Fault Tolerance and Resilience, Raft, Cyber 3

14 June 2026
Lecture 13

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Topics for Today

- Failures and Resilience
- Raft and Consensus
- Cyber 3: Consensus and Failure

- Source: TvS 8

Dependability

- A component provides services to clients. To provide services, the component may require the services from other components → a component may depend on some other component.
- A component C depends on C^* if the correctness of C's behavior depends on the correctness of C^* 's behavior.
- Note: in the context of distributed systems, components are generally processes or channels.

Availability	Readiness for usage
Reliability	Continuity of service delivery
Safety	Very low probability of catastrophes
Maintainability	How easily can a failed system be repaired

Reliability versus Availability

- Reliability $R(t)$: probability that a component has been up and running continuously in the time interval $[0, t)$:

- Traditional metrics:

Mean Time to Failure $(MTTF)$: Average time until a component fails

Mean Time to Repair $(MTTR)$: Average time it takes to repair a failed component.

Mean Time Between Failures $(MTBF)$: $MTTF + MTTR$

Reliability versus Availability

Availability $A(t)$: Average fraction of time that a component has been up and running in the interval $[0, t)$:

- (Long term) availability A: $A(\infty)$

Note:

$$A = \frac{MTTF}{MTBF} = \frac{MTTF}{MTTF + MTTR}$$

Observation

Reliability and availability make sense only if we have an accurate notion of what a failure is

Terminology

Term	Description	Example
Failure	May occur when a component is not living up to its specification	A crashed program
Error	Part of a component that may lead to a failure	A programming bug
Fault	The cause of an error	A sloppy programmer

Handling Faults

Term	Description	Example
Fault Prevention	Prevent the occurrence of a fault	Don't hire sloppy programmers
Fault Tolerance	Build a component such that it can mask the occurrence of a fault	Build each component by two independent programmers
Fault Removal	Reduce the presence, number, or seriousness of a fault	Get rid of sloppy programmers
Fault Forecasting	Estimate current presence, future incidence, and consequences of bugs	Estimate how a recruiter is doing when it comes to hiring sloppy programmers

Handling Faults

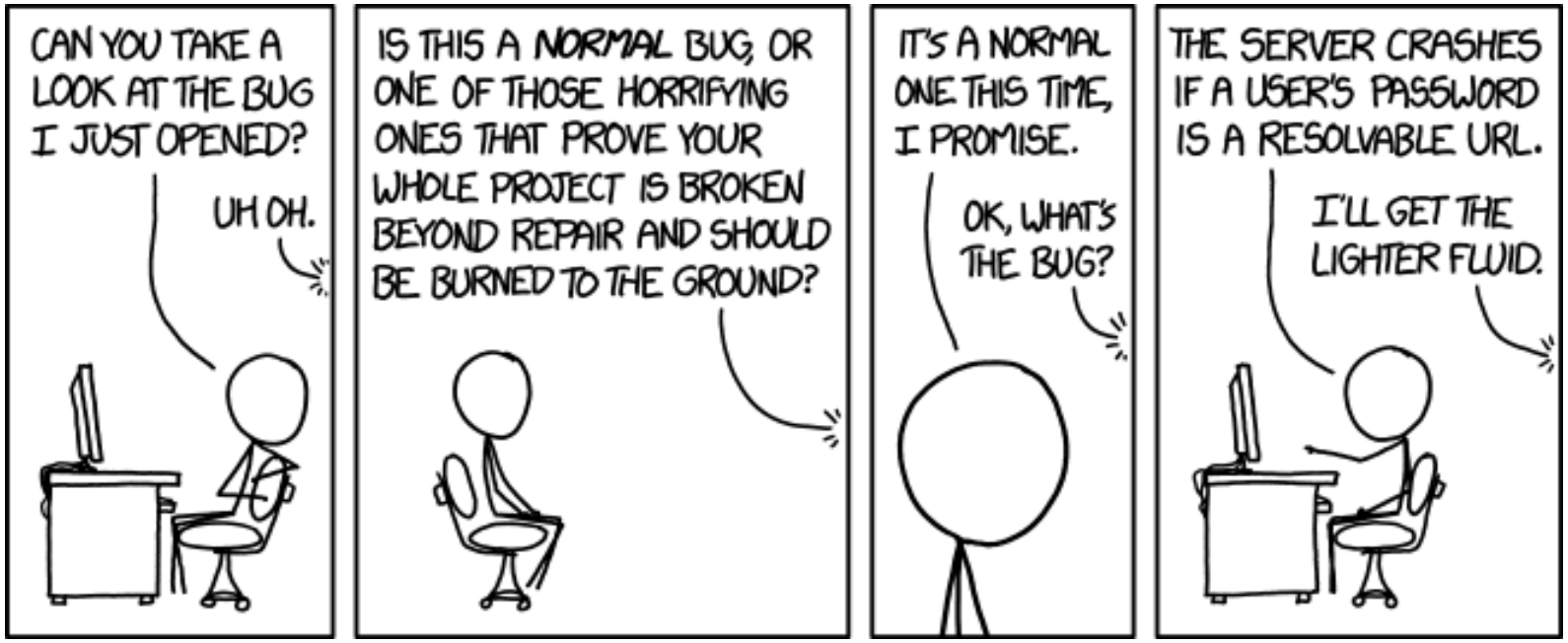


Image: https://xkcd.com/1700/

Failure models

Crash failures:

- Halt, but correct behavior until halting

General omission failures:

- Failure in sending or receiving messages
- Receiving omissions: Sent messages are not received
- Send omissions: Messages are not sent that should have

Timing failures:

- Correct output but provided outside a specified time interval.

Failure models

Response failures:

- Response is incorrect
- Value failures: Wong output values
- State transition failures: Deviation from correct flow of control

Arbitrary failures:

- May produce arbitrary responses at arbitrary times

Dependability versus Security

- Omission failure: A component fails to take an action that it should have taken
- Commission failure: A component takes an action that it should not have taken

Observations

Deliberate failures, be they omission or commission failures, stretch out to the field of security

There is a thin line between dependability and security

Halting Failures

Scenario: C no longer perceives any activity from C^* → a halting failure? Distinguishing between a crash or omission/timing failure may be impossible:

Asynchronous system

- No assumptions about process execution speeds or message delivery times
- → cannot reliably detect crash failures.

Synchronous system

- Process execution speeds and message delivery times are bounded
- → we can reliably detect omission and timing failures.

