

Distributed Software Development Consensus and Agreement

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Previously on CS 682

- Time is a big challenge in systems that don't share a clock.
- Insight: we often don't need to know the exact time that events occur.
- Instead, we need to know the order in which they happened.

Cause and Effect

- Cause and effect can be used to produce a partial ordering.
- Local events are ordered by identifier.
- Send and receive events are ordered.
 - If p_1 sends a message m_1 to p_2 , $send(m_1)$ must occur before $receive(m_1)$.
 - Assume that messages are uniquely identified.
- If two events do not influence each other, even indirectly, we won't worry about their order.

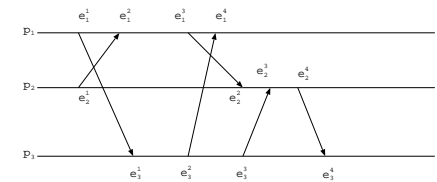
Happens before

- The *happens before* relation is denoted \rightarrow .
- Happens before is defined:
 - If e_i^k, e_i^l and $k < l$, then $e_i^k \rightarrow e_i^l$
 - (sequentially ordered events in the same process)
 - If $e_i = send(m)$ and $e_j = receive(m)$, then $e_i \rightarrow e_j$
 - (send must come before receive)
 - If $e \rightarrow e'$ and $e' \rightarrow e''$, then $e \rightarrow e''$
 - (transitivity)
- If $e \not\rightarrow e'$ and $e' \not\rightarrow e$, then we say that e and e' are concurrent. ($e || e'$)
- These events are unrelated, and could occur in either order.

Happens before

- Happens before provides a partial ordering over the global history. (H, \rightarrow)
- We call this a distributed computation.
- A distributed computation can be represented with a space-time diagram.

Space-time diagram



Space-time diagram

- Arrows indicate messages sent between processes.
- Causal relation between events is easy to detect
- Is there a directed path between events?
- $e_1^1 \rightarrow e_3^4$
- $e_1^2 || e_3^1$

Monitoring a distributed computation

- Recall that we want to know what the global state of the system is at some point in time.
- Active monitoring won't work
 - Updates from different processes may arrive out of order.
- We need to restrict our monitor to looking at *consistent cuts*
- A cut is consistent if, for all events e and e'
 - $(e \in C \text{ and } e' \rightarrow e) \Rightarrow e' \in C$
- In other words, we retain causal ordering and preserve the 'happens before' relation.

Synchronous communication

- How could we solve this problem with synchronous communication and a global clock?
- Assume FIFO delivery, delays are bounded by δ
 - $send(i) \rightarrow send(j) \Rightarrow deliver(i) \rightarrow deliver(j)$
 - Receiver must buffer out-of-order messages.
- Each event e is stamped with the global clock: $RC(e)$.
- When a process notifies p_0 of event e , it includes $RC(e)$ as a timestamp.
- At time t , p_0 can process all messages with timestamps up to $t - \delta$ in increasing order.
- No earlier message can arrive after this point.

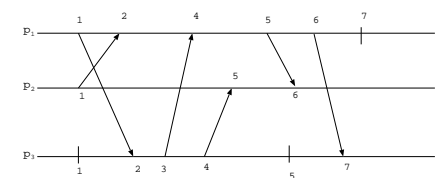
Why does this work?

- If we assume a delay of δ , at time t , all messages sent before $t - \delta$ have arrived.
- By processing them in increasing order, causality is preserved.
- $e \rightarrow e' \Rightarrow RC(e) < RC(e')$
- But we don't *have* a global clock!!

Logical clocks

- Each process maintains a logical clock. (LC).
- Maps events to natural numbers. $(0, 1, 2, 3, \dots)$.
- In the initial state, all LCs are 0.
- Each message m contains a timestamp indicating the logical clock of the sending process.
- After each event, the logical clock for a process is updated as follows:
 - $LC(e) = LC + 1$ if e is a local or send event.
 - $LC(e) = \max(LC, TS(m)) + 1$ if $e = receive(m)$.
- The LC is updated to be greater than both the previous clock and the timestamp.

