Garage

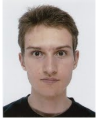
NGI POINTER

Alex Auvolat, Deuxfleurs Association

`https://garagehq.deuxfleurs.fr/`

Matrix channel: `#garage:deuxfleurs.fr`

Who I am



Alex Auvolat
PhD; co-founder of Deuxfleurs

Deuxfleurs
A non-profit self-hosting collective,
member of the CHATONS network

Our objective at Deuxfleurs

Promote self-hosting and small-scale hosting as an alternative to large cloud providers

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Why is it hard?

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**Promote self-hosting and small-scale hosting
as an alternative to large cloud providers**

Why is it hard?

<u>Resilience</u>

(we want good uptime/availability with low supervision)

How to make a stable system

Enterprise-grade systems typically employ:

- RAID
- Redundant power grid + UPS
- Redundant Internet connections
- Low-latency links
- ...

$\rightarrow$ it's costly and only worth it at DC scale

How to make a resilient system

Instead, we use:

- Commodity hardware (e.g. old desktop PCs)

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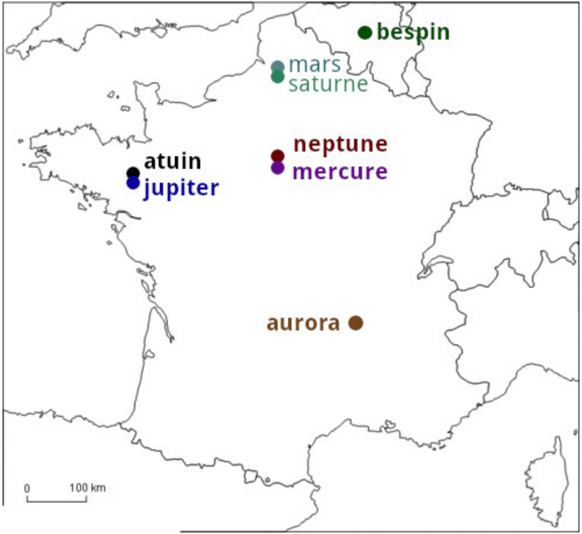
- Commodity Internet (e.g. FTTB, FTTH) and power grid

How to make a resilient system

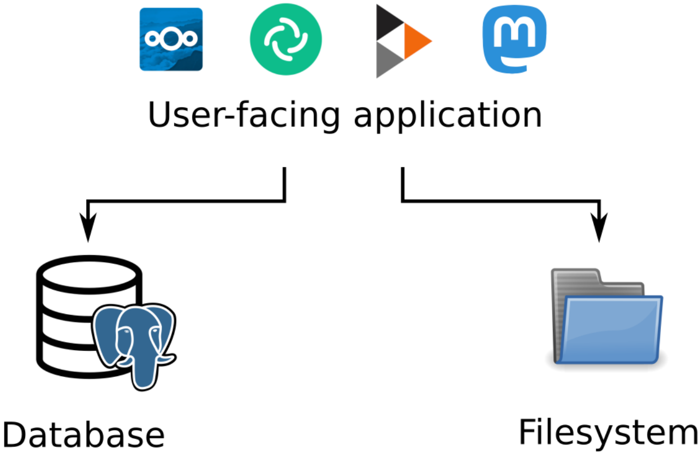
Instead, we use:

- Commodity hardware (e.g. old desktop PCs)
- Commodity Internet (e.g. FTTB, FTTH) and power grid
- **Geographical redundancy** (multi-site replication)

How to make a resilient system



How to make this happen



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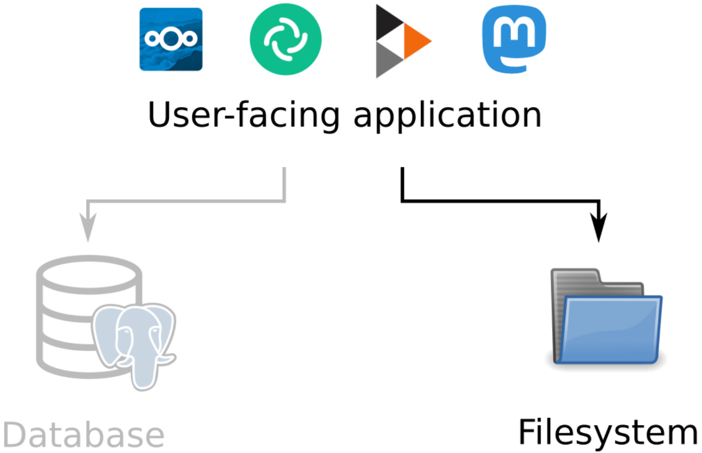

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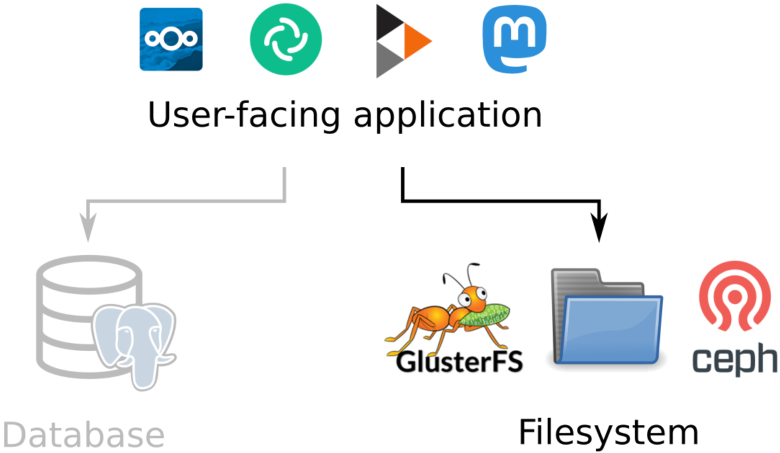

Distributed file systems are slow

File systems are complex, for example:

- Concurrent modification by several processes
- Folder hierarchies
- Other requirements of the POSIX spec

Coordination in a distributed system is costly

Costs explode with commodity hardware / Internet connections
(we experienced this!)