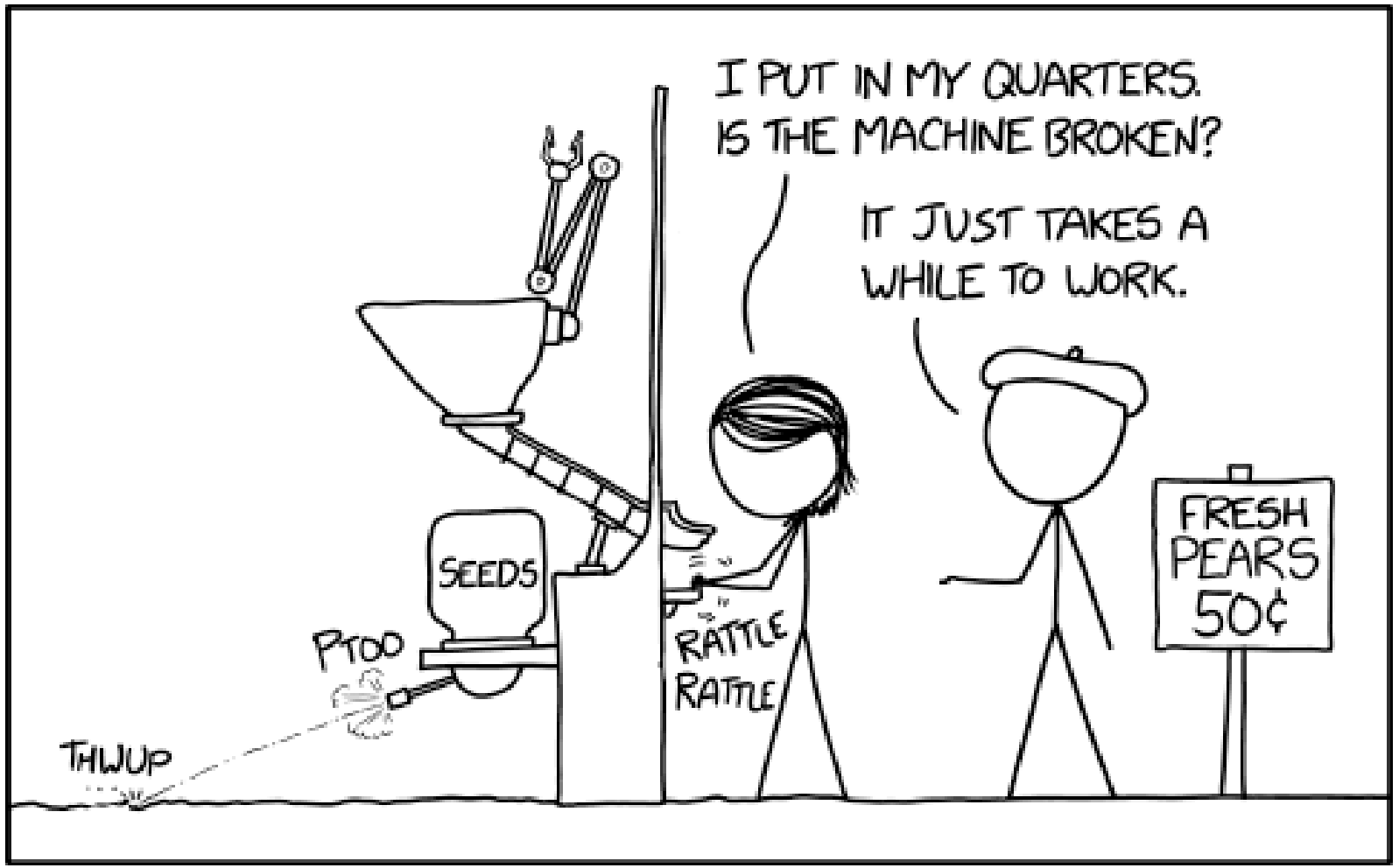
Halting Failures

Scenario: C no longer perceives any activity from C^* → a halting failure? Distinguishing between a crash or omission/timing failure may be impossible:

Partially synchronous systems

- Most of the time, we can assume the system to be synchronous
- Yet there is no bound on the time that a system is asynchronous
- → can normally reliably detect crash failures

https://xkcd.com/2209/



Halting Failures Assumptions

Fail-stop: Crash failures, but reliably detectable

Fail-noisy: Crash failures, eventually reliably detectable

Fail-silent: Omission or crash failures: clients cannot tell what went wrong.

Fail-safe: Arbitrary, yet benign failures (can't do any harm).

Fail-arbitrary: Arbitrary, with malicious failures

Ways to Mask Failure

Information redundancy

- Add extra bits to data units so that errors can recovered when bits are garbled.

Time redundancy

- Design a system so actions can be performed again if something is wrong.
- Used when faults are transient or intermittent.

Physical redundancy

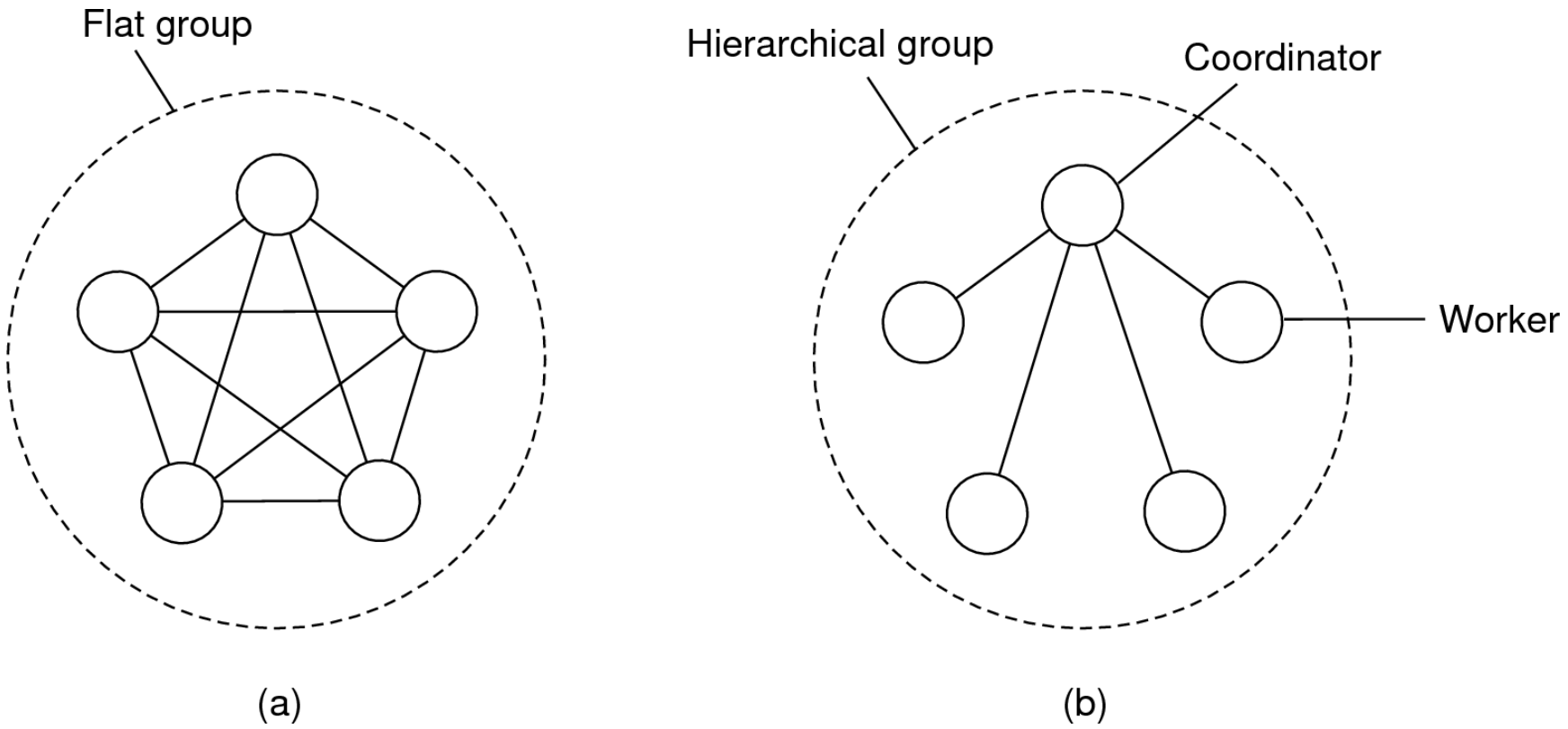
- Add equipment or processes to allow failure of one or more components
- Extensively used in distributed systems.

