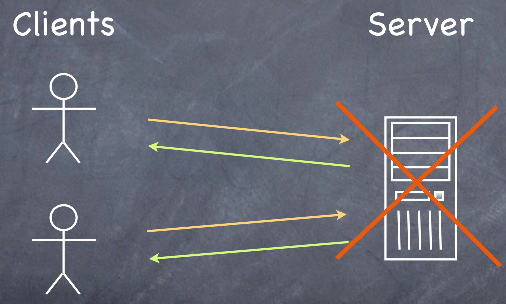
State-Machine Replication

The Problem



Solution: replicate server!

The Solution

1. Make server deterministic (state machine)

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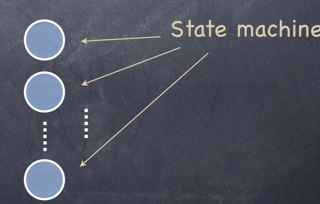
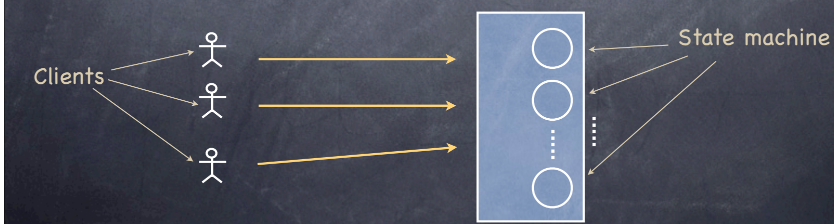


The Solution

1. Make server deterministic (state machine)
2. Replicate server
3. Ensure correct replicas step through the same sequence of state transitions



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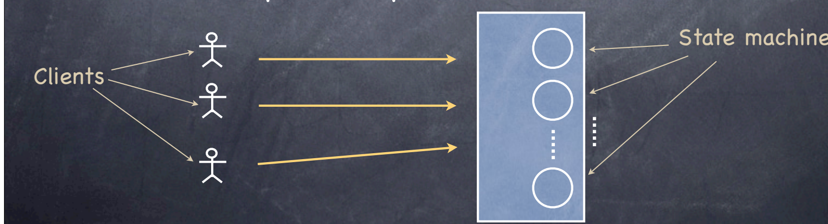

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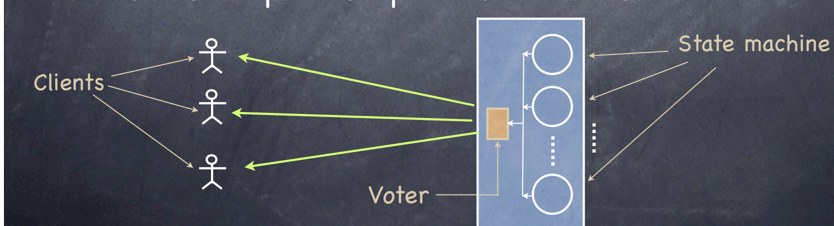
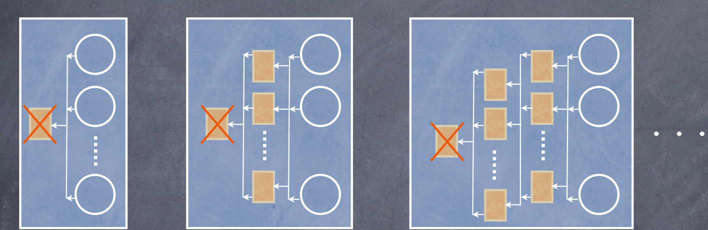
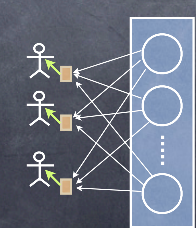


A conundrum



A: voter and client share fate!



Consensus and Reliable Broadcast

Broadcast

- If a process sends a message m, then every process eventually delivers m

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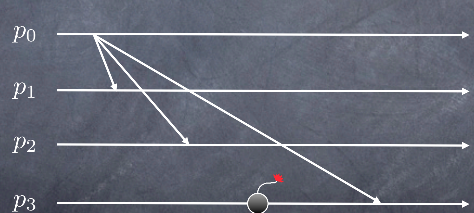

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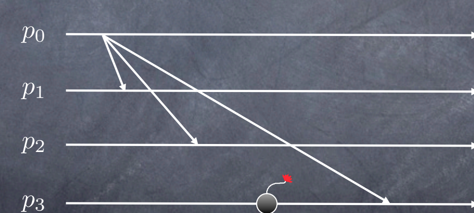

- How can we adapt the spec for an environment where processes can fail?

