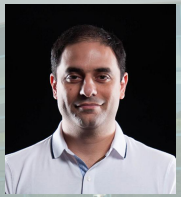
Fault-Tolerant Distributed Transactions on Blockchain

Introduction

Suyash Gupta

Jelle Hellings

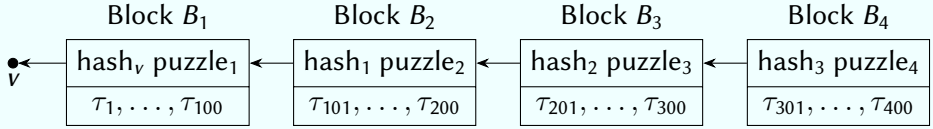


Mohammad Sadoghi

A Quick Overview of Bitcoin

What is Bitcoin?

- A *monetary token*, the Bitcoin.
- An open and decentralized way to *transfer* these tokens.
- A representation of the history of these transfers: the *blockchain*:



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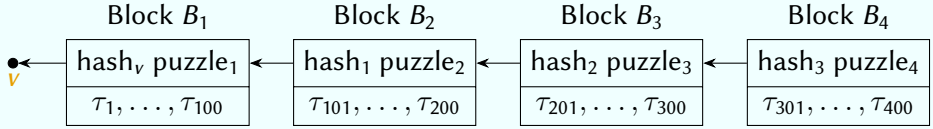

- A chain of blocks starting at a predefined initial *genesis block* v.

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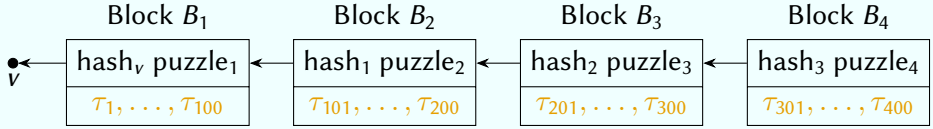

- Each block holds a *list of transactions* transferring Bitcoins.

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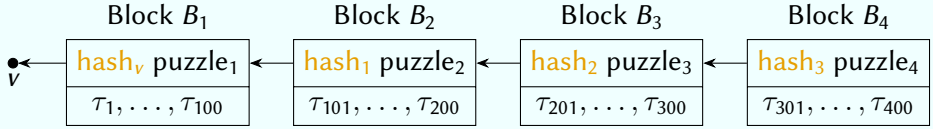

- Each block holds the *hash* of a previous block.

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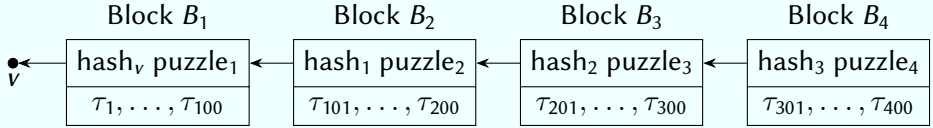

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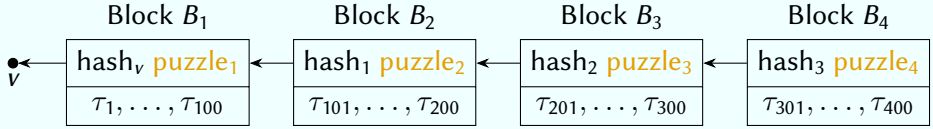
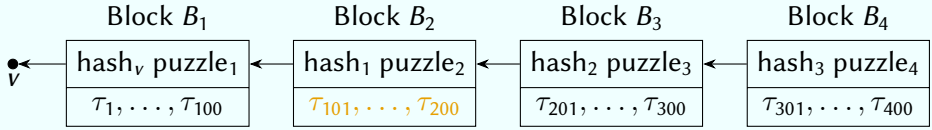


- Each block contains contains a solution to a computational *complex puzzle*, used to make the blockchain *tamper-proof*.

The Tamper-Proof Design of Bitcoin

Incentive: The creator of a block that is part of the chain gets a reward.

Assumption: A malicious participant P wants to replace τ_{123} by τ'



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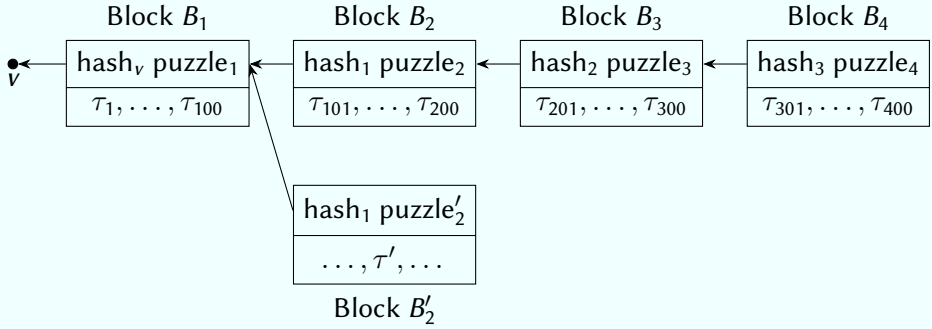
1. P creates a new block B_2' with τ'.



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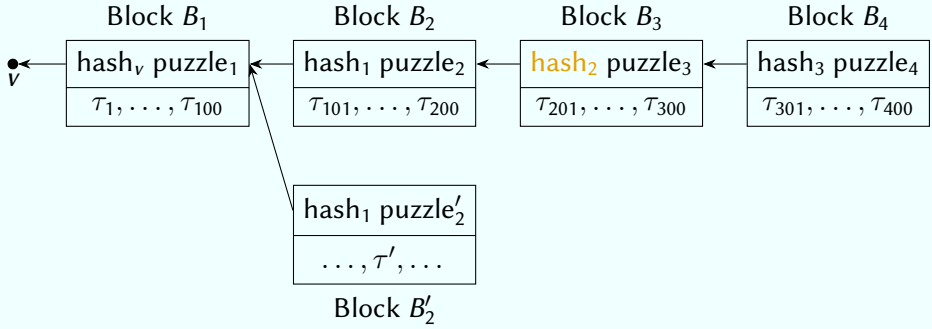
2. $B_2 \neq B_2'$. Hence, $hash_2$ still points to B_2.



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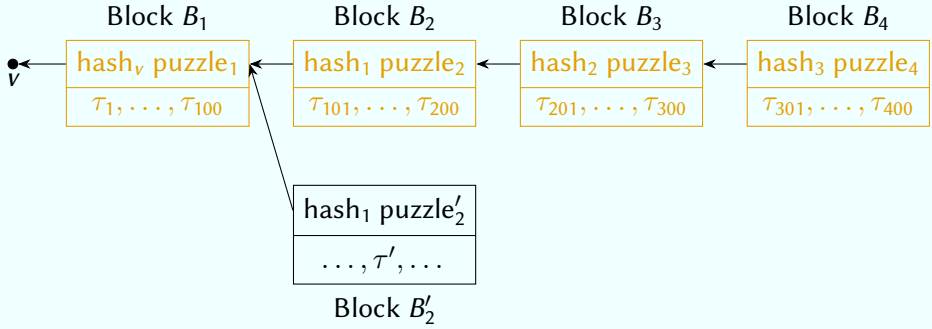

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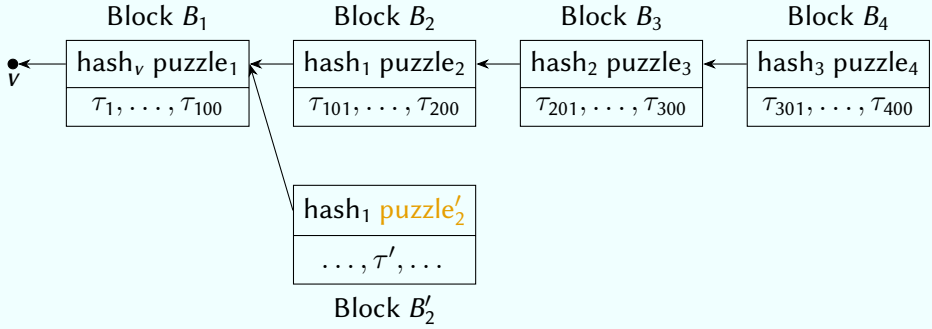
   Long chains give rewards to *more participants*: incentive to work on long chains.



