CS514: Intermediate Course in Computer Systems

Lecture 9: Sept. 26, 2003

Overview of reliability techniques

Outline

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- This lecture is designed to help you think about how to approach your project reliability requirements and mechanisms
  - Noting that some of you have “artificial” requirements

What requirements do we care about

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- How much “Fault-tolerance” or “Reliability”
  - Stuff still works when something breaks
- How much Availability
  - How long it takes for stuff to still work after something breaks
- These two will drive our thinking

Other requirements (mentioned in Kens book)

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- Recoverability
  - How a failed component can rejoin the system
  - Really part of “fault tolerance”
- Consistency
  - Coordinating related actions by multiple components
  - Really part of “availability”

And still more…

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- These are things you'd consider for any software development…they only get harder with distributed systems
  - Scalability
  - Security
  - Privacy
  - Correct specification
  - Correct implementation
  - Predictable performance
  - Timeliness

Replication, replication, and replication

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- Fundamentally there is only one way to get fault tolerance and availability
  - Replicate
- But many ways to replicate
  - Mainly what this lecture overviews
- For performance reasons, may also require replication when using parallel or distributed techniques

A theoretical diversion

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- Engineering issues are messy
- Yet, we want to think precisely about fault tolerance
- Therefore, theory folks derive simplistic models for failure
- These are good to understand for "how to think" about fault tolerance
  - But don't apply much to the real world

Theoretical failures

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- Halting
  - A process just stops without doing anything wrong
  - Dynamic memory is lost, stable memory is not (and is correct up to point of failure)
- Fail-stop
  - A halting process where the failure is reliably reported to all other processes
- Byzantine
  - A process may exhibit any behavior, including malicious

Theoretical system models

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- Asynchronous model
  - No clock synchronization, messages and processes may take arbitrarily long
- Synchronous model
  - Clocks are synchronized, message and process times are bounded
  - All messages and processing can happen in well-defined “rounds”

Upper and lower bounds on solvability and impossibility

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- Byzantine failures and asynchronous systems are unrealistically hostile
  - If problem is solvable here, probably you can do at least as well in the real world
- Fail-stop failures and synchronous systems are unrealistically benign
  - If problem is impossible here, then you are unlikely to have any luck in the real world

What do your failures look like?

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- In designing your reliability solution, think hard about what kinds of failures you may have
- Design rule of thumb:
  - First eliminate or simplify specific point failures where possible/cost effective
  - Only after this should you design system-level features that can tolerate the remaining types of failures

Example I: Process failures

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- Real software failures are not quite byzantine, but they are very unpredictable
- Use monitoring procedures that make them look like fail-stop
  - Don't ask a process if it is alive, rather ask it to perform a predictable task
    - Write/read a database entry
    - GET a web page
  - If task not performed right, or with too much delay, declare the process dead

Example I: Process failures

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- Keep your monitoring process very simple, and test the hell out of it
  - I.e., eliminate possibility of a monitoring process failure
  - (Ultimately the turtle has to stand on something!)
- In other words, don't over-design your monitoring task
  - (but don't under design it either)

Example II: MSCS Cluster

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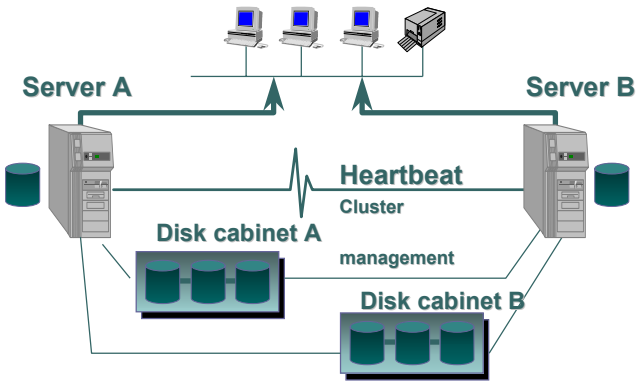
Why is the server replicated, but not the disk???



Example II: MSCS Cluster

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- Disk operation is relatively simple
  - Scan, read, write, …
  - Failures can be well-defined and detected (parity errors etc.)
  - You can build a (pretty) reliable disk
- Windows software on the other hand…

Example II: MSCS Cluster

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- Microsoft followed the rule of thumb:
- Eliminate specific point failures where possible
  - The disk
- Design a fault-tolerant system where not possible
  - Server failover

Questions to ask about replication

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- Do you even need replication?
- If multiple active replicas, do they all have to be perfectly identical?
- If backup (non-active) replica, does failover need to be 100% accurate?
- How many replicas do you need?
- Where do they need to be?
- How much non-availability can you tolerate during failover?

Do you even need replication?

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- Consider this scenario:
  - Company has 10 national offices
  - Each office needs to query and update the customer database frequently, reliably, and with little delay
- Solution:
  - Replicate the database at all 10 sites?

Do you even need replication?

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- Digging deeper:
  - Each site typically queries/updates for local customers (not those at other sites)
  - Queries about other site customers turn out not to be time critical
- Better solution:
  - Partition database into 10 different local partitions
  - Use redundant networking (e.g. multihoming) to maximize access to other partitions

Do active replicas need to be perfectly identical?

