Fault-Tolerant Distributed Transactions on Blockchain

Introduction

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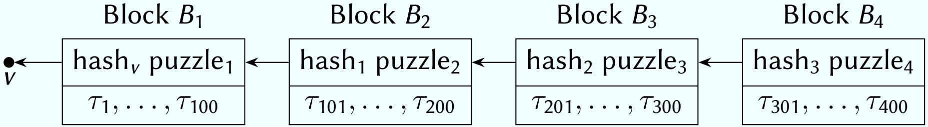
McMaster University

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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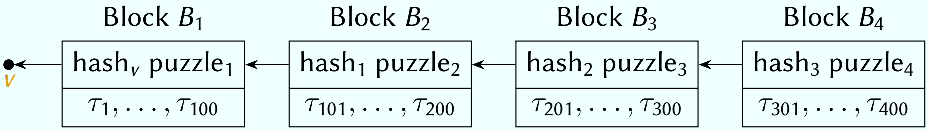

  - A chain of blocks starting at a predefined initial *genesis block* v.

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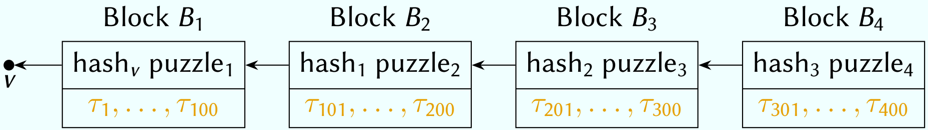

  - Each block holds a *list of transactions* transferring Bitcoins.

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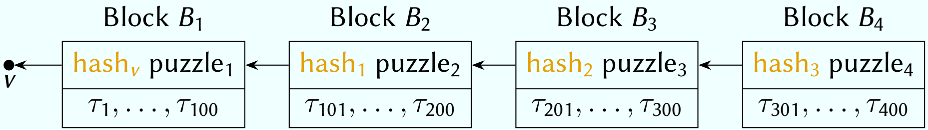

  - Each block holds the *hash* of a previous block.

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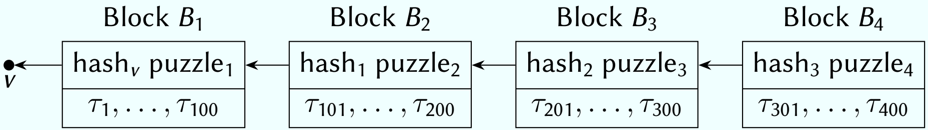

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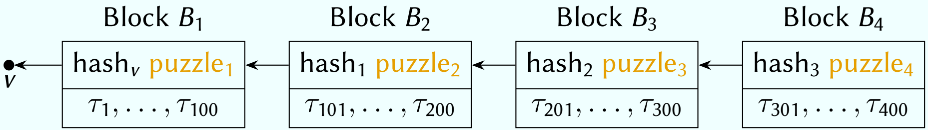
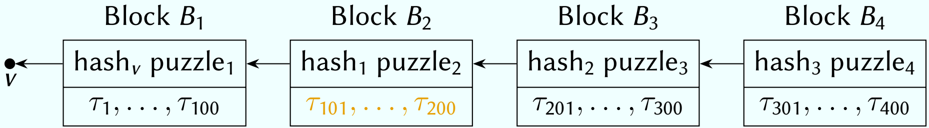


  - Each block contains contains a solution to a computational *complex puzzle*, used to make the blockchain *tamper-proof*.

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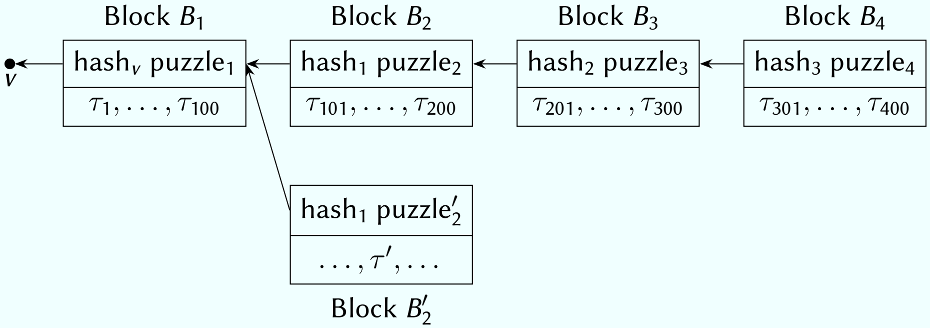
1. P creates a new block B_2' with τ'.



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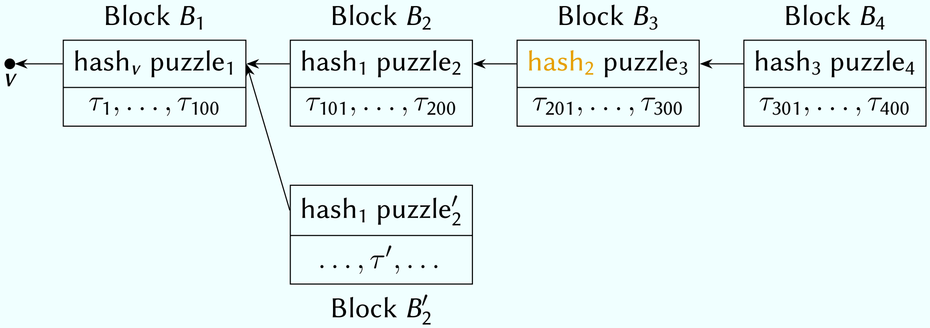
2. $B_2 \neq B_2'$. Hence, *$hash_2$* still points to B_2.



