19: Distributed Coordination

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Last Time

- We talked about the potential benefits of distributed systems
- We also talked about some of the reasons they can be so difficult to build
- Today we are going to tackle some of these problems!

Recall

- Distributed systems
  - Components can fail (not fail-stop)
  - Network partitions can occur in which each portion of the distributed system thinks they are the only ones alive
  - Don't have a shared clock
  - Can't rely on hardware primitives like test-and-set for mutual exclusion
  - …

Distributed Coordination

- To tackle this complexity we are going to build distributed algorithms for:
  - Event Ordering
  - Mutual Exclusion
  - Atomicity
  - Deadlock Handling
  - Election Algorithms
  - Reaching Agreement

Event Ordering

- Problem: distributed systems do not share a clock
  - Many coordination problems would be simplified if they did ("first one wins")
- Distributed systems do have some sense of time
  - Events in a single process happen in order
  - Messages between processes must be sent before they can be received
  - How helpful is this?

Happens-before

- Define a *Happens-before* relation (denoted by $\rightarrow$).
  - 1) If A and B are events in the same process, and A was executed before B, then $A \rightarrow B$.
  - 2) If A is the event of sending a message by one process and B is the event of receiving that message by another process, then $A \rightarrow B$.
  - 3) If $A \rightarrow B$ and B $\rightarrow C$ then $A \rightarrow C$.

Total ordering?

- Happens-before gives a partial ordering of events
- We still do not have a total ordering of events

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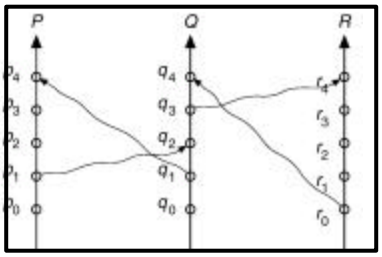
Partial Ordering



Pi ->Pi+1; Qi -> Qi+1; Ri -> Ri+1 R0->Q4; Q3->R4; Q1->P4; P1->Q2

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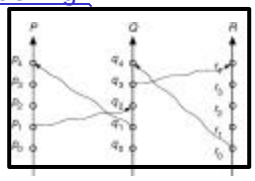
Total Ordering?



P0, P1, Q0, Q1, Q2, P2, P3, P4, Q3, R0, Q4, R1, R2, R3, R4

P0, Q0, Q1, P1, Q2, P2, P3, P4, Q3, R0, Q4, R1, R2, R3, R4

P0, Q0, P1, Q1, Q2, P2, P3, P4, Q3, R0, Q4, R1, R2, R3, R4

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Timestamps

- Assume each process has a local logical clock that ticks once per event and that the processes are numbered
  - Clocks tick once per event (including message send)
  - When send a message, send your clock value
  - When receive a message, set your clock to MAX(your clock, timestamp of message + 1)
    - Thus sending comes before receiving
    - Only visibility into actions at other nodes happens during communication, communicate synchronizes the clocks
  - If the timestamps of two events *A* and *B* are the same, then use the process identity numbers to break ties.
- This gives a total ordering!

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Distributed Mutual Exclusion (DME)

- Problem: We can no longer rely on just an atomic test and set operation on a single machine to build mutual exclusion primitives
- Requirement
  - If P_i is executing in its critical section, then no other process P_j is executing in its critical section.

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Solution

- We present three algorithms to ensure the mutual exclusion execution of processes in their critical sections.
  - Centralized Distributed Mutual Exclusion (CDME)
  - Fully Distributed Mutual Exclusion (DDME)
  - Token passing

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CDME: Centralized Approach

- One of the processes in the system is chosen to coordinate the entry to the critical section.
  - A process that wants to enter its critical section sends a *request* message to the coordinator.
  - The coordinator decides which process can enter the critical section next, and its sends that process a *reply* message.
  - When the process receives a *reply* message from the coordinator, it enters its critical section.
  - After exiting its critical section, the process sends a *release* message to the coordinator and proceeds with its execution.
- 3 messages per critical section entry

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Problems of CDME

- Electing the master process? Hardcoded?
- Single point of failure? Electing a new master process?
- Distributed Election algorithms later…

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DDME: Fully Distributed Approach

- When process P_i wants to enter its critical section, it generates a new timestamp, TS, and sends the message *request* (P_i, TS) to all other processes in the system.
- When process P_j receives a *request* message, it may reply immediately or it may defer sending a reply back.
- When process P_i receives a *reply* message from all other processes in the system, it can enter its critical section.
- After exiting its critical section, the process sends *reply* messages to all its deferred requests.

