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Distributed Systems
Synchronization

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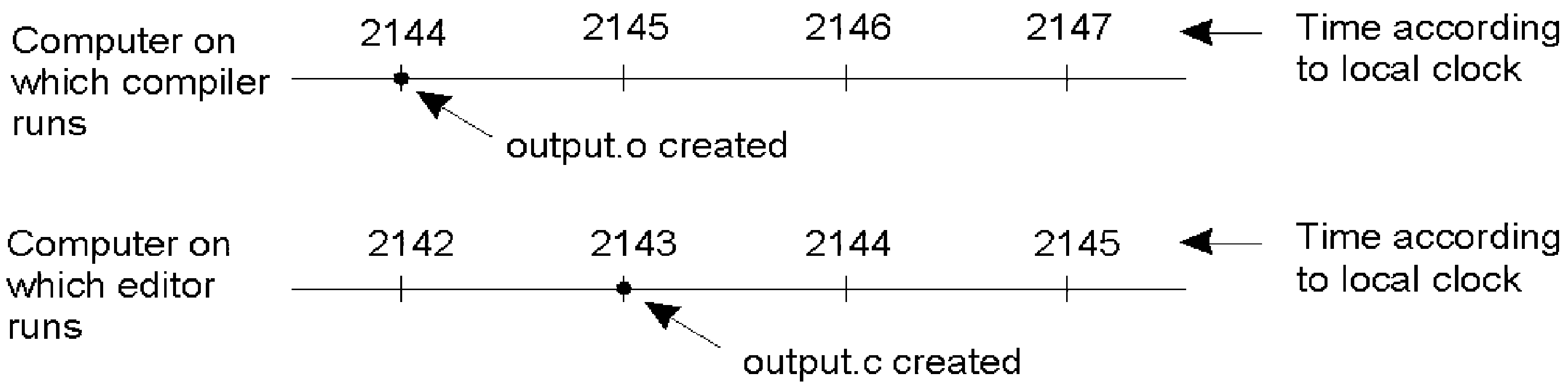
- **Synchronization in distributed systems: An Introduction**
- Synchronizing physical clocks
- Logical time
  - Scalar clocks
  - Vector clocks
- Mutual exclusion
- Leader election
- Collecting global state
  - Termination detection
- Distributed transactions
  - Detecting distributed deadlocks

Synchronization in distributed systems

- The problem of synchronizing concurrent activities arises also in non-distributed systems
- However, distribution complicates matters:
  - Absence of a global physical clock
  - Absence of globally shared memory
  - Partial failures
- In these lectures, we study distributed algorithms for:
  - Synchronizing physical clocks
  - Simulating time using logical clocks & preserving event ordering
  - Mutual exclusion
  - Leader election
  - Collecting global state & termination detection
  - Distributed transactions
  - Detecting distributed deadlocks

Time and distributed systems

- Time plays a fundamental role in many applications:
  - Execute a given action at a given time
  - Time stamping objects/data/messages enables reconstruction of event ordering
    - File versioning
    - Distributed debugging
    - Security algorithms
- Problem: ensure all machines "see" the same global time
- Example: The make case



Computer on which compiler runs

2144 2145 2146 2147

Time according to local clock

output.o created

Computer on which editor runs

2142 2143 2144 2145

Time according to local clock

output.c created

share the file system

may not compile

per se 英 [ˌpɜː ˈseɪ]
(from Latin) 本身；本质上
used meaning ‘by itself’ to show that
you are referring to sth on its own, rather
than in connection with other things

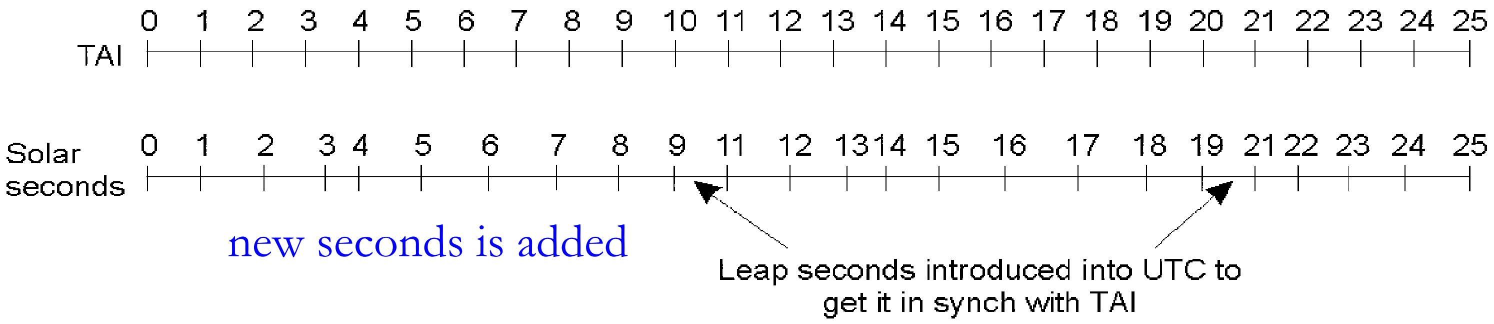
Time

- Time is a tricky issue per se:
  - Up to 1940, time is measured astronomically
    - 1 second = 1/86400th of a mean solar day (the mean time interval between two consecutive transits of the sun)
    - Earth is slowing down, making measures “inaccurate”
  - Since 1948, time is measured physically (International Atomic Time)
    - 1 second = 9,192,631,770 transitions of an atom of Cesium 133
    - Collected and averaged in Paris from 50 labs around the world
  - Skew between TAI and solar days accommodated by UTC (Coordinated Universal Time) when greater than 800ms
    - Greenwich Mean Time is only astronomical
    - About 30 leap seconds from 1958 to now
    - UTC disseminate via radio stations (DCF77 in Europe, WWV in US), GPS and GEOS satellite systems

astronomical 英 [ˌæstrəˈnɒmɪkl]
adj. 天文学的

skew: [skjuː] to move or lie at an angle, especially in a position that is not normal

leap 英 [liːp] to increase suddenly and by a large amount



Leap seconds introduced into UTC to get it in synch with TAI

new seconds is added

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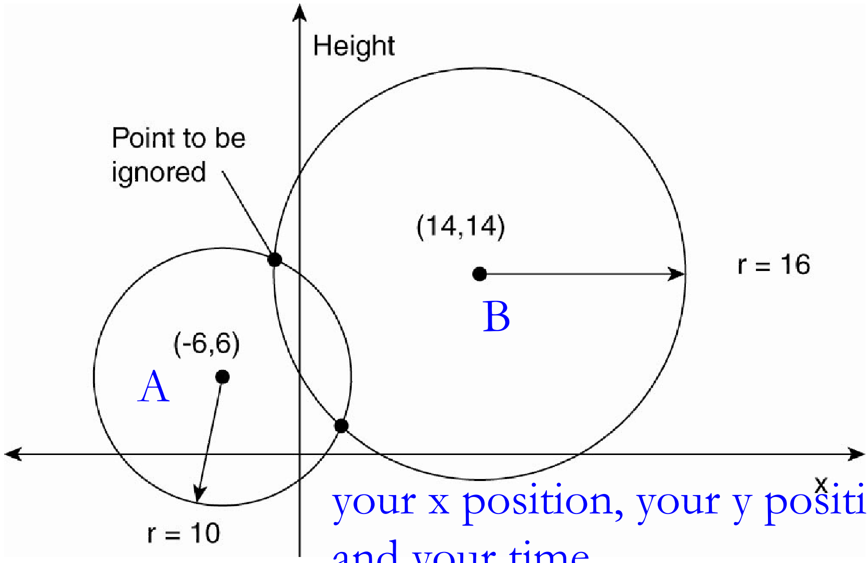
Synchronizing physical clocks

- First of all: Computer clocks are not clocks, they are timers
- To guarantee synchronization:
  - Maximum *clock drift rate* ρ is a constant of the timer
    - For ordinary quartz crystals, $\rho=10^{-6}$ s/s, i.e., 1s every 11.6 days
  - Maximum allowed *clock skew* δ is an engineering parameter
  - If two clocks are drifting in opposite directions, during a time interval Δt they accumulate a skew of $2\rho\Delta t$
    ➔ resynch needed at least every $\delta/2\rho$ seconds
- The problem is either:
  - Synchronize all clocks against a single one, usually the one with external, accurate time information (accuracy)
  - Synchronize all clocks among themselves (agreement)
- At least time monotonicity must be preserved
- Several protocols have been devised

we cannot jump to the opposite direction we can slow and wait for resynchronization

Positioning and time: GPS



your x position, your y position and your time

clock are monotonic clock, so they are same (A, B)

- Basic idea: get an accurate account of time as a side effect of GPS
- How GPS works:
  - Position is determined by triangulation from a set of satellites whose position is known
  - Distance can be measured by the delay of signal
  - But satellite and receiver clock must be in sync
  - Since they are not we must take clock skew into account

Positioning and time: GPS

- Let:
  - Δ_r be the unknown deviation of the receiver's clock w.r.t. the atomic clocks installed on board of satellites
  - x_r, y_r, z_r be the unknown coordinates of the receiver
  - T_i be the timestamp of message sent by a satellite i
- Suppose that the messages sent by the i-th satellite is received at time T_r according to the receiver time, which corresponds to T_{now} in the real, actual time. Then:
  - $T_{now} = T_r - \Delta_r$ my skew
  - $\Delta_i = T_r - T_i$ is the measured delay of message
  - $c\times \Delta_i$ is the measured distance of satellite i
- So $c\times \Delta_i = c \times (T_{now} - T_i + \Delta_r) = c \times (T_{now} - T_i) + c \times \Delta_r$

  where the first addendum must be equal to the real distance:

  $\sqrt{(x_i - x_r)^2 + (y_i - y_r)^2 + (z_i - z_r)^2}$

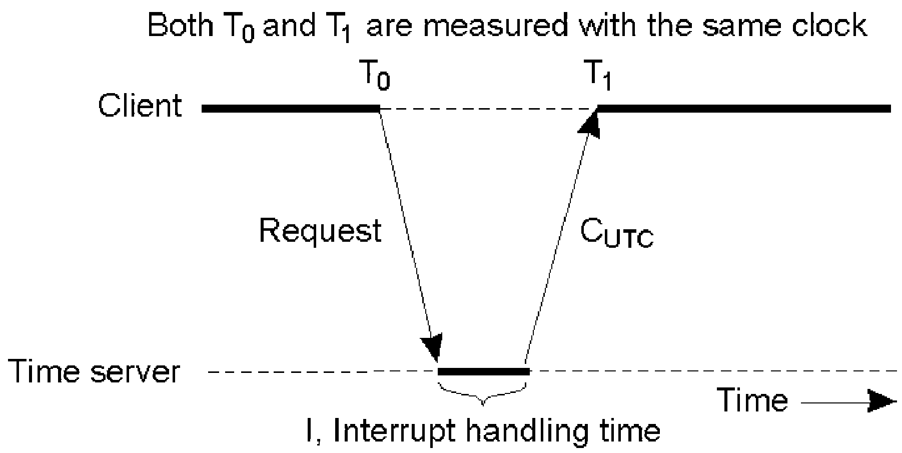
  addendum英 [ə'dendəm] 美 [ə'dendəm]
  n. (尤指书籍的)补遗，补篇
- With four satellites we have four equations in four unknowns (including Δ_r)
  - We can solve them and determine both the node position and its clock skew

Positioning and time: GPS

- Notice that things are more complex than previous description could suggest
  - Earth is not spherical spherical 英 ['sferɪkl] 美 ['sferɪkl] adj. 球形的;
  - Atomic clocks in the satellites are not perfectly in sync
  - The position of satellites is not know precisely
  - The receiver's clock has a finite accuracy
  - The signal propagation speed is not constant
  - ...
- In any case, even cheap GPS receivers can be precise within range of few meters and few tens of nanoseconds distance / speed of light

Simple algorithms: Cristian’s (1989)

- Periodically, each client sends a request to the time server
- Messages are assumed to travel fast w.r.t. required time accuracy
- Problems:
  - Major: time might run backwards on client machine. Therefore, introduce change gradually (e.g., advance clock 9ms instead of 10ms on each clock tick)
  - Minor: it takes a non-zero amount of time to get the message to the server and back
    - Measure round-trip time and adjust, e.g., $T_1 = C_{UTC} + T_{round}/2$
    - Average over several measurements


Both T_0 and T_1 are measured with the same clock
T_0
T_1
Client
Request
C_{UTC}
Time server
Time
I, Interrupt handling time

