Distributed systems

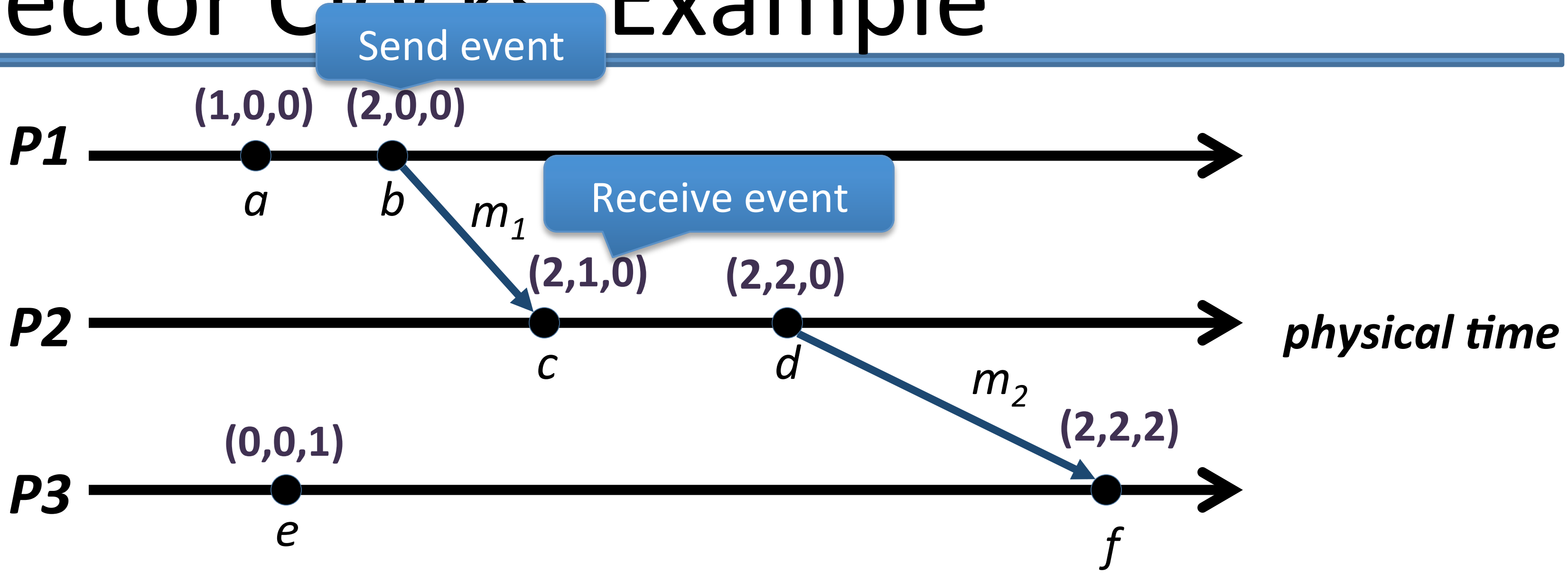
Lecture 5: Consistent cuts, process groups, and mutual exclusion

Dr Robert N. M. Watson

Last time

- Saw physical time can't be kept exactly in sync; instead use **logical clocks** to track ordering between events:
  - Defined ***a*** → ***b*** to mean '***a* happens-before *b***'
  - Easy inside single process, & use causal ordering (*send* → *receive*) to extend relation across processes
  - if $\text{send}_i(m_1)$ → $\text{send}_j(m_2)$ then $\text{deliver}_k(m_1)$ → $\text{deliver}_k(m_2)$
- **Lamport clocks, L(*e*)**: an integer
  - Increment to (**max** of (sender, receiver)) + 1 on receipt
  - But given L(*a*) < L(*b*), know nothing about order of *a* and *b*
- **Vector clocks**: list of Lamport clocks, one per process
  - Element $V_i[j]$ captures #events at P_j observed by P_i
  - Crucially: **if $V_i(a) < V_j(b)$, can infer that *a* → *b*** , and
    if $V_i(a) \sim V_j(b)$, can infer that a ~ b

