Fault-Tolerant Distributed Transactions on Blockchain

Toward Scalable Blockchain


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Scalability versus Fully-Replicated Blockchains

Scalability: adding resources $\Longrightarrow$ *adding performance.*

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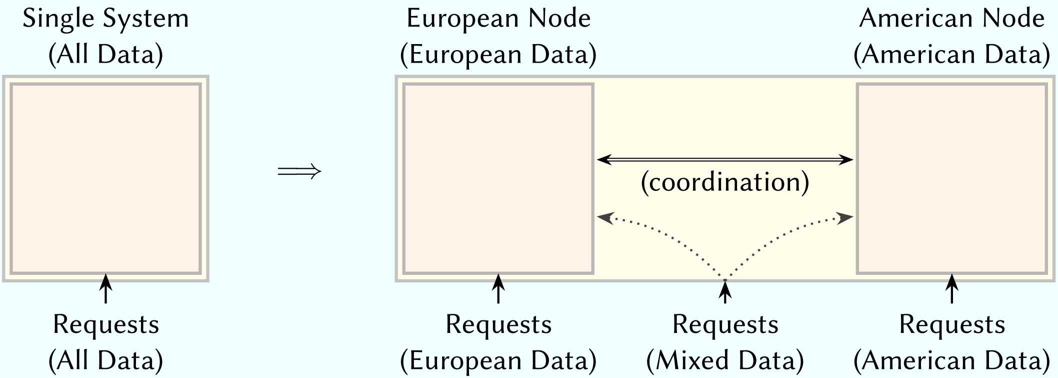
Scalability: adding resources $\Longrightarrow$ *adding performance.*

Full replication: adding resources (replicas) $\Longrightarrow$ less performance!

Distributed Systems: Scalability



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

Potentially *lower latencies* if data ends up closer to users.

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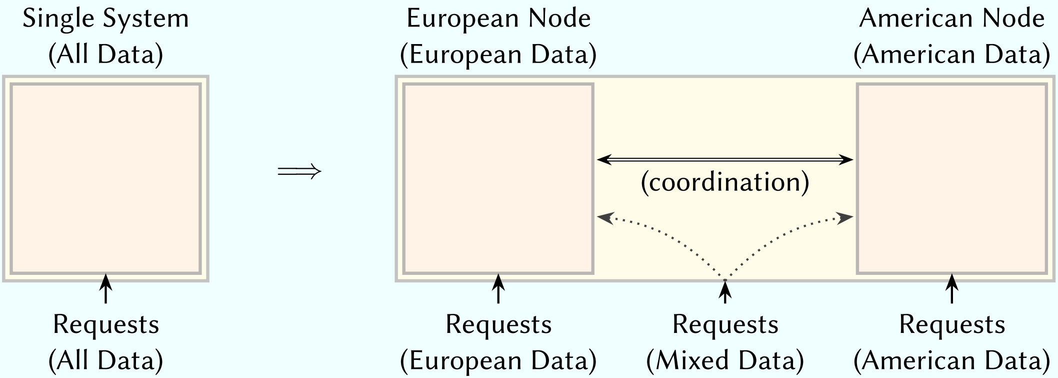

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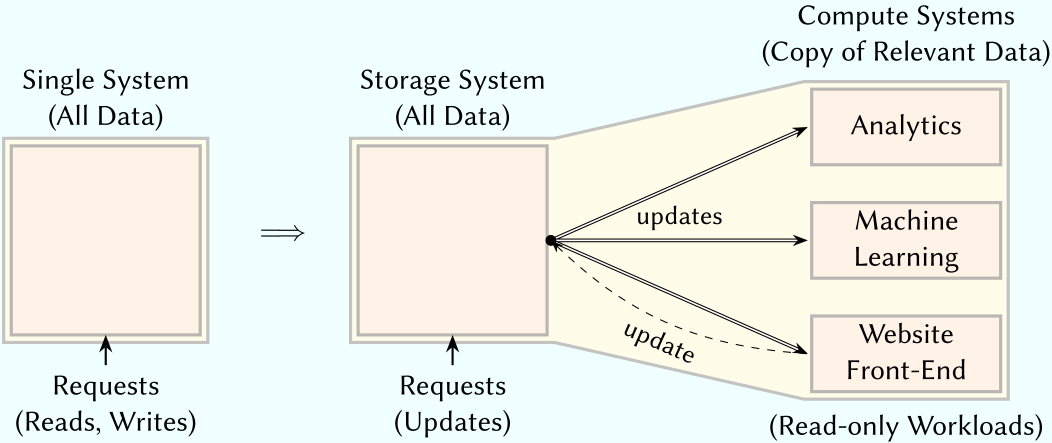
Adding shards $\Longrightarrow$ adding throughput (parallel processing), adding storage.

Distributed Systems: Specialization



Specialize the system: Different nodes have distinct tasks.

Specialized hardware and software *per* task.

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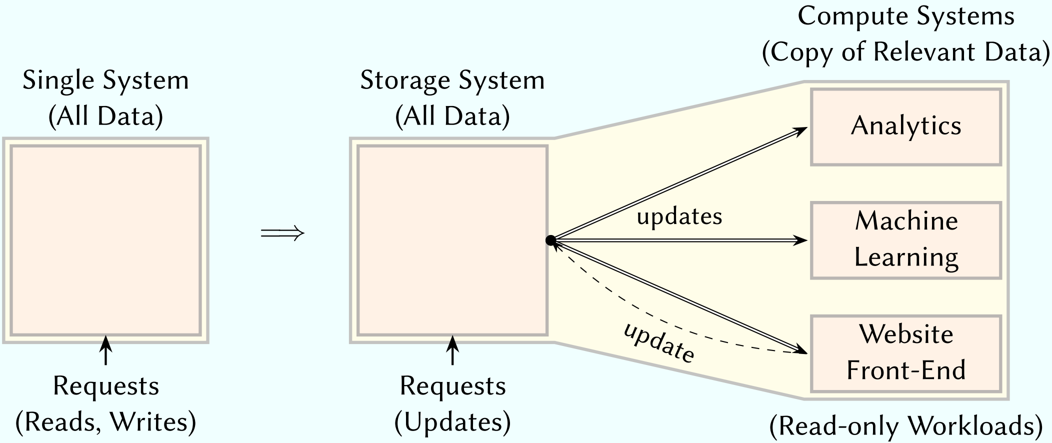

Specialize the system: Different nodes have distinct tasks.
Specialized hardware and software *per* task.

Specializing roles $\Longrightarrow$ adding throughput (parallel processing, specialized hardware, ...).

Central Ideas for Improvement

Reminder

We can make a resilient system that manages data: e.g., fully-replicated blockchains.

- **Role Specialization**: make the storage system a blockchain.
  Requires: *reliable read-only updates of the blockchain.*
  Permissionless blockchains: light clients!
- **Sharding**: make each shard an independent blockchain.
  Requires: *reliable communication between blockchains.*
  Permissionless blockchains: relays, atomic swaps!

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  Permissionless blockchains: relays, atomic swaps!

Consensus is of no use here if we want efficiency.

Reliable Read-Only Updates of Fault-Tolerant Clusters

Definition

Let $\mathcal{C}$ be a cluster deciding on a sequence of transactions $\mathcal{L}$ and L be a learner.

The *Byzantine learning problem* is the problem of sending $\mathcal{L}$ from $\mathcal{C}$ to L such that:

- the learner L will eventually *receive all* decided transactions;
- the learner L will *only receive* decided transactions.

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Practical requirements

- Minimizing overall communication.
- Load balancing among all replicas in $\mathcal{C}$.

Background: Information Dispersal Algorithms

Definition

Let v be a value with storage size $s = \|v\|$.
An *information dispersal algorithm* can encode v in $\mathbf{n}$ pieces v'
such that v can be *decoded* from every set of $\mathbf{n} - \mathbf{f}$ such pieces.

Theorem (Rabin 1989)

The IDA algorithm is an optimal information dispersal algorithm:

- *Each piece v' has size* $\left\lceil \frac{\|v\|}{\mathbf{n}-\mathbf{f}} \right\rceil$.
- *The $\mathbf{n} - \mathbf{f}$ pieces necessary for decoding have a total size of* $(\mathbf{n} - \mathbf{f}) \left\lceil \frac{\|v\|}{(\mathbf{n}-\mathbf{f})} \right\rceil \approx \|v\|$.

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4. L *receives at least* $\mathbf{n} - \mathbf{f}$ *distinct pieces and decodes* S.

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Idea: $\mathcal{C}$ sends a ledger to learner $\textsc{l}$

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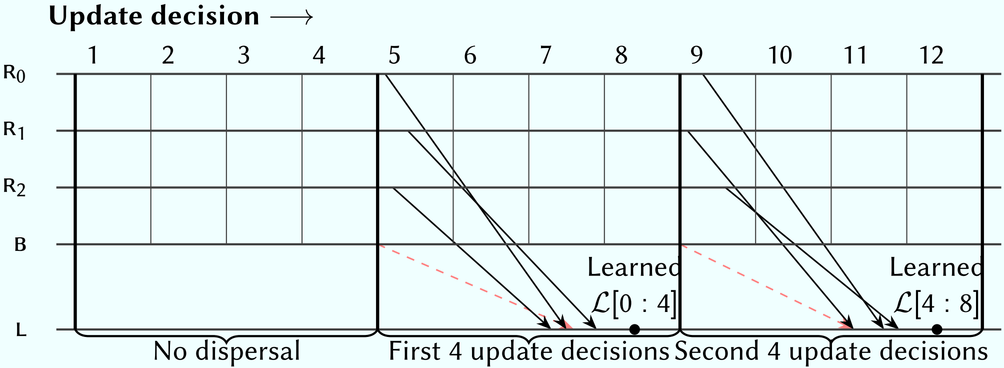
3. Replica $\textsc{r}_i \in \mathcal{C}$ sends S_i with a checksum $C_i(S)$ of S to $\textsc{l}$.
4. $\textsc{l}$ *receives at least* $\mathbf{n} - \mathbf{f}$ *distinct pieces and decodes* S.

Observation ($\mathbf{n} > 2\mathbf{f}$)

- Replica $\textsc{r}_i$ sends at most $B = \left\lceil \frac{\|S\|}{\mathbf{n}-\mathbf{f}} \right\rceil + c \leq \frac{2\|S\|}{\mathbf{n}} + 1 + c = \mathcal{O}(\frac{\|S\|}{\mathbf{n}} + c)$ bytes.
- Learner $\textsc{l}$ receives at most $\mathbf{n} \cdot B = \mathcal{O}(\|S\| + c\mathbf{n})$ bytes.

Communication by the Delayed-Replication Algorithm



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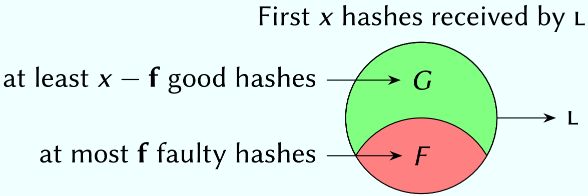

Wait until $\mathbf{f} + 1 \leq \mathbf{nf}$ identical hashes: hash(S).