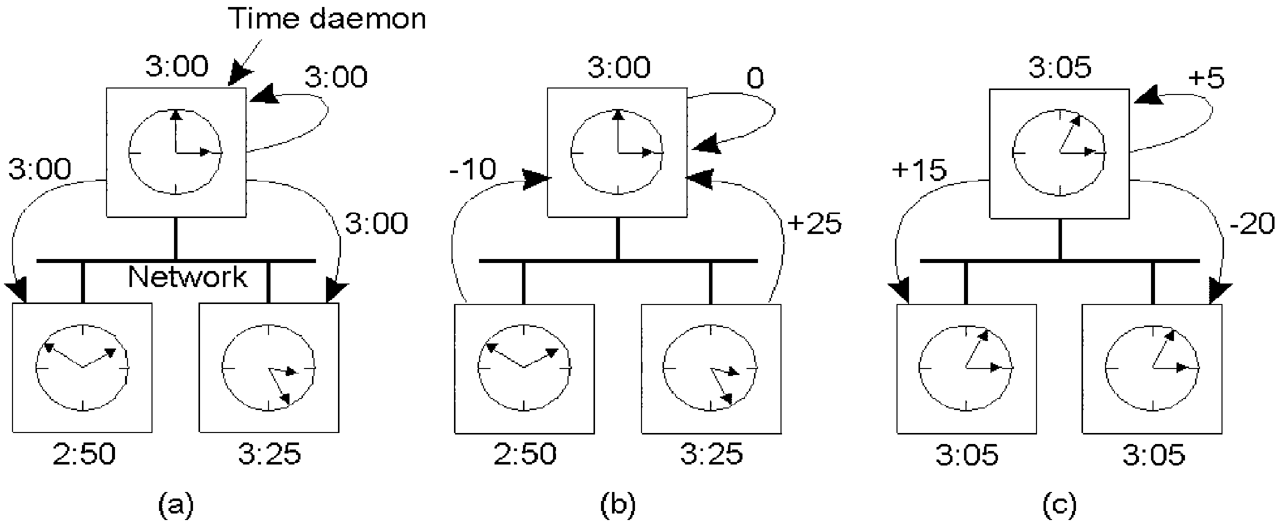
put Tround
the travel of the request equal to
the time time reply
if not, better not consider the
Tround

$$\mathbf{T_{round} = T_1 - T_0 - I}$$

difference in time is accurate

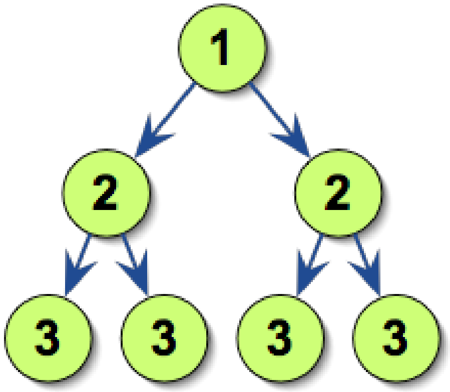
Simple algorithms: Berkeley (1989)

- Introduced by Berkeley UNIX
- The time server is active: It collects the time from all clients, averages it, and then retransmits the required adjustment



Network Time Protocol (NTP)

- Designed for UTC synch over large-scale networks
  - Used in practice over the Internet, on top of UDP
  - Estimate of 10-20 million NTP clients and servers
  - Widely available (even under Windows)
  - Synchronization accuracy: ~1ms over LANs, 1-50ms over the Internet
  - More info at www.ntp.org
- Hierarchical synchronization subnet organized in strata
  - Servers in stratum 1 are directly connected to a UTC source
  - Lower strata (higher levels) provide more accurate information
  - Leaf servers execute in users' workstations
  - Connections and strata membership change over time
- Synchronization mechanisms
  - Multicast (over LAN)
    - Servers periodically multicast their time to other computers on the s
  - Procedure-call mode
    - Similar to Cristian's
  - Symmetric mode
    - For higher levels that need the highest accuracies



NTP: Procedure-call and symmetric mode

server and client

- Servers exchange pairs of messages, each bearing timestamps of recent message events
  - The local time when the previous message between the pairs was sent and received, and the local time when the current message was transmitted
- If t and t' are the messages' transmission times, and o is the time offset of the clock at B relative to that at A, then:
  - $T_{i-2} = T_{i-3} + t + o$ and $T_i = T_{i-1} + t' - o$ error difference between the two clocks

error

This leads to calculate the total transmission time d_i as:

- $d_i = t + t' = T_{i-2} - T_{i-3} + T_i - T_{i-1}$

If we define o_i as:

- $o_i = (T_{i-2} - T_{i-3} + T_{i-1} - T_i)/2$

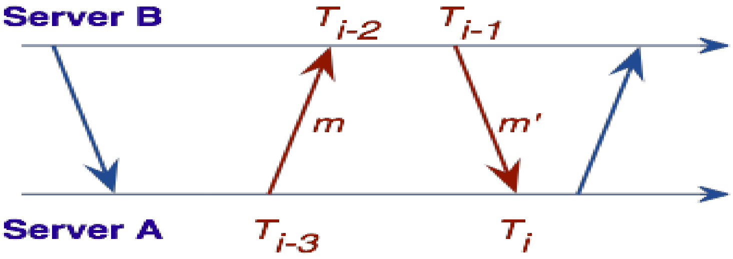
from the first two formulas we have:

- $o = o_i + (t'-t)/2$

and since $t, t' \geq 0$

- $o_i - d_i/2 = o_i + (t'-t)/2 - t' \leq o \leq o_i + (t'-t)/2 + t = o_i + d_i/2$

Thus o_i is an estimate of the offset and d_i is a measure of the accuracy of this estimate



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Some observations

- In many applications it is sufficient to agree on a time, even if it is not accurate w.r.t. the absolute time
- What matters is often the ordering and causality relationships of events, rather than the timestamp itself
- If two processes do not interact, it is not necessary that their clocks be synchronized

Logical time – Scalar clocks

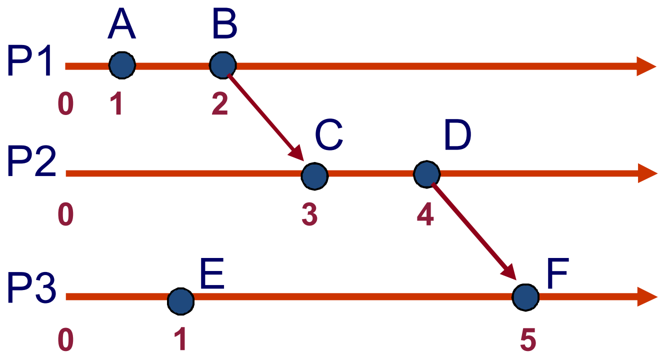
L. Lamport. "Time, clocks, and the ordering of events in a distributed system". Communications of the ACM, 21(7):558-565, July 1978.

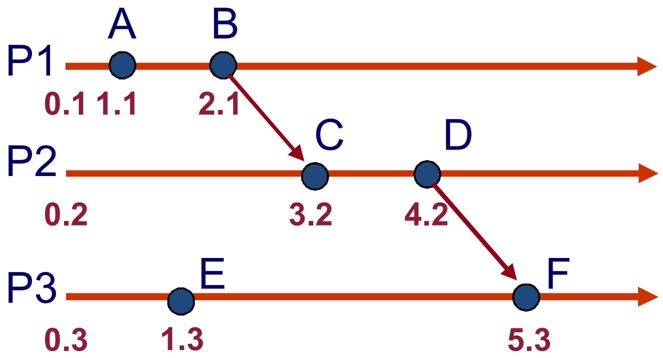
- Let define the *happens-before* relationship *e*→*e'*, as follows:
  - If events *e* and *e'* occur in the same process and *e* occurs before *e'*, then *e*→*e'*
  - If *e=send(msg)* and *e'=recv(msg)*, then *e*→*e'*
  - → is transitive
- If neither *e*→*e'* nor *e'*→*e*, they are concurrent (*e* | | *e'*)
- The happens-before relationship captures *potential causal ordering* among events
  - Two events can be related by the happens-before relationship even if there is no real (causal) connection among them
  - Also, since information can flow in ways other than message passing, two events may be causally related even neither of them happens-before the other
- Lamport invented a simple mechanism by which the happened before ordering can be captured numerically
  - Using integers to represent the clock value
  - No relationship with a physical clock whatsoever

Logical time – Scalar clocks

L. Lamport. "Time, clocks, and the ordering of events in a distributed system". Communications of the ACM, 21(7):558-565, July 1978.

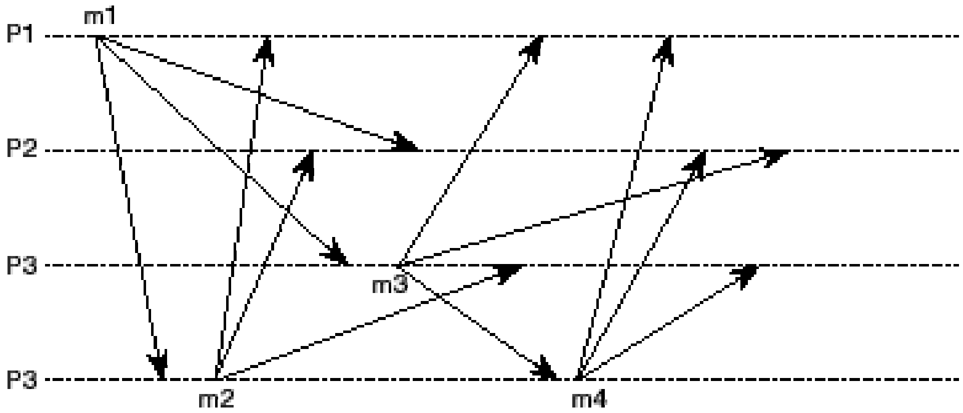
- Each process p_i keeps a logical scalar clock L_i
  - L_i starts at zero
  - L_i is incremented before p_i sends a message
  - Each message sent by p_i is timestamped with L_i
  - Upon receipt of a message, p_i sets L_i to: MAX(msg timestamp, L_i) + 1
- It can easily be shown, by induction on the length of any sequence of events relating two events e and e', that: $e \rightarrow e' \Rightarrow L(e) < L(e')$
- Note that only partial ordering is achieved. Total ordering can be obtained trivially by attaching process IDs to clocks





Exercise

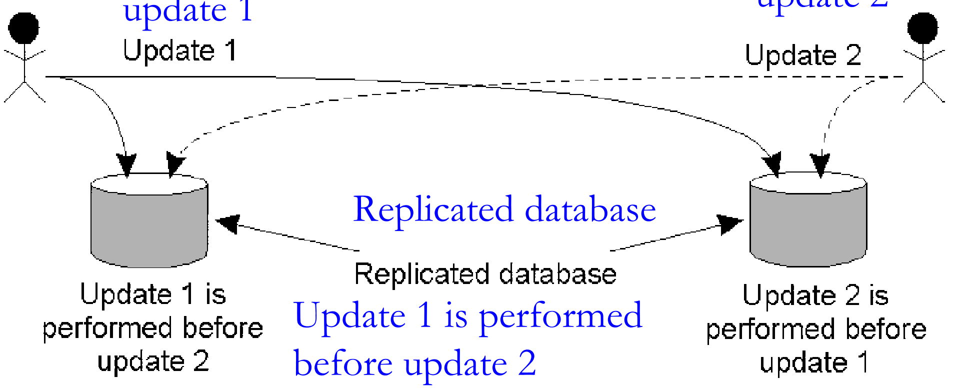
- Consider 4 processes exchanging messages as in figure:



Which is the value of Lamport's clocks at the end of the reported period?

