# CS514: Intermediate Course in Operating Systems

Professor Ken Birman
Vivek Vishnumurthy: TA

## Fault-tolerance concern

- Our reason for discussing transactions was to improve fault-tolerance
  - They ensured that a server can restart in a cleaned up state
- But sometimes we need high availability and yet we want consistent behavior
  - What issues arise if things can fail and we can't wait for restart, or "abort" what we were doing?

## Failure models

- Issues related to failures
  - How do systems "fail?"
  - Given a category of failures, are there limits to what can we do about it?
- Today explore this issue
  - Real world studies of failure rates
  - Experience with some big projects that failed
  - Formal models of failure (crash, fail-stop, Byzantine)
  - A famous (but confusing) impossibility result

## Who needs failure "models"?

- The problem is that processes can fail in so many ways
  - Hardware failures are rare, but they happen
  - Software bugs can cause a program to malfunction by crashing, corrupting data, or just failing to "do its job"
  - Intruders might inject some form of failure to disrupt or compromise a system
  - A failure *detector* could malfunction, signaling a failure even though nothing is wrong

## Bohrbugs and Heisenbugs

- A categorization due to Bruce Lindsey
  - Bohrbugs are dull, boring, debuggable bugs
    - They happen every time you run the program and are easy to localize and fix using modern development tools
    - If "purify" won't find it… try binary search
  - Heisenbugs are hard to pin down
    - Often associated with threading or interrupts
    - Frequently a data structure is damaged but this is only noticed much later
    - Hence hard to reproduce and so hard to fix
    - In mature programs, Heisenbugs dominate

## Clean-room development

- Idea is that to write code
  - First, the team develops a good specification and refines it to modules
  - A primary coding group implements them
  - Then the whole group participates in code review
  - Then the primary group develops a comprehensive test suite and runs it
  - Finally passes off to a Q/A group that redoes these last stages (code review, testing)
  - Later, upgrades require same form of Q/A!

## Reality?

- Depends very much on the language
  - With Java and C# we get strong type checking and powerful tools to detect many kinds of mistakes
  - Also clean abstraction boundaries
- But with C++ and C and Fortran, we lack such tools
- The methodology tends to require good tools

## Why do systems fail?

- Many studies of this issue suggest that
  - Incorrect specifications (e.g. the program just doesn't "work" in the first place)
  - Lingering Heisenbugs, often papered-over
  - Administrative errors
  - Unintended side-effects of upgrades and bug fixes
- ... are dominant causes of failures.

## What can we do about it?

- Better programming languages, approaches and tools can help
  - For example shift from C to Java and C# has been hugely beneficial
- But we should anticipate that large systems will exhibit problems
- Failures are a side-effect of using technology to solve complex problems!

## Who needs failure "models"?

- Role of a failure model
  - Lets us reduce fault-tolerance to a mathematical question
    - In model M, can problem P be solved?
    - How costly is it to do so?
    - What are the best solutions?
    - What tradeoffs arise?
  - And clarifies what we are saying
    - Lacking a model, confusion is common

## Categories of failures

- Crash faults, message loss
  - These are common in real systems
  - Crash failures: process simply stops, and does nothing wrong that would be externally visible before it stops
- These faults can't be directly detected

## Categories of failures

- Fail-stop failures
  - These require system support
  - Idea is that the process fails by crashing, and the system notifies anyone who was talking to it
  - With fail-stop failures we can overcome message loss by just resending packets, which must be uniquely numbered
  - Easy to work with... but rarely supported

## Categories of failures

- Non-malicious Byzantine failures
  - This is the best way to understand many kinds of corruption and buggy behaviors
  - Program can do pretty much anything, including sending corrupted messages
  - But it doesn't do so with the intention of screwing up our protocols
- Unfortunately, a pretty common mode of failure