Decoding S Using Simple Checksums ($\mathbf{n} > 2\mathbf{f}$)

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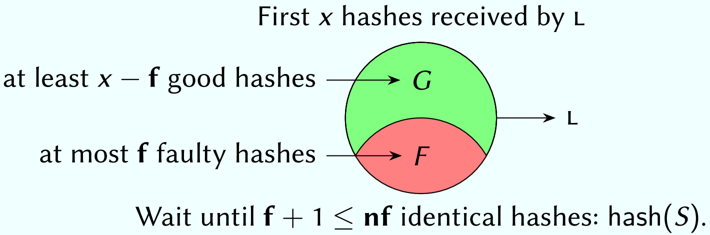


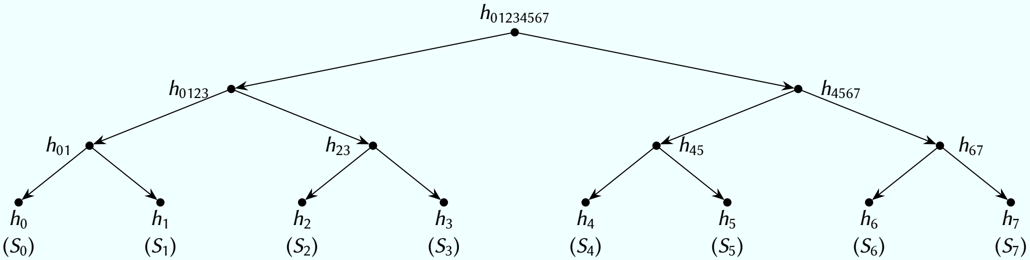
- Intensive for learners: one can choose $\mathbf{n} - \mathbf{f}$ out of $\mathbf{n}$ messages in $\binom{\mathbf{n}}{\mathbf{n}-\mathbf{f}}$ ways
  only one such choice is guaranteed to be correct!

Decoding S Using Tree Checksums

Use Merkle-trees to construct checksums

Consider 8 replicas and a sequence S.

We construct the checksum $C_5(S)$ of S (used by R_5).



Construct a Merkle tree for pieces $S_0, \ldots, S_7$.

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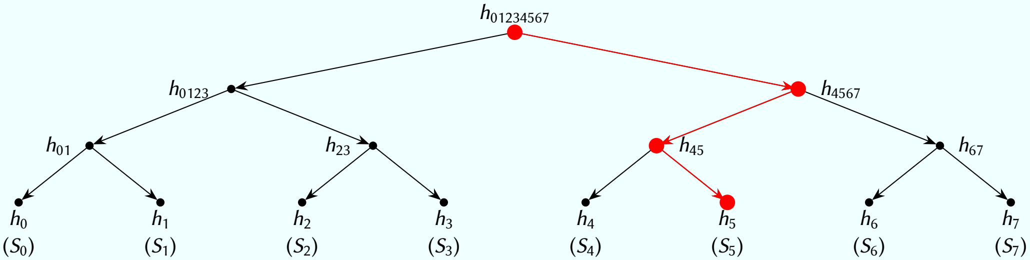

Determine the path from root to S_5.

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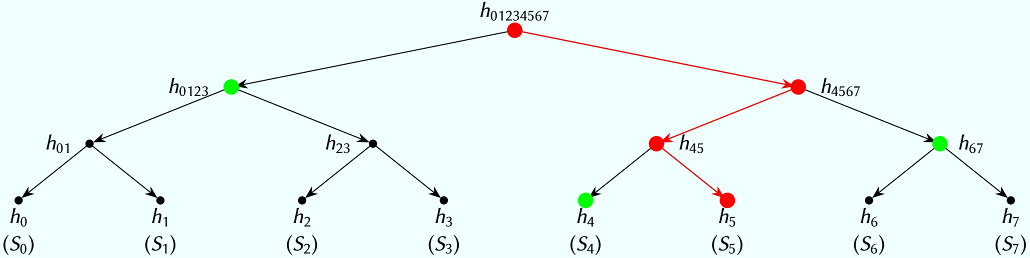

Select *root* and *neighbors*: $C_5(S) = [h_4, h_{67}, h_{0123}, h_{01234567}]$.

Delayed-Replication: Main Result ($\mathbf{n} > 2\mathbf{f}$)

Theorem

Consider the learner L*, replica* R*, and decided transactions* $\mathcal{T}$*. The delayed-replication algorithm with tree checksums guarantees*

1. L *will learn* $\mathcal{T}$*;*
2. L *will receive at most* $|\mathcal{T}|$ *messages with a total size of* $\mathcal{O}(\|\mathcal{T}\| + |\mathcal{T}| \log \mathbf{n})$*;*
3. L *will only need at most* $\frac{|\mathcal{T}|}{\mathbf{n}}$ *decode steps;*
4. R *will sent at most* $\frac{|\mathcal{T}|}{\mathbf{n}}$ *messages to* L *of size* $\mathcal{O}(\frac{\|\mathcal{T}\|+|\mathcal{T}| \log \mathbf{n}}{\mathbf{n}})$*.*

Application: Scalable Storage for Resilient Systems

- Replicas typically only need the *current data* V to decide on future updates.
- Replicas only need the full ledger $\mathcal{L}$ for *recovery*.
- We can use *delayed-replication* to reduce the data each replica has to store.

Theorem

The storage cost per replica can be reduced from

$$\mathcal{O}(\|\mathcal{L}\| + \|V\|) \quad \textit{to} \quad \mathcal{O}(\frac{\|\mathcal{L}\|}{\mathbf{n}-\mathbf{f}} + \frac{|\mathcal{L}|}{\mathbf{n}}\log(\mathbf{n}) + \|V\|).$$

Reliable Communication between Fault-Tolerant Clusters

Definition

Let $\mathcal{C}_1, \mathcal{C}_2$ be two clusters, both having non-faulty replicas.

The *cluster-sending problem* is the problem of sending a value v from $\mathcal{C}_1$ to $\mathcal{C}_2$ such that:

1. non-faulty replicas in $\mathcal{C}_2$ *receive* v;
2. non-faulty replicas in $\mathcal{C}_1$ *confirm* that v was received by the non-faulty replicas in $\mathcal{C}_2$;
3. replicas in $\mathcal{C}_2$ only receive v if all non-faulty replicas in $\mathcal{C}_1$ *agree* upon sending v.

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Informal Definition

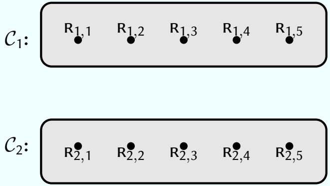
Successfully sending a value v from a cluster $\mathcal{C}_1$ to a $\mathcal{C}_2$ without any faulty replicas being able to *disrupt sending* or send *alternative forged values*.

Basic Cluster-Sending via Broadcasting

Goal: send a value v from cluster $\mathcal{C}_1$ to cluster $\mathcal{C}_2$.

Assumptions

- Every replica in $\mathcal{C}_1$ has a *certificate* $\text{cert}(v, \mathcal{C}_1)$ that proves agreement.
- Communication is *reliable*.
- At-most *two* replicas faulty in each cluster.



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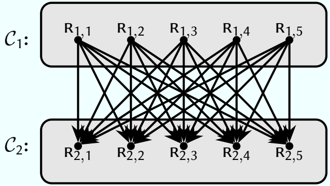

Broadcast: every replica in $\mathcal{C}_1$ sends pairs $(v, \text{cert}(v, \mathcal{C}_1))$ to every replica in $\mathcal{C}_2$.

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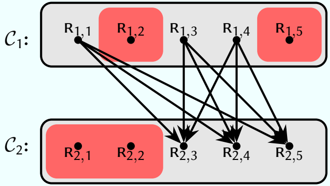

Faulty replicas can *fail* to send (in $\mathcal{C}_1$) or to receive (in $\mathcal{C}_2$).

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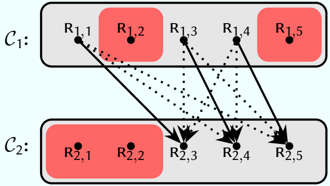

Non-faulty replicas in $\mathcal{C}_2$ only need at-least one message $(v, \text{cert}(v, \mathcal{C}_1))$.

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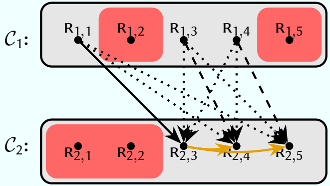

Replicas in $\mathcal{C}_2$ can redistribute $(v, \text{cert}(v, \mathcal{C}_1))$.

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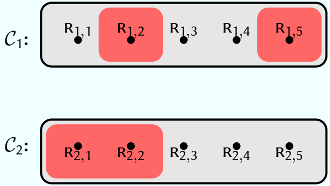

With certificates: a *single* message between non-faulty sender and receiver is sufficient!

Basic Cluster-Sending via Broadcasting (Without Certificates)

Goal: send a value v from cluster $\mathcal{C}_1$ to cluster $\mathcal{C}_2$.

Assumptions

- Every replica $\textsc{r} \in \mathcal{C}_1$ can only *claim* agreement via a digital signature $\mathrm{cert}(v, \textsc{r})$.
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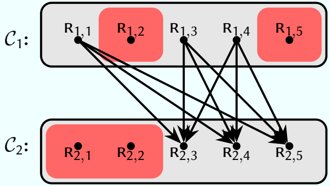

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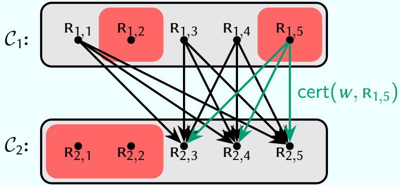

Faulty replicas can *lie* and send $\text{cert}(w, \textsc{r})$ without agreement on w.

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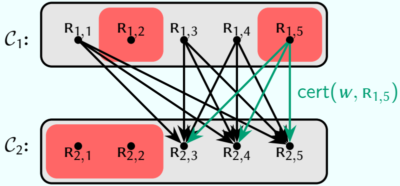

Claims from *three* distinct replicas in $\mathcal{C}_1$: at-least one from a non-faulty replica.

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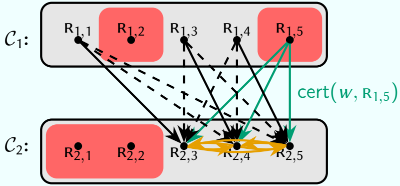

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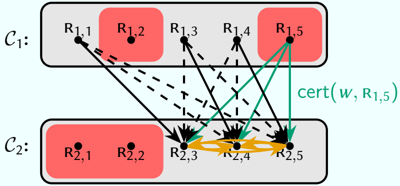

Without certificates: *at least* $\mathbf{f}_{\mathcal{C}_1} + 1$ distinct received messages by non-faulty senders!

Efficient Cluster-Sending

Cluster-Sending via broadcasting: straightforward, *not efficient*:

- With certificates: $(\mathbf{f}_{\mathcal{C}_1} + 1)(\mathbf{f}_{\mathcal{C}_2} + 1) \approx \mathbf{f}_{\mathcal{C}_1} \times \mathbf{f}_{\mathcal{C}_2}$ messages.
- With claims: $(2\mathbf{f}_{\mathcal{C}_1} + 1)(\mathbf{f}_{\mathcal{C}_2} + 1) \approx 2\mathbf{f}_{\mathcal{C}_1} \times \mathbf{f}_{\mathcal{C}_2}$ messages.

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Local communication versus global communication

	Ping round-trip times (ms)						*Bandwidth (Mbit/s)*					
	OR	IA	Mont.	BE	TW	Syd.	OR	IA	Mont.	BE	TW	Syd.
Oregon	≤ 1	38	65	136	118	161	7998	669	371	194	188	136
Iowa		≤ 1	33	98	153	172		10004	752	243	144	120
Montreal			≤ 1	82	186	202			7977	283	111	102
Belgium				≤ 1	252	270				9728	79	66
Taiwan					≤ 1	137					7998	160
Sydney						≤ 1						7977

Goal: Minimize communication *between* clusters.

