Modern Databases

Persistent storage in three flavors

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Agenda

- Introduction
- Background
- AWS' *Physalia*
- Cockroach Labs' *CockroachDB*
- TigerBeetle Inc.'s *TigerBeetle*
- Conclusion

Introduction

- **Evolution of databases:**
  - *Primitive* databases: Flat files and hierarchical models.
  - *Relational* databases: Introduction of SQL and normalization.
  - *NoSQL* shift: Adopting non-relational models for scalability.
  - *NewSQL* and distributed databases: Combining scalability with consistency.
- **Modern challenges:**

🌎Data volume/velocity: Manage big data and real-time processing globally.

📈Scalability: Monitor performance as data and user numbers grow.

💝High availability and disaster recovery: Minimize downtime and data loss.

👮Security/privacy: Avoid hackers, observe policies, and comply with regulations.

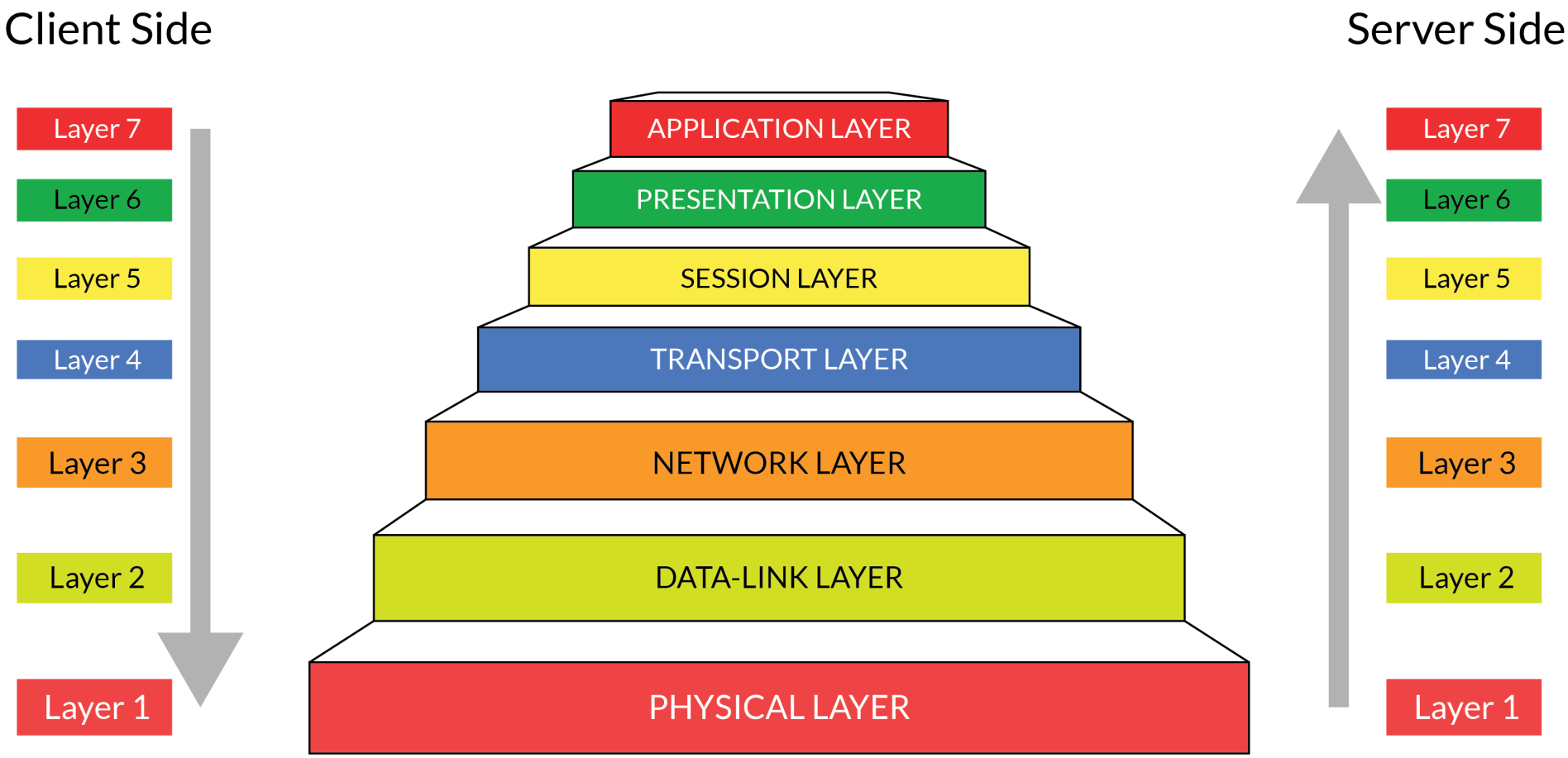
Background

- Networks?
- Distributed computing
- ACID vs. BASE
- Catalogs of Databases

Image generated using Adobe Photoshop.