A simpler solution: object storage

Only two operations:

- Put an object at a key
- Retrieve an object from its key

(and a few others)

Sufficient for many applications!

A simpler solution: object storage

S3: a de-facto standard, many compatible applications

MinIO is self-hostable but not suited for geo-distributed deployments

Garage is a self-hosted drop-in replacement for the Amazon S3 object store

The data model of object storage

Object storage is basically a key-value store:

Key: file path + name	**Value: file data + metadata**

`index.html`	`Content-Type: text/html; charset=utf-8`
	`Content-Length: 24929`
	`<binary blob>`

`img/logo.svg`	`Content-Type: text/svg+xml`
	`Content-Length: 13429`
	`<binary blob>`

`download/index.html`	`Content-Type: text/html; charset=utf-8`
	`Content-Length: 26563`
	`<binary blob>`

Two big problems

1. **How to place data on different nodes?**

   Constraints: heterogeneous hardware
   Objective: n copies of everything, maximize usable capacity, maximize resilience

   $\rightarrow$ the Dynamo model + optimization algorithms

Two big problems

1. **How to place data on different nodes?**

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   Objective: n copies of everything, maximize usable capacity, maximize resilience

   → the Dynamo model + optimization algorithms

2. **How to guarantee consistency?**

   Constraints: slow network (geographical distance), node unavailability/crashes
   Objective: maximize availability, read-after-write guarantee

   → CRDTs, monotonicity, read and write quorums

Problem 1: placing data

Key-value stores, upgraded: the Dynamo model

Two keys:

- Partition key: used to divide data into partitions (shards)
- Sort key: used to identify items inside a partition

Partition key: bucket	**Sort key: filename**	**Value**
`website`	`index.html`	(file data)
`website`	`img/logo.svg`	(file data)
`website`	`download/index.html`	(file data)
`backup`	`borg/index.2822`	(file data)
`backup`	`borg/data/2/2329`	(file data)
`backup`	`borg/data/2/2680`	(file data)
`private`	`qq3a2nbe1qjq0ebbvo6ocsp6co`	(file data)

Key-value stores, upgraded: the Dynamo model

- Data with different partition keys is stored independantly, on a different set of nodes

  → no easy way to list all partition keys
  → no cross-shard transactions

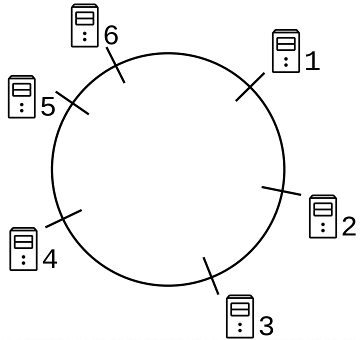
- Placing data: hash the partition key, select nodes accordingly

  → distributed hash table (DHT)

- For a given value of the partition key, items can be listed using their sort keys

How to spread files over different cluster nodes?

Consistent hashing (Dynamo):



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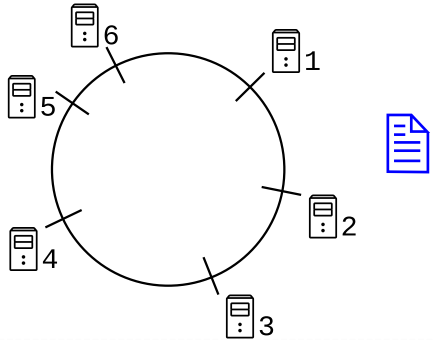

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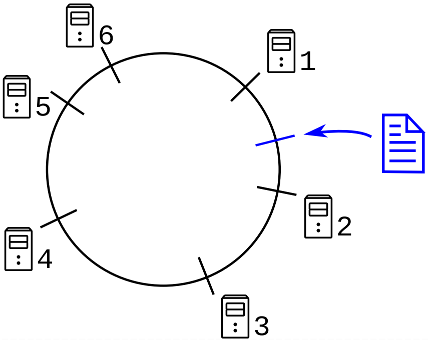

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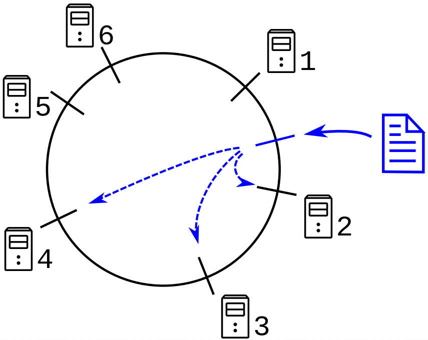
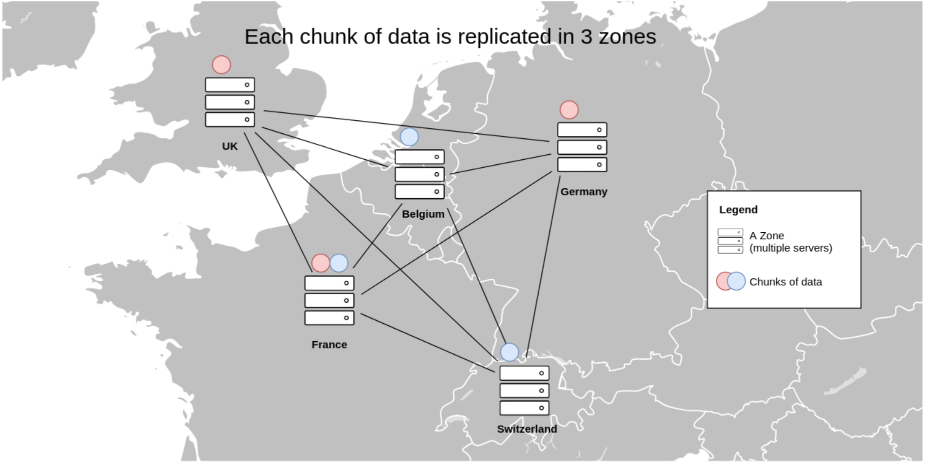