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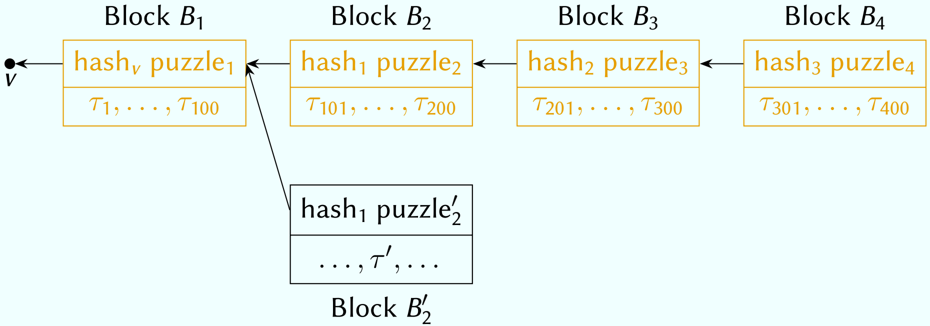

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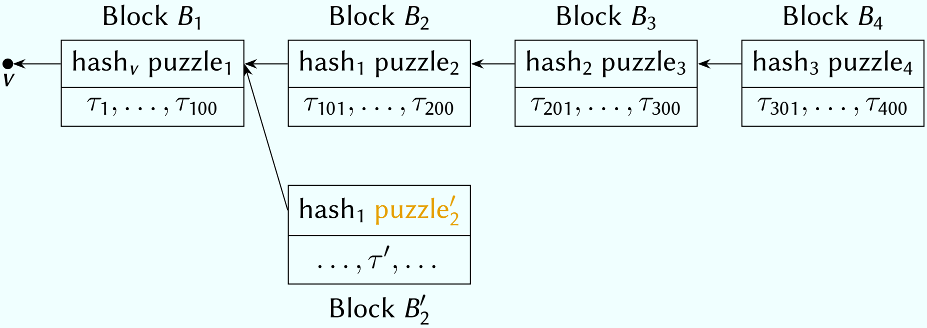
   Long chains give rewards to *more participants*: incentive to work on long chains.



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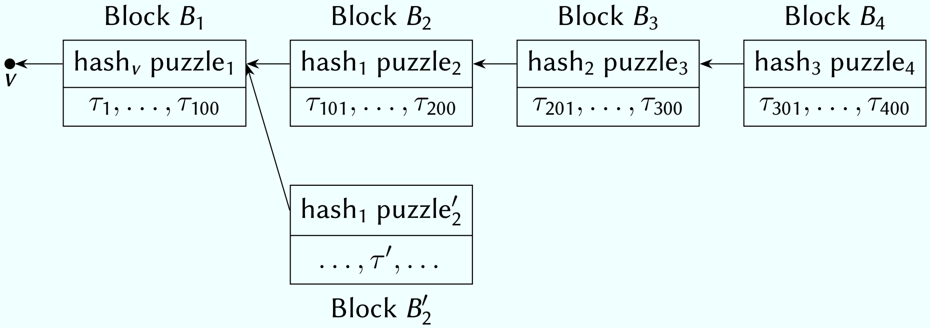

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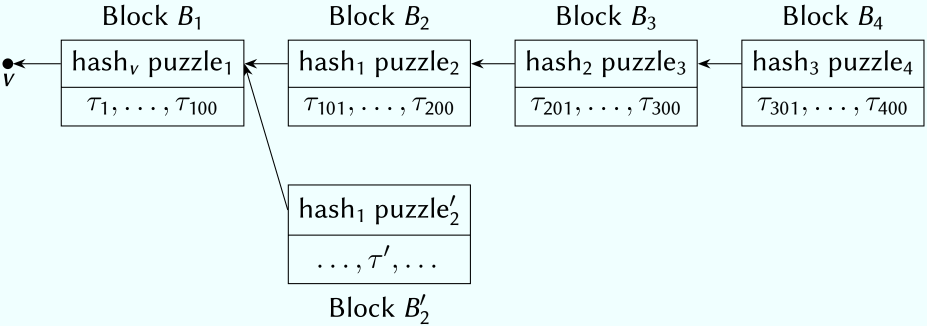
   More incentives to continue from block B_4 than block B_2'!



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Can be implemented using PBFT-style consensus.

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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.

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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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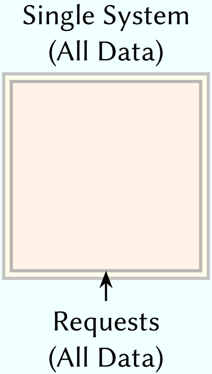
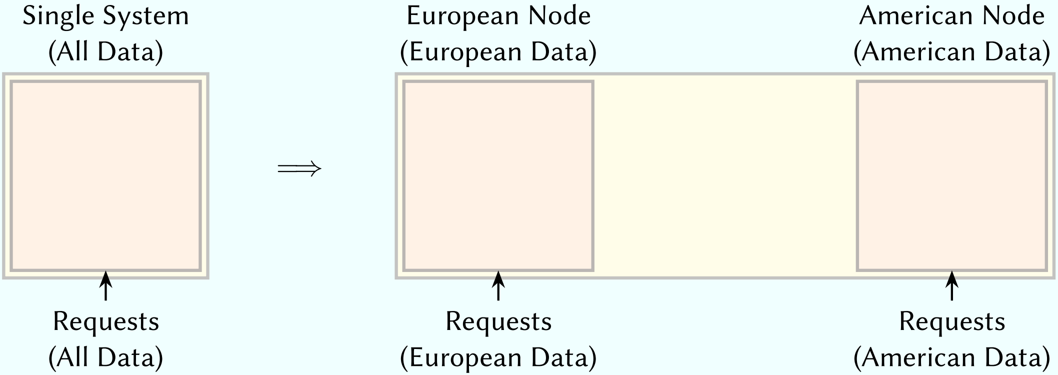
Distributed Systems: Scalability



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

Distributed Systems: Scalability



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

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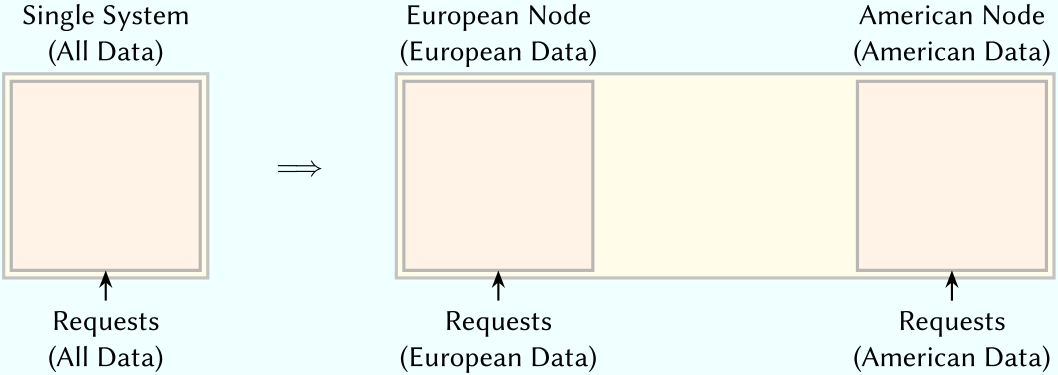

Partition the system: More storage and *potentially* more performance.
Potentially *lower latencies* if data ends up closer to users.