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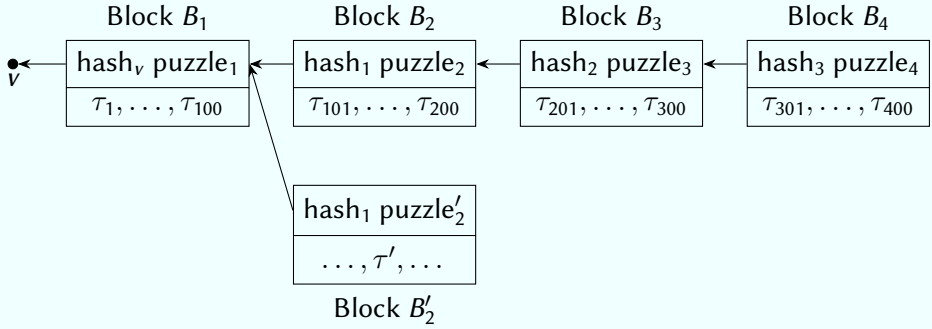

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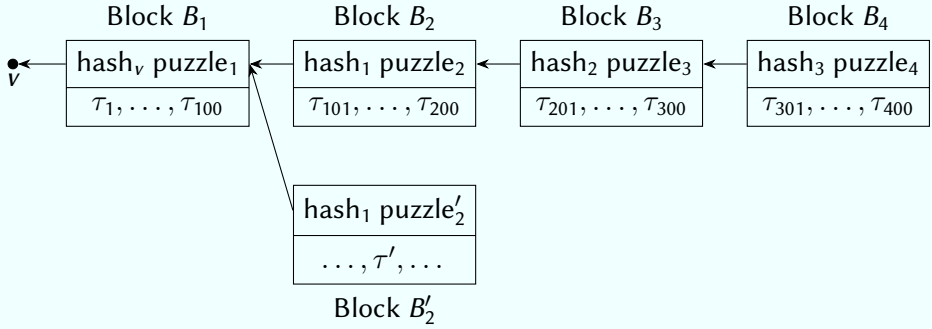
   More incentives to continue from block B_4 than block B_2'!



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- Each *vetted participant* manages their own systems (e.g., different software).
- Failure of individual participants should not break the system!
- Blockchains: *federated data management* and *resilience*.

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Can be implemented using PBFT-style consensus.

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Challenge: *Sybil attacks*

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Requires a consensus protocol that does not rely on *identities*.

Distributed Systems

Definition[1]

A distributed system is a collection of autonomous computing elements that appears to its users as a single coherent system.

[1] M. van Steen & A.S. Tanenbaum, *Distributed Systems*, 3rd ed., distributed-systems.net, 2017.

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- Autonomous computing elements: nodes, replica, ...
- Single coherent system: "should behave as a single system".
  - Users should see a *single* system.
  - Nodes must *collaborate* to provide that system.

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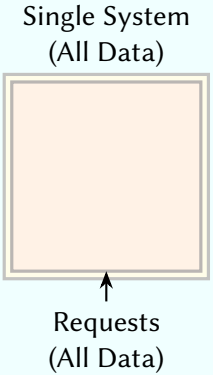
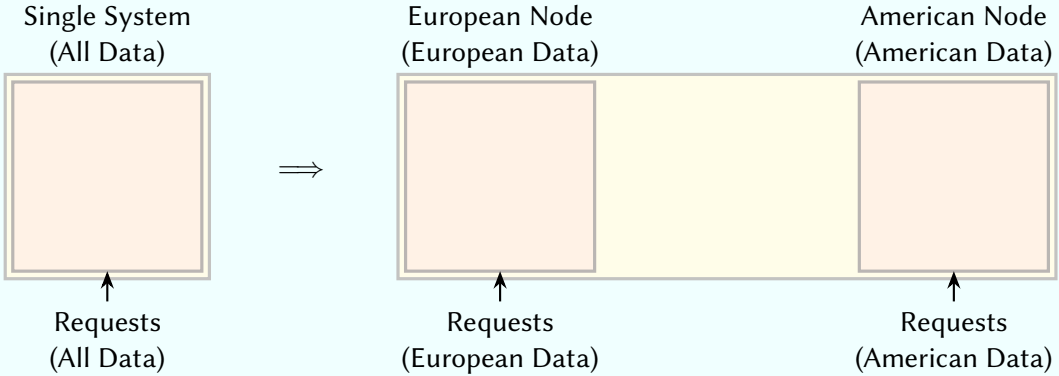
Distributed Systems: Scalability



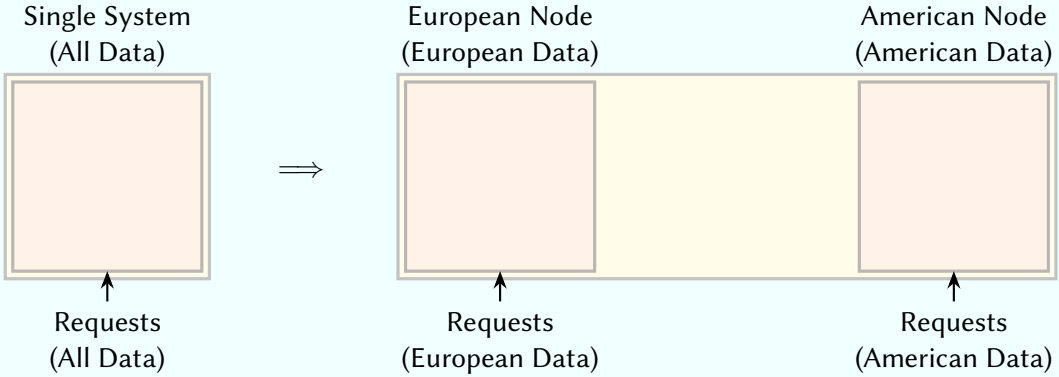
Single system: Storage and performance *bounded* by hardware.

Distributed Systems: Scalability



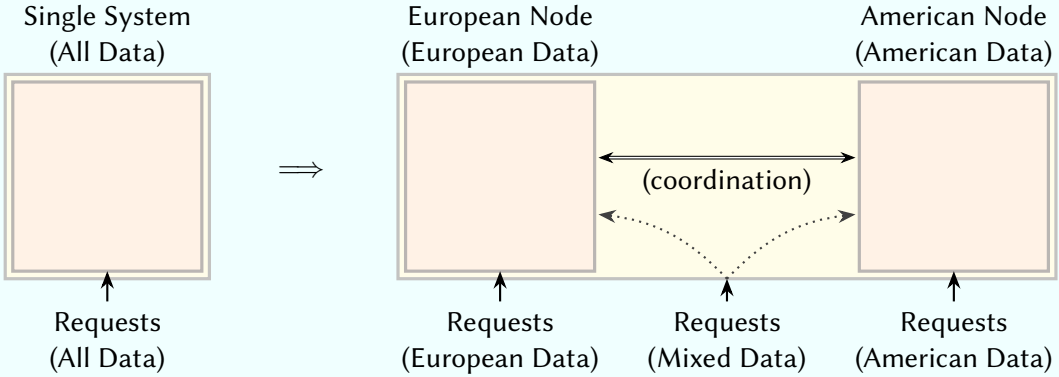
Partition the system: More storage and *potentially* more performance.

Distributed Systems: Scalability



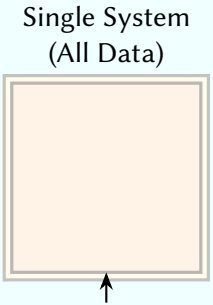
Partition the system: More storage and *potentially* more performance.
Potentially *lower latencies* if data ends up closer to users.

