CS5412: CONSENSUS AND THE FLP IMPOSSIBILITY RESULT

Lecture XII

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Generalizing Ron and Hermione's challenge

- Recall from last time: Ron and Hermione had difficulty agreeing where to meet for lunch
  - The central issue was that Ron wanted to reason in a perfectly logical way. They never knew for sure if email was delivered... and always ended up in the "default" case
- In general we often see cases in which N processes must agree upon something
  - 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
- Can we implement a fault-tolerant agreement protocol?

Connection to consistency

- A system behaves consistently if users can't distinguish it from a non-distributed system that supports the same functionality
  - Many notions of consistency reduce to 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

Consensus ≡ Agreement?

- For CS5412 we treat these as synonyms
- The theoretical distributed systems community has detailed definitions and for that group, the terms refer to very similar but not identical problems
- Today we're "really" focused on Consensus, but don't worry about the distinctions

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 an asynchronous system of N processes with inputs that are all the same
  - All 0's must decide 0, all 1's decides 1
- They are assume we are given a correct consensus protocol that will "vote" (somehow) to pick one of the inputs, e.g. perhaps the majority value
  - Now they focus on an initial set of inputs with an uncertain ("bivalent") outcome (nearly a tie)
  - For example: N=5 and with a majority of 0's the protocol picks 0, *but with a tie, it picks 1*. Thus if one of process with a 0 happens to fail, the outcome is different than if all vote