## Categories of failure

- Malicious, true Byzantine, failures
  - Model is of an attacker who has studied the system and wants to break it
  - She can corrupt or replay messages, intercept them at will, compromise programs and substitute hacked versions
- This is a worst-case scenario mindset
  - In practice, doesn't actually happen
  - Very costly to defend against; typically used in very limited ways (e.g. key mgt. server)

## Models of failure

- Question here concerns how failures appear in formal models used when proving things about protocols
- Think back to Lamport's happens-before relationship, $\rightarrow$
  - Model already has processes, messages, temporal ordering
  - Assumes messages are reliably delivered

## Recall: Two kinds of models

- We tend to work within two models
  - Asynchronous model makes no assumptions about time
    - Lamport's model is a good fit
    - Processes have no clocks, will wait indefinitely for messages, could run arbitrarily fast/slow
    - Distributed computing at an "eons" timescale
  - Synchronous model assumes a lock-step execution in which processes share a clock

## Adding failures in Lamport's model

- Also called the asynchronous model
- Normally we just assume that a failed process "crashes:" it stops doing anything
  - Notice that in this model, a failed process is indistinguishable from a delayed process
  - In fact, the decision that something has failed takes on an arbitrary flavor
    - Suppose that at point *e* in its execution, process *p* decides to treat *q* as faulty...."

## What about the synchronous model?

- Here, we also have processes and messages
  - But communication is usually assumed to be reliable: any message sent at time t is delivered by time t+$\delta$
  - Algorithms are often structured into rounds, each lasting some fixed amount of time $\Delta$, giving time for each process to communicate with every other process
  - In this model, a crash failure is easily detected
- When people *have* considered malicious failures, they often used this model

## Neither model is realistic

- Value of the asynchronous model is that it is so stripped down and simple
  - If we can do something “well” in this model we can do at least as well in the real world
  - So we’ll want “best” solutions
- Value of the synchronous model is that it adds a lot of “unrealistic” mechanism
  - If we can’t solve a problem with all this help, we probably can’t solve it in a more realistic setting!
  - So seek impossibility results

## Examples of results

- We saw an algorithm for taking a global snapshot in an asynchronous system
- And it is common to look at problems like agreeing on an ordering
  - Often reduced to “agreeing on a bit” (0/1)
  - To make this non-trivial, we assume that processes have an input and must pick some legitimate input value

## Connection to consistency

- We started by talking about consistency
  - We found that many (not all) notions of consistency reduce to forms of agreement on the events that occurred and their order
  - Could imagine that our “bit” represents
    - Whether or not a particular event took place
    - Whether event A is the “next” event
  - Thus fault-tolerant consensus is deeply related to fault-tolerant consistency

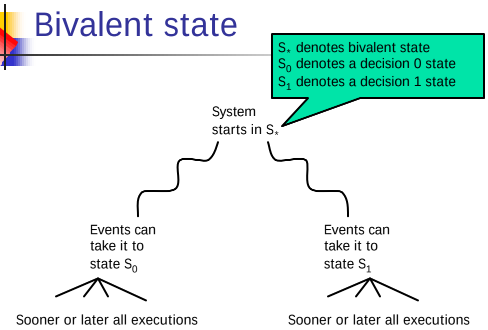
## Fischer, Lynch and Patterson

- A surprising result
  - *Impossibility of Asynchronous Distributed Consensus with a Single Faulty Process*
- They prove that no asynchronous algorithm for agreeing on a one-bit value can guarantee that it will terminate in the presence of crash faults
  - And this is true even if no crash actually occurs!
  - Proof constructs infinite non-terminating runs

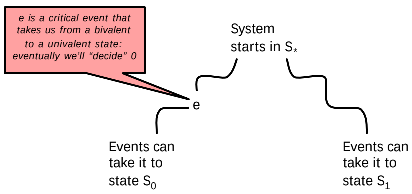
## Core of FLP result

- They start by looking at a system with inputs that are all the same
  - All 0’s must decide 0, all 1’s decides 1
- Now they explore mixtures of inputs and find some initial set of inputs with an uncertain (“bivalent”) outcome
- They focus on this bivalent state