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DDME: Fully Distributed Approach (Cont.)

- The decision whether process P_j replies immediately to a *request*(P_i, TS) message or defers its reply is based on three factors:
  - If P_j is in its critical section, then it defers its reply to P_i.
  - If P_j does *not* want to enter its critical section, then it sends a *reply* immediately to P_i.
  - If P_j wants to enter its critical section but has not yet entered it, then it compares its own request timestamp with the timestamp TS.
    - If its own request timestamp is greater than TS, then it sends a *reply* immediately to P_i (P_i asked first).
    - Otherwise, the reply is deferred.

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Problems of DDME

- Requires complete trust that other processes will play fair
  - Easy to cheat just by delaying the reply!
- The processes needs to know the identity of all other processes in the system
  - Makes the dynamic addition and removal of processes more complex.
- If one of the processes fails, then the entire scheme collapses.
  - Dealt with by continuously monitoring the state of all the processes in the system.
- Constantly bothering people who don't care
  - Can I enter my critical section? Can I?

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Token Passing

- Circulate a token among processes in the system
- Possession of the token entitles the holder to enter the critical section
- Organize processes in system into a logical ring
  - Pass token around the ring
  - When you get it, enter critical section if need to then pass it on when you are done (or just pass it on if don't need it)

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Problems of Token Passing

- If machines with token fails, how to regenerate a new token?
- A lot like electing a new coordinator
- If process fails, need to repair the break in the logical ring

Compare: Number of Messages?

- CDME: 3 messages per critical section entry
- DDME: The number of messages per critical-section entry is 2 x (n – 1)
  - Request/reply for everyone but myself
- Token passing: Between 0 and n messages
  - Might luck out and ask for token while I have it or when the person right before me has it
  - Might need to wait for token to visit everyone else first

Compare : Starvation

- CDME : Freedom from starvation is ensured if coordinator uses FIFO
- DDME: Freedom from starvation is ensured, since entry to the critical section is scheduled according to the timestamp ordering. The timestamp ordering ensures that processes are served in a first-come, first served order.
- Token Passing: Freedom from starvation if ring is unidirectional
- Caveats
  - network reliable (I.e. machines not "starved" by inability to communicate)
  - If machines fail they are restarted or taken out of consideration (I.e. machines not "starved" by nonresponse of coordinator or another participant)
  - Processes play by the rules

Why DDME?

- Harder
- More messages
- Bothers more people
- Coordinator just as bothered

Atomicity

- Recall: Atomicity = either all the operations associated with a program unit are executed to completion, or none are performed.
- In a distributed system may have multiple copies of the data , replicas are good for reliability/availability
- PROBLEM: How do we atomically update all of the copies?

Replica Consistency Problem

- Imagine we have multiple bank servers and a client desiring to update their back account
  - How can we do this?
- Allow a client to update any server then have server propagate update to other servers
  - Simple and wrong!
  - Simultaneous and conflicting updates can occur at different servers?
- Have client send update to all servers
  - Same problem - race condition – which of the conflicting update will reach each server first

Two-phase commit

- Algorithm for providing atomic updates in a distributed system
- Give the servers (or replicas) a chance to say no and if any server says no, client aborts the operation

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Framework

- Goal: Update all replicas atomically
  - Either everyone commits or everyone aborts
  - No inconsistencies even if face of failures
  - Caveat: Assume no byzantine failures (servers stop when they fail – do not continue and generate bad data)
- Definitions
  - Coordinator: Software entity that shepherds the process (client in our example could be one of the servers)
  - Ready to commit: side effects of update safely stored non-volatilely (recall: write ahead logging)
    - Even if crash, once say I am ready to commit then when recover will find evidence and continue with commit protocol

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Two Phase Commit: Phase 1

- Coordinator send a PREPARE message to each replica
- Coordinator waits for all replicas to reply with a vote
- Each participant send vote
  - Votes PREPARED if ready to commit and locks data items being updated
  - Votes NO if unable to get a lock or unable to ensure ready to commit

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Two Phase Commit: Phase 2

- If coordinator receives PREPARED vote from all replicas then it may decide to commit or abort
- Coordinator send its decision to all participants
- If participant receives COMMIT decision then commit changes resulting from update
- If participant received ABORT decision then discard changes resulting from update
- Participant replies DONE
- When Coordinator received DONE from all participants then can delete record of outcome

