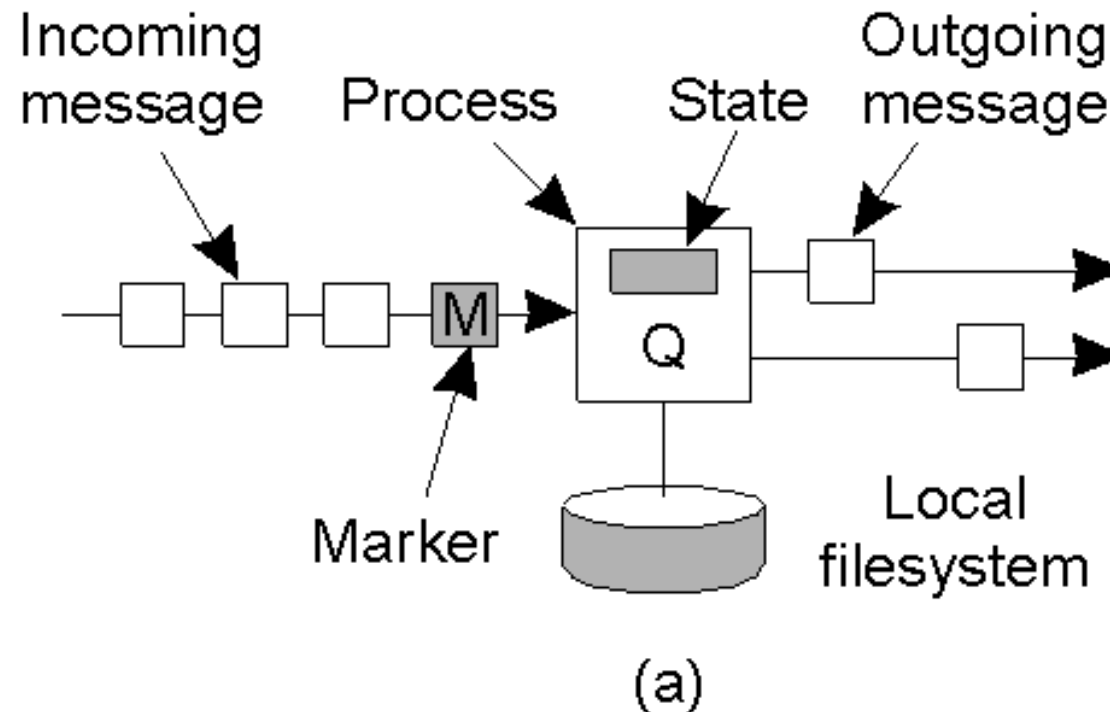
event: a change of the local x
 \Rightarrow increase the vector clock

$\{S_i\}$ 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)

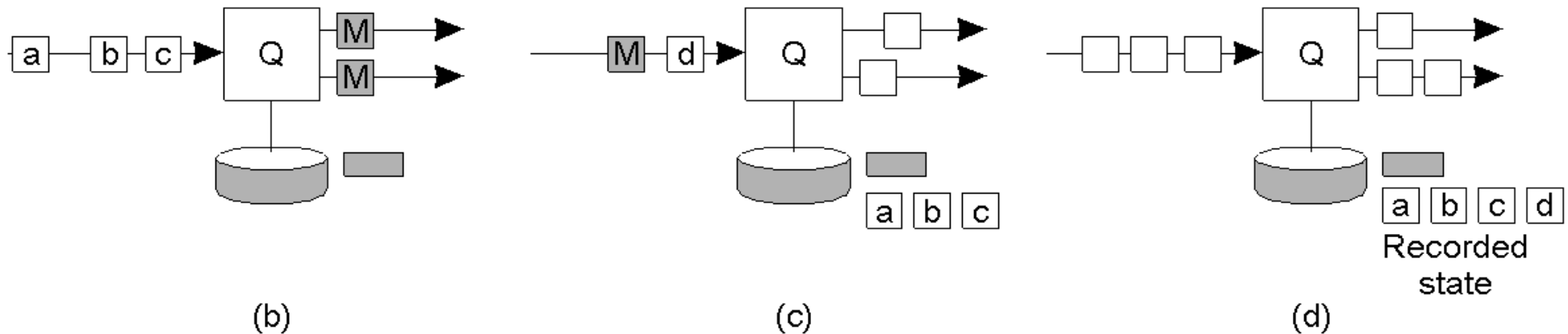


The snapshot algorithm of Chandy and Lamport

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

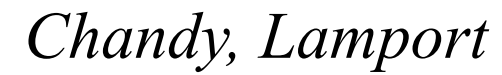
Marker sending rule for process p_i

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).

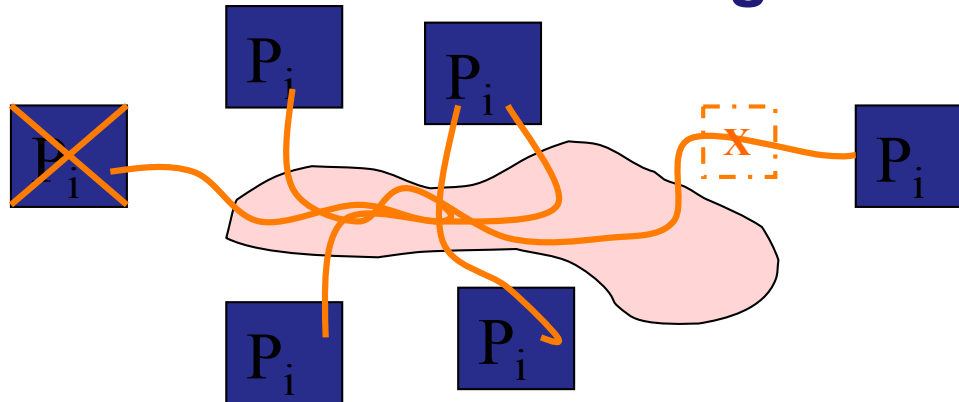
Figure 11.10



point-to-point, order-preserving connections

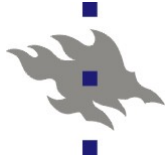


Coordination and Agreement



Coordination of functionality

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

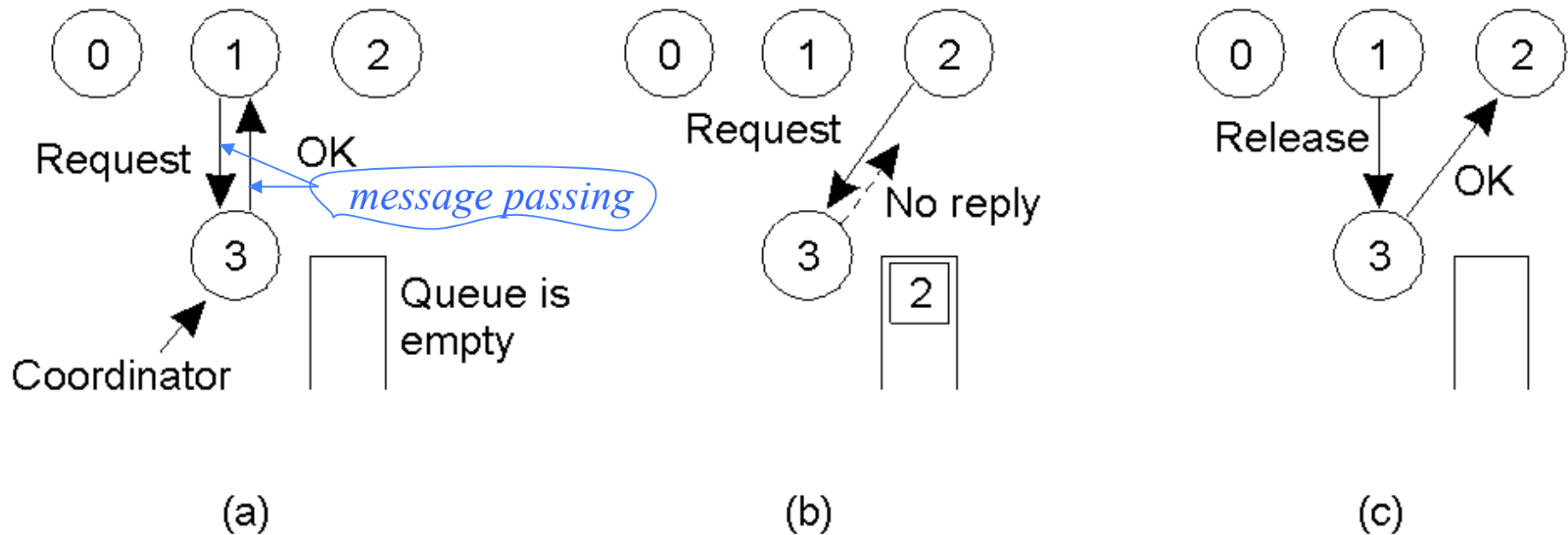


Decision Making

- 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

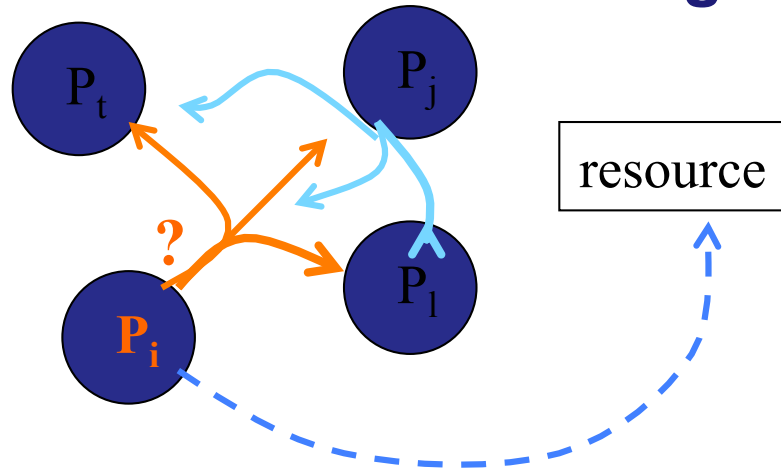


Mutual Exclusion: A Centralized Algorithm (2)