Reliable Broadcast

Validity If the sender is correct and broadcasts a message m, then all correct processes eventually deliver m

Agreement If a correct process delivers a message m, then all correct processes eventually deliver m

Integrity Every correct process delivers at most one message, and if it delivers m, then some process must have broadcast m

Terminating Reliable Broadcast

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Consensus

Termination Every correct process eventually decides some value

Validity If all processes that propose a value propose v, then all correct processes eventually decide v

Agreement If a correct process decides v, then all correct processes eventually decide v

Integrity Every correct process decides at most one value, and if it decides $v \neq$ NU, then some process must have proposed v

Properties of send(m) and receive(m)

Benign failures:

Validity If p sends m to q, and p, q, and the link between them are correct, then q eventually receives m

Uniform* Integrity For any message m, q receives m at most once from p, and only if p sent m to q

* A property is uniform if it applies to both correct and faulty processes

Properties of send(m) and receive(m)

Arbitrary failures:

Integrity For any message m, if p and q are correct then q receives m at most once from p, and only if p sent m to q

Questions, Questions...

- Are these problems solvable at all?
- Can they be solved independent of the failure model?
- Does solvability depend on the ratio between faulty and correct processes?
- Does solvability depend on assumptions about the reliability of the network?
- Are the problems solvable in both synchronous and asynchronous systems?
- If a solution exists, how expensive is it?

Plan

- Synchronous Systems
  - Consensus for synchronous systems with crash failures
  - Lower bound on the number of rounds
  - Early stopping protocols for Reliable Broadcast
  - Reliable Broadcast for arbitrary failures with message authentication
  - Lower bound on the ratio of faulty processes for Consensus with arbitrary failures
  - Reliable Broadcast for arbitrary failures
- Asynchronous Systems
  - Impossibility of Consensus for crash failures

Model

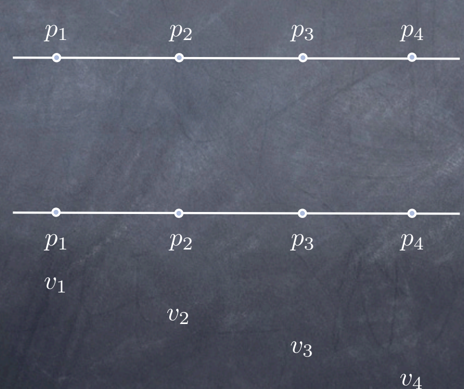
- Synchronous Message Passing
  - Execution is a sequence of rounds
  - In each round every process takes a step
    - sends messages to neighbors
    - receives messages sent in that round
    - changes its state
- Network is fully connected (an n-clique)
- No communication failures

A simple Consensus algorithm

Process p_i:

```
Initially V={v_i}
To execute propose(v_i)
    send {v_i} to all
decide(x) occurs as follows:
    for all j, 0 ≤ j ≤ n-1, j ≠ i do
      receive S_j from p_j
      V:= V U S_j
    decide min(V)
```

An execution



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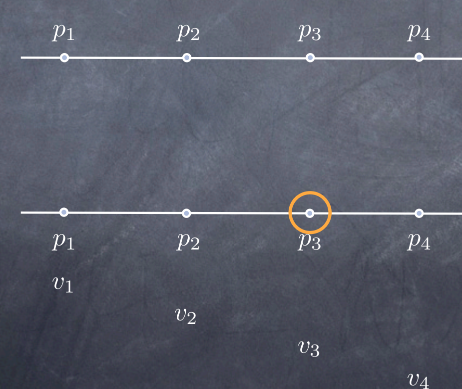
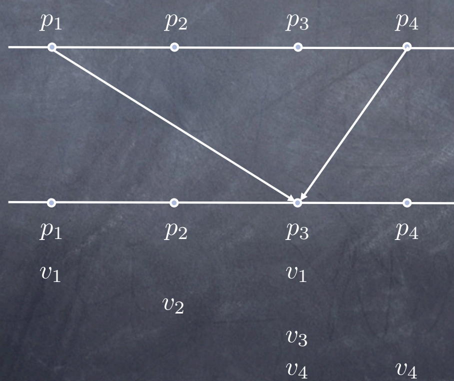


An execution

Suppose $v_1 = v_3 = v_4$ at the end of round 1
Can p_3 decide?