Example:Totally ordered multicast

- Updates in sequence:
  - Customer deposits $100
  - Bank adds 1% interest
- Updates are propagated to all locations:
  - If updates in the same order at each copy, consistent result (e.g., $1111)
  - If updates arrive in opposite orders, inconsistent result (e.g., $1110)



update 1

Update 1

update 2

Update 2

Replicated database

Replicated database

Update 1 is performed before update 2

Update 1 is performed before update 2

Update 2 is performed before update 1

Update 2 is performed before update 1

- Totally ordered multicast delivers messages in the same global order
- Using logical clocks (assuming reliable and FIFO links):
  - Messages are sent and acknowledged using multicast
  - All messages (including acks) carry a timestamp with the sender's scalar clock
  - Scalar clocks ensures that the timestamps reflect a consistent global ordering of events
  - Receivers (including the sender) store all messages in a queue, ordered according to its timestamp
  - Eventually, all processes have the same messages in the queue
  - A message is delivered to the application only when it is at the highest in the queue and all its acks have been received
    - Since each process has the same copy of the queue, all messages are delivered in the same order everywhere

Vector Clocks

- Problem:
  - In scalar clocks, $e \rightarrow e' \Rightarrow L(e) < L(e')$
  - But the reverse does not necessarily hold, e.g., if $e \,||\, e'$
- Solution: Vector clocks
- In vector clocks each process p_i maintains a vector V_i of N values (N=#processes) such that:
  - $V_i[i]$ is the number of events that have occurred at P_i
  - If $V_i[j]=k$ then P_i knows that k events have occurred at P_j
- Rules for updating the vectors:
  - Initially, $V_i[j]=0$ for all i,j
  - Local event at P_i causes an increment of $V_i[i]$
  - P_i attaches a timestamp $t=V_i$ in all messages it sends (incrementing $V_i[i]$ just before sending the message, according to previous rule)
  - When P_i receives a message containing t, it sets $V_i[j]=max(V_i[j], t[j])$ for all $j \neq i$ and then increments $V_i[i]$

is receiving the message an event?

for each value, update according to the max(except the local position)

Vector Clocks (cont'd)

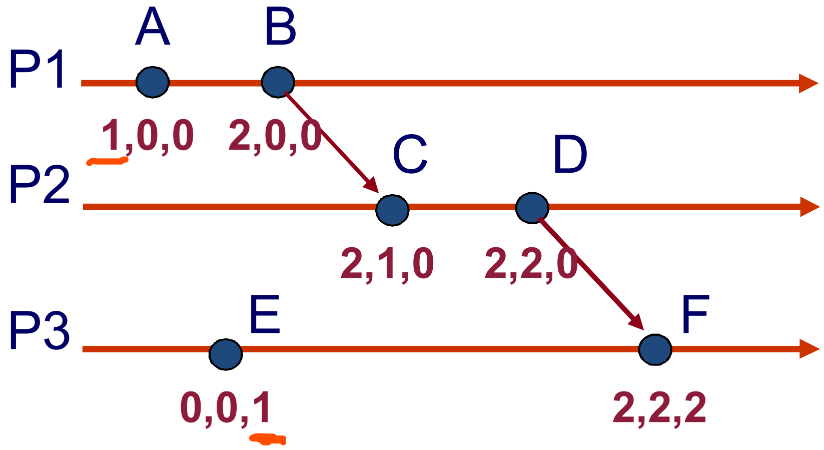
- Definitions (partial ordering)
  - $V = V'$ *iff* $V[j] = V'[j]$, for all j
  - $V \leq V'$ *iff* $V[j] \leq V'[j]$, for all j
  - $V < V'$ *iff* $V \leq V' \wedge V \neq V'$
  - $V \parallel V'$ *iff* $\neg(V < V') \wedge \neg(V' < V)$
- An isomorphism between the set of partially ordered events and their timestamps (i.e., vector clocks)
- Determining causality:
  - $e \rightarrow e' \Leftrightarrow V(e) < V(e')$
  - $e \parallel e' \Leftrightarrow V(e) \parallel V(e')$

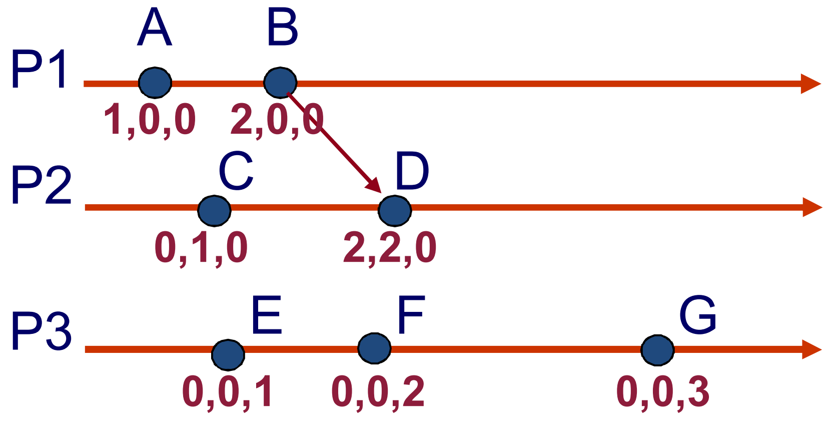
e->e'

e happens before e'

Examples

VA < VF, so A happens before F





- By looking *only* at the timestamps we are able to determine whether two events are causally related or concurrent

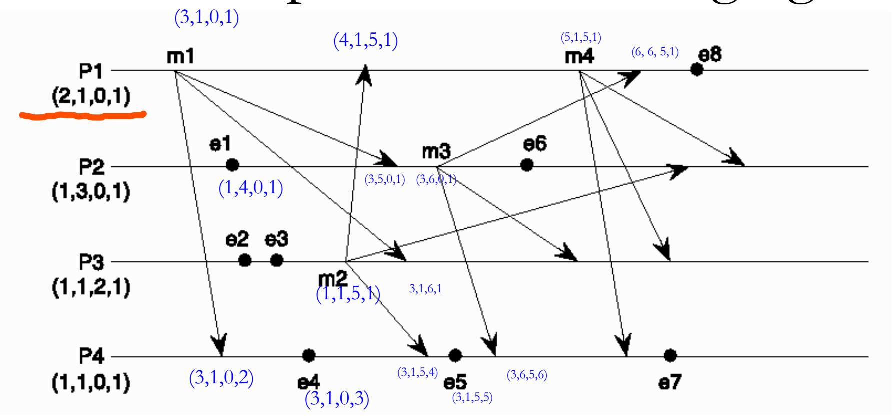
the local position is always the greatest one, so there are no two vectors that are exactly the same

not possible, P2[1] = 5 > P1[1] = 4,
the maximum of the process must

Exercise

- Three processes are involved in a distributed algorithm. At the end their vector clocks are:
  - P1 : (~~4~~, 5, 6) P2 : (5, 6, 6) P3 : (3, 2, 7)

  Is this possible? Why?
- Consider 4 processes exchanging messages as in figure:

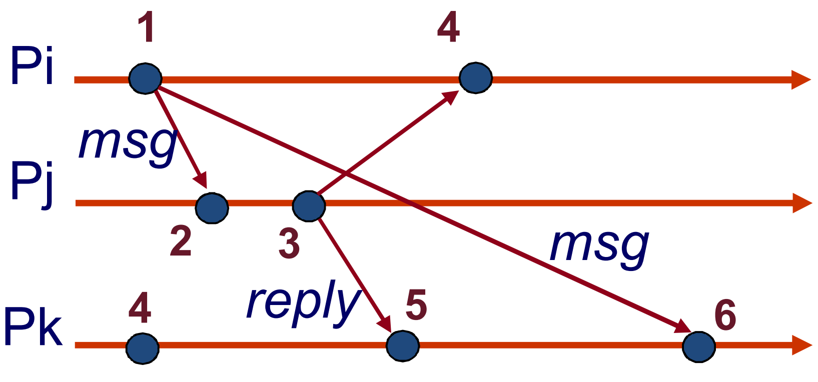


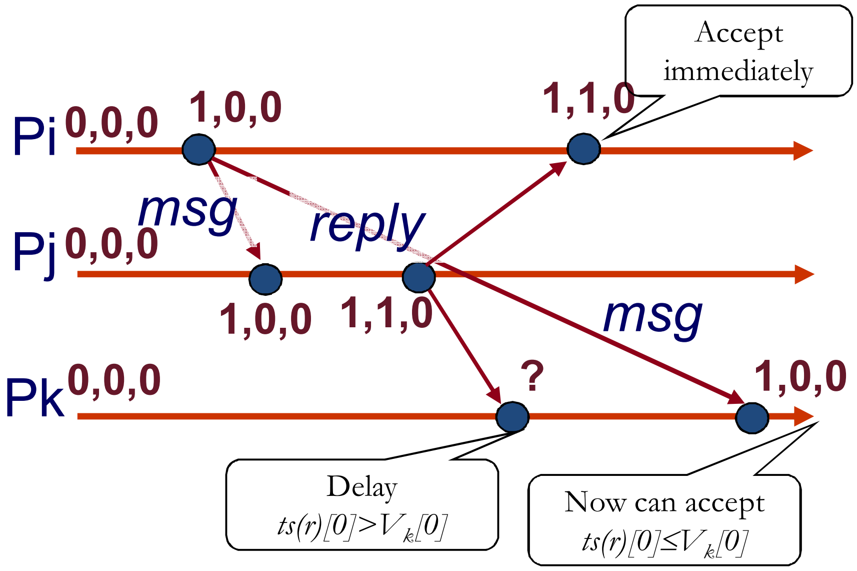
Which is the value of each process' vector clock at the end of the reported period?

lamport for ordering

not global order, if it's not causal related, we don't need to keep the order of them

Vector clocks for causal delivery





j knows that P1 sends a message

- A slight variation of vector clocks can be used to implement causal delivery of messages in a totally distributed way
- Example: bulletin boards
  - Messages and replies sent (using reliable, FIFO ordered, channels) to all the boards in parallel
  - Need to preserve the ordering *only* between messages and replies
  - Totally ordered multicast is too strong
    - If M1 arrives before M2, it does not necessarily mean that the two are related
  - Using vector clocks:
    - Variation: Increment clock only when sending a message. On receive, just merge, not increment
    - Hold a reply until the previous messages are received:
      - $ts(r)[j] = V_k[j]+1$
      - $ts(r)[i] \leq V_k[i]$ for all $i \neq j$

reply?

Describe how vector clocks can be used to implement a broadcast communication system that guarantees causal ordering among exchanged messages?

use Vector clock with causal

Is it possible to obtain the same guarantees (causally ordered messages) using scalar clocks instead of vector clocks?

slide 23 Example: Totally ordered multicast

The ordering of lamport is stronger

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Mutual exclusion

interference 英 [ˌɪntəˈfɪərəns]

- Required to prevent interference and ensure consistency of resource access
- Critical section problem, typical of OS
  - But here, no shared memory
- Requirements:
  - Safety property: At most one process may execute in the critical section at a time
  - Liveness property: All requests to enter/exit the critical section eventually succeed (no deadlock, no starvation)
  - Optional: If one request happened-before another, then entry is granted in that order
- Assumptions:
  - **Reliable channels and processes**
- Simplest solution: A server coordinating access
  - Emulates a centralized solution
  - Server manages the lock using a "token"
  - Resource access request and release obtained with respective messages to the coordinator
  - Easy to guarantee mutual exclusion and fairness
  - Drawbacks: Performance bottleneck and single point of failure