Vector Clocks: Example

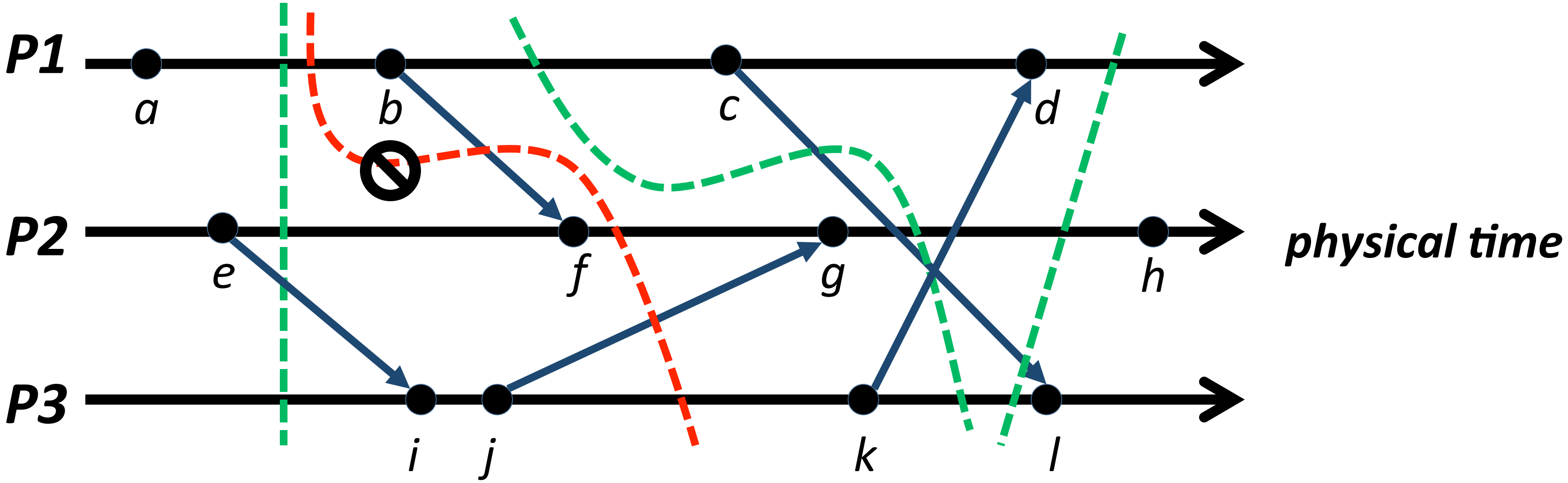


- When P_2 receives m_1, it **merges** the entries from P_1's clock
  - choose the maximum value in each position
- Similarly when P_3 receives m_2, it merges in P_2's clock
  - this incorporates the changes from P_1 that P_2 already saw
- Vector clocks ***explicitly track the transitive causal order***: *f*'s timestamp captures the history of *a*, *b*, *c* & *d*

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

Consistent Cuts: Example



- 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 >>

- Chandy/Lamport Snapshot Algorithm (1985):
  - Distributed algorithm for generating a 'snapshot' of relevant system-wide state (e.g. all memory, locks held, …)
  - Based on flooding 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} = { *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

Fear not! This is not examinable.