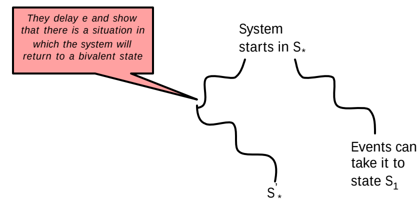
## Bivalent state



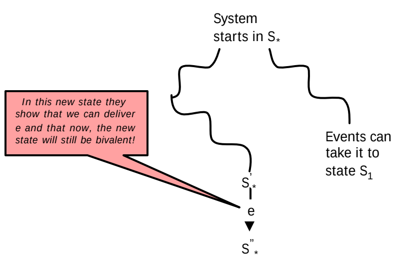
## Bivalent state



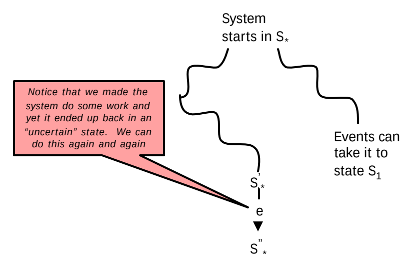

## Bivalent state




## Bivalent state




## Bivalent state




## Core of FLP result in words

- In an initially bivalent state, they look at some execution that would lead to a decision state, say "0"
  - At some step this run switches from bivalent to univalent, when some process receives some message *m*
  - They now explore executions in which *m* is delayed

## Core of FLP result

- So:
  - Initially in a bivalent state
  - Delivery of *m* would make us univalent but we delay *m*
  - They show that if the protocol is fault-tolerant there must be a run that leads to the other univalent state
  - And they show that you can deliver *m* in this run without a decision being made
- This proves the result: they show that a bivalent system can be forced to do some work and yet remain in a bivalent state.
  - If this is true once, it is true as often as we like
  - In effect: we can delay decisions indefinitely

## But how did they "really" do it?

- Our picture just gives the basic idea
- Their proof actually proves that there is a way to force the execution to follow this tortured path
- But the result is very theoretical…
  - … to much so for us in CS514
- So we'll skip the real details

## *Intuition* behind this result?

- Think of a real system trying to agree on something in which process p plays a key role
- But the system is fault-tolerant: if p crashes it adapts and moves on
- Their proof "tricks" the system into treating p as if it had failed, but then lets p resume execution and "rejoin"
- This takes time… and no real progress occurs

## But what did "impossibility" mean?

- In formal proofs, an algorithm is totally correct if
  - It computes the right thing
  - And it *always* terminates
- When we say something is possible, we mean "there is a totally correct algorithm" solving the problem
- FLP proves that any fault-tolerant algorithm solving consensus has runs that never terminate
  - These runs are extremely unlikely ("probability zero")
  - Yet they imply that we can't find a totally correct solution
  - And so "consensus is impossible" ( "not always possible")

## Recap

- We have an asynchronous model with crash failures
  - A bit like the real world!
- In this model we know how to do some things
  - Tracking "happens before" & making a consistent snapshot
  - Later we'll find ways to do ordered multicast and implement replicated data and even solve consensus
- But now we also know that there will always be scenarios in which our solutions can't make progress
  - Often can engineer system to make them extremely unlikely
  - Impossibility doesn't mean these solutions are wrong – only that they live within this limit

## Tougher failure models

- We've focused on crash failures
  - In the synchronous model these look like a "farewell cruel world" message
  - Some call it the "failstop model". A faulty process is viewed as first saying goodbye, then crashing
- What about tougher kinds of failures?
  - Corrupted messages
  - Processes that don't follow the algorithm
  - Malicious processes out to cause havoc?