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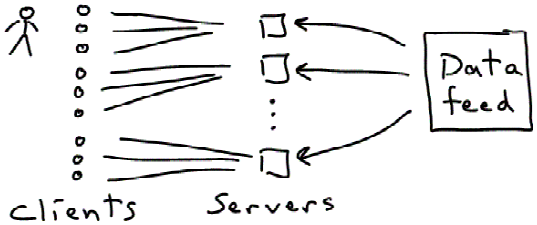
- If Google, they don't
  - There is no "right" answer
- If financial data feeds to stock brokers, they had better be identical quickly and reliably
- Other applications may fall in-between
  - Eventual consistency, probabilistic reliability
  - Epidemic (gossip) approach



Does failover have to be perfect (no lost data)?

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- Amazon (lots of small transactions, at least used to be!), but huge volume
- Large volume makes it hard to have perfect failover
- Fortunately, occasional errors not that big a deal
  - Customer will complain, just take customer's word
    - If no history of complaints
    - Or if time of error coincides with known failure
  - Alternatively keep a local log on disk and consult only to resolve complaints

Does failover have to be perfect (no lost data)?

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- Million dollar bank transfers, on the other hand…
  - Fortunately volume tends to be smaller
  - Can afford a higher per-transaction cost to pay for perfect failover
- Again, other applications may fall in between these extremes

How many replicas do you need?

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- Try to have as few as possible, but no fewer!
- Answer depends on a lot of factors
  - Reliability of components, cost of downtime, restoration speed, …
- But usually the answer will be one (if not zero)
  - If the answer is not one, try to make it one!

Where do the replicas need to be?

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- Same room
  - Survive equipment failure, but not a fire
- Across the street
  - Survive fire, but not an earthquake
- In another city . . .
  - But network latency or bandwidth may kill you . . .
  - You might need this for performance reasons even if not fault-tolerance reasons

Where do the replicas need to be?

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- At Tahoe, I saw major wireless carriers with only a single data center
  - Replication within the data center, but no geographically distant replica
  - They wanted to, but just didn't have the budget, and weren't sure they could do it
- One option:
  - Two "partitioned" data centers, with capability to fail-over within hours
    - Fail-over managed by humans

What are your availability requirements?

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- Can you wait:
  - One minute?
  - Ten minutes?
  - One hour?

  for the backup to take over operations…
- True continuous availability scenarios are relatively rare, but certainly exist
  - Air traffic control
  - Weapons systems on a battleship
  - Online games

A strong but typical fault-tolerant situation

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- One replica is adequate
  - Physically separated
    - In another building across the street
  - Strong attention to redundancy at all levels
    - Redundant network, power, air conditioning, etc.
- Performance can be handled with a single server
  - Albeit maybe very high-end
  - So hot-standby model ok
- Non-availability on the order of a few minutes
- Occasional error acceptable, as long as it can be recovered later

A strong but typical fault-tolerant situation

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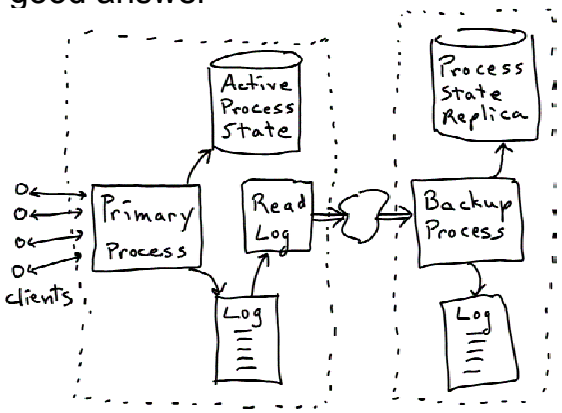
- Asynchronous log-based replication is a good answer



Basic procedure

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1. Primary process reliably writes to log
   - The log is the authoritative state!
2. Primary process updates active process state
3. Read log process ships latest log updates to backup process
   - With some delay
4. Backup process reliably writes to log
5. Backup process updates process state replica

Asynch versus sync

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- Procedure is asynchronous . . . primary "commits" to its log and process state without an ack from the backup
  - Primary and backup logs will be out-of-sync
  - Even 100ms out of sync may mean a thousand or more transactions
- But….synchronous performance would suck by comparison

Issues in asynchronous log-based replication

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- How to decide when to fail-over
  - And if/when to switch back to primary after it is healthy
- How to redirect clients after fail-over
- How to avoid both servers being active
  - How to merge process state if both server can be active!
- How to sync up logs and process state after a partition or failed server resumes
  - Including gaps in the log
- How to roll-back to stable process state (if necessary) after failover