- **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;

Multicast *request* to all processes;

Wait until (number of replies received = $(N-1)$);

state := HELD;

} request processing deferred here

On receipt of a request $\langle T_i, p_i \rangle$ *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;

Fig. 11.4 **Ricart - Agrawala**

■ Multicast Synchronization ■

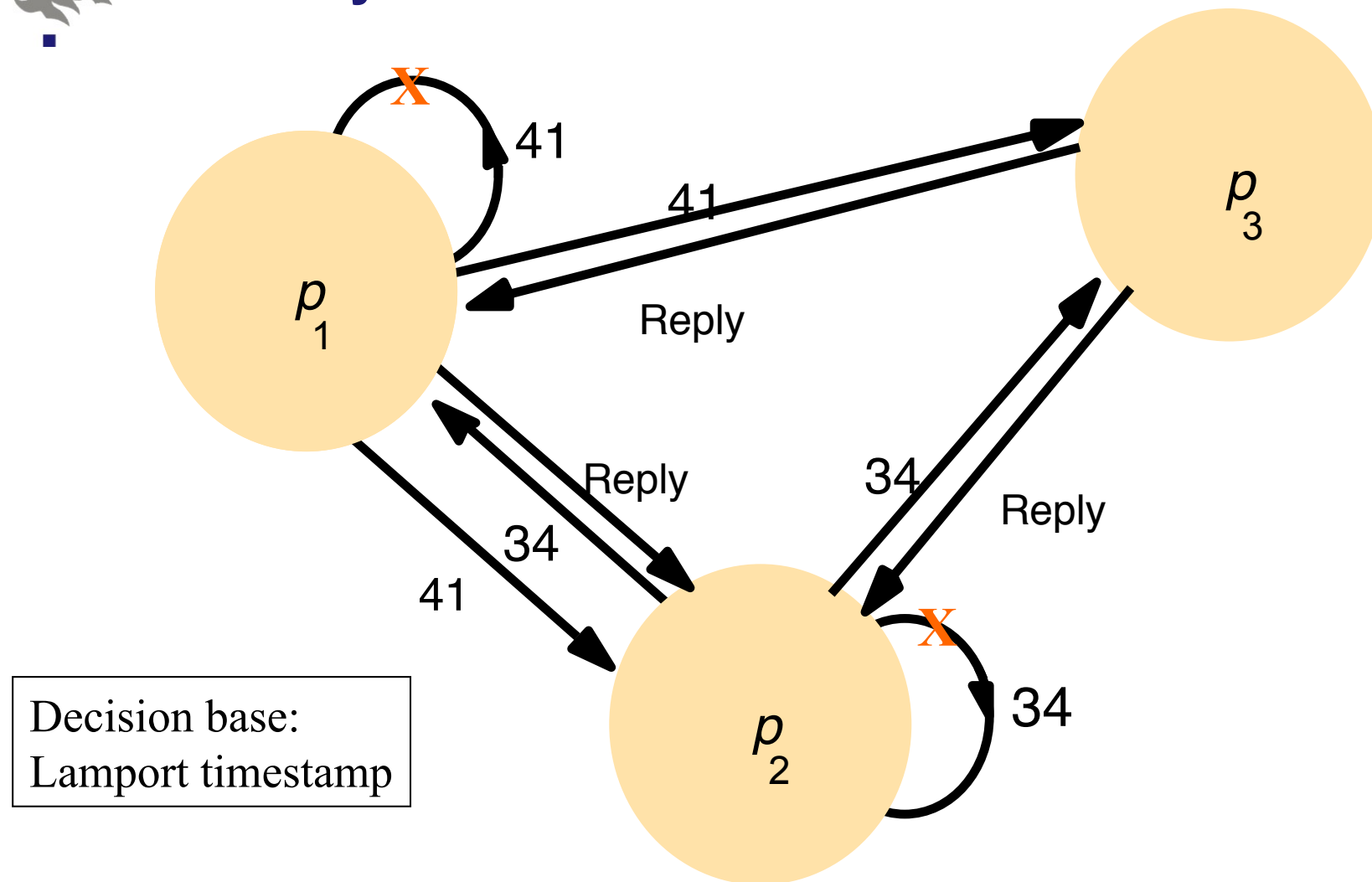
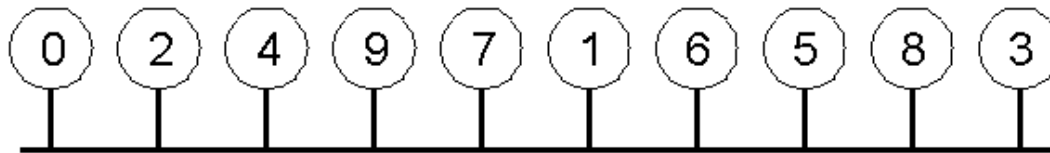


Fig. 11.5 Ricart - Agrawala

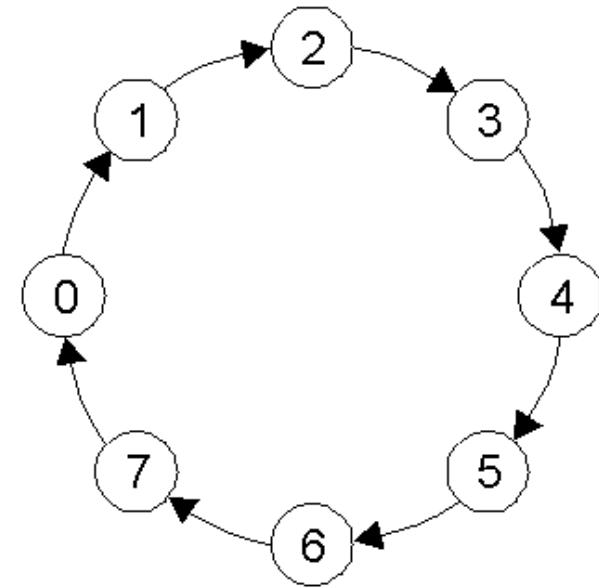


A Token Ring Algorithm



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 $\{P_i\}$
 - 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 P_i
- Several algorithms exist

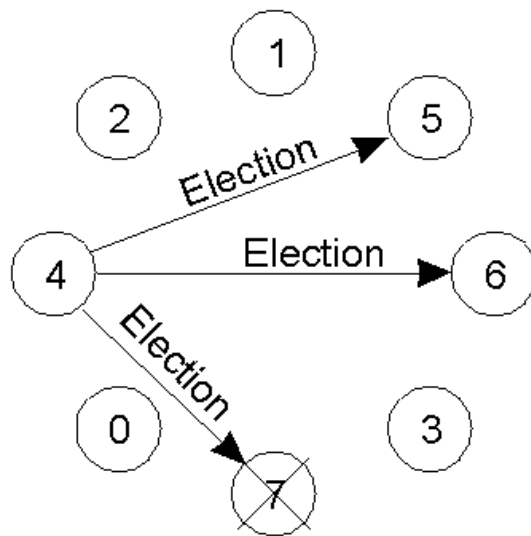


The Bully Algorithm (1)

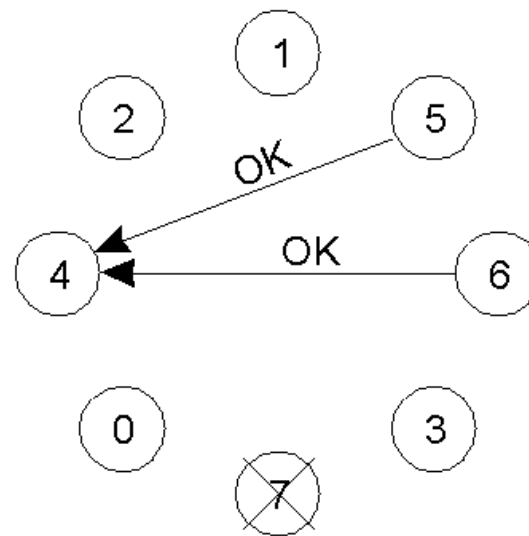
- P_i notices: coordinator lost
 1. P_i to $\{ \text{all } P_j \text{ st } P_j > P_i \}$: **ELECTION!**
 2. if no one responds $\Rightarrow P_i$ is the coordinator
 3. some P_j responds $\Rightarrow P_j$ takes over, P_i 's job is done
- P_i gets an **ELECTION!** message:
 1. reply **OK** to the sender
 2. if P_i 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)