Background: Networks?

...I thought this was a database class?



Open Systems Interconnection model (OSI model) reference model for how applications communicate over a network. 5

Background: Networked databases

- **Single** database ⇌ **single** client (same host):

  Maybe a network?

- **Single** database ⇌ **single** client (different host):

  Networked

- **Single** database ⇌ **multiple** clients:

  Networked

- **Clustered** database ⇌ **multiple** clients:

  *Networked...maybe **multiple** networks*

Background: Distributed computing

- Terms
- Data replication and consistency
- Consensus algorithms
- CAP Theorem with PACELC Extension
- Types of failures

Image generated using Adobe Photoshop.

Background: Distributed computing

Leveraging *multiple* computers to collaboratively solve tasks over a *network*.

...sounds like the generic case of a clustered database...

Advantages of a clustered solution:

- *Scalable:* Easily add or remove nodes to handle varying loads.
- *Fault Tolerant:* The system remains operational even if some nodes fail.
- *Resource Pool:* Utilize the combined resources of all nodes in the network.

Biggest single challenge: Keeping data **consistent** across nodes can be *difficult*.

Background: Distributed databases key terms

- **Shared-Nothing Architecture**: Each node is independent and self-sufficient, with no shared components that could become a bottleneck.
- **Data Sharding**: The process of splitting a large database into smaller, more manageable pieces called shards, each of which can be stored on a different node.
- **Quorum-Based Replication**: Ensuring data consistency by requiring a majority of nodes (a *quorum*) to agree on the value of data.
- **Two-Phase Commit (2PC)**: A protocol to ensure the consistency of transactions across multiple nodes by using a two-step process.
- **Eventual Consistency**: Updates to the database will propagate to all nodes eventually, but not necessarily immediately, allowing for higher availability.
- **Vector Clocks**: Tracks causal relationships between events and ensure data consistency by associating a timestamp with each update.
- **Scaling**: *Scale-out* (horizontal) → more nodes. *Scale-up* (vertical) → more `resources`.
- **Distributed Transactions**: Spans multiple nodes, requiring coordination.

Background: Data partitioning

Dividing the database into smaller, manageable segments.

Types:

- *Horizontal* partitioning (**sharding**): Distributing rows across multiple nodes.
- *Vertical* partitioning: Distributing columns across different nodes.

Strategies:

- *Range-based:* Assigning data based on a range of values.
- *Hash-based:* Assigning data based on a hash function.
- *List-based:* Assigning data based on a predefined list.
- *Composite:* Combining multiple strategies.

Question:

- *Which type is better?*

Background: Replication

Copying data across different nodes for redundancy and availability.

- *Synchronous* replication: Ensuring data consistency across nodes in real-time.
- *Asynchronous* replication: Allowing for slight delays in data synchronization.

Active/Active:

- Both nodes are active and can handle read and write operations.
- Data is replicated bi-directionally for synchronization.
- Offers high availability and load balancing.

Primary/Replica:

- The primary node handles write operations, while replica nodes are read-only.
- Changes are propagated from the primary to the replicas.
- Provides data redundancy and read scalability.

Background: Data consistency

Ensuring that all nodes in a distributed system have the same data.

Consistency models: Balancing consistency, availability, and partition tolerance.

- *Strong* consistency: Ensuring all nodes have the same data at the same time.
- *Eventual* consistency: Allowing temporary inconsistencies for more performance.
- *Causal* consistency: Orders causally related operations consistently across nodes.
- *Weak* consistency: Delays data updates' visibility to prioritize performance.

Question:

- *Why different models?*

Background: Consensus algorithms

Achieve agreement on a distributed *single data value*, even in the presence of failures.

Paxos:

- Developed by Leslie Lamport in late 80's.
- Theoretical foundation, complex implementation.
- *Active replication:* Each replica executes operations.