Simple fail-over protocol and client redirection

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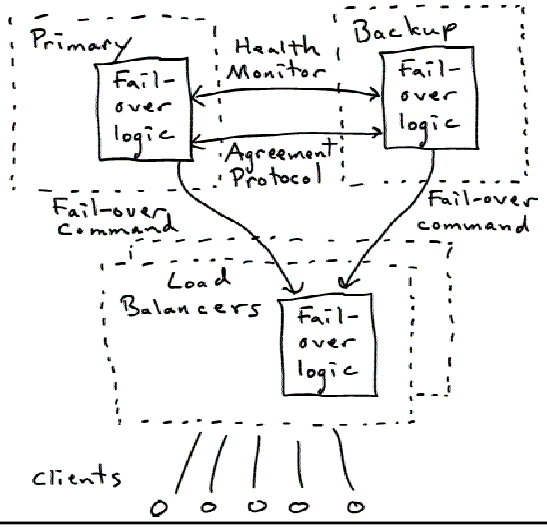

Simple fail-over protocol and client redirection

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- Involves primary, backup, and load-balancer
- If crash, backup (or primary) can direct load balancer to switch when it is ready to take over
  - I.e. after roll-back is finished
- If primary is up, it directs timing of fail-over
  - I.e., after process state is synchronized

Avoiding two active servers

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- Would only happen if servers can both talk to the load balancers, but not each other
  - Can design local network so that this is virtually impossible
- *Harder to do across the Internet*
  - Though in this case, load balancing might be DNS, which would itself be replicated and might get confused!

Synching up logs

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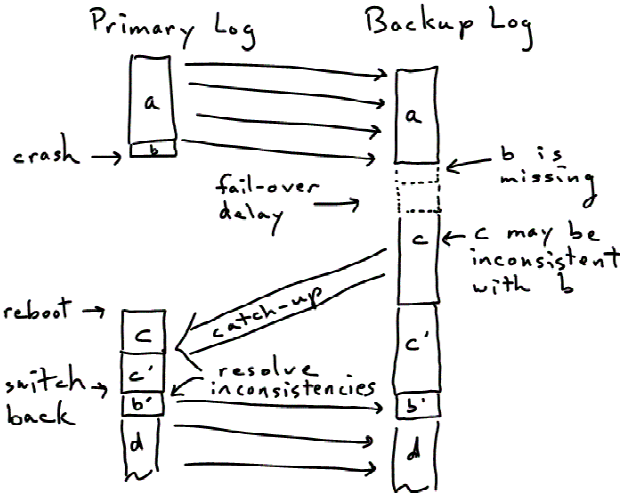

Issues with gaps in log

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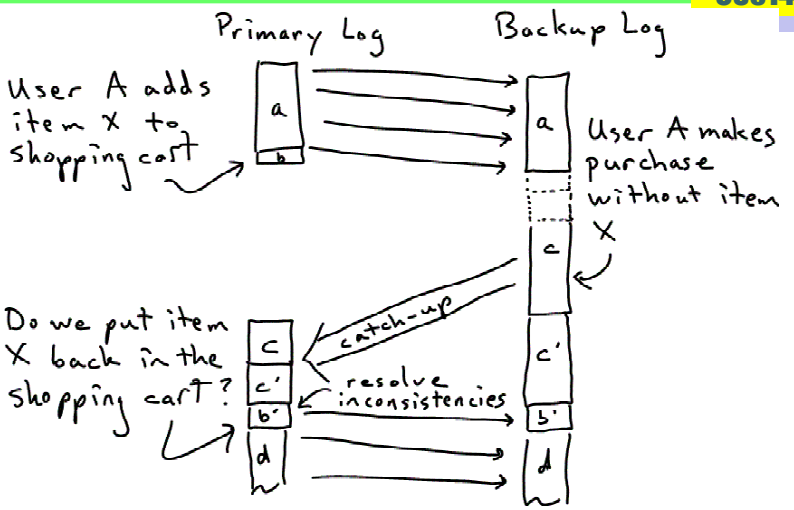

Rolling back to stable process state

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- Transactions consist of “tentative” reads and writes followed by a commit or an abort
  - Two-phase commit (2PC)
- Log may contain reads and writes, but not the commit (or abort)
- After failover, backup may abort the transaction
  - Unlikely you’d want to try to complete the transaction at that point

Rolling back to stable process state

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- There may be thousands of uncompleted transactions
- Rollback process may take minutes as a result

Revisiting our typical fault-tolerant situation

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- One nearby replica, single primary server, brief non-availability and occasional error ok
- If some of these assumptions are too weak, then things get more interesting!
  - Multiple replicas
  - Multiple active servers
  - Geographically distant servers
  - Continuous or near-continuous availability
  - No errors

Stronger requirements

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- Stronger requirements takes us into the realm of *group communications systems*:
  - Membership tracking
  - Multicast with various ordering and delivery guarantees
  - Virtual synchrony

What are Group Communications Systems?

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- Simply put:
  - *A group of processes, all of which can communicate with all others*
- But:
  - In such a way that all members will respond identically (and correctly) to external systems
  - And in a way that is (to the extent possible) transparent to external systems
  - (oh, and with good performance…)

How can multiple processes act identically?

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- They have exactly the same state at the same time…
  - This is the crux of the problem
- But, who are *they*?
  - Membership changes over time
- And when is "*the same time*"?
  - System clocks are inaccurate and not synchronized
- And how can any process be sure the others have the *same state*?