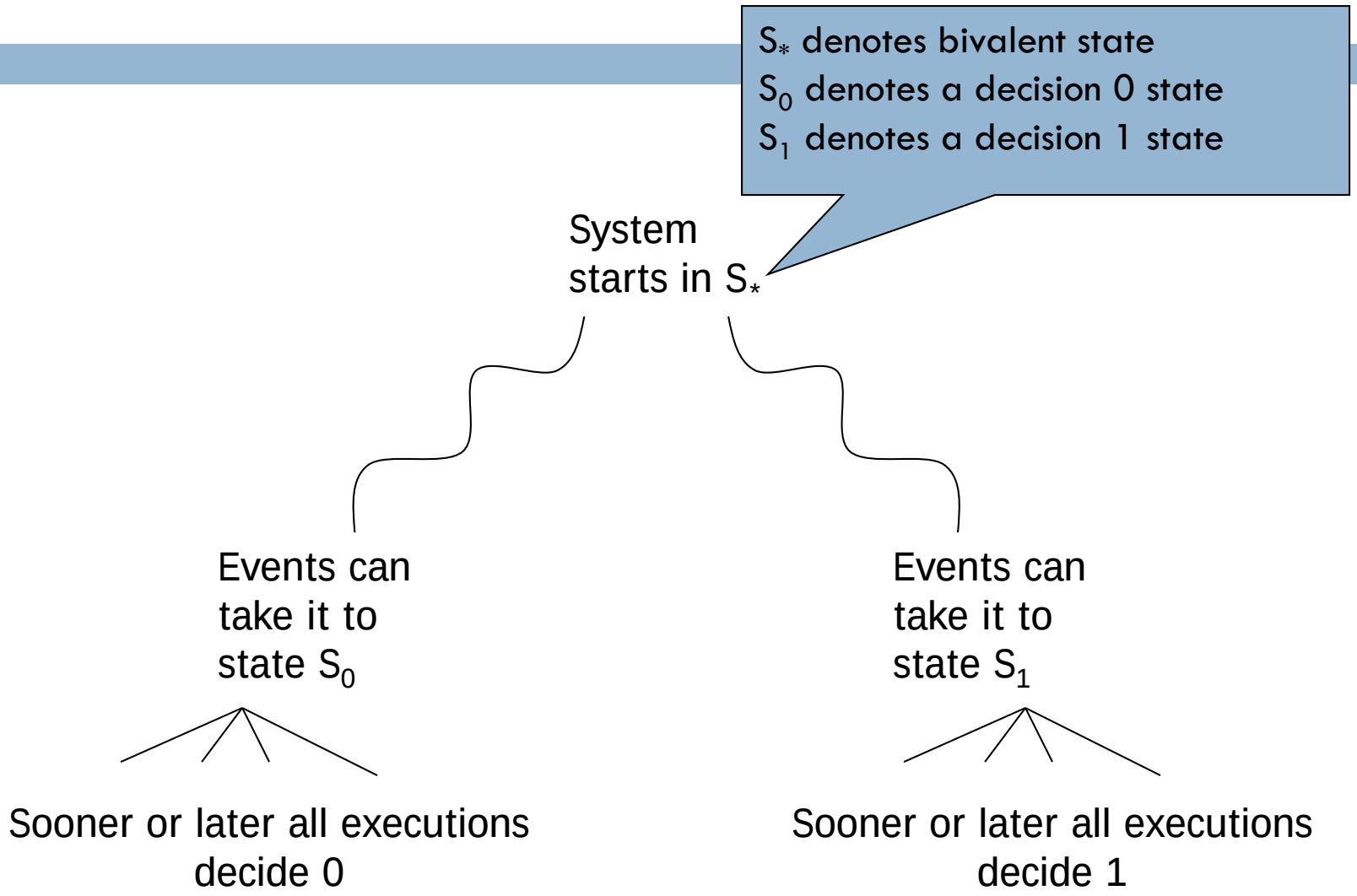
Core of FLP result

- Now they will show that from this bivalent state we can force the system to do some work and yet still end up in an equivalent bivalent state

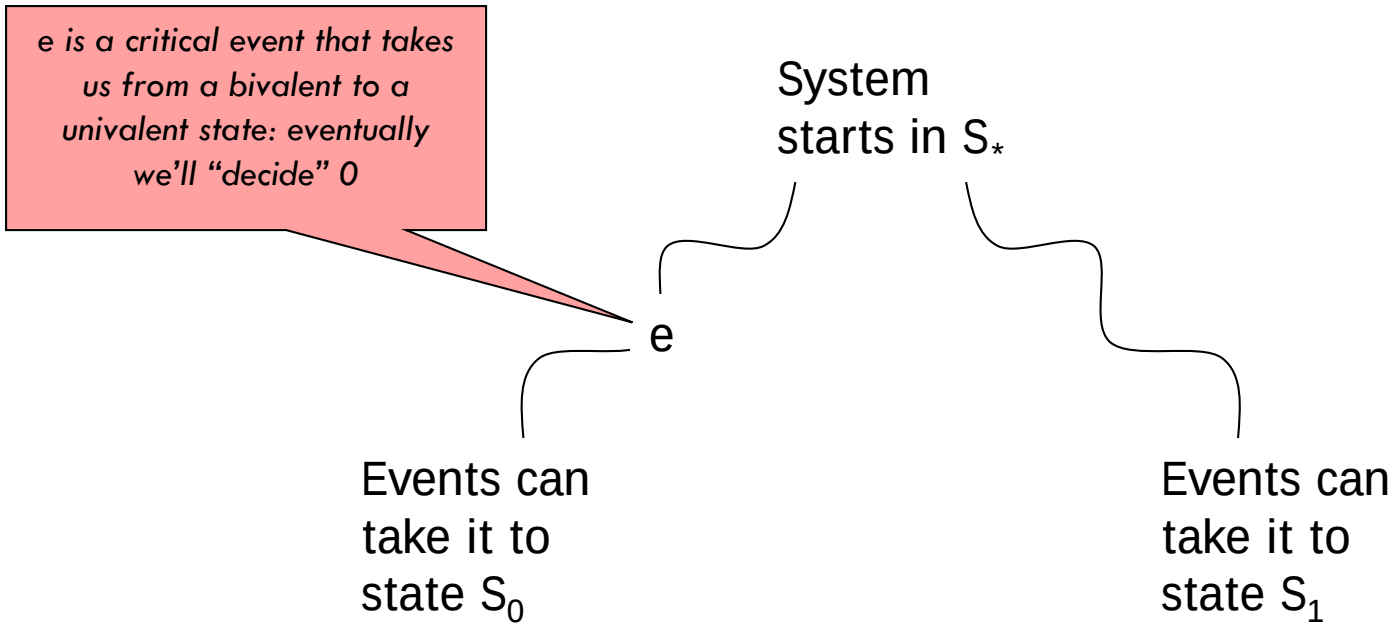
- Then they repeat this procedure

- Effect is to force the system into an infinite loop!
  - And it works *no matter what correct consensus protocol you started with.* This makes the result very general