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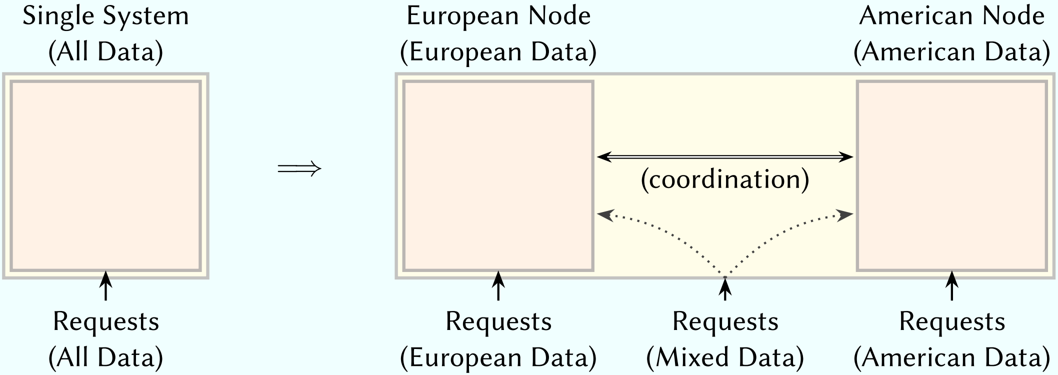
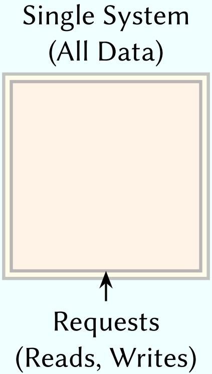


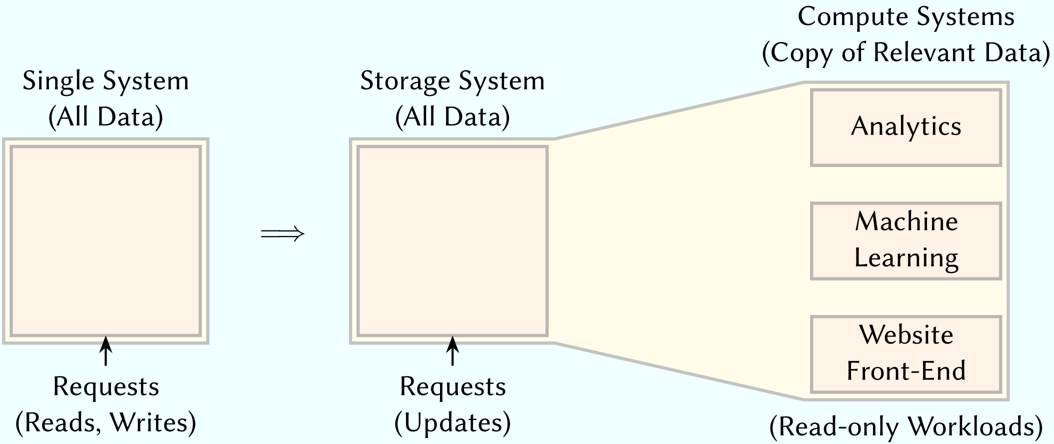
Complex requests: become more *costly* to answer!

Distributed Systems: Specialization



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

Distributed Systems: Specialization



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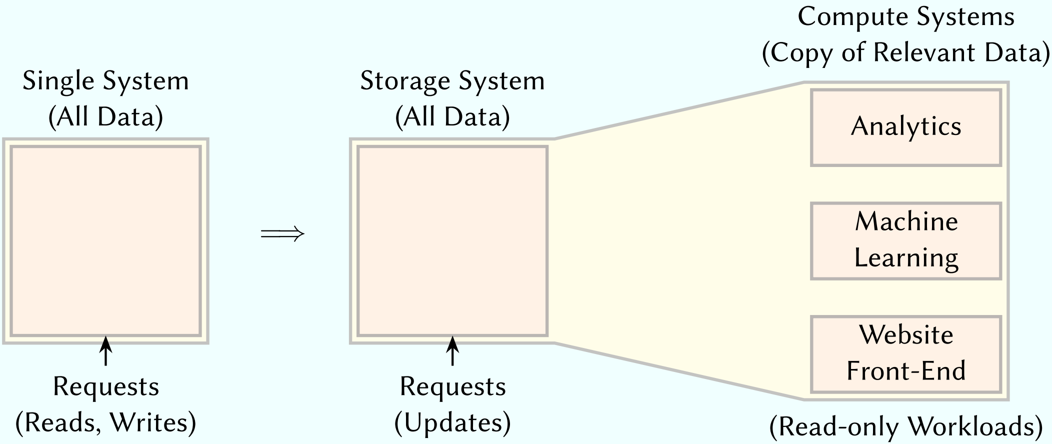
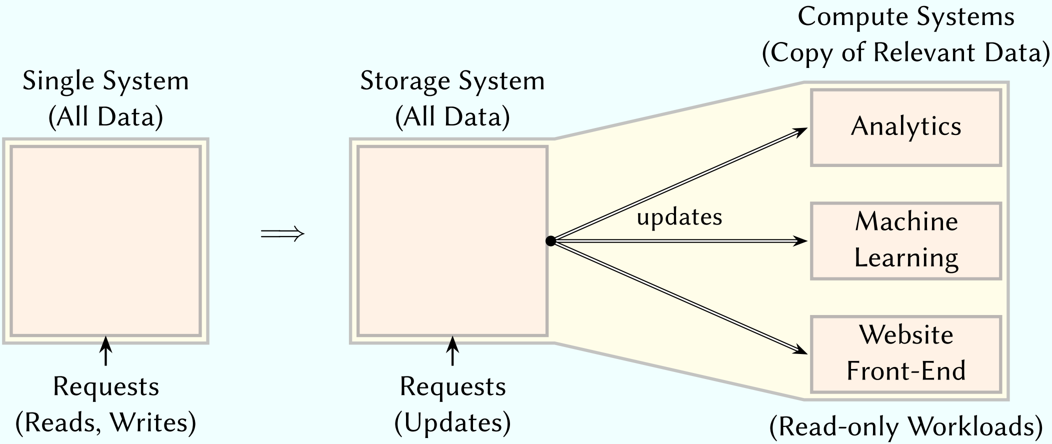