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Performance

- In absence of failure, 2PC makes a total of 2 (1.5?) round trips of messages before decision is made
  - Prepare
  - Vote NO or PREPARE
  - Commit/abort
  - Done (but done just for bookkeeping, does not affect response time)

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Failure Handling in 2PC – Replica Failure

- The log contains a <commit *T*> record. In this case, the site executes **redo**(*T*).
- The log contains an <abort *T*> record. In this case, the site executes **undo**(*T*).
- The contains a <ready *T*> record; consult C_i. If C_i is down, site sends **query-status** *T* message to the other sites.
- The log contains no control records concerning *T*. In this case, the site executes **undo**(*T*).

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Failure Handling in 2PC – Coordinator C_i Failure

- If an active site contains a <commit T> record in its log, the T must be committed.
- If an active site contains an <abort T> record in its log, then T must be aborted.
- If some active site does *not* contain the record <ready T> in its log then the failed coordinator C_i cannot have decided to commit T. Rather than wait for C_i to recover, it is preferable to abort T.
- All active sites have a <ready T> record in their logs, but no additional control records. In this case we must wait for the coordinator to recover.
  - Blocking problem – T is blocked pending the recovery of site S_i.

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Failure Handling

- Failure detected with timeouts
- If participant times out before getting a PREPARE can abort
- If coordinator times out waiting for a vote can abort
- If a participant times out waiting for a decision it is blocked!
  - Wait for Coordinator to recover?
  - Punt to some other resolution protocol
- If a coordinator times out waiting for done, keep record of outcome
- other sites may have a replica.

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Deadlock Handling

- Recall our discussion of deadlock in the single node case
- Same problem can occur in distributed system
- Worse? Because harder to do manual detection and recovery
  - Can't just note single machine is slow/hung and and reboot
- How can we deal with deadlock in a distributed system?

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Global Ordering

- Resource-ordering deadlock-prevention – define a *global* ordering among the system resources.
  - Assign a unique number to all system resources.
  - A process may request a resource with unique number *i* only if it is not holding a resource with a unique number grater than *i*.
- Simple to implement; requires little overhead but how easy is it to establish a global ordering?
  - We had this same issue in the single node case. This is a good approach when you can make it work.

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Extend the Banker's Algorithm

- Recall the Banker's algorithm
  - Avoids deadlock by not committing resources unless there is a guaranteed way to complete all
- Banker's algorithm is a distributed system?
  - Designate one of the processes in the system as the process that maintains the information necessary to carry out the Banker's algorithm.
- Straight-forward extension of single node case but
  - Banker is bottleneck
  - Messages on each resource acquire/release
  - Same as in single node case: sounds good but pretty expensive!

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Other choices?

- Recall the necessary conditions for deadlock
  - Mutual Exclusion
  - Hold-and-Wait
  - Circular Wait
  - No preemption
- In the single node case, we showed how to invalidating one of these conditions
- How about in the distributed case?
- What about borrowing from how databases deal with deadlock?

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Recall: Timestamp-Based Protocols

- Method for selecting the order among conflicting transactions
- Associate with each transaction a number which is the timestamp or clock value when the transaction begins executing
- Associate with each data item the largest timestamp of any transaction that wrote the item and another the largest timestamp of a transaction reading the item

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Timestamp-Ordering

- If timestamp of transaction wanting to read data < write timestamp on the data then it would have needed to read a value already overwritten so abort the reading transaction
- If timestamp if transaction wanting to write data < read timestamp on the data then the last read would be invalid but it is committed so abort the writing transaction
- Ability to abort/rollback is crucial!