Bivalent state



Bivalent state



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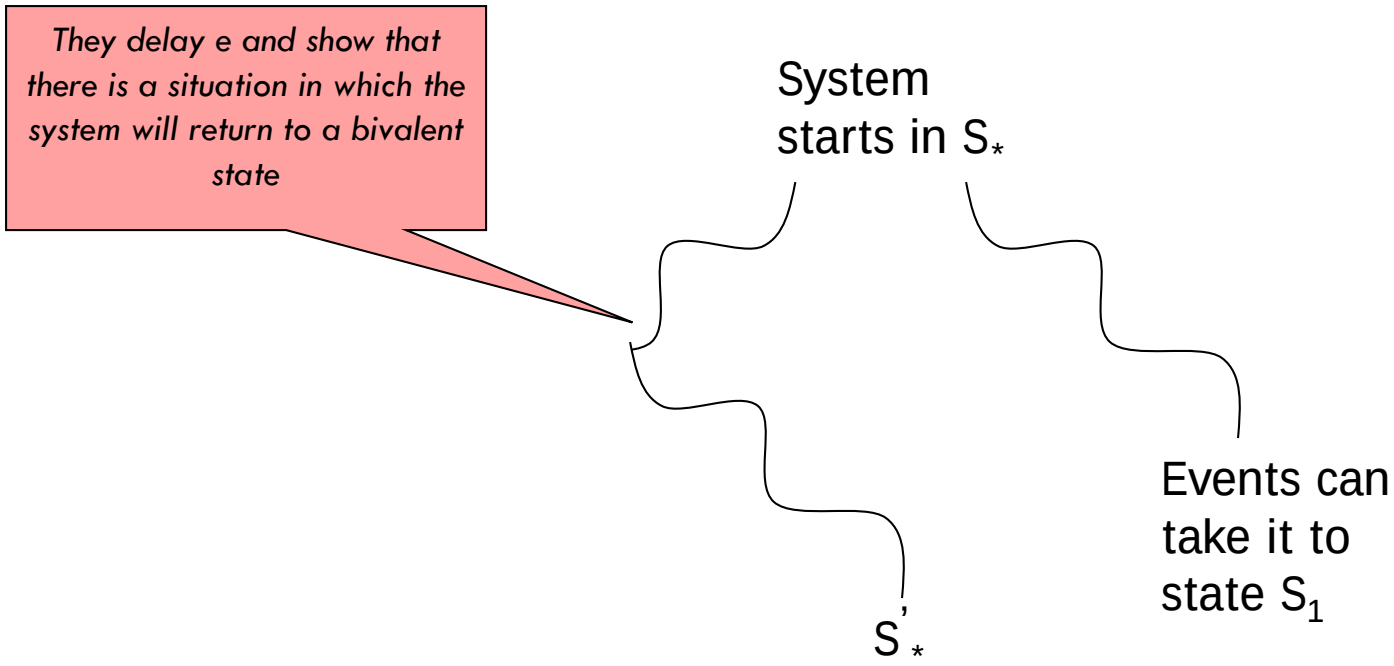