These are hard questions

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- Even though a relatively small number of real world applications require these kinds of guarantees . . .
- These applications are important
  - Military, transportation, energy . . .
- And anyway, if you can understand this stuff, the simpler problems will be that much easier

First, lets consider Time . . .

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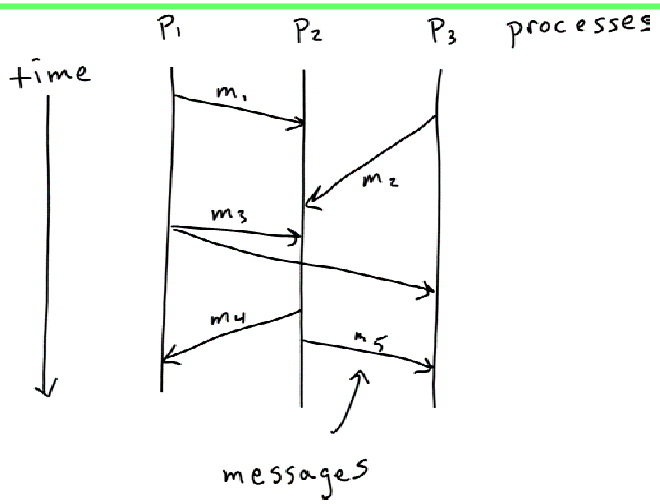

Picture with 3 processes

The log files of p1 and p3

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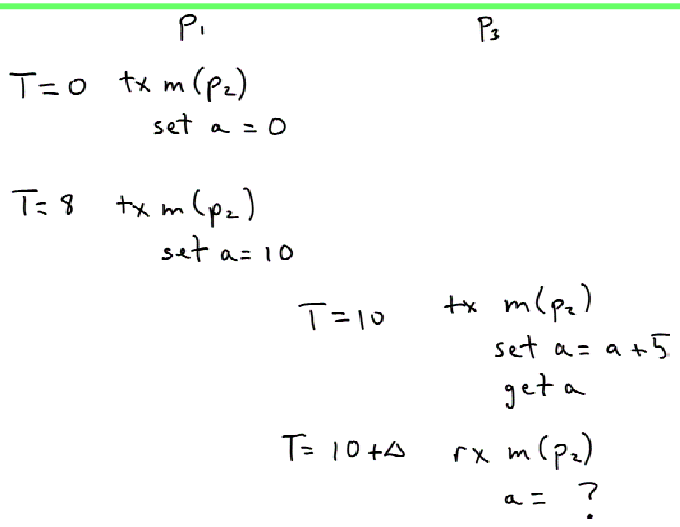

What is the value of a?

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- We don't know!

Because the clocks are unsynchronized…

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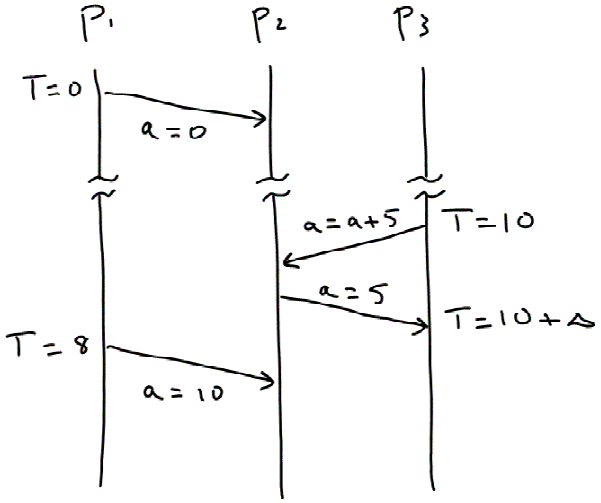

Group Communications Systems provide ordering

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- Through concept of causality
  - *a* causes *b*
- Lamport's notations:
  - $snd_p(m)$, $rcv_p(m)$, $deliv_p(m)$
  - Three message events
    - Process *p* sends message *m*
    - Process *p* receives message *m* (by lower layer)
    - Process *p* delivers message *m* (from lower layer to application)

Some messages are obviously ordered

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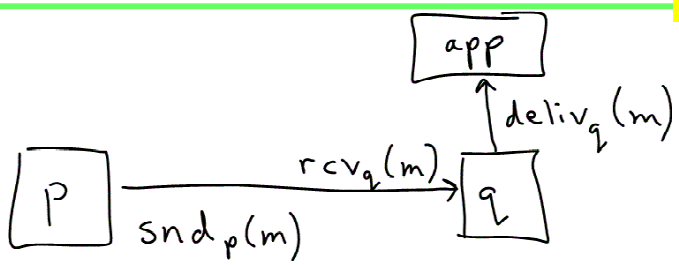

- $snd_p(m)$ happens before $rcv_q(m)$
- Denote this as:
  - $snd_p(m) <_m rcv_q(m)$