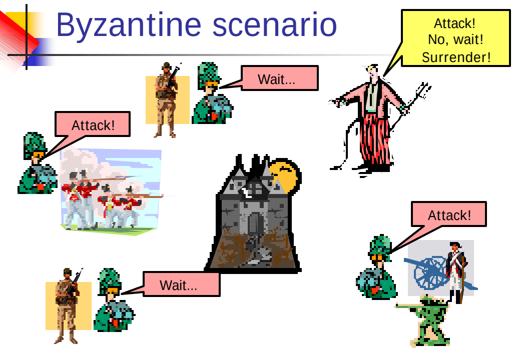
## Here the situation is much harder

- Generally we need at least 3f+1 processes in a system to tolerate f Byzantine failures
  - For example, to tolerate 1 failure we need 4 or more processes
- We also need f+1 "rounds"
- Let's see why this happens

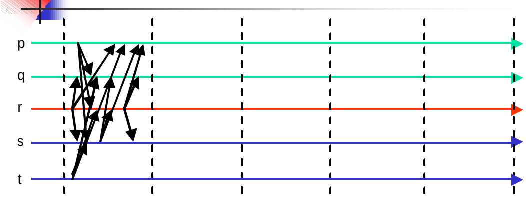
## Byzantine scenario

- Generals (N of them) surround a city
  - They communicate by courier
- Each has an opinion: “attack” or “wait”
  - In fact, an attack would succeed: the city will fall.
  - Waiting will succeed too: the city will surrender.
  - But if some attack and some wait, disaster ensues
- Some Generals (f of them) are traitors… it doesn’t matter if they attack or wait, but we must prevent them from disrupting the battle
  - Traitor can’t forge messages from other Generals

## Byzantine scenario

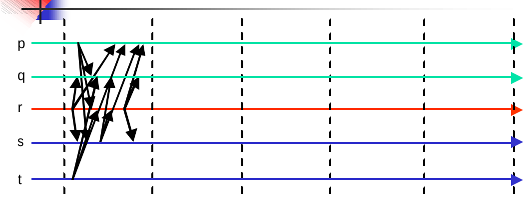



## A timeline perspective




- Suppose that p and q favor attack, r is a traitor and s and t favor waiting… assume that in a tie vote, we attack

## A timeline perspective




- After first round collected votes are:
  - {attack, attack, wait, wait, traitor’s-vote}

## What can the traitor do?

- Add a legitimate vote of “attack”
  - Anyone with 3 votes to attack knows the outcome
- Add a legitimate vote of “wait”
  - Vote now favors “wait”
- Or send different votes to different folks
- Or don’t send a vote, at all, to some

## Outcomes?

- Traitor simply votes:
  - Either all see {a,a,a,w,w }
  - Or all see {a,a,w,w,w }
- Traitor double-votes
  - Some see {a,a,a,w,w } and some {a,a,w,w,w }
- Traitor withholds some vote(s)
  - Some see {a,a,w,w }, perhaps others see {a,a,a,w,w ,} and still others see {a,a,w,w,w }
- Notice that traitor can’t manipulate votes of loyal Generals!

## What can we do?

- Clearly we can't decide yet; some loyal Generals might have contradictory data
  - In fact if anyone has 3 votes to attack, they can already "decide".
  - Similarly, anyone with just 4 votes can decide
  - But with 3 votes to "wait" a General isn't sure (one could be a traitor…)
- So: in round 2, each sends out "witness" messages: here's what I saw in round 1
  - General Smith send me: "attack$_{\text{(signed) Smith}}$"

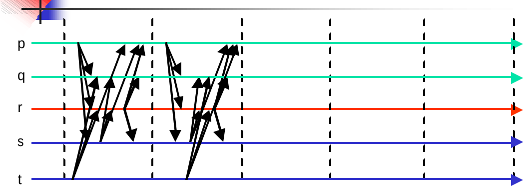
## Digital signatures

- These require a cryptographic system
  - For example, RSA
  - Each player has a secret (private) key $K^{-1}$ and a public key K.
    - She can publish her public key
  - RSA gives us a single "encrypt" function:
    - $\text{Encrypt}(\text{Encrypt}(M,K),K^{-1}) = \text{Encrypt}(\text{Encrypt}(M,K^{-1}),K) = M$
    - Encrypt a hash of the message to "sign" it