Viewstamped Replication (VR):

- Developed by Brian Oki & Barbara Liskov around the same time as Paxos.
- *Passive replication:* Only the primary executes operations.

Raft:

- Developed by Diego Ongaro and John Ousterhout in 2013.
- Designed for simplicity, easier to understand and implement than Paxos.

Background: Raft example

https://raft.github.io/

Background: Types of Failures in Distributed Systems

Network Failures: Communication issues between nodes: soft (TTL) / hard (partitions).

Node Failures: Hardware/software failures that cause a node to become unresponsive.

Replication Failures:

- **Bad Data Replication:** Incorrect/corrupted data is replicated across nodes.
- **Replication Lag:** Delays in replicating data from the primary to replicas.
- **Conflicts:** Simultaneous updates to the same data can lead to value conflicts.

Consistency Failures: Violations of the consistency model → incorrect data being read.

Byzantine Failures: Malicious or arbitrary failures where a node behaves unpredictably.

Question:

- *What is "blast radius"?*

Background: Failure effect "Split-Brain"

- A split-brain occurs when a network partition divides a cluster into subclusters.
- Each subcluster may operate independently, risking data inconsistency.
- Solutions include quorum-based decisions, fencing, and manual intervention.

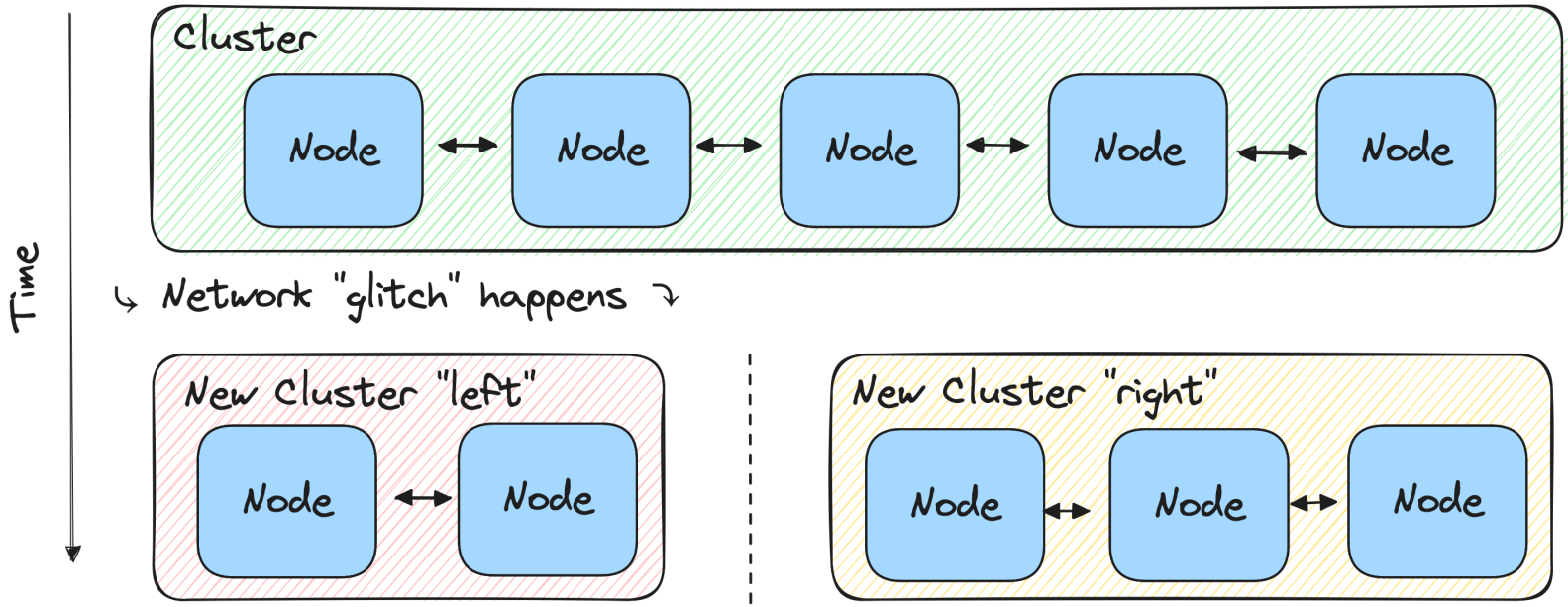
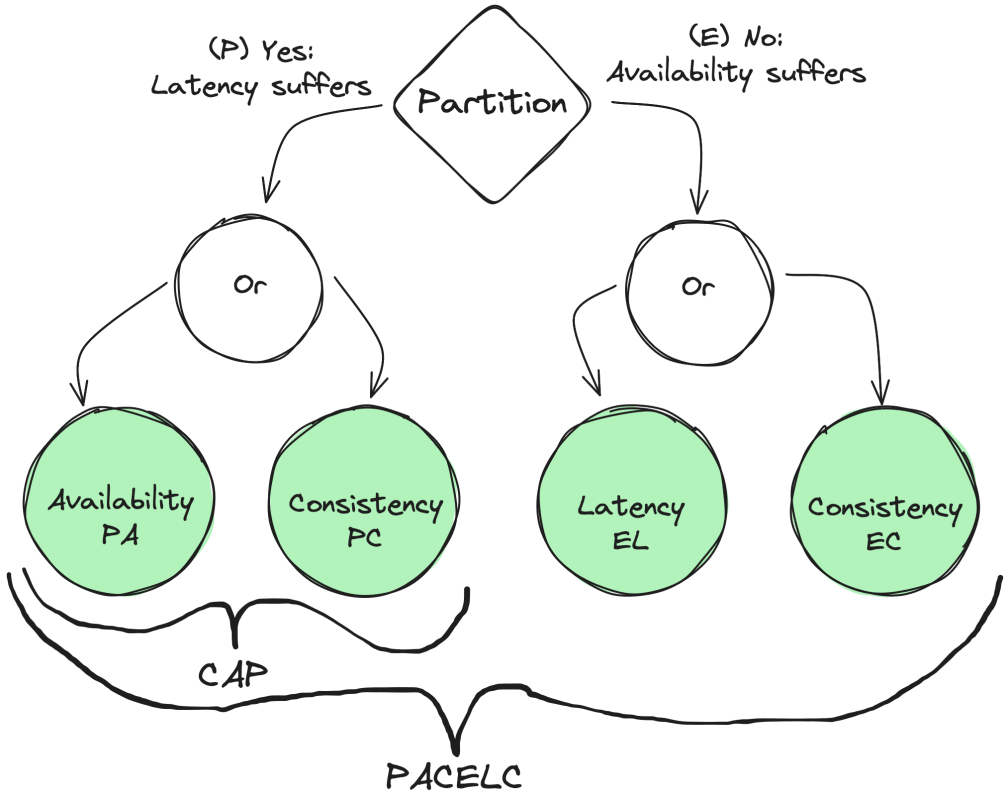