So Far

- Failures and Resilience
- Raft and Consensus
- Cyber 3: Consensus and Failure

Process Resilience

Basic idea: protect yourself against faulty processes through process replication:



Groups and Failure Masking

k-Fault-tolerant group

- When a group can mask any k concurrent member failures
- k is degree of fault tolerance

Group size

Halting failures:

- $k + 1$ members: no member will produce an incorrect result, so one good member suffices

Arbitrary failures

- $2k + 1$ members: Correct result can be obtained only through a majority vote.

Groups and Failure Masking

- Important:
  - All members are identical
  - All members process commands in the same order

- Result:
  - Only then do we know that all processes are programmed to do exactly the same thing

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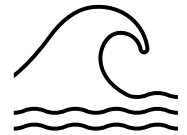
Observation

The processes need to have consensus on which command to execute next

Flood-based Consensus



System Model

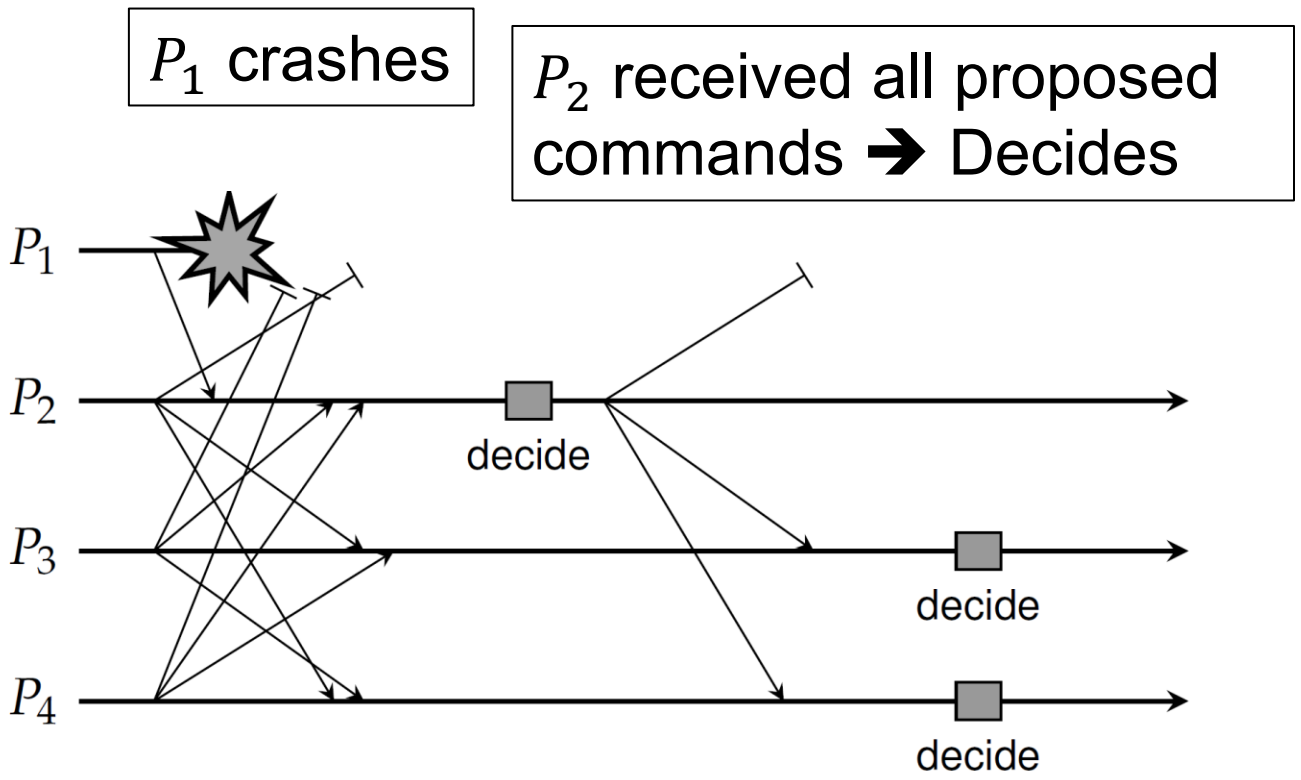
- Process group $P = \{P_1, P_2, \ldots, P_n\}$
- Fail-stop semantics
- Reliable failure detection

- Client contacts P_i requesting it to execute a command
- Every P_i maintains a list of proposed commands

Basic idea (Rounds)