Java keyword: synchronized

just use it to compare time

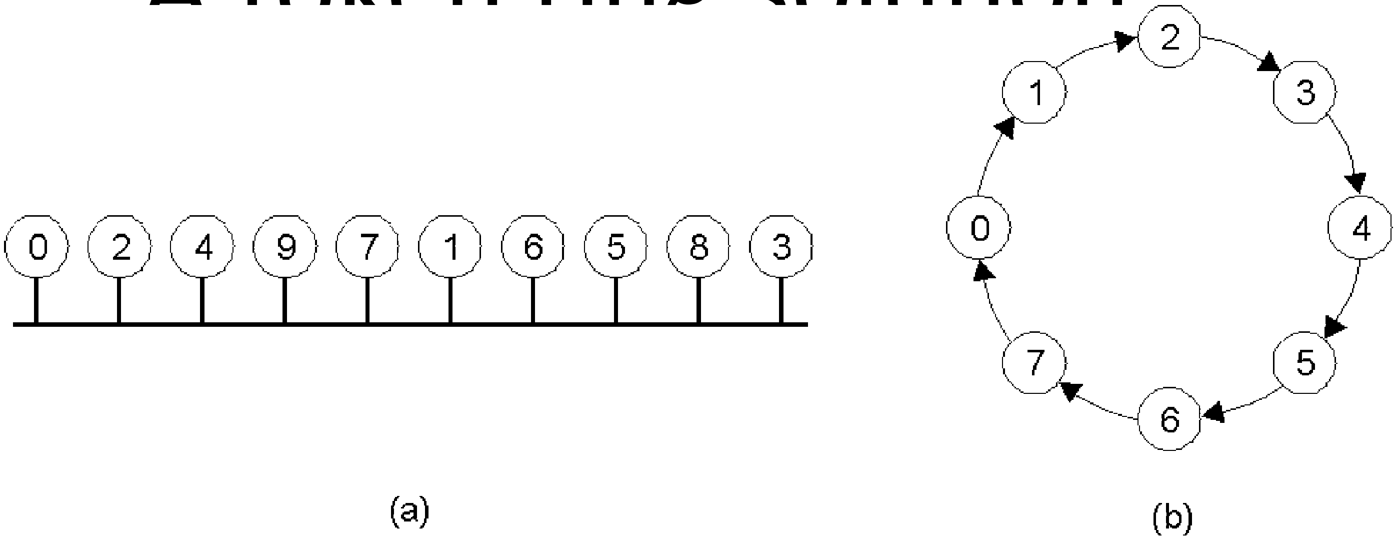
Mutual exclusion with scalar clocks

in this case, no central server

- To request access to a resource:
  - A process *Pi* multicasts a resource request message *m*, with timestamp *Tm*, to all processes (including itself)
  - Upon receipt of *m*, a process *Pj*:
    - If it does not hold the resource and it is not interested in holding the resource, *Pj* sends an acknowledgment to *Pi*
    - If it holds the resource, *Pj* puts the requests into a local queue ordered according to *Tm* (process ids are used to break ties)
    - If it is also interested in holding the resource and has already sent out a requests, *Pj* compares the timestamp *Tm* with the timestamp of its own requests
      - If the *Tm* is the lowest one, *Pj* sends an acknowledgement to *Pi*, otherwise it put the request into the local queue above
- On releasing the resource, a process *Pi* acknowledges all the requests queued while using the resource
- A resource is granted to *Pi* when its request has been acknowledged by all the other processes

must guarantee that no equal, must use the lamp clock that are equal

A token ring solution



- Processes are logically arranged in a ring, regardless of their physical connectivity
  - At least for the purpose of mutual exclusion
- Access is granted by a token that is forwarded along a given direction on the ring
  - A process not interested in accessing the resource forwards the token
  - Resource access is achieved by retaining the token
  - Resource release is achieved by forwarding the token

retaining 英 [rɪ'teɪnɪŋ] intended to keep sth in the correct position

not guarantee the optional requirement

Comparison

Request, grant

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

If nobody wants to enter the critical section, the token circulates indefinitely

Comments?

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Leader election

- Many distributed algorithms require a process to act as a coordinator (or some other special role)
  - E.g., for server-based mutual exclusion
- Problem: Make everybody agree on a new leader
  - When the old is no longer available, e.g., because of failure or applicative reasons
- Minimal assumption: **Nodes are distinguishable**
  - Otherwise, no way to perform selection
  - Typically use the identifier (the process with the highest ID becomes the leader) or some other measure (e.g., 1/load)
- Also, closed system: **Processes know each other and their IDs**
  - But do not know who is up and who has failed
- The non-crashed process with the highest ID at the end of the election must be the winner
  - And every other non-crashed process must agree on this
- Algorithms differ on the selection process

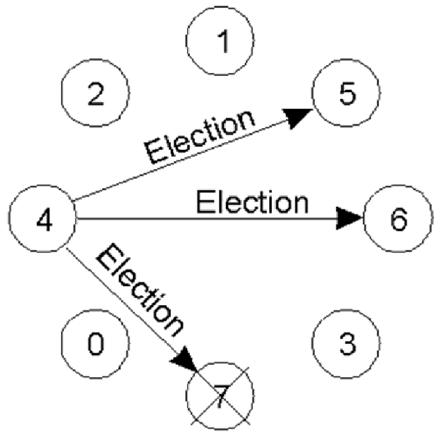
In general, agreement are not possible

The bully election algorithm

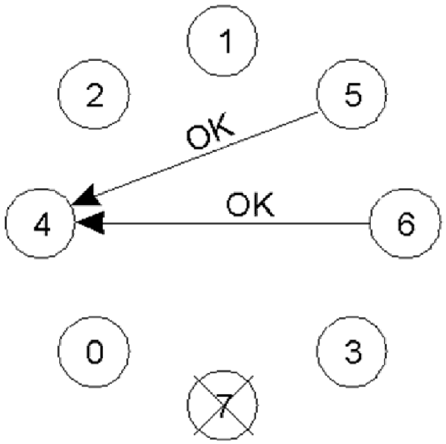
- Additional assumptions
  - **Reliable links**
  - **It is possible to decide who has crashed** (synchronous system)
- Algorithm
  - When any process *P* notices that the actual coordinator is no longer responding requests it initiates an election
  - *P* sends an *ELECT* message, including its ID, to all other processes with higher IDs
  - If no-one responds *P* wins and sends a *COORD* message to the processes with lower IDs if no one response, P wins
  - If a process *P'* receives an *ELECT* message it responds (stopping the former candidate) and starts a new election (if it has not started one already)
  - If a process that was previously down comes back up, it holds an election
    - If it happens to be the highest-numbered process currently running it wins the election and takes over the coordinator's job (hence the name of the algorithm)

恶霸选举

The bully election algorithm: Example

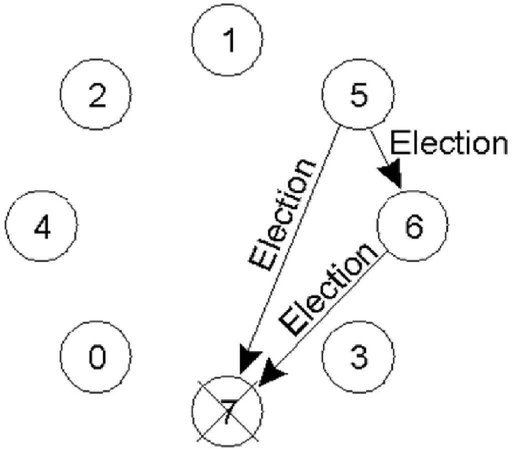


(a)

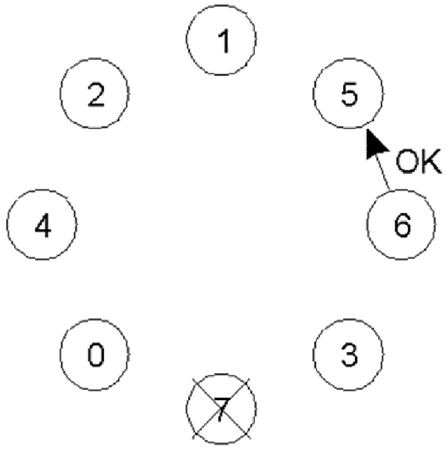


Previous coordinator has crashed

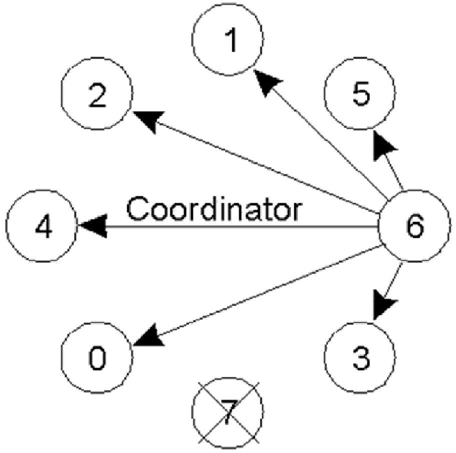
(b)



(c)



(d)



(e)

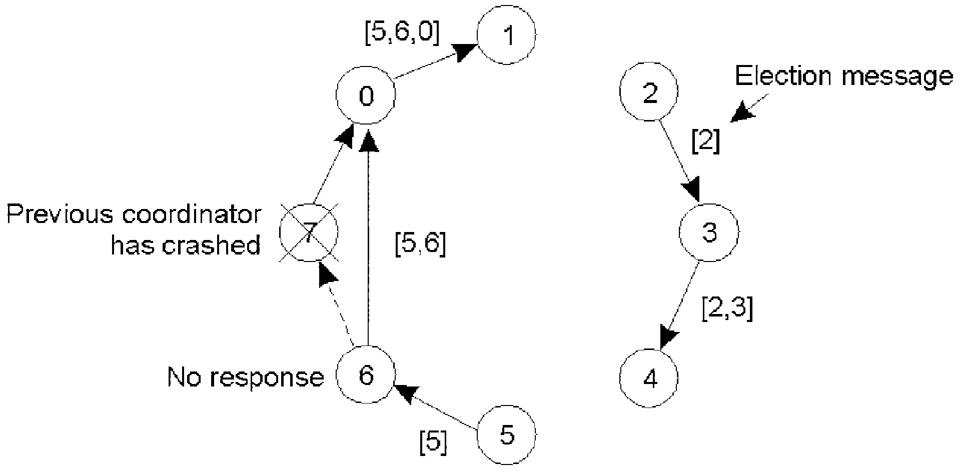
- The leader, 7, fails
  - Process 4 (noticing the failure of 7) holds an election
  - Process 5 and 6 respond, telling 4 to stop
  - Now 5 and 6 each hold an election
  - 6 tells 5 to stop
  - 6 wins and tells everyone
- When 7 comes back it holds an election and wins

A ring-based algorithm

- Assume a (physical or logical) ring topology among nodes
- When a process detects a leader failure, it sends an *ELECT* message containing its ID to the closest alive neighbor
- Upon receipt of the election message a process *P*:
  - If *P* is not in the message, add *P* and propagate to next alive neighbor
  - If *P* is in the list, change message type to *COORD*, and re-circulate

- On receiving a *COORD* message, a node considers the process with the highest ID as the new leader (and is also informed about the remaining members of the ring)
- Multiple messages may circulate at the same time
  - Eventually converge to the same content

Both 2 and 5 detect server crash



Exercise

- Compare the two election algorithms in terms of:
  - Number of messages required to end the election
  - Assumptions
  - Ease of guaranteeing such assumptions

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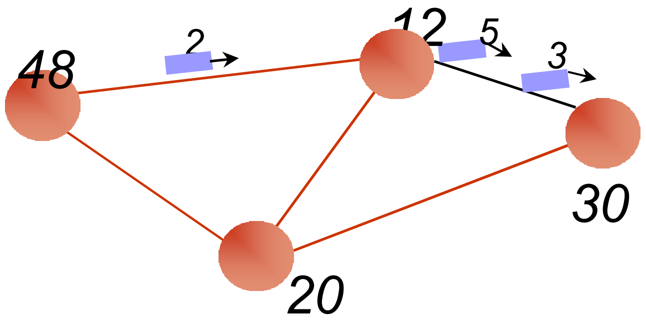
- Mutual exclusion
- Leader election
- **Collecting global state**
  - **Termination detection**
- Distributed transactions
  - Detecting distributed deadlocks

Capturing global state

- The global state of a distributed system consists of the local state of each process (depends on the application), together with the message in transit over the links
- Useful to know for distributed debugging, termination detection, deadlock detection, …
- Banking example:
  - Constant amount of money in the bank system (e.g., 120)
  - Money is transferred among banks in messages
  - Problem: find out of any money accidentally lost