Constraint: location-awareness

```
alex@io:~$ docker exec -ti garage /garage status
==== HEALTHY NODES ====
ID                Hostname   Address                       Tags                 Zone     Capacity
7d50f042280fea98  io         [2a01:e0a:5e4:1d0::57]:3901   [io,jupiter]         jupiter  20
d9b5959e58a3ab8c  drosera    [2a01:e0a:260:b5b0::4]:3901   [drosera,atuin]      atuin    20
966dfc7ed8049744  datura     [2a01:e0a:260:b5b0::2]:3901   [datura,atuin]       atuin    10
8cf284e7df17d0fd  celeri     [2a06:a004:3025:1::33]:3901   [celeri,neptune]     neptune  5
156d0f7a88b1e328  digitale   [2a01:e0a:260:b5b0::3]:3901   [digitale,atuin]     atuin    10
5fcb3b6e39db3dcb  concombre  [2a06:a004:3025:1::31]:3901   [concombre,neptune]  neptune  5
a717e5b618267806  courgette  [2a06:a004:3025:1::32]:3901   [courgette,neptune]  neptune  5
alex@io:~$
```

Garage replicates data on different zones when possible

Constraint: location-awareness



Issues with consistent hashing

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- Consistent hashing doesn't dispatch data based on geographical location of nodes
- Geographically aware adaptation, try 1:
  data quantities not well balanced between nodes
- Geographically aware adaptation, try 2:
  too many reshuffles when adding/removing nodes

How to spread files over different cluster nodes?

Garage's method: build an index table

Realization: we can actually precompute an optimal solution

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Realization: we can actually precompute an optimal solution

Partition	**Node 1**	**Node 2**	**Node 3**
Partition 0	Io (jupiter)	Drosera (atuin)	Courgette (neptune)
Partition 1	Datura (atuin)	Courgette (neptune)	Io (jupiter)
Partition 2	Io(jupiter)	Celeri (neptune)	Drosera (atuin)
⋮	⋮	⋮	⋮
Partition 255	Concombre (neptune)	Io (jupiter)	Drosera (atuin)

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⋮	⋮	⋮	⋮
Partition 255	Concombre (neptune)	Io (jupiter)	Drosera (atuin)

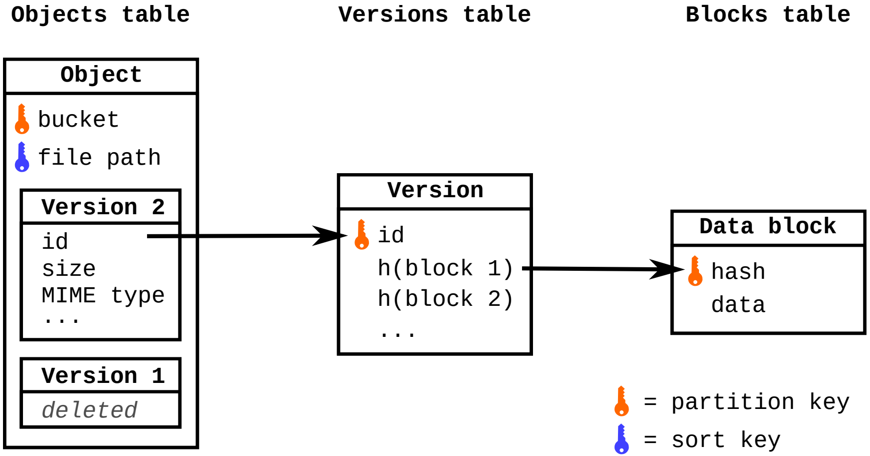
The index table is built centrally using an optimal algorithm,
then propagated to all nodes

The relationship between *partition* and *partition key*

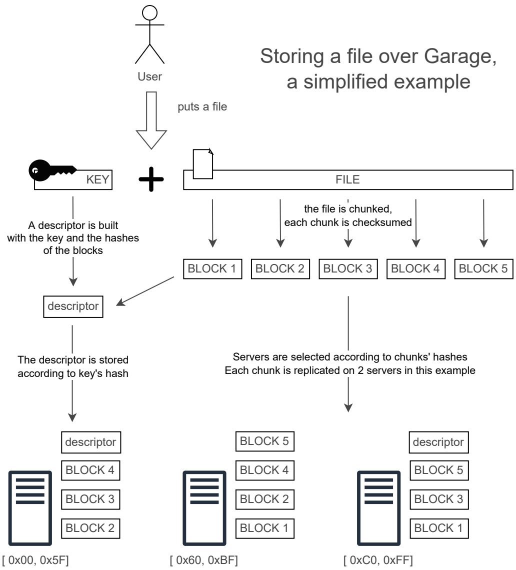
Partition key	Partition	Sort key	Value
`website`	Partition 12	`index.html`	(file data)
`website`	Partition 12	`img/logo.svg`	(file data)
`website`	Partition 12	`download/index.html`	(file data)
`backup`	Partition 42	`borg/index.2822`	(file data)
`backup`	Partition 42	`borg/data/2/2329`	(file data)
`backup`	Partition 42	`borg/data/2/2680`	(file data)
`private`	Partition 42	`qq3a2nbe1qjq0ebbvo6ocsp6co`	(file data)

To read or write an item: hash partition key
→ determine partition number (first 8 bits)
→ find associated nodes