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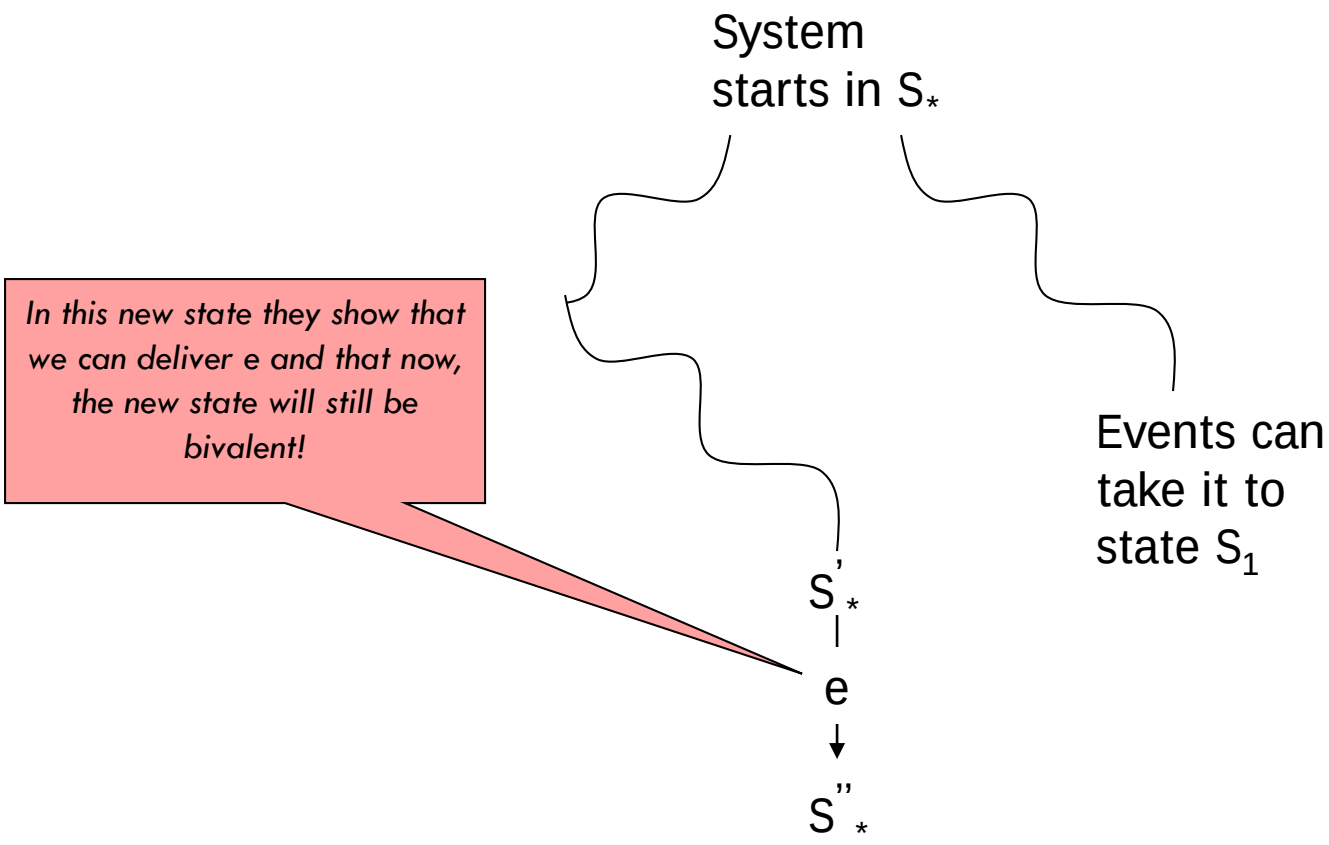
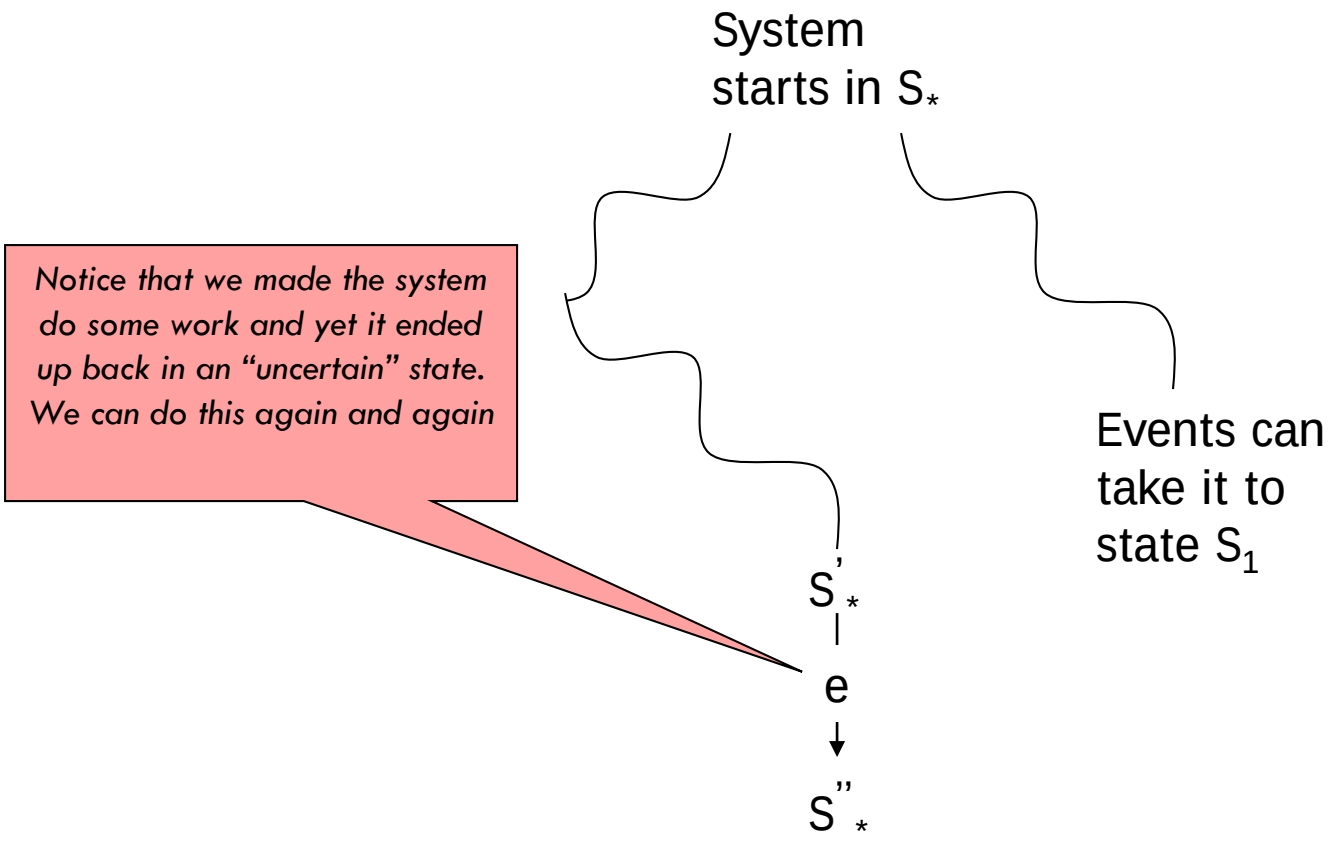