Process Groups

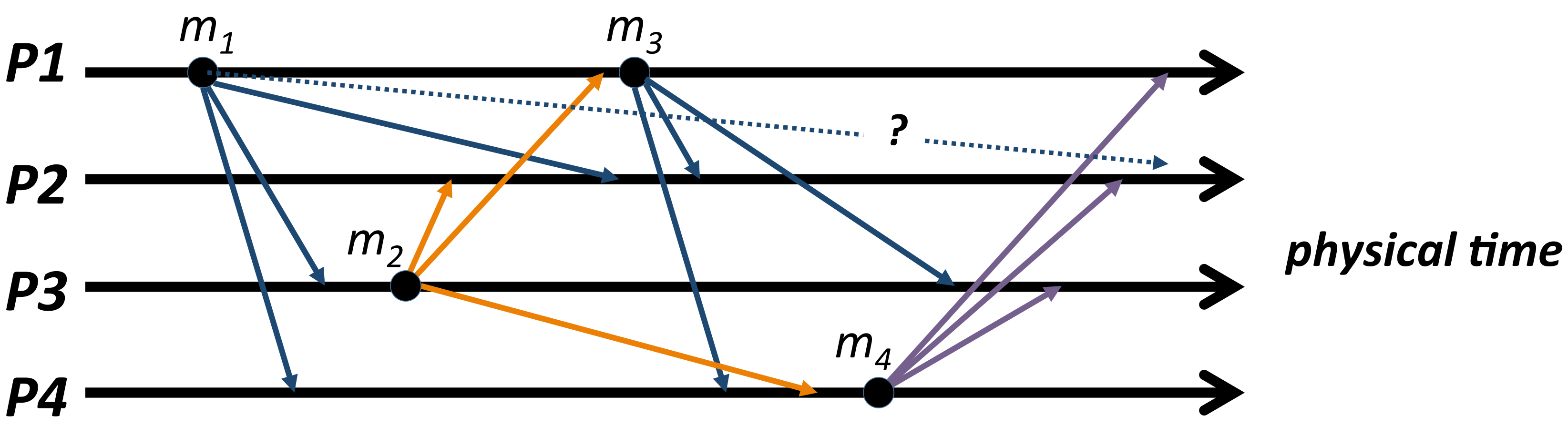
- Often useful to build distributed systems around the notion of a **process group**
  - Set of processes on some number of machines
  - Possible to **multicast** messages to all members
  - Allows fault-tolerant systems even if some processes fail
- Membership can be **fixed** or **dynamic**
  - if 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 the distributed-system context, we mean something stronger than conventional network multicasting using datagrams – be careful not to 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



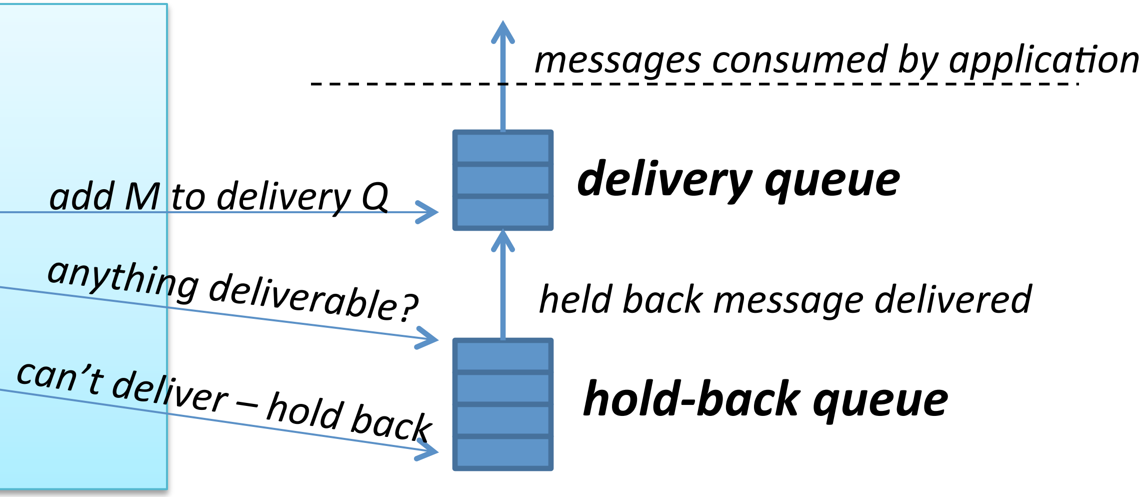
- With **FIFO ordering**, messages from a particular process P_i must be received at all other processes P_j in the order they were sent
  - e.g. in the above, everyone must see m_1 before m_3
  - (ordering of m_2 and m_4 is not constrained)
- Seems easy but not trivial in case of delays / retransmissions
  - e.g. what if message m_1 to P2 takes a loooong time?
- Hence receivers may need to **buffer** messages to ensure order