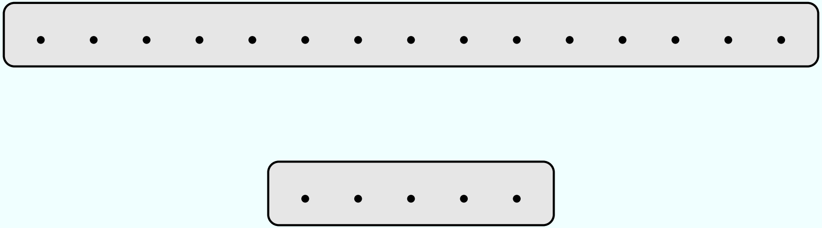
Towards a Lower-Bound for Cluster-Sending (Example)

$$\mathbf{n}_{\mathcal{C}_1} = 15 \qquad \mathbf{f}_{\mathcal{C}_1} = 7$$

$$\mathbf{n}_{\mathcal{C}_2} = 5 \qquad \mathbf{f}_{\mathcal{C}_2} = 2$$

Proposition (assuming certificates)

Any correct algorithm needs to send at least 14 *messages*.



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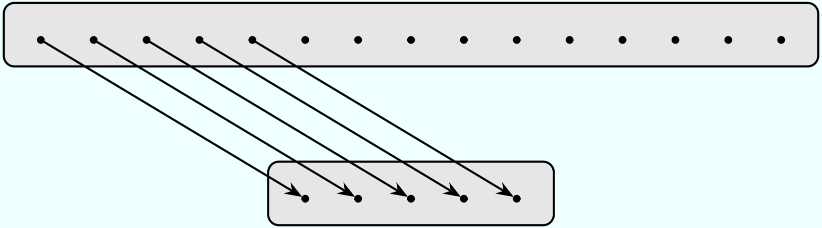

Minimize impact of faulty replicas: minimum number of messages per participant.

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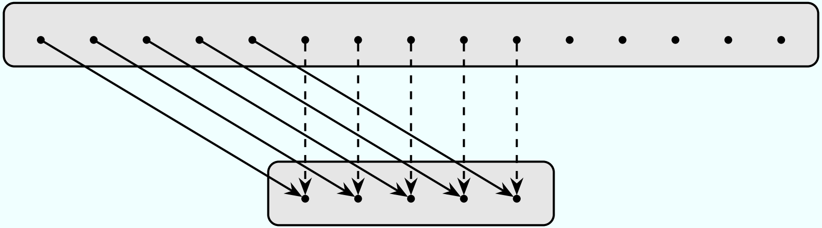

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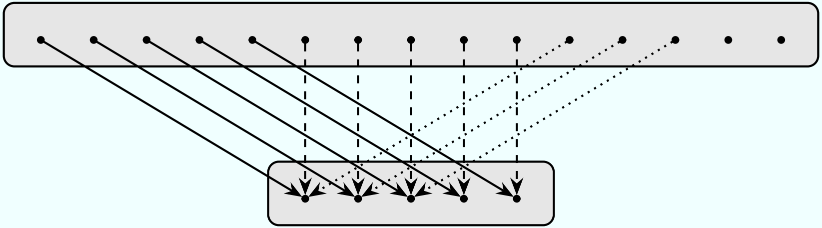

Minimize impact of faulty replicas: minimum number of messages per participant.

Towards a Lower-Bound for Cluster-Sending (Example)

$\mathbf{n}_{\mathcal{C}_1} = 15$ $\mathbf{f}_{\mathcal{C}_1} = 7$

$\mathbf{n}_{\mathcal{C}_2} = 5$ $\mathbf{f}_{\mathcal{C}_2} = 2$

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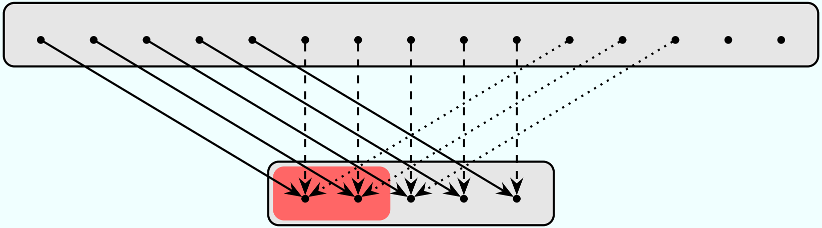

Any $\mathbf{f}_{\mathcal{C}_2}$ replicas in $\mathcal{C}_2$ can be faulty: top $\mathbf{f}_{\mathcal{C}_2}$ receivers receive at-least 6 messages.

Towards a Lower-Bound for Cluster-Sending (Example)

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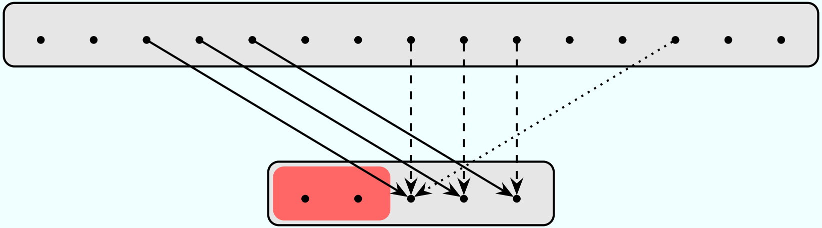

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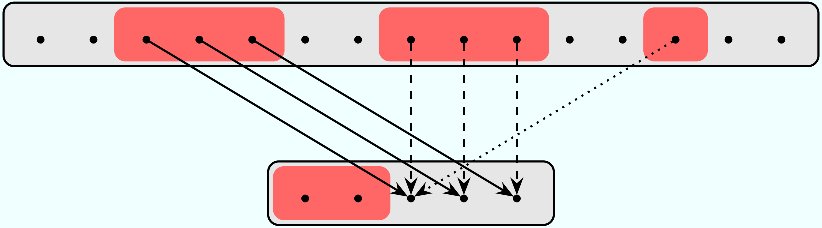

Only $\mathbf{f}_{\mathcal{C}_1}$ messages remaining, can all be sent by faulty replicas in $\mathcal{C}_1$.

Towards a Lower-Bound for Cluster-Sending (Example)

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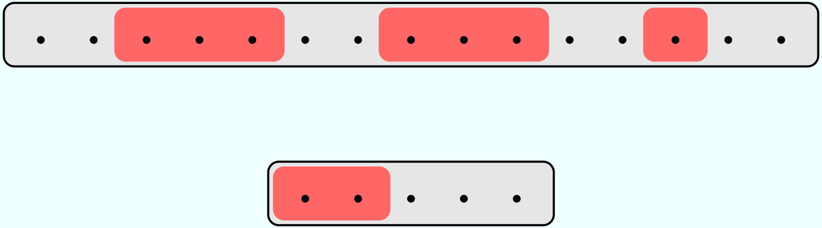

Lower-Bound for Cluster-Sending with Certificates

Basic Idea

- One message needs to be exchanged between a non-faulty sender and receiver.
- Have to deal with size imbalances between clusters.

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Theorem

Let $\mathcal{C}_1, \mathcal{C}_2$ be two clusters and let $\{i, j\} = \{1, 2\}$ such that $\mathbf{n}_{\mathcal{C}_i} \geq \mathbf{n}_{\mathcal{C}_j}$. Let

$$q_i = (\mathbf{f}_{\mathcal{C}_i} + 1) \operatorname{div} \mathbf{nf}_{\mathcal{C}_j},$$
$$r_i = (\mathbf{f}_{\mathcal{C}_i} + 1) \bmod \mathbf{nf}_{\mathcal{C}_j},$$
$$\sigma_i = q_i \mathbf{n}_{\mathcal{C}_j} + r_i + \mathbf{f}_{\mathcal{C}_j} \operatorname{sgn} r_i.$$

Any protocol that solves the cluster-sending problem in which $\mathcal{C}_1$ sends a value v to $\mathcal{C}_2$ needs to exchange at least σ_i messages.

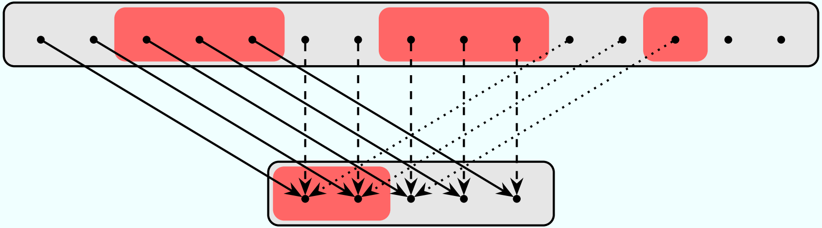
Lower-Bound for Cluster-Sending with Certificates (Example)

Theorem

Let $\mathcal{C}_1, \mathcal{C}_2$ *be two clusters and let*

$$q_1 = (\mathbf{f}_{\mathcal{C}_1} + 1) \operatorname{div} \mathbf{nf}_{\mathcal{C}_2} = 7 \operatorname{div} 3 = 2,$$
$$r_1 = (\mathbf{f}_{\mathcal{C}_1} + 1) \bmod \mathbf{nf}_{\mathcal{C}_2} = 7 \bmod 3 = 1,$$
$$\sigma_1 = q_1 \mathbf{n}_{\mathcal{C}_2} + r_1 + \mathbf{f}_{\mathcal{C}_2} \operatorname{sgn} r_1 = 2 \cdot 5 + 1 + 3 = 14.$$

Any protocol that solves the cluster-sending problem in which $\mathcal{C}_1$ *sends a value v to* $\mathcal{C}_2$ *needs to exchange at least* $\sigma_1 = 14$ *messages.*



Lower-Bound for Cluster-Sending with Certificates (Example)

Theorem

Let $\mathcal{C}_1, \mathcal{C}_2$ be two clusters and let

$$\begin{aligned} q_1 &= (\mathbf{f}_{\mathcal{C}_1} + 1) \operatorname{div} \mathbf{nf}_{\mathcal{C}_2} = 7 \operatorname{div} 3 = 2, \\ r_1 &= (\mathbf{f}_{\mathcal{C}_1} + 1) \bmod \mathbf{nf}_{\mathcal{C}_2} = 7 \bmod 3 = 1, \\ \sigma_1 &= \boxed{q_1 \mathbf{n}_{\mathcal{C}_2}} + r_1 + \mathbf{f}_{\mathcal{C}_2} \operatorname{sgn} r_1 = \boxed{2 \cdot 5} + 1 + 3 = 14. \end{aligned}$$

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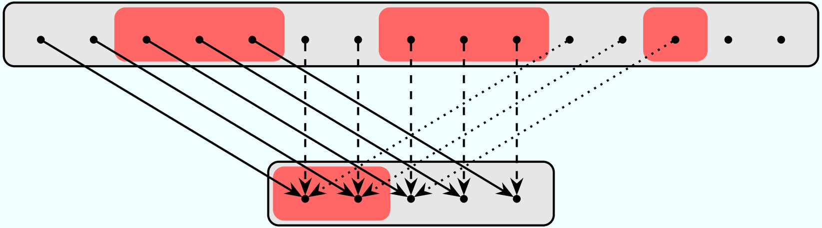

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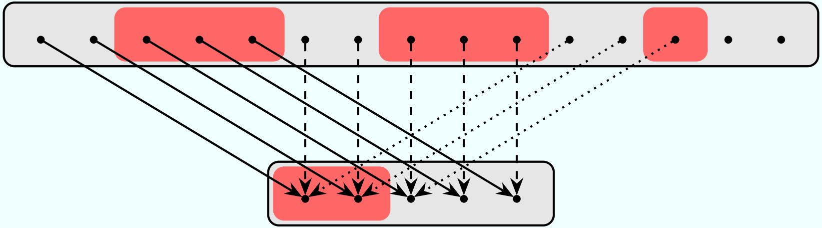

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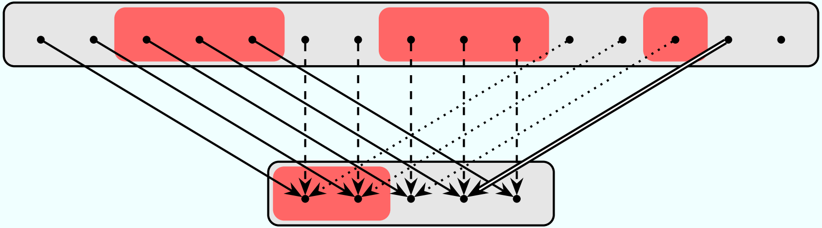

Lower-Bound for Cluster-Sending with Claims

Basic Idea

- $\mathbf{f}_{\mathcal{C}_1} + 1$ message needs to be sent by distinct non-faulty senders to non-faulty receiver.
- Have to deal with size imbalances between clusters.