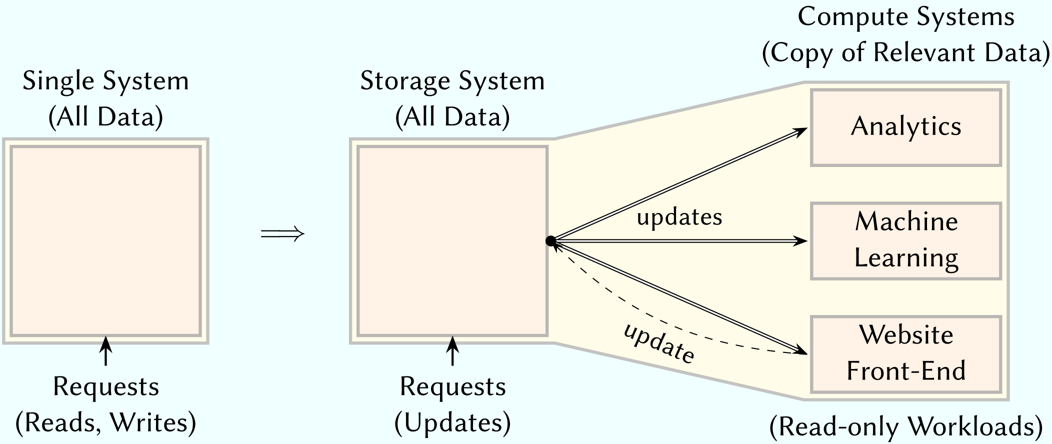
Specialize the system: Different nodes have distinct tasks.
Specialized hardware and software *per* task.

Distributed Systems: Specialization



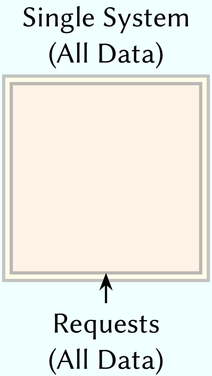
Added cost: Keeping the compute systems *up-to-date*.

Distributed Systems: Specialization



Design complexity: Updates from the compute systems?

Distributed Systems: Reliability (Primary-Backup)



Single system: Single point of *failure*.

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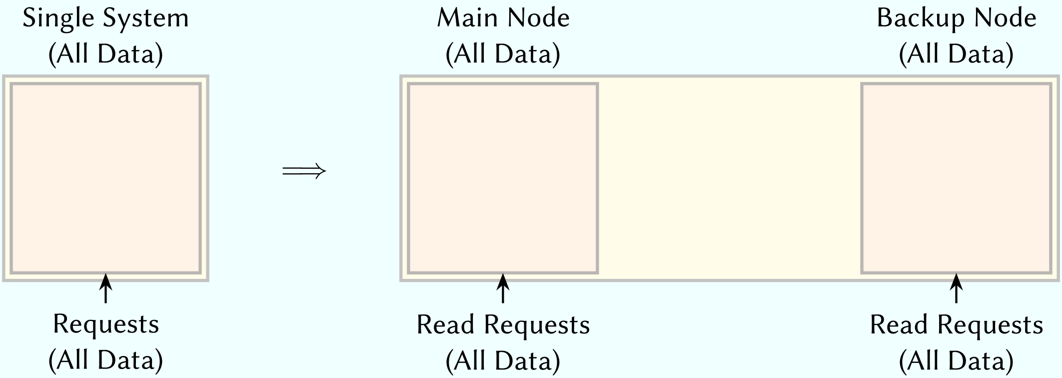

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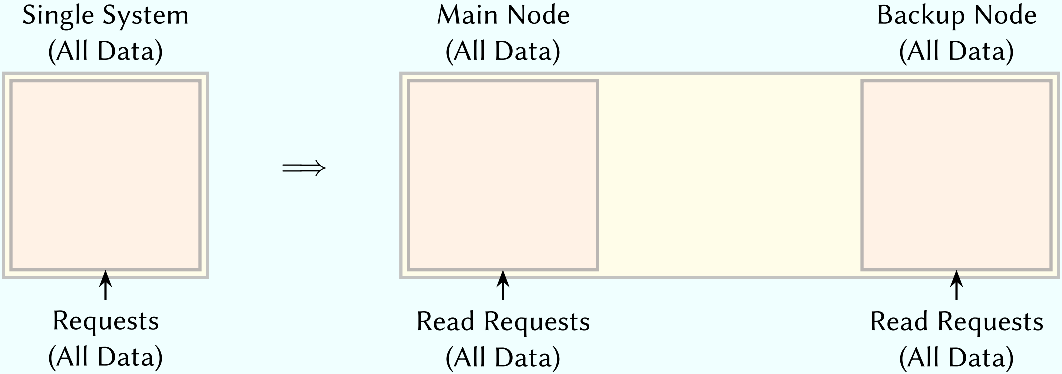

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Potentially *lower latencies & more performance* when users read data.