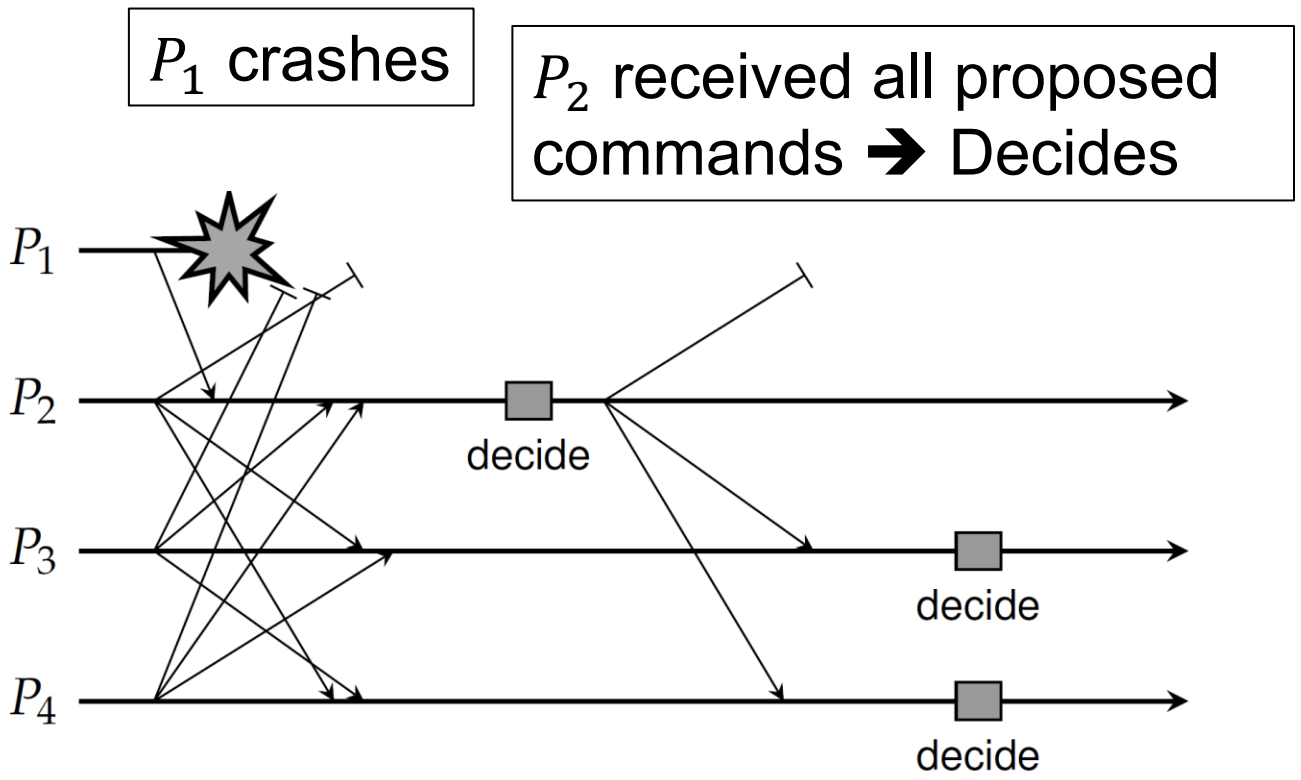
- Round r, P_i multicasts its known set of commands C_i^r to all others
- At the end of r, each P_i merges all received commands into new C_i^{r+1}
- Next command cmd_i selected through globally shared deterministic function $cmd_i \leftarrow select(C_i^{r+1})$

Flood-based Consensus



- P_3 may detect P_1 crashed, but does not know if P_2 received anything
- P_3 cannot know if it has same information as P_2 → cannot make decision

Flood-based Consensus



- P_3 and P_4 can't decide yet – they know P_1 crashed
- P_2 tells the others what it decided
- P_3 and P_4 then follows P_2's choice

Raft

Image source and © https://raft.github.io/

- Developed for understandability

Straightforward leader-election algorithm

- Current leader operates during the current term.

Log

- Every server (5) keeps a log of operations, some of which have been committed.
- Backup will not vote for a new leader if its own log is more up to date.

All committed operations have the same position in the log of every server.

Leader decides which pending operation is to be committed next

- ⇒ a primary-backup approach.

Leader election in Raft

Image source and © https://raft.github.io/

Relatively small group of servers

States

- Follower
- Candidate
- Leader

Each server starts in the follower state.

Protocol works in terms, starting with term 0

A leader regularly broadcasts messages

- Updates or
- A simple heartbeat

Selecting a new Leader

Image source and © https://raft.github.io/

Follower **A** hasn't received anything from leader **L** for some time

A broadcasts that it volunteers to be the next leader, increasing the term by 1.

A enters the candidate state.

Selecting a new Leader 1

Image source and © https://raft.github.io/

Leader **L** receives the election message

Responds by acknowledging that it is still the leader.

A returns to the follower state.

End

Selecting a new Leader 2

Image source and © https://raft.github.io/

Another follower **B** gets the election message from **A**

B hasn't heard other candidates in the current round

B votes for **A**.

A collects a majority of votes

A is leader of new term

End

Things could go wrong

Image source and © https://raft.github.io/

Multiple Candidates, no Majority

- Two candidates started
  - Both received 2 votes
- Election times out, try again

- Solution: Slightly differ the timeout values per follower for deciding when to start an election
- Avoids concurrent elections

Network Partition

- Network divided into parts
- Part with majority elects leader
- Part with minority doesn't elect leader

- Solution: Minority part doesn't commit anything
- When network heals, minority part re-syncs

Things could go wrong

Image source and © https://raft.github.io/

Bad Candidate

- Candidate has less up to date log than recipient
- Might lead to leader who is ignorant

- Solution: Node will not vote for candidate who is less up to date
- Eventually most up to date node will candidate

Animation Project

- http://thesecretlivesofdata.com/raft/

Submitting an operation

Image source and © https://raft.github.io/

Client submits a request for operation *o*.

Leader appends the request $\langle o, t, k \rangle$ to its own log

Current term *t*

k location in leader's log

Log is (conceptually) broadcast to the other servers.

Others (conceptually) copy the log

Acknowledge receipt.

When majority of acks arrive

Leader commits *o*

Leader responds to client

Log replication in practice

Image source and © https://raft.github.io/

- Only updates are really broadcast
- At the end, every server has the same view and knows about the *c* committed operations.
- Effectively, any information at the backups is overwritten.