Logical clock example

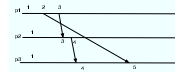


Logical clocks

- Notice that logical clock values are increasing with respect to causal precedence.
 - Whenever $e \rightarrow e'$, $LC(e) < LC(e')$
- The monitor can process messages according to their logical clocks to always have a consistent global state.
- Are we done?
 - Maybe. If we have synchronous communication, this is great.
 - In an asynchronous model, this delivery rule lacks *liveness*.
 - Without a bound on message delay, we can never be sure that we won't have another message with a lower logical clock.
 - We can't detect gaps in the clock sequence.
 - Example: we'll wait forever for the nonexistent message for e_3 from p_1 .
 - We can solve this by waiting to deliver e_3 until we've received messages with higher LCs from all other processes.

Causal delivery

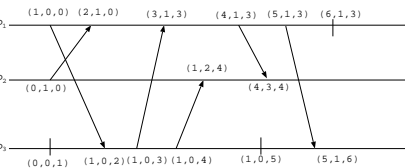
- Recall that FIFO only refers to messages sent by the same process.
- causal delivery* is a more general property which says that if $send(m_1) \rightarrow send(m_2)$, then $deliver(m_1) \rightarrow (m_2)$ when different processes are sending m_1 and m_2 .
- Logical clocks aren't enough to give us causal delivery.



Vector clocks

- Solution: keep a "logical clock" for each process.
- these are stored in a vector VC .
 - Assumes number of processes is known and fixed.
- Update rule:
 - $VC(e)[i] = VC[i] + 1$ for send and internal.
 - $VC(e) = \max(VC, TS(m))$ for receive; then $VC(e)[i] = VC[i] + 1$
- On receive, the vector clock takes the max on a component-by-component basis, then updates the local clock.

Vector Clock example



Vector clocks

- The monitor can then process events in order of ascending vector clocks.
- This ensures causality.
- Two clocks are inconsistent if $c_1[i] < c_2[i]$ and $c_1[j] > c_2[j]$
- If a cut contains no inconsistent clocks, it is consistent.
- Vector clocks allow the implementation of causal delivery.

Using

- Cuts are useful if we need to rollback or restore a system.
- Consistent global cuts provide a set of consistent system states.
- Let us answer questions about the global properties of the system.
- Note that we still don't necessarily have the 'true' picture of the system.
 - Concurrent events may appear in an arbitrary order in a consistent run.
- We have enough information to reproduce all relevant ordering.

Applying causal delivery

- Causal delivery gives us almost all of the functionality that we need from a global clock.
- We can build on top of this to solve more complex coordination problems.
- Coordination often requires not only that all processes agree on state, but that all processes can ensure that every other process sees the same state.

Consensus and agreement

- A fundamental problem in distributed systems is getting a set of processes or nodes to agree on one or more values.
 - Is a procedure continuing or aborted?
 - What value is stored in a distributed database?
 - Which process is serving as coordinator?
 - Has a node failed?
- There are a set of related problems that require a set of processes to coordinate their states or actions.

Coordination via e

- An example:
 - Two people (A and B) want to meet at dusk tomorrow evening at a local hangout.
 - Each wants to show up only if the other one will be there.
 - They can send email to each other, but email may not arrive.
 - Can either one guarantee that the other will be there?

Failure models

- We'll want to distinguish what sorts of failures these algorithms can tolerate.
- No failure
 - Some of the algorithms we'll see can't tolerate a failure.
- Crash failure
 - This means that a node stops working and fails to respond to all messages.
- Byzantine failure
 - A node can exhibit arbitrary behavior.
 - This makes things pretty hard for us ...

Failure detection

- How can we detect whether a failure has happened?
- A simple method:
 - Every t seconds, each process sends an "I am alive" message to all other processes.
 - Process p knows that process q is either *unsuspected*, *suspected*, or *failed*
- If p sees q 's message, it knows q is alive, and sets its status to unsuspected.
- What if it doesn't receive a message?

Failure detec

- Depends on our communication model.
- Synchronous communication: if after d seconds (where d is the maximum delay in message delivery) we haven't received a message from p , p has failed.
- Asynchronous or unreliable communication: if the message is not received, we can say that p is suspected of failure.

Failure detection

- Other problems:
 - What if d is fairly large?
 - We can think processes are still running that have in fact crashed.
- This is what's called an *unreliable* failure detector.
- It will make mistakes, but, given enough information, it may still be of use.
- Can provide hints and partial information.
- As we look at different algorithms, we'll need to think about whether we can detect that a process has failed.