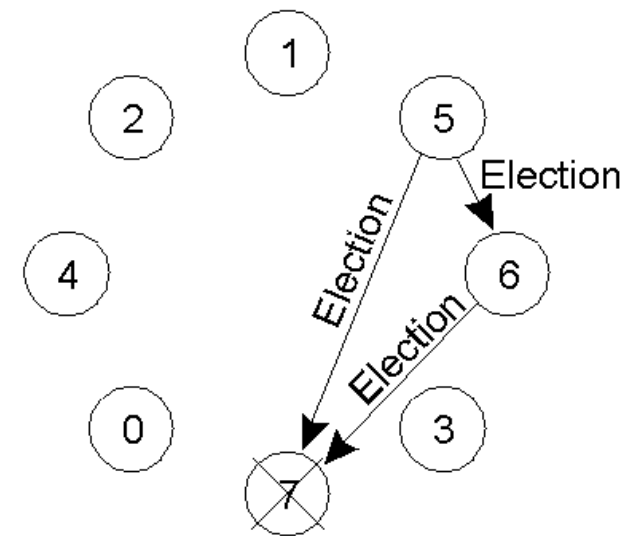


(a)



Previous coordinator
has crashed

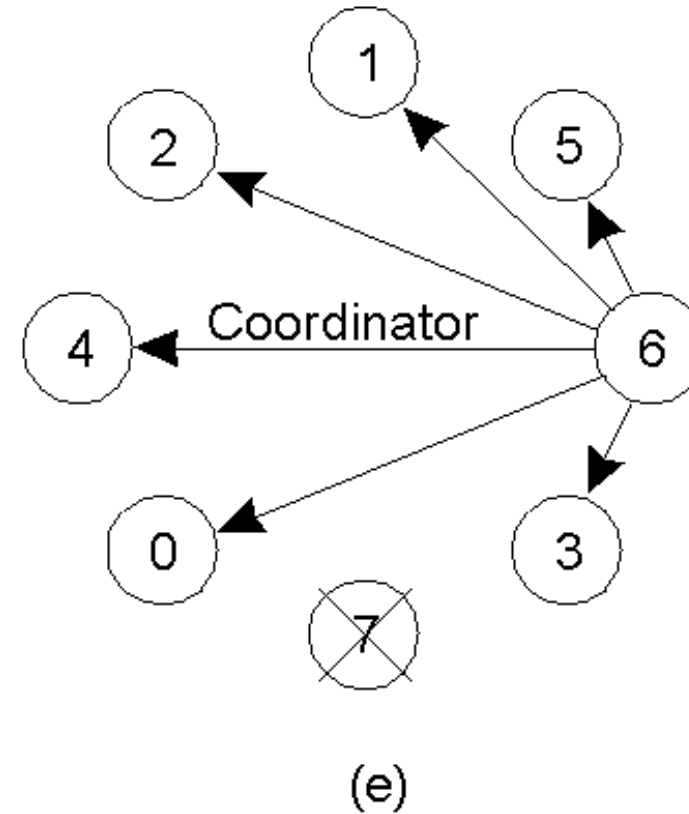
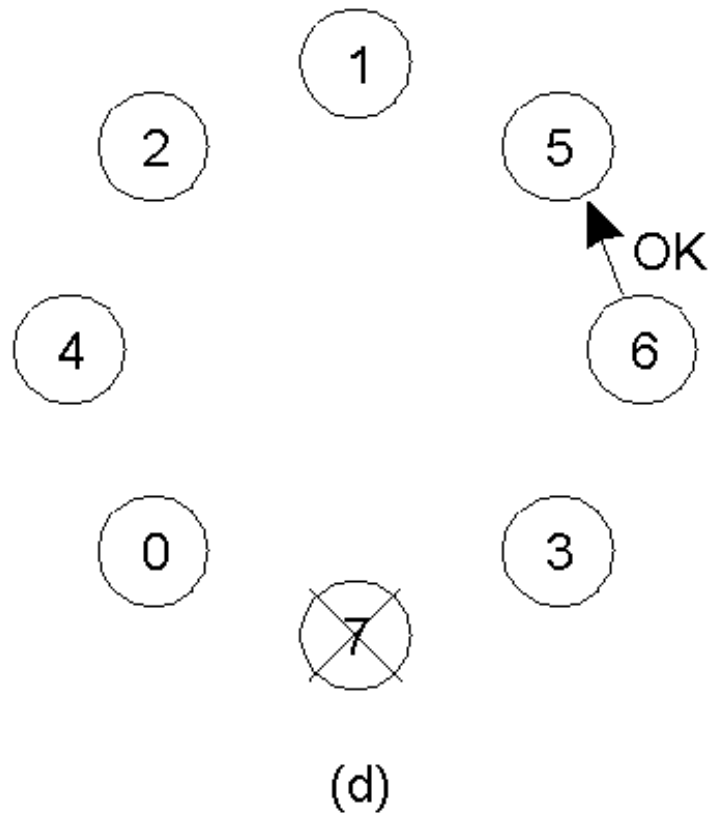
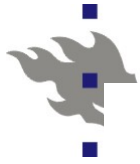
(b)



(c)

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

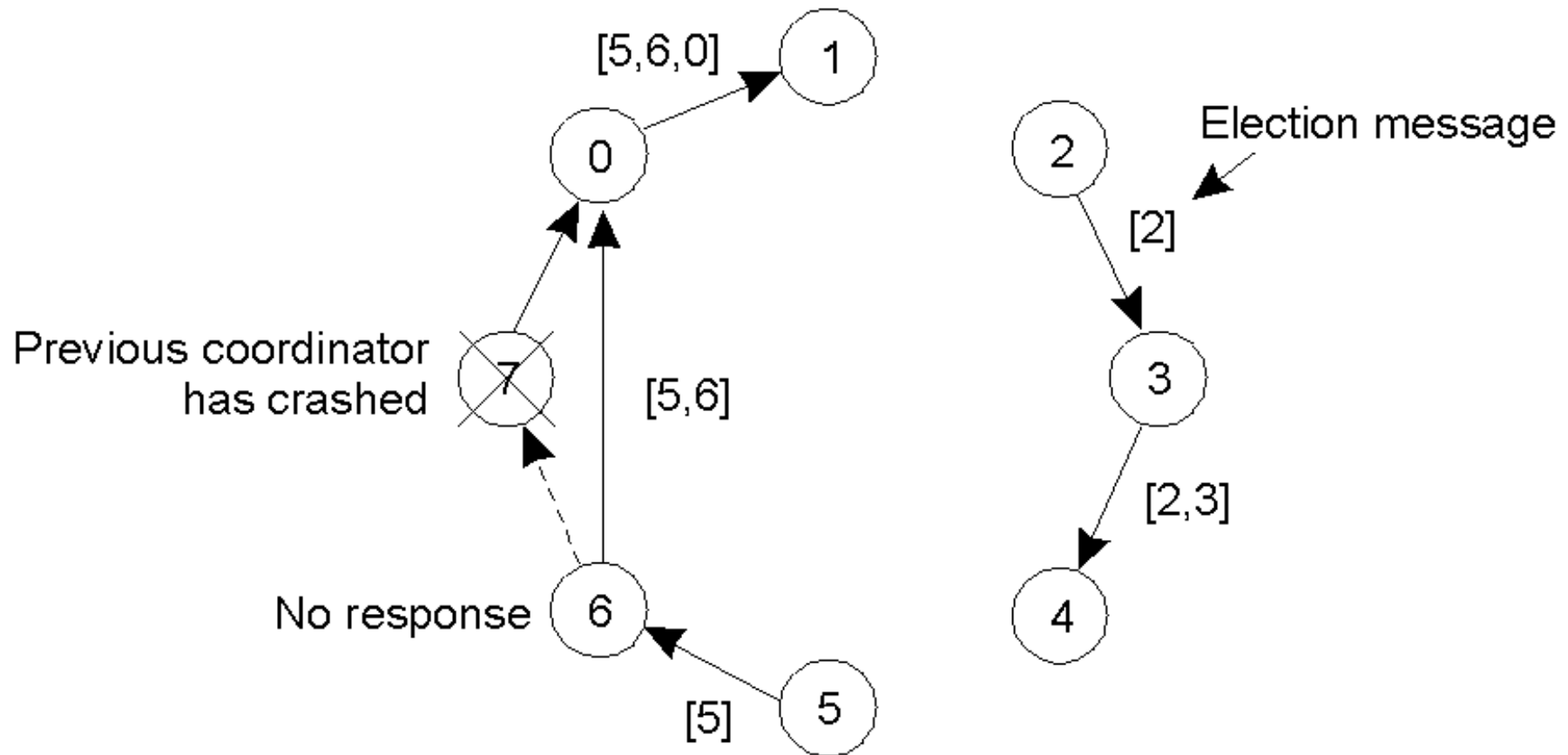


A Ring Algorithm (1)

- Group $\{P_i\}$ "fully connected"; election: ring
- P_i notices: coordinator lost
 - send **ELECTION(P_i)** to the next P
- P_j receives **ELECTION(P_i)**
 - send **ELECTION(P_i, P_j)** to successor
- ...
- P_i receives **ELECTION(..., P_i , ...)**
 - $\text{active_list} = \{\text{collect from the message}\}$
 - $\text{NC} = \max \{\text{active_list}\}$
 - send **COORDINATOR(NC; active_list)** to the next P
- ...



