CS514: Intermediate Course in Operating Systems

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RECAP: Agreement Protocols

- These are used when a set of processes needs to make a decision of some sort
- The problem arises often and can take many forms
  - An *agreement protocol* solves a simple (single-bit) instance of the general problem
  - Gives us a "template" for building fancier protocols that solve other problems

When is agreement needed?

- Recall Sam and Jill from lecture 5
  - Sam was hoping he and Jill could eat outside but they couldn't get their act together and ended up eating inside
  - It illustrated a type of impossibility result:
    - Impossible to learn new "common knowledge" facts in an asynchronous distributed system
    - Defn: "I know that you know that I know…" without any finite limit on the chain

FLP was about agreement

- There we focused on agreement on the value of a single bit
- We concluded that
  - One can build decision protocols
    - And prove that they decide correctly
    - And can even include failure handling
  - But they can't guarantee progress
    - If if we have *many* processes and know that *at most one* of them might crash

We don't always need the FLP "version" of agreement

- Sam and Jill needed an impossible-to-achieve form of agreement!
  - Had they sought a weaker guarantee they might have been able to eat outside without risk!
    - For example: suppose Sam sends "Let's eat outside" and Jill replies "Sounds good," and Sam replies "See yah!"
    - 3-way handshake has risk built in (if the last message doesn't get through, what to do?) but the risk isn't large.
    - If they can live with that risk… it solves the problem
- FLP is about impossible "progress" properties

When is agreement needed?

- Situations where agreement arises
  - Ordering updates to a replicated data item
    - Might allow concurrent updates from sources that don't coordinate their actions
    - Or could have updates that are ordered by, say, use of locking but that might then get disordered in transmission through the network
  - Decision on which updates "occurred"
    - An issue in systems that experience faults

More needs for agreement

- Agreement on the membership
- Agreement on the leader, or some other process with a special role
- Agreement on a ranking
- Agreement on loads or other inputs to a load balancing service
- Agreement on the mapping of a name to a target IP address, or on routing

One protocol isn't enough!

- We'll need different solutions for these different agreement problems
  - But if we abstract away the detail can learn basic things about how such protocols should be structured
  - Also can learn to prove correctness
  - Then can build specific specialized ones, optimized for a particular use and *engineered to perform well*

Agreement: Paradigms

- We've already seen two examples
  - FLP involved consensus on a single bit
    - Processes have a bit values 0 or 1
    - Protocol executes
    - Outcome: all agree on a value (and it was a legitimate input, and they tolerate faults, and we are faithful to the decisions of the dead)
  - Byzantine Agreement: same idea; different model
- But paradigms are about clean theory. *Engineering* implies a focus on speed!

Things we know

- From FLP we know that this statement of the problem…
  - … can be solved in asynchronous settings
  - … but solution can't guarantee liveness
    - There is at least one input scenario and "event sequence" that prevents progress
- From BA, we know that in a system with synchronized rounds, solutions *can* be found, but they are costly
  - Anyhow, that synchronous model is impractical

What about real systems?

- Real world is neither synchronous nor asynchronous
  - We've got a good idea of messages latency
  - … and pretty good clocks
  - Like Sam and Jill, we may be able to tolerate undesired but unlikely outcomes
  - Anyhow, no real system can achieve perfect correctness (at best we depend on the compiler, the operating system)

Real world goals?

- Practical solutions that:
  - Work if most of the system is working
  - Tolerate crashes and perhaps even some mild forms of "Byzantine" behavior, like accidental data corruption
  - "Strive to be live" (to make progress) but accept that some crash/partitioning scenarios could prevent this, like it or not
- We still want to be rigorous

Performance goals

- Want solutions that are cheap, but what should this mean?
  - Traditionally: low total number of messages sent (today, only rarely an important metric)
  - Have low costs in per-process messages sent, received (often important)
  - Have low delay from when update was generated to when it was applied (always VERY important)

Other goals

- Now we'll begin to work our way up to really good solutions. These:
  - Are efficient in senses just outlined
  - Are packaged so that they can be used to solve real problems
  - Are well structured, so that we can understand the code and (hopefully) debug/maintain it easily

Roadmap

- To do this
  - First look at 2-phase and 3-phase commit
    - This pattern of communication arises in many protocols and will be a basic building block
  - Next look at "agreeing on membership"
    - Protocols that track membership give fastest update rates, often by orders of magnitude!
  - Then, implement an ordered update (or multicast) over these mechanisms
  - Finally, think about software architecture issues

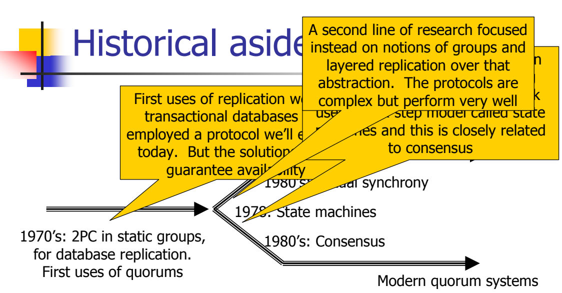
Roadmap

- This will give us
  - A notion of a "process group"
    - Has a name… and a set of members… and the system can dynamically track membership
    - Membership *ranking* is useful in applications
  - Ways to do ordered, reliable, multicast
  - Things built over these primitives: leader election, replication, fault-tolerant request execution, etc