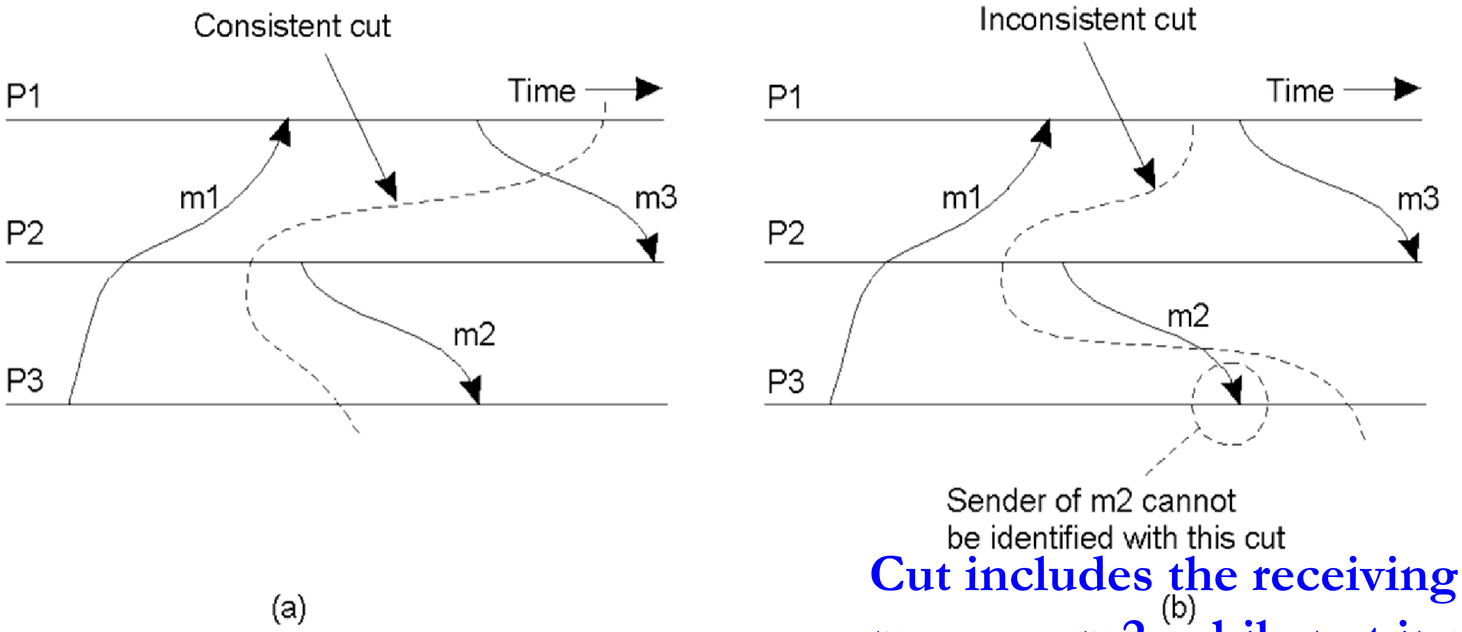


- Capturing the global state of a distributed system would be easy if we could access a global clock… but we do not have one
- We must accept recording the state of each process at, potentially, different times

impossible to capture the real global state

Cuts & distributed snapshots

- A *distributed snapshot* reflects a (consistent, global) state in which the distributed system might have been
- Particular care must be taken when reconstructing the global state to preserve consistency
  - If a message receipt is recorded, the message sending must as well, but the contrary is not required
- Conceptual tool: *Cut*



Sender of m2 cannot be identified with this cut

Cut includes the receiving of the message m2, while not include the receiving of m3

More on consistent cuts

- Formally a *cut* of a system S composed of N processes $p_1,\ldots,p_n$ can be defined as the union of the histories of all its processes up to a certain event

  $C = h_1^{k_1} \cup h_2^{k_2} \cup \ldots \cup h_n^{k_n}$

  where

  $h_i^{k_i} = < e_i^0, e_i^1 \ldots e_i^{k_i} >$

- A cut C is consistent if for any event e it includes, it also includes all the events that happened before e. Formally:

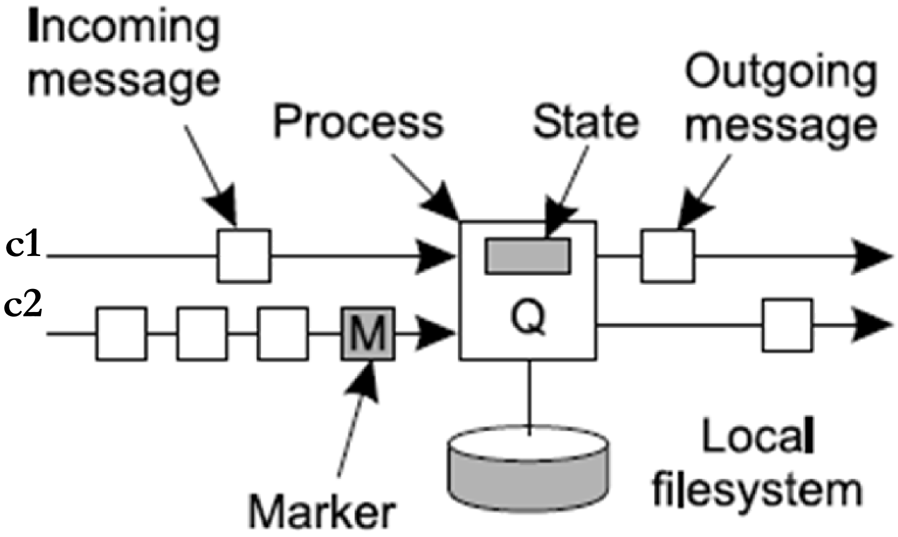
  $\forall e,f : e \in C \wedge \underline{f \rightarrow e} \Rightarrow f \in C$

Distributed snapshot

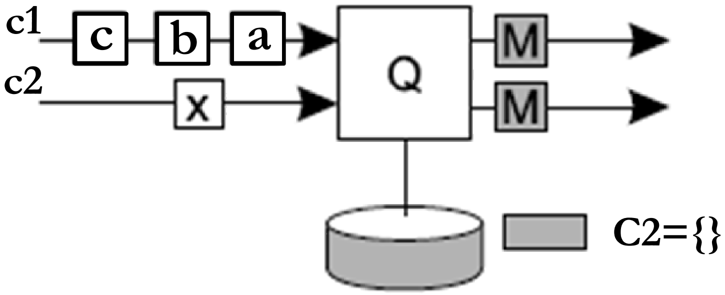
Chandy-Lamport, 1985

- Assume FIFO, reliable links/nodes + strongly connected graph
- Any process *p* may initiate a snapshot by
  - Recording its internal state
  - Sending a token on all outgoing channels
    - This signals a snapshot is being run
  - Start recording a local snapshot
    - I.e., record messages arriving on every incoming channel
- Upon receiving a token, a process *q*
  - If not already recording local snapshot
    - Records its internal state
    - Sends a token on all outgoing channels
    - Start recording a local snapshot (see above)
  - In any case stop recording incoming message on the channel the token arrived along
- Recording messages
  - If a message arrives on a channel which is recording messages, record the arrival of the message, then process the message as normal
  - Otherwise, just process the message as normal
- Each process considers the snapshot ended when tokens have arrived on all its incoming channels
  - Afterwards, the collected data can be sent to a single collector of the global state

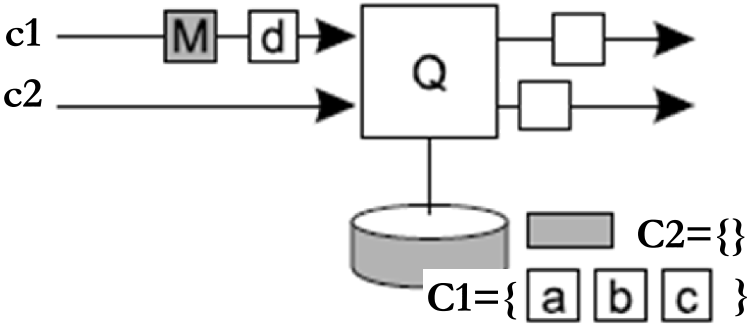
for example, if we add the value, we will first keep the local state of the addition, then we save the added one



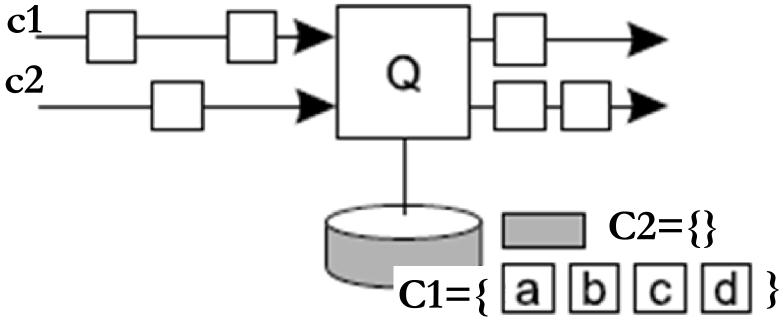
Normal processing, first marker about to be received



Token just received for the first time, state saved, token forwarded to outgoing links, begin recording messages



Recording of messages from the incoming links from which a token has not been received, yet



Token received, state recording is stopped

Characterizing the observed state

Theorem

The distributed snapshot algorithm selects a consistent cut

Proof

Let e_i and e_j be two events occurring at p_i and p_j, respectively, such that $e_i \rightarrow e_j$

Suppose e_j is part of the cut and e_i is not. This means e_j occurred before p_j saved its state, while e_i occurred after p_i saved its state

If $p_i = p_j$ this is trivially impossible, so suppose $p_i \neq p_j$

Let $m_1,\dots m_h$ be the sequence of messages that give rise to the relation $e_i \rightarrow e_j$

If e_i occurred after p_i saved its state then p_i sent a marker ahead of $m_1,\dots m_h$

By FIFO ordering over channels and by the marker propagating rules it results that p_j received a marker ahead of $m_1,\dots m_h$

By the marker processing rule it results that p_j saved its state before receiving $m_1,\dots m_h$, i.e., before e_j , which contradicts our initial assumption

Some observations

- Important: the distributed snapshot algorithm does not require blocking of the computation
  - Collecting the snapshot is interleaved with processing
- What happens if the snapshot is started at more than one location at the same time?
  - Easily dealt with by associating an identifier to each snapshot, set by the initiator
- Several variations have been devised
  - E.g., incremental snapshots take an initial snapshot, each node remembers where it has sent/received messages, and when a new snapshot is requested, only these links are included in the result
- How is the snapshot result collected?
  - Again, several variations (this step is not part of the algorithm)

Termination detection

- Want to know when a computation has completed or deadlocked (no more useful work can be done)
  - All processes should be idle
  - There should be no messages in the system
    - Messages need to be processed, i.e., some process must become non-idle
- Can a distributed snapshot be used?
  - Yes, but channels must be empty when finished
  - Simple solution (from Tanenbaum):
    - Let call *predecessor* of a process *p*, the process *q* from which it got the first marker. The successors of *p* are all those processes *p* sent the marker
    - When a process *p* finishes its part of the snapshot, it sends a DONE message back to its predecessor only if two conditions are met:
      - All of *p*'s successors have returned a DONE message
      - *P* has not received any message between the point it recorded its state and the point it had received the marker along each of its incoming channels
    - In any other case *p* sends a CONTINUE
    - If the initiator receives all DONE the computation is over; otherwise, another snapshot is necessary

Does it work?

Diffusing computations

- In a diffusing computation, initially all process are idle except the init process
- A process is activated only by a message being sent to it
- Termination condition (same as before): when processing is complete at each node, and there are no more messages in the system

Dijkstra-Scholten termination detection

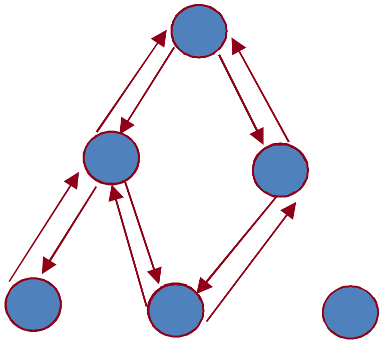
- Works for diffusing computations
- Key concepts

diffusing传播; 普及; 使分散; 散布; 扩散，弥漫，渗透; 模糊，漫射

  - Create a tree out of the active processes
  - When a node finishes processing and it is a leaf, it can be pruned from the tree
  - When only the root remains, and it has completed processing, the system has terminated
- Challenges
  - How to create a tree, and keep it acyclic
  - Must detect when a node is a leaf

Dijkstra-Scholten termination detection

- Each node keeps track of nodes it sends a message to (those it may have woken up), its children
- If a node was already awake when the message arrived, then it is already part of the tree, and should not be added as a child of the sender
- When a node has no more children and it is idle, it tells its parent to remove it as a child



🟢 Processing

🔵 Idle

Comparison of termination detection approaches

- Use distributed snapshot
  - Overhead is one message per link
  - Plus cost to collect result
  - If system not terminated, need to run again!
- Use Dijkstra-Scholten
  - Overhead depends on the number of messages in the system
    - Acknowledgments sent when already part of network and when become idle
    - Can be added to network more than once, so this value is not fixed
  - Does not involve never-activated processes
  - Termination detected when last ack received

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  - **Detecting distributed deadlocks**

Distributed transactions

- Protect a shared resource against simultaneous access by several concurrent processes
- Transactions are sequences of operations, defined with appropriate programming primitives, e.g.:

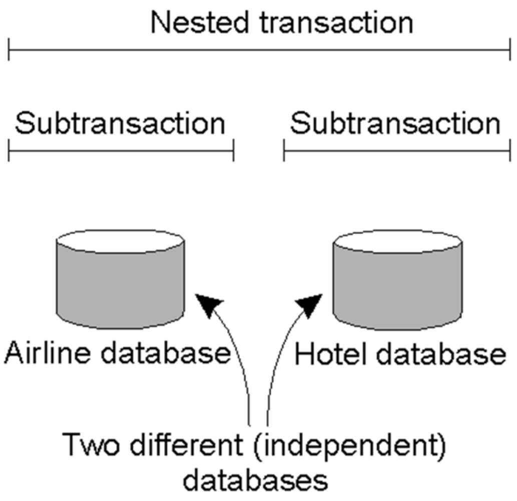
Primitive	**Description**
BEGIN_TRANSACTION	Make the start of a transaction
END_TRANSACTION	Terminate the transaction and try to commit
ABORT_TRANSACTION	Kill the transaction and restore the old values
READ	Read data from a file, a table, or otherwise
WRITE	Write data to a file, a table, or otherwise

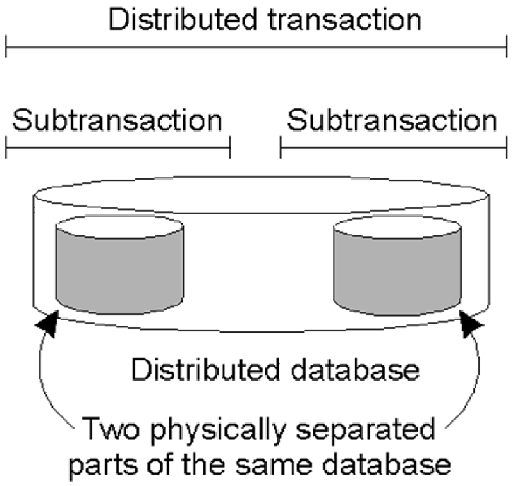
- All-or-nothing (ACID properties):
  – *Atomic*: to the outside world, the transaction happens indivisibly
  – *Consistent*: the transaction does not violate system invariants
  – *Isolated* (or serializable): concurrent transactions do not interfere with each other
  – *Durable*: once a transaction commits, the changes are permanent

Transaction types

the original transaction

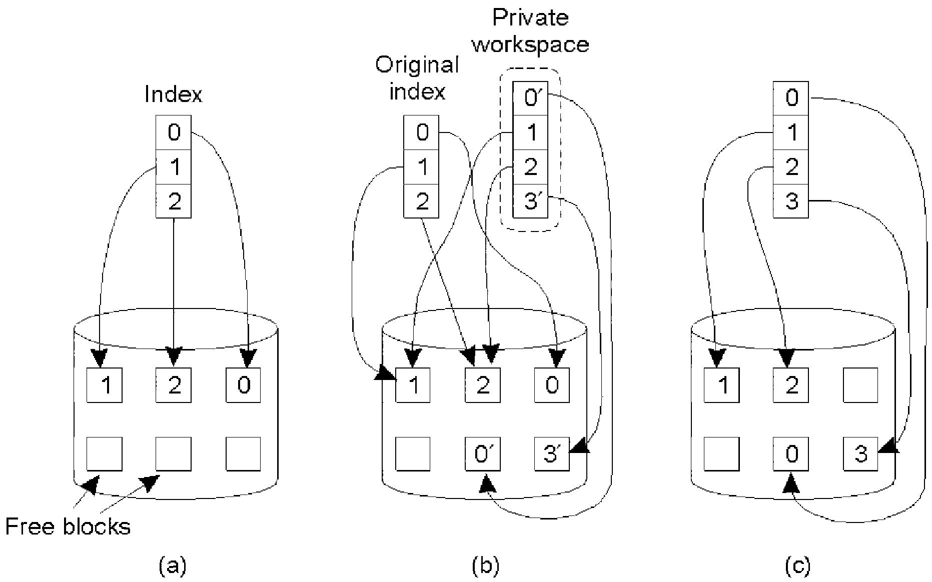
- *Flat*
  - ACID transactions as defined earlier
- *Nested*
  - Constructed from sub-transactions
  - Sub-transactions can be undone once committed (if their parent transaction aborts): durability applies only to top-level transactions
  - Sub-transactions conceptually operate on a private copy of the data:
    - If it aborts the private copy disappears
    - If it commits, the modified private copy is available to the next sub-transaction
  - Typically, each sub-transaction runs on a different host, providing a given service
- *Distributed*
  - Accounts for data distribution
  - Essentially flat transactions on distributed data
    - Instead, nested transactions are hierarchical
  - Need distributed locking





Achieving atomicity

- Approach 1. Private workspace
  - Copy what the transaction modifies into a separate memory space, creating *shadow blocks* of the original file private workspace
  - If the transaction is aborted, this private workspace is deleted, otherwise they are copied into the parent's workspace
  - Optimize by replicating the index, and not the whole file
  - Works fine also for the local part of distributed transactions

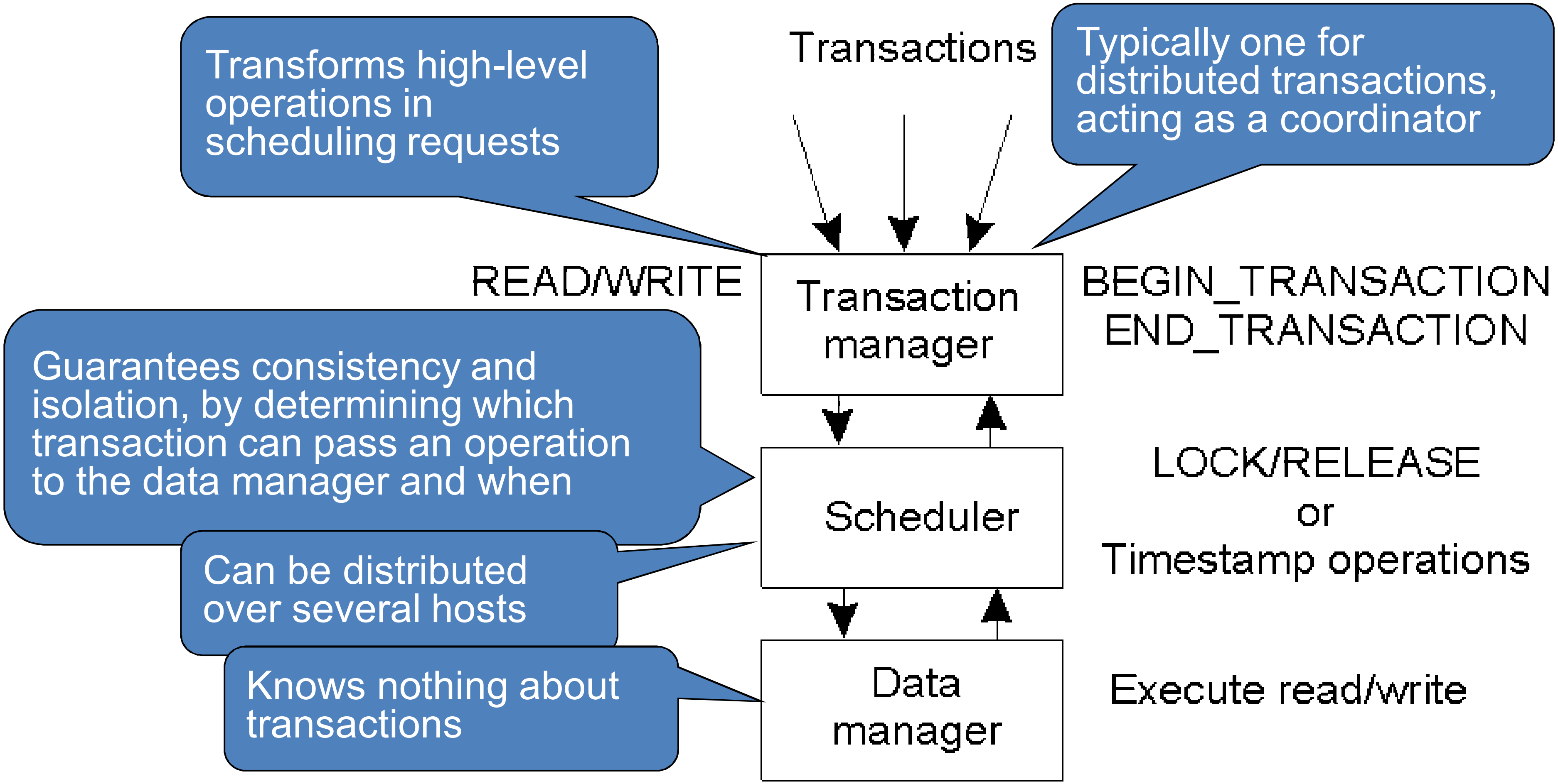


Achieving atomicity

- Approach 2. Writeahead log
  - Files are modified in place (commit is fast), but a log is kept with
    - Transaction that made the change
    - Which file/block
    - Old and new values
  - After the log is written successfully, the file is actually modified
  - If transaction succeeds, commit written to log; if it aborts, original state restored based on logs, starting at the end (rollback)

	Log	Log	Log
x = 0;			
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)

Controlling concurrency



Transactions

Transaction manager

Scheduler

Data manager

READ/WRITE

BEGIN_TRANSACTION
END_TRANSACTION

LOCK/RELEASE
or
Timestamp operations

Execute read/write

Transforms high-level operations in scheduling requests

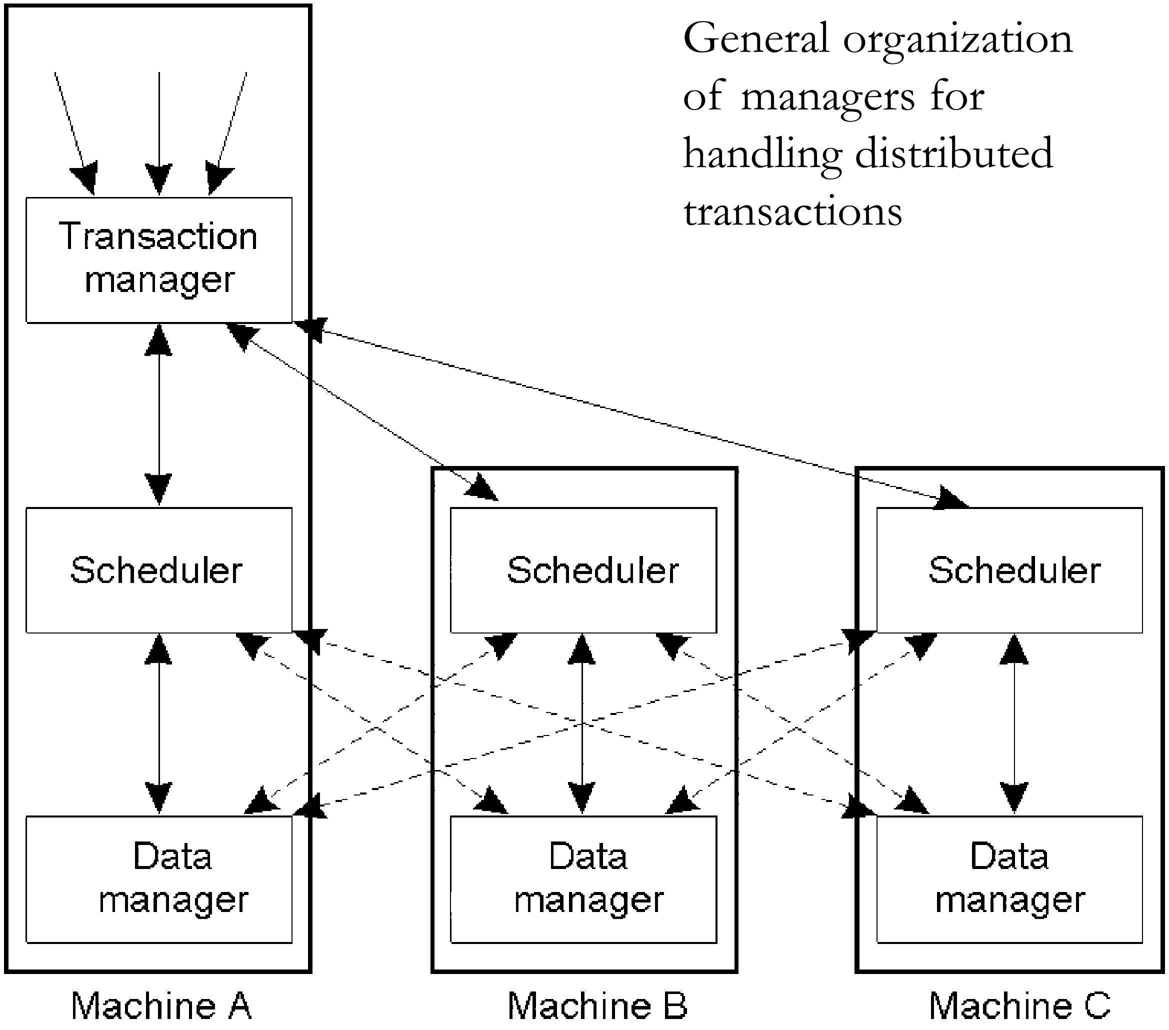
Typically one for distributed transactions, acting as a coordinator