Distributed Systems: Scalability



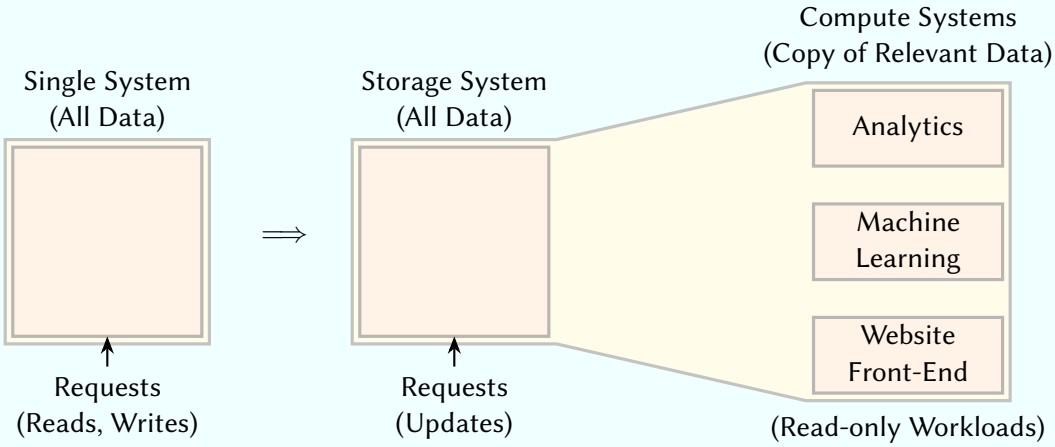
Complex requests: become more *costly* to answer!

Distributed Systems: Specialization



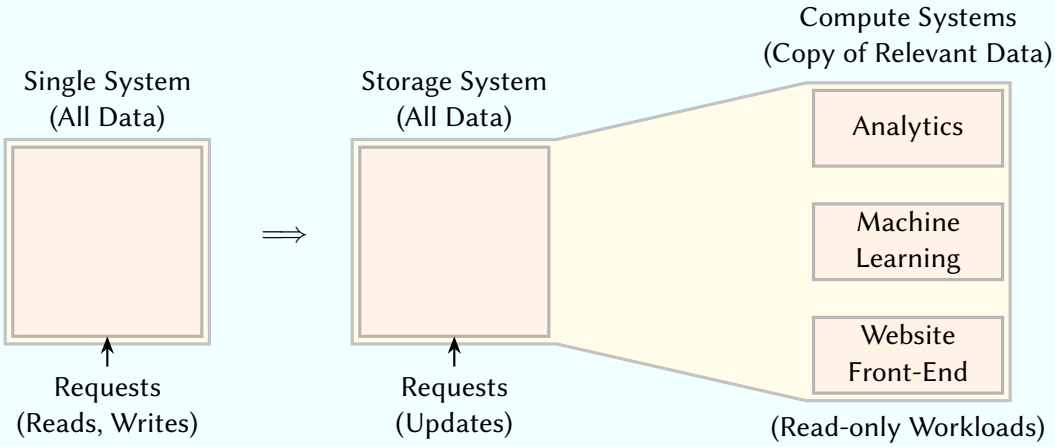
Single system: Compromise—cannot be optimized for *all* tasks.

Distributed Systems: Specialization



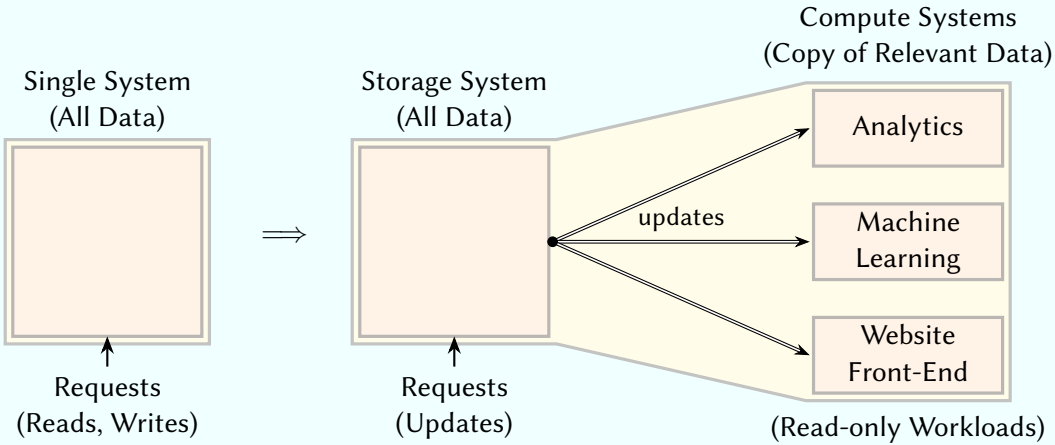
Specialize the system: Different nodes have distinct tasks.

Distributed Systems: Specialization



Specialize the system: Different nodes have distinct tasks.
Specialized hardware and software *per* task.

Distributed Systems: Specialization



Added cost: Keeping the compute systems *up-to-date*.

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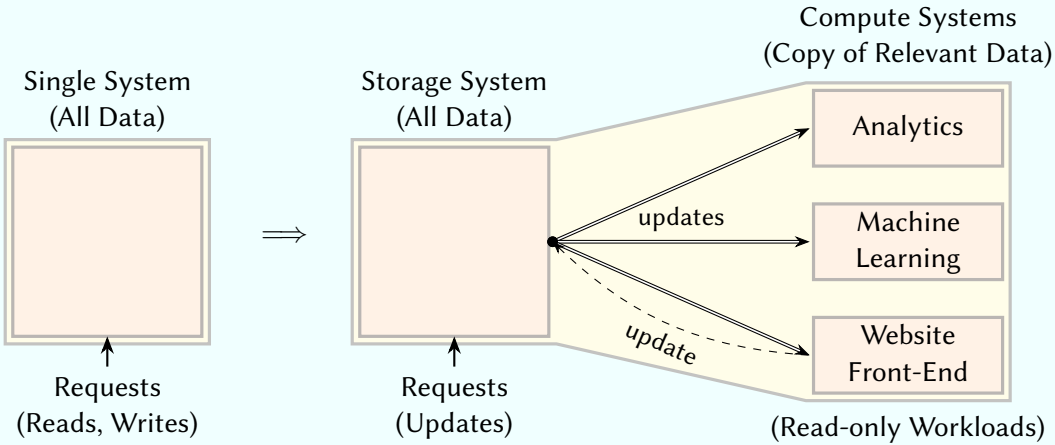
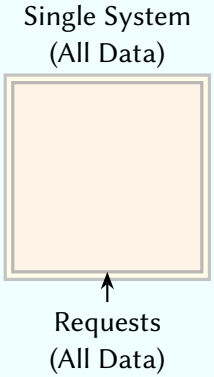


Design complexity: Updates from the compute systems?

Distributed Systems: Reliability (Primary-Backup)



Single system: Single point of *failure*.

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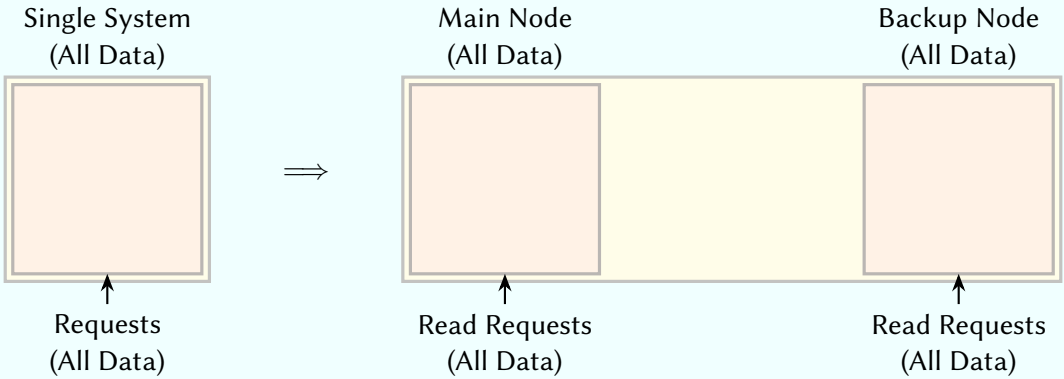

Multiple copies: Copies available after single failure.