Theorem

Let $\mathcal{C}_1, \mathcal{C}_2$ be two clusters and let $\{i, j\} = \{1, 2\}$ such that $\mathbf{n}_{\mathcal{C}_i} \geq \mathbf{n}_{\mathcal{C}_j}$. Let

$$q_1 = (2\mathbf{f}_{\mathcal{C}_1} + 1) \operatorname{div} \mathbf{nf}_{\mathcal{C}_2}, \qquad q_2 = (\mathbf{f}_{\mathcal{C}_2} + 1) \operatorname{div} (\mathbf{nf}_{\mathcal{C}_1} - \mathbf{f}_{\mathcal{C}_1})$$

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$$\tau_1 = q_1 \mathbf{n}_{\mathcal{C}_2} + r_1 + \mathbf{f}_{\mathcal{C}_2} \operatorname{sgn} r_1 \qquad \tau_2 = q_2 \mathbf{n}_{\mathcal{C}_1} + r_2 + 2\mathbf{f}_{\mathcal{C}_1} \operatorname{sgn} r_2.$$

Any protocol that solves the cluster-sending problem in which $\mathcal{C}_1$ sends a value v to $\mathcal{C}_2$ needs to exchange at least τ_i messages.

Bijective Sending with Certificates

Assume $\mathbf{f}_{\mathcal{C}_1} + \mathbf{f}_{\mathcal{C}_2} + 1 \leq \min(\mathbf{n}_{\mathcal{C}_1}, \mathbf{n}_{\mathcal{C}_2})$.

We have $\sigma_1 = \sigma_2 = \mathbf{f}_{\mathcal{C}_1} + \mathbf{f}_{\mathcal{C}_2} + 1$.

Protocol for the sending cluster $\mathcal{C}_1$:

```
All replicas in 𝒢_{𝒞1} agree on v and construct cert(v, 𝒞1).
Choose replicas S1 ⊆ 𝒞1 and S2 ⊆ 𝒞2 with n_{S2} = n_{S1} = f_{𝒞1} + f_{𝒞2} + 1.
Choose a bijection b : S1 → S2.
for R1 ∈ S1 do
    R1 sends (v, cert(v, 𝒞1)) to b(R1).
```

Protocol for the receiving cluster $\mathcal{C}_2$:

```
event R2 ∈ 𝒢_{𝒞2} receives (w, cert(w, 𝒞1)) from R1 ∈ 𝒞1 do
    Broadcast (w, cert(w, 𝒞1)) to all replicas in 𝒞2.
event R2′ ∈ 𝒢_{𝒞2} receives (w, cert(w, 𝒞1)) from R2 ∈ 𝒞2 do
    R2′ considers w received.
```

Bijective Sending with Certificates: Example

$$\mathbf{n}_{\mathcal{C}_1} = 8 \qquad \mathbf{f}_{\mathcal{C}_1} = 3$$

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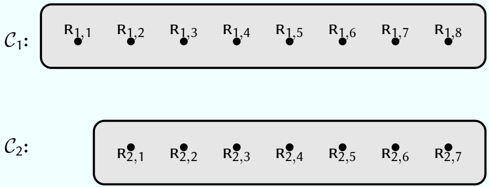
$$\sigma_1 = 6.$$



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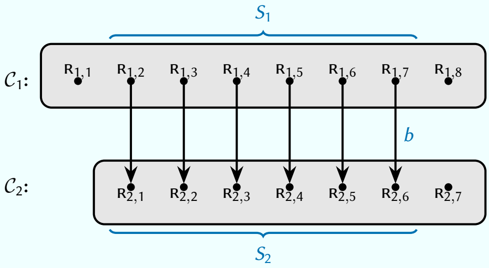

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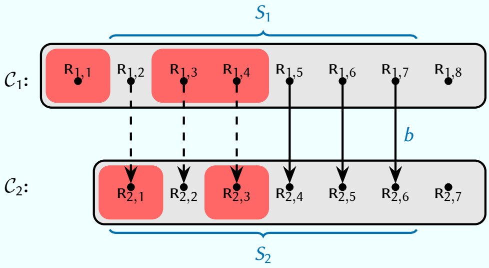

Bijective Sending with Claims

Assume $2\mathbf{f}_{\mathcal{C}_1} + \mathbf{f}_{\mathcal{C}_2} + 1 \leq \min(\mathbf{n}_{\mathcal{C}_1}, \mathbf{n}_{\mathcal{C}_2})$.

We have $\tau_1 = \tau_2 = 2\mathbf{f}_{\mathcal{C}_1} + \mathbf{f}_{\mathcal{C}_2} + 1$.

Protocol for the sending cluster $\mathcal{C}_1$:

All replicas in $\mathcal{G}_{\mathcal{C}_1}$ agree on v.
Choose replicas $S_1 \subseteq \mathcal{C}_1$ and $S_2 \subseteq \mathcal{C}_2$ with $\mathbf{n}_{S_2} = \mathbf{n}_{S_1} = 2\mathbf{f}_{\mathcal{C}_1} + \mathbf{f}_{\mathcal{C}_2} + 1$.
Choose bijection $b : S_1 \to S_2$.
for $\textsc{r}_1 \in S_1$ **do**
    $\textsc{r}_1$ sends $(v, \text{cert}(v, \textsc{r}_1))$ to $b(\textsc{r}_1)$.

Protocol for the receiving cluster $\mathcal{C}_2$:

. . . .

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. . . .

Protocol for the receiving cluster $\mathcal{C}_2$:

event $\mathrm{R}_2 \in \mathcal{G}_{\mathcal{C}_2}$ receives $(w, \mathrm{cert}(w, \mathrm{R}_1'))$ from $\mathrm{R}_1' \in \mathcal{C}_1$ **do**

  Broadcast $(w, \mathrm{cert}(w, \mathrm{R}_1'))$ to all replicas in $\mathcal{C}_2$.

event $\mathrm{R}_2' \in \mathcal{G}_{\mathcal{C}_2}$ receives $\mathbf{f}_{\mathcal{C}_1} + 1$ messages $(w, \mathrm{cert}(w, \mathrm{R}_1'))$:

(i) each message is sent by a replica in $\mathcal{C}_2$;

(ii) each message carries the same value w; and

(iii) each message has a distinct signature $\mathrm{cert}(w, \mathrm{R}_1')$, $\mathrm{R}_1' \in \mathcal{C}_1$

do

  R_2' considers w *received*.

Generalizing Bijective Sending

Consider bijective sending from $\mathcal{C}_1$ to $\mathcal{C}_2$, $\mathbf{n}_{\mathcal{C}_1} \geq \sigma_1 > \mathbf{n}_{\mathcal{C}_2}$, with certificates.

- Bijective sending requires $\mathbf{f}_{\mathcal{C}_1} + \mathbf{f}_{\mathcal{C}_2} + 1$ distinct replicas in both clusters.
- Restrictive: clusters of roughly the same size.

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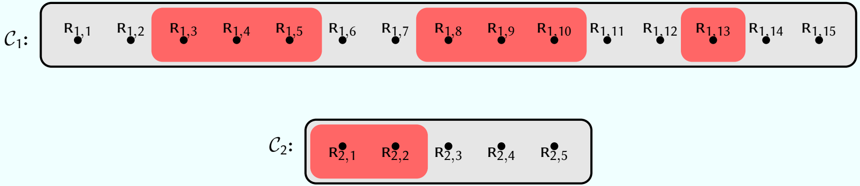

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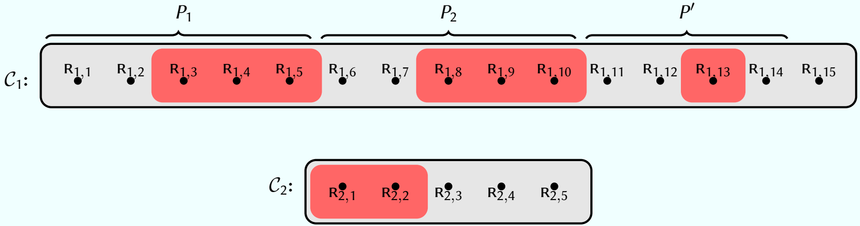

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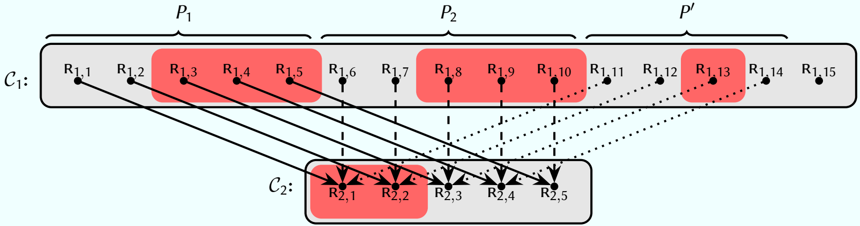

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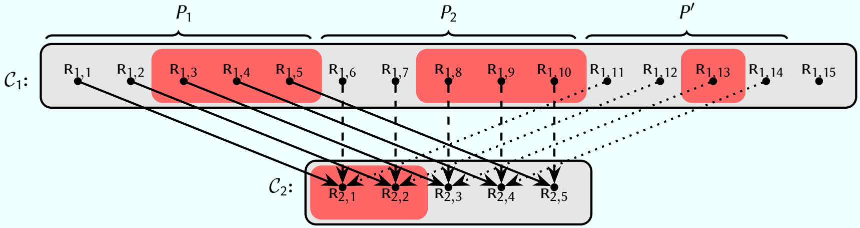
Generalize bijective sending

- Partition σ_1 replicas of $\mathcal{C}_1$ into $\mathbf{n}_{\mathcal{C}_2}$-sized clusters.
- Bijective send from each cluster in the partition to $\mathcal{C}_2$.
- $\mathbf{n}_{\mathcal{C}_1} \geq \sigma_1$ holds always if $\mathbf{n}_{\mathcal{C}_1} > 3\mathbf{f}_{\mathcal{C}_1}$ and $\mathbf{n}_{\mathcal{C}_2} > 3\mathbf{f}_{\mathcal{C}_2}$.



Partitioned Bijective Sending

Corollary

Consider the cluster-sending problem in which $\mathcal{C}_1$ sends a value v to $\mathcal{C}_2$.