Guarantees consistency and isolation, by determining which transaction can pass an operation to the data manager and when

Can be distributed over several hosts

Knows nothing about transactions

Controlling concurrency: Distributed scheduler



General organization of managers for handling distributed transactions

Serializability

```
BEGIN_TRANSACTION        BEGIN_TRANSACTION        BEGIN_TRANSACTION
  x = 0;                   x = 0;                   x = 0;
  x = x + 1;               x = x + 2;               x = x + 3;
END_TRANSACTION          END_TRANSACTION          END_TRANSACTION
```

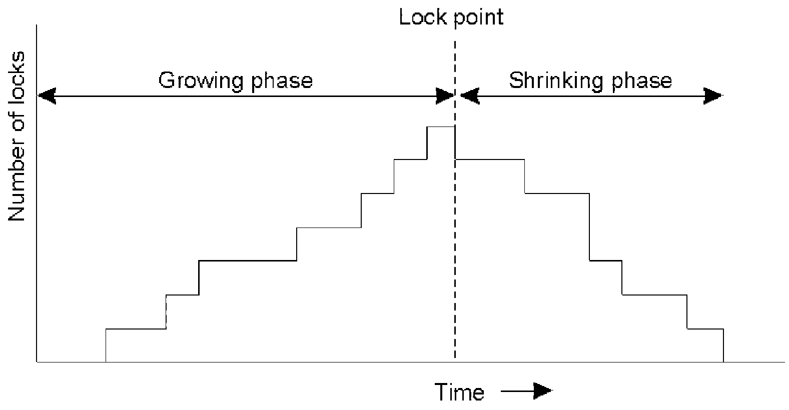
Schedule 1	x = 0; x = x + 1; x = 0; x = x + 2; x = 0; x = x + 3	Legal
Schedule 2	x = 0; x = 0; x = x + 1; x = x + 2; x = 0; x = x + 3	Legal
Schedule 3	x = 0; x = 0; x = x + 1; x = 0; x = x + 2; x = x + 3	Illegal

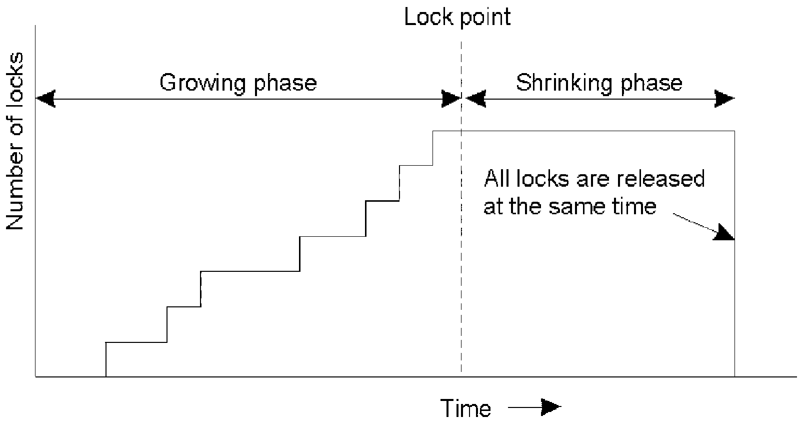
- Various interleavings are possible
  - Only the ones corresponding to some linearization of the involved transactions are legal
- Transaction systems must ensure operations are interleaved correctly, but also free the programmer from the burden of programming mutual exclusion
- Need to properly schedule conflicting operations
  - Read-write and write-write…but not read-read
- Mutual exclusion (locks) vs. explicit operation ordering
- Pessimistic vs. optimistic concurrency control

Two-Phase Locking (2PL)

the only responsible of the scheduler is lock

- When a process needs to access data it requests the scheduler to grant a lock
- Two-phase locking
  - The scheduler tests whether the requested operation conflicts with another that has already received the lock: if so, the operation is delayed
  - Once a lock for a transaction T has been released, T can no longer acquire it
  - *Strict 2PL*, i.e., releasing the locks all at the same time, prevents cascaded aborts by requiring the shrink phase to take place only after transaction termination
  - Proven that 2PL leads to serializability… but it may deadlock
  - Widely used





Implementing 2PL

- Centralized 2PL
  - The transaction manager contacts a centralized lock manager, receives lock grant, interacts directly with the data manager, then returns the lock to the lock manager
- Primary 2PL
  - Multiple lock managers exist
  - Each data item has a primary copy on a host: The lock manager on that host is responsible for granting locks
  - The transaction manager is responsible for interacting with the data managers
- Distributed 2PL
  - Assume data may be replicated on multiple hosts
  - The lock manager on a host is responsible for granting locks on the local replica and for contacting the (local) data manager

Pessimistic timestamp ordering

- Assign a timestamp to each transaction (e.g., using logical clocks)
- Write operations on a data item x are recorded in tentative versions, each with its own write timestamp $ts_{wr}(x_i)$, until commit is performed
  - We refer to the write timestamp of the committed version of x as $ts_{wr}(x)$
- Each data item x has also a read timestamp $ts_{rd}(x)$: That of the last transaction which read x

both are already done

- The scheduler operates as follow:
  - When receives $write(T,x)$ at $time=ts$
    - If $ts>ts_{rd}(x)$ and $ts>ts_{wr}(x)$ perform tentative write x_i with timestamp $ts_{wr}(x_i)$
    - else abort T since the write request arrived too late

arrive too late since it is a operation that need to performed before(but the operation before has already comitted)

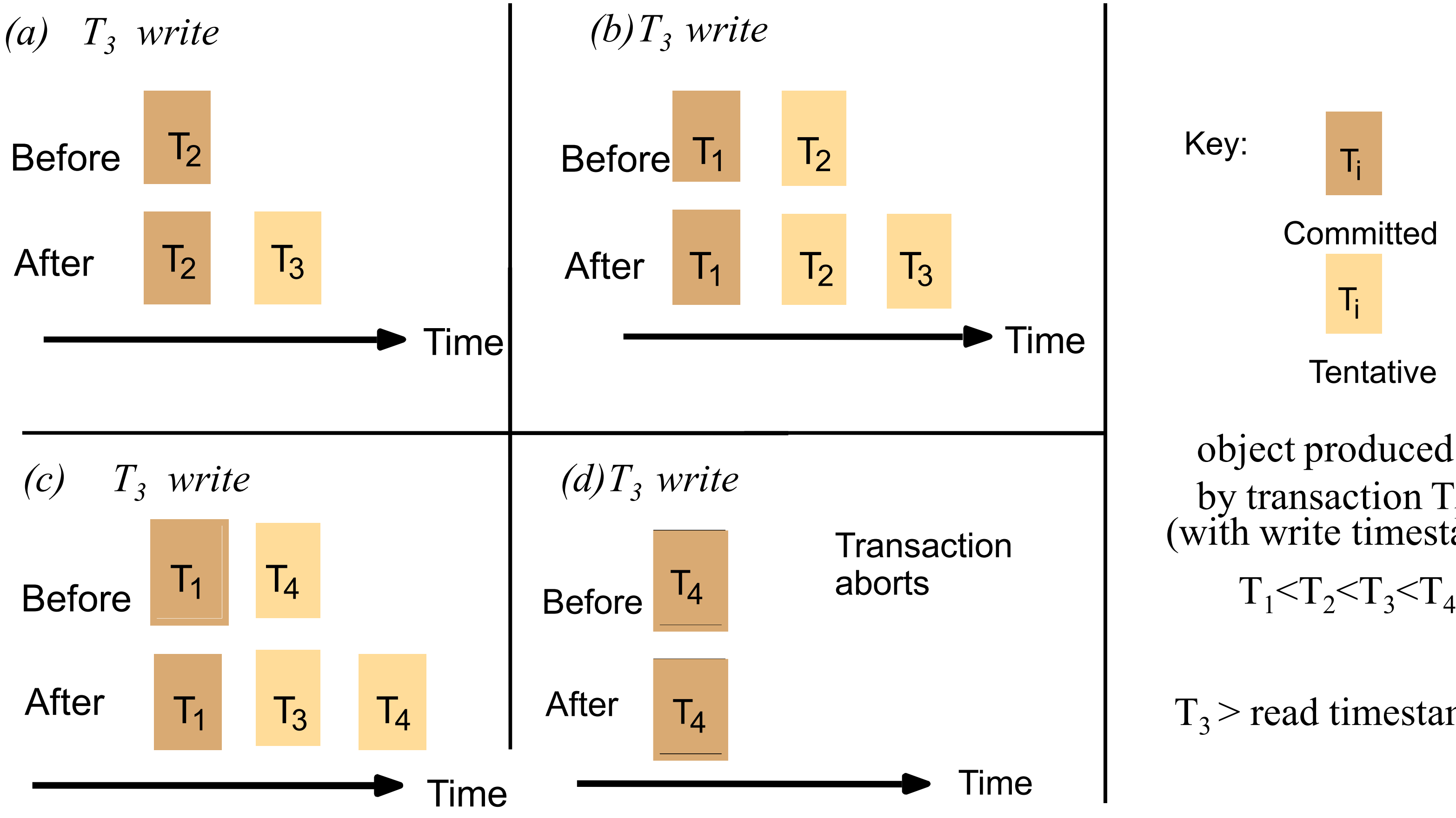
  - Scheduler receives $read(T,x)$ at $time=ts$
    - If $ts>ts_{wr}(x)$
      - Let x_{sel} be the latest version of x with the write timestamp lower than ts
      - If x_{sel} is committed perform read on x_{sel} and set $ts_{rd}(x)=max(ts, ts_{rd}(x))$
      - else wait until the transaction that wrote version x_{sel} commits or abort then reapply the rule
    - else abort T since the read request arrived too late

we cannot read that value anymore since something new has been written

- Aborted transactions will reapply for a new timestamp and simply retry
- Deadlock-free

