Distributed systems
Lecture 13: Vector clocks, consistent cuts, process groups, and distributed mutual exclusion

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Last time

• Saw physical time can’t be kept exactly in sync; instead use **logical clocks** to track ordering between events:
  – Defined $a \rightarrow b$ to mean ‘$a$ happens-before $b$’
  – Easy inside single process, & use causal ordering ($send \rightarrow receive$) to extend relation across processes
  – If $send_i(m_1) \rightarrow send_j(m_2)$
    then $deliver_k(m_1) \rightarrow deliver_k(m_2)$

• **Lamport clocks, $L(e)$**: an integer
  – Increment to (max of (sender, receiver)) + 1 on receipt
  – But given $L(a) < L(b)$, order of $a$ and $b$ is unknown

• The obvious question arises: How can we extend logical time to work “in the other direction”? 
Vector clocks

• With Lamport clocks, given $L(a)$ and $L(b)$, we can’t tell if $a \rightarrow b$ or $b \rightarrow a$ or $a \sim b$

• One solution is **vector clocks**:
  – An **ordered list of logical clocks**, one per-process
  – Each process $P_i$ maintains $V_i[]$, initially all zeroes
  – On a local event $e$, $P_i$ increments $V_i[i]$
    • If the event is message send, new $V_i[]$ copied into packet
  – If $P_i$ receives a message from $P_j$ then, for all $k = 0, 1, \ldots$, it sets $V_i[k] := \max(V_j[k], V_i[k])$, and increments $V_i[i]$

• Intuitively $V_i[k]$ captures the number of events at process $P_k$ that have been observed by $P_i$
Vector clocks: example

- When P2 receives $m_1$, it **merges** entries from P1’s clock
  – choose the maximum value in each position
- Similarly when P3 receives $m_2$, it merges in P2’s clock
  – this incorporates the changes from P1 that P2 already saw
- Vector clocks **explicitly track transitive causal order**: timestamp of $f$ captures the history of $a, b, c & d$
Using vector clocks for ordering

• Can compare vector clocks piecewise:
  – $V_i = V_j \iff V_i[k] = V_j[k]$ for $k = 0, 1, 2, \ldots$
  – $V_i \leq V_j \iff V_i[k] \leq V_j[k]$ for $k = 0, 1, 2, \ldots$
  – $V_i < V_j \iff V_i \leq V_j$ and $V_i \neq V_j$
  – $V_i \sim V_j$ otherwise

• For any two event timestamps $T(a)$ and $T(b)$
  – if $a \rightarrow b$ then $T(a) < T(b)$ ; and
  – if $T(a) < T(b)$ then $a \rightarrow b$

• Hence can use timestamps to determine if there is a causal ordering between any two events
  – i.e. determine whether $a \rightarrow b$, $b \rightarrow a$, or $a \sim b$

Does this seem familiar? Recall Time-Stamp Ordering and Optimistic Concurrency Control for transactions
Consistent global state

• We have the notion of “\(a\) happens-before \(b\)” \((a \rightarrow b)\) or “\(a\) is concurrent with \(b\)” \((a \sim b)\)

• What about ‘instantaneous’ system-wide state?
  – distributed debugging, GC, deadlock detection, ...

• Chandy/Lamport introduced consistent cuts:
  – draw a (possibly wiggly) line across all processes
  – this is a consistent cut if the set of events (on the LHS) is closed under the happens-before relationship
  – i.e. if the cut includes event \(x\), then it also includes all events \(e\) which happened before \(x\)

• In practical terms, this means every delivered message included in the cut was also sent within the cut
• Vertical cuts are always consistent (due to the way we draw these diagrams), but some curves are ok too:
  – providing we don’t include any receive events without their corresponding send events
• Intuition is that a consistent cut could have occurred during execution (depending on scheduling etc)
Observing consistent cuts – sketch

We will skip this material in lecture and it is not examinable – but it is helpful in thinking about distributed algorithms:

- Chandy/Lamport Snapshot Algorithm (1985)
- Distributed algorithm to generate a snapshot of relevant system-wide state (e.g. all memory, locks held, …)
- Flood a special marker message $M$ to all processes; causal order of flood defines the cut
- If $P_i$ receives $M$ from $P_j$ and it has yet to snapshot:
  - It pauses all communication, takes local snapshot & sets $C_{ij}$ to {}
  - Then sends $M$ to all other processes $P_k$ and starts recording $C_{ik} = \{ \text{set of all post local snapshot messages received from } P_k \}$
- If $P_i$ receives $M$ from some $P_k$ after taking snapshot
  - Stops recording $C_{ik}$, and saves alongside local snapshot
- Global snapshot comprises all local snapshots & $C_{ij}$
- Assumes reliable, in-order messages, & no failures
Process groups

- **Process groups** are a key distributed-systems primitive:
  - Set of processes on some number of machines
  - Possible to **multicast** messages to all members
  - Allows fault-tolerant systems even if some processes fail
- Membership can be **fixed** or **dynamic**
  - If dynamic, have explicit `join()` and `leave()` primitives
- Groups can be **open** or **closed**:
  - Closed groups only allow messages from members
- Internally can be structured (e.g. coordinator and set of slaves), or symmetric (peer-to-peer)
  - Coordinator makes e.g. concurrent join/leave easier...
  - ... but may require extra work to **elect** coordinator

*When we use “multicast” in distributed systems, we mean something stronger than conventional network datagram multicasting – do not confuse them*
Group communication: assumptions

• Assume we have ability to send a message to multiple (or all) members of a group
  – Don’t care if ‘true’ multicast (single packet sent, received by multiple recipients) or “netcast” (send set of messages, one to each recipient)

• Assume also that message delivery is **reliable**, and that messages arrive in **bounded time**
  – But may take different amounts of time to reach different recipients

• Assume (for now) that processes don’t crash

• What delivery **orderings** can we enforce?
FIFO ordering

• With **FIFO ordering**, messages from process $P_i$ must be received at each process $P_j$ in the order they were sent
  – E.g. in the above, each receiver must see $m_1$ before it sees $m_3$
  – But other relative delivery orders are unconstrained – e.g., $m_1$ vs $m_2$, $m_2$ vs. $m_4$, etc.

• Looks easy, but is non-trivial on delays/retransmissions
  – E.g. what if message $m_1$ to $P_2$ takes a loooong time?

• Receivers may need to **buffer** messages to ensure order
  – Must “hold back” $m_3$ until $m_1$ has been delivered to $P_2$
Receiving versus delivering

• Group communication middleware provides extra features above ‘basic’ communication
  – e.g. providing reliability and/or ordering guarantees on top of IP multicast or netcast
• Assume that OS provides `receive()` primitive:
  – returns with a packet when one arrives on wire
• Received messages either delivered or held back:
  – Delivered means inserted into `delivery queue`
  – Held back means inserted into `hold-back queue`
  – Held back messages are delivered later as the result of the receipt of another message...
Implementing FIFO ordering

- Each process $P_i$ maintains sequence number (SeqNo) $S_i$
- New messages sent by $P_i$ include $S_i$, incremented after each send
  - Not including retransmissions, which retransmit with the same SeqNo!
- $P_j$ maintains $S_{ji}$: the SeqNo of the last *delivered* message from $P_i$
  - If receive message from $P_i$ with SeqNo ≠ ($S_{ji}$+1), hold back
  - When receive message with SeqNo = ($S_{ji}$+1), enqueue for delivery
  - Also deliver consecutive messages in hold-back queue (if present)
  - Update $S_{ji}$
- Apps. receive asynchronously as they read from delivery queue

```
receive(M from Pi) {
    s = SeqNo(M);
    if (s == (S_{ji}+1)) {
        deliver(M);
        s = flush(hbq);
        S_{ji} = s;
    } else holdback(M);
}
```
Stronger orderings

• Can also implement FIFO ordering by just using a reliable FIFO transport like TCP/IP

• But the general ‘receive versus deliver’ model also allows us to provide stronger orderings:
  – **Causal ordering**: if event $\text{multicast}(g, m_1) \rightarrow \text{multicast}(g, m_2)$, then all processes will see $m_1$ before $m_2$
  – **Total ordering**: if any process delivers a message $m_1$ before $m_2$, then all processes will deliver $m_1$ before $m_2$