1. *If $\mathbf{n}_{\mathcal{C}} > 3\mathbf{f}_{\mathcal{C}}$ for all clusters $\mathcal{C}$ and replicas only have crash failures or omit failures, then (partitioned) bijective sending solves cluster-sending with optimal message complexity.*
2. *If $\mathbf{n}_{\mathcal{C}} > 3\mathbf{f}_{\mathcal{C}}$ for all clusters $\mathcal{C}$ and clusters can produce certificates, then (partitioned) bijective sending solves cluster-sending with optimal message complexity.*
3. *If $\mathbf{n}_{\mathcal{C}} > 4\mathbf{f}_{\mathcal{C}}$ for all clusters $\mathcal{C}$ and replicas can digitally sign claims, then (partitioned) bijective sending solves cluster-sending with optimal message complexity.*

These protocols solve cluster-sending using $\mathcal{O}(\max(\mathbf{n}_{\mathcal{C}_1}, \mathbf{n}_{\mathcal{C}_2}))$ messages of size $\mathcal{O}(\|v\|)$ each.

Cluster-sending: Can we do Better?

Pessimistic

No: these algorithms are worst-case optimal.
Cannot do better than *linear communication* in the size of the clusters.

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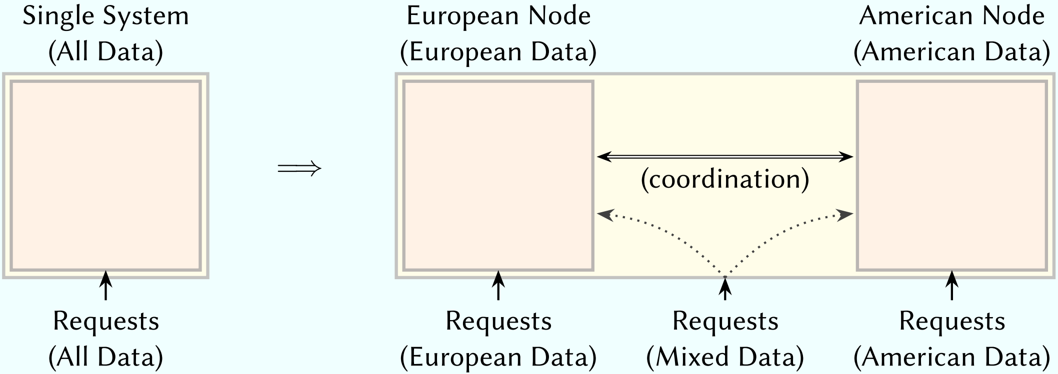
Probabilistic

Yes: if we randomly choose sender and receiver, then we often do much better!
Probabilistic approach: expected-case only *constant communication* (four steps).

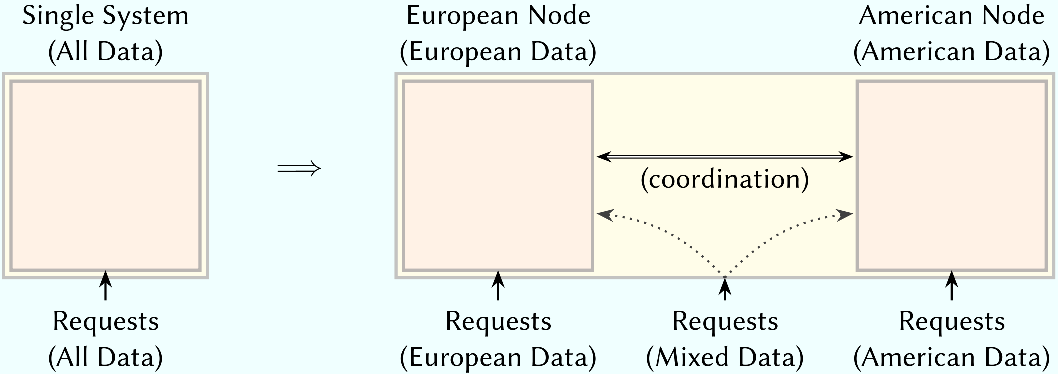
Motivation: High-Performance Resilient Systems



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

Adding shards $\Longrightarrow$ adding throughput (parallel processing), adding storage.

Motivation: High-Performance Resilient Systems



Resilient system

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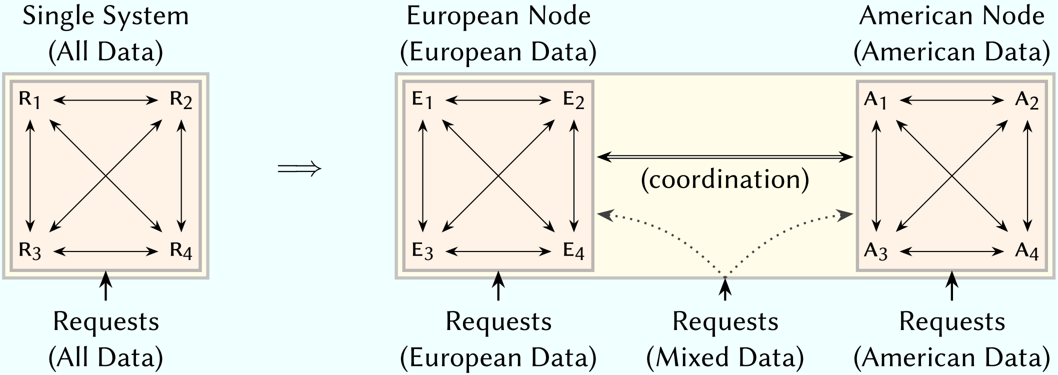

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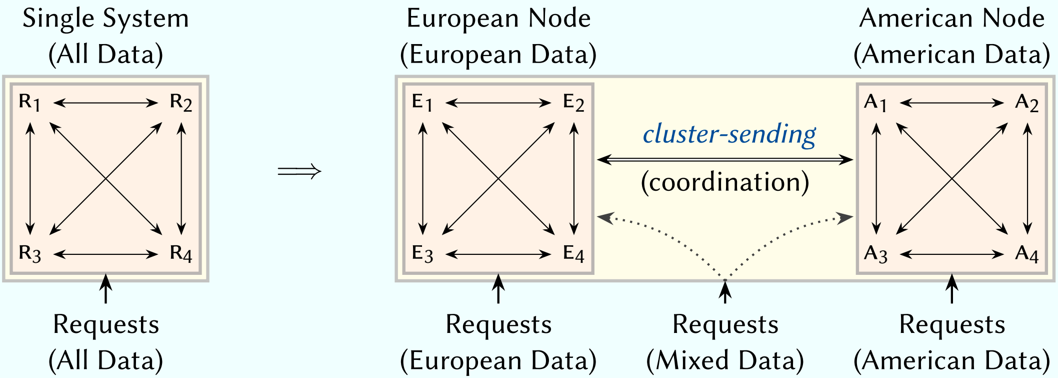

Resilient system

- Individual shards are consensus-operated *blockchains*.
- Communication between shards via *cluster-sending*.

Transactions

A user interaction with a DBMS: *transaction*.

Definition

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- a interactive dialog between DBMS and program;
- ....

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Contract between a DBMS and its users.

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Atomicity. Either all or none of the operations of τ are reflected in the database.

Consistency Execution of τ in *isolation* preserves data consistency.
E.g., integrety constraints—this is *stronger* than CAP-Consistency.

Isolation τ is "unaware" of other transactions executing concurrently
"As-if" all transactions are executed in a *sequential order*.

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Durability is *strong*: crashing or killing the DBMS program, power outage, ...
Typical assumption: *storage* is permanent & reliable.

Background on Resilience

Consider a transaction τ requested by client c in a resilient system.

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Consider a transaction τ requested by client c in a resilient system.

τ is processed in *five* steps

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Non-sharded resilient systems

- Consensus solves all of the above.
- In particular *replication order* is *execution order*.
- Consecutive execution guarantees ACID.

Running Example: A Banking System

Setting: Transactions change the balance of one or more accounts

The *current state* is the balance of each account obtained by executing transactions.

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$\tau_1 =$ "add \$500 to *Ana*";

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Ana	\$0
Bo	\$0
Elisa	\$0

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$\tau_4 =$ "remove \$70 from *Elisa*";

Ana	\$0
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_1}$

Ana	\$500
Bo	\$0
Elisa	\$0

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The *current state* is the balance of each account obtained by executing transactions.

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τ_4 = "remove \$70 from *Elisa*";

Ana	\$0
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_1}$

Ana	\$500
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_2}$

Ana	\$500
Bo	\$200
Elisa	\$300

Running Example: A Banking System

Setting: Transactions change the balance of one or more accounts

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$$\tau_3 = \text{“move \$30 from } \textit{Ana} \text{ to } \textit{Elisa}\text{”;}$$
$$\tau_4 = \text{“remove \$70 from } \textit{Elisa}\text{”;}$$

Ana	\$0
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_1}$

Ana	\$500
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_2}$

Ana	\$500
Bo	\$200
Elisa	\$300

$\xrightarrow{\tau_3}$

Ana	\$470
Bo	\$200
Elisa	\$330

Running Example: A Banking System

Setting: Transactions change the balance of one or more accounts

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$$\tau_3 = \text{“move \$30 from } \textit{Ana} \text{ to } \textit{Elisa}\text{”};$$
$$\tau_4 = \text{“remove \$70 from } \textit{Elisa}\text{”};$$

Ana	\$0
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_1}$

Ana	\$500
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_2}$

Ana	\$500
Bo	\$200
Elisa	\$300

$\xrightarrow{\tau_3}$

Ana	\$470
Bo	\$200
Elisa	\$330

$\xrightarrow{\tau_4}$

Ana	\$470
Bo	\$200
Elisa	\$260

Running Example: A Banking System

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$$\tau_3 = \text{“move \$30 from } \textit{Ana} \text{ to } \textit{Elisa}\text{”};$$
$$\tau_4 = \text{“remove \$70 from } \textit{Elisa}\text{”};$$
$$\tau_5 = \text{“move \$500 from } \textit{Ana} \text{ to } \textit{Bo}\text{”}.$$

Ana	\$0
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_1}$

Ana	\$500
Bo	\$0
Elisa	\$0

$\xrightarrow{\tau_2}$

Ana	\$500
Bo	\$200
Elisa	\$300

$\xrightarrow{\tau_3}$

Ana	\$470
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Ana	\$470
Bo	\$200
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Setting: Transactions change the balance of one or more accounts

The *current state* is the balance of each account obtained by executing transactions.

τ_1 = “add \$500 to *Ana*”;

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τ_3 = “move \$30 from *Ana* to *Elisa*”;

τ_4 = “remove \$70 from *Elisa*”;

τ_5 = *aborted* (would invalidate balances).

Ana	$0
Bo	$0
Elisa	$0

$\xrightarrow{\tau_1}$

Ana	$500
Bo	$0
Elisa	$0

$\xrightarrow{\tau_2}$

Ana	$500
Bo	$200
Elisa	$300

$\xrightarrow{\tau_3}$

Ana	$470
Bo	$200
Elisa	$330

$\xrightarrow{\tau_4}$

Ana	$470
Bo	$200
Elisa	$260

Toward a Sharded and Resilient System

Consider a transaction τ requested by client c in a resilient system.

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τ must be *replicated* among all replicas of all shards affected by τ!

Toward a Sharded and Resilient System

Consider a transaction τ requested by client c in a resilient system.

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What is a consistent execution order *across* shards? Does it relate to the *replication order*?