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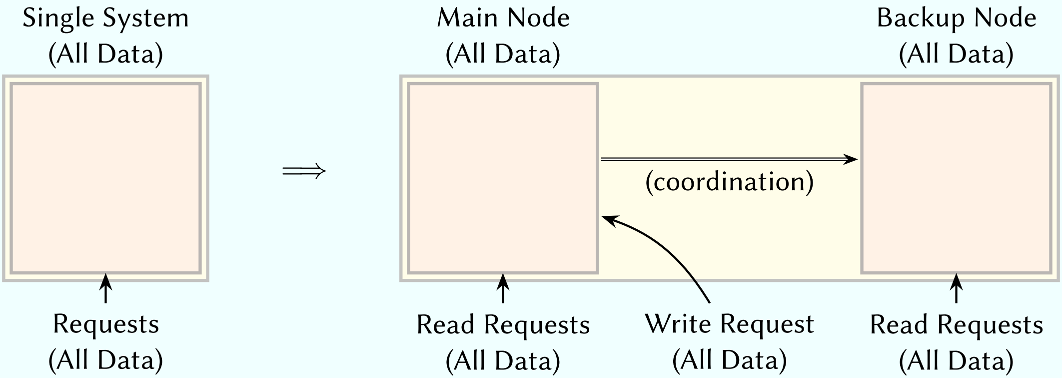
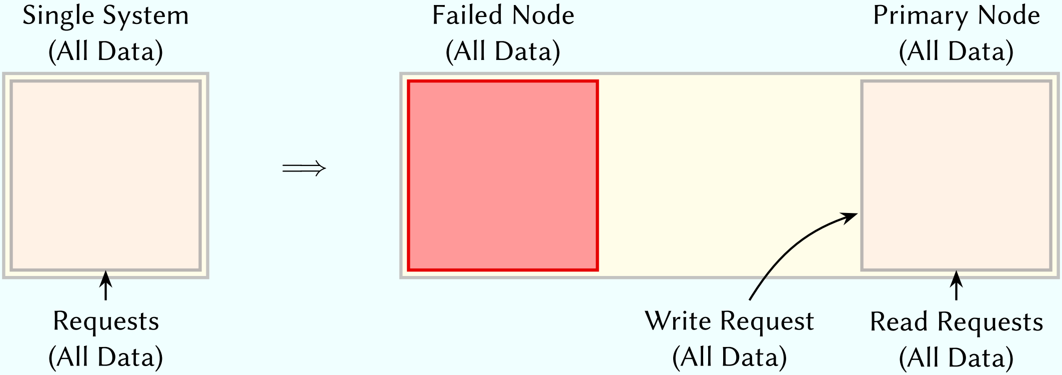


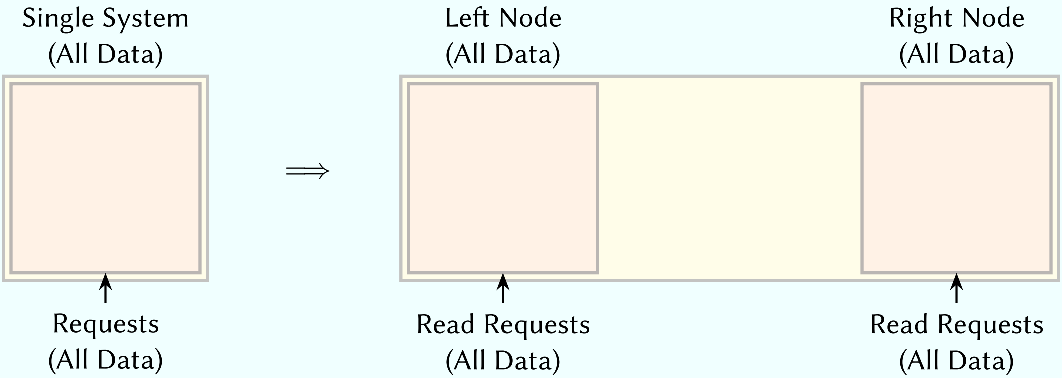
Changes to data requests: Primary *leads*, backups *follow*.

Distributed Systems: Reliability (Primary-Backup)



Failure: Recovery mechanisms—typically *complex*.

Distributed Systems: Reliability (Decentralized)



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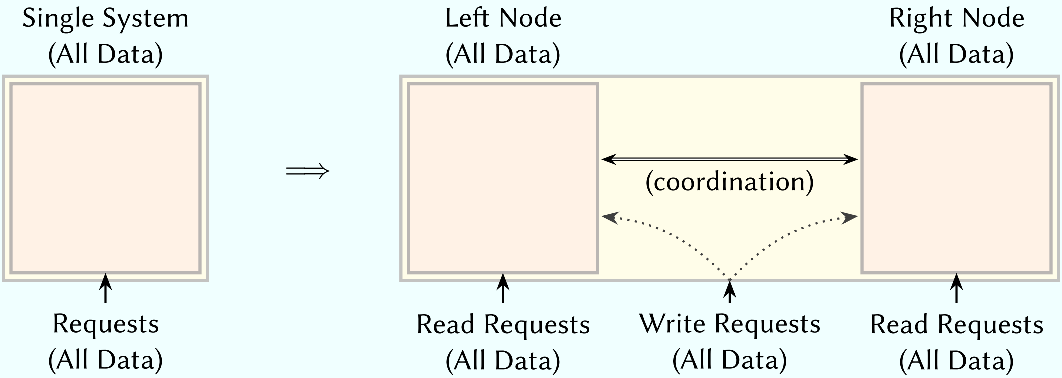

Changes to data requests: *Costly* coordinated decision among all active nodes.

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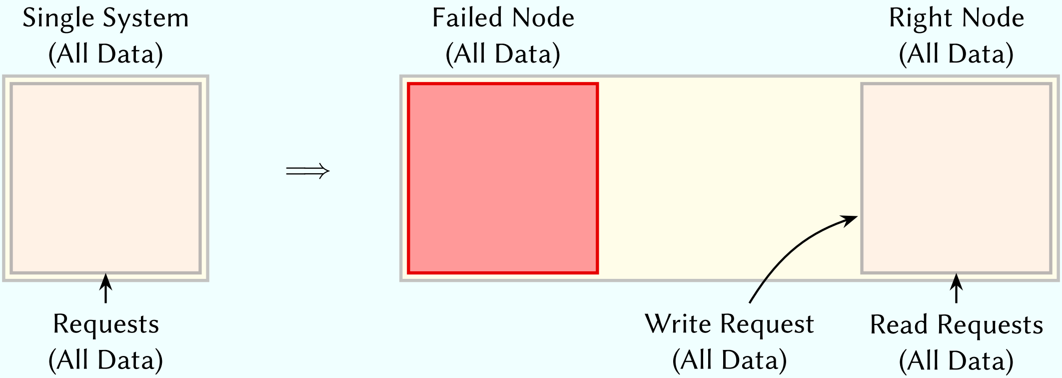
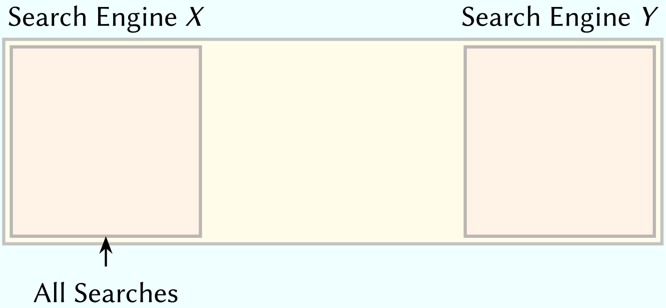


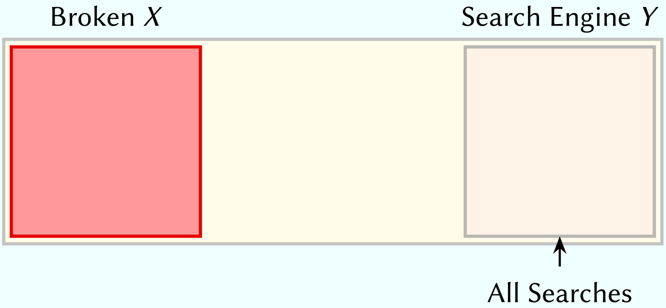
Failure: Recovery mechanisms—typically *easier* (or even *free*).