Bivalent state



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 CS5412
  - 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 thinking p failed
  - Then they allow p to resume execution, but make the system believe that perhaps q has failed
  - The original protocol can only tolerate1 failure, not 2, so it needs to somehow let p rejoin in order to achieve progress
- 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")

How did they pull this off?

- A very clever adversarial attack
  - They assume they have perfect control over which messages the system delivers, and when
  - They can pick the exact state in which a message arrives in the protocol
- They use this ultra-precise control to force the protocol to loop in the manner we've described
- In practice, no adversary ever has this much control

In the real world?

- The FLP scenario "could happen"
  - After all, it is a valid scenario.
  - … And any valid scenario can happen

- But step by step they take actions that are incredibly unlikely. For many to happen in a row is just impossible in practice
  - A "probability zero" sequence of events
  - Yet in a temporal logic sense, FLP shows that if we can prove correctness for a consensus protocol, we'll be unable to prove it live in a realistic network setting, like a cloud system

So…

- Fault-tolerant consensus is…
  - Definitely possible (not even all that hard). Just vote!
  - And we can prove protocols of this kind correct.

- But we can't prove that they will terminate
  - If our goal is just a probability-one guarantee, we actually *can* offer a proof of progress
  - But in temporal logic settings we want perfect guarantees and we can't achieve that goal

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?