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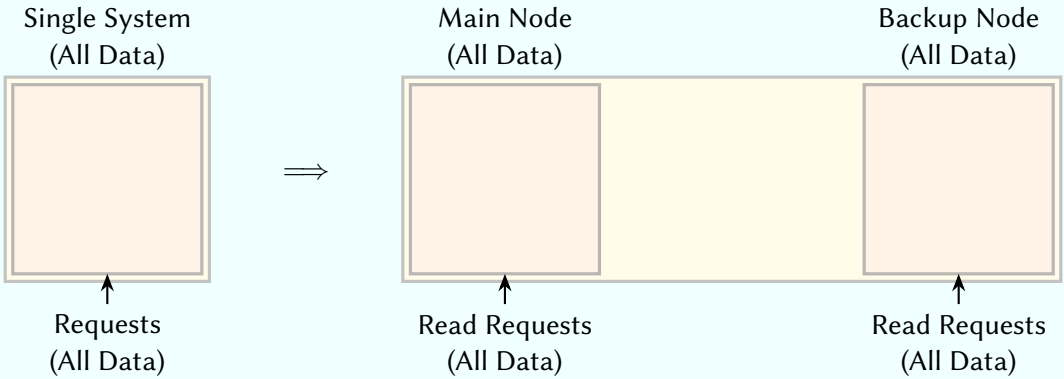

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Potentially *lower latencies & more performance* when users read data.

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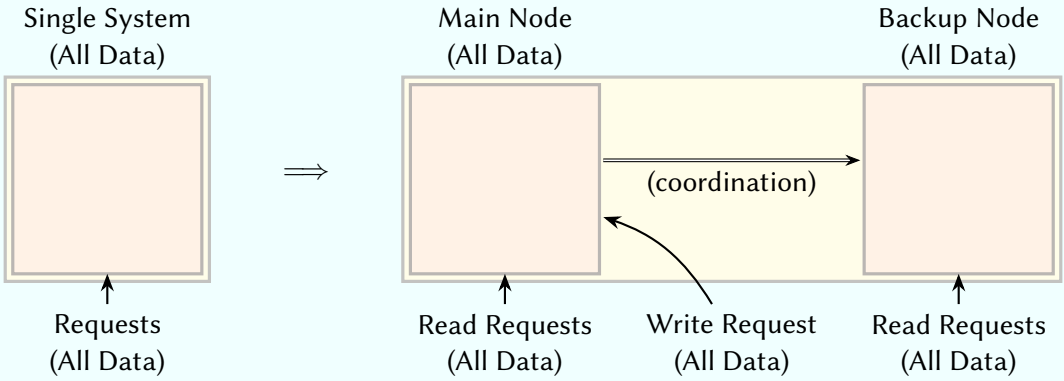
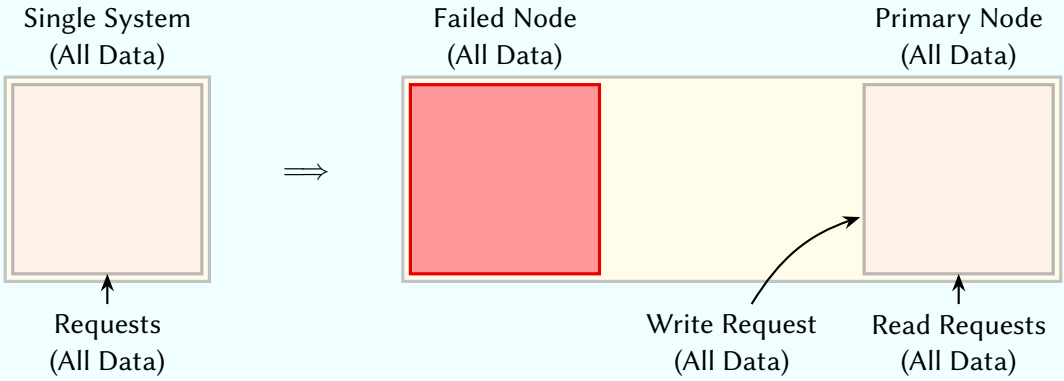


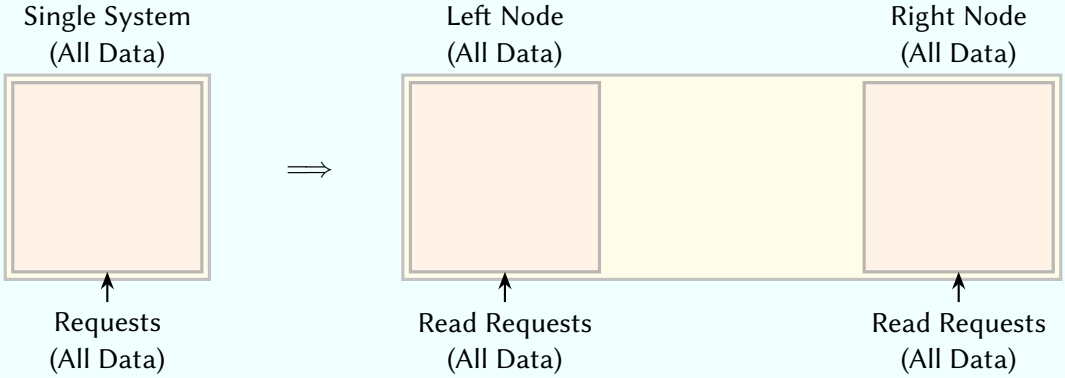
Changes to data requests: Primary *leads*, backups *follow*.

Distributed Systems: Reliability (Primary-Backup)



Failure: Recovery mechanisms—typically *complex*.

Distributed Systems: Reliability (Decentralized)



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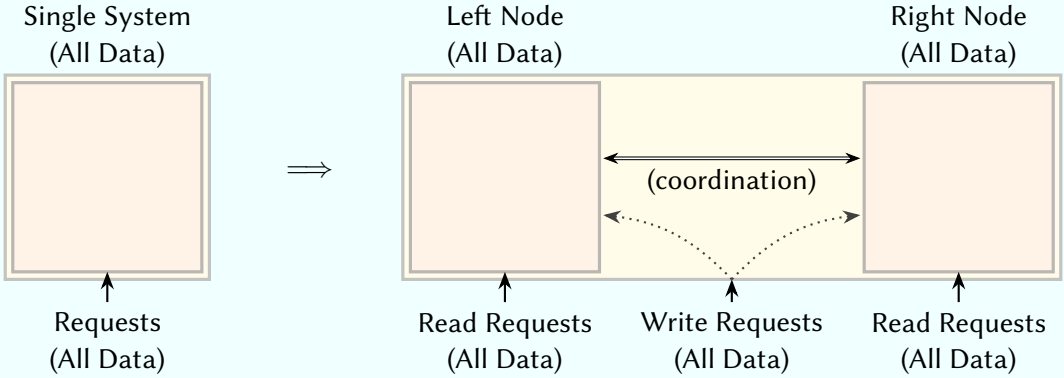
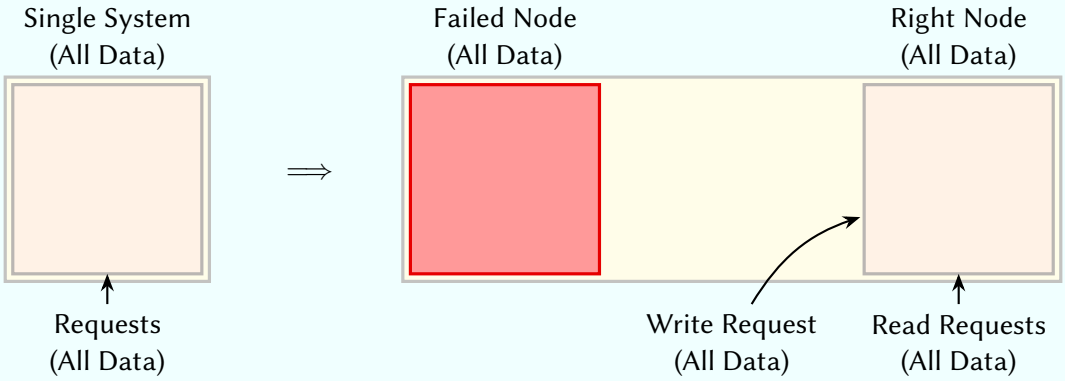


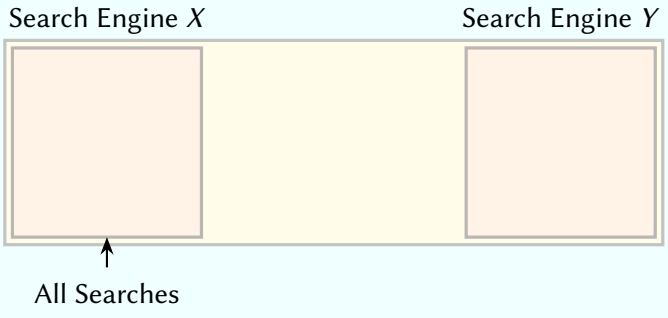
Changes to data requests: *Costly* coordinated decision among all active nodes.

