

Dancing with Uncertainty

Challenges of Distributed Systems

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distributed systems | microservices | async | reactive | java

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CAP Theorem

- Consistency
- Availability
- Partition tolerance

Consistency

every read receives the most recent write

(a single-copy illusion)

Availability

every request receives a non-error response

(even if some nodes are down)

Partition tolerance

system continues to operate even if network links are lost

What makes
systems...distributed?

distributed systems are systems that communicate over
unreliable channels

Network is unreliable

as of 2025



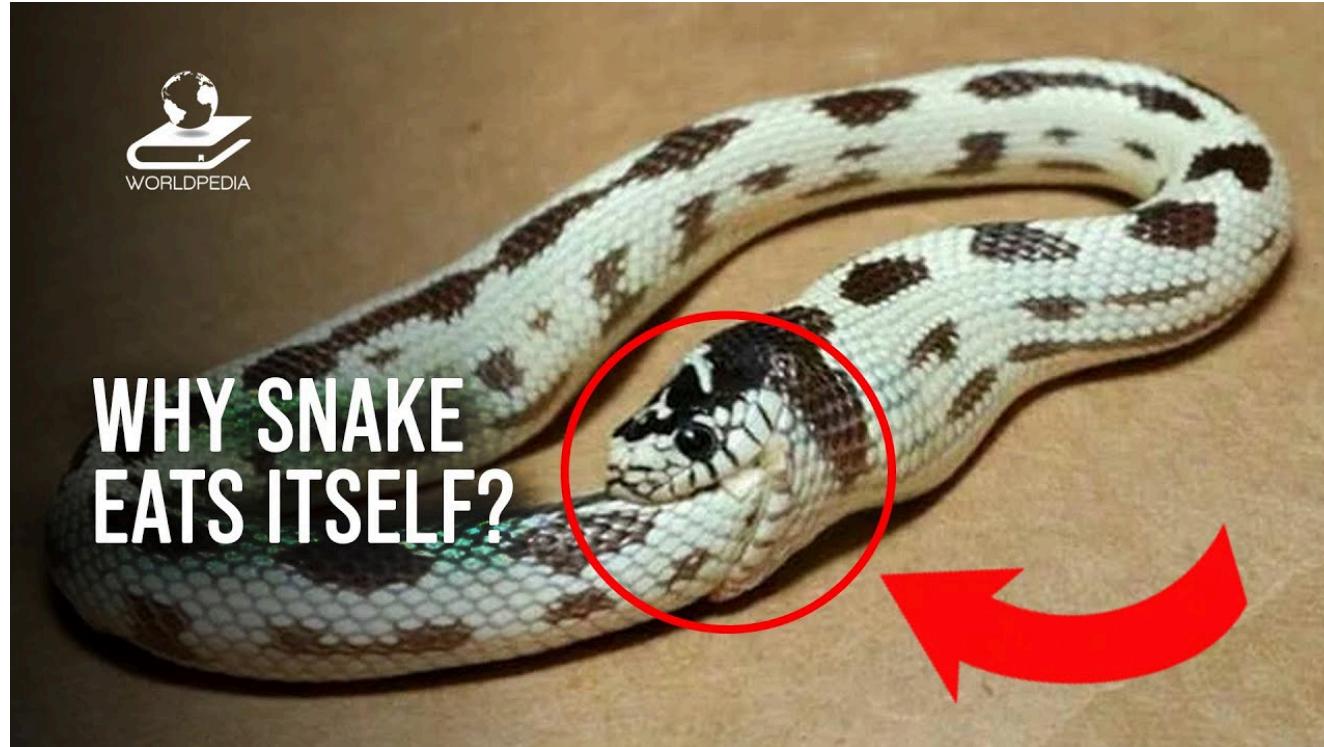
<https://slate.com/technology/2014/08/shark-attacks-threaten-google-s-undersea-internet-cables-video.html>

Rule: In the presence of a network partition, a distributed system must choose either *Consistency* or *Availability*.