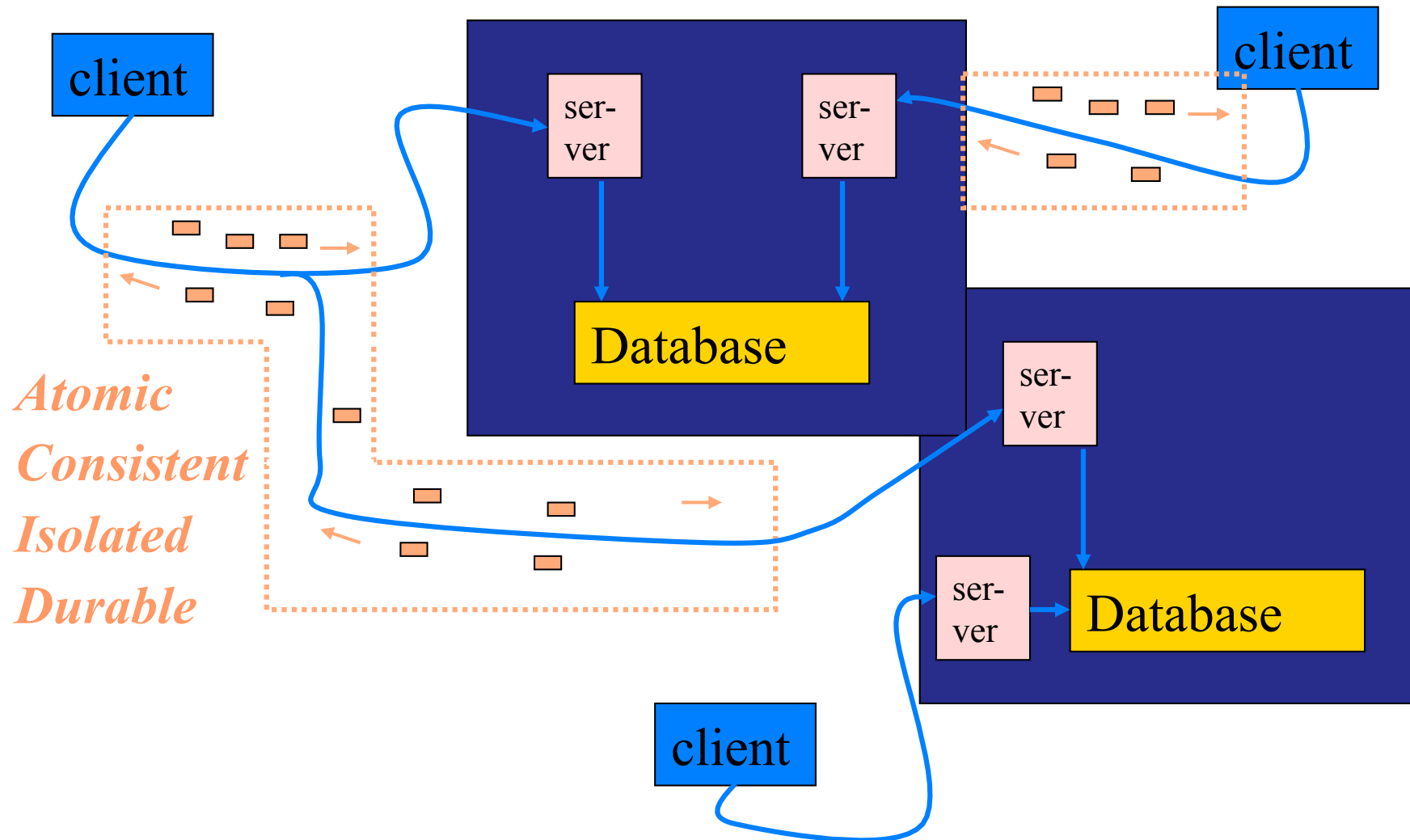
A Ring Algorithm (2)



Election algorithm using a ring.

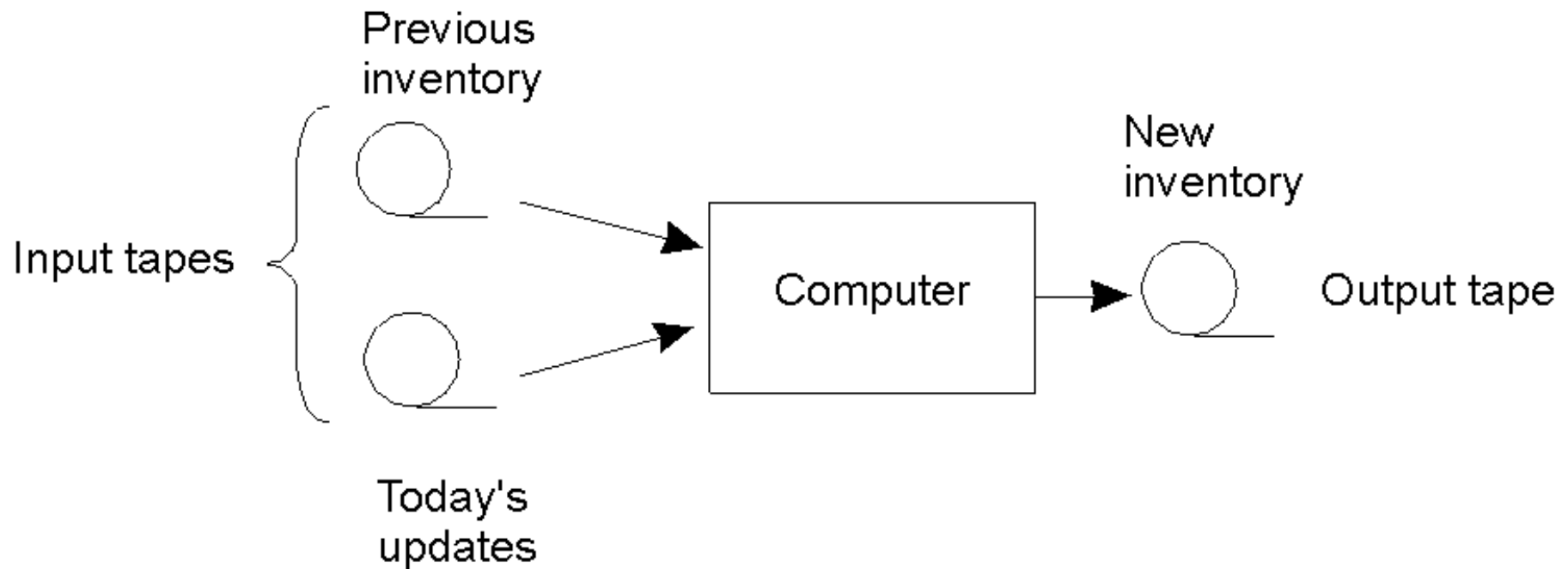


Distributed Transactions





The Transaction Model (1)



Updating a master tape is fault tolerant.



The Transaction Model (2)

Primitive	Description
BEGIN_TRANSACTION	Make the start of a transaction
END_TRANSACTION	Terminate the transaction and try to commit
ABORT_TRANSACTION	Kill the transaction and restore the old values
READ	Read data from a file, a table, or otherwise
WRITE	Write data to a file, a table, or otherwise

Examples of primitives for transactions.



The Transaction Model (3)

BEGIN_TRANSACTION

reserve WP -> JFK;

reserve JFK -> Nairobi;

reserve Nairobi -> Malindi;

END_TRANSACTION

(a)

BEGIN_TRANSACTION

reserve WP -> JFK;

reserve JFK -> Nairobi;

reserve Nairobi -> Malindi full =>

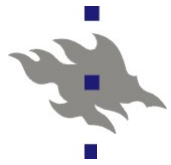
ABORT_TRANSACTION

(b)

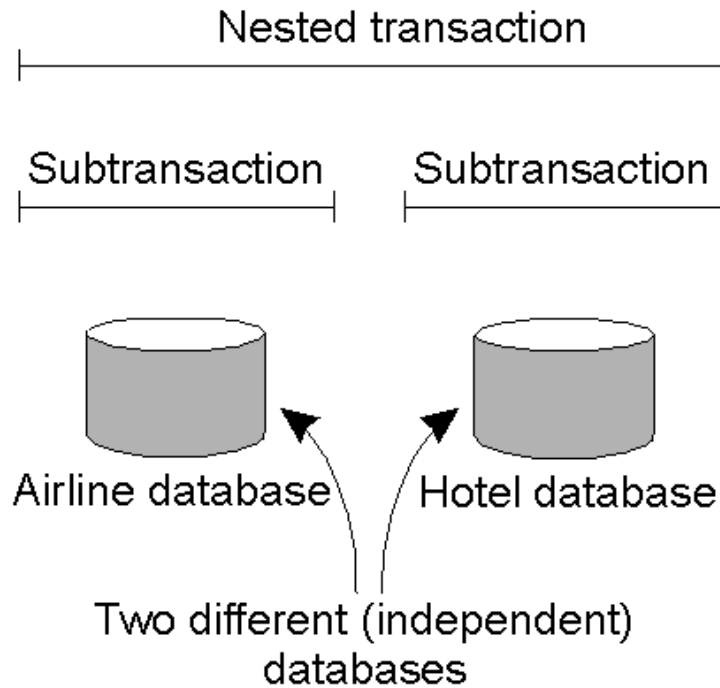
- a) Transaction to reserve three flights commits
- b) Transaction aborts when third flight is unavailable