Garage's internal data structures



Storing and retrieving files



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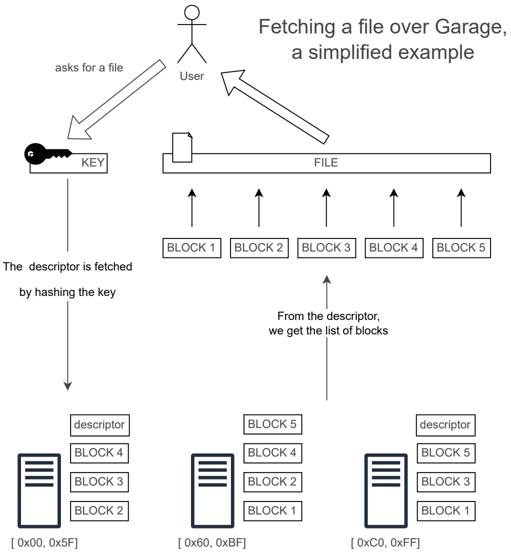

Problem 2: ensuring consistency

Consensus vs weak consistency

Consensus-based systems:

- **Leader-based:** a leader is elected to coordinate all reads and writes
- **Linearizability** of all operations (strongest consistency guarantee)
- Any sequential specification can be implemented as a **replicated state machine**
- **Costly**, the leader is a bottleneck; leader elections on failure take time

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Weakly consistent systems:

- **Nodes are equivalent**, any node can originate a read or write operation
- **Read-after-write consistency** with quorums, eventual consistency without
- **Operations have to commute**, i.e. we can only implement CRDTs
- **Fast**, no single bottleneck; works the same with offline nodes

Consensus vs weak consistency

From a theoretical point of view:

<u>Consensus-based systems:</u>

Require **additionnal assumptions** such as a fault detector or a strong RNG (FLP impossibility theorem)

<u>Weakly consistent systems:</u>

Can be implemented in **any asynchronous message passing distributed system** with node crashes

They represent **different classes of computational capability**

Consensus vs weak consistency

The same objects cannot be implemented in both models.

Consensus-based systems:

Any sequential specification

Easier to program for: just write your program as if it were sequential on a single machine

Weakly consistent systems:

Only CRDTs
(conflict-free replicated data types)

Part of the complexity is **reported to the consumer of the API**

Understanding the power of consensus

Consensus: an API with a single operation, *propose*(x)

1. nodes all call *propose*(x) with their proposed value;
2. nodes all receive the same value as a return value, which is one of the proposed values

Understanding the power of consensus

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Equivalent to a distributed algorithm that gives a total order on all requests

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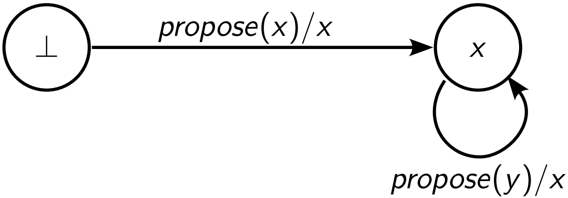
Equivalent to a distributed algorithm that gives a total order on all requests

Implemented by this simple replicated state machine:



Can my object be implemented without consensus?

Given the specification of an API:

- **Using this API, we can implement the consensus object** (the *propose* function)
  $\rightarrow$ the API is equivalent to consensus/total ordering of messages
  $\rightarrow$ the API cannot be implemented in a weakly consistent system

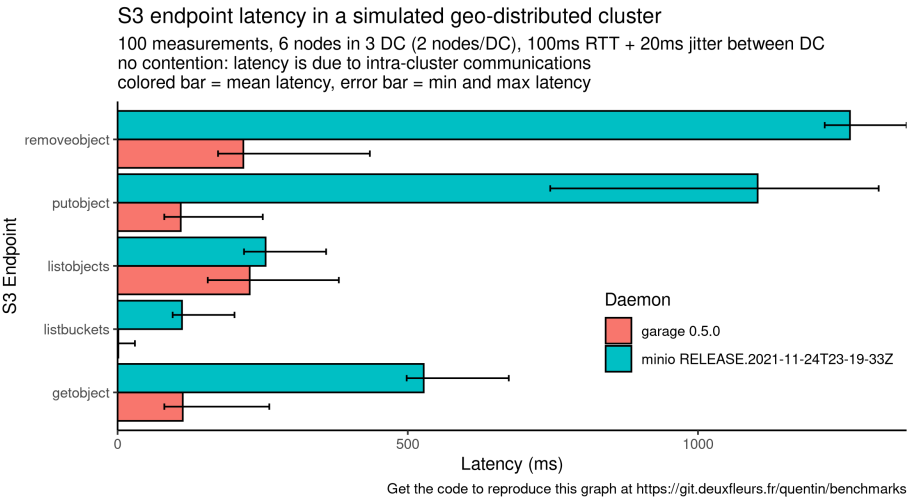
- **This API can be implemented using only weak primitives**
  (e.g. in the asynchronous message passing model with no further assumption)
  $\rightarrow$ the API is strictly weaker than consensus
  $\rightarrow$ we can implement it in Garage!

Why avoid consensus?

Consensus can be implemented reasonably well in practice, so why avoid it?

- **Software complexity:** RAFT and PAXOS are complex beasts; harder to prove, harder to reason about
- **Performance issues:**
  - Theoretical requirements (RNG, failure detector) translate into **practical costs**
  - The leader is a **bottleneck** for all requests; even in leaderless approaches, **all nodes must process all operations in order**
  - Particularly **sensitive to higher latency** between nodes

Performance gains in practice



What can we implement without consensus?