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

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

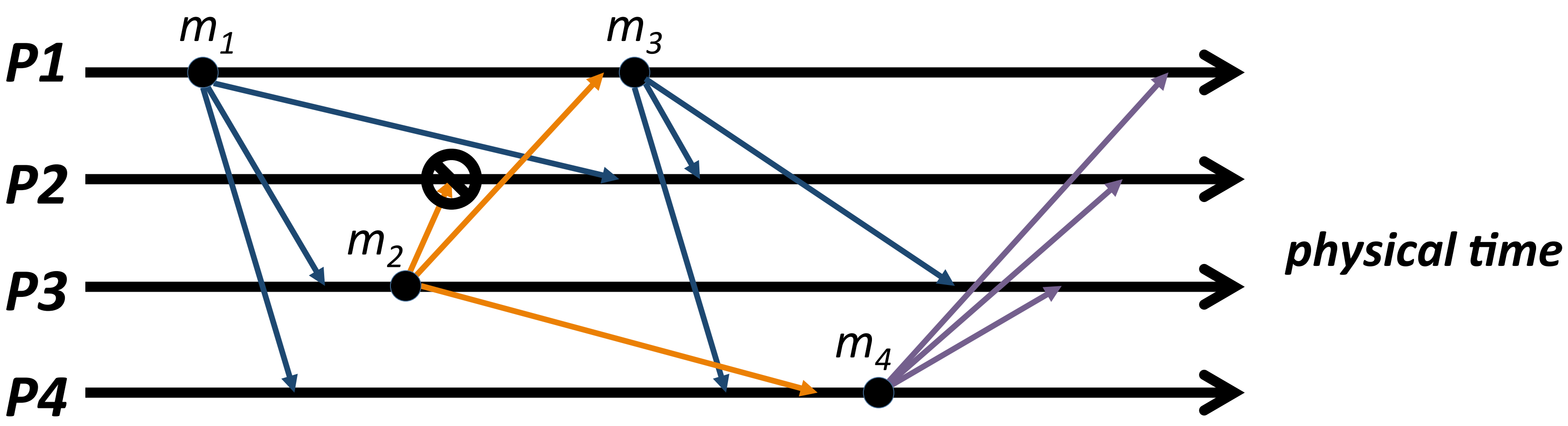

messages consumed by application
delivery queue
add M to delivery Q
held back message delivered
anything deliverable?
can't deliver – hold back
hold-back queue

- Each process P_i maintains a message sequence number (SeqNo) S_i
- Every message sent by P_i includes S_i, incremented after each send
  - not including retransmissions!
- 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), deliver it … and also deliver any consecutive messages in hold back queue … and update S_{ji}

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 *multicast(g, m_1)* → *multicast(g, m_2)*, then all processes will see m_1 before m_2
  - **Total ordering**: if any processes 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 →
- Total ordering (as defined) does *not* imply FIFO (or causal) ordering, just says that all processes must agree
  - In reality often want **FIFO-total** ordering (combines the two)