Note:

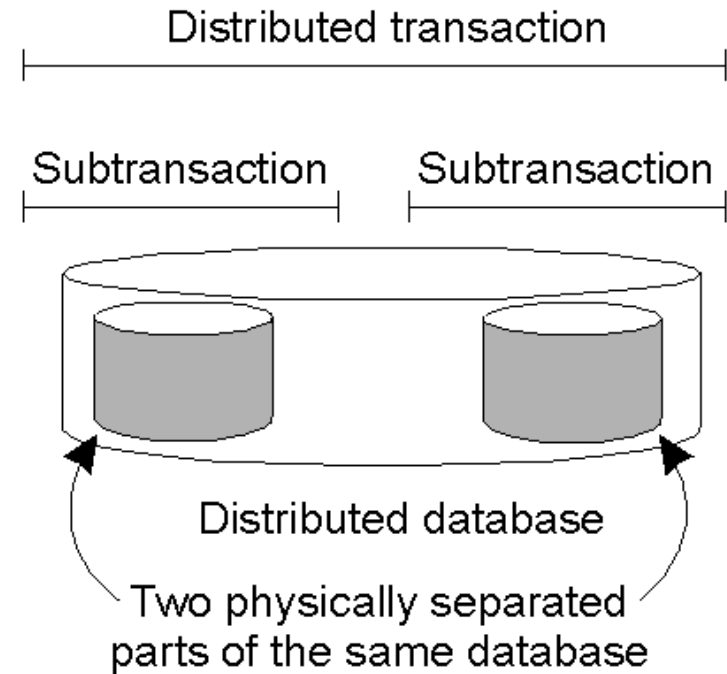
- a transaction must have a name
- the name must be attached to each operation, which belongs to the transaction



Distributed Transactions



(a)



(b)

- a) A nested transaction
- b) A distributed transaction



Concurrent Transactions

- Concurrent transactions proceed in parallel
- Shared data (database)
- Concurrency-related problems (if no further transaction control):
 - lost updates
 - inconsistent retrievals
 - dirty reads
 - etc.



The lost update problem

Transaction <i>T</i> :	Transaction <i>U</i> :
<i>balance</i> = <i>b.getBalance</i> (); <i>b.setBalance</i> (<i>balance</i> *1.1); <i>a.withdraw</i> (<i>balance</i> /10)	<i>balance</i> = <i>b.getBalance</i> (); <i>b.setBalance</i> (<i>balance</i> *1.1); <i>c.withdraw</i> (<i>balance</i> /10)
<i>balance</i> = <i>b.getBalance</i> (); \$200 <i>b.setBalance</i> (<i>balance</i> *1.1); \$220 <i>a.withdraw</i> (<i>balance</i> /10) \$80	<i>balance</i> = <i>b.getBalance</i> (); \$200 <i>b.setBalance</i> (<i>balance</i> *1.1); \$220 <i>c.withdraw</i> (<i>balance</i> /10) \$280

Figure 12.5 Initial values **a**: \$100, **b**: \$200 **c**: \$300



The inconsistent retrievals problem

Transaction V :		Transaction W :	
<i>a.withdraw(100)</i> <i>b.deposit(100)</i>		<i>aBranch.branchTotal()</i>	
<i>a.withdraw(100);</i>	\$100	<i>total = a.getBalance()</i>	\$100
		<i>total = total+b.getBalance()</i>	\$300
		<i>total = total+c.getBalance()</i>	
<i>b.deposit(100)</i>	\$300	⋮	

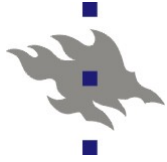
Figure 12.6 Initial values **a**: \$200, **b**: \$200



A serially equivalent interleaving of *T* and *U*

Transaction <i>T</i> :	Transaction <i>U</i> :
<i>balance</i> = <i>b.getBalance()</i>	<i>balance</i> = <i>b.getBalance()</i>
<i>b.setBalance(balance*1.1)</i>	<i>b.setBalance(balance*1.1)</i>
<i>a.withdraw(balance/10)</i>	<i>c.withdraw(balance/10)</i>
<i>balance</i> = <i>b.getBalance()</i> \$200	
<i>b.setBalance(balance*1.1)</i> \$220	
	<i>balance</i> = <i>b.getBalance()</i> \$220
	<i>b.setBalance(balance*1.1)</i> \$242
<i>a.withdraw(balance/10)</i> \$80	
	<i>c.withdraw(balance/10)</i> \$278

Figure 12.7 The result corresponds the sequential execution *T*, *U*



A dirty read when transaction *T* aborts

Transaction <i>T</i> :	Transaction <i>U</i> :
<i>a.getBalance()</i> <i>a.setBalance(balance + 10)</i>	<i>a.getBalance()</i> <i>a.setBalance(balance + 20)</i>
<i>balance = a.getBalance()</i> \$100 <i>a.setBalance(balance + 10)</i> \$110	<i>balance = a.getBalance()</i> \$110 <i>a.setBalance(balance + 20)</i> \$130 <i>commit transaction</i>
<i>abort transaction</i>	

Figure 12.11



Methods for ACID

■ Atomic

- private workspace,
- writeahead log

■ Consistent

concurrency control => serialization

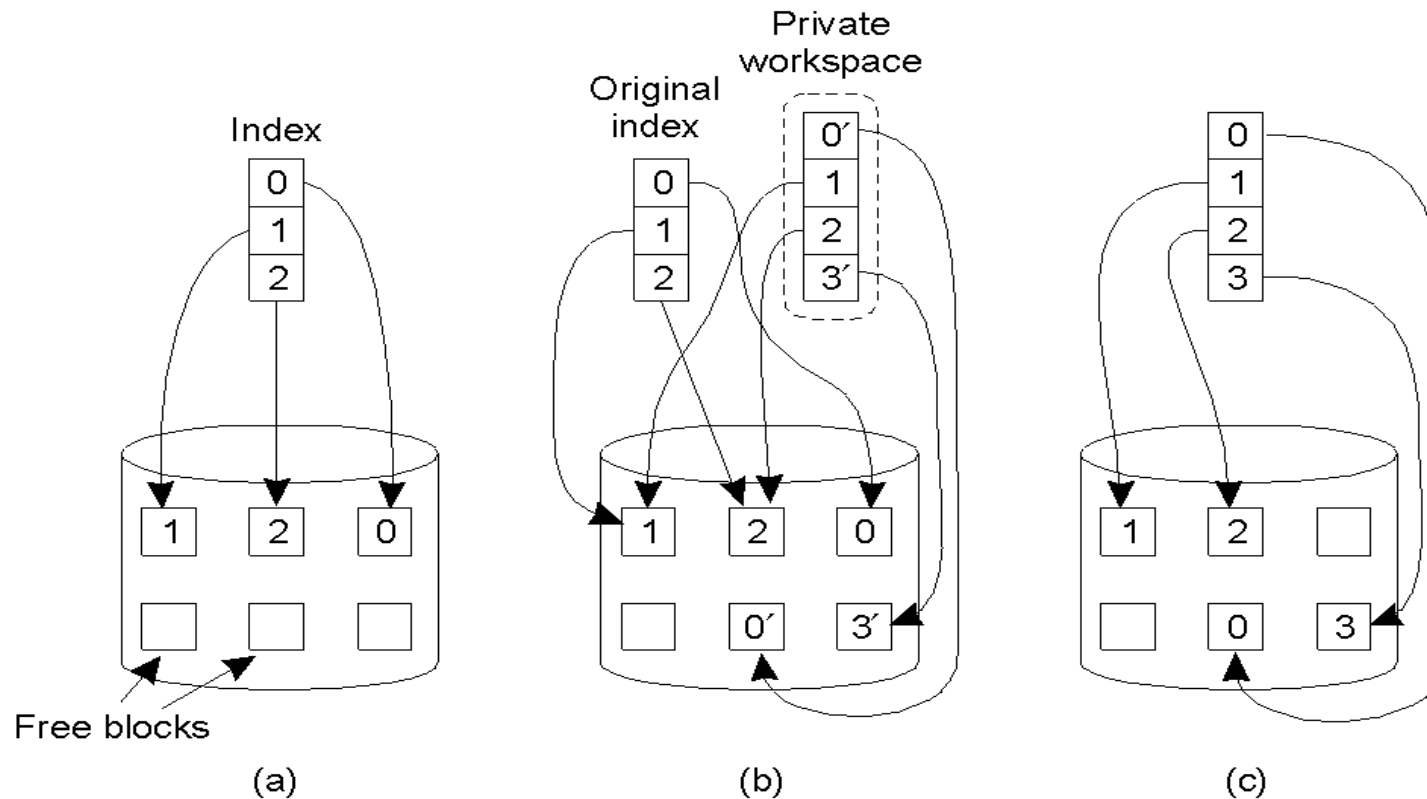
- locks
- timestamp-based control
- optimistic concurrency control

■ Isolated (see: atomic, consistent)

■ Durable (see: Fault tolerance)



Private Workspace



- a) The file index and disk blocks for a three-block file
- b) The situation after a transaction has modified block 0 and appended block 3
- c) After committing