And this defines a partial ordering of events

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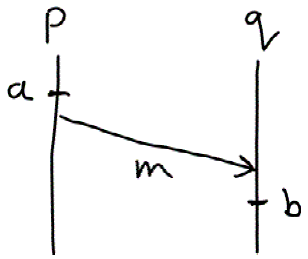
- Event *a* at process *p* happened before $snd_p(m)$
- $rcv_q(m)$ happened before event *b* at process *q*
- Therefore, event *a* happened before event *b*
- Denote as: $a \rightarrow b$
  - Concurrent means neither $a \rightarrow b$ nor $b \rightarrow a$



$a \rightarrow b$ doesn't mean "*a* caused *b*"

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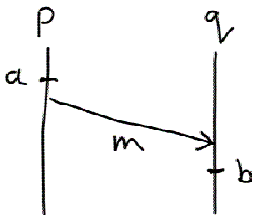
- For all we know, *m* is just a keep alive ping unrelated to events *a* and *b*
- But we can say that *a* has *potential causality* for *b*
- We can build *logical clocks* using this notion



A simple logical clock

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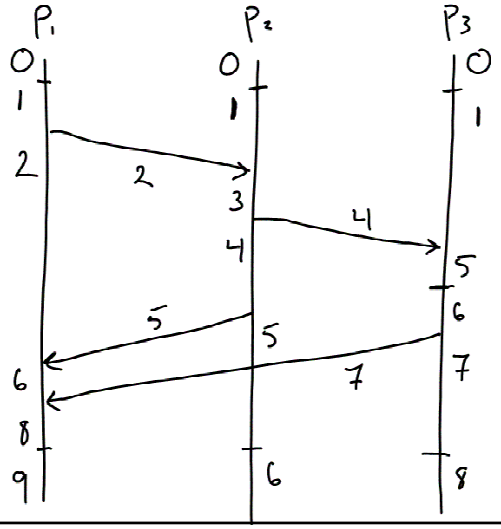

A simple logical clock

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- Each process and message has a logical time (LT_p and LT_m)
- Set LT_m of transmitted messages to that of process LT_p
- If received message LT_m > process LT_p, set process LT_p to LT_m +1

Our simple example revisited with logical clocks

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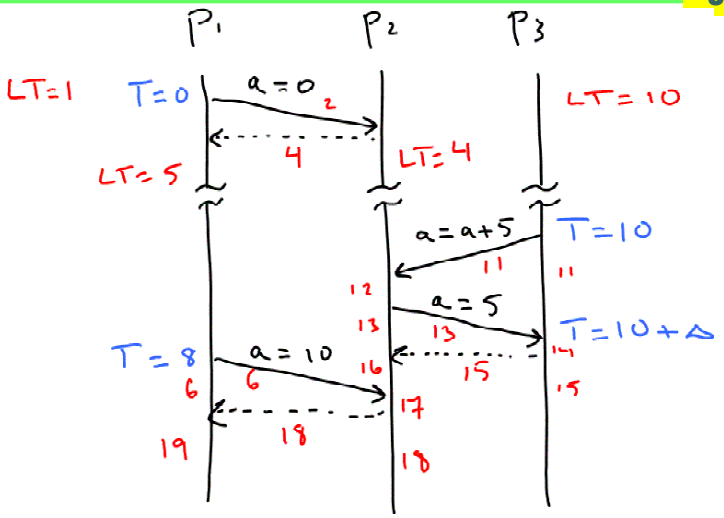

And their corresponding logs

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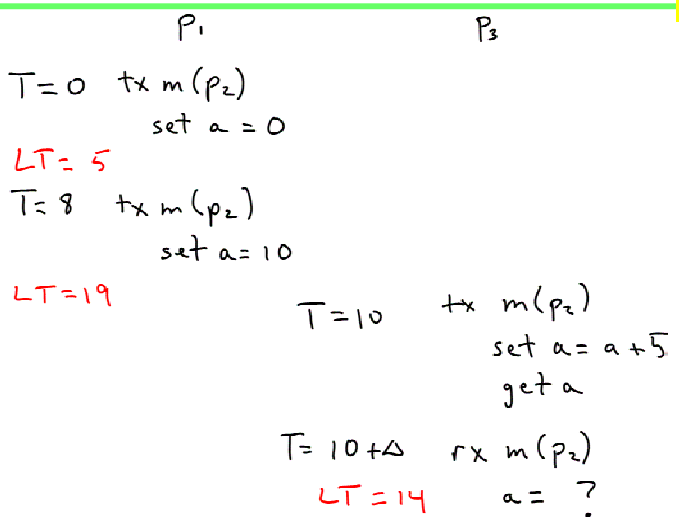

Next, let's consider Multicast

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- Multicast: one system transmits the same message to multiple other systems
- Clearly needed to provide consistent state among a group of communicating systems
- There are lots of flavors of multicast

What about IP multicast?

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- IP multicast model:
  - Individual members join a multicast group through interaction with local router
  - Members don't know who is in the group
  - Any member can transmit IP packets to the group
  - Delivery is unreliable: any member may or may not receive a multicast
  - Delivery is unordered
- Essentially an extension of LAN multicast

IP Multicast clearly inadequate for our purpose

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- We need reliable delivery
- We need ordered delivery
  - "Go up, turn right" different from "turn right, go up"
- Ok, so why not add sequence numbers to packets, and receivers send acks to sender?