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Timestamped Deadlock-Prevention Scheme

- Each process P_i is assigned a unique timestamp (or priority)
  - Timestamps are used to decide whether a process P_i should wait for a process P_j; otherwise P_i is rolled back.
  - The scheme prevents deadlocks. For every edge $P_i \rightarrow P_j$ in the wait-for graph, P_i has a higher priority than P_j. Thus a cycle cannot exist.
  - Ability to abort/rollback is crucial

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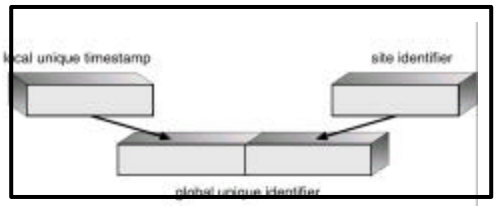
Unique Timestamps in Distributed Environment



Use site identifier as least significant to ensure that the global timestamps generated at one site not always bigger

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Variations

- Wait-Die
  - Non-preemptive
- Wound-wait
  - Preemptive
- Both prevent deadlock by avoiding cycles in the wait-for graph

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Wait-Die Scheme

- Nonpreemptive
- If P_I requests a resource currently held by P_J, P_I is allowed to wait only if it has a smaller timestamp than P_J (P_I is older than P_J). Otherwise, P_I is rolled back (dies).
  - Example: Suppose that processes P_1, P_2, and P_3 have timestamps 1, 2, and 3 respectively.
    - if P_1 request a resource held by P_2, then P_1 will wait.
    - If P_3 requests a resource held by P_2, then P_3 will be rolled back.

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Wound-Wait Scheme

- Preemptive technique
- If P_I requests a resource currently held by P_J, P_I is allowed to wait only if it has a larger timestamp than does P_J (P_I is younger than P_J). Otherwise P_J is rolled back (P_J is wounded by P_I).
  - Example: Suppose that processes P_1, P_2, and P_3 have timestamps 1, 2, and 3 respectively.
    - If P_1 requests a resource held by P_2, then the resource will be preempted from P_2 and P_2 will be rolled back.
    - If P_3 requests a resource held by P_2, then P_3 will wait.

Summary

	Holder has lower timestamp	Holder has higher timestamp
Wait-Die	Requester waits	Requester dies
Wound-Wait	Holder dies (Requester wounds holder)	Requester waits

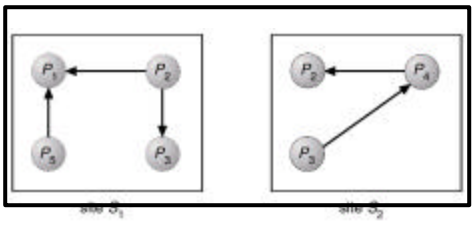
Avoiding Starvation

- Both are a priority based scheme and so subject to starvation
- Avoid starvation if when rollback a process allow it to keep its timestamp
- Eventually it should be the highest priority process and will never be rolled back

Deadlock detection

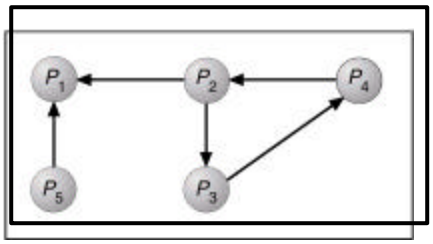
- If instead of deadlock prevention, we could allow deadlocks to occur
- Manual detection and recovery is harder
  - Notice whole distributed system is slow/hung and reboot?
- But automatic detection would global knowledge to find cycles in the wait-for graph

Two Local Wait-For Graphs



Local graphs have no cycles

Global Wait-For Graph



Global graph has a cycle!

Deadlock Detection – Centralized Approach

- Each site keeps a *local* wait-for graph. The nodes of the graph correspond to all the processes that are currently either holding or requesting any of the resources local to that site.
- A global wait-for graph is maintained in a *single* coordination process; this graph is the union of all local wait-for graphs.

Centralized Approach (con't)

- There are three different options (points in time) when the wait-for graph may be constructed:
  1. Whenever a new edge is inserted or removed in one of the local wait-for graphs (implies communication with coordinator on every resource acquire/release!)
  2. Periodically, when a number of changes have occurred in a wait-for graph (at least this can batch info sent to coordinator)
  3. Whenever the coordinator needs to invoke the cycle-detection algorithm..

False Cycles

- Unnecessary rollbacks may occur as a result of *false cycles* due to communication latency
- Local graph snapshots may be taken at different points in time such that the union suggests a cycle that isn't really there

Fully Distributed Approach

- All controllers share equally the responsibility for detecting deadlock.
  - Every site constructs a wait-for graph that represents a part of the total graph.
- We add one additional node P_{ex} to each local wait-for graph.
  - If a local wait-for graph contains a cycle that does not involve node P_{ex}, then the system is in a deadlock state.
  - A cycle involving P_{ex} implies the possibility of a deadlock.
- To ascertain whether a deadlock does exist, info on cycle sent to some other site where they will either detect a deadlock or augment the graph with their information and pass on to another site until all sites have contributed.

