From Byzantine Generals to Hackers

Leslie Lamport
Microsoft Research

Part I

Designing Computer Systems

To Fly an Airplane

The 1970s

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How do we make computers reliable?

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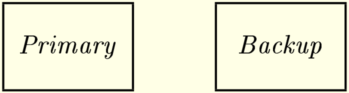

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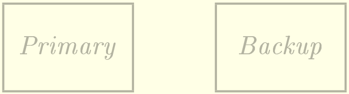

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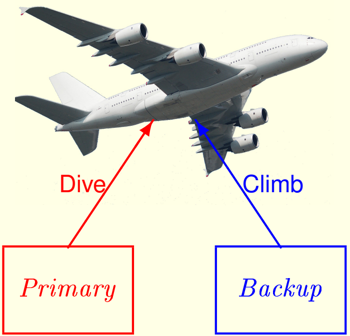

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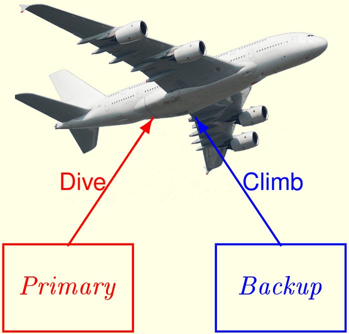

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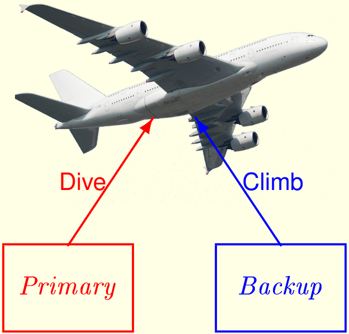

Which one does the airplane listen to?

the actuators that control the flaps, landing gear, etc.

Simple solution: the backup turns off a bad primary.

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A system with two computers cannot tolerate the failure of one of them.

Typical engineering solution:

Assume that such failures are highly improbable.

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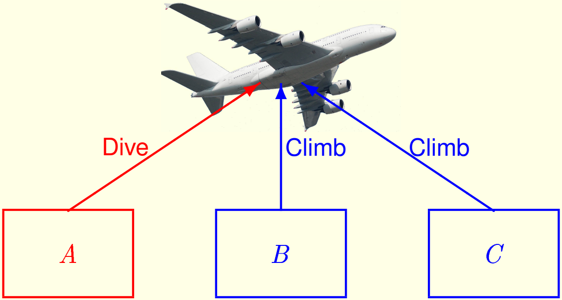
The plane listens to a majority.



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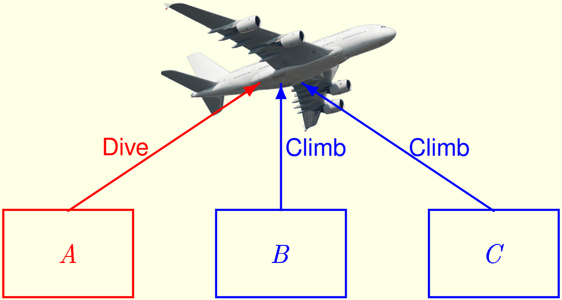

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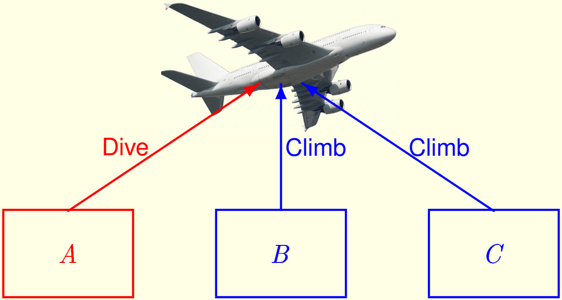

Majority voting done by actuators.

Control surface moved by three motors, any two of which can overpower the third.

One problem

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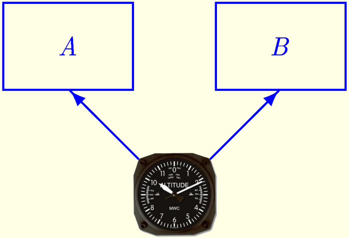
Good computers reading a sensor



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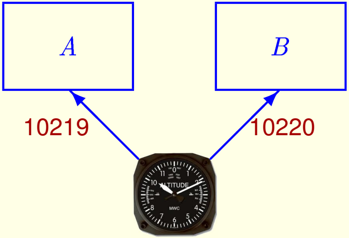

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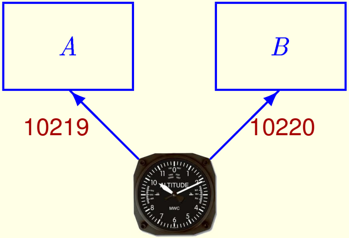

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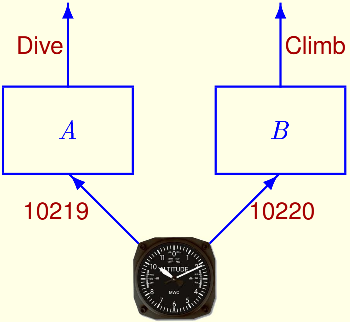
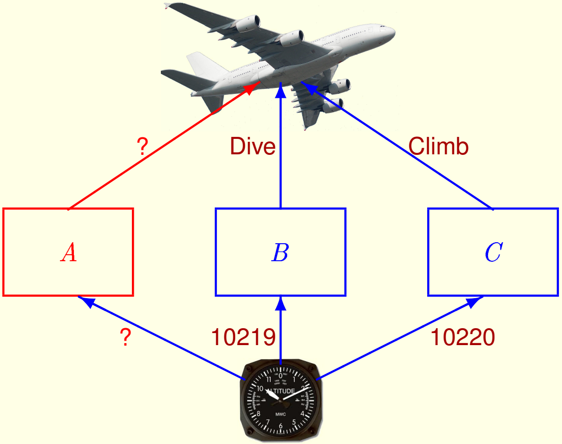


This can lead to very different decisions.

Leading to disaster.



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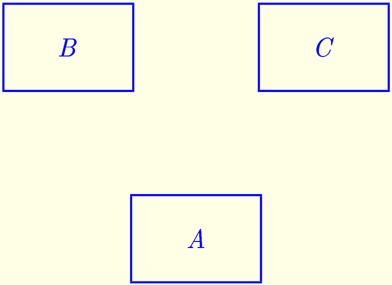

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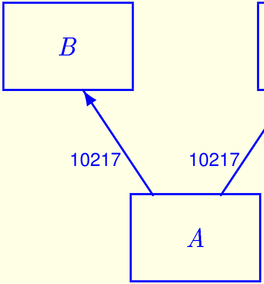

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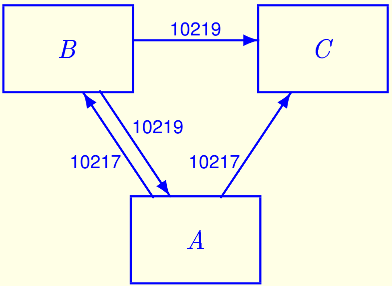

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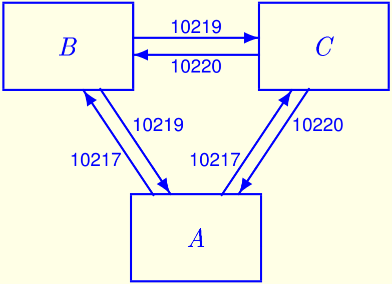

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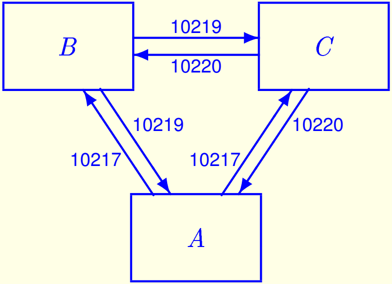

All computers get the same inputs: $\{$10217, 10219, 10220$\}$,
so they all make the same decision.