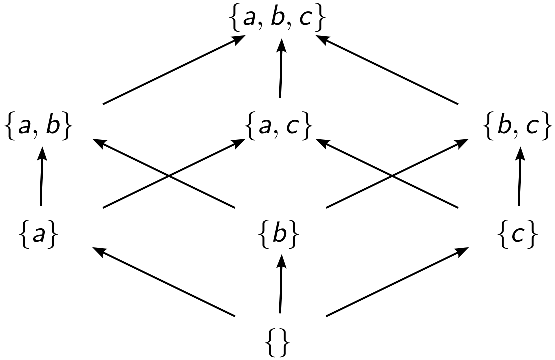
- Any **conflict-free replicated data type** (CRDT)

- Non-transactional key-value stores such as S3 are equivalent to a simple CRDT: a **last-writer-wins registry**

- **Read-after-write consistency** can be implemented using quorums on read and write operations

- **Monotonicity of reads** can be implemented with repair-on-read (makes reads more costly, not implemented in Garage)

CRDTs and quorums: read-after-write consistency



CRDTs and quorums: read-after-write consistency

$write(\{a\})$:

- 🟣 $\not\supseteq \{a\}$
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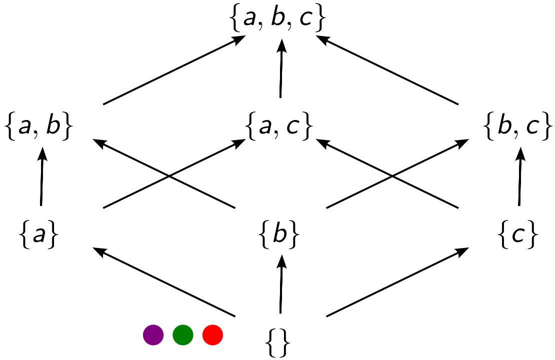
- 🔴 $\not\supseteq \{a\}$



CRDTs and quorums: read-after-write consistency

$write(\{a\})$:

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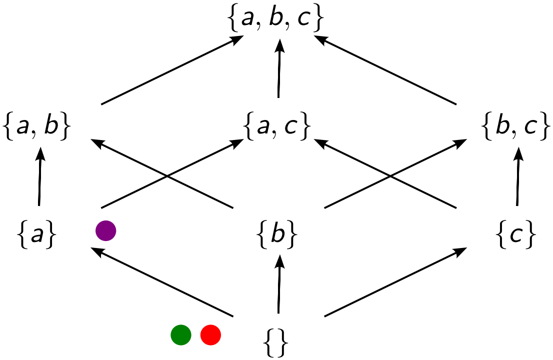

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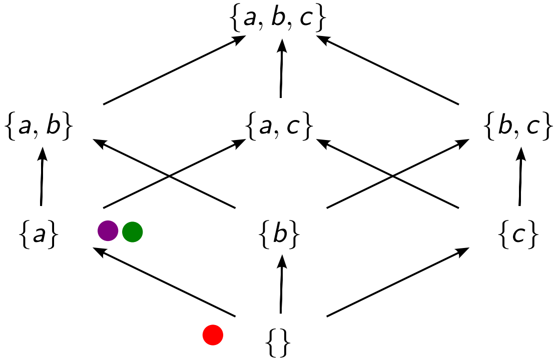
return OK



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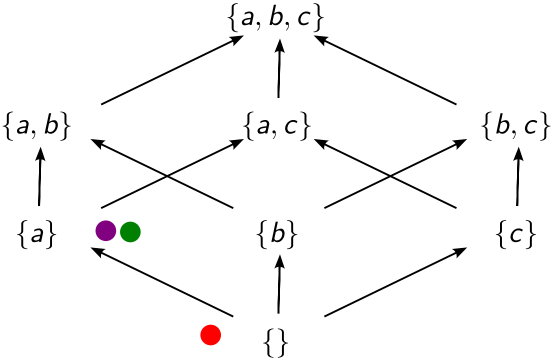
$read()$:



CRDTs and quorums: read-after-write consistency

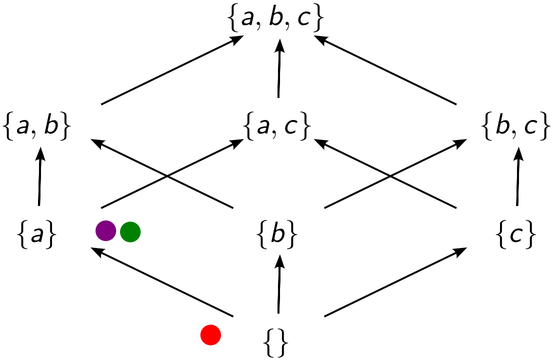
$\mathit{write}(\{a\})$:

- $\sqsupseteq \{a\} \to \mathrm{OK}$
- $\sqsupseteq \{a\} \to \mathrm{OK}$
- $\not\sqsupseteq \{a\}$

return OK

$\mathit{read}()$:

- $\to \{\}$



CRDTs and quorums: read-after-write consistency

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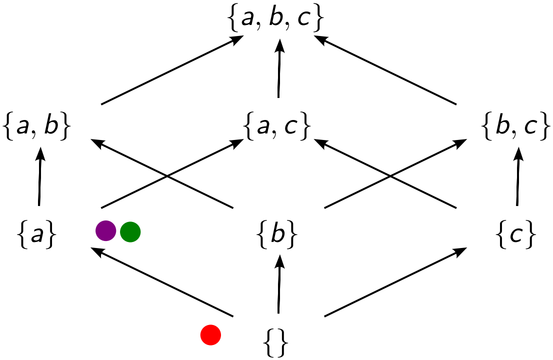
return OK

$read()$:

- $\rightarrow \{\}$
- $\rightarrow \{a\}$

return $\{\} \sqcup \{a\} = \{a\}$



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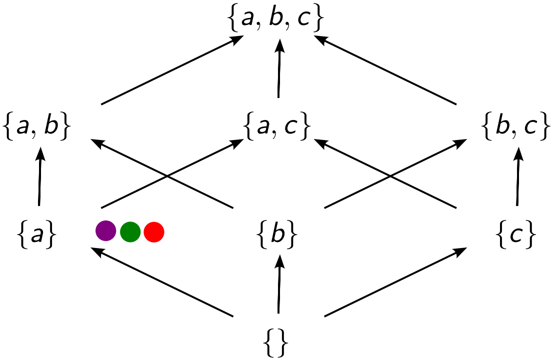

CRDTs and quorums: read-after-write consistency

Property: If node A did an operation $write(x)$ and received an OK response, and node B starts an operation $read()$ after A received OK, then B will read a value $x' \sqsupseteq x$.