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WHY SNAKE
EATS ITSELF?





Monolith



Microservices

<https://twitter.com/ddprrt/status/1425418538257428488>

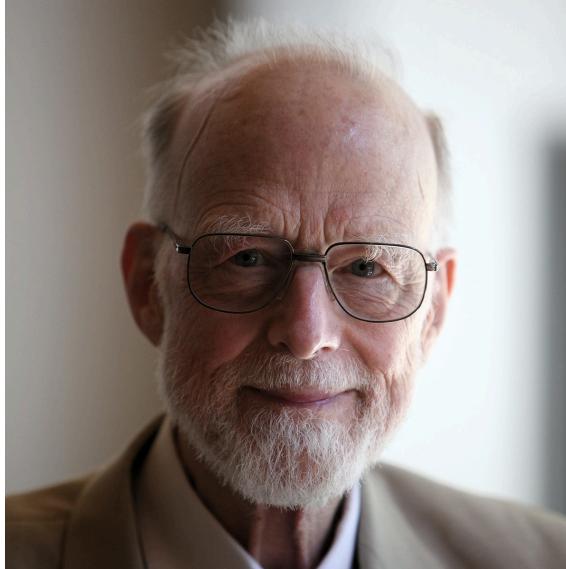


Monolith



Microservices

<https://twitter.com/ddprrt/status/1425418538257428488>

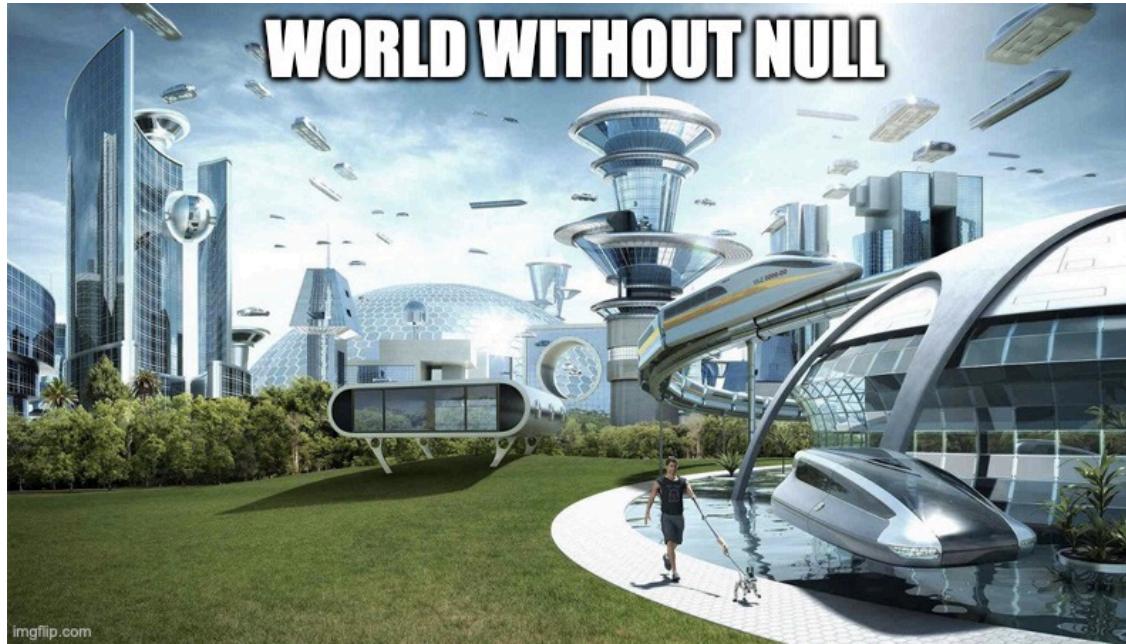


*"It was the invention of the null reference
in 1965...I call it my billion-dollar
mistake."*

Tony Hoare

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WORLD WITHOUT NULL



imgflip.com

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Another "*billion-dollar mistake*":
Microservices

Another "*billion-dollar mistake*":
"Micro"

Microservice vs service?