• Causal ordering implies FIFO ordering, since any two multicasts by the same process are related by $\rightarrow$

• Total ordering (as defined) does *not* imply FIFO (or causal) ordering, just says that all processes must agree
  – Sometimes want **FIFO-total** ordering (combines the two)
Causal ordering

• Same example as before, but causal ordering requires:
  (a) everyone must see $m_1$ before $m_3$ (as with FIFO), and
  (b) everyone must see $m_1$ before $m_2$ (due to happens-before)

• Is this ok?
  – No! $m_1 \rightarrow m_2$, but $P_2$ sees $m_2$ before $m_1$
  – To be correct, must hold back (delay) delivery of $m_2$ at $P_2$
  – But how do we know this?
Implementing causal ordering

• Turns out this is pretty easy!
  – Start with receive algorithm for FIFO multicast...
  – and replace sequence numbers with vector clocks

• Some care needed with dynamic groups
Total ordering

• Sometimes we want all processes to see exactly the same, FIFO, sequence of messages
  – particularly for state machine replication (see later)
• One way is to have a ‘can send’ token:
  – Token passed round-robin between processes
  – Only process with token can send (if they want)
• Or use a dedicated sequencer process
  – Other processes ask for global sequence no. (GSN), and then send with this in packet
  – Use FIFO ordering algorithm, but on GSNs
• Can also build non-FIFO total-order multicast by having processes generate GSNs themselves and resolving ties
Ordering and asynchrony

• FIFO ordering allows quite a lot of **asynchrony**
  – E.g. any process can delay sending a message until it has a batch (to improve performance)
  – Or can just tolerate variable and/or long delays
• Causal ordering also allows some asynchrony
  – But must be careful queues don’t grow too large!
• Traditional total-order multicast not so good:
  – Since every message delivery transitively depends on every other one, delays holds up the entire system
  – Instead tend to an (almost) synchronous model, but this performs poorly, particularly over the wide area ;-)  
  – Some clever work on **virtual synchrony** (for the interested)
    • Key insight: allow applications to define ordering operator(s)
Distributed mutual exclusion

• In first part of course, saw need to coordinate concurrent processes / threads
  – In particular considered how to ensure mutual exclusion: allow only 1 thread in a critical section

• A variety of schemes possible:
  – test-and-set locks; semaphores; monitors; active objects

• But most of these ultimately rely on hardware support (atomic operations, or disabling interrupts...)
  – not available across an entire distributed system

• Assuming we have some shared distributed resources, how can we provide mutual exclusion in this case?
Solution #1: central lock server

• Nominate one process $C$ as coordinator
  – If $P_i$ wants to enter critical section, simply sends $lock$ message to $C$, and waits for a reply
  – If resource free, $C$ replies to $P_i$ with a $grant$ message; otherwise $C$ adds $P_i$ to a wait queue
  – When finished, $P_i$ sends $unlock$ message to $C$
  – $C$ sends $grant$ message to first process in wait queue
Central lock server: pros and cons

• Central lock server has some good properties:
  – **Simple** to understand and verify
  – **Live** (providing delays are bounded, and no failure)
  – **Fair** (if queue is fair, e.g. FIFO), and easily supports priorities if we want them
  – **Decent performance**: lock acquire takes one round-trip, and release is ‘free’ with asynchronous messages

• But **C** can become a performance bottleneck...
• ... and can’t distinguish crash of **C** from long wait
  – can add additional messages, at some cost
Solution #2: token passing

- Avoid central bottleneck
- Arrange processes in a logical ring
  - Each process knows its predecessor & successor
  - Single token passes continuously around ring
  - Can only enter critical section when possess token; pass token on when finished (or if don’t need to enter critical section)
Token passing: pros and cons

• Several advantages:
  – Simple to understand: only 1 process ever has token => mutual exclusion guaranteed by construction
  – No central server bottleneck
  – Liveness guaranteed (in the absence of failure)
  – So-so performance (between 0 and N messages until a waiting process enters, 1 message to leave)

• But:
  – Doesn’t guarantee fairness (FIFO order)
  – If a process crashes must repair ring (route around)
  – And worse: may need to regenerate token – tricky!