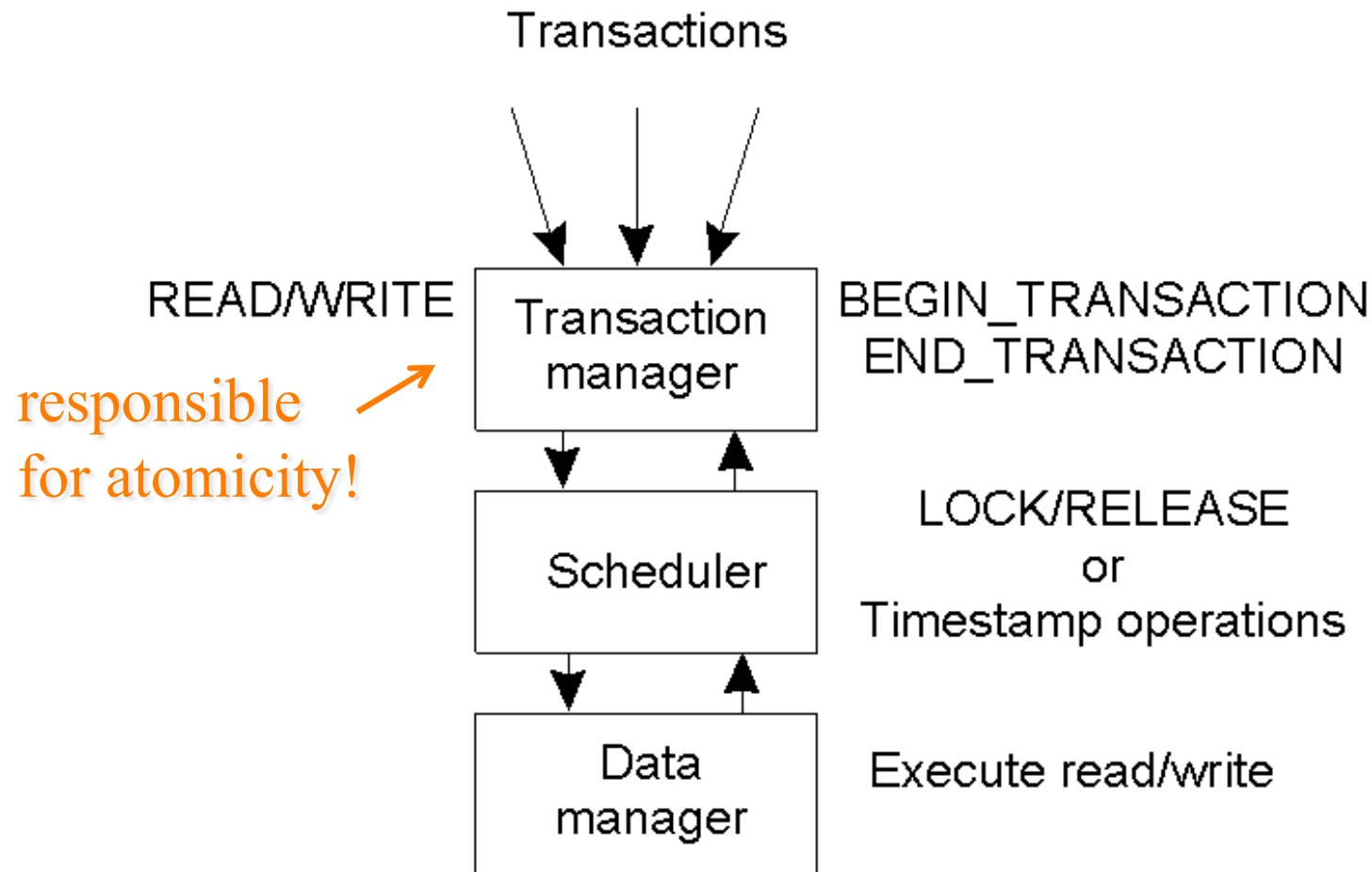
Writeahead Log

x = 0;	Log	Log	Log
y = 0;			
BEGIN_TRANSACTION;			
x = x + 1;	[x = 0 / 1]	[x = 0 / 1]	[x = 0 / 1]
y = y + 2		[y = 0/2]	[y = 0/2]
x = y * y;			[x = 1/4]
END_TRANSACTION;			
(a)	(b)	(c)	(d)

- a) A transaction
- b) – d) The log before each statement is executed



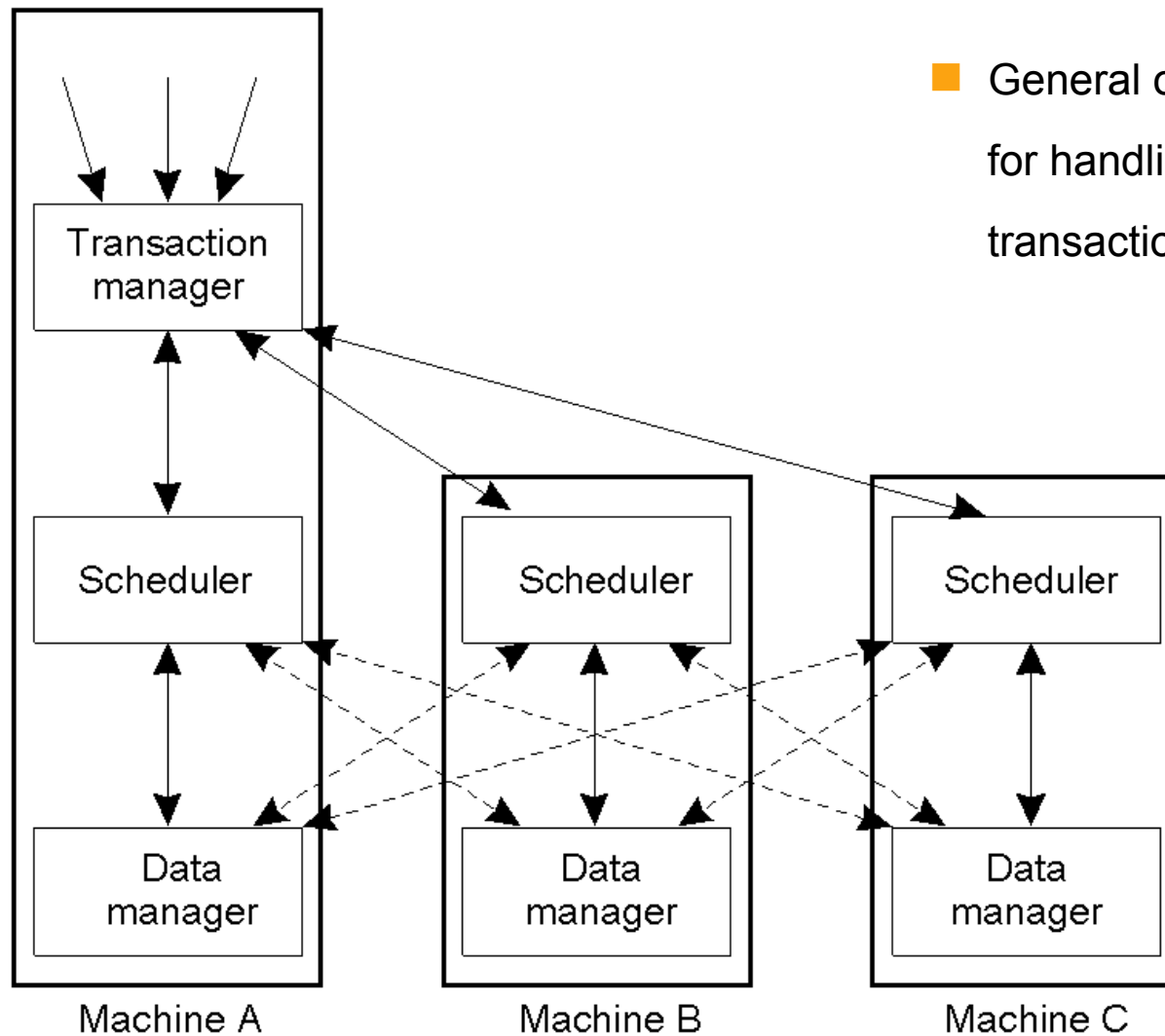
Concurrency Control (1)



General organization of managers for handling transactions.



Concurrency Control (2)



- General organization of managers for handling distributed transactions.



Serializability

BEGIN_TRANSACTION

$x = 0;$

$x = x + 1;$

END_TRANSACTION

(a)

BEGIN_TRANSACTION

$x = 0;$

$x = x + 2;$

END_TRANSACTION

(b)

BEGIN_TRANSACTION

$x = 0;$

$x = x + 3;$

END_TRANSACTION

(c)

Schedule 1	$x = 0; x = x + 1; x = 0; x = x + 2; x = 0; x = x + 3$	Legal
Schedule 2	$x = 0; x = 0; x = x + 1; x = x + 2; x = 0; x = x + 3;$	Legal
Schedule 3	$x = 0; x = 0; x = x + 1; x = 0; x = x + 2; x = x + 3;$	Illegal

(d)

a) – c) Three transactions T_1 , T_2 , and T_3 ; d) Possible schedules
Legal: there exists a **serial execution** leading to the **same result**.