How small is "micro"?

N lines of code?

N endpoints?

N classes?

N MBs?

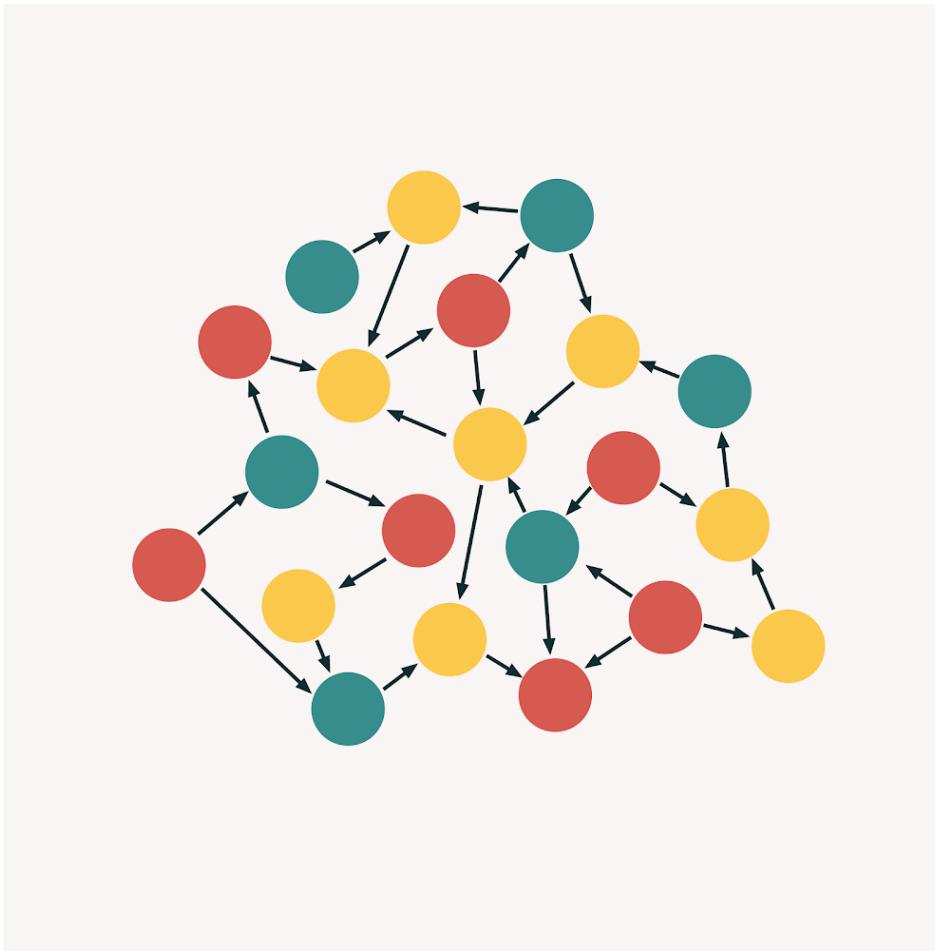
N responsibilities?

Rewritable in X time?