Distributed Systems: Reliability (Decentralized)



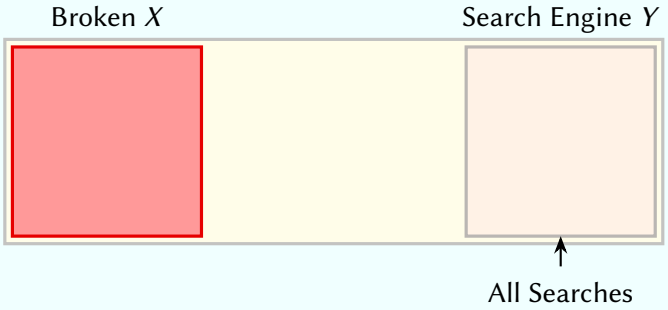
Failure: Recovery mechanisms—typically *easier* (or even *free*).

Distributed System?



I perform all my searches on the web with Search Engine X.

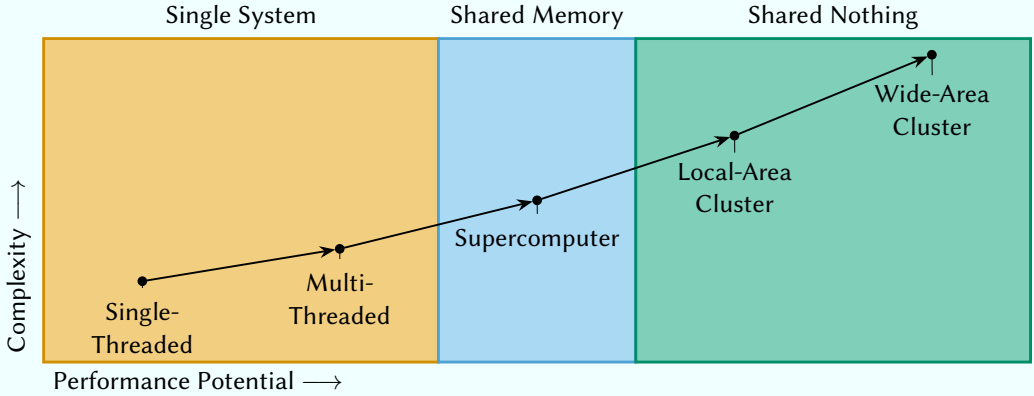
Distributed System?



Today Search Engine X failed—I remembered the alternative Search Engine Y.

Do we need Distributed Systems?

Distributed computing is *complex*



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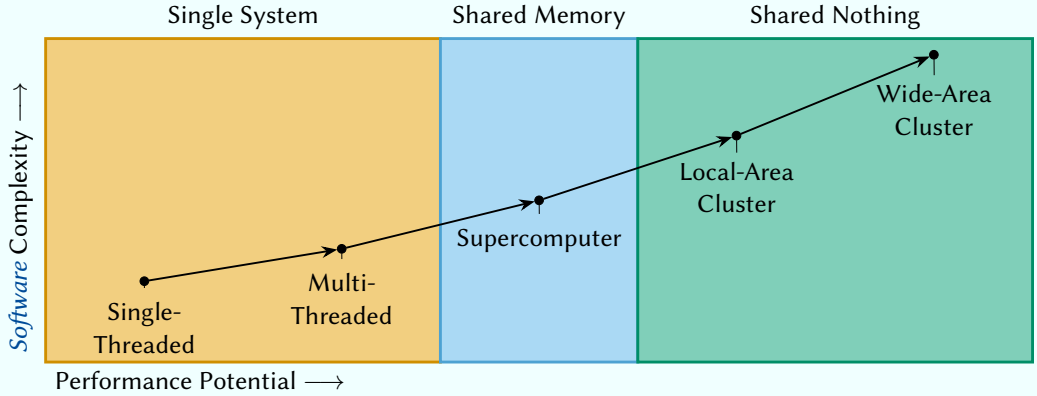

Complexity to write *efficient* software that solve a given problem.

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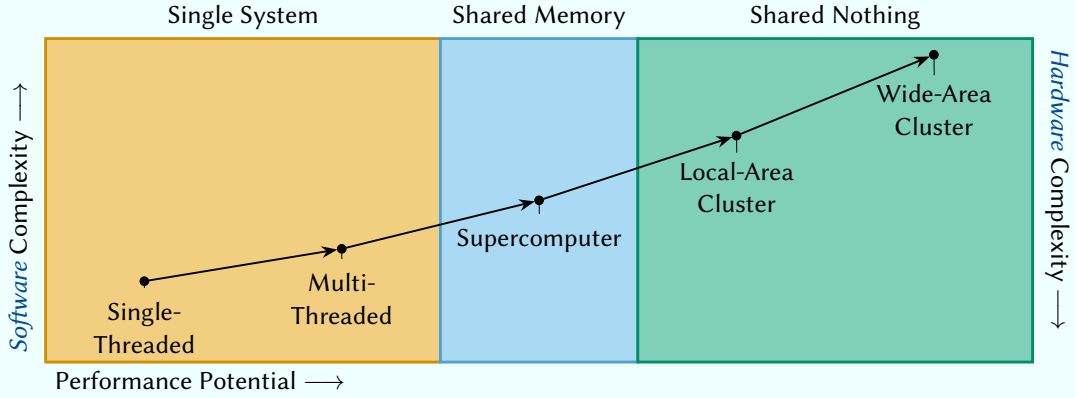
Distributed computing is *complex*



Complexity of *hardware* to solve a given problem in time t.

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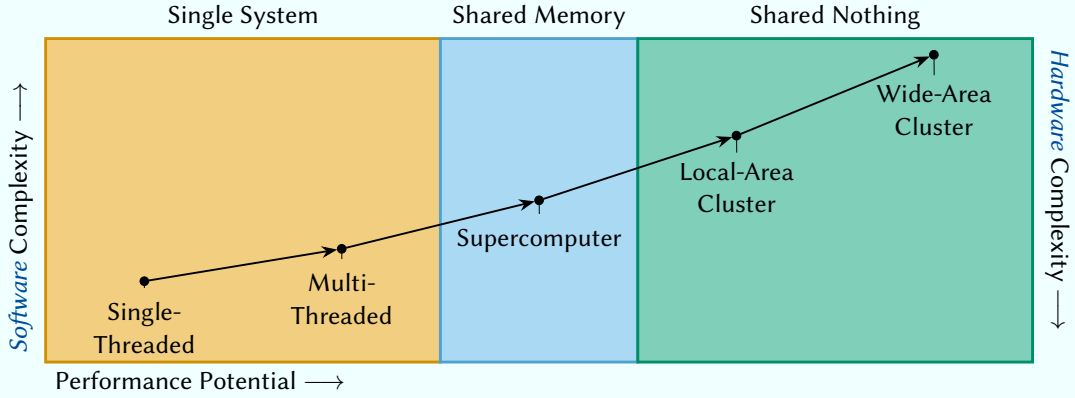

Increased software complexity is *fundamental*: Problems become theoretically harder.