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.

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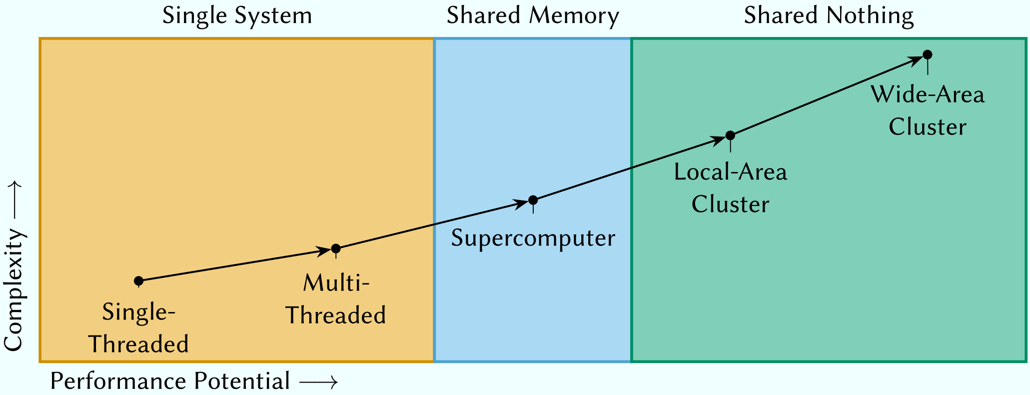
Distributed computing is *complex*



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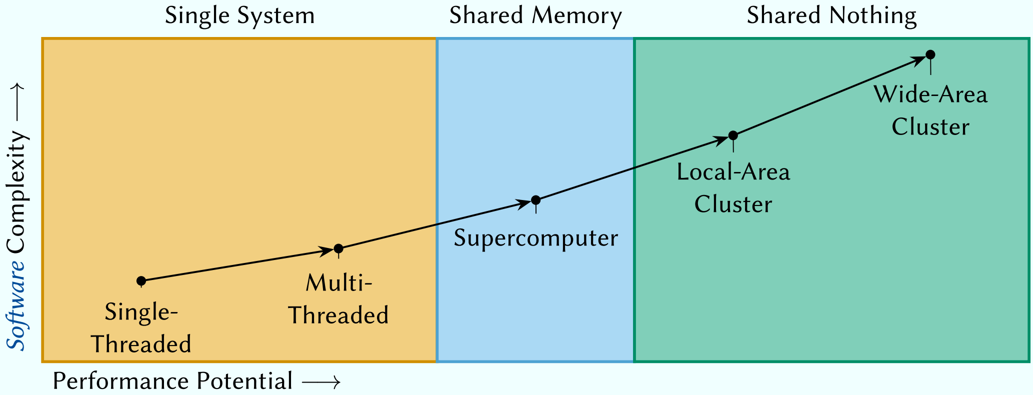

Complexity to write *efficient* software that solve a given problem.

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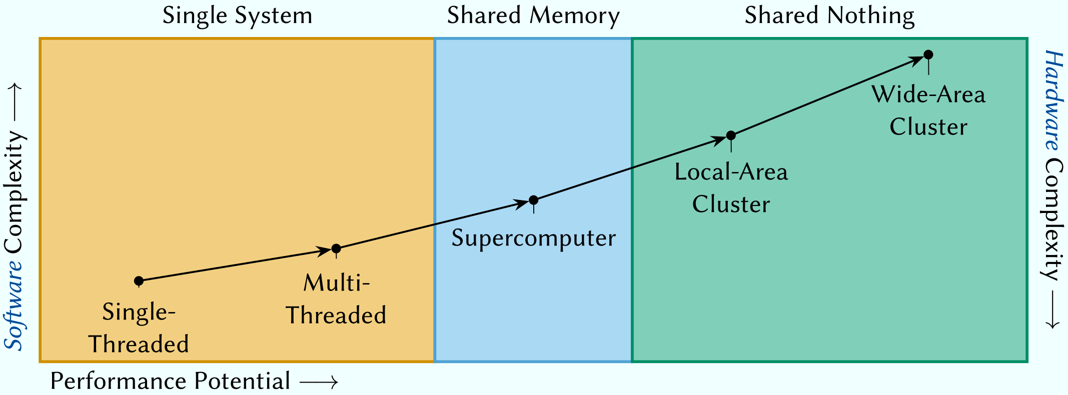

Complexity of *hardware* to solve a given problem in time t.

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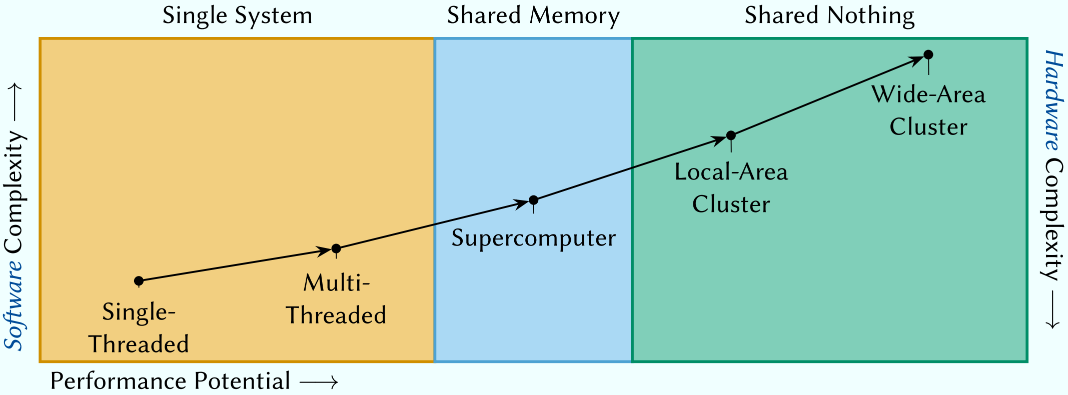

Increased software complexity is *fundamental*: Problems become theoretically harder.