guarantee serializability and deadlock-free

Write operations and timestamps



(a) T_3 write

Before T_2

After T_2 T_3

Time

(b) T_3 write

Before T_1 T_2

After T_1 T_2 T_3

Time

(c) T_3 write

Before T_1 T_4

After T_1 T_3 T_4

Time

(d) T_3 write

Before T_4

After T_4

Transaction aborts

Time

Key: T_i Committed

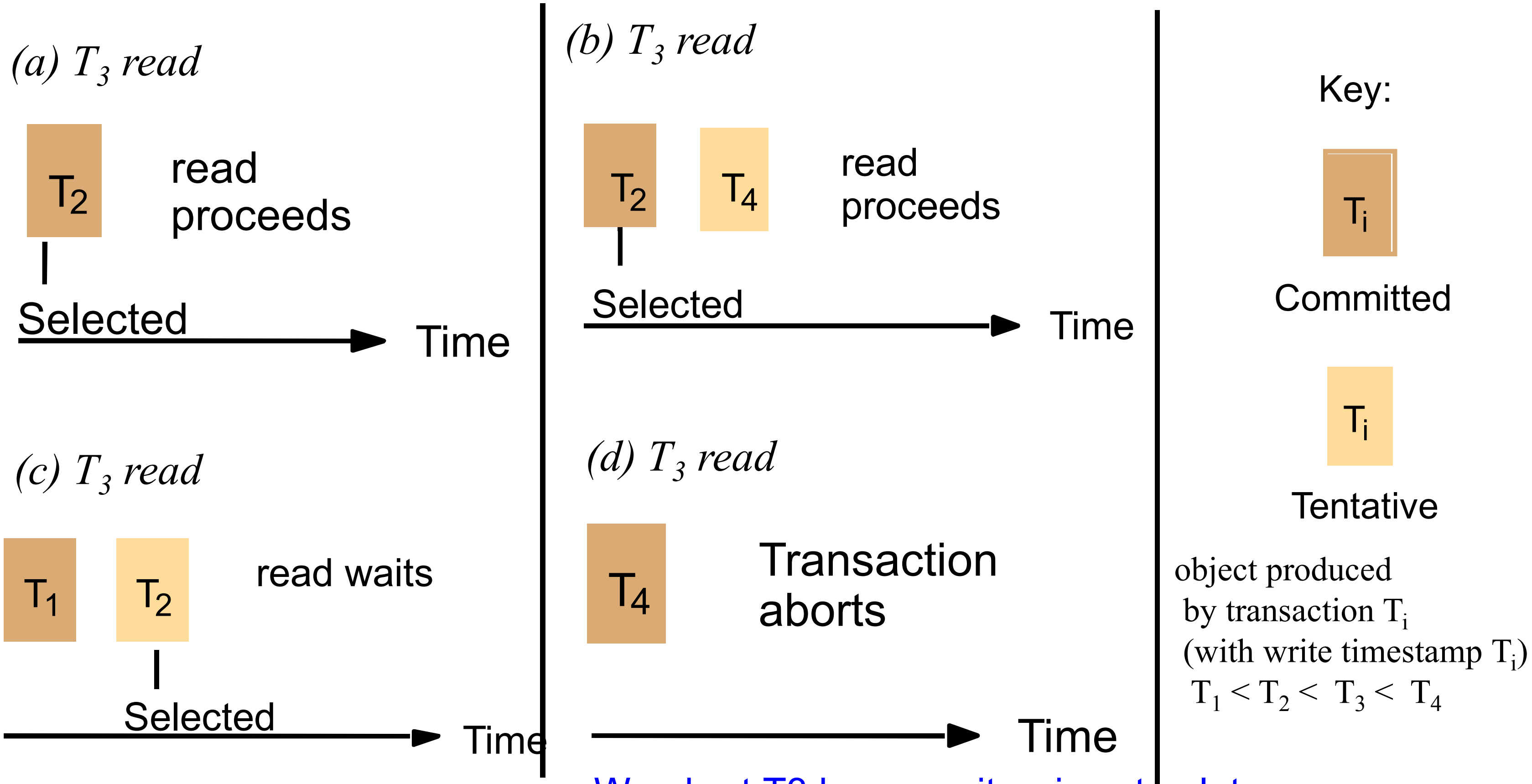
T_i Tentative

object produced by transaction T_i (with write timestamp T_i)

$T_1 < T_2 < T_3 < T_4$

$T_3 >$ read timestamp

Read operations and timestamps



(a) T_3 read

T_2

read proceeds

Selected

Time

(b) T_3 read

T_2 T_4

read proceeds

Selected

Time

(c) T_3 read

T_1 T_2

read waits

Selected

Time

(d) T_3 read

T_4

Transaction aborts

Time

Key:

T_i

Committed

T_i

Tentative

object produced by transaction T_i (with write timestamp T_i) $T_1 < T_2 < T_3 < T_4$

if T2 commit, we unlock and read T1

We abort T3 because it arrives too late

locking vs timestamp

Optimistic timestamp ordering

- Based on the assumption that conflicts are rare
- Therefore: do what you want without caring about others, fix conflicts later
  - Stamp data items with start time of transaction
  - At commit, if any items have been changed since start, transaction is aborted, otherwise committed
  - Best implemented with private workspaces
- Deadlock-free, allows maximum parallelism
- Under heavy load, there may be too many rollbacks
- Not widely used, especially in distributed systems

Distributed deadlocks

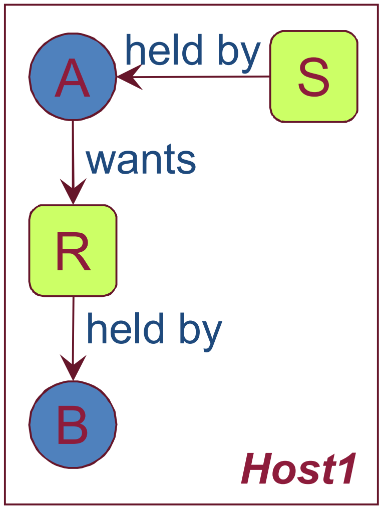
- Same concept as in conventional systems
  - But worse to deal with, since in a distributed system resources are spread out
- Approaches
  - Ignore the problem
    - Most often employed, actually meaningful in many settings
  - Detection
    - And recovery: typically by killing one of the processes
  - Prevention
  - Avoidance
    - Never used in (distributed) systems, as it implies a priori knowledge about resource usage
- Distributed transactions are helpful
  - To abort a transaction (and perform a rollback) is less disruptive than killing a process

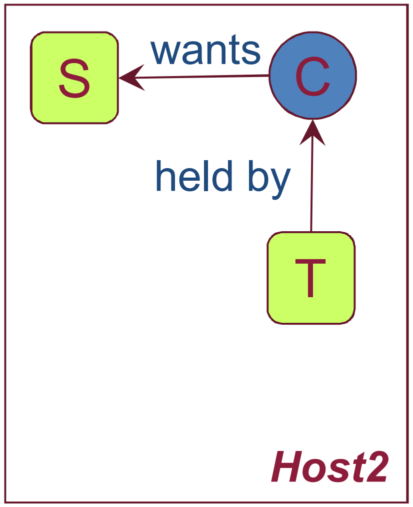
disruptive 英 [dɪs'rʌptɪv]　adj. 引起混乱的

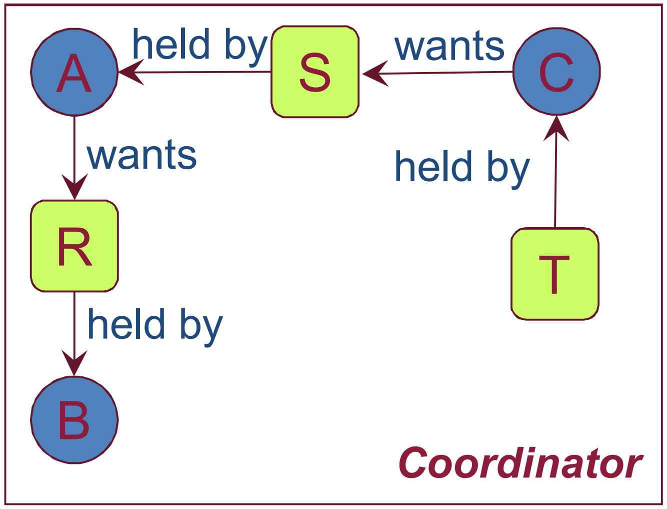
Centralized deadlock detection

- Each machine maintains a resource graph for its own resources and reports it to a coordinator
- Options for collecting this information:
  - Whenever an arc is added or deleted, a message is sent to the coordinator with the update
  - Periodically, every process sends a list of arcs added or deleted since the last update
  - Coordinator can request information on-demand
- None works well, because of false deadlocks
  - For instance, if B releases R and acquires T and the coordinator receives data from host 1 before receiving data from host 2

how to determine if there is a loop



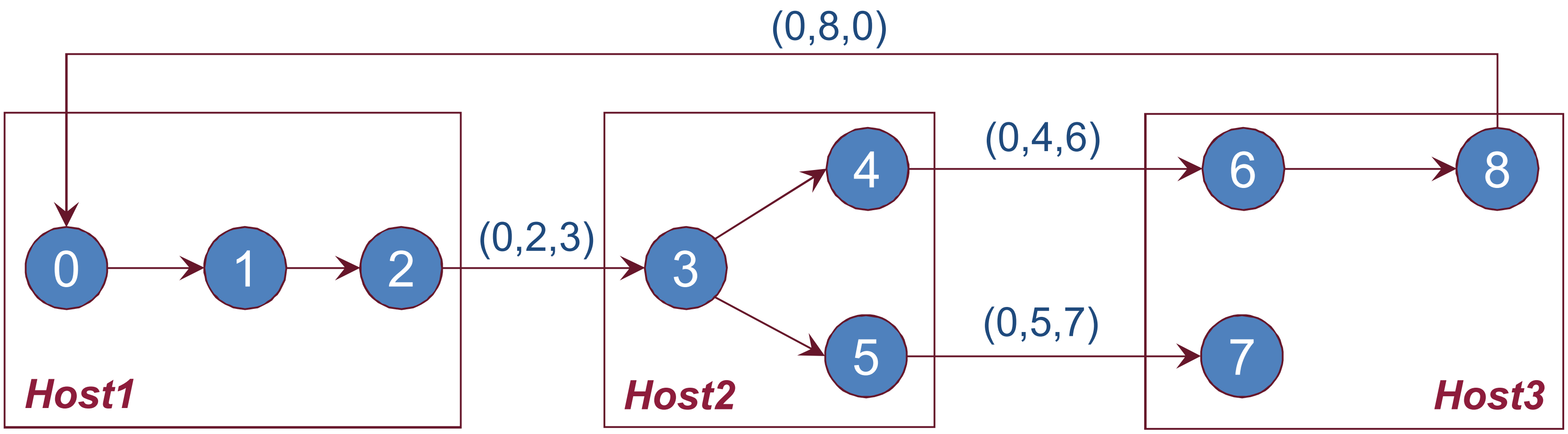




Distributed deadlock detection

Chandy-Misra-Haas (1983)

- There is no coordinator in charge of building the global wait-for graph
- Processes are allowed to request multiple resources simultaneously
- When a process gets blocked, it sends a probe message to the processes holding resources it wants to acquire
  - Probe message: (initiator, sender, receiver)
  - A cycle is detected if the probe makes it back to the initiator

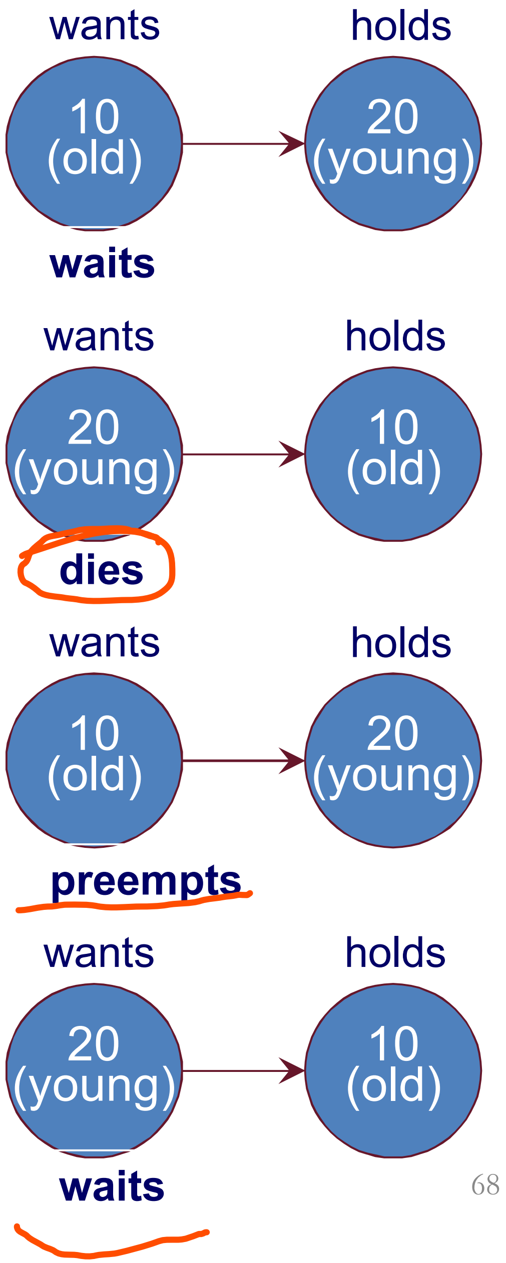


Distributed detection in practice

- How to recover when a deadlock is detected?
  - Initiator commits suicide
    - Many processes may be unnecessarily aborted if more than one initiator detects the loop
  - Alternative
    - The initiator picks the process with the higher identifier and kills it
    - Requires each process to add its identifier to the probe
- In practice: 90% of all deadlock cycles involve just 2 processes [Gray, 1981]
  - At least in databases

Distributed prevention

- Make deadlocks impossible by design
- For instance, using global timestamps (wait-die algorithm):
  - When a process A is about to block for a resource that another process B is using, allow A to wait only if A has a lower timestamp (it is older) than B; otherwise kill the process A
  - Following a chain of waiting processes, the timestamps will always increase (no cycles)
  - In principle, could have the younger wait
- If a process can be preempted, i.e., its resource taken away, an alternative can be devised (wound-wait algorithm):
  - Preempting the young process aborts its transaction, and it may immediately try to reacquire the resource, but will wait
  - In wait-die, young process may die many times before the old one releases the resource: here, this is not the case



wants holds

10 (old) 20 (young)

waits

wants holds

20 (young) 10 (old)

dies

wants holds

10 (old) 20 (young)

preempts

wants holds

20 (young) 10 (old)

waits