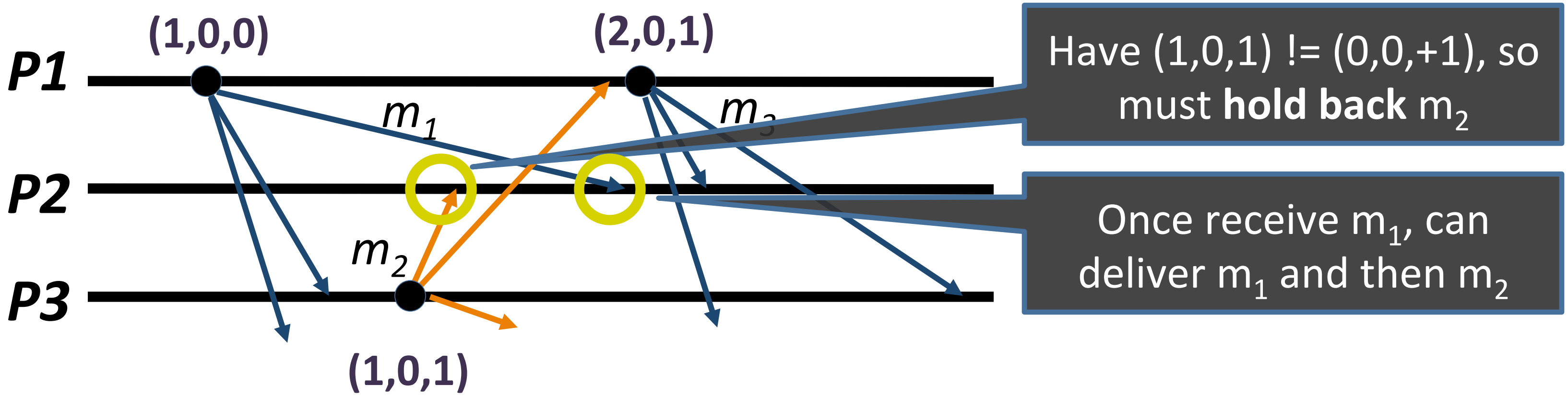
Causal Ordering



- Same example as previously, but now causal ordering means that
  (*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 P2 sees m_2 before m_1
  - To be correct, must hold back (delay) delivery of m_2 at P2
  - 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



Have (1,0,1) != (0,0,+1), so must **hold back** m_2

Once receive m_1, can deliver m_1 and then m_2

- Need some care with dynamic groups
  - must encode variable-length vector clock, typically using positional notation, and deal with joins and leaves

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 he wants)
- 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

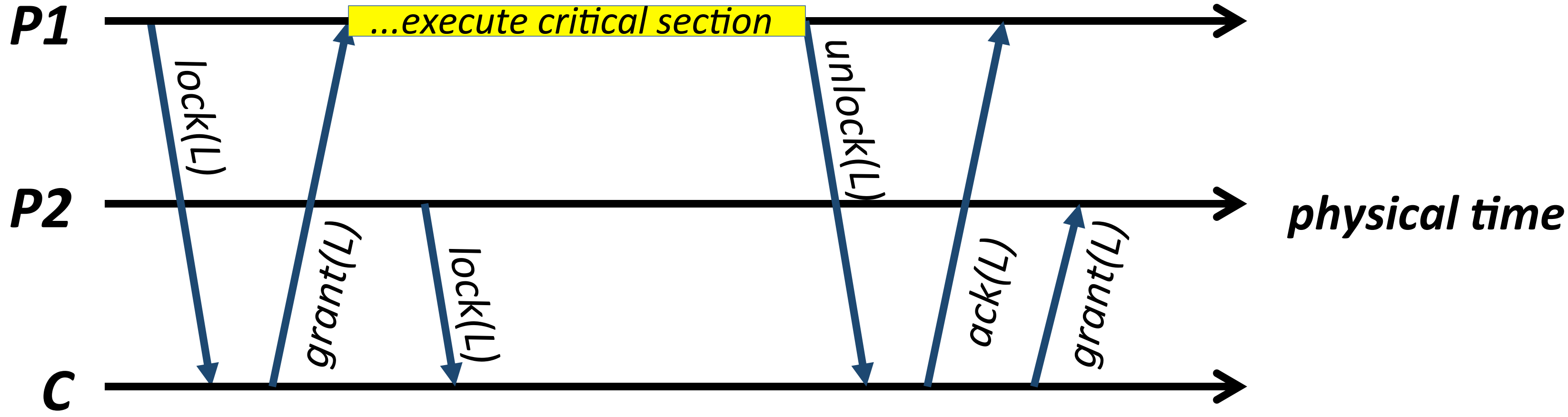
Ordering and Asynchrony

- 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)

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

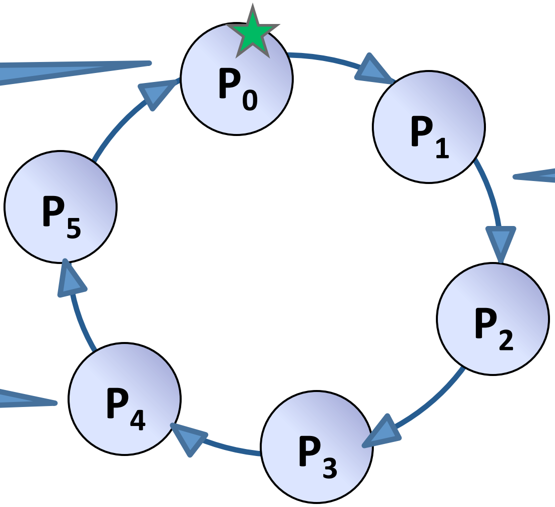


- Nominate one process C as coordinator
  - If P_i wants to enter critical section, simply sends *lock* message to C, and waits for a reply
  - If resource free, C replies to P_i with a *grant* message; otherwise C adds P_i to a wait queue
  - When finished, P_i sends *unlock* message to C
  - C sends *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