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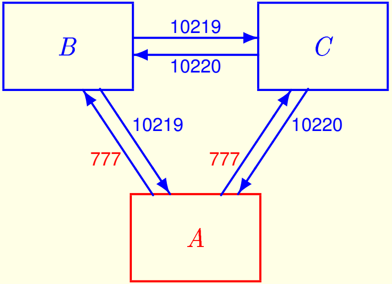

All computers get the same inputs: {777, 10219, 10220},
so the good ones all make the same decision.

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Someone at SRI (probably John Wensley) realized that TMR doesn't work.

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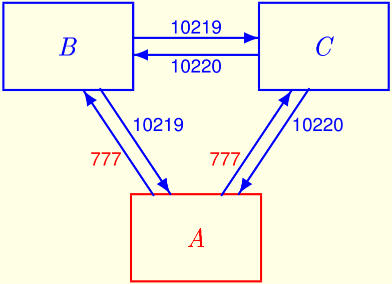

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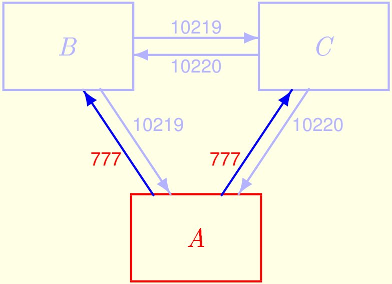

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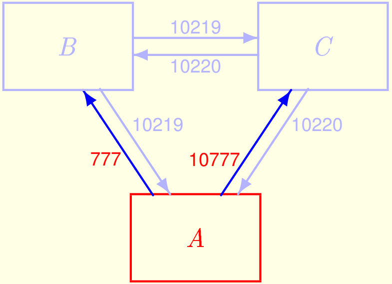

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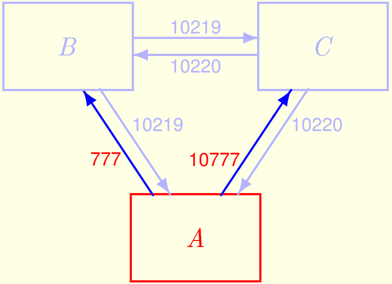

B gets $\{$777, 10219, 10220$\}$, decides Dive

C gets $\{$10777, 10219, 10220$\}$, decides Climb

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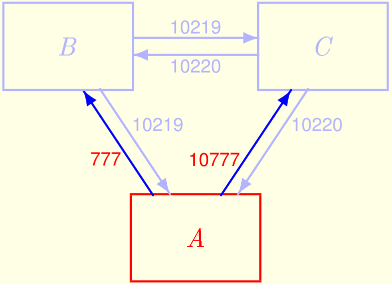

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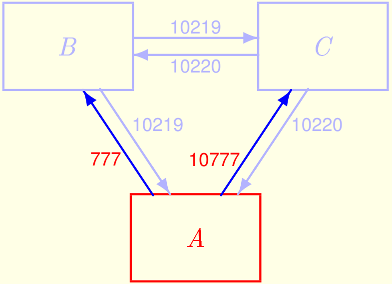

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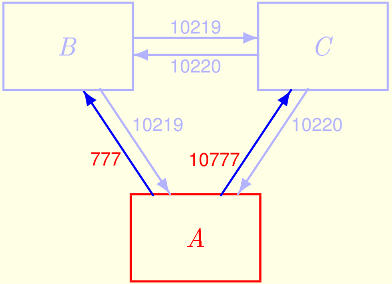

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Is the probability less than 10^{-10} per hour?

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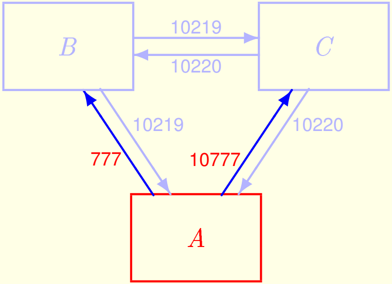

Is this highly improbable? Yes.

Is the probability less than 10^{-10} per hour? How can we tell?

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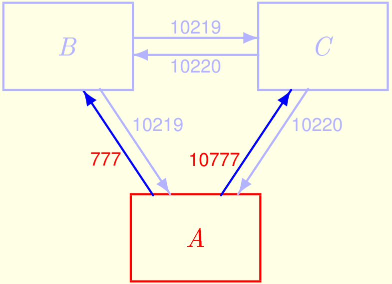

It's not hard to come up with plausible failure scenarios that produce this situation.

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2 follows from 1 if P is nonfaulty.

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Problem described with generals, some of whom may be traitors.

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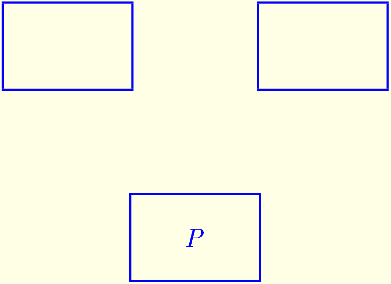

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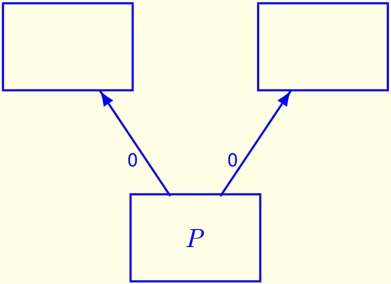

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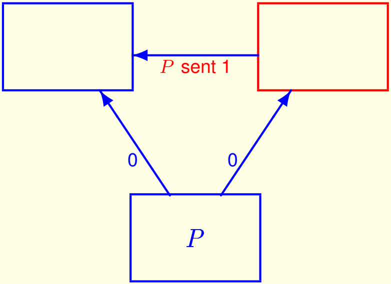

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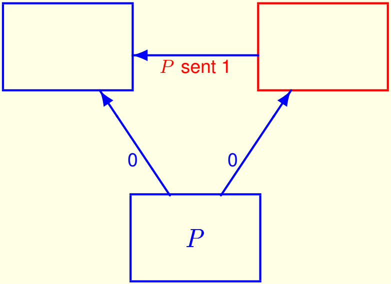