• And constant network traffic: an advantage???
Solution #3: Totally ordered multicast

• Scheme due to Ricart & Agrawala (1981)
• Consider \( N \) processes, where each process maintains local variable \textit{state} which is one of \{ \textit{FREE}, \textit{WANT}, \textit{HELD} \}
• \textbf{Invariant}: At most one process is in \textit{HELD} state at a time.
• To obtain lock, a process \( P_i \) sets \textit{state} := \textit{WANT}, and then multicasts lock request to all other processes
• When a process \( P_j \) receives a request from \( P_i \):
  – If \( P_j \)'s local state is \textit{FREE}, then \( P_j \) replies immediately with \textit{OK}
  – If \( P_j \)'s local state is \textit{HELD}, \( P_j \) queues the request to reply later
• A requesting process \( P_i \) waits for \textit{OK} from \( N-1 \) processes
  – Once received, sets \textit{state} := \textit{HELD}, and enters critical section
  – Once done, sets \textit{state} := \textit{FREE}, & replies to any queued requests
• What about \textbf{concurrent requests}?
  – By \textbf{concurrent} we mean: \( P_j \) is already in the \textit{WANT} state when it receives a request from \( P_i \)
Handling concurrent requests

• Need to decide upon a **total order**:  
  – Each process maintains a Lamport timestamp, $T_i$  
  – Processes put current $T_i$ into request message  
  – Insufficient on its own (recall that Lamport timestamps can be identical) => use **process ID** (or similar) to break ties  
  – Note: may not be “fair” as the same process always “wins”  

• Hence if a process $P_j$ receives a request from $P_i$ and $P_j$ is also acquiring the lock (i.e. $P_j$’s local state is **WANT**)  
  – If $(T_j, P_j) < (T_i, P_i)$ then queue request from $P_i$  
  – Otherwise, reply with **OK**, and continue waiting  

• Note that using the total order ensures **correctness**, but not **fairness** (i.e. no FIFO ordering)  
  – Q: can we fix this by using vector clocks?
• Imagine \textbf{P1} and \textbf{P2} simultaneously try to acquire lock...
  – Both set \textbf{state} to \textbf{WANT}, and both send multicast message
  – Assume that timestamps are \textbf{17} (for \textbf{P1}) and \textbf{9} (for \textbf{P2})
• \textbf{P3} has no interest (\textbf{state} is \textbf{FREE}), so replies \textbf{Ok} to both
• \textbf{9 < 17}: \textbf{P1} replies \textbf{Ok}; \textbf{P2} stays quiet & enqueues \textbf{P1}
• \textbf{P2} enters the critical section and executes...
• and when done, replies to \textbf{P1} (to enter critical section)
Additional details

• Completely decentralized solution ... but:
  – Lots of messages (1 multicast + N-1 unicast)
  – OK for most recent holder to re-enter CS without any messages
• Variant scheme (Lamport) - **multicast for total ordering**
  – Processes each maintain (and collectively agree on) an ordered queue of requests and ACKs, relying on total ordering
  – To enter, process $P_i$ multicasts `request($P_i$, $T_i$)` [same as before]
  – On receipt of a message, $P_j$ replies with an `ack($P_j$, $T_j$)` unless `request($P_j$, $T_j$)` is currently first in the queue and $P_j$ is waiting for $P_i$ to ACK
  – Processes add all requests and ACKs to the queue in order
  – If process $P_i$ sees their request is earliest and ACK’d by all, can enter CS ... and when done, multicasts a `release($P_i$, $T_i$)` message
  – When $P_j$ receives release, removes $P_i$’s request from queue
  – If $P_j$’s request is now earliest in queue, can enter CS...
• Both Ricart & Agrawala and Lamport’s scheme have $N$ points of failure: doomed if *any* process dies :-(

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[27]
Summary + next time

- Vector clocks
- Consistent global state + consistent cuts
- Process groups and reliable multicast
- Implementing order
- Distributed mutual exclusion

- Leader elections and distributed consensus
- Distributed transactions and commit protocols
- Replication and consistency