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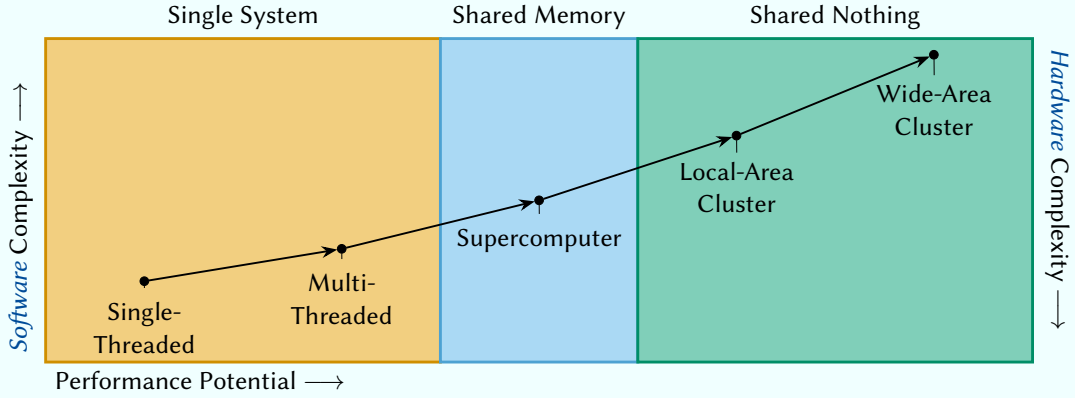

Do we really need distributed systems?

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Distributed designs can provide resilience.

Desirable Properties of a Distributed System

Consider a simple & minimalistic distributed system

Fully-replicated: each node (replica) holds the *same data*.

[2] E. Brewer, *CAP Twelve Years Later: How the "Rules" Have Changed*, 2012.

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There is a huge design space—CAP only covers a tiny part.

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Distributed Databases

Definition[3]

Distributed database A collection of multiple, logically interrelated databases located at the nodes of a distributed system.

Distributed DBMS the software system that manages the distributed database & makes the distribution transparent to the users

[3] M.T. Özsu & P. Valduriez, *Principles of Distributed Database Systems*, 4th ed., 2020.

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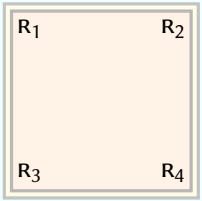
  Crash fault tolerance versus Byzantine fault tolerance.

- *Continuous services*: No downtime, manual intervention, restarts, ...

Outline of a Blockchain-Based Resilient System

1. Replicas.



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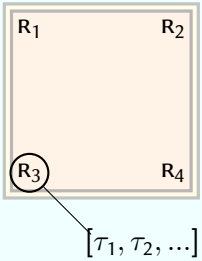

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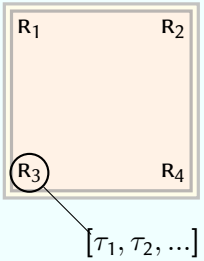

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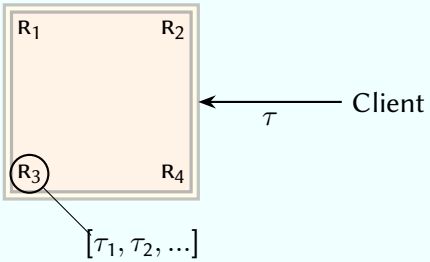

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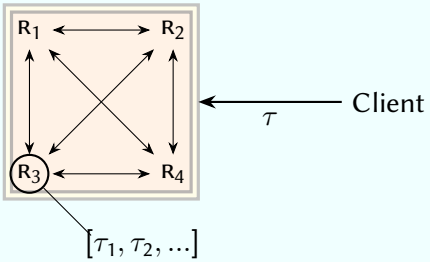

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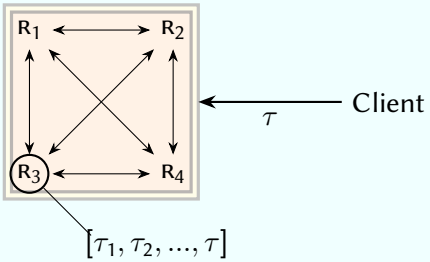

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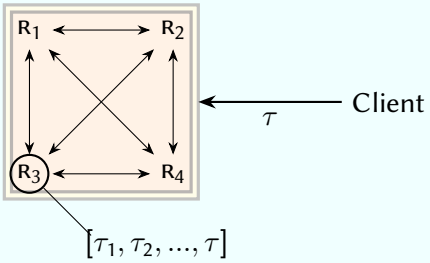

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Classifying Resilient Systems

The complexity of operating a resilient system depends on many factors:

Failures. In what ways can replicas fail?

Communication. What assumptions are made on communication?

Authentication. How are messages and their senders identified and verified?

Failure Models

We say that a replica is

initially crashed if it will never do anything;

crashed if it stops doing anything at some point;

omitting if it can omit coordination steps;

Byzantine if it can behave *arbitrary*
(e.g., omitting steps, performing the wrong steps.).

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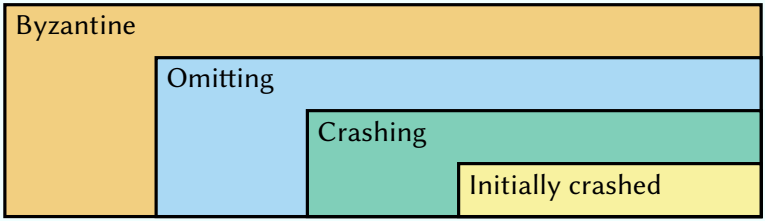

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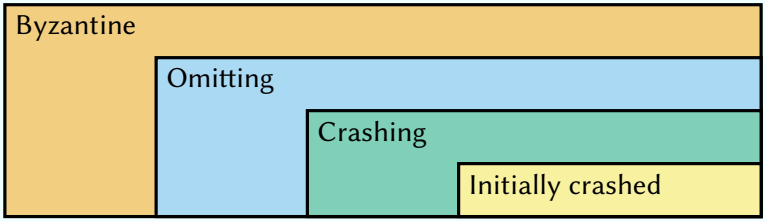

Both *omitting* and *Byzantine* replicas can be **malicious**:
these replicas can **coordinate** among themselves in attempts to disrupt the system.

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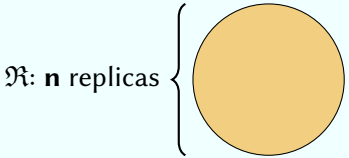

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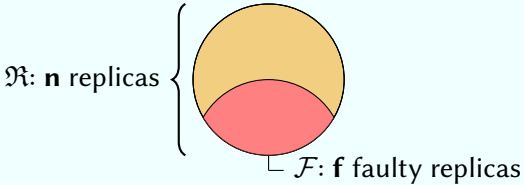

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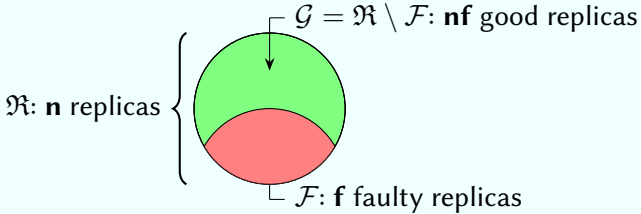

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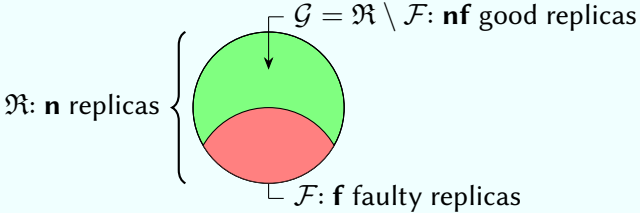
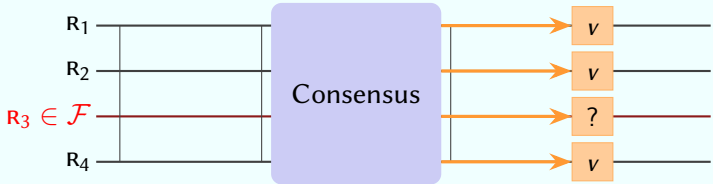


Coordination in Resilient Systems: Consensus

A protocol provides *consensus* if upon completion of the protocol:

Termination Eventually, each good replica $\mathrm{R} \in \mathcal{G}$ decides on a value $v(\mathrm{R})$.