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Consider a transaction τ requested by client c in a resilient system.

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Dependencies on data in *other shards*? Writes to data in *other shards*?

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A single consensus does no longer solve all of the above!

Sharding Data

Sharded system: Data is distributed over all shards.

A sharded banking system

Say we have 26 shards: $\mathcal{C}_a, \mathcal{C}_b, \ldots, \mathcal{C}_z$,
such that shard $\mathcal{C}_\xi$ holds accounts of people whose name starts with ξ.

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We write shards(τ) to denote the shards affected by transaction τ.

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We write $\text{shards}(\tau)$ to denote the shards affected by transaction τ.

$\tau_1 =$ "add \$500 to *Ana*",

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$\tau_3 =$ "move \$30 from *Ana* to *Elisa*";

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We write $\text{shards}(\tau)$ to denote the shards affected by transaction τ.

$\tau_1 =$ "add \$500 to *Ana*", $\text{shards}(\tau_1) = \{\mathcal{C}_a\}$;

$\tau_2 =$ "add \$200 to *Bo* and \$300 to *Elisa*", $\text{shards}(\tau_2) = \{\mathcal{C}_b, \mathcal{C}_e\}$;

$\tau_3 =$ "move \$30 from *Ana* to *Elisa*"; $\text{shards}(\tau_3) = \{\mathcal{C}_a, \mathcal{C}_e\}$;

$\tau_4 =$ "remove \$70 from *Elisa*", $\text{shards}(\tau_4) = \{\mathcal{C}_e\}$.

Sharding Data

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A sharded banking system

Say we have 26 shards: $\mathcal{C}_a, \mathcal{C}_b, \ldots, \mathcal{C}_z$,
such that shard $\mathcal{C}_\xi$ holds accounts of people whose name starts with ξ.

We write shards(τ) to denote the shards affected by transaction τ.

$\tau_1 =$ "add \$500 to *Ana*",	$\text{shards}(\tau_1) = \{\mathcal{C}_a\}$;	(single-shard)
$\tau_2 =$ "add \$200 to *Bo* and \$300 to *Elisa*",	$\text{shards}(\tau_2) = \{\mathcal{C}_b, \mathcal{C}_e\}$;	(multi-shard)
$\tau_3 =$ "move \$30 from *Ana* to *Elisa*";	$\text{shards}(\tau_3) = \{\mathcal{C}_a, \mathcal{C}_e\}$;	(multi-shard)
$\tau_4 =$ "remove \$70 from *Elisa*",	$\text{shards}(\tau_4) = \{\mathcal{C}_e\}$.	(single-shard)

An Example of Concurrent Execution

Consider a banking example in which

- Bo wants to transfer \$400 to Ana
  if Ana has at-least \$100 and Bo has at-least \$700,
- Ana wants to transfer \$300 to Elisa
  if Ana has at-least \$500,

and no account is allowed to have a negative balance.

An Example of Concurrent Execution

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  if Ana has at-least \$100 and Bo has at-least \$700,
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  if Ana has at-least \$500,

and no account is allowed to have a negative balance.

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

An Example of Concurrent Execution

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
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A	\$100
B	\$300
E	\$0

An Example of Concurrent Execution

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
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A	\$100
B	\$300
E	\$0

$$\xrightarrow[\substack{A \geq 100? \\ A := A + 400}]{\tau_1 \text{ at } \mathcal{C}_a}$$

A	\$500
B	\$300
E	\$0

An Example of Concurrent Execution

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$

$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

A	\$100
B	\$300
E	\$0

$$\xrightarrow[\substack{A \geq 100? \\ A := A + 400}]{\tau_1 \text{ at } \mathcal{C}_a}$$

A	\$500
B	\$300
E	\$0

$$\xrightarrow[\substack{A \geq 500? \\ A := A - 300}]{\tau_2 \text{ at } \mathcal{C}_a}$$

A	\$200
B	\$300
E	\$0

An Example of Concurrent Execution

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$

$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

A	\$100
B	\$300
E	\$0

$\xrightarrow[A \geq 100?\; A := A + 400]{\tau_1 \text{ at } \mathcal{C}_a}$

A	\$500
B	\$300
E	\$0

$\xrightarrow[A \geq 500?\; A := A - 300]{\tau_2 \text{ at } \mathcal{C}_a}$

A	\$200
B	\$300
E	\$0

$\xrightarrow[B \geq 700?\; \text{(cancel)}]{\tau_1 \text{ at } \mathcal{C}_b}$

A	\$200
B	\$300
E	\$0

An Example of Concurrent Execution

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

A	\$100
B	\$300
E	\$0

$\xrightarrow[A \geq 100?,\ A := A + 400]{\tau_1 \text{ at } \mathcal{C}_a}$

A	\$500
B	\$300
E	\$0

$\xrightarrow[A \geq 500?,\ A := A - 300]{\tau_2 \text{ at } \mathcal{C}_a}$

A	\$200
B	\$300
E	\$0

$\xrightarrow[B \geq 700?\ \text{(cancel)}]{\tau_1 \text{ at } \mathcal{C}_b}$

A	\$200
B	\$300
E	\$0

$\xrightarrow[A := A - 400\ \text{(undo)}]{\tau_1 \text{ at } \mathcal{C}_a}$

A	-\$200
B	\$300
E	\$0

An Example of Concurrent Execution

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

A	\$100
B	\$300
E	\$0

$\xrightarrow[A \geq 100?,\ A := A + 400]{\tau_1 \text{ at } \mathcal{C}_a}$

A	\$500
B	\$300
E	\$0

$\xrightarrow[A \geq 500?,\ A := A - 300]{\tau_2 \text{ at } \mathcal{C}_a}$

A	\$200
B	\$300
E	\$0

$\xrightarrow[B \geq 700?\ \text{(cancel)}]{\tau_1 \text{ at } \mathcal{C}_b}$

A	\$200
B	\$300
E	\$0

$\xrightarrow[A := A - 400\ \text{(undo)}]{\tau_1 \text{ at } \mathcal{C}_a}$

A	-\$200
B	\$300
E	\$0

$\xrightarrow[E := E + 300]{\tau_2 \text{ at } \mathcal{C}_e}$

A	-\$200
B	\$300
E	\$300

An Example of Concurrent Execution–Revisited

Consider a banking example in which

- Bo wants to transfer \$400 to Ana
  if Ana has at-least \$100 and Bo has at-least \$700,
- Ana wants to transfer \$300 to Elisa
  if Ana has at-least \$500,

and no account is allowed to have a negative balance.

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
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An Example of Concurrent Execution–Revisited

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$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
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Transactions τ_1 and τ_2 make sense:
their isolated execution will never make balances negative.

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- Ana wants to transfer \$300 to Elisa
  if Ana has at-least \$500,

and no account is allowed to have a negative balance.

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Transactions τ_1 and τ_2 make sense:
their isolated execution will never make balances negative.

Guarantee by an ACID-compliant system

No account will ever have a negative balance.

Serializability: a High Standard for Isolation

Consider a set of transactions $S = \{\tau_1, \ldots, \tau_n\}$.

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Definition

A *serial schedule* is an execution of S without *interleaving* of transaction steps.
Hence, each transaction is executed in sequence, one at a time.

Serializability: a High Standard for Isolation

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A *serializable schedule* is a schedule whose effect on any consistent instance is guaranteed to be identical to that of some serial schedule over the *committed transactions* in S.

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Serializability assumes *aborted* transactions have no side effects.

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Definition

A *serial schedule* is an execution of S without *interleaving* of transaction steps.
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Definition

A *serializable schedule* is a schedule whose effect on any consistent instance is guaranteed to be identical to that of some serial schedule over the *committed transactions* in S.

Serializability assumes *aborted* transactions have no side effects.
This is not always the case (example later).

Simplified Transaction Notation

Consider the transaction τ:

$\tau =$ "if *Ana* has \$500 and *Bo* has \$200, then
move \$400 from *Ana* to *Elisa*;
move \$100 from *Bo* to *Elisa*".

Simplified Transaction Notation

Consider the transaction τ:

$\tau =$ "if *Ana* has \$500 and *Bo* has \$200, then
move \$400 from *Ana* to *Elisa*;
move \$100 from *Bo* to *Elisa*".

What are the operations of τ?

Depending on *how* the system executes τ and the database state:

- Might read from *Ana*'s account.
- Might read from *Bo*'s account.
- Might write to *Ana*'s account.
- Might write to *Bo*'s account.
- Might write to *Elisa*'s account.

Simplified Transaction Notation

Consider the transaction τ:

$\tau =$ "if *Ana* has \$500 and *Bo* has \$200, then
move \$400 from *Ana* to *Elisa*;
move \$100 from *Bo* to *Elisa*".

Simplifying assumption

Each transaction is a sequence of read and write operations ending in *commit* or *abort*.

Simplified Transaction Notation

Consider the transaction τ:

$\tau =$ "if *Ana* has \$500 and *Bo* has \$200, then
move \$400 from *Ana* to *Elisa*;
move \$100 from *Bo* to *Elisa*".

Simplifying assumption

Each transaction is a sequence of read and write operations ending in *commit* or *abort*.

$\mathsf{Read}_\tau(\mathit{Ana}), \mathsf{Read}_\tau(\mathit{Bo}), \mathsf{Write}_\tau(\mathit{Ana}), \mathsf{Write}_\tau(\mathit{Bo}), \mathsf{Read}_\tau(\mathit{Elisa}), \mathsf{Write}_\tau(\mathit{Elisa}), \mathsf{Commit}_\tau.$

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$

$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Serial schedule: τ_1, then τ_2 (insufficient funds)

Instance (initial)

A	\$100
B	\$300
E	\$0

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
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Serial schedule: τ_1, then τ_2 (insufficient funds)

Instance (initial)

A	\$100
B	\$300
E	\$0

Schedule

$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(A)$	
Abort_{τ_1}	
	$\text{Read}_{\tau_2}(A)$
	Abort_{τ_2}

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Serial schedule: τ_1, then τ_2 (insufficient funds)

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A	\$100
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Schedule

$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(A)$	
Abort_{τ_1}	
	$\text{Read}_{\tau_2}(A)$
	Abort_{τ_2}

Instance (final)

A	\$100
B	\$300
E	\$0

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Serial schedule: τ_1, then τ_2 (Bob has sufficient funds)

Instance (initial)

A	\$100
B	\$800
E	\$0

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$

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Serial schedule: τ_1, then τ_2 (Bob has sufficient funds)

Instance (initial)

A	\$100
B	\$800
E	\$0

Schedule

$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	
	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$

$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Serial schedule: τ_1, then τ_2 (Bob has sufficient funds)

Instance (initial)

A	\$100
B	\$800
E	\$0

Schedule

$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	
	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}

Instance (final)

A	\$200
B	\$400
E	\$300

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Serial schedule: τ_2, then τ_1 (Bob has sufficient funds)

Instance (initial)

A	\$100
B	\$800
E	\$0

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Serial schedule: τ_2, then τ_1 (Bob has sufficient funds)

Instance (initial)

A	\$100
B	\$800
E	\$0

Schedule

	$\text{Read}_{\tau_2}(A)$
	Abort_{τ_2}
$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	

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$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	

Instance (final)

A	\$500
B	\$400
E	\$0

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Serial schedule: τ_2, then τ_1 (Ana has sufficient funds)

Instance (initial)

A	\$500
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E	\$0

Schedule

	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}
$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(A)$	
Abort_{τ_1}	

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B	\$300
E	\$0

Schedule

	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}
$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(A)$	
Abort_{τ_1}	

Instance (final)

A	\$200
B	\$300
E	\$300

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
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Non-serial schedule—Earlier example

Instance (initial)

A	\$100
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E	\$0

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B	\$300
E	\$0

Schedule

$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}
$\text{Read}_{\tau_1}(B)$	
$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
Abort_{τ_1}	

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$\text{Write}_{\tau_1}(A)$	
	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}
$\text{Read}_{\tau_1}(B)$	
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	$\text{Write}_{\tau_2}(A)$
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	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	

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	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	

Instance (final)

A	\$900
B	\$400
E	\$300

An Example of Schedules

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$

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Non-serial schedule—A third example

Instance (initial)

A	\$500
B	\$800
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An Example of Schedules

Consider again the transactions

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Non-serial schedule—A third example

Instance (initial)

A	\$500
B	\$800
E	\$0

Schedule

	$\text{Read}_{\tau_2}(A)$
$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}

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Instance (initial)

A	\$500
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	$\text{Read}_{\tau_2}(A)$
$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}

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$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
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A serializable schedule (that is non-serial)

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	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
	Commit_{τ_2}
Commit_{τ_1}	

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	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
$\text{Read}_{\tau_1}(A)$	
$\text{Write}_{\tau_1}(A)$	
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
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Key observation: Serial schedules

Individual transactions *make sense* (do not violate consistency):

- No balance will ever get negative.
- No money disappears or appears out of thin air.