Illustration of a split-brain scenario caused by a network partition in a clustered system, leading to two separate subclusters operating independently.

Background: CAP Theorem with PACELC Extension

CAP Theorem (2000): any distributed data store can provide only 2 of 3 guarantees.
PACELC Extension (2012): extends CAP for partitioned and non-partitioned states.



If a partition (P) occurs, the system must balance availability (A) and consistency (C); otherwise (E), in normal operation without partitions, it must balance latency (L) and consistency (C).

Background: Back to Databases with 'ACID' vs. 'BASE'

ACID:

- ***A*tomicity:** Transactions are all-or-nothing.
- ***C*onsistency:** Database stays consistent before/after transactions.
- ***I*solation:** Transactions are executed independently.
- ***D*urability:** Committed transactions are permanent.

ACID is used in relational databases for strict consistency.

BASE:

- ***B*asically *A*vailable:** Data is available, but not always up-to-date.
- ***S*oft state:** System state may change without input.
- ***E*ventual Consistency:** Consistency achieved over time, not immediately.

BASE is common in distributed databases for scalability and availability.

Background: Back to networks...

The "Fallacies of distributed computing" are:

```
1. The network is reliable;
2. Latency is zero;
3. Bandwidth is infinite;
4. The network is secure;
5. Topology doesn't change;
6. There is one administrator;
7. Transport cost is zero;
8. The network is homogeneous.
```

Sun Microsystems' Peter Deutsch (1994).

Questions:

- *What are the implications for networked databases?*
- *What are the implications for distributed databases?*
- *Better to scale "up" or scale "out"?*

Background: Database of Databases

The On-line Database of Databases: https://dbdb.io/

- Created and maintained by the *Carnegie Mellon University Database Group*
- Provides detailed information about a wide range of database systems, including their features, history, and underlying technologies.
- Contains some very esoteric (academic/specialized) databases.