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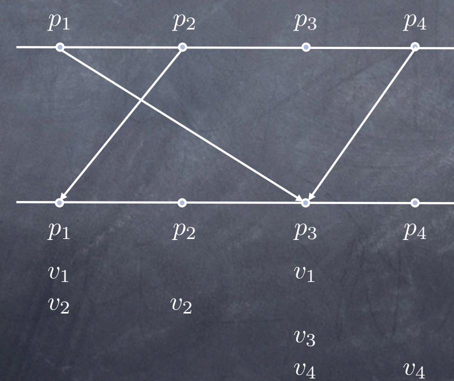

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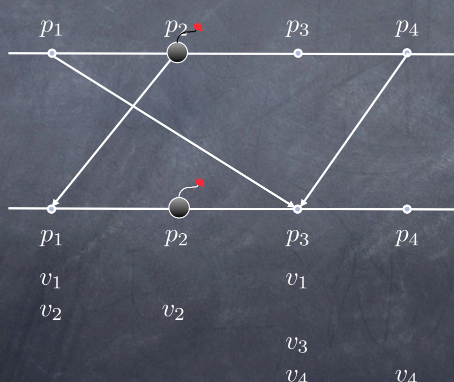

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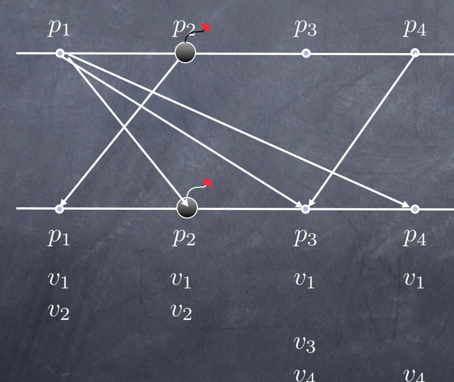

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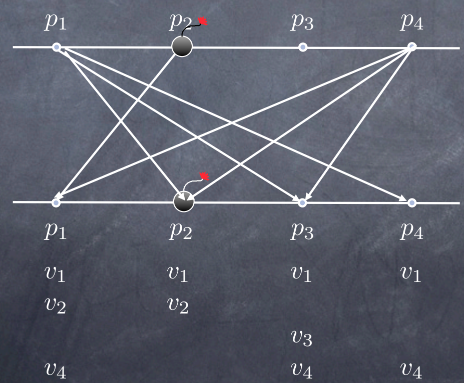

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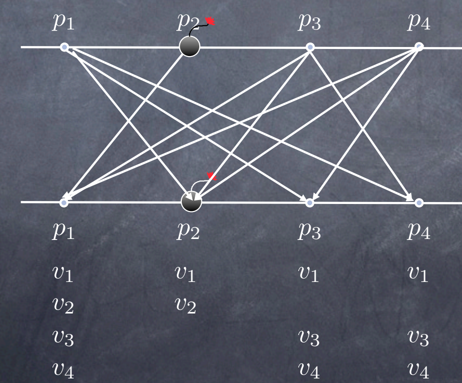

Echoing values

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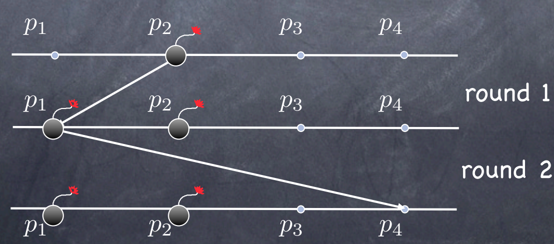


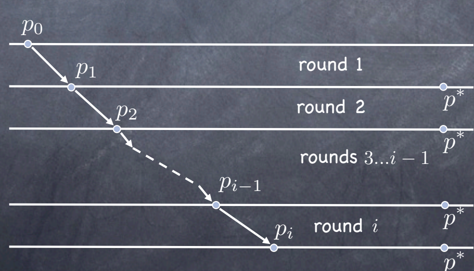
What is going on

- A correct process p^* has not received all proposals by the end of round i. Can p^* decide?
- Another process may have received the missing proposal at the end of round i and be ready to relay it in round $i+1$

Dangerous Chains

Dangerous chain

The last process in the chain is correct, all others are faulty



Living dangerously

How many rounds can a dangerous chain span?

- f faulty processes
- at most $f+1$ nodes in the chain
- spans at most f rounds

It is safe to decide by the end of round $f+1$!