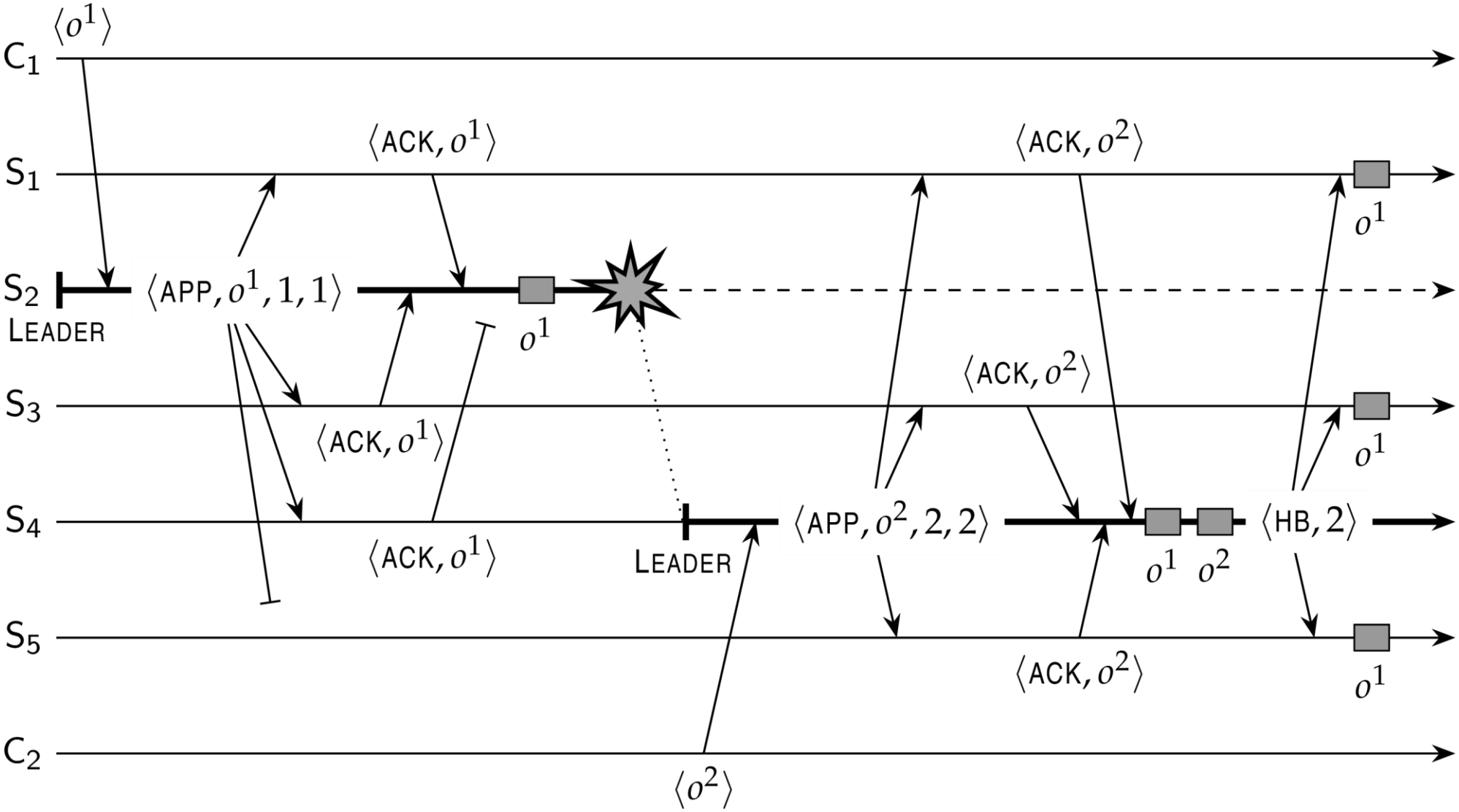
- If a follower doesn't ack an operation, leader will keep sending until it does

- Follower has pending operations list that can be overwritten if a new leader takes over

- If a new leader has a larger term or more operations in log, followed makes its log adapt

Raft Crashing

Image source and © https://raft.github.io/



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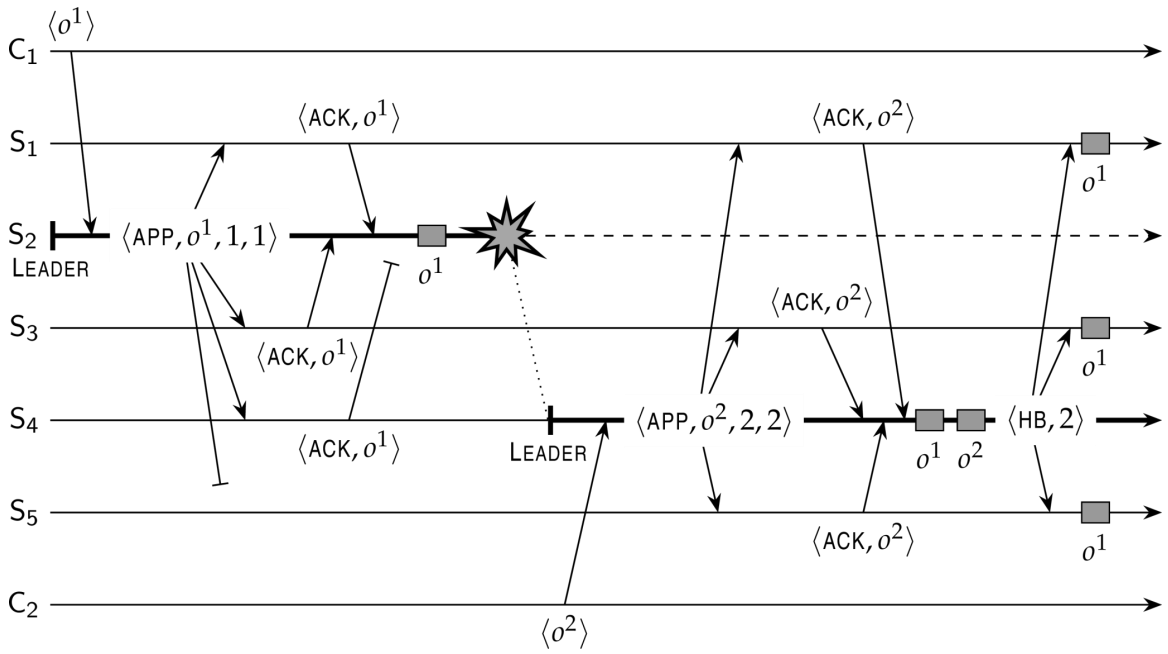

1. Client C_1 sends an operation o_1 to the leader (S_2)
2. S_2 records o_1 as index 1 term 1
3. S_2 sends Append (APP) messages to others $\langle APP, o_1, 1,1 \rangle$
4. Majority acknowledge - S_1, S_3, S_4
5. S_5 does not receive APP
6. S_2 commits o_1
7. S_2 crashes