Multicast: a brief digression

- The Coulouris chapter talks quite a bit about how to achieve different properties with multicast communication.
 - Reliable multicast
 - Ordered multicast
 - FIFO ordering
 - Total ordering
 - Causal ordering
- The punchline: Totally ordered multicast is equivalent to the consensus problem.

What is multicast

- Consider that a process needs to send a message to a *group* of other processes.
- It could:
 - Send a point-to-point message to every other process.
 - Inefficient, plus need to know all other processes in group.
 - Broadcast to all processes in subnet.
 - Wasteful, won't work in wide-area network.
- Multicast allows the process to do a single send. Packet is delivered to all members of the group.

Multicast groups

- Notice that multicast is a packet-oriented communication.
 - Same send/receive semantics as UDP
- A process joins a multicast group (designated by an IP address)
- It then receives all messages sent to that IP address.
- Groups can be closed or open.
- Multicast can be effectively used to do shared whiteboards, video or audio conferencing, or to broadcast speeches or presentations.
 - Middleware needed to provide ordering.

Mutual exclusion

- Mutual exclusion is a familiar problem from operating systems.
 - There is some resource that is shared by several processes.
 - Only one process can use the resource at a time.
 - Shared file, database, communications medium
- Processes request to enter their *critical section*, then enter, then exit.
- In a centralized system, this can be negotiated with shared objects. (locks or mutexes).
- Distributed systems rely only on message passing!

Mutual exclusion

- Our goals for mutual exclusion:
 - **safety**: Only one process uses the resource at a time.
 - **liveness**: everyone eventually gets a turn.
 - This implies no deadlock or starvation.
 - **ordering**: if process i 's request to enter its CS happens-before (in the causal sense) process j 's, then process i should enter first.

Mutual exclusion: centralized server

- One solution is to use a centralized server to manage access.
- To enter the critical section, a process sends a request to the server.
 - If no one is in a critical section, the server returns a token. When the process exits the critical section, the token is returned.
 - If someone already has the token, the request is queued.
- Requests are serviced in FIFO order.

Mutual exclusion: centralized server

- If no failures occur, this ensures safety and liveness.
- Ordering is not satisfied.
- Central server provides a bottleneck and a single point of failure.

Mutual exclusion: token

- Rather than dedicating a server, processes are logically arranged in a ring.
 - This may not have anything to do with network topology; we just assign an order.
- The token is passed clockwise (for example) around the ring.
- When the token is received, a process can enter its critical section.
- If the token is not needed, it is immediately passed on.

Mutual exclusion: token ring

- Achieves liveness and safety, but not ordering.
- Also can use a lot of bandwidth when no process needs the resource.
- Also can't handle failure.
 - What if the process with the token fails?
 - If we can detect failure, we can generate a new token.
 - Leader election can deal with this.

Mutual exclusion: multicast

- Assume each process has a distinct identifier
- Assume each process can keep a logical clock.
- A process has three states: Released, waiting, held.
- When a process p wants to enter the critical section:
 - p sets its state to waiting
 - p sends a message to all other processes containing its ID and logical timestamp.
 - Once all other processes respond, p can enter.

Mutual exclusion: multi

- When a message is received:
 - If state is held, queue message
 - If state is waiting and timestamp is after local timestamp, queue message.
 - Else, reply immediately.
- When exiting the critical section:
 - set state to released
 - reply to queued requests.

Mutual exclusion: multicast

- Example: consider p_1, p_2, p_3 .
- p_3 doesn't need CS. $T(p_1) = 41, T(p_2) = 34$.
- p_1 and p_2 request CS.
- p_3 replies immediately to both.
- When p_2 gets p_1 's request, it queues it.
- p_1 replies to p_2 immediately.
- Once p_2 exits, it replies to p_1 .

Mutual exclusion: multicast

- Provides liveness, safety
- Also provides ordering
 - That's the reason for logical clocks.
- Still can't deal with failure.
- Also scaling problems.
- Optimization: can enter the CS when a majority of replies are received.

Dealing with failure

- If a failure occurs, it must first be detected.
 - As we've seen, this can be difficult.
- Once failure is detected, a new group can be formed and the protocol restarted.
- Group formation involves a two-phase protocol.
 - Coordinator broadcasts group change to all members.
 - Once all reply, a commit is broadcast to all members.
 - Once all members reply to the commit, a new group is formed.