Guaranteeing Isolation

Simplified point-of-view

- A transaction is a *thread* in a multi-threaded program.

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This will enforce a *serial schedule*.

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As all data is shared: should the entire transaction be a single critical section?

What if each transaction *locks the system*, executes, *releases the system*?

This will enforce a *serial schedule* and eliminate any concurrency.

Improving Isolation using Locks

Idea: Use a fine-grained set of locks on *database objects*.

E.g., accounts, tables, rows, ...

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Using fine-grained locks

A transaction τ that wants to access database object O will:

- waits until it obtains a lock on O ($\text{Lock}_\tau(O)$),
- then perform its operations on O (e.g., $\text{Read}_\tau(O)$ and $\text{Write}_\tau(O)$), and
- finally release the lock on O ($\text{Release}_\tau(O)$).

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Lock-based access solves *some* issues ...

Instance (initial)

A	\$500
B	\$800
E	\$0

Schedule

$\text{Read}_{\tau_1}(A)$	
	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(E)$
	$\text{Write}_{\tau_2}(E)$
	Commit_{τ_2}
$\text{Write}_{\tau_1}(A)$	
$\text{Read}_{\tau_1}(B)$	
$\text{Write}_{\tau_1}(B)$	
Commit_{τ_1}	

Instance (final)

A	\$900
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$\text{Read}_{\tau_1}(A)$	

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$\text{Read}_{\tau_1}(A)$	
	$\text{Lock}_{\tau_2}(A)$

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$\text{Release}_{\tau_1}(A)$	

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	$\text{Read}_{\tau_2}(A)$

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	$\text{Lock}_{\tau_2}(A)$
$\text{Write}_{\tau_1}(A)$	
$\text{Release}_{\tau_1}(A)$	
	$\text{Read}_{\tau_2}(A)$
	...
	Commit_{τ_2}

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	...
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$\text{Release}_{\tau_1}(A)$	
	$\text{Lock}_{\tau_2}(A)$
	$\text{Read}_{\tau_2}(A)$
	$\text{Write}_{\tau_2}(A)$
	...
	Commit_{τ_2}
...	
Abort_{τ_1}	

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	...
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...	
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...and introduces *new* issues.
Consider two transactions that both want to access *Ana* and *Bo*:

$$\tau_1 = \mathsf{Lock}_{\tau_1}(A), \mathsf{Lock}_{\tau_1}(B), \ldots; \qquad \tau_2 = \mathsf{Lock}_{\tau_2}(B), \mathsf{Lock}_{\tau_1}(A), \ldots$$

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Schedule

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	$\mathsf{Lock}_{\tau_2}(B)$
$\mathsf{Lock}_{\tau_1}(B)$	
	$\mathsf{Lock}_{\tau_2}(A)$

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Schedule

$\text{Lock}_{\tau_1}(A)$	
	$\text{Lock}_{\tau_2}(B)$
$\text{Lock}_{\tau_1}(B)$	
	$\text{Lock}_{\tau_2}(A)$

Both transactions will wait forever: a deadlock!

Achieving Serializability with Locks

Locking itself does not guarantee *serializability*.

Some *locking protocols* (sets of rules on when to use locks) that do guarantee *serializability*.

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Two-phase locking protocol (2PL)

Execution of transaction τ adheres to 2PL if the execution is performed in two phases:

Growing phase during which execution can obtains locks, and *not* release them; and

Shrinking phase during which execution can release locks, and *not* obtain them,

and any database object O is only operated on while holding lock $\text{Lock}_{\tau}(O)$.

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Strict 2PL: locks are only released after completion (Commit_τ or Abort_τ).

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Strict 2PL: locks are only released after completion (Commit_τ or Abort_τ).

Notice—Nothing to deal with *deadlocks*.

An Example of 2PL

Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

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Consider again the transactions

$$\tau_1 = A \geq 100?, A := A + 400, B \geq 700?, B := B - 400;$$
$$\tau_2 = A \geq 500?, A := A - 300, E := E + 300.$$

Assumption: Both transactions will succeed (Alice and Bob have sufficient funds)

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An Example of 2PL

Consider again the transactions

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These are all *strict* 2PL: locks are released after the transactions commit.

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Two-Phase Locking and Deadlocks

Consider the transactions

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Some schedules will cause a deadlock

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Deadlocks are one of the issues arising from *lock contention*.

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Pessimistic: make sure deadlocks *cannot happen*

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Example

Consider the transaction

$$\tau = \text{“if } \textit{Bo} \text{ has \$500, then move \$200 from } \textit{Bo} \text{ to } \textit{Ana}\text{”.}$$

Any schedule for τ needs to start with:

$$\mathsf{Lock}_\tau(\mathit{Ana}), \mathsf{Lock}_\tau(\mathit{Bo}), \dots,$$

we even lock Ana if Bo does *not have funds*.

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Optimistic: Optimize for no lock-contention

If a transaction tries to obtain a lock that is already held: *abort the transaction entirely*.

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- Very easy to implement.
- Minimizes the costs for transactions that are able to commit.
- Will perform badly when there is a high amount of lock-contention.

Practice: Read and Write locks

- Locks need to be *fine-grained* to maximize concurrency.
- Concurrency issues only arise when a transaction is writing.
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Result

- Many transactions can read at the same time.
- Read-write, write-read, and write-write conflicts are prevented.

The Cost of Serializability

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To improve performance, you can *give up* on serializability!

Degrees of Isolation in SQL[1]

Level	Dirty Reads	Unrepeatable Read	Phantoms
READ UNCOMMITTED	Possible	Possible	Possible
READ COMMITTED	Not Possible	Possible	Possible
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Locking protocol for **READ UNCOMMITTED**

- no read locks,
- *long-duration* write (and predicate) locks before writing data.

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Locking protocol for **READ COMMITTED**

- *short-duration* read (and predicate) locks before reading data, and
- *long-duration* write (and predicate) locks before writing data.

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Locking protocol for **REPEATABLE READ**

- *short-duration* predicate locks and *long-duration* read locks before reading data, and
- *long-duration* write (and predicate) locks before writing data.

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Locking protocol for **SERIALIZABLE**

- *long-duration* read (and predicate) locks before reading data, and
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Locking protocol for **SERIALIZABLE** (2PL)

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Concurrent transaction execution can make sense *without* isolation.
E.g., one can use application-specific knowledge!

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Observe: undoing a withdraw increases balance, undoing deposits decreases balance!

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Consider executions in which all steps can:

- always withdraw money;
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A Banking System

Observe: undoing a withdraw increases balance, undoing deposits decreases balance!

Consider executions in which all steps can:

- always withdraw money;
- only deposit money after either *commit* or *abort* is decided.

These executions guarantee that no account will have a negative balance!

Ingredients of Sharding in a Resilient Environment

Multi-shard transaction execution of τ requires

Replication of τ among shards.
E.g., a two-phase commit step.

Concurrency control to guarantee consistent execution of τ.
E.g., using *locks* to prevent concurrent access to accounts.

To One needs *computations* within a shard and *communication* between shards.

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Fault-tolerant shards

Each shard is a cluster of replicas that can be faulty.

Consensus for each *computation* within shards.

Cluster-sending for any *communication* between shards.

Consensus is costly: Minimize its use.

The Orchestrate-Execute Model for Multi-Shard Transactions

Consider a multi-shard transaction τ:

- Processing is broken down into three types of *shard-steps*: vote, commit, and abort.
- Each shard-step is performed via *one* consensus step.
- Transfer control between steps using *cluster-sending*.

Execution method determines the local operations of a shard-step:
locks, *checking conditions*, *updating state*, *...*.

Orchestration method determines how *control is transferred* between shard-steps:
perform *votes*, collect *votes*, decide *commit* or *abort* τ.

Example of the Orchestrate-Execute Model

Shard accounts by first letter of name

$\tau =$ "if *Ana* has \$500 and *Bo* has \$200, then move \$400 from *Ana* to *Bo*."

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$$\sigma_1 = \text{“}\mathsf{Lock}_\tau(\textit{Ana})\text{; if } \textit{Ana} \text{ has \$500, then forward } \sigma_2 \text{ to } \mathcal{C}_b \text{ (commit vote) else } \mathsf{Release}_\tau(\textit{Ana}) \text{ (abort vote).”}$$

vote-step

σ_1 at $\mathcal{C}_a$

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vote-step σ_1 at $\mathcal{C}_a$ —*vote commit*→ **vote-step** σ_2 at $\mathcal{C}_b$

Example of the Orchestrate-Execute Model

Shard accounts by first letter of name

$$\tau = \text{“if } \textit{Ana} \text{ has \$500 and } \textit{Bo} \text{ has \$200, then move \$400 from } \textit{Ana} \text{ to } \textit{Bo}\text{.”}$$

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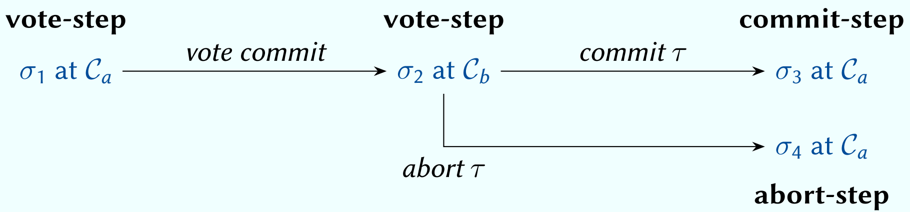
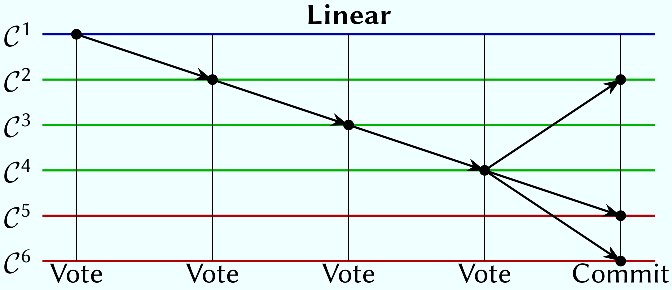


Resilient Orchestration Methods

Orchestration ≈ two-phase commit, except that *shards never fail*.