Reliable IP multicast

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- Multicast version of TCP
- Sequenced IP packets traverse outgoing multicast tree to receivers
- ACKs (or NAKs) of IP packets "implode" uptree from receivers towards sender
  - May be aggregated at intermediate points
  - Retransmissions may come from intermediate points
  - Lots of clever schemes have been designed

Reliable IP multicast example 1/4

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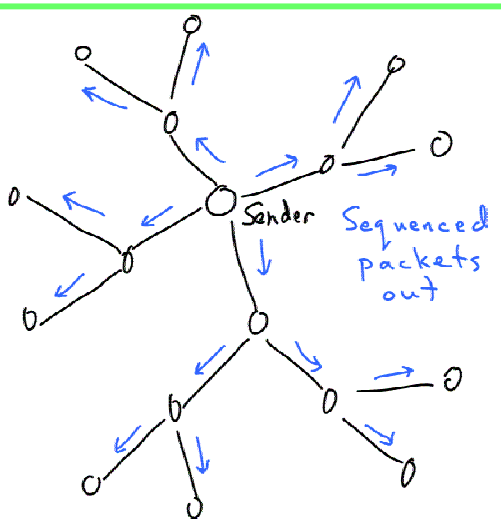

Reliable IP multicast example 2/4

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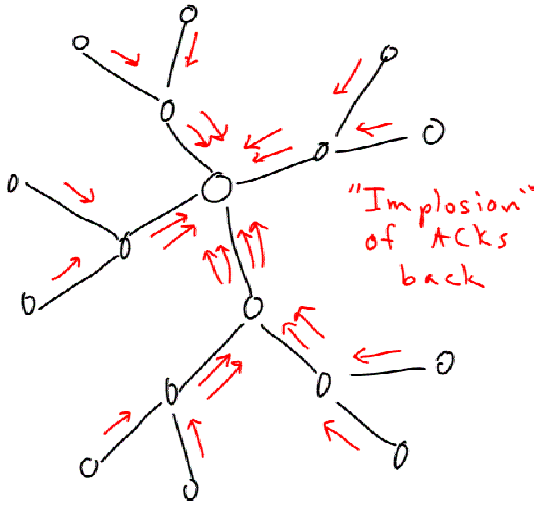

Reliable IP multicast example 3/4

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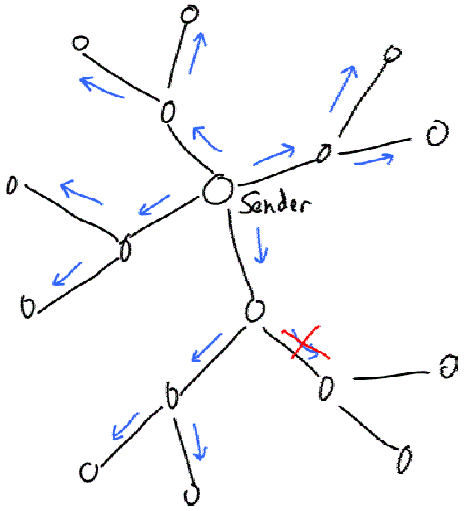

Reliable IP multicast example 4/4

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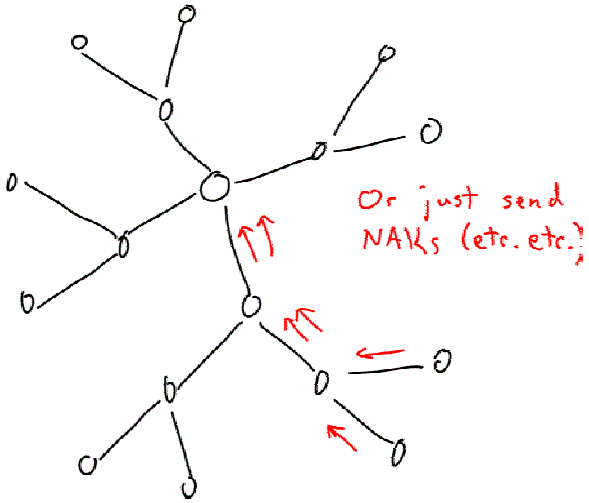

Ultimately Reliable IP Multicast wrong model

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- TCP: If sender dies, nothing can be done
  - "Reliable" not defined for case where sender dies
- Reliable multicast: Same thing!
- If group member X says a plane is entering an air space, other members better learn that even if X crashes immediately after transmission!