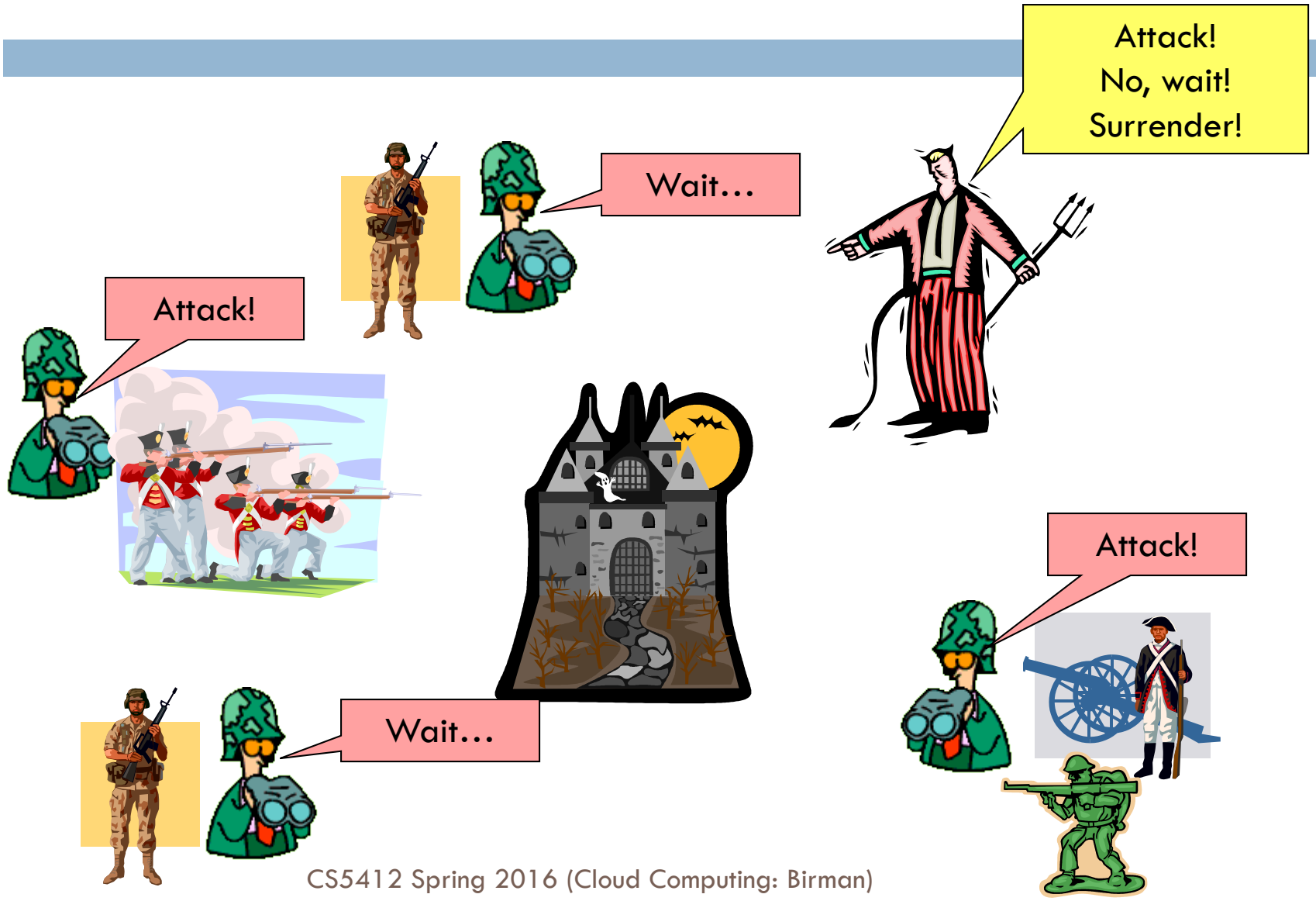
Here the situation is much harder

- 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

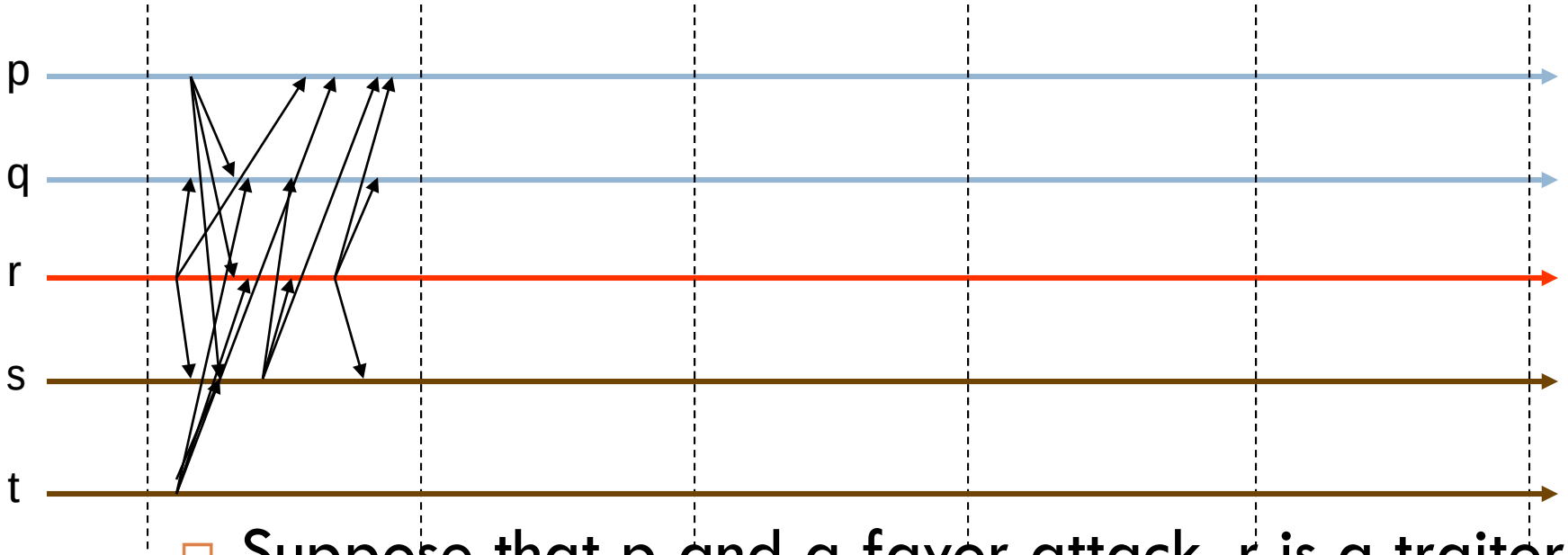
Byzantine scenario