Initial token generated by P0

Passes clockwise around 'ring'

If e.g. P4 wants to enter CS, holds onto token for duration

- 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 CS)

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

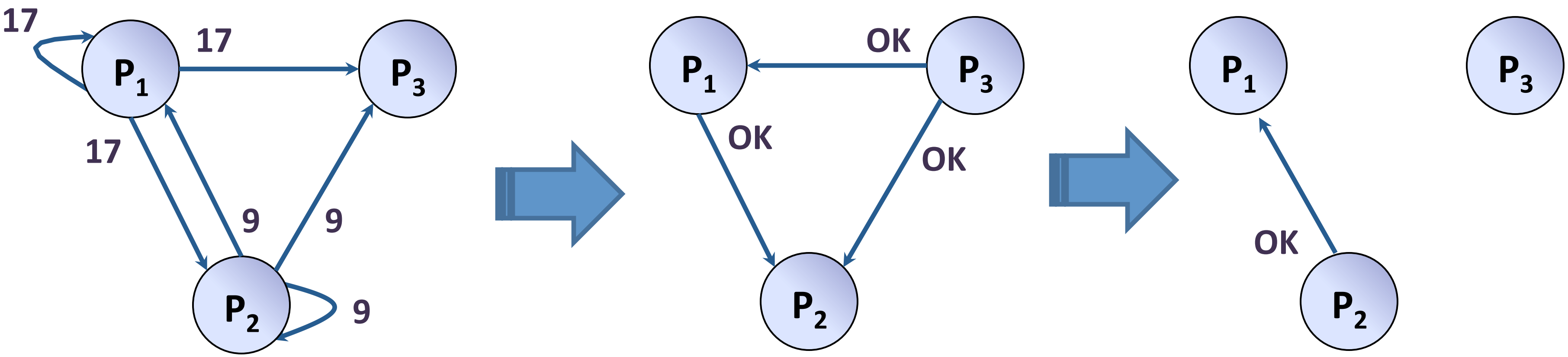
- Scheme due to Ricart & Agrawala (1981)
- Consider N processes, where each process maintains local variable state which is one of { FREE, WANT, HELD }
- To obtain lock, a process P_i sets state:= WANT, and then multicasts lock request to all other processes
- When a process P_j receives a request from P_i:
  - If P_j's local state is FREE, then P_j replies immediately with **OK**
  - If P_j's local state is HELD, P_j queues the request to reply later
- A requesting process P_i waits for **OK** from N-1 processes
  - Once received, sets state:= HELD, and enters critical section
  - Once done, sets state:= FREE, & replies to any queued requests
- What about **concurrent requests**?

By concurrent we mean: P_j is in the WANT state already when it receives a request from P_i

Handling Concurrent Requests

- Need to decide upon a total order:
  - Each processes 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
- Hence if a process P_j receives a request from P_i and P_j has an outstanding request (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?

Totally-Ordered Multicast: Example



- Imagine P1 and P2 simultaneously try to acquire lock…
  - Both set state to WANT, and both send multicast message
  - Assume that timestamps are 17 (for P1) and 9 (for P2)
- P3 has no interest (state is FREE), so replies Ok to both
- Since 9 < 17, P1 replies Ok; P2 stays quiet & queues P1's request
- P2 enters the critical section and executes…
- … and when done, replies to P1 (who can now enter critical section)

Additional Details

- Completely unstructured 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 (due to Lamport):
  - 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)**
  - Processes keep all requests and acks in ordered queue
  - If process P_i sees his request is earliest, 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…
- Note that both Ricart & Agrawala and Lamport's scheme, have N points of failure: doomed if *any* process dies :-(

Next time

- Distributed transactions
  - Commit protocol examples
- Leader election and distributed consensus
- Replication of data, services
  - Types of replicated data consistency
- Google and Amazon case studies