Algorithm $write(x)$**:**

1. Broadcast $write(x)$ to all nodes
2. Wait for $k > n/2$ nodes to reply OK
3. Return OK

Algorithm $read()$**:**

1. Broadcast $read()$ to all nodes
2. Wait for $k > n/2$ nodes to reply with values $x_1, \ldots, x_k$
3. Return $x_1 \sqcup \ldots \sqcup x_k$

Why does it work? There is at least one node at the intersection between the two sets of nodes that replied to each request, that "saw" x before the $read()$ started ($x_i \sqsupseteq x$).

CRDTs and quorums: monotonic-reads consistency

write($\{a\}$):

- ● $\not\supseteq \{a\}$
- ● $\not\supseteq \{a\}$
- ● $\not\supseteq \{a\}$

write($\{b\}$):

- ● $\not\supseteq \{b\}$
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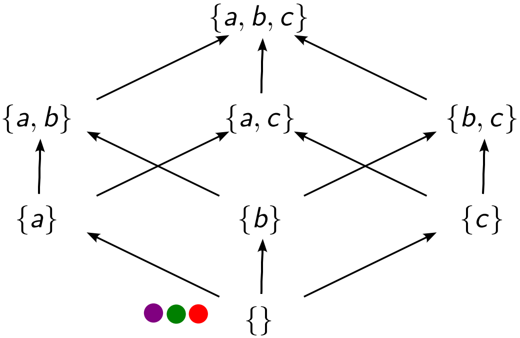

CRDTs and quorums: monotonic-reads consistency

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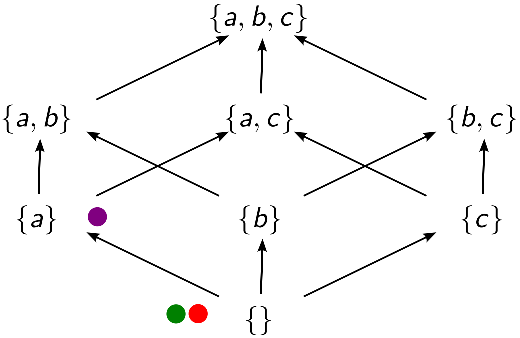

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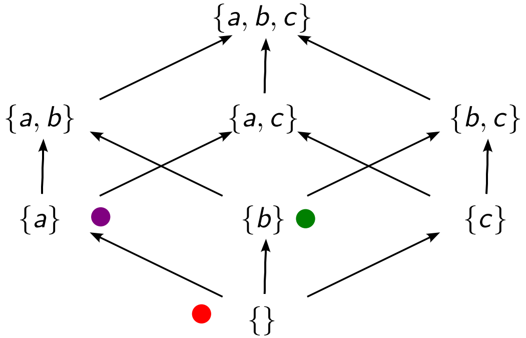

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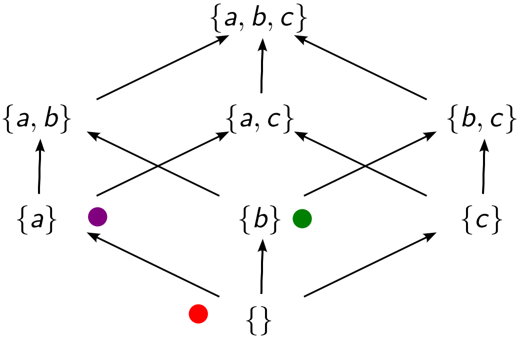

$read()$:

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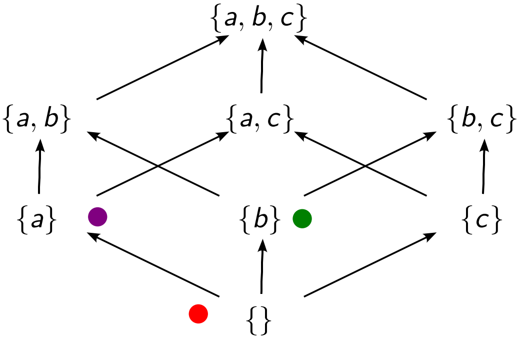

$read()$:

● $\rightarrow \{a\}$

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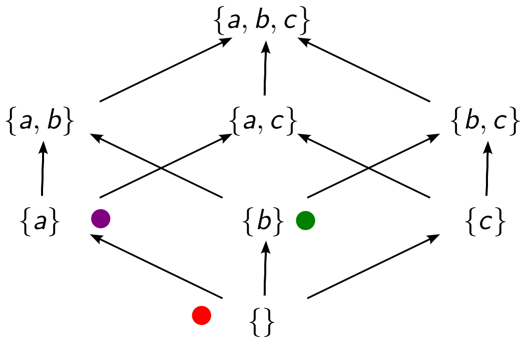
- ● $\not\sqsupseteq \{b\}$
- ● $\sqsupseteq \{b\} \rightarrow$ OK
- ● $\not\sqsupseteq \{b\}$



$read()$:

- ● $\rightarrow \{a\}$
- ● $\rightarrow \{\}$

return $\{a\}$

CRDTs and quorums: monotonic-reads consistency

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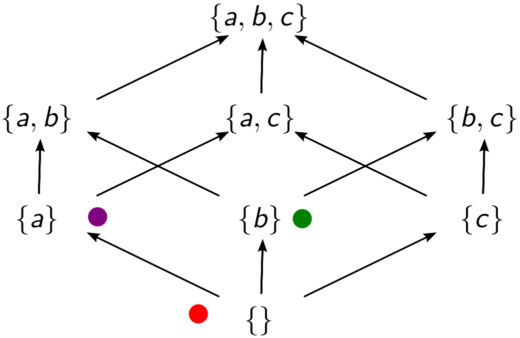

read():

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;

read():

CRDTs and quorums: monotonic-reads consistency

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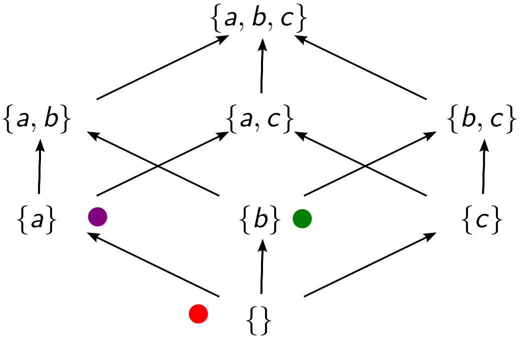

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- ● $\rightarrow \{\}$

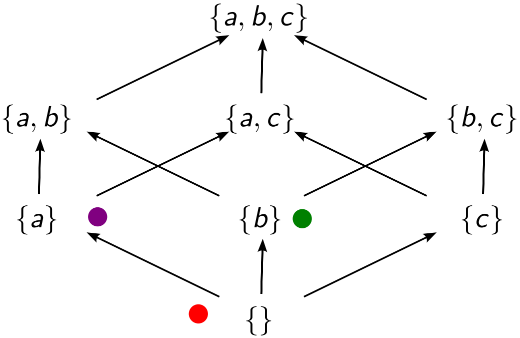
CRDTs and quorums: monotonic-reads consistency

write({*a*}):

- ● $\sqsupseteq \{a\} \to$ OK
- ● $\not\sqsupseteq \{a\}$
- ● $\not\sqsupseteq \{a\}$

write({*b*}):

- ● $\not\sqsupseteq \{b\}$
- ● $\sqsupseteq \{b\} \to$ OK
- ● $\not\sqsupseteq \{b\}$



read():

- ● $\to \{a\}$
- ● $\to \{\}$

return $\{a\}$

;

read():

- ● $\to \{\}$
- ● $\to \{b\}$

return $\{b\}$

CRDTs and quorums: monotonic-reads consistency

write$(\{a\})$:

● $\sqsupseteq \{a\} \to$ OK

● $\not\sqsupseteq \{a\}$

● $\not\sqsupseteq \{a\}$

write$(\{b\})$:

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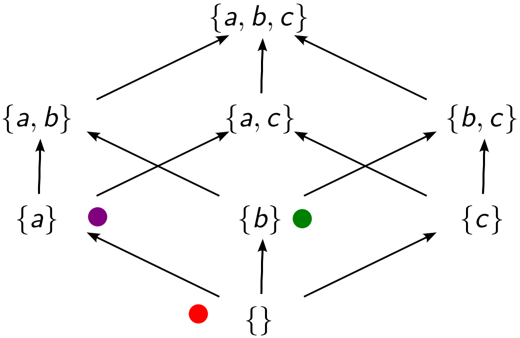


read():

● $\to \{a\}$

● $\to \{\}$

return $\{a\}$

;

read():

● $\to \{\}$

● $\to \{b\}$

return $\{b\}$

??!

$\{a\} \not\sqsubseteq \{b\}$

CRDTs and quorums: monotonic-reads consistency

Property: If node A did an operation *read*() and received x as a response,
and node B starts an operation *read*() after A received x,
then B will read a value $x' \sqsupseteq x$.

Algorithm *read*()**:**

1. Broadcast *read*() to all nodes
2. Wait for $k > n/2$ nodes to reply with values $x_1, \dots, x_k$
3. If $x_i \neq x_j$ for some nodes i and j,
   then call $write(x_1 \sqcup \dots \sqcup x_k)$ and wait for OK from $k' > n/2$ nodes
4. Return $x_1 \sqcup \dots \sqcup x_k$

This makes reads slower in some cases, and is **not implemented in Garage**.

A hard problem: layout changes

- We rely on quorums $k > n/2$ within each partition:

$$n = 3, \qquad k \geq 2$$

- When rebalancing, the set of nodes responsible for a partition can change:

$$\{n_A, n_B, n_C\} \to \{n_A, n_D, n_E\}$$

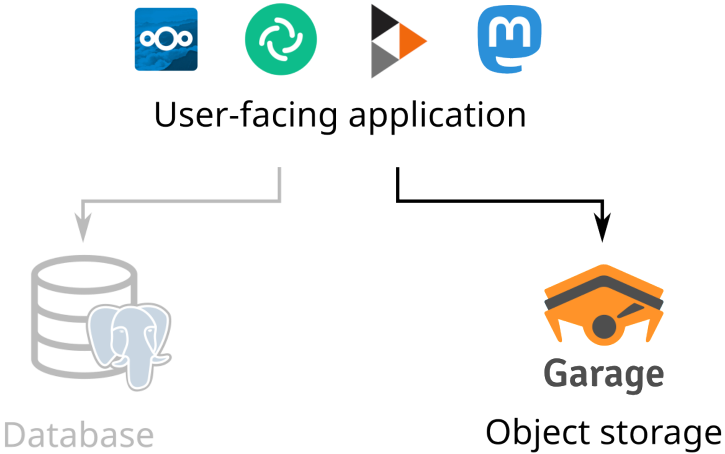
- During the rebalancing, D and E don't yet have the data,
  and B and C want to get rid of the data to free up space