DB-engines: https://db-engines.com/

- Created and maintained by an Austrian IT consulting company.
- Provides "ranking" (popularity method) of databases with metadata about them.
- Contains more "mainstream" databases.
- Encyclopedia Index is a glossary of database terms.

Physalia

- Overview
- Handling failures
- NSDI '20 presentation

Portuguese man-of-war (Physalia physalis). Image courtesy of NSDI '20 AWS Physalia presentation.

Physalia: An Overview

"Millions of tiny databases" by Marc Brooker, Tao Chen, and Fan Ping. DOI

NSDI'20: Proceedings of the 17th Usenix Conference on Networked Systems Design and Implementation, February 2020, Pages 463–478

- Stores configuration info for the AWS Elastic Block Storage (EBS) control plane.
- Strongly consistent, critical for replication protocol correctness.
- Consists of numerous small databases (cells) for fault isolation

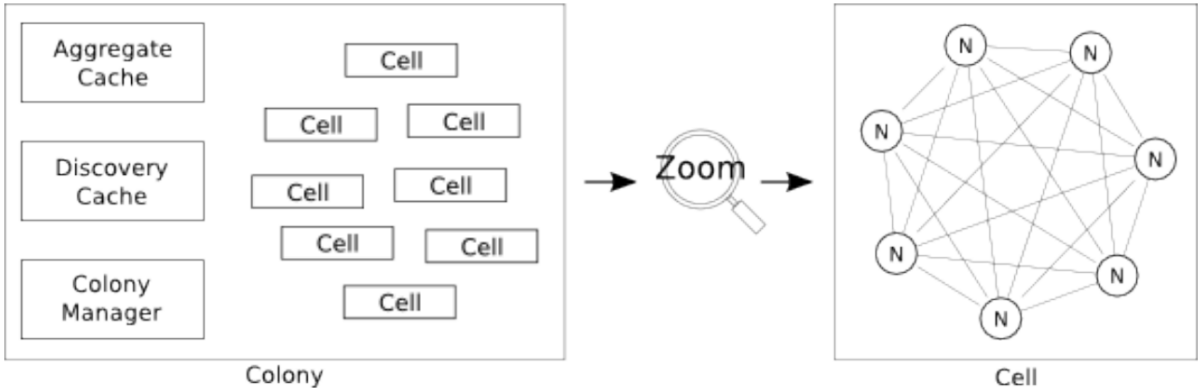


Figure 2: Overview of the relationship between the colony, cell and node.

Physalia: Handling failures

- Designed to minimize the blast radius of network partitions and fail gracefully.
- Uses chain-replication and Paxos-based consensus for reconfiguration.
- Incrementally deployemented to limit blast radius, with careful color-coded zones.
- Rigorous testing, including TLA$^+$ protocols modeling and Jepsen tests for linearizability under network failures.

For a more in-depth exploration, read Adrian Colyer's summary on The Morning Paper.