Historical aside

- We're following the evolution of the area now called "distributed systems"
- But we're focused on the path that gave the highest performance solutions
  - Also known as virtual synchrony systems
- Historically, many researchers focused on quorum systems, a second path
  - Much slower, although also has some benefits
  - Closely related to "State Machine" replication

Historical aside



Historical Aside

- Two major classes of real systems
  - Virtual synchrony
    - Weaker properties – not quite "FLP consensus"
    - Much higher performance (orders of magnitude)
    - Requires that majority of system remain connected. Partitioning failures force protocols to wait for repair
  - Quorum-based state machine protocols are
    - Closer to FLP definition of consensus
    - Slower (by orders of magnitude)
    - Sometimes can make progress in partitioning situations where virtual synchrony can't

Names of some famous systems

- Isis was first practical virtual synchrony system
  - Later followed by Transis, Totem, Horus
  - Today: Best options are Jgroups, Spread, Ensemble
  - Technology is now used in IBM Websphere and Microsoft Windows Clusters products!
- Paxos was first major state machine system
  - BASE and other Byzantine Quorum systems now getting attention from the security community
- (End of Historical aside)

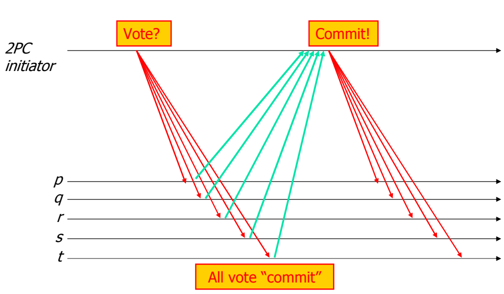
We're already on track "A"

- We're actually focused more on the virtual synchrony "track"
  - Not enough time to do justice to both
  - And systems engineers tend to prefer very high performance
  - But for systems doing secure replication, the Byzantine Quorums approach is probably better despite costs

The commit problem

- An initiating process communicates with a group of actors, who vote
  - Initiator is often a group member, too
  - Ideally, if all vote to commit we perform the action
  - If any votes to abort, none does so
- Asynchronous model
  - Network is reliable, but no notion of time
  - Fail-stop processes
- In practice we introduce timeouts;
  - If timeout occurs the leader can presume that a member wants to abort. Called the *presumed abort* assumption.

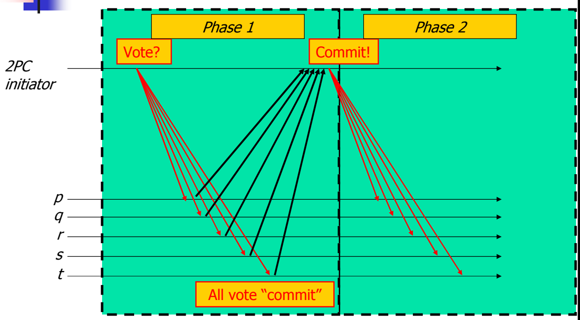
As a time-line picture



Observations?

- Any member can abort any time it likes, even before the protocol runs
  - E.g. if we are talking "about" some pending action that the group has known for a while
- We call it "2 phase" even though it actually has 3 rounds of messages

As a time-line picture



In fact we're missing stuff

- Eventually will need to do some form of garbage collection
  - Issue is that participants need memory of the protocol, at least for a while
  - But can delay garbage collection and run it later on behalf of many protocol instances
- Part of any real implementation but not thought of as part of the protocol

Fault tolerance

- We can separate this into three cases
  - Group member fails; initiator remains healthy
  - Initiator fails; group members remain healthy
  - Both initiator and group member fail
- Further separation
  - Handling recovery of a failed member
  - Recovery after "total" failure of the whole group

Fault tolerance

- Some cases are pretty easy
  - E.g. if a member fails before voting we just treat it as an abort
  - If a member fails after voting commit, we assume that when it recovers it will finish up the commit and perform whatever action we requested
- Hard cases involve crash of initiator

Initiator fails, members healthy

- Must ask "when did it fail"?
  - Could fail before starting the 2PC protocol
    - In this case if the members were expecting the protocol to run, e.g. to terminate a pending transaction on a database, they do "unilateral abort"
  - Could fail after some are prepared to commit
    - Those members need to learn the outcome before they can "finish" the protocol
  - Could fail after some have learned the outcome
    - Others may still be in a prepared state

Ideas?