We need stronger "reliability" models

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- Dynamically Uniform:
  - If any member delivers message (even if it crashes immediately afterwards), all alive members will deliver it to app
- Failure-atomic:
  - If any alive member delivers a message, all alive members will deliver it
  - But, even if no alive member delivers it, some crashed members may still have delivered it

Failure-Atomic

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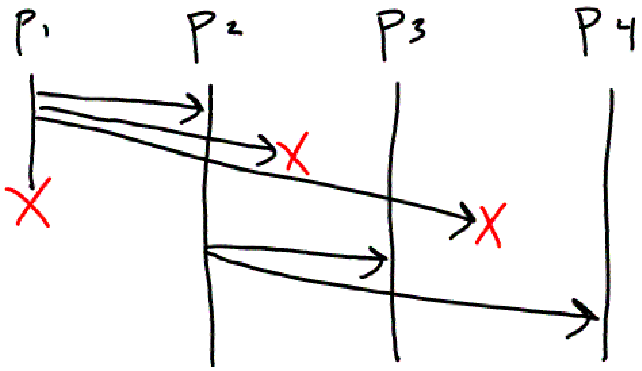
- If any alive member delivers a message, all alive members will deliver it



Failure-Atomic

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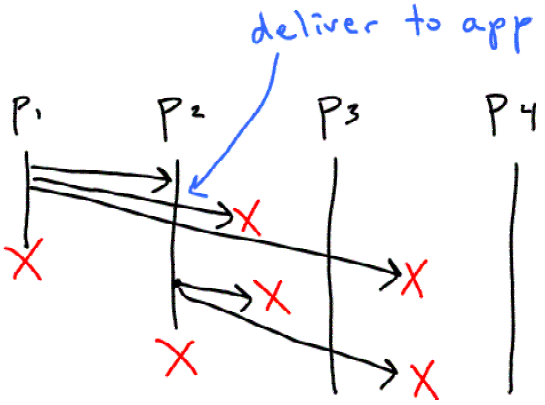
- But, even if no alive member delivers it, some crashed members may still have delivered it



Dynamically Uniform

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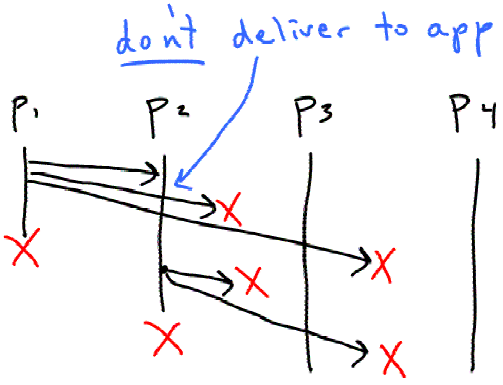
- If any member delivers message (even if it crashes immediately afterwards), all alive members will deliver it to app



Dynamically Uniform

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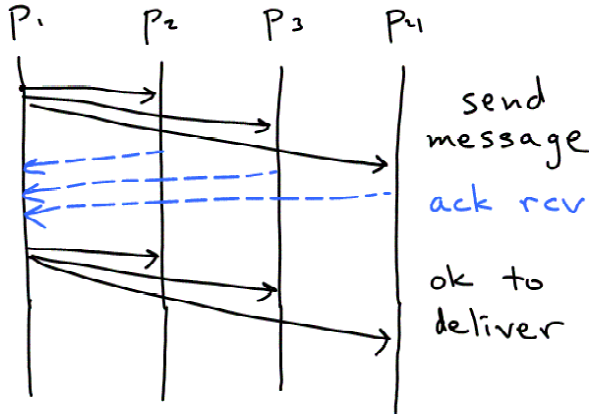
- Implemented as a 2-phase process
  - So substantially slower than failure-atomic



And richer ordering models

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- fbcast: fifo ordered by sender
- cbcast: causally ordered, but concurrent message order not defined
  - Different members may see concurrent messages in different order
- abcast: totally ordered (but not causally ordered)
  - Used for membership services
- cabcast: totally and causally ordered

Total ordering? (aka "agreed ordering")

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- Define a lexicographic ordering
  - i.e. {LT, process ID}
- Collect all messages at a given LT
  - This means that each process must explicitly state that they won't send any more messages for a given LT!
- Order by process ID and deliver

Total ordering is slow

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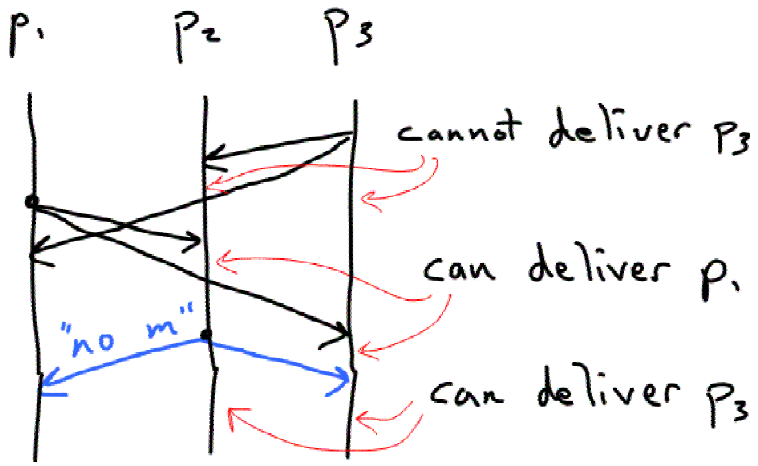

Next, lets consider Membership…

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- Core to any group communications system is the notion of membership
- Reason is obvious:
  - If all members of a group communications system don't agree on the membership, they cannot possibly insure consistent state among members