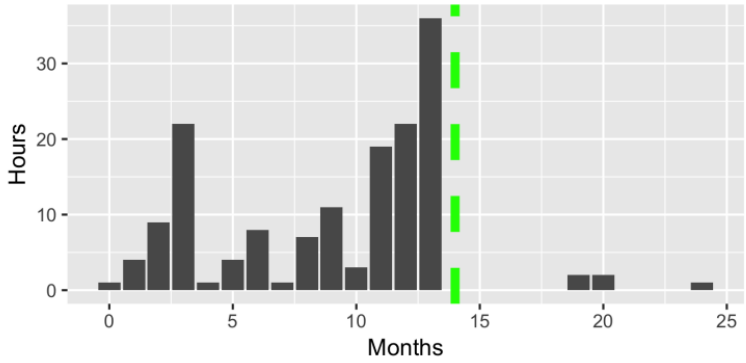
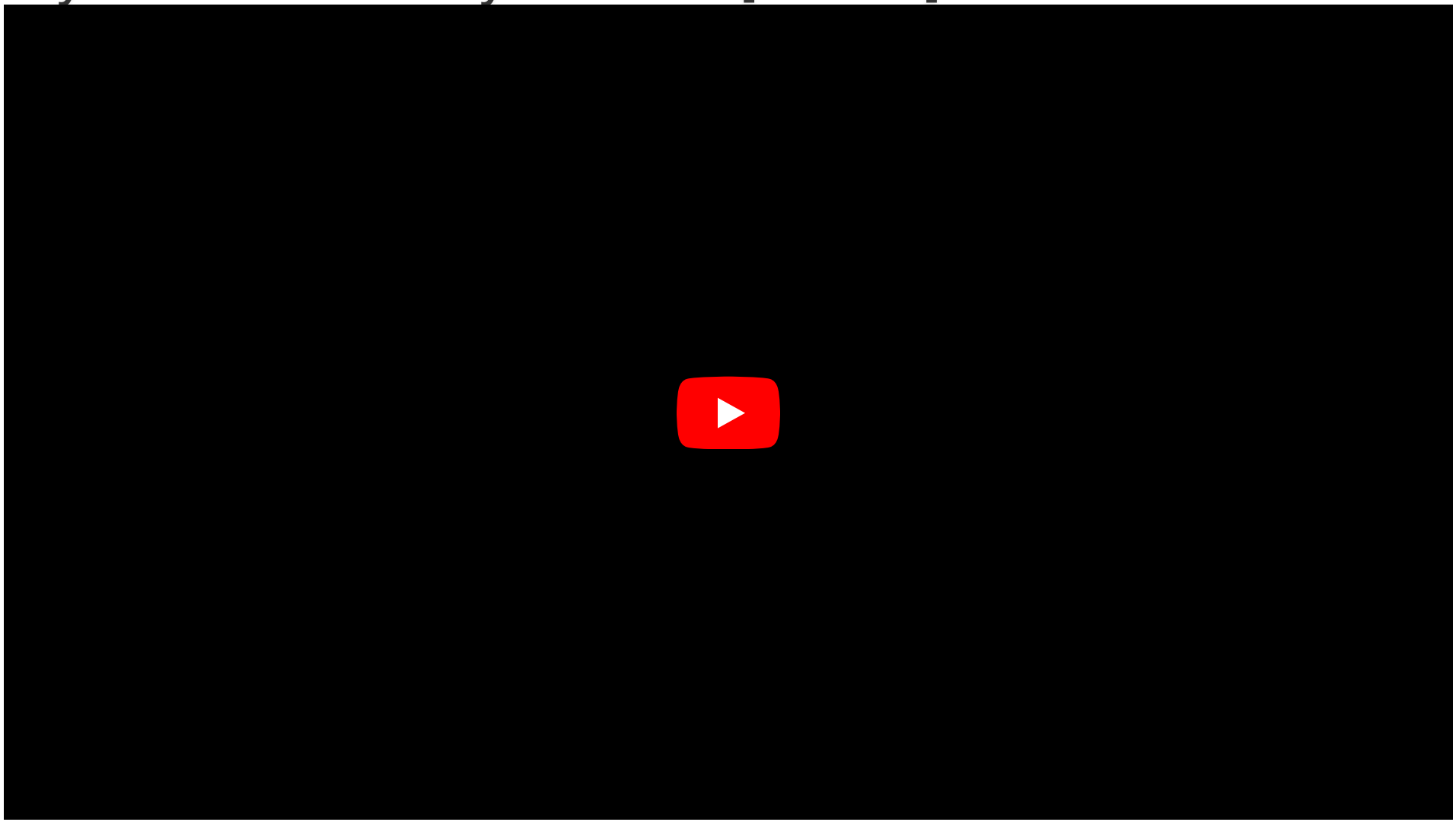


Figure 9: Number of hours per month where EBS masters experienced an error rate > 0.05% in a production colony. The vertical line shows the deployment of Physalia.

Physalia: Millions of Tiny Databases [NSDI '20]



NSDI '20 presentation

CockroachDB

- Overview
- Transaction techniques
- SIGMOD '20 presentation

Cockroach Labs logo. Image courtesy of Cockroach Labs.

CockroachDB: An Overview

"CockroachDB: The Resilient Geo-Distributed SQL Database" by Cockroach Labs, Inc. DOI

SIGMOD '20: Proceedings of the 2020 ACM SIGMOD International Conference on Management of Data, June 2020, Pages 1493–1509

- ACID-compliant and provides transactional guarantees.
- Fault tolerant and highly availability, geo-distributed partitioned and replica placed, with high-performance transactions.