Election algorithms

- How can we decide which process should play the role of server or coordinator?
- We need for all processes to agree.
- We can do this by means of an election.
- Any process can start an election
 - for example, if it notices that the coordinator fails.
- We would still like safety (only one process is chosen) and liveness (the election process is guaranteed to find a winner).
 - Even when more than one election is started simultaneously.

Choosing a leader

- Assume each process has an identifying value.
- Largest value will be the new leader.
 - We could use load, or uptime, or a random number.

Ring-based election algorithm

- Assume processes are arranged in a logical ring.
- A process starts an election by placing its identifier and value in a message and sending it to its neighbor.

Ring-based election algorithms

- When a message is received:
 - If the value is greater than its own, it saves the identifier and forwards the value to its neighbor.
 - Else if the receiver's value is greater and the receiver has not participated in an election already, it replaces the identifier and value with its own and forwards the message.
 - Else if the receiver has already participated in an election, it discards the message.
 - If a process receives its own identifier and value it knows it is elected. It then sends an elected message to its neighbor.
- When an elected message is received, it is forwarded to the next neighbor.

Ring-based election algorithms

- Safety is guaranteed - only one value can be largest and make it all the way through the ring.
- Liveness is guaranteed if there are no failures.
- Inability to handle failure once again ...

Bully algorithm

- The *bully* algorithm can deal with crash failures.
 - Assumption: synchronous, reliable communication
- When a process notices that the coordinator has failed, it sends an election message to all higher-numbered processes.
- If no one replies, it declares itself coordinator and sends a new-coordinator message to all processes.
- If someone replies, its job is done.
- When process q receives an election message from a lower-numbered process:
 - Return a reply.
 - Start an election.

Bully algorithm

- Guarantees safety and liveness.
- Can deal with crash failures
- Assumes that there is bounded message delay
 - Otherwise, how can we distinguish between a crash and a long delay?

Consensus

- All of these algorithms are examples of the consensus problem.
 - All processes must agree on a state
- Let's take a step back and think about when the consensus problem can be solved.

Consensus

- We'll start with a set of processes p_1, p_2, \dots, p_n .
- All processes can propose a value, and everyone must agree at the end.
- We'll assume that communication is reliable.
- Processes can fail.
 - Both Byzantine and crash failures.
- We'll also specify whether processes can digitally sign messages.
 - This limits the damage Byzantine failures can do.
- We'll specify whether communication is synchronous or asynchronous.

Consensus

- Our goals:
 - Termination: eventually every process decides on a value
 - Agreement: All processes agree on a value
 - Integrity: If all correct processes propose the same value, that value is the one selected.

Byzantine generals

- All commanders must agree whether to attack or not.
- Commanders can be treacherous and send different messages each commander
 - Slightly different from consensus: one process supplies a value that others must agree on.
- Can this be solved? Can the head commander get consensus?
 - Depends on our communication assumptions.

Consensus in synchronous systems

- If we don't have reliable communication, consensus is impossible, even without failures.
 - Email example
- With reliable communication, we can solve consensus for crash failures.
- Multiple rounds of communication are required to account for failures.

Byzantine generals in a synchronous system

- In the Byzantine generals problem, we can solve it in a synchronous system if less than 1/3 of the processors fail.
 - Three-processor problem is impossible.
- Couloris shows how to solve this - intuition is to use majority.
- If processes can sign their messages, we can solve the Byzantine generals problem for any number of failures.

Byzantine generals in an asynchronous system

- In asynchronous systems, the news is not so good.
- In asynchronous systems, it is impossible to guarantee that we will reach consensus, even in the presence of a single crash failure.
- This means that we can't do:
 - Asynchronous Byzantine generals
 - Asynchronous totally ordered multicast

What do we do in practice

- Notice the word *guaranteed*. We may be able to reach consensus in some cases, we just can't promise it.
- We can introduce systems that can survive crash failures.
- We can introduce failure detectors.
- We can use randomized behavior to foil Byzantine processes.

Summarizing

- We can survive $1/3$ Byzantine failures in a synchronous system with reliable delivery.
- In an asynchronous system, we can't guarantee consensus after a single crash failure.
- Without reliable communication, consensus is impossible to guarantee.
- In general, we can trade off process reliability for network reliability.

Summary

- Consensus can take a number of forms:
 - Mutual exclusion
 - Leader election
 - Consensus
- Many special-purpose algorithms exist.
- General results about what is possible can help in designing a system or deciding how (or whether) to tackle a problem.