- 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

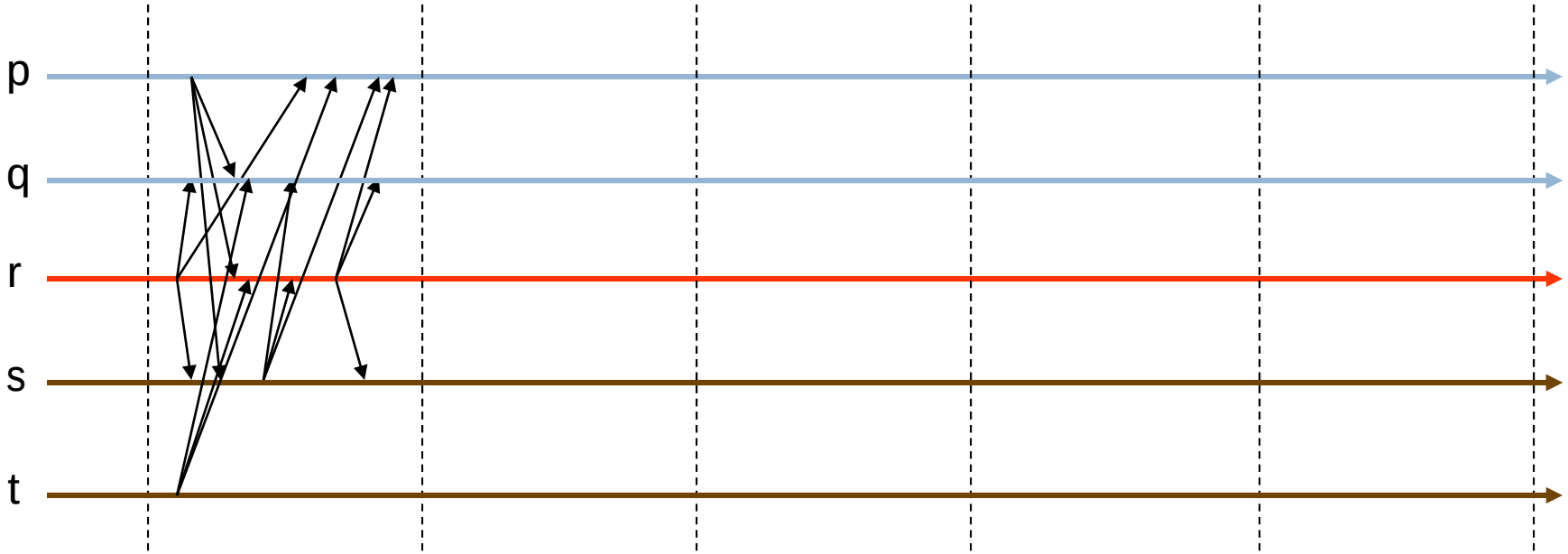


A timeline perspective



- 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$_{\text{(signed) Smith}}$"