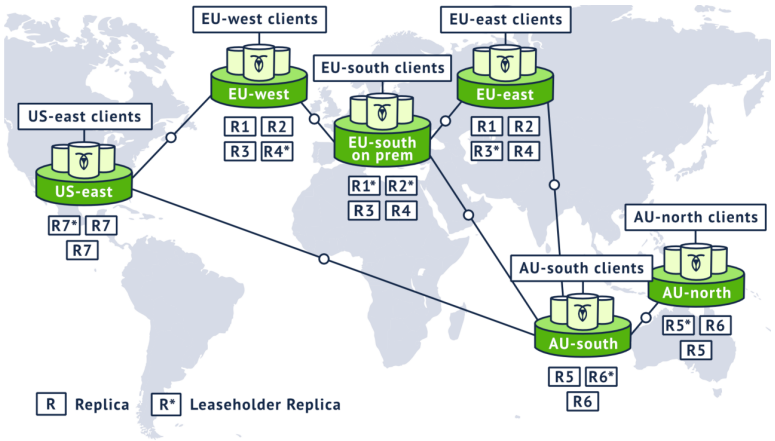


Figure 1: A global CockroachDB cluster (showing Replicas and Leaseholder Replicas)

CockroachDB: Transactions techniques

- Reduces commit wait times with transactional *Write Pipelining*.
- Speeds up transaction completion with *Parallel Commits*.
- Ensures data consistency and durability through *Raft* consensus.
- Indicates pending writes for isolation with *Write Intents*.
- Helps maintain transaction order through a *Timestamp Cache*.

(Also wire-compatible with PostgreSQL, allowing for easy migration.)

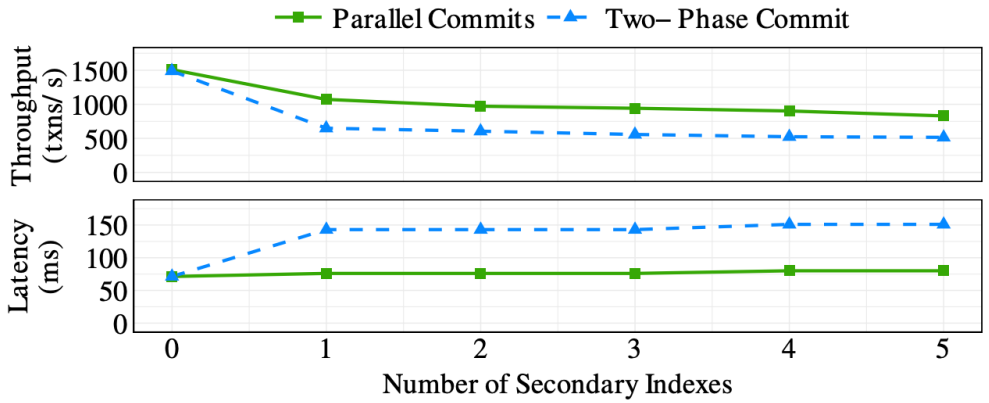


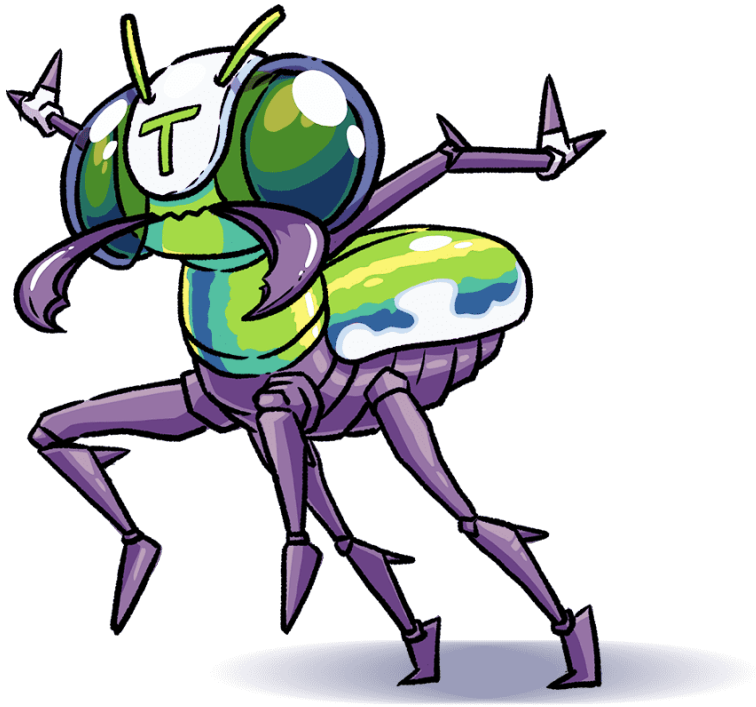
Figure 2: Performance impact of Parallel Commits