Non-divergence All good replicas decide on the same value.
Hence, if $\mathrm{R}_1, \mathrm{R}_2 \in \mathcal{G}$ decide $v(\mathrm{R}_1)$ and $v(\mathrm{R}_2)$, then $v(\mathrm{R}_1) = v(\mathrm{R}_2)$.



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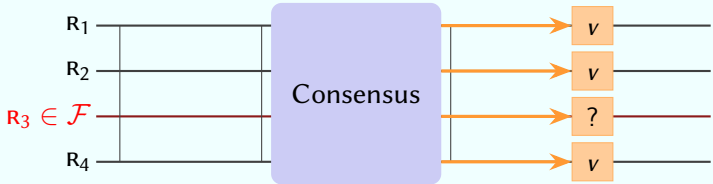
Non-triviality In different runs of the protocol, replicas can decide on different values.

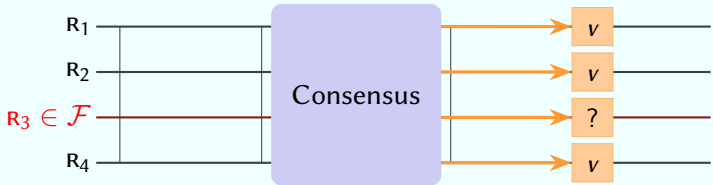


Excludes trivial solutions: e.g., good replicas always deciding a pre-defined value.

Coordination in Resilient Systems: Consensus

A protocol provides *consensus* if upon completion of the protocol:

Termination	Eventually, each good replica $\mathrm{R} \in \mathcal{G}$ decides on a value $v(\mathrm{R})$.	*Liveness*
Non-divergence	All good replicas decide on the same value. Hence, if $\mathrm{R}_1, \mathrm{R}_2 \in \mathcal{G}$ decide $v(\mathrm{R}_1)$ and $v(\mathrm{R}_2)$, then $v(\mathrm{R}_1) = v(\mathrm{R}_2)$.	*Safety*
Non-triviality	In different runs of the protocol, replicas can decide on different values.	



Excludes trivial solutions: e.g., good replicas always deciding a pre-defined value.

Consensus: From Formalization to Practice

Formal consensus is *abstract*: Where do the decided values come from?

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Towards consensus in practice

Expand *non-triviality* by putting application-specific requirements on decided values.

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Expand *non-triviality* by putting application-specific requirements on decided values.

Example: System processing client transactions

Decided-upon values that are not-yet executed client-requested transactions.

Coordination in Resilient Systems: Interactive Consistency

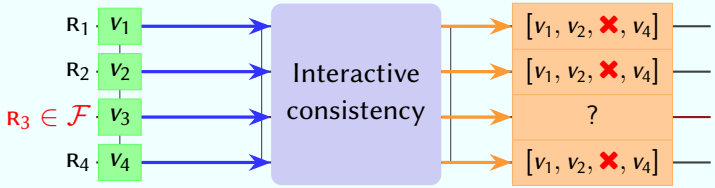
Assumption: Each replica R holds an initial value $v(\mathrm{R})$

A protocol provides *interactive consistency* if upon completion of the protocol:

Termination Eventually, each good replica $\mathrm{R} \in \mathcal{G}$ decides on a list $L(\mathrm{R})$ of $\mathbf{n}$ values.

Non-divergence All good replicas decide on the same list.
Hence, if $\mathrm{R}_1, \mathrm{R}_2 \in \mathcal{G}$ decide $L(\mathrm{R}_1)$ and $L(\mathrm{R}_2)$, then $L(\mathrm{R}_1) = L(\mathrm{R}_2)$.

Dependence Let $\mathrm{R} \in \mathcal{G}$. Good replicas will have $v(\mathrm{R})$ as the $\mathrm{id}(\mathrm{R})$-th list value.
Hence, if replica $\mathrm{Q} \in \mathcal{G}$ decided on $L(\mathrm{Q})$, then $L(\mathrm{Q})[\mathrm{id}(\mathrm{R})] = v(\mathrm{R})$.



From Interactive Consistency to Consensus

Example: System processing client transactions

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3. At least $\mathbf{nf} = \mathbf{n} - \mathbf{f}$ values in L are *valid new client transactions*.

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   Each good replica obtains the same list L of $\mathbf{n}$ values.

3. At least $\mathbf{nf} = \mathbf{n} - \mathbf{f}$ values in L are *valid new client transactions*.
4. Good replicas use a *deterministic method* to choose a valid transaction from L. E.g.,
   - the first valid transaction in L; or
   - all valid transactions in L (optimization).

Coordination in Resilient Systems: Byzantine Broadcast

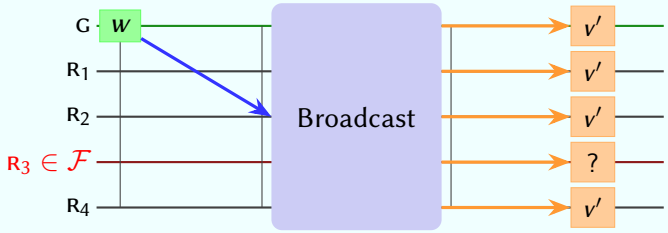
Assumption: Some replica G holds an initial value w

A protocol provides *byzantine broadcast* if upon completion of the protocol:

Termination Eventually, each good replica $\mathrm{R} \in \mathcal{G}$ decides on a value $v(\mathrm{R})$.

Non-divergence All good replicas decide on the same value.
Hence, if $\mathrm{R}_1, \mathrm{R}_2 \in \mathcal{G}$ decide $v(\mathrm{R}_1)$ and $v(\mathrm{R}_2)$, then $v(\mathrm{R}_1) = v(\mathrm{R}_2)$.

Dependence If G is good, then good replicas decide w.
Hence, if $\mathrm{G} \in \mathcal{G}$ and $\mathrm{Q} \in \mathcal{G}$, then $v(\mathrm{Q}) = w$.



$(v' = w \text{ if } \mathrm{G} \in \mathcal{G})$

From Byzantine Broadcasts to Interactive Consistency

Assumption: Each replica R holds an initial value $v(\mathrm{R})$

1. Each replica R performs Byzantine broadcast of $v(\mathrm{R})$.

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Interactive consistency and Byzantine broadcasts solve the same problem.

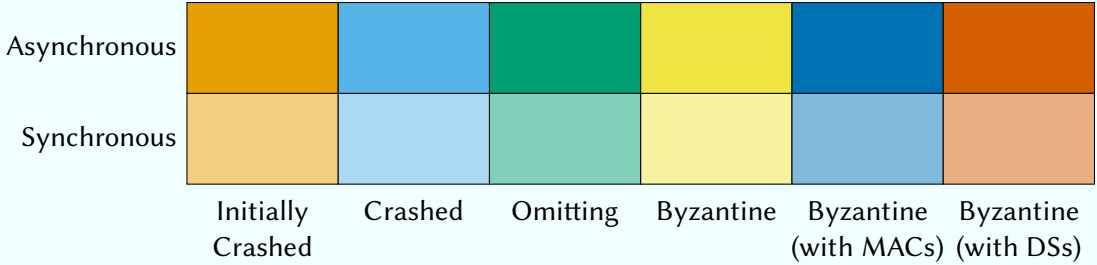
Both can be used to provide practical consensus.

On the Complexity of Consensus

Consider a system with **n** replicas of which **f** are faulty.

The consensus problem (informal)

Can the good replicas reach *agreement* on a value?