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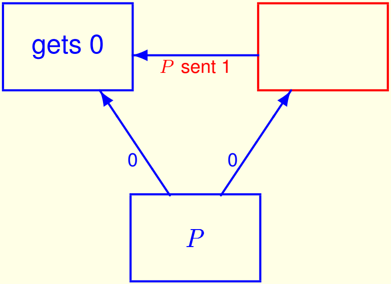

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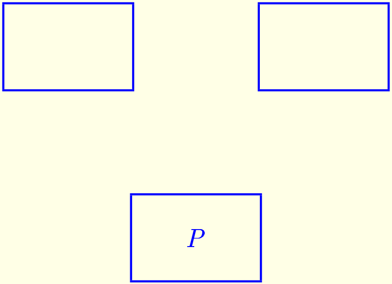

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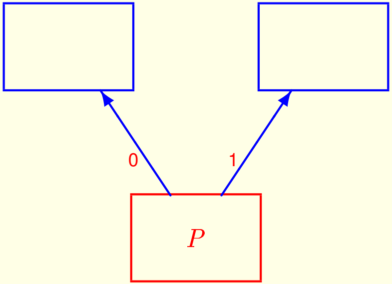

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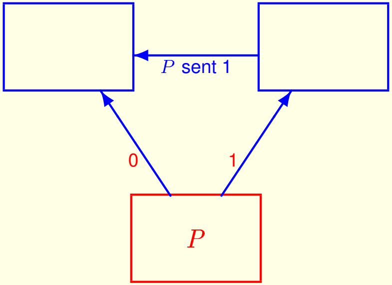

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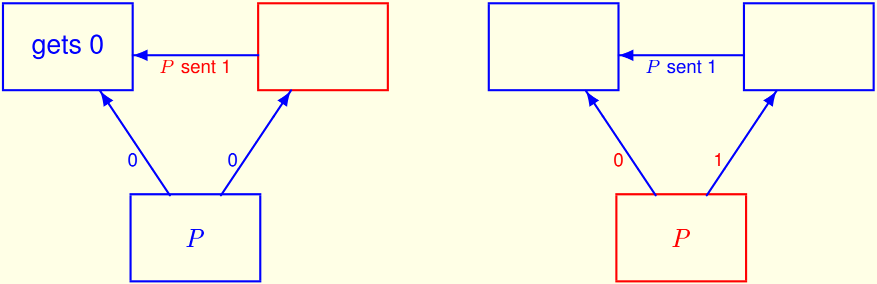

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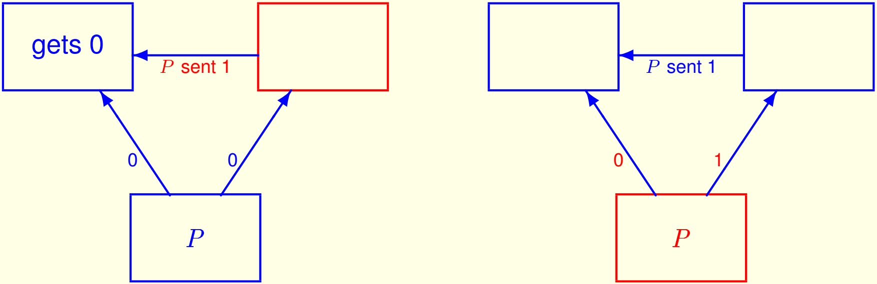

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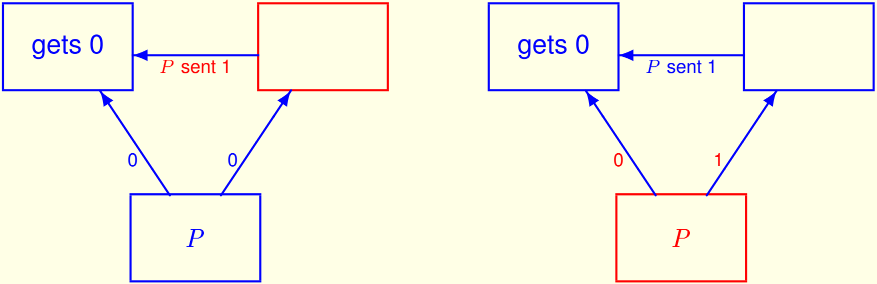

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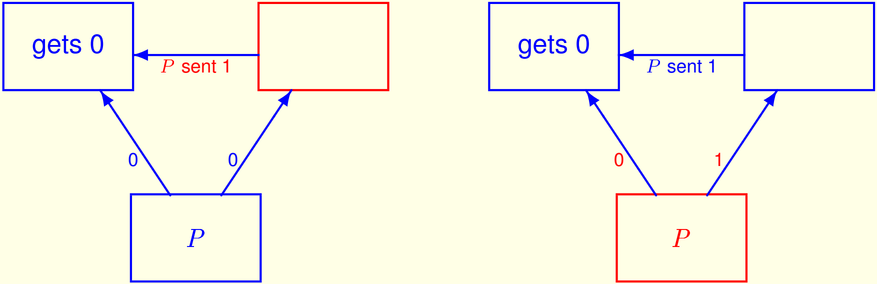
gets 0
P sent 1
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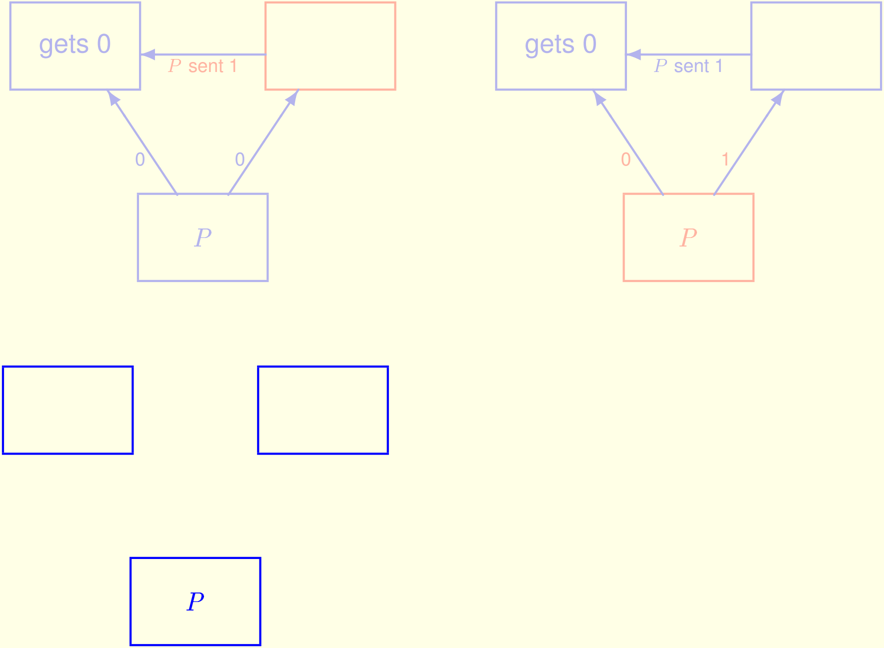
1
P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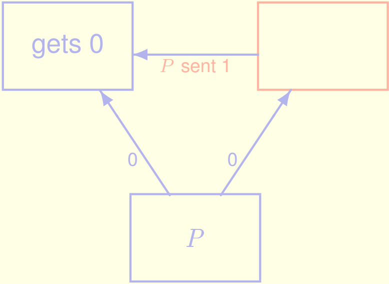
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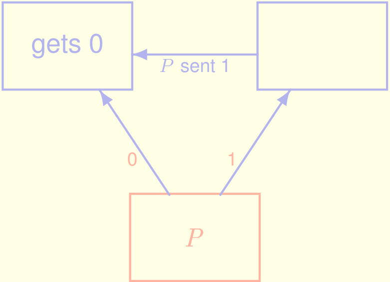
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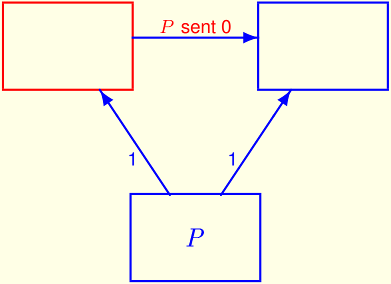
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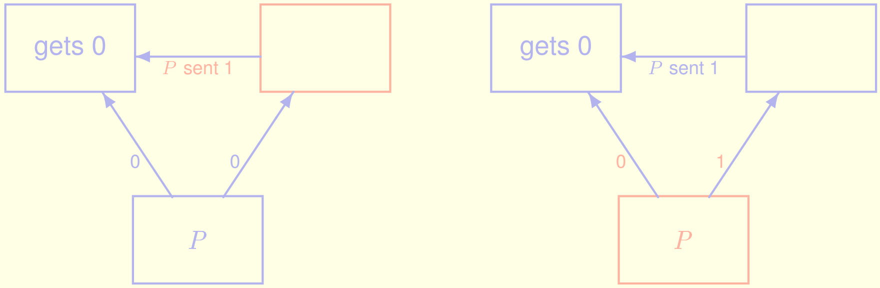