Raft Crashing

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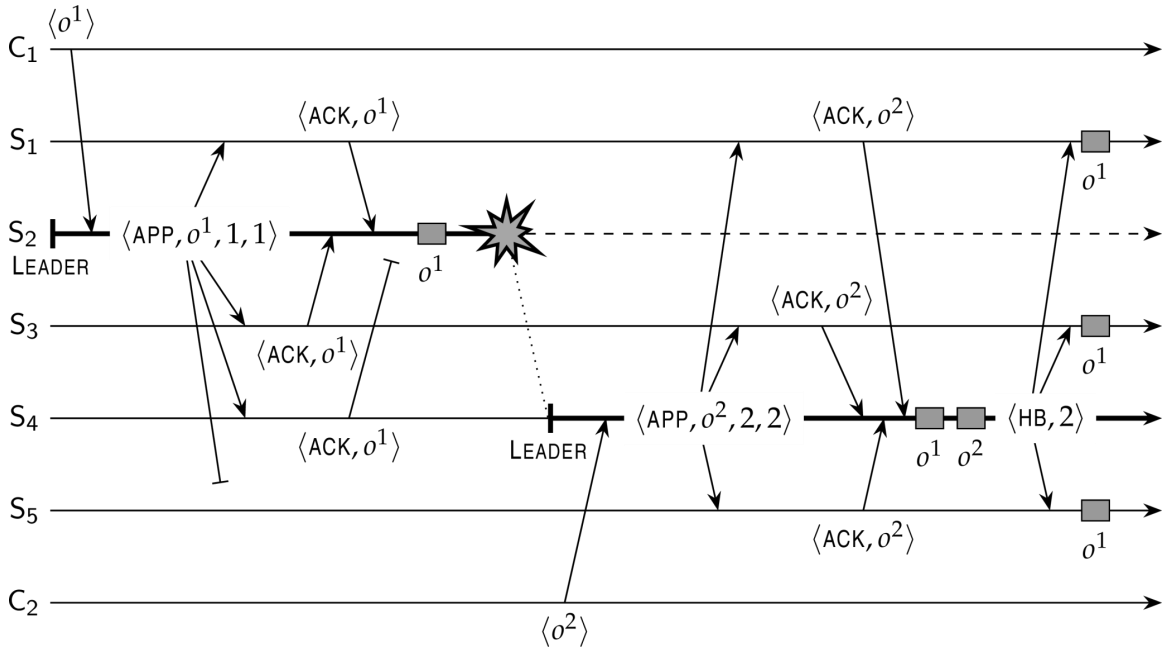


1. S_4 notices crash, declares candidacy
2. S_4 elected leader
3. Client C_2 sends an operation o_2 to leader (S_4)
4. S_4 records o_2 as index 2 term 2
5. S_4 sends APP messages $\langle APP, o_2, 2,2\rangle$
6. Majority acknowledge
7. S_4 commits o_1, o_2
8. S_4 sends heartbeat message (HB) with current index (2)
   - Includes entire log
9. S_1, S_3, S_5 commit o_1

Paxos: A hint

Assumptions

- Partially synchronous (may even be asynchronous)
- Communication between processes may be unreliable
  - lost, duplicated, reordered
- Corrupted message can be detected (and ignored)
- All operations are deterministic
  - Once an execution is started, we know exactly what it will do
- Processes crash-fail, but not arbitrary fail
- Processes do not collude

Essentials

- Assume a client-server configuration, with initially one primary server (the leader)
- For robustness, we add a backup server
- To ensure that all commands are executed in the same order at both servers, primary assigns unique sequence numbers to all commands
- Actual commands can always be restored (either from clients or servers), so we consider only control messages.

For more info, read the paper

- Kirsch J. and Amir Y. Paxos for System Builders. Technical Report CNDS-2008-2, John Hopkins University, Mar. 2008 http://www.cnds.jhu.edu/pub/papers/cnds-2008-2.pdf

Failure Detection

Issue

How can we reliably detect that a process has actually crashed?

- General model:
  - Each process is equipped with a failure detection module
  - A process p probes another process q for a reaction
  - q reacts → q is alive
  - q does not react within t time unites → q is suspected to have crashed
- Note: in a synchronous system:
  - A suspected crash is a known crash
  - Referred to as a perfect failure detector

Failure Detection

- Practice: the eventually perfect failure detector

- Has two important properties:
  - Strong completeness: every crashed process is eventually suspected to have crashed by every correct process
  - Eventual strong accuracy: eventually, no correct process is suspected by any other correct process to have crashed

- Implementation:
  - If p did not receive heartbeat from q within time t → p suspects q
  - If q later sends a message (received by p):
    - p stops suspecting q
    - p increases timeout value t
    - Note: If q does crash, p will keep suspecting q

Reliable Communication

So far: Concentrated on process resilience (by process groups). What about reliable communication channels?

Error detection:

- Framing of packets to allows for bit error detection
- Use of frame numbering to detect packet loss

Error correction:

- Add so much redundancy that corrupted packets can be automatically corrected.
- Request retransmission of lost, or last N packets

Reliable RPC

RPC Communication: What can go wrong?

1: Client can't locate server

2: Client request is lost

3: Server crashes

4: Server response is lost

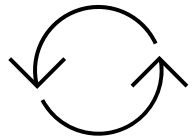
5: Client crashes

Solutions: #1: Client can’t locate server

Relatively simple – just report back to client

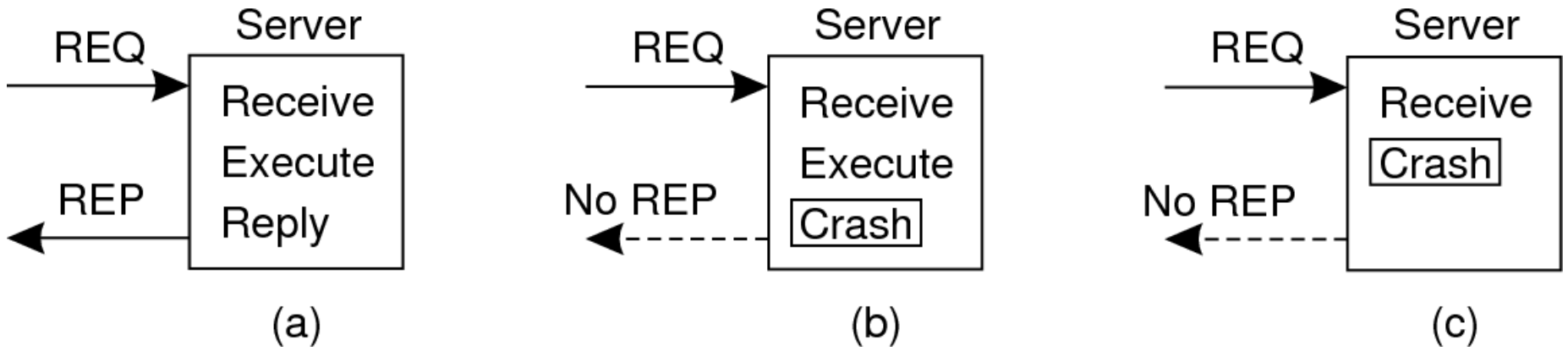
Solutions: #2: Client request is lost

Just resend the request



Solutions: #3 Server Crashes

Harder because you don't know what server did:



Need to decide on what we expect from the server:

- At-least-once semantics: The server guarantees it will carry out an operation at least once
- At-most-once-semantics: The server guarantees it will carry out an operation at most once.