## With such a system

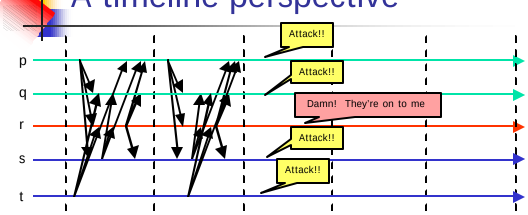
- A can send a message to B that only A could have sent
  - A just encrypts the body with her private key
- … or one that only B can read
  - A encrypts it with B's public key
- Or can sign it as proof she sent it
  - B can recompute the signature and decrypt A's hashed signature to see if they match
- These capabilities limit what our traitor can do: he can't forge or modify a message

## A timeline perspective




- In second round if the traitor didn't behave identically for all Generals, we can weed out his faulty votes

## A timeline perspective




- We attack!

## Traitor is stymied

- Our loyal generals can deduce that the decision was to attack
- Traitor can't disrupt this…
  - Either forced to vote legitimately, or is caught
  - But costs were steep!
    - $(f+1) \cdot n^2$ ,messages!
    - Rounds can also be slow….
  - "Early stopping" protocols: min(t+2, f+1) rounds; t is true number of faults

## Recent work with Byzantine model

- Focus is typically on using it to secure particularly sensitive, ultra-critical services
  - For example the "certification authority" that hands out keys in a domain
  - Or a database maintaining top-secret data
- Researchers have suggested that for such purposes, a "Byzantine Quorum" approach can work well
- They are implementing this in real systems by simulating rounds using various tricks

## Byzantine Quorums

- Arrange servers into a $\sqrt{n} \times \sqrt{n}$ array
  - Idea is that any row or column is a quorum
  - Then use Byzantine Agreement to access that quorum, doing a read or a write
- Separately, Castro and Liskov have tackled a related problem, using BA to secure a file server
  - By keeping BA out of the critical path, can avoid most of the delay BA normally imposes

## Split secrets

- In fact BA algorithms are just the tip of a broader "coding theory" iceberg
- One exciting idea is called a "split secret"
  - Idea is to spread a secret among *n* servers so that any *k* can reconstruct the secret, but no individual actually has all the bits
  - Protocol lets the client obtain the "shares" without the servers seeing one-another's messages
  - The servers keep but can't read the secret!
- Question: In what ways is this better than just encrypting a secret?

## How split secrets work

- They build on a famous result
  - With k+1 distinct points you can uniquely identify an order-k polynomial
    - i.e 2 points determine a line
    - 3 points determine a unique quadratic
  - The polynomial is the "secret"
  - And the servers themselves have the points – the "shares"
  - With coding theory the shares are made just redundant enough to overcome n-k faults

## Byzantine Broadcast (BB)

- Many classical research results use Byzantine Agreement to implement a form of fault-tolerant multicast
  - To send a message I initiate "agreement" on that message
  - We end up agreeing on content and ordering w.r.t. other messages
- Used as a primitive in many published papers

## Pros and cons to BB

- On the positive side, the primitive is very powerful
  - For example this is the core of the Castro and Liskov technique
- But on the negative side, BB is slow
  - We'll see ways of doing fault-tolerant multicast that run at 150,000 small messages per second
  - BB: more like 5 or 10 per second
- The right choice for infrequent, very sensitive actions... but wrong if performance matters

## Take-aways?

- Fault-tolerance matters in many systems
  - But we need to agree on what a "fault" is
  - Extreme models lead to high costs!
- Common to reduce fault-tolerance to some form of data or "state" replication
  - In this case fault-tolerance is often provided by some form of broadcast
  - Mechanism for *detecting* faults is also important in many systems.
    - Timeout is common... but can behave inconsistently
    - "View change" notification is used in some systems. They typically implement a fault agreement protocol.