Membership "views"

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- Members may join and leave a group
  - Leaving may be announced or abrupt (a crash)
- The list of members at a given time is known as the "view"
- Group multicast is always with respect to the current view
  - Before a new view is established, multicasts in the current view are completed

A series of views

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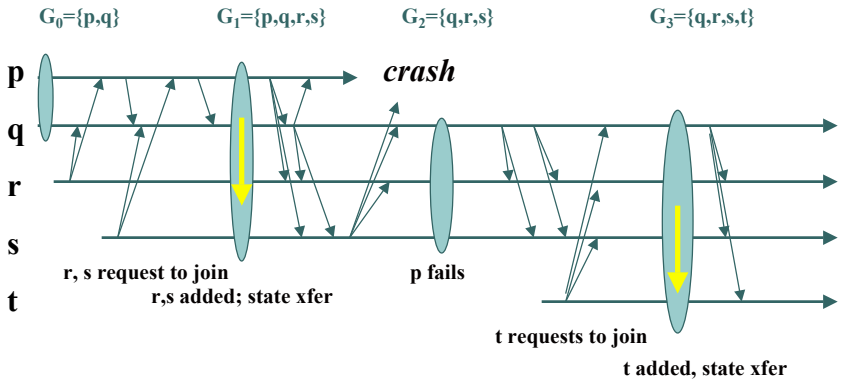

Group Membership System (GMS)

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- Views are managed by a GMS
- A GMS is a small number of processes that:
  - Monitor processes in the group
  - Force a faulty process out of the group
  - Notify the group of new views
- The GMS will dynamically select a coordinator among themselves to be the arbiter

Group Membership System (GMS)

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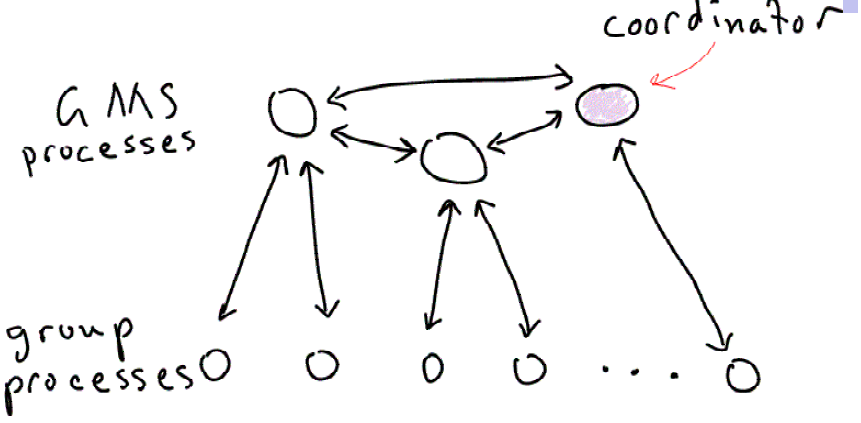

Group Communications Systems

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- Spread (www.spread.org)
  - John Hopkins
  - I recommend you use this
  - Programming APIs for C/C++, C#, Java, Perl, Python, and Ruby
- Ensemble, Horus, Isis
  - Cornell (Ken Birman)
- Others
  - Relacs, Transis, Totem, Phoenix, xAMP

Spread

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- Allows processes to organize into groups (join and leave)
- Manages multicast communications in the group
- Manages group membership
- LAN and WAN operation
  - (you'll just deal with LAN in the project)

Spread API

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- Get group membership (callback)
- Join and leave group
  - First join creates group, last leave destroys group
- Send to group
  - Unreliable, reliable, and SAFE
    - SAFE: Not delivered until all alive processes have received it. Uses Agreed ordering
  - FIFO, Causal, and Agreed

Spread API: Receive Events

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- Receive message
- Receive membership change
  - If add, application can
- Receive pending membership change "warning" (trans_memb)
  - Indication that all subsequent messages, up to next membership change, are completions of current multicasts

Spread View Change

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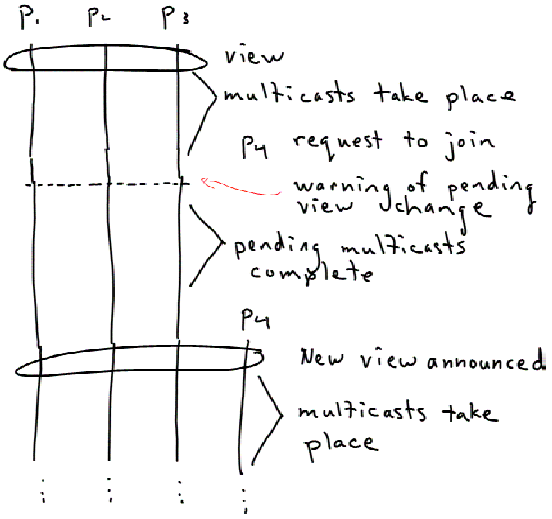

Summary

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- Eliminate failure in individual components where possible
- Use single-primary, hot-standby approach where possible
  - Avoid too much synchronization if possible
- Use group communications concepts otherwise