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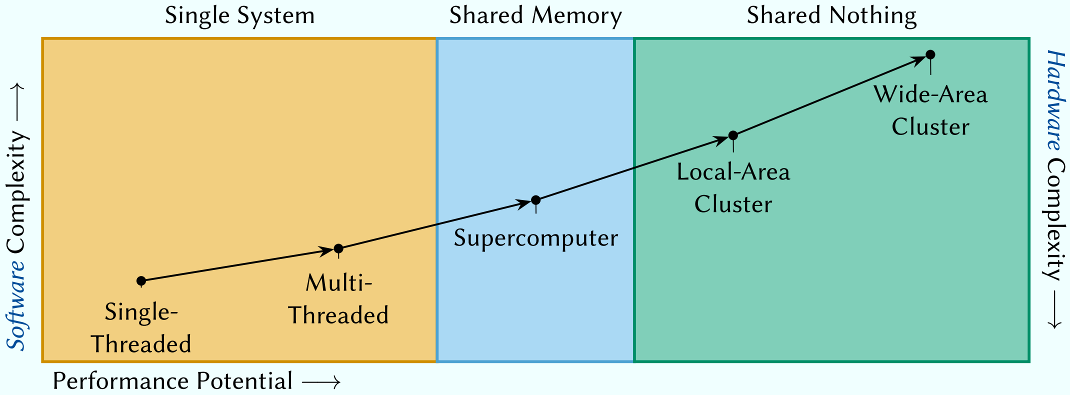

Do we really need distributed systems?

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Distributed designs can provide resilience.

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Consider a simple & minimalistic distributed system

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

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Availability All data is always accessible & updateable.
(The system can always provide services to clients).

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Consistency: All replicas have a single up-to-date copy of the data. (All replicas always have the same date).

Availability: All data is always accessible & updateable. (The system can always provide services to clients).

Partitioning: The system can tolerate network partitions. (The system can cope with network failures).

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Desirable Properties of a Distributed System

Consider a simple & minimalistic distributed system

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Theorem

A fully-replicated system can only privide two-out-of-three CAP properties.

[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.

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

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.

Resilient Systems

Definition

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

Outline of a Blockchain-Based Resilient System

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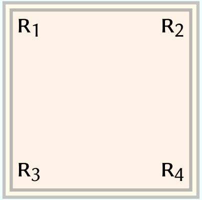

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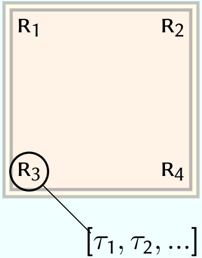

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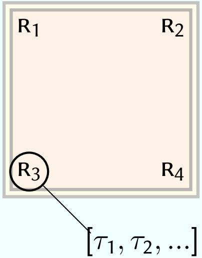

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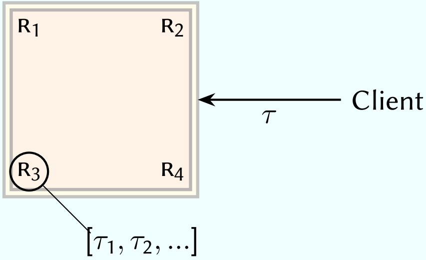

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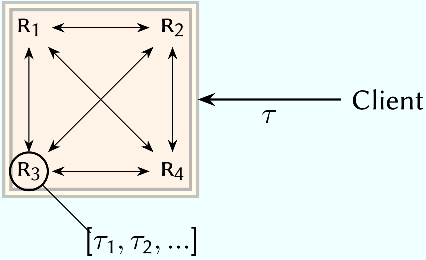

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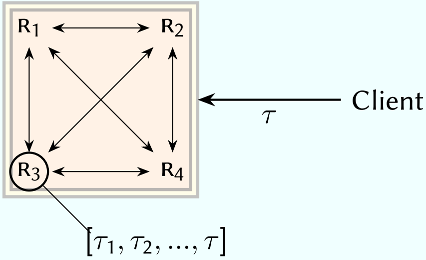

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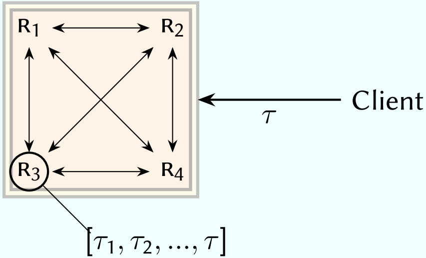

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Classifying Resilient Systems

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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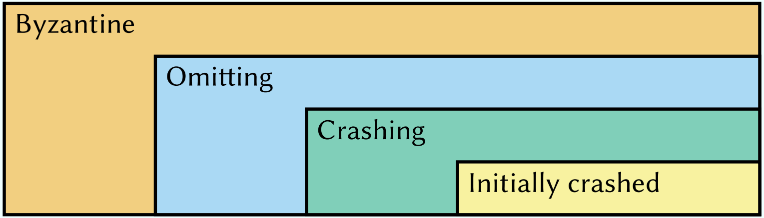

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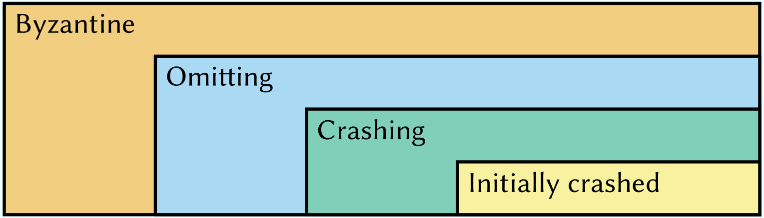

Both *omitting* and *Byzantine* replicas can be **malicious**: these replicas can **coordinate** among themselves in attempts to disrupt the system.

Communication Models

We say that communication is

synchronous if every message sent will arrive only at its destination, will do so exactly once within some *known delay*. Communication can be modeled in *rounds*.

asynchronous if messages can be arbitrarily delayed, duplicated, or *dropped*. Arbitrary delay: message can arrive *out of order*.