Microservices: the Main Idea

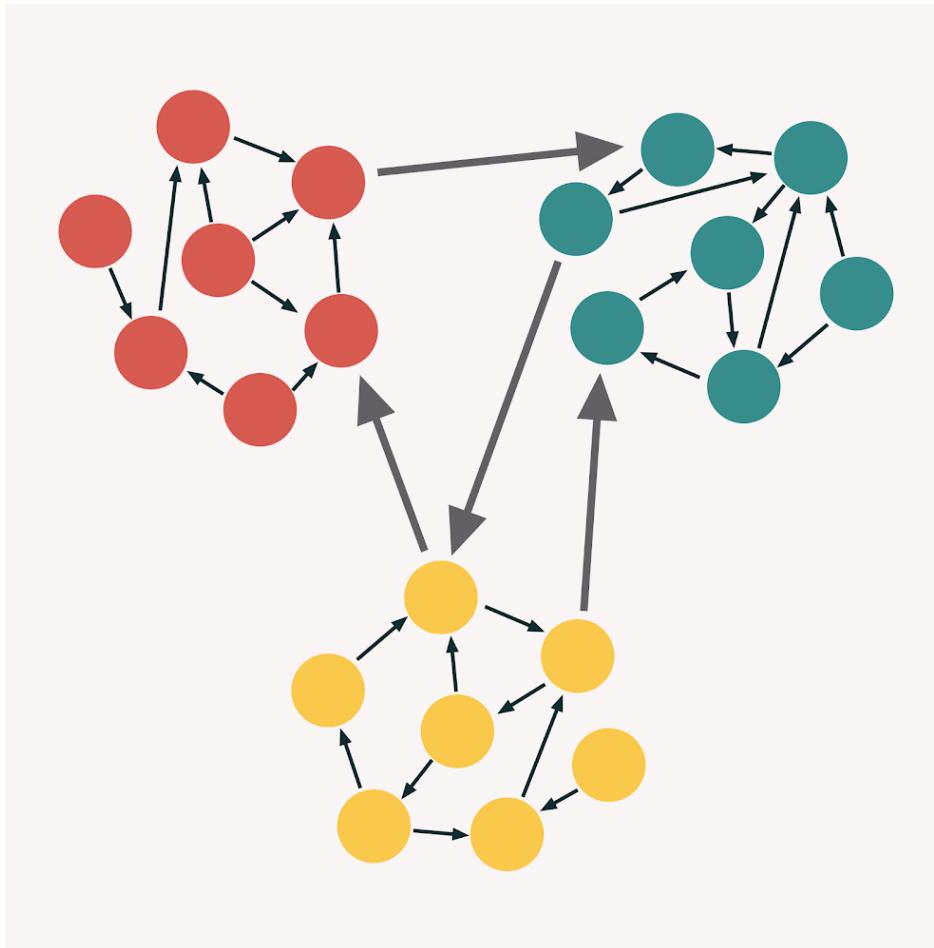
Enable scalability through
independence and modularity

Tight coupling - Low cohesion



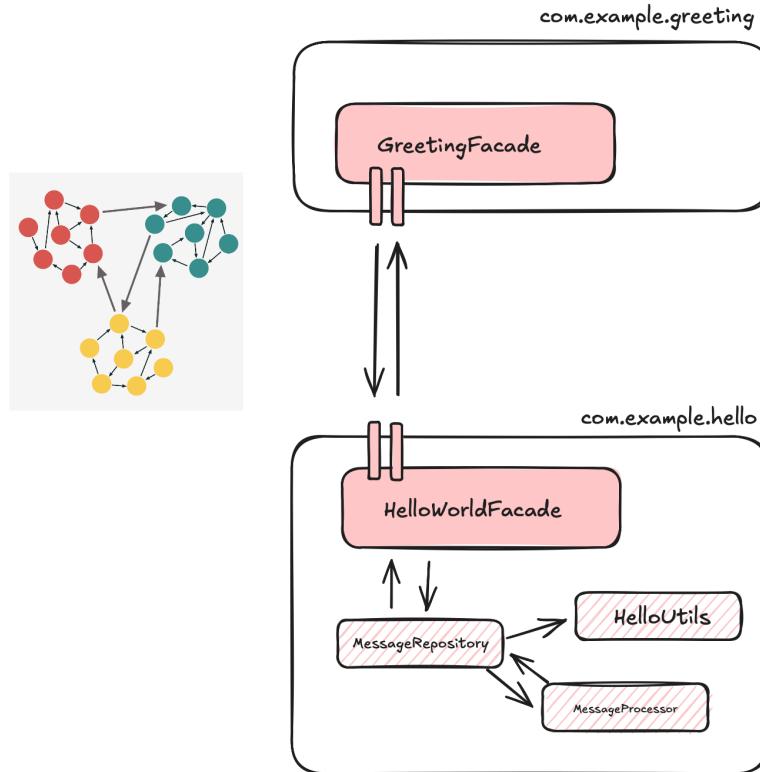
source: <https://enterprisecraftsmanship.com/posts/cohesion-coupling-difference/>