- Members could do an all-to-all broadcast
  - But this won't actually work… problem is that if a process seems to have failed, perhaps some of us will have seen its messages and some not
- Could elect a leader to solve the problem
  - Forces us to inject leader election into our system
- Could use some sort of highly available log server that remembers states of protocols
  - This is how Web Services does it

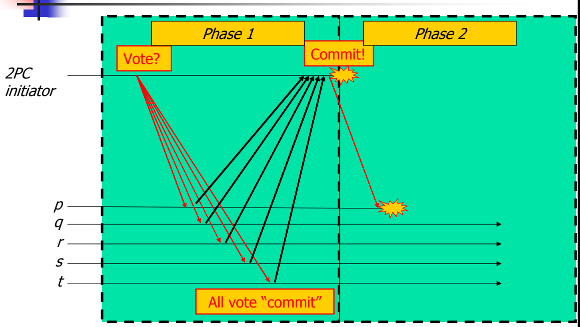
Leads to two ideas

- Initiator should record the decision in a logging server for use after crashes
  - We saw this in the Web Services transactional systems slide set last week
- Also, members can help one-another terminate the protocol
  - E.g., a leader can take over if the initiator fails
  - This is needed if a failure happens before the initiator has a chance to log its decision

Problems?

- 2PC has a "bad state"
  - Suppose that the initiator and a member both fail and we aren't using a "log"
    - As 2PC is normally posed, we don't have a log server in the problem statement
    - (In practice, log server can eliminate this issue)
  - There is a case in which we can't terminate the protocol!

As a time-line picture



Why do we get stuck?

- If process p voted "commit", the coordinate may have committed the protocol
  - And p may have learned the outcome
  - Perhaps it transferred $10M from a bank account…
  - So we want to be consistent with that
- If p voted "abort", the protocol must abort
  - And in this case we can't risk committing

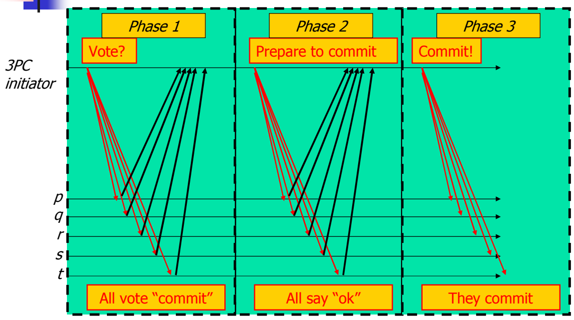
Why not always have a log?

- In some sense, a log service is just another member
  - In effect, Web Services is willing to wait if its log server crashes and must reboot
  - And guarantees that if this doesn't happen you never need to wait
  - But in many systems we just want to use 2PC. Using a separate server is a pain
- Can we solve the problem without it?

3 phase commit

- Protocol was introduced by Skeen and Stonebraker
- And it assumes *detectable* failures
  - We happen to know that real systems can't detect failures, unless they can unplug the power for a faulty node
  - But Skeen and Stonebraker set that to the side
- Idea is to add an extra "prepared to commit" stage

3 phase commit



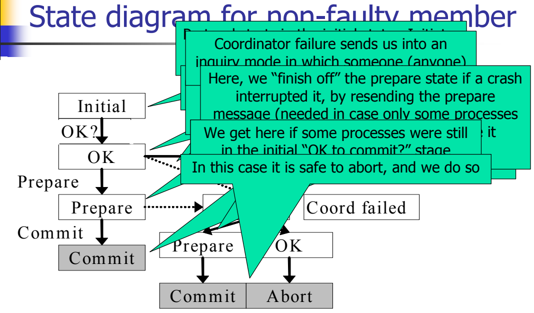
Why 3 phase commit?

- A "new leader" in the group can deduce the outcomes when this protocol is used
- Main insight?
  - Nobody can enter the commit state unless all are first in the prepared state
  - Makes it possible to determine the state, then push the protocol forward (or back)
- But does require accurate failure detections
  - If it didn't, would violate the FLP result!

Value of 3PC?

- Even with inaccurate failure detections, it greatly reduces the window of vulnerability
  - The bad case for 2PC is not so uncommon
    - Especially if a group member is the initiator
    - In that case one badly timed failure freezes the whole group
  - With 3PC in real systems, the troublesome case becomes very unlikely
- But the risk of a freeze-up remains

State diagram for non-faulty member



Some additional details

- Like 2PC, 3PC needs some extra work
  - Issue is that members need to save some information about the protocol until it terminates
  - In practice this requires an extra round for garbage collection
  - Often we do this just now and then, on behalf of *many* terminated protocols, so costs are amortized and very low

What next?

- We'll use a protocol based on 2PC and 3PC (both are used) to build a group membership service
  - This is a system service that tracks membership of process groups
  - The service itself tries to be highly available (but can't always do so)
  - Other processes use it in place of a failure detection system

Layering

Robust Web Services: We'll build them with these tools

Tools for solving practical replication and availability problems: we'll base them on ordered multicast

Ordered multicast: We'll base it on fault-tolerant multicast

Fault-tolerant multicast: We'll use membership

Tracking group membership: We'll base 2PC and 3PC

2PC and 3PC: Our first "tools" (lowest layer)

But first…

- We've seen several new mechanisms
- Let's pause and ask if we can already apply them in some practical real-world settings
- Then resume and work our way up the protocol stack!

What should you be reading?

- We're working our way through Chapter 14 of the textbook now
- Read the introduction to Part III and Chapters 13, 14 and 15