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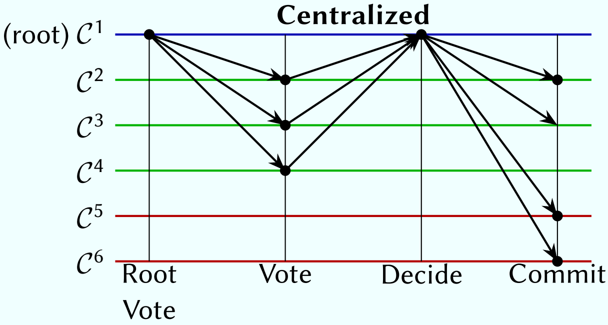

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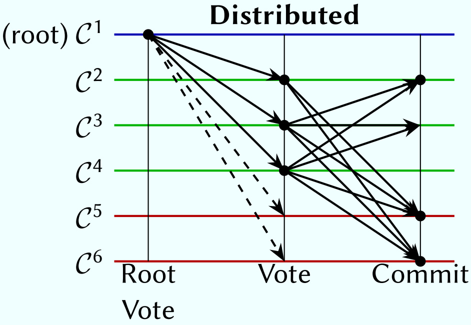


Vote-steps in *parallel*, decide *decentralized*, commit or abort in *parallel*.

Resilient Execution Methods

Execution updates state and performs *concurrency control*.

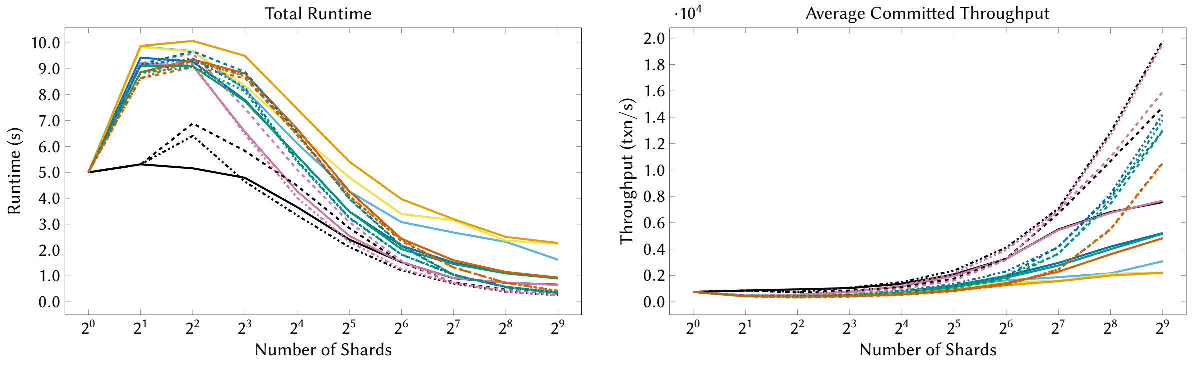
- Write uncommitted execution for *free*:
  Due to consensus, shard-steps are performed in sequence on that shard.

- Higher isolation levels via *two-phase locking*:
  - read uncommitted execution: only *write locks*;
  - read committed execution: *read locks* during steps;
  - serializable execution: *read and write locks*.

- Blocking locks (with linear orchestration) versus non-blocking locks.

Evaluation

	Isolation-Free execution (write uncommitted)		Lock-based execution: Read Uncommitted		Read Committed		Serializable	
	unsafe	*safe*	*blocking*	*non-blocking*	*blocking*	*non-blocking*	*blocking*	*non-blocking*
Linear	LIFu	LIFs	LRUb	LRUnb	LRCb	LRCnb	LSb	LSnb
Centralized	CIFu	CIFs		CRUnb		CRCnb		CSnb
Distributed	DIFu	DIFs		DRUnb		DRCnb		DSnb



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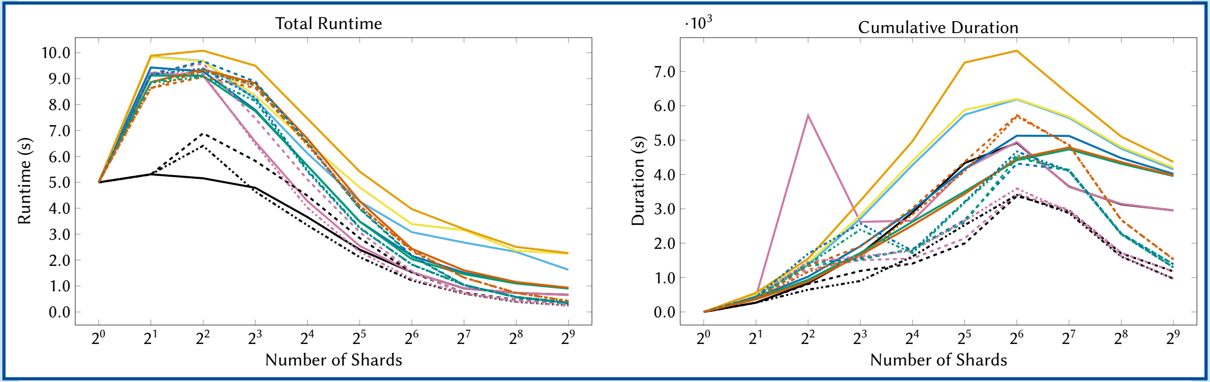

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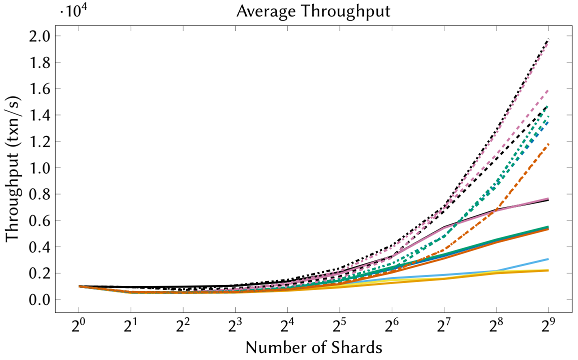
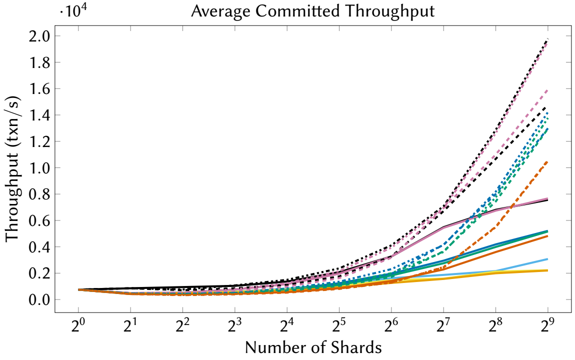
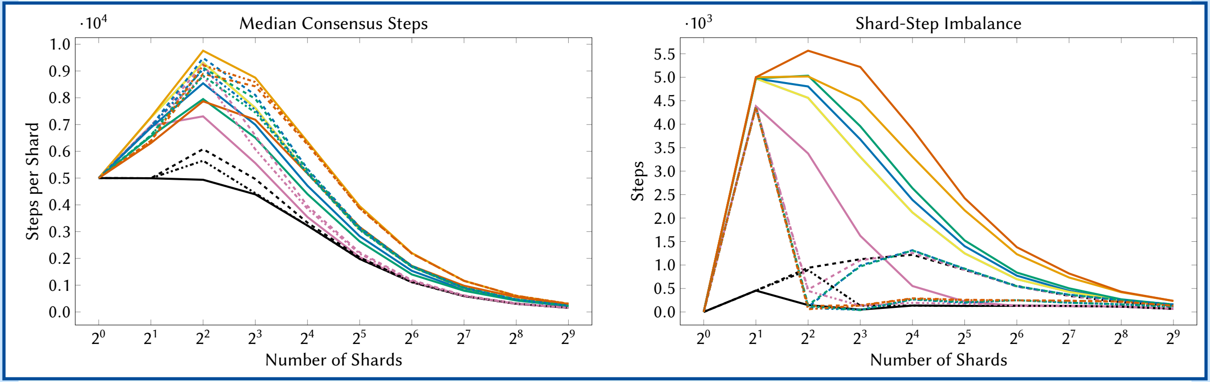
Linear	LIFu	LIFs	LRUb	LRUnb	LRCb	LRCnb	LSb	LSnb
Centralized	CIFu	CIFs		CRUnb		CRCnb		CSnb
Distributed	DIFu	DIFs		DRUnb		DRCnb		DSnb





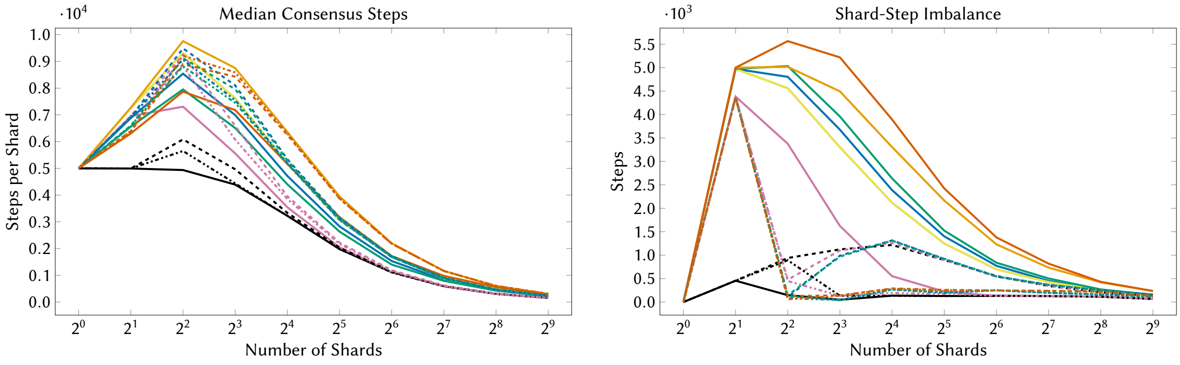
Evaluation

	Isolation-Free execution (write uncommitted)		Lock-based execution: Read Uncommitted		Lock-based execution: Read Committed		Lock-based execution: Serializable	
	unsafe	*safe*	*blocking*	*non-blocking*	*blocking*	*non-blocking*	*blocking*	*non-blocking*
Linear	LIFu	LIFs	LRUb	LRUnb	LRCb	LRCnb	LSb	LSnb
Centralized	CIFu	CIFs		CRUnb		CRCnb		CSnb
Distributed	DIFu	DIFs		DRUnb		DRCnb		DSnb



Evaluation

	Isolation-Free execution (write uncommitted)		Lock-based execution					
			Read Uncommitted		Read Committed		Serializable	
	unsafe	*safe*	*blocking*	*non-blocking*	*blocking*	*non-blocking*	*blocking*	*non-blocking*
Linear	LIFu	LIFs	LRUb	LRUnb	LRCb	LRCnb	LSb	LSnb
Centralized	CIFu	CIFs		CRUnb		CRCnb		CSnb
Distributed	DIFu	DIFs		DRUnb		DRCnb		DSnb



Evaluation

	Isolation-Free execution (write uncommitted)		Lock-based execution					
			Read Uncommitted		Read Committed		Serializable	
	unsafe	*safe*	*blocking*	*non-blocking*	*blocking*	*non-blocking*	*blocking*	*non-blocking*
Linear	LIFu	LIFs	LRUb	LRUnb	LRCb	LRCnb	LSb	LSnb
Centralized	CIFu	CIFs		CRUnb		CRCnb		CSnb
Distributed	DIFu	DIFs		DRUnb		DRCnb		DSnb