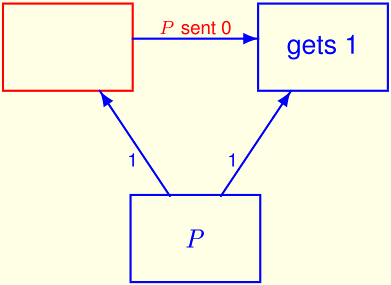

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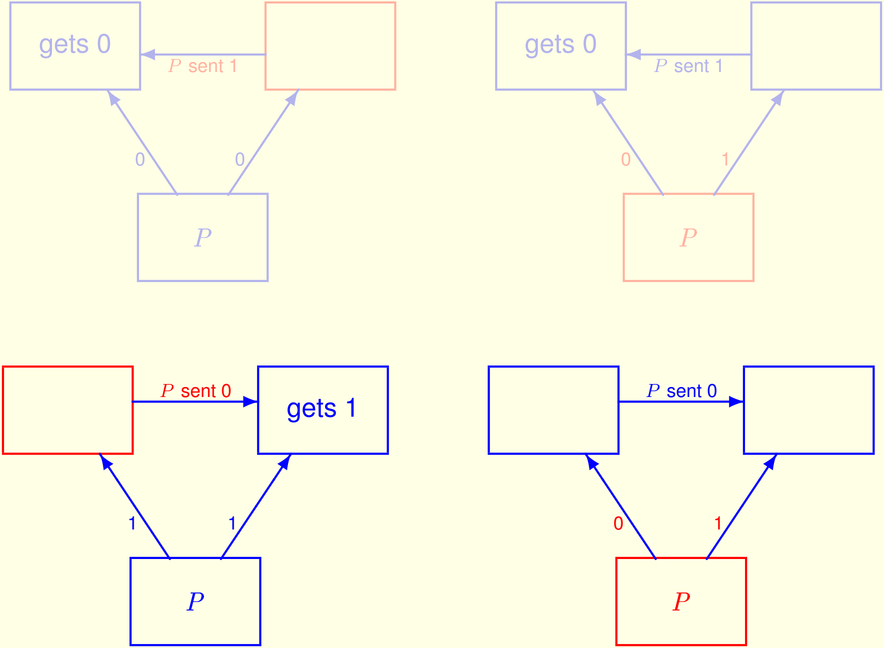
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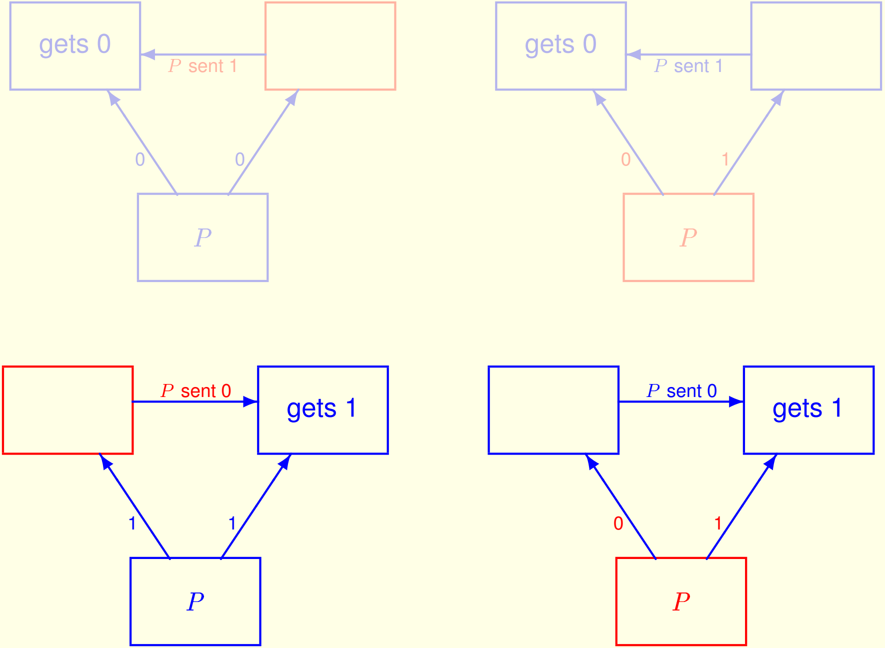
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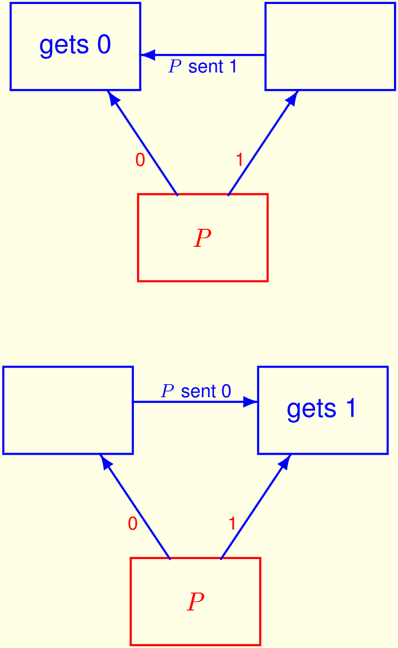
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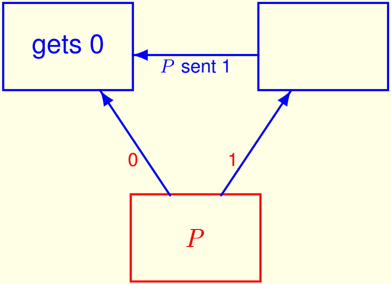
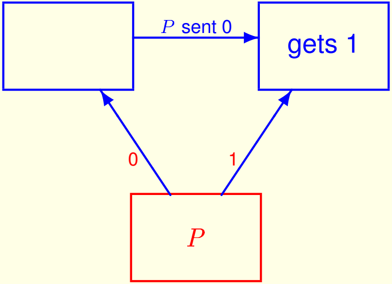
These are two views
of the same scenario.