Solutions: #4 Server Response Lost

Detecting lost replies can be hard, because it can also be that the server had crashed. You don't know whether the server has carried out the operation.

- Solution: None, except that you can try to make your operations idempotent: repeatable without any harm done if it happened to be carried out before.

Solutions: #5 Client crashes

Problem: The server is doing work and holding resources for nothing (called doing an orphan computation).

- Orphan is killed (or rolled back) by client when it reboots
- Broadcast new epoch number when recovering → servers kill orphans
- Requires computations to complete in T time units. Old ones are simply removed.

Question: What's the rolling back for?

Groups and Failure Masking

- k-Fault-tolerant group: When a group can mask any k concurrent member failures (k is called degree of fault tolerance).
- How large must a k-fault-tolerant group be:
  - With halting failures (crash/omission/timing failures): we need $k + 1$ members: no member will produce an incorrect result, so the result of one member is good enough.
  - With arbitrary failures: we need $2k + 1$ members: the correct result can be obtained only through a majority vote.

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- Result:
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Observation

The processes need to have consensus on which command to execute next

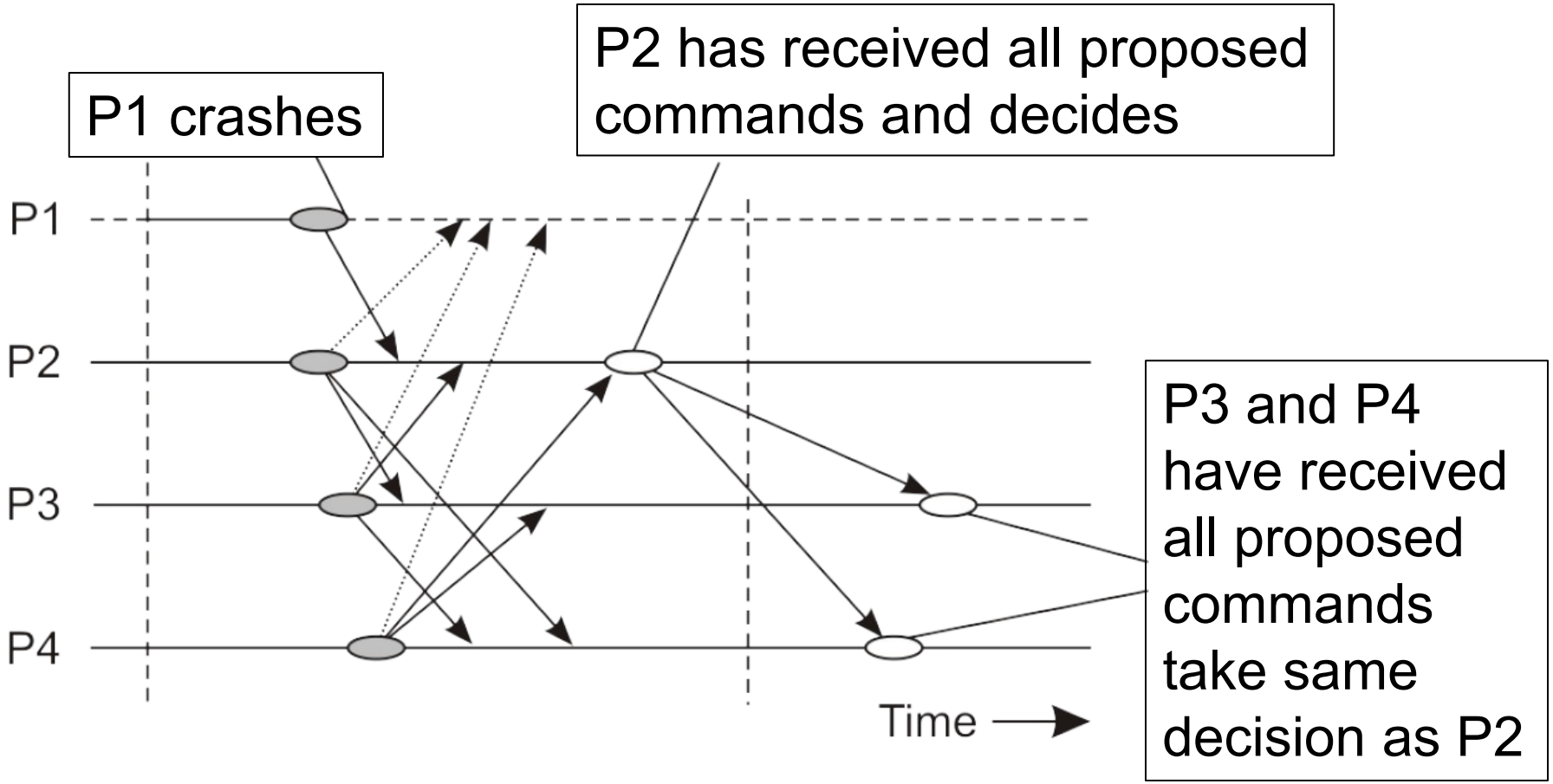
Flood-based Consensus

- Assume:
  - Fail-crash semantics
  - Reliable failure detection
  - Unreliable communication

- Basic idea:
  - Processes multicast their proposed operations
  - All apply the same selection procedure → all processes will execute the same if no failures occur

- Problem:
  - Suppose a process crashes before completing its multicast

Flood-based Consensus



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RPC Communication: Solutions