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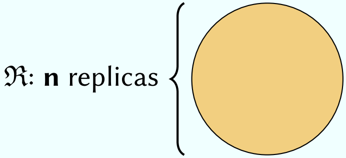
Notations for Resilient Systems

A resilient system is a *system* with

- A set of **n** *replicas* $\mathfrak{R}$.



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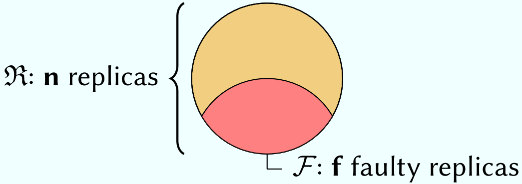

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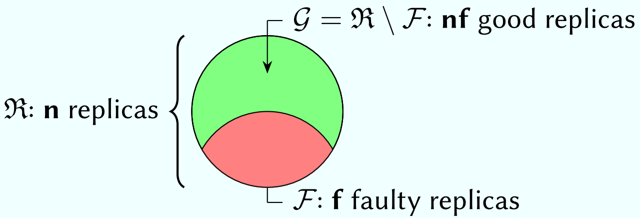

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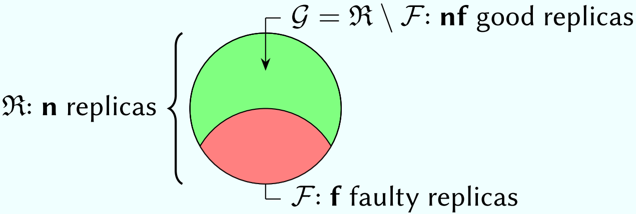
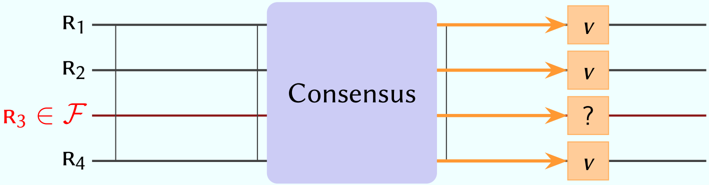


Coordination in Resilient Systems: Consensus

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

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

Non-divergence All good replicas decide on the same value.
Hence, if $R_1, R_2 \in \mathcal{G}$ decide $v(R_1)$ and $v(R_2)$, then $v(R_1) = v(R_2)$.



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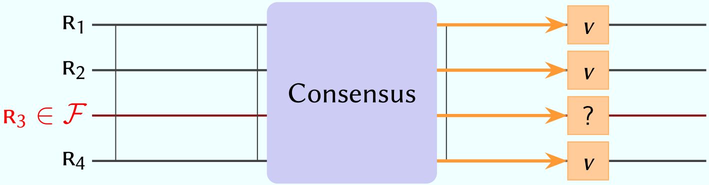
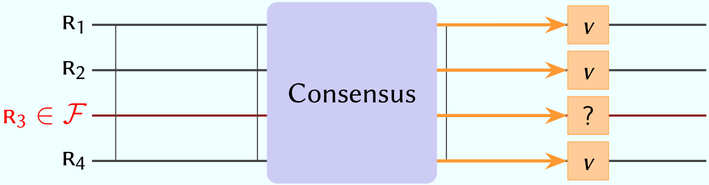


Excludes trivial solutions: e.g., good replicas always deciding a pre-defined value.

Coordination in Resilient Systems: Consensus

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

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



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Example: System processing client transactions

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

Coordination in Resilient Systems: Interactive Consistency

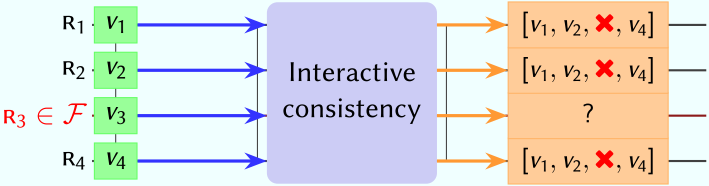
Assumption: Each replica R holds an initial value $v(\text{R})$

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

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

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

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



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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:

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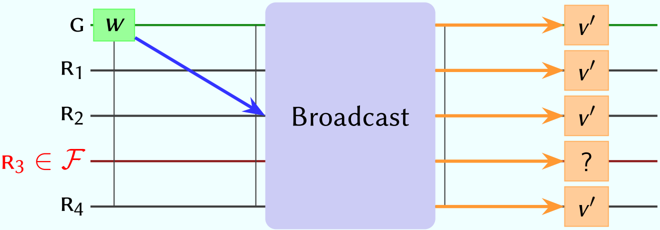
Hence, if $R_1, R_2 \in \mathcal{G}$ decide $v(R_1)$ and $v(R_2)$, then $v(R_1) = v(R_2)$.

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



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

From Byzantine Broadcasts to Interactive Consistency

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

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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?

	Initially Crashed	Crashed	Omitting	Byzantine	Byzantine (with MACs)	Byzantine (with DSs)
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Synchronous						

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Synchronous	$\mathbf{n} > \mathbf{f}$	$\mathbf{n} > \mathbf{f}$				

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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[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*
- *allows faulty replicas to crash.*

Real-world networks: Asynchronous, but mostly well-behaved

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Each good replica $\textsc{r} \in \mathcal{G}$ decides on a value $v(\textsc{r})$.

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Do not solve consensus: weaken the *termination* guarantee:

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

Weak termination Good replicas decide *when communication is well-behaved*.

Probabilistic termination Good replicas decide *with high probability*.

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[5] Weak or probabilistic termination.

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Synchronous	$\mathbf{n} > \mathbf{f}$	$\mathbf{n} > \mathbf{f}$	$\mathbf{n} > \mathbf{f}$	Impossible	$\mathbf{n} > 3\mathbf{f}$	~~$\mathbf{n} > \mathbf{f}$~~ $\mathbf{n} > 2\mathbf{f}$

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Synchronous	$\mathbf{n} > \mathbf{f}$	$\mathbf{n} > \mathbf{f}$	$\mathbf{n} > \mathbf{f}$	Impossible	$\mathbf{n} > 3\mathbf{f}$	~~$\mathbf{n} > \mathbf{f}$~~ $\mathbf{n} > 2\mathbf{f}$

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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.