Choosing a Coordinator

- In many of the distributed coordination algorithms, we've seen some machine is playing the role of a coordinator
  - Examples: Coordinators for Centralized Deadlock Detection or 2 phase commit
- How do we choose such a coordinator?
- Or elect a new one if the current fails?

Election Algorithms

- GOAL: Determine where a new copy of the coordinator should be started/restarted.
- Assume that a unique priority number is associated with each active process in the system, and assume that the priority number of process P_i is i.
- The coordinator is always the process with the largest priority number. When a coordinator fails, the algorithm must elect that active process with the largest priority number
- Two variants: bully and ring based on topology (ring for ring network topology, bully for everything else)

Ring Algorithm

- Applicable to systems organized as a ring (logically or physically).
  - Assumes that the links are unidirectional, and that processes send their messages to their right neighbors.
- Each process maintains an *active list*, consisting of all the priority numbers of all active processes in the system when the algorithm ends.
- If process P_i detects a coordinator failure (timeout waiting for response), it creates a new active list that is initially empty.
  - It then sends a message *elect(i)* to its right neighbor, and adds the number *i* to its active list.

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Ring Algorithm (Cont.)

- If P_i receives a message elect(*j*) from the process on the left, it must respond in one of three ways:
  1. If this is the first (in some time) *elect* message it has seen or sent, P_i creates a new active list with the numbers *i* and *j*. It then sends the message *elect(i)*, followed by the message *elect(j)*.
  2. If the message does not contain Pi's number then Pi adds j to its active list and forwards it to its
  3. If the message does contain Pi's number, then Pi should have seen all previous messages and its active list should be full

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Recovery in Ring Algorithm

- Recovering process can send a message around the ring requesting to know who is the coordinator
- Coordinator will see message as it goes around ring and reply with its identity

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Bully Algorithm

- For network topologies other than ring
  - Must know all other processes in the system
- Process P_i sends a request that is not answered by the coordinator within a specified time => assume that the coordinator has failed
- P_i tries to elect itself as the new coordinator

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Bully Algorithm (Cont.)

- P_i sends an election message to every process with a higher priority number, P_i then waits for any of these processes to answer within *T*.
  - If no response within *T*, assume that all processes with numbers greater than i have failed; P_i elects itself the new coordinator.
  - If answer is received, P_i begins time interval *T´*, waiting to receive a message that a process with a higher priority number has been elected.
    - If no such message is received within *T´*, assume the process with a higher number has failed; P_i should restart the algorithm

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Bully Algorithm (Cont.)

- If P_i is not the coordinator, then, at any time during execution, P_i may receive one of the following two messages from process P_j.
  - P_j is the new coordinator ($j > i$). P_i, in turn, records this information.
  - P_j started an election ($j > i$). P_i, sends a response to P_j and begins its own election algorithm, provided that *Pi* has not already initiated such an election.

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Recovery in Bully Algorithm

- After a failed process recovers, it immediately begins execution of the same algorithm.
- If there are no active processes with higher numbers, the recovered process forces all processes with lower number to let it become the coordinator process, even if there is a currently active coordinator with a lower number.

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Byzantine Generals Problem

- Deals with reaching agreement in the face of both faulty communications and untrustworthy peers
- Problem:
  - Divisions of an army each commanded by a general surrounding an enemy camp
  - Generals must reach agreement on whether to attack (a certain number must attack or defeat is certain)
  - Divisions are geographically separated such that they must communicate via messengers
  - Messengers may be caught and never reach the other side (lost messages)
  - Generals may be traitors (faulty/compromised processes)

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Problem 1: Losts Messengers/Messages

- How can we deal with the fact that messages may be lost? (We saw this in TCP)
- Detect failures using a time-out scheme.
  - When send a message, specifies a time interval to wait for an acknowledgment
  - When receives a message, sends an acknowledgment
  - Acknowledgment can be lost too!.
  - If receives the acknowledgment message within the specified time interval can conclude that message was received its message. If a time-out occurs, retransmit message and wait for another acknowledgment.
  - Continue until either receives an acknowledgment, or give up after some time?

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The Last Word?