Implementation of Serializability

Decision making: the transaction scheduler

■ Locks

- data item ~ lock
- request for operation
 - a corresponding lock (read/write) is granted **OR**
 - the operation is delayed until the lock is released

■ Pessimistic timestamp ordering

- transaction \leq timestamp; data item \leq R-, W-stamps
- each request for operation:
 - check serializability
 - continue, wait, abort

■ Optimistic timestamp ordering

- serializability check: at END_OF_TRANSACTION, only



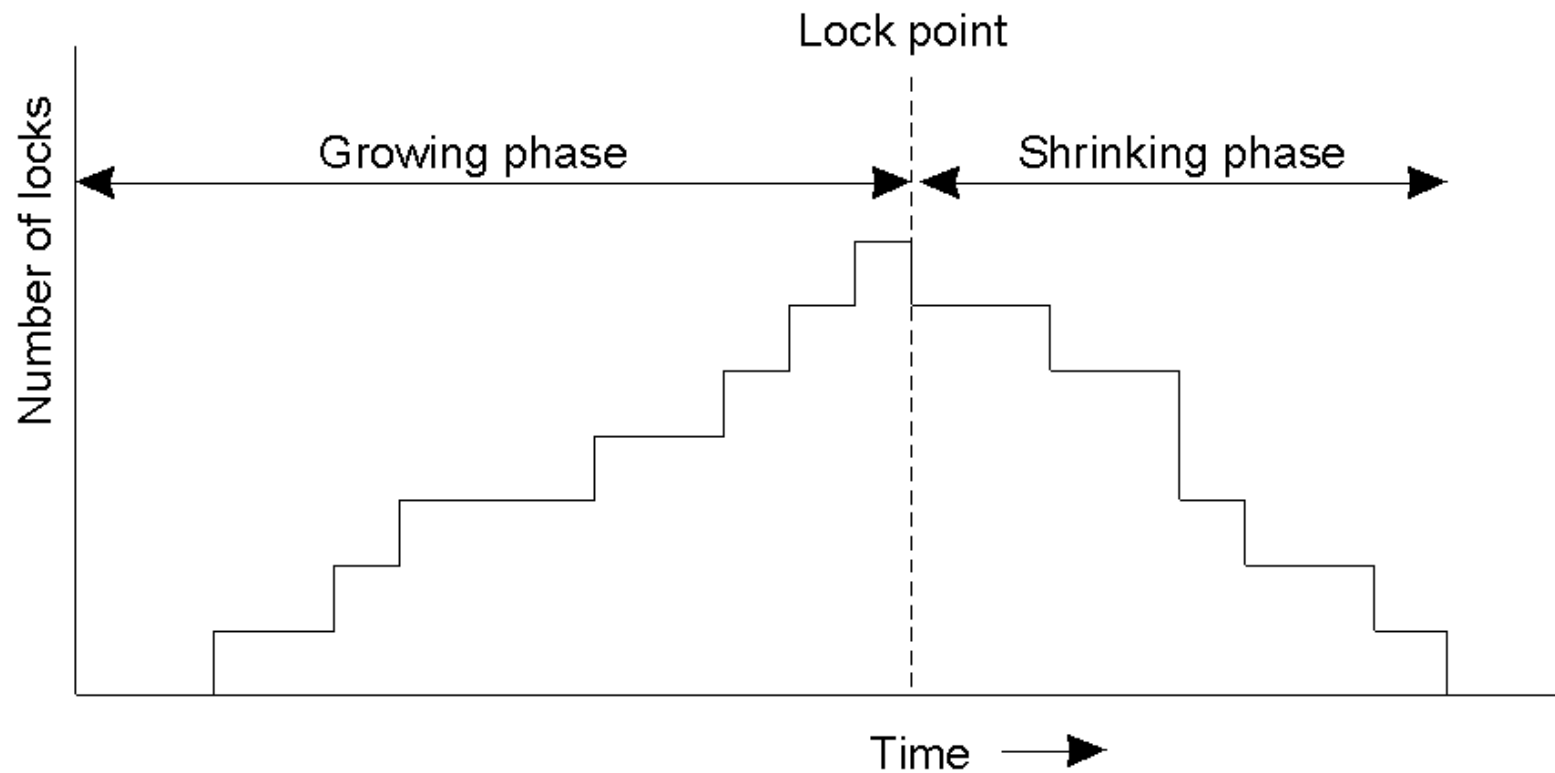
Transactions *T* and *U* with Exclusive Locks

Transaction <i>T</i> :		Transaction <i>U</i> :	
<i>balance = b.getBalance()</i> <i>b.setBalance(bal*1.1)</i> <i>a.withdraw(bal/10)</i>		<i>balance = b.getBalance()</i> <i>b.setBalance(bal*1.1)</i> <i>c.withdraw(bal/10)</i>	
Operations	Locks	Operations	Locks
<i>openTransaction</i>		<i>openTransaction</i>	
<i>bal = b.getBalance()</i>	lock <i>B</i>	<i>bal = b.getBalance()</i>	waits for <i>T</i> 's lock on <i>B</i>
<i>b.setBalance(bal*1.1)</i>		...	
<i>a.withdraw(bal/10)</i>	lock <i>A</i>		lock <i>B</i>
<i>closeTransaction</i>	unlock <i>A</i> , <i>B</i>		
		<i>b.setBalance(bal*1.1)</i>	
		<i>c.withdraw(bal/10)</i>	lock <i>C</i>
		<i>closeTransaction</i>	unlock <i>B</i> , <i>C</i>

Figure 12.14



Two-Phase Locking (1)

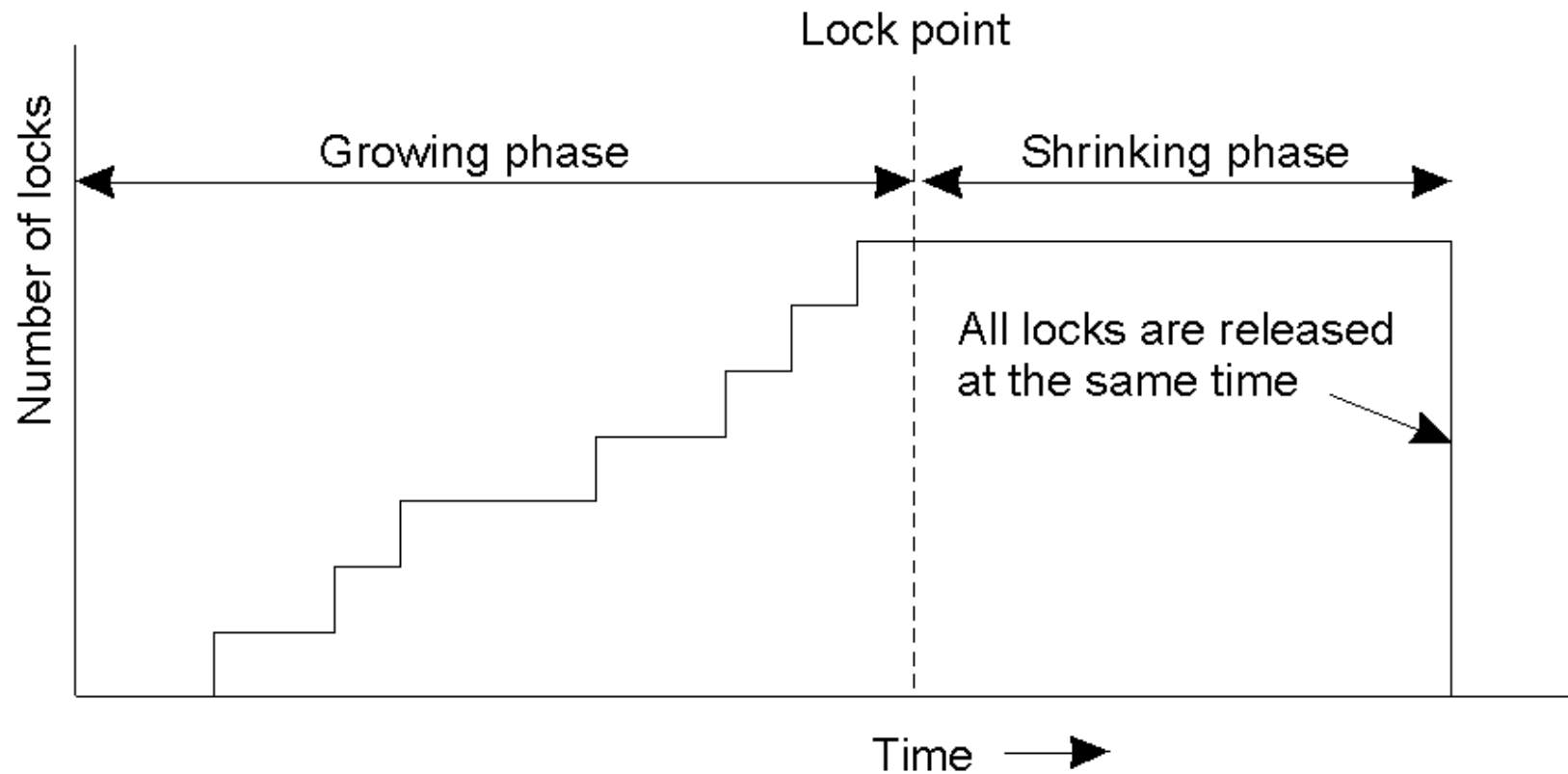


Two-phase locking (2PL).