Low coupling - High cohesion

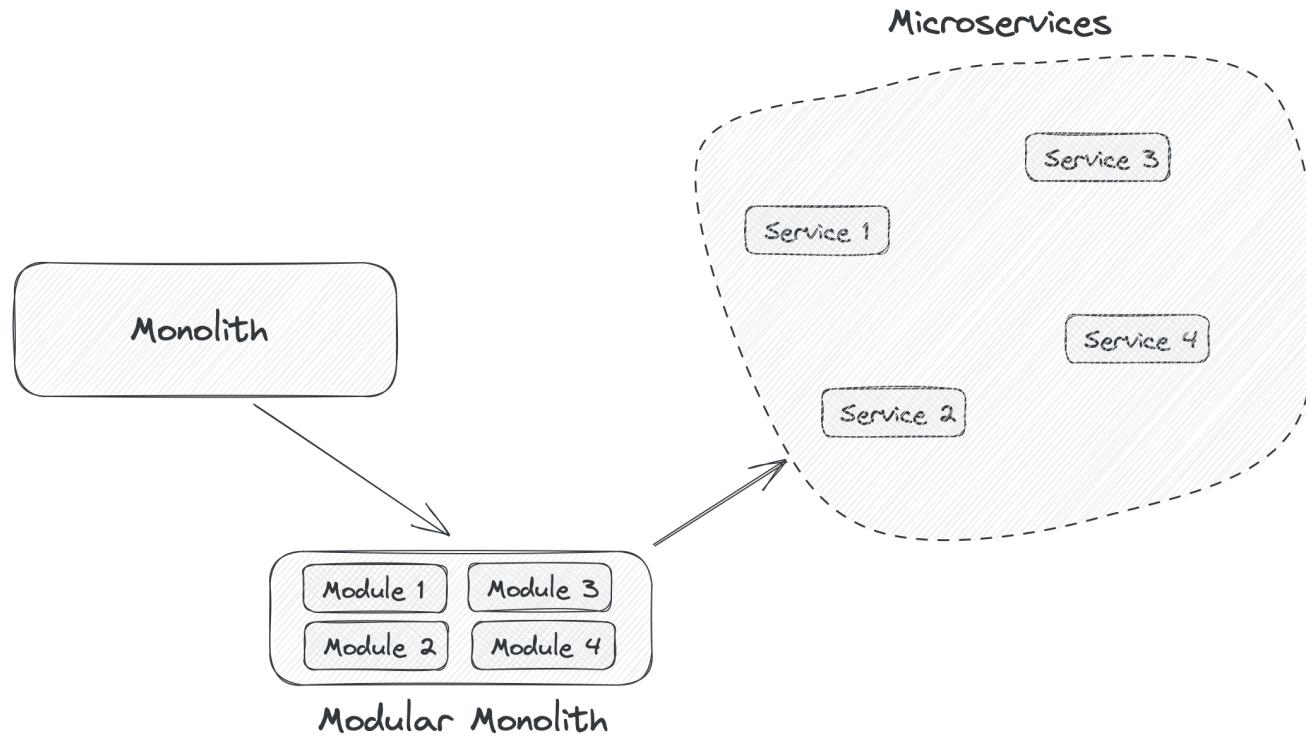


source: <https://enterprisecraftsmanship.com/posts/cohesion-coupling-difference/>

You can have modularity without microservices