- Suppose, the receiver needs to know that the sender has received its acknowledgment message, in order to decide on how to proceed
- Actually, in the presence of failure, it is not possible to accomplish this task
- It is not possible in a distributed environment for processes P_I and P_J to agree completely on their current respective states
- Always level of uncertainty about last message

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Traitors?

- Consider that generals can be traitors (processes can be faulty)
- What could traitors do?
  - Refuse to send any messages
  - Delay sending messages
  - Send incorrect messages
  - Send different messages to different generals

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Formalize Agreement

- Consider a system of n processes, of which no more than m are faulty.
- Devise an algorithm that allows each non-faulty P_I to construct a vector $X_I = (A_{I1}, A_{I2}, ..., A_{In})$ such that::
  - Each process P_I has some private value of V_I.
  - If P_J is a nonfaulty process, then $A_{IJ} = V_J$.
  - If P_I and P_J are both nonfaulty processes, then $X_I = X_J$.

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Solutions to Problem of Reaching Agreement

- Solutions share the following properties.
  - Assume reliable communication
  - Bound maximum number of traitors to m
  - A correct algorithm can be devised only if $n \geq 3 \times m + 1$.
  - The worst-case delay for reaching agreement is proportionate to $m + 1$ message-passing delays.

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Simplest Example

- An algorithm for the case where $m = 1$ and $n = 4$ (>= 3*m+1) requires m+1 = 2 rounds of information exchange:
  - Each process sends its private value to the other 3 processes.
  - Each process sends the information it has obtained in the first round to all other processes.

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Simplest Example (con't)

- If a faulty process refuses to send messages, a nonfaulty process can choose an arbitrary value and pretend that that value was sent by that process.
- After the two rounds are completed, a nonfaulty process P_i can construct its vector $X_i = (A_{i,1}, A_{i,2}, A_{i,3}, A_{i,4})$ as follows:
  - $A_{i,j} = V_j$.
  - For $j \neq i$, if at least two of the three values reported for process P_j agree, then the majority value is used to set the value of $A_{i,j}$. Otherwise, a default value (*nil*) is used.

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Consider

- What if n < 4
  - If n=3 and there was one traitor then it could lie differently to the two non-traitors and they could not resolve the discrepancy by a majority vote
- What if only one round?

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Outtakes

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- Ensuring atomicity in a distributed system requires a *transaction coordinator*, which is responsible for the following:
  - Starting the execution of the transaction.
  - Breaking the transaction into a number of subtransactions, and distribution these subtransactions to the appropriate sites for execution.
  - Coordinating the termination of the transaction, which may result in the transaction being committed at all sites or aborted at all sites.

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Two-Phase Commit Protocol (2PC)

- Assumes fail-stop model.
- Execution of the protocol is initiated by the coordinator after the last step of the transaction has been reached.
- When the protocol is initiated, the transaction may still be executing at some of the local sites.
- The protocol involves all the local sites at which the transaction executed.
- Example: Let T be a transaction initiated at site S_i and let the transaction coordinator at S_i be C_i.

Phase 1: Obtaining a Decision

- C_i adds <prepare T> record to the log.
- C_i sends <prepare T> message to all sites.
- When a site receives a <prepare T> message, the transaction manager determines if it can commit the transaction.
  - If no: add <no T> record to the log and respond to C_i with <abort T>.
  - If yes:
    - add <ready T> record to the log.
    - force *all log records* for T onto stable storage.
    - transaction manager sends <ready T> message to C_i.

Phase 1 (Cont.)

- Coordinator collects responses
  - All respond "ready", decision is *commit*.
  - At least one response is "abort", decision is *abort*.
  - At least one participant fails to respond within time out period, decision is *abort*.

Phase 2: Recording Decision in the Database

- Coordinator adds a decision record

  <abort T> or <commit T>

  to its log and forces record onto stable storage.
- Once that record reaches stable storage it is irrevocable (even if failures occur).
- Coordinator sends a message to each participant informing it of the decision (commit or abort).
- Participants take appropriate action locally.

Concurrency Control

I cut this all together – too similar to mutual Exclusion – does it deserve a separate discussion

Concurrency Control

- Modify the centralized concurrency schemes to accommodate the distribution of transactions.
- Transaction manager coordinates execution of transactions (or subtransactions) that access data at local sites.
- Local transaction only executes at that site.
- Global transaction executes at several sites.

Locking Protocols

- Nonreplicated scheme – each site maintains a local lock manager which administers lock and unlock requests for those data items that are stored in that site.
  - Simple implementation involves two message transfers for handling lock requests, and one message transfer for handling unlock requests.
  - Deadlock handling is more complex.