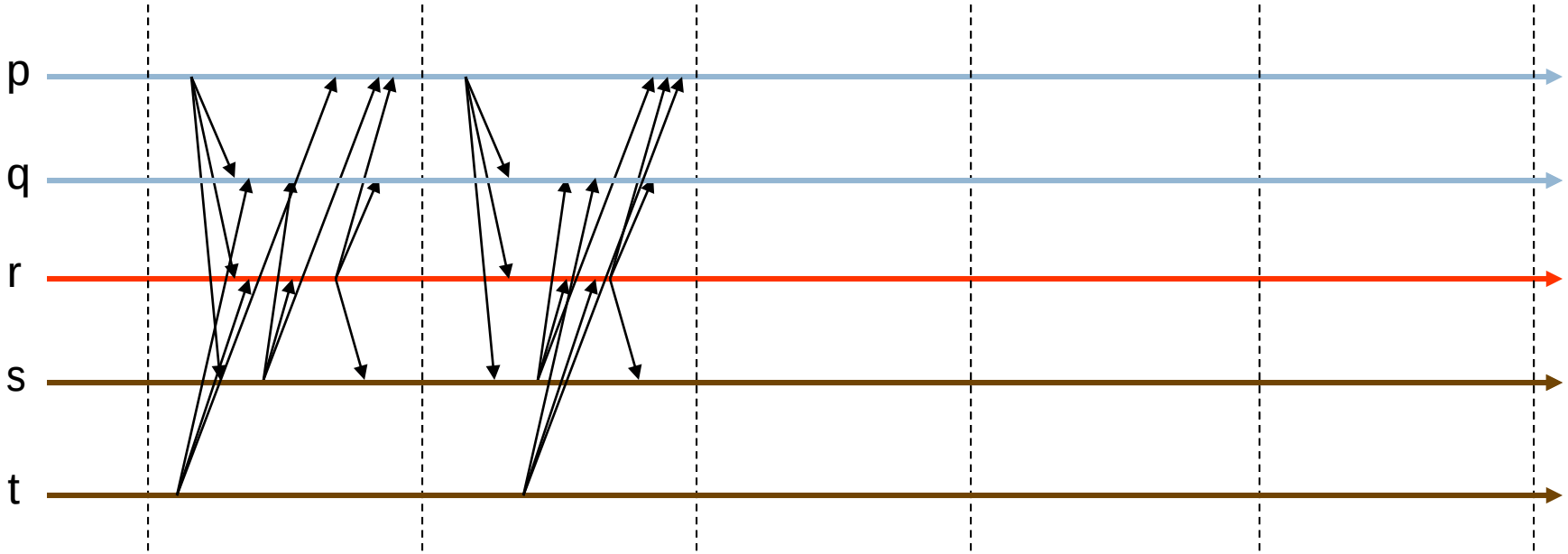
Digital signatures

- 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:
    - Encrypt(Encrypt(M,K),K^{-1}) = Encrypt(Encrypt(M,K^{-1}),K) = M
    - Encrypt a hash of the message to "sign" it

With such a system

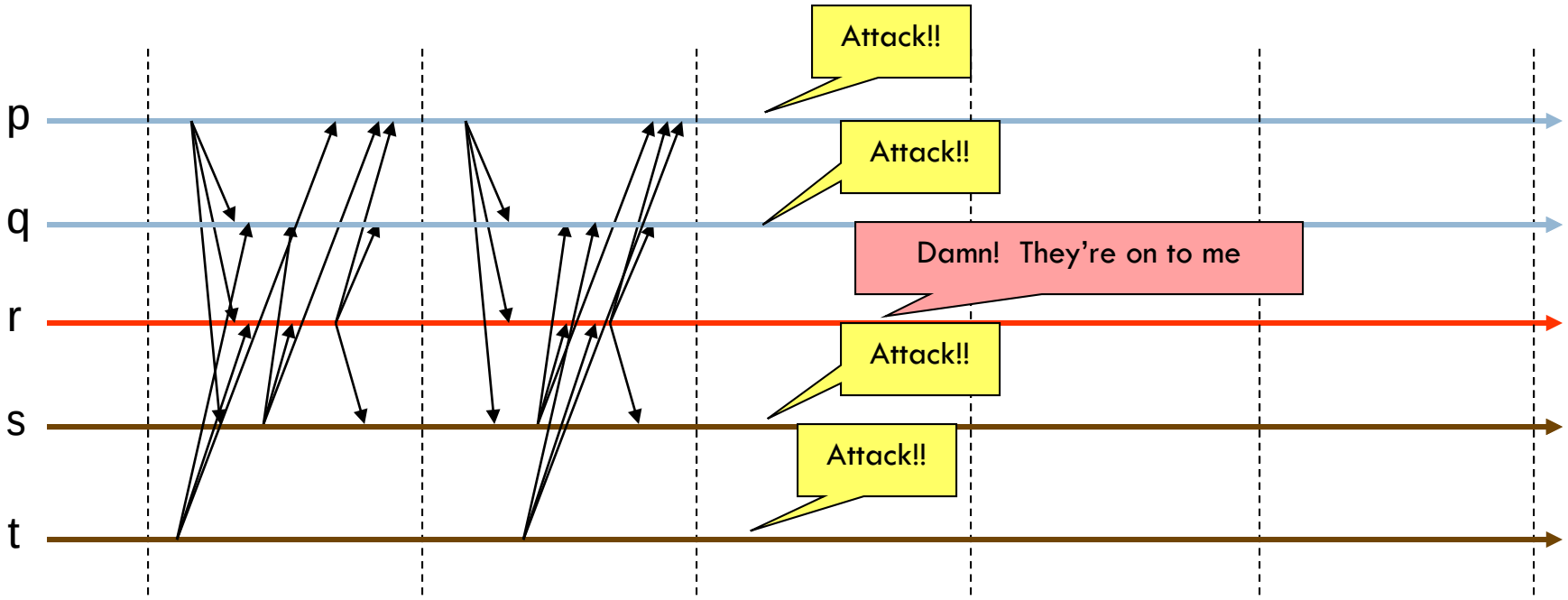
- A can send a message to B that only A could have sent
  - A just encrypts the body with her private key
- … or one that only B can read
  - A encrypts it with B's public key
- Or can sign it as proof she sent it
  - B can recompute the signature and decrypt A's hashed signature to see if they match
- 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!
    - $(f+1)*n^2$,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.