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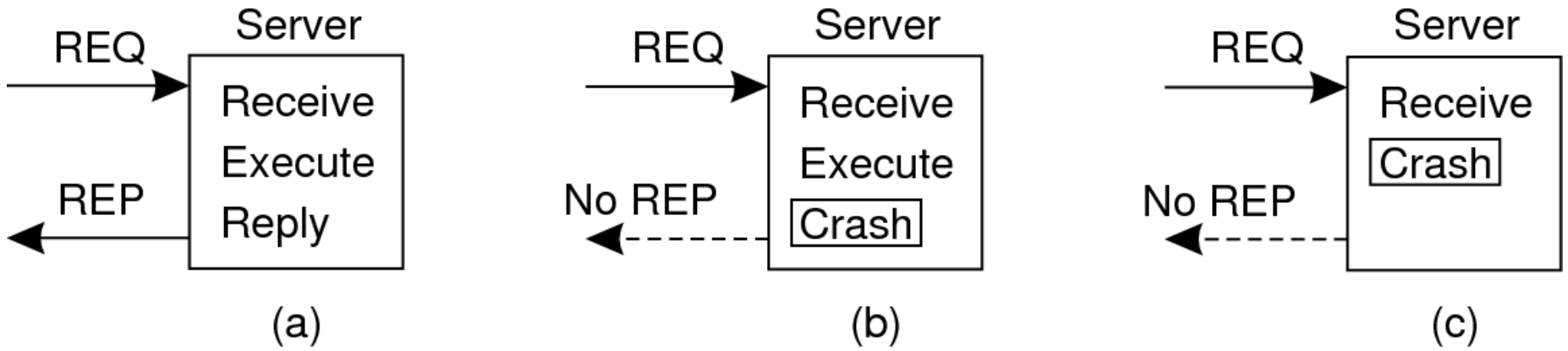
2. Just resend message

RPC: Solutions

3. Server crashes: Server crashes are harder as you don't know what it had already done:



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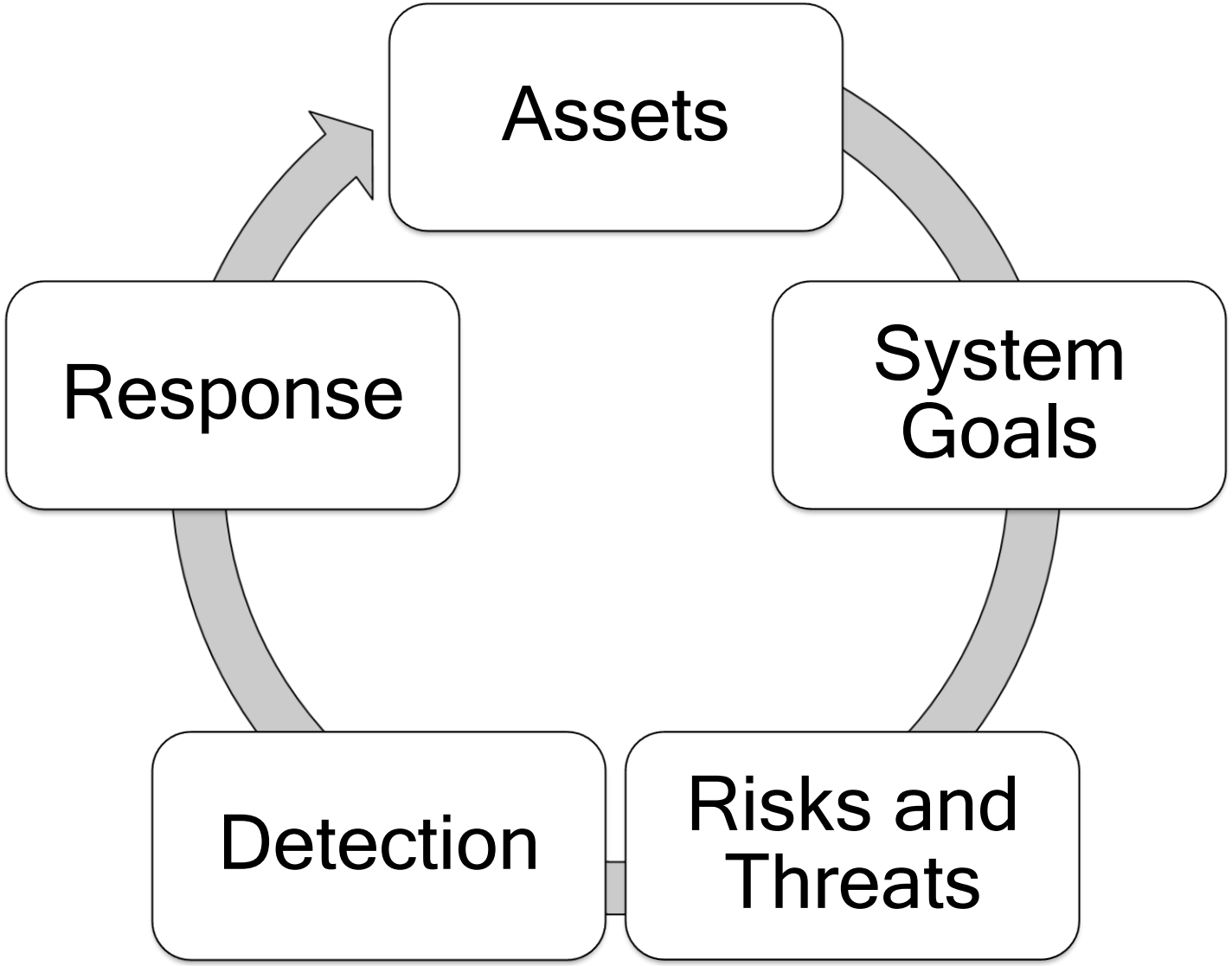
- Raft and Consensus
- Cyber 3: Consensus and Failure

Consistency and Consensus Cyber



Assets – Consistency and Consensus

Databases	Data items	Transaction servers
Transaction logs	Communication links	Communication protocols

System Goals – Consistency and Consensus

Provide consistent data

Allow timely writing

Keep nodes up to date

Don’t lose data or transactions

Permit servers to come and leave

Tolerate failure and recover

Make it “just work” from user perspective

Identify problematic operations and undo/flag

Risks and Threats – Consistency and Consensus

Malicious customers/users provide bad data

Network provider disrupts communication

Malicious server corrupts data

Misconfigured user/server causes system freeze

Misconfigured user/server causes system crash

Crash occurs, losing data or transactions

Network communications lag too much, breaking time assumptions

Detection - Consistency and Consensus

Event monitoring

Dashboards for performance

Watch for network heartbeats and updates

Watch for client interaction delays

Test data for consistency and responsiveness

Monitor server communications and down time

Run test jobs to ensure they complete on time and consistently

Response

Ignore/kick out malicious users/customers

Bring up additional servers when crashes occur

Watch for network partitions

Locate data near where it's needed to provide service in case of outage

Add servers or bandwidth connections if crashes occur often

Conclusion

- Failures and Resilience