CRDB: The Resilient Geo-Distributed SQL Database [SIGMOD '20]

SIGMOD '20 presentation

TigerBeetle

- Overview
- Safety and testing
- Simulator presentation

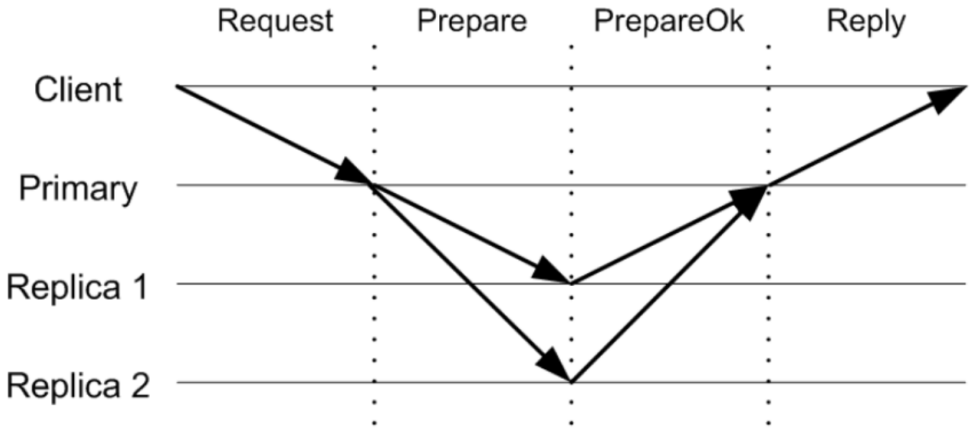


TigerBeetle mascot. Courtesy of TigerBeetle Inc.

TigerBeetle: An Overview

TigerBeetle: A High-Performance Financial Accounting Database by TigerBeetle Inc.

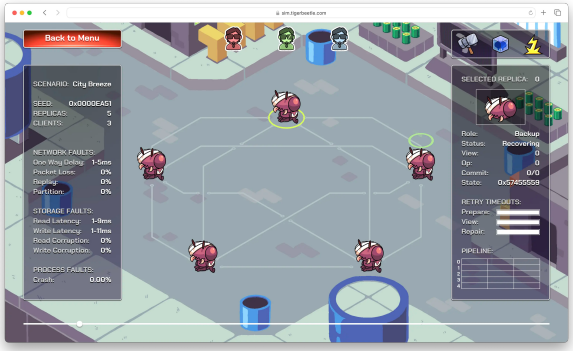
- Purpose-built for financial transactions to ensure critical safety and performance.
- Adheres to double-entry accounting principles for financial consistency.
- ACID-compliant with two-phase transfers for reliable staged fund movements.
- Aims for 1M transfers per second on OTS hardware.
- Viewstamped Replication & Protocol-Aware Recovery for Consensus-Based Storage.



Viewstamped Replication: Normal case processing in VR for a configuration with $f = 1$

TigerBeetle: Safety and testing

- Utilizes the Zig programming language for safety features such as OOM safety, bounds checking, and explicit control flow.
- Protects against varying storage-related failures with a robust storage fault model.
- Rigorous testing regime, including automated testing, audits of consensus and replication protocols, and state machine verification.
- *Viewstamped Operation Replicator (VOPR)* is a deterministic game to simulate TigerBeetle's protocol to test distributed behaviors.



VOPR Level 1: City Breeze, simulating a perfect environment. No network partitions. No packet loss or replays. No crashes o disk corruption, and, of course, low latency network and disk I/O.

TigerBeetle: SimTigerBeetle [The TigerBeetle Sessions]

SimTigerBeetle Director's Cut!: SimTigerBeetle, a TigerBeetle simulator in your browser.

Conclusion

- **Evolution of Databases:** From primitive to NewSQL and distributed databases, adapting to modern challenges like scalability, availability, and security.
- **Distributed Systems:** Key concepts like CAP/PACELC, consensus algorithms, and types of failures highlight the complexities of distributed computing.
- **Physalia:** Demonstrates fault isolation and graceful failure handling in AWS' EBS contro plane.
- **CockroachDB:** Combines ACID compliance with fault tolerance and high availability in a geo-distributed setup.
- **TigerBeetle:** Specializes in financial transactions with high performance and safety, leveraging Zig for robustness.

Thank you

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