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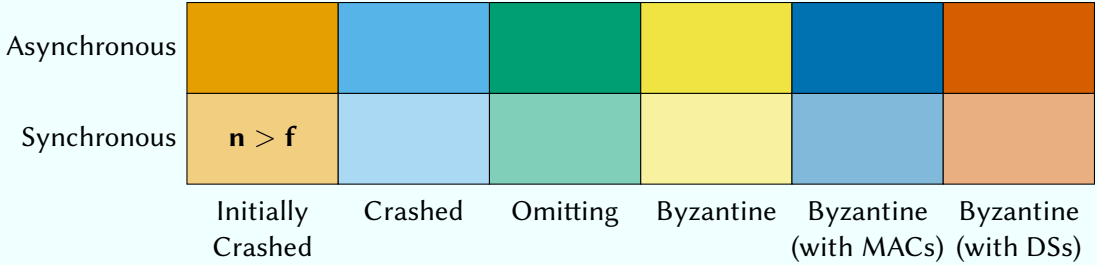

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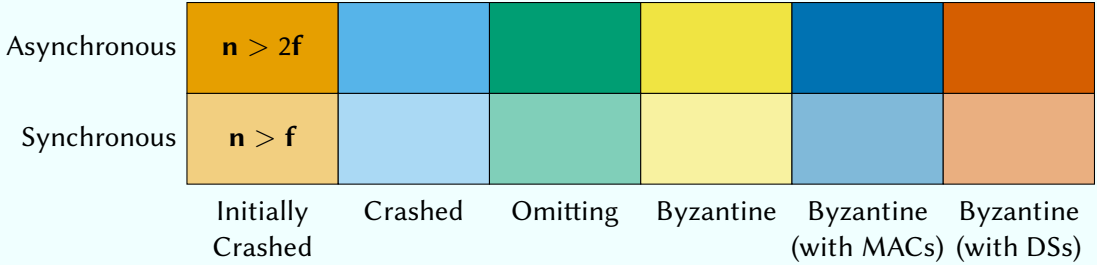

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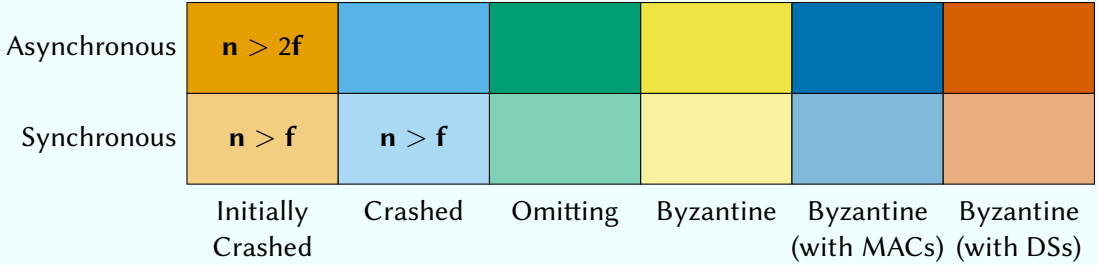

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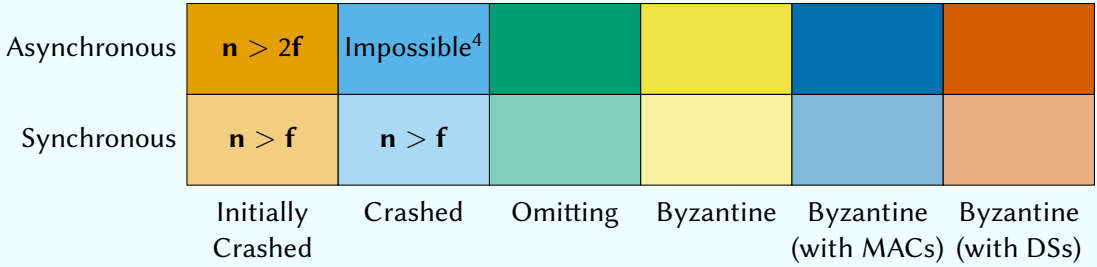

[4] The FLP Impossibility Theorem.

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Consensus in Practice: Impossible?

Theorem (FLP Impossibility Theorem)

The consensus problem cannot be solved for systems that

- *uses asynchronous communication; and*
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Real-world networks: Asynchronous, but mostly well-behaved

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$$\text{Each good replica } \mathrm{R} \in \mathcal{G} \text{ decides on a value } v(\mathrm{R}).$$

Weak termination	Good replicas decide *when communication is well-behaved*.
Probabilistic termination	Good replicas decide *with high probability*.

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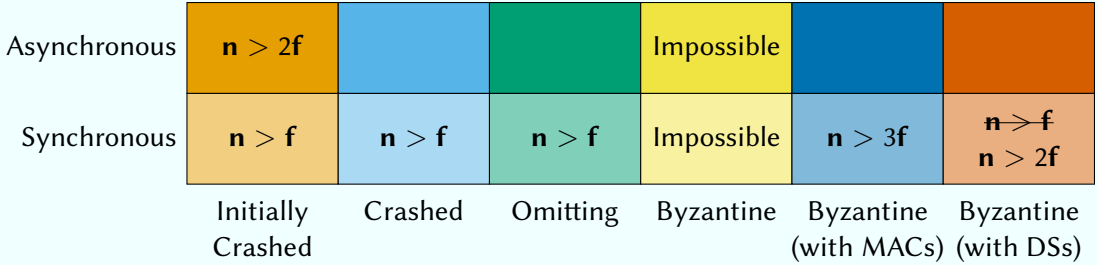

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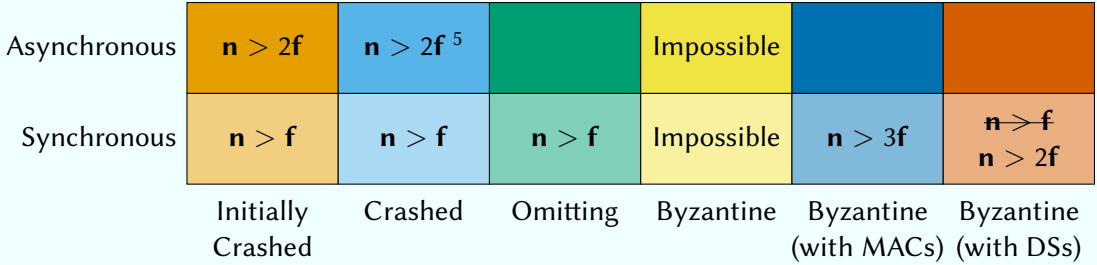

[5] Weak or probabilistic termination.

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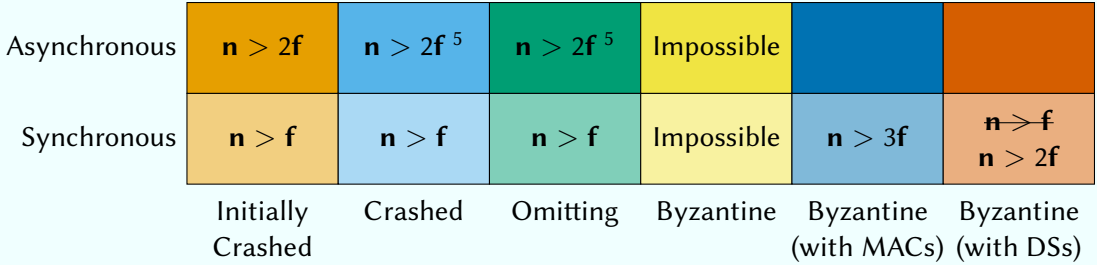

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The Complexity and Cost of Consensus

Many other limitations on consensus are known

Communication phases a worst-case approach in at-least $\mathbf{f} + 1$ phases;
at-least $t + 2$ phases if $t \leq \mathbf{f}$ replicas behave faulty (optimistic);

Communication cost an exchange of at-least $\mathbf{nf}$ signatures;
an exchange of at least $\mathbf{n} + \mathbf{f}^2$ messages;

Network structure at-least $2\mathbf{f} + 1$ disjoint communication paths
between every pair of replicas.