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Single-Coordinator Approach

- A single lock manager resides in a single chosen site, all lock and unlock requests are made a that site.
  - Simple implementation
  - Simple deadlock handling
  - Possibility of bottleneck
  - Vulnerable to loss of concurrency controller if single site fails
- *Multiple-coordinator approach* distributes lock-manager function over several sites.

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Majority Protocol

- Avoids drawbacks of central control by dealing with replicated data in a decentralized manner.
- Must get ok from at least n/2 +1 participants
- Deadlock-handling algorithms must be modified; possible for deadlock to occur in locking only one data item.
  - Example: two processes trying to lock each get 2 out of 4 processes to say ok – each need a third?

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Biased Protocol (OUTTAKE)

- Similar to majority protocol, but requests for shared locks prioritized over requests for exclusive locks.
- Less overhead on read operations than in majority protocol; but has additional overhead on writes.
- Like majority protocol, deadlock handling is complex.

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Primary Copy

- One of the sites at which a replica resides is designated as the primary site. Request to lock a data item is made at the primary site of that data item.
- Concurrency control for replicated data handled in a manner similar to that of unreplicated data.
- Simple implementation, but if primary site fails, the data item is unavailable, even though other sites may have a replica.

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Example Centralized Deadlock Detection Algorithm

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Detection Algorithm Based on Option 3

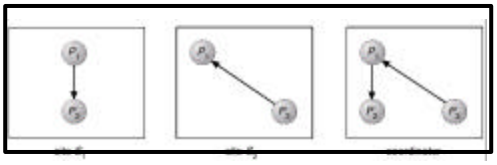
- Append unique identifiers (timestamps) to requests form different sites.
- When process P_i, at site A, requests a resource from process P_j, at site B, a request message with timestamp TS is sent.
- The edge $P_i \rightarrow P_j$ with the label TS is inserted in the local wait-for of A. The edge is inserted in the local wait-for graph of B only if B has received the request message and cannot immediately grant the requested resource.

The Algorithm

1. The controller sends an initiating message to each site in the system.
2. On receiving this message, a site sends its local wait-for graph to the coordinator.
3. When the controller has received a reply from each site, it constructs a graph as follows:
   (a) The constructed graph contains a vertex for every process in the system.
   (b) The graph has an edge P_i ® P_j if and only if (1) there is an edge P_i ® P_j in one of the wait-for graphs, or (2) an edge P_i ® P_j with some label TS appears in more than one wait-for graph.

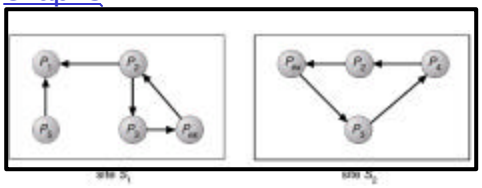
   If the constructed graph contains a cycle ⇒ deadlock.

Local and Global Wait-For Graphs

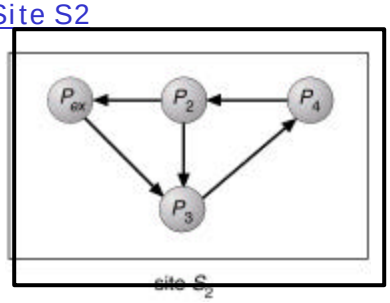


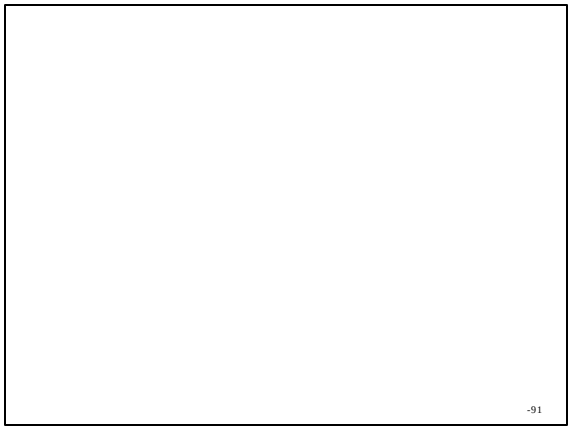
Distributed Deadlock Detection

Augmented Local Wait-For Graphs



Augmented Local Wait-For Graph in Site S2

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