Problem: dirty reads?



Two-Phase Locking (2)



Strict two-phase locking.

Centralized or distributed.



Pessimistic Timestamp Ordering

- Transaction timestamp $ts(T)$
 - given at BEGIN_TRANSACTION (must be unique!)
 - attached to each operation
- Data object timestamps $ts_{RD}(x)$, $ts_{WR}(x)$
 - $ts_{RD}(x) = ts(T)$ of the last T which read x
 - $ts_{WR}(x) = ts(T)$ of the last T which changed x
- Required serial equivalence: $ts(T)$ order of T 's



Pessimistic Timestamp Ordering

- The rules:
 - you are **not** allowed to **change** what
later transactions already have seen (or changed!)
 - you are **not** allowed to **read** what
later transactions already have changed
- Conflicting operations
 - process the older transaction first
 - violation of rules: the transaction is aborted (i.e,
the older one: it is too late!)
 - if tentative versions are used, the final decision is made at
END_TRANSACTION

Write Operations and Timestamps

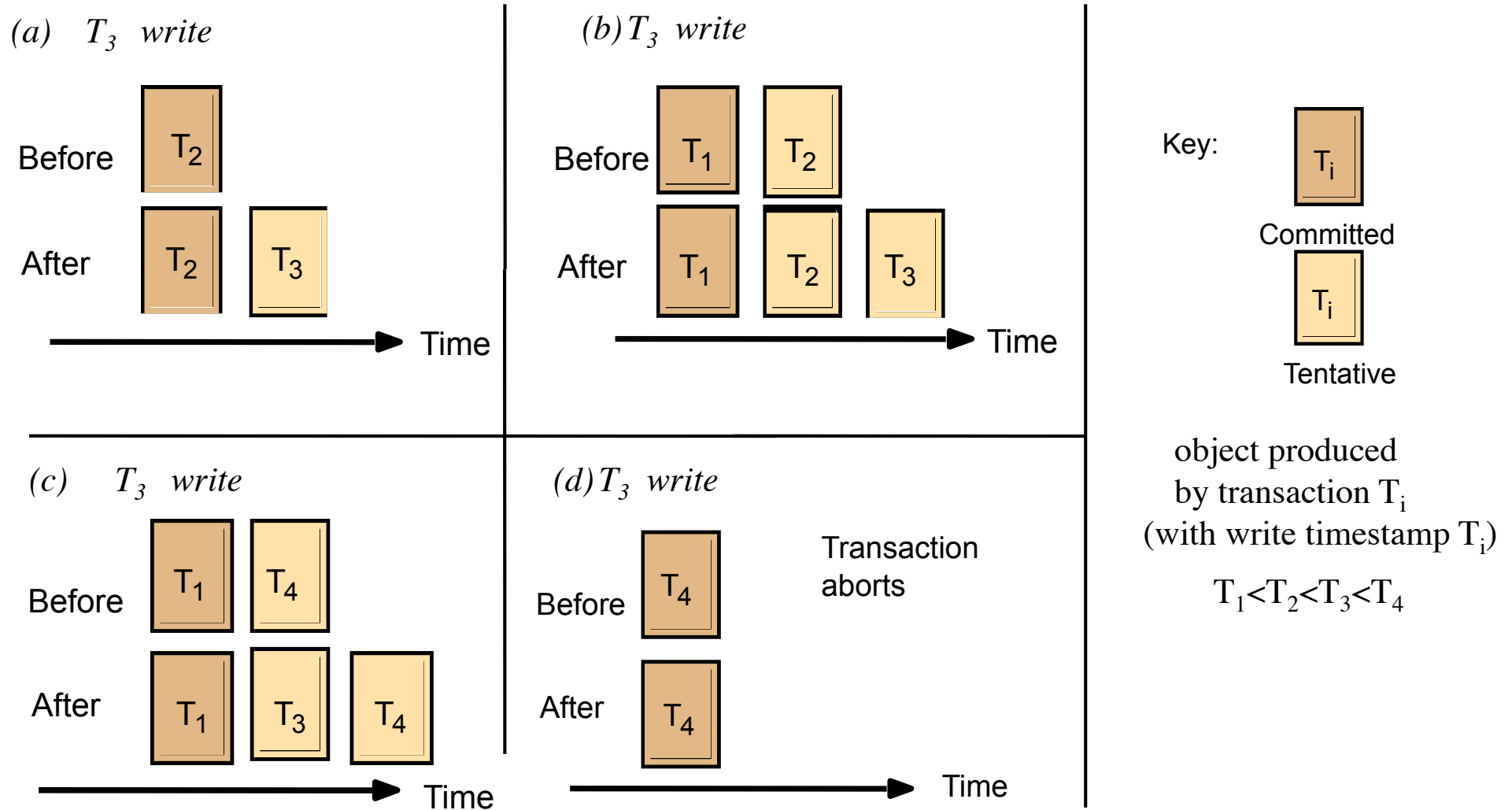


Figure 13.30



Optimistic Timestamp Ordering

■ Problems with locks

- general overhead (must be done whether needed or not)
- possibility of deadlock
- duration of locking (=> end of the transaction)

■ Problems with pessimistic timestamps

- overhead

■ Alternative

- proceed to the end of the transaction
- validate
- applicable if the probability of conflicts is low



Validation of Transactions

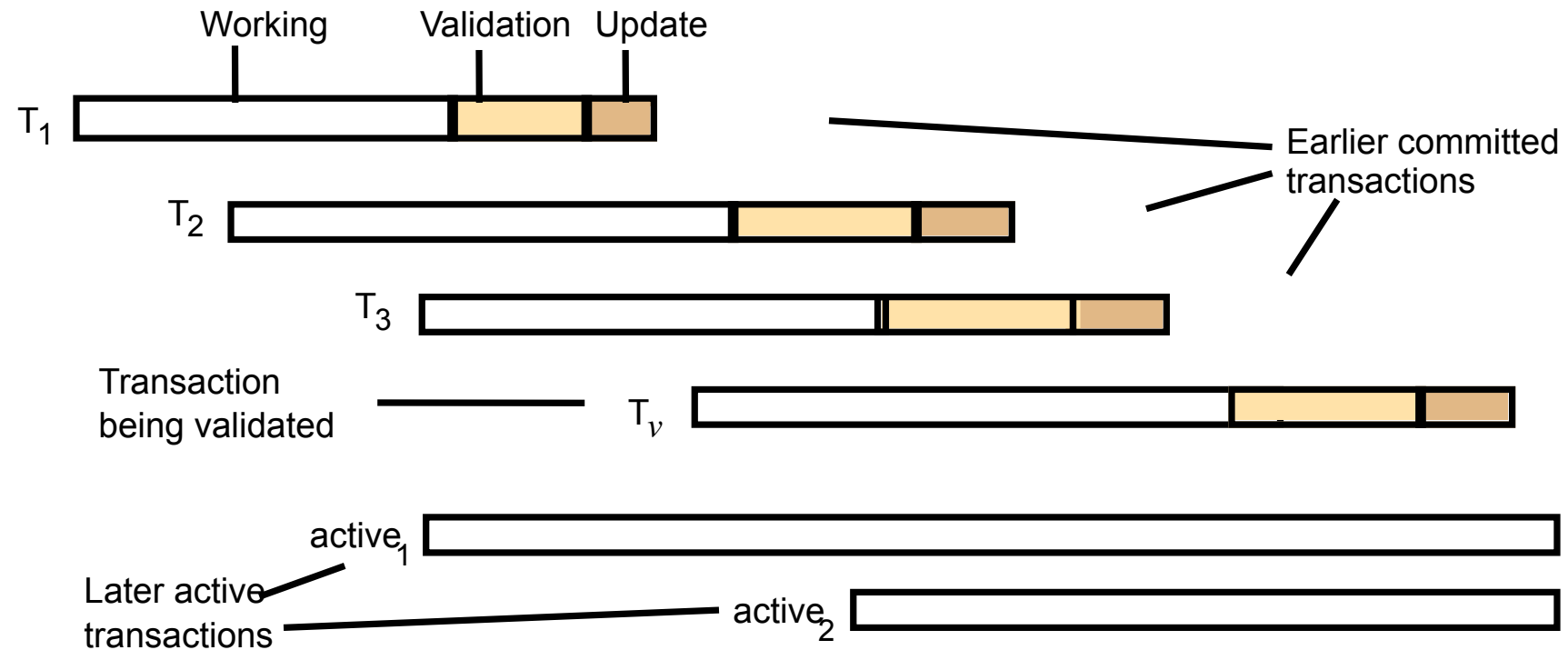


Figure 12.28



Validation of Transactions

Backward validation of transaction T_v

```
boolean valid = true;
for (int  $T_i = startTn+1$ ;  $T_i \leq finishTn$ ;  $T_i++$ ) {
    if (read set of  $T_v$  intersects write set of  $T_i$ ) valid = false;
}
```

Forward validation of transaction T_v

```
boolean valid = true;
for (int  $T_{id} = active1$ ;  $T_{id} \leq activeN$ ;  $T_{id}++$ ) {
    if (write set of  $T_v$  intersects read set of  $T_{id}$ ) valid = false;
}
```

CoDoKi: Page 547-548



Chapter Summary

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