  $\to$ quorums only within the new set of nodes don't work

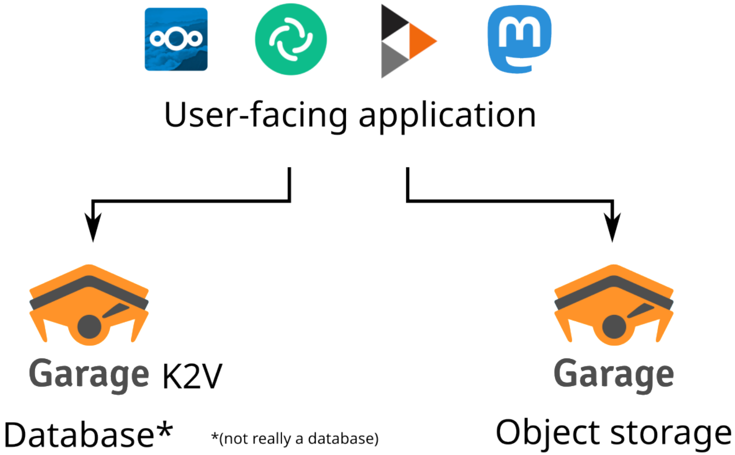
  $\to$ how to coordinate? **currently, we don't...**

Going further than the S3 API

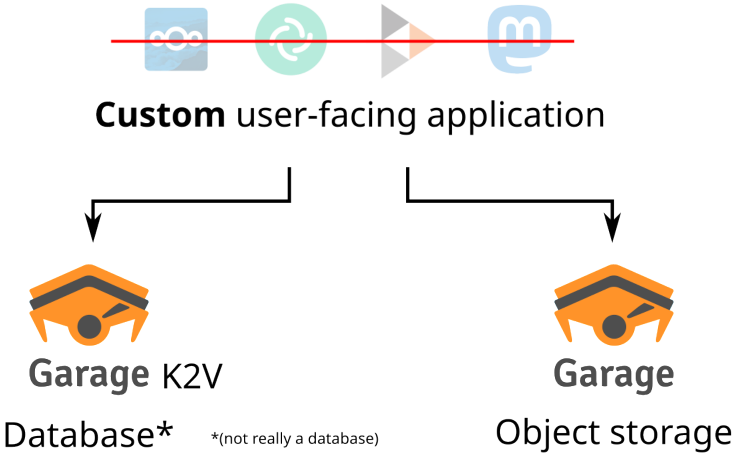
Further plans for Garage



Further plans for Garage



Further plans for Garage



K2V Design

- A new, custom, minimal API
  - Single-item operations
  - Operations on ranges and batches of items
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  K2V = partition key / sort key / value (like Dynamo)

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- Cryptography-friendly: values are binary blobs

Handling concurrent values

How to handle concurrency? Example:

1. Client A reads the initial value of a key, x_0

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1. Client A reads the initial value of a key, x_0
2. Client B also reads the initial value x_0 of that key
3. Client A modifies x_0, and writes a new value x_1
4. Client B also modifies x_0, and writes a new value x'_1, without having a chance to first read x_1

   $\rightarrow$ what should the final state be?

Handling concurrent values

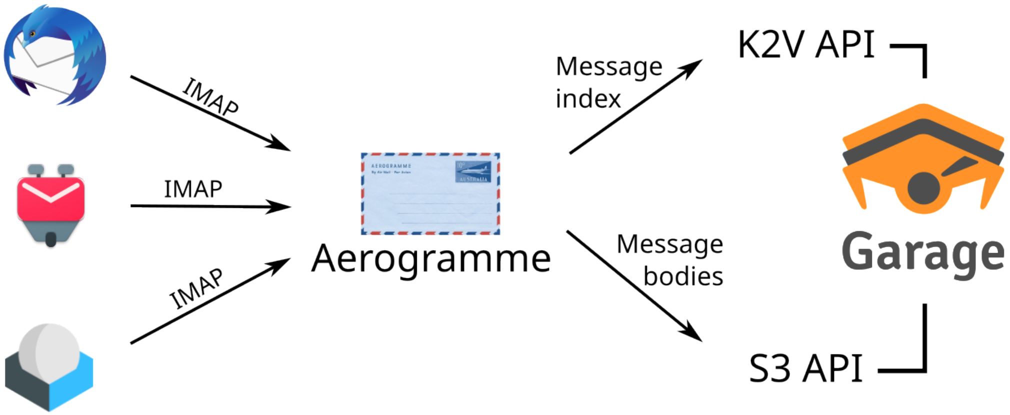
- If we keep only x_1 or x_1', we risk **loosing application data**
- Values are opaque binary blobs, **K2V cannot resolve conflicts** by itself (e.g. by implementing a CRDT)
- Solution: **we keep both!**
  $\rightarrow$ the value of the key is now $\{x_1, x_1'\}$
  $\rightarrow$ the client application can decide how to resolve conflicts on the next read

Keeping track of causality

How does K2V know that x_1 and x'_1 are concurrent?

- *read*() returns **a set of values** and an associated **causality token**
- When calling *write*(), the client sends **the causality token from its last read**
- The causality token represents the set of values **already seen by the client**
  $\rightarrow$ those values are the **causal past** of the write operation
  $\rightarrow$ K2V can keep concurrent values and overwrite all ones in the causal past
- Internally, the causality token is **a vector clock**

Application: an e-mail storage server



A new model for building resilient software

1. Design a data model suited to K2V
   (see Cassandra docs on porting SQL data models to Cassandra)

   - Use CRDTs or other eventually consistent data types (see e.g. Bayou)

   - Store opaque binary blobs to provide End-to-End Encryption

2. Store big blobs (files) using the S3 API

3. Let Garage manage sharding, replication, failover, etc.

Research perspectives

- TODO

Where to find us

Garage

https://garagehq.deuxfleurs.fr/

mailto:garagehq@deuxfleurs.fr

#garage:deuxfleurs.fr on Matrix