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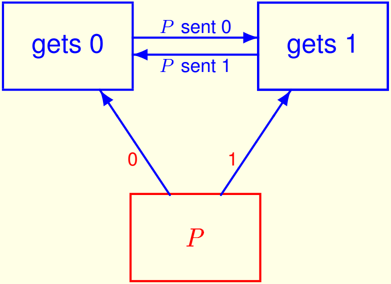
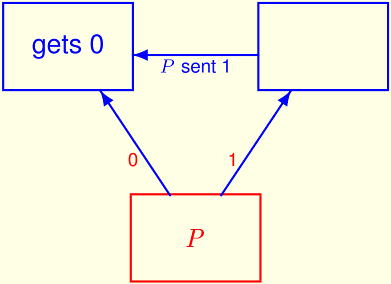
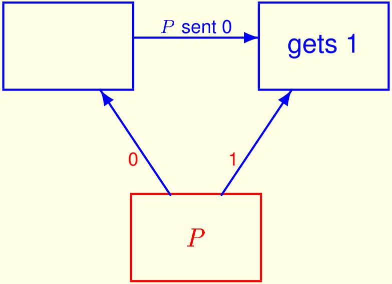
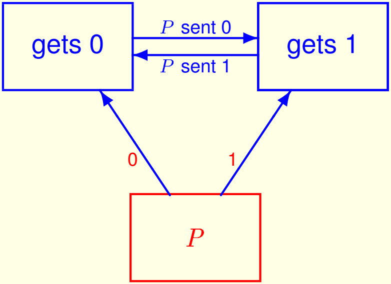




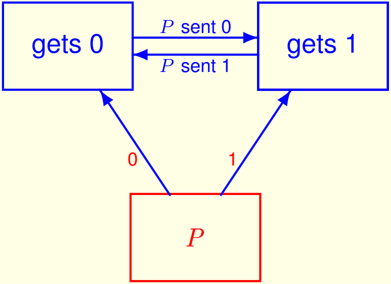


Condition 2 is violated.

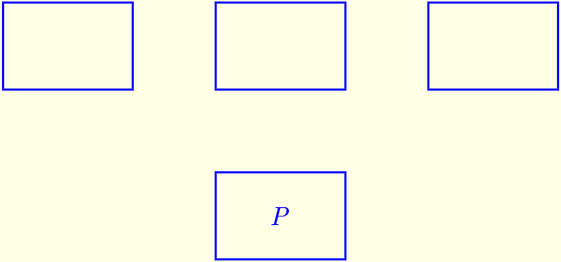


A rigorous version of this argument proves:

Theorem (Shostak) A solution to the Byzantine generals problem that tolerates one failure requires at least 4 computers.



A 4-computer solution



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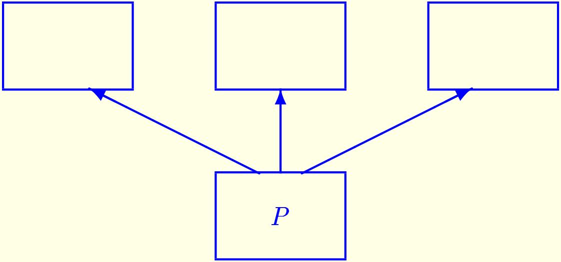

P sends its value to the other computers.

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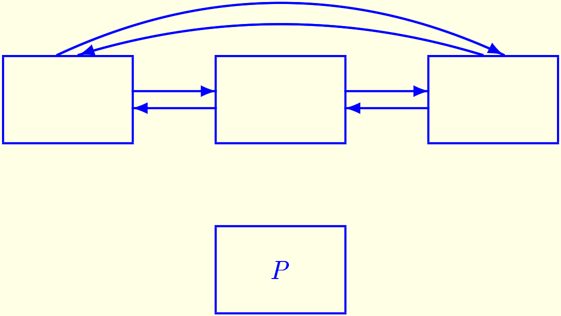
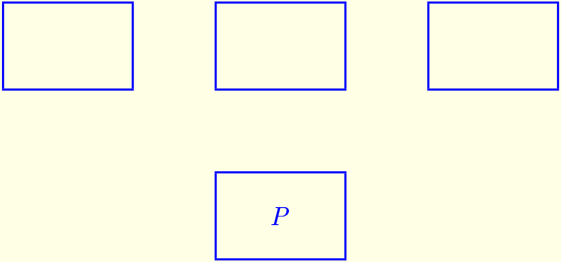


P sends its value to the other computers.

The other computers relay the value to one another.

A 4-computer solution



If P is nonfaulty, then each other computer receives at least 2 copies of P's value:

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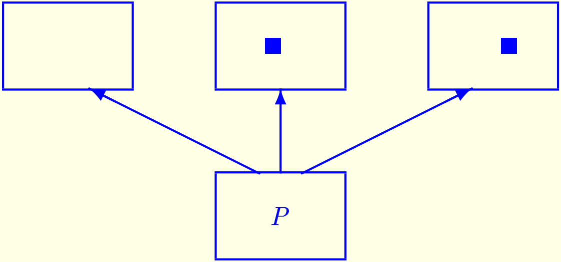

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It gets one directly from P.

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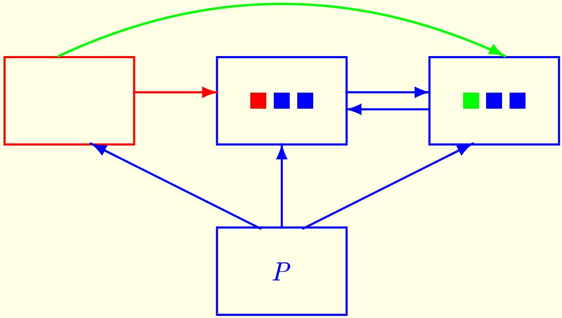
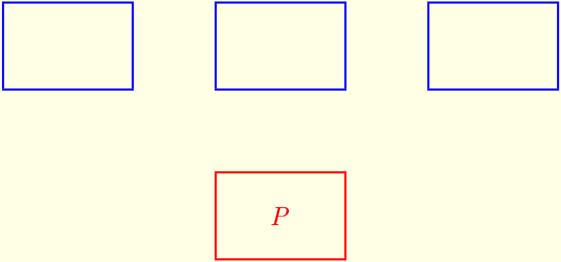


If P is nonfaulty, then each other computer receives at least 2 copies of P's value:

It gets one directly from P.

It gets one from another nonfaulty computer.

A 4-computer solution



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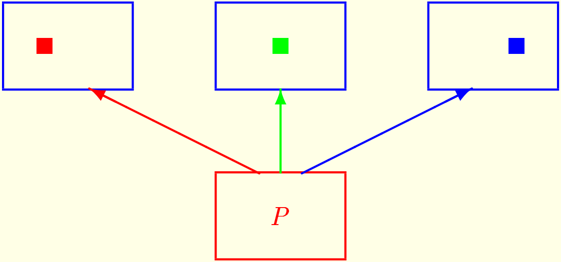

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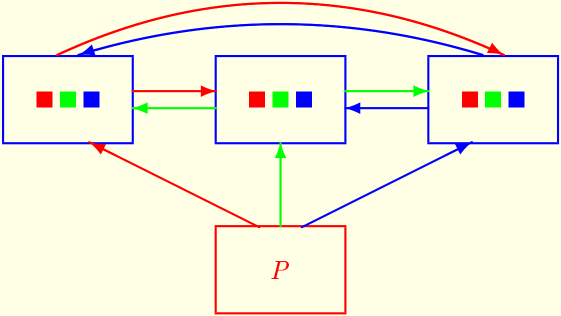

If P is faulty, then every other computer receives the same set of values.

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For each other computer:

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- P uses its own value.
- For each other computer:
  - If it receives 2 copies of a value, it takes that value.

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The Algorithm (Shostak)

P uses its own value.

For each other computer:

If it receives 2 copies of a value, it takes that value.

If P is nonfaulty, it sent the value.
If P is faulty, all others received those two values.

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- P uses its own value.
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  - If it receives 2 copies of a value, it takes that value.
  - Otherwise, it takes 42.

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- P uses its own value.
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  - If it receives 2 copies of a value, it takes that value.
  - Otherwise, it takes 42.
    - P must be faulty, so all others will choose 42.

The General Case

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This produces a solution that tolerates 1 failure with three computers, which is impossible.

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⋮

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There is a solution (due to Pease) that tolerates f failures with $3f + 1$ computers and takes $f + 1$ rounds.

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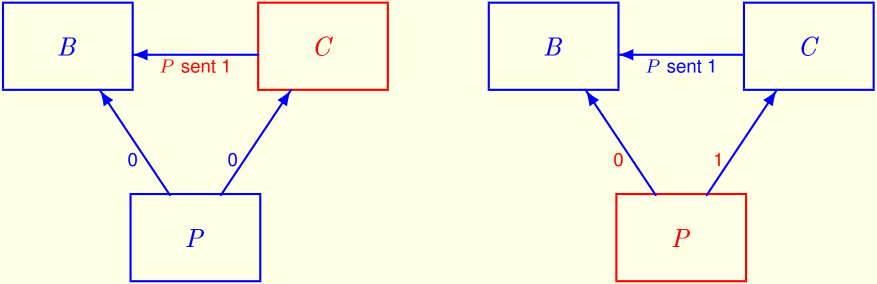
Can we get a solution with fewer computers that works with very high probability?

The problem: B can't distinguish these two cases.



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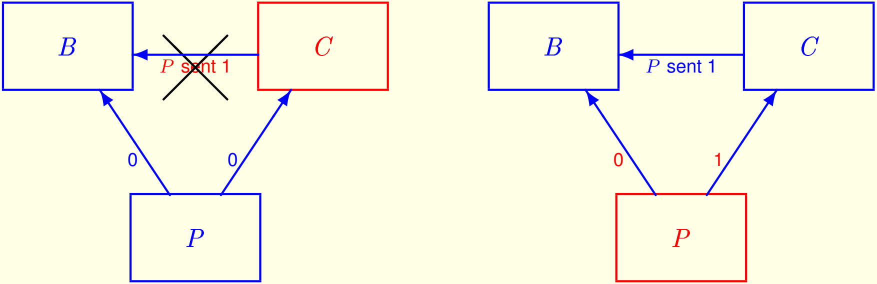

The solution: prevent C from pretending P sent a value it didn't.

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Easy to implement against forgery by failure.

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I don't know, but here's what I have heard.

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But engineers often think they can solve an unsolvable problem by reducing it to another unsolvable problem.

Part II

Designing Computer Systems To Run a Business

c. 1990

Why running a business is like flying an airplane

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Given a solution to this problem, building a reliable system to run a business is a straightforward engineering task.

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Can tolerate occasional delays of a few seconds (or a few minutes for some businesses).

The business will not crash if the system stops for 20ms.

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Messages are lost or late only if a computer fails.

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In a business, computers communicate asynchronously.

- Messages are delivered by complex software-controlled networks.
- Messages can be lost or take arbitrarily long to arrive.

Why designing a system to run a business is harder

In an airplane, computers can communicate synchronously.

In a business, computers communicate asynchronously.

FLP Theorem (Fischer, Lynch, and Paterson) No algorithm can ensure agreement among computers in an asynchronous system if a single computer can fail by stopping.

Overcoming FLP

Ensure that computers never disagree.

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Ensure that they get lucky, except for occasional short periods.

The system then never makes a mistake, and it keeps working except for occasional short periods of bad luck.

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A widely-used algorithm for reaching agreement in asynchronous computer systems.

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A unique, good leader is required only to reach a decision.

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Paxos uses $2f + 1$ computers and can choose a command if at most f of them fail.

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Here's what happens if we're lucky and L is the unique leader.

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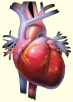

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When L learns that at least f other computers have voted for c, then it knows that c has been chosen and informs the other computers.

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If at most f computers have failed, that leader will start a ballot that completes and chooses a command.

Paxos will not fly an airplane

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The data center doing your cloud computing is probably using Paxos.

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The data center doing your cloud computing is probably using Paxos.

It’s certainly using Paxos if it’s run by Microsoft or Google.

Part III

Designing Computer Systems
To Run a Byzantine Business

the 2000s

The Problem

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Run a business with computers that may have Byzantine (malicious) failures.

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Why?

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Why? For now, because it's fun.

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The same basic problem: The computers must choose which one of a set of proposed commands to perform next.

The Solution

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Byzantine Paxos (Castro and Liskov) [they called it something else].

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This is optimal. (Bracha and Toueg)

Another Approach: Byzantizing Paxos

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The idea: Have $2f + 1$ good computers execute Paxos, while f malicious computers try to foil them.

A good computer doesn't know which of the other computers are malicious.

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Copies of the messages in S then prove those messages were sent, so they prove that Paxos allows sending M.

Paxos With Proofs

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L sends a *start ballot* message to the other computers.

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Allowed at any time, no proof needed.

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The other computers reply with information about any votes they've cast in other ballots.

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They send proofs that each of their votes was allowed by a leader's $vote\ for$ message.

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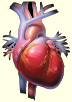
When L has heard from at least f other computers, either (a) it learns that a particular command c might already have been chosen, or else (b) it lets c be any proposed command.



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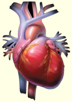

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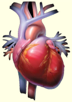

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L sends a proof for this message consisting of all the messages and their proofs it received from those $2f$ other computers.

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Paxos does not allow different computers to vote for different commands in the same ballot.

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Convenient to pretend computers send themselves messages.

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Every computer that receives $ok\ to\ vote\ for\ c$ messages from $2f+1$ computers votes for v and sends a message to all computers saying it has.

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A good computer will send only one $ok\ to\ vote\ for\ c$ message in any ballot; with $2f+1$ good computers, it's impossible for two good computers to vote for different commands.

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Because $f + 1$ are good computers executing Paxos, and a command is chosen in Paxos if $f + 1$ computers vote for it.

The Fine Print

This doesn’t quite work.

To make it work, we need to Byzantize a variant of the Paxos algorithm that differs slightly from the standard algorithm that I showed you.

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Castro-Liskov solution:

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– Select leader by rotating through computers in a fixed order.

– Use timeouts to switch to next leader if command not chosen.

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They can't run a business because they fail if messages are lost or delivered too late.

To run a business, only need to choose a command when lucky.

Let "being lucky" mean messages are *not* lost or delivered late.

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Byzantine Paxos tolerates a malicious leader.

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When system is lucky, the algorithm works, the virtual leader is good, and Byzantine Paxos chooses a command.

When system is unlucky, the virtual leader may do nothing or be malicious, but this cannot cause disagreement.

Eventually, the system will be lucky, the virtual leader will be good, and a command will be chosen.

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I can describe them at the end if you're interested.

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- How do you avoid choosing too many malicious users' computers?
- Is random choice from a large number of mostly non-malicious users good enough?

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Algorithms to do it may lead to new techniques for tolerating faults

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Algorithms to do it may lead to new techniques for tolerating faults and foiling hackers.

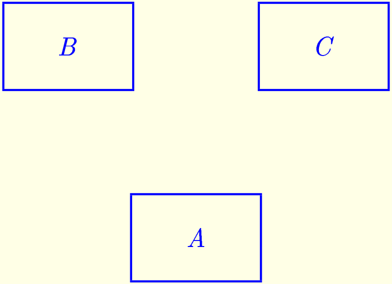
Thank you.

Addendum

Two Methods of Eliminating Digital Signatures

Method 1 (Castro and Liskov)

How digital signatures are used.



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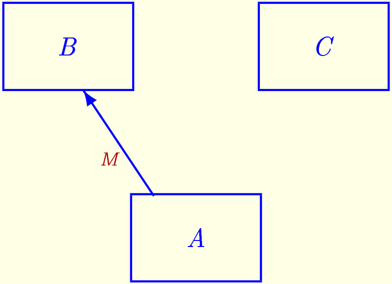

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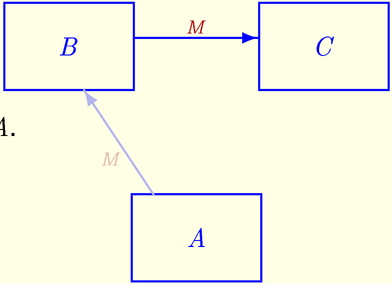

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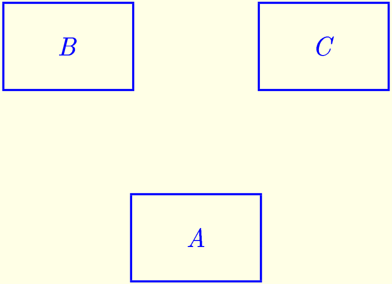

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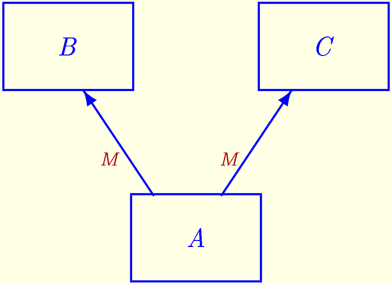
Message M unsigned.



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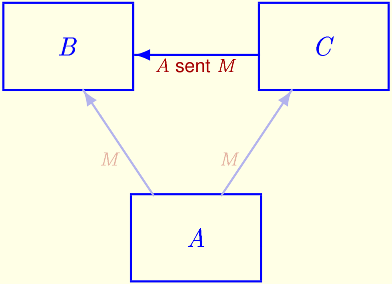

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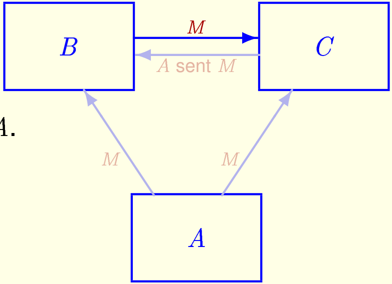

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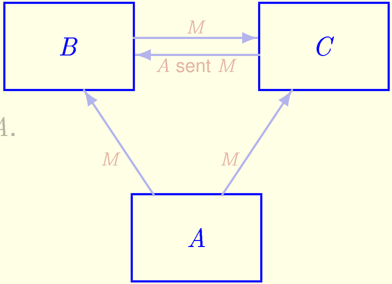
Assumes a computer knows the immediate sender of a message.



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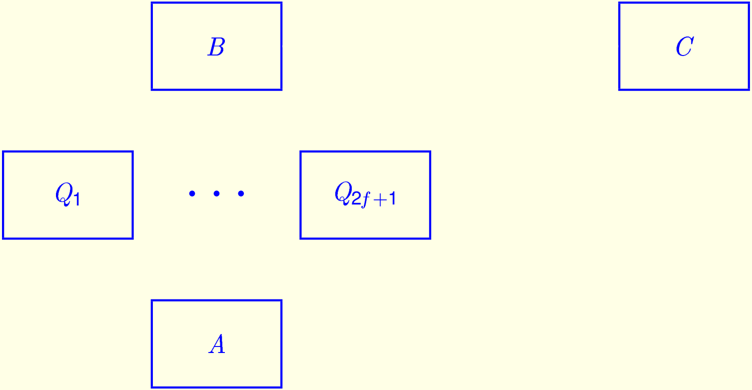
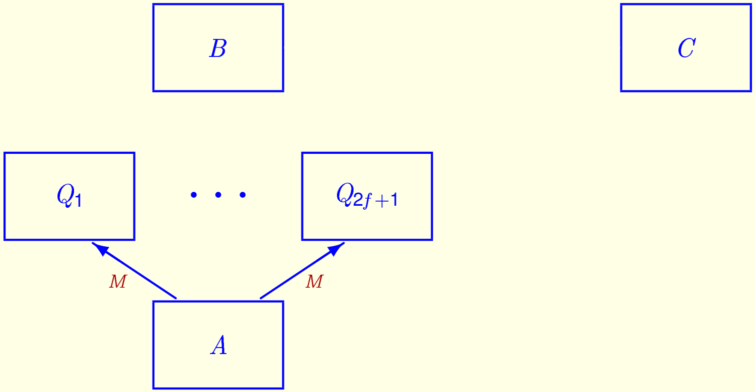
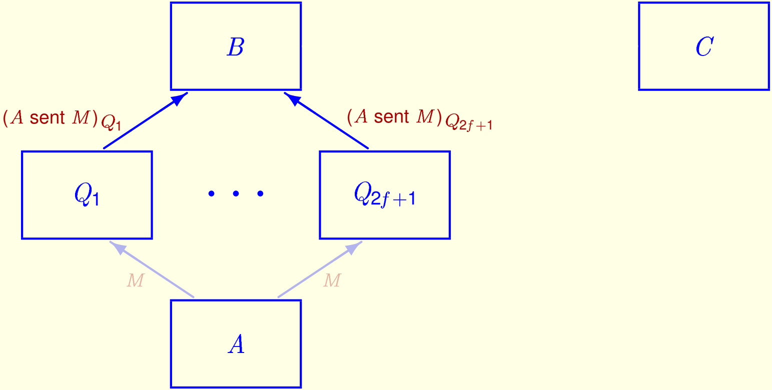
M_A is not as good as a digitally signed message M.

It proves to B that A sent M, but B doesn't know if it proves that to C because A could be malicious and the M_{AC} entry in the vector could be garbage.

But vectors of authenticators are good enough.


B
C
Q_1
$\cdots$
Q_{2f+1}
A


B
C
Q1
. . .
Q2f+1
M
M
A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. . .
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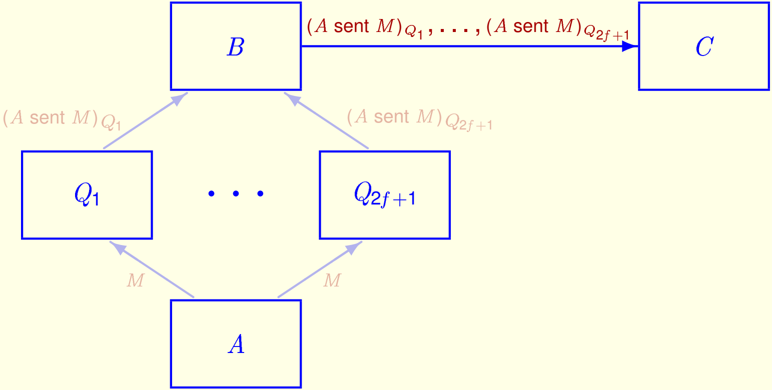
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$\cdots$
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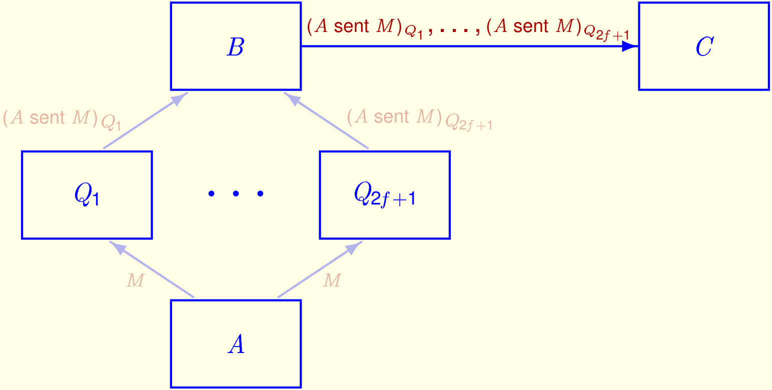
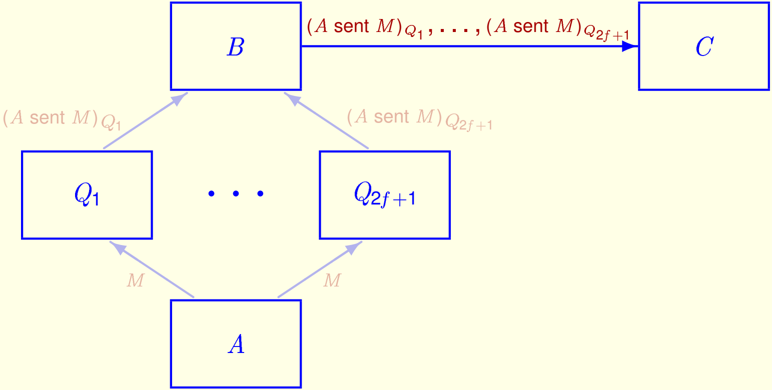
M
A

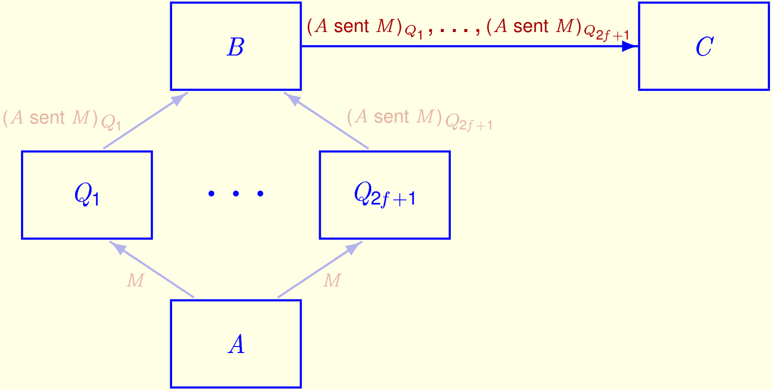


B knows C will know M sent by A



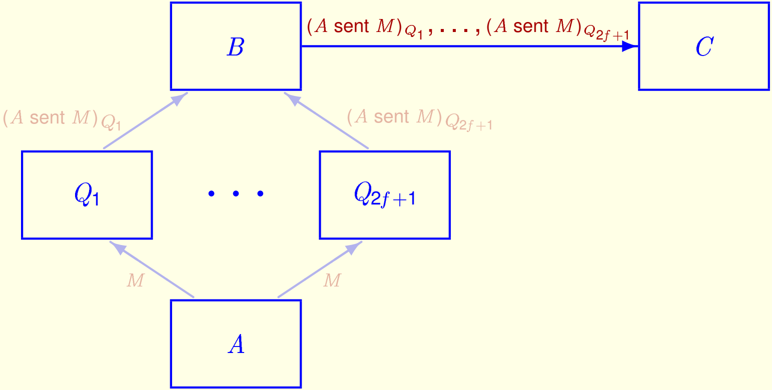
B knows C will know M sent by A

Because at most f of the Q_i are malicious



B knows C will know M sent by A

Because at most f of the Q_i are malicious, so C will receive properly authenticated messages from $f + 1$ computers saying A sent M



B knows C will know M sent by A

Because at most f of the Q_i are malicious, so C will receive properly authenticated messages from $f + 1$ computers saying A sent M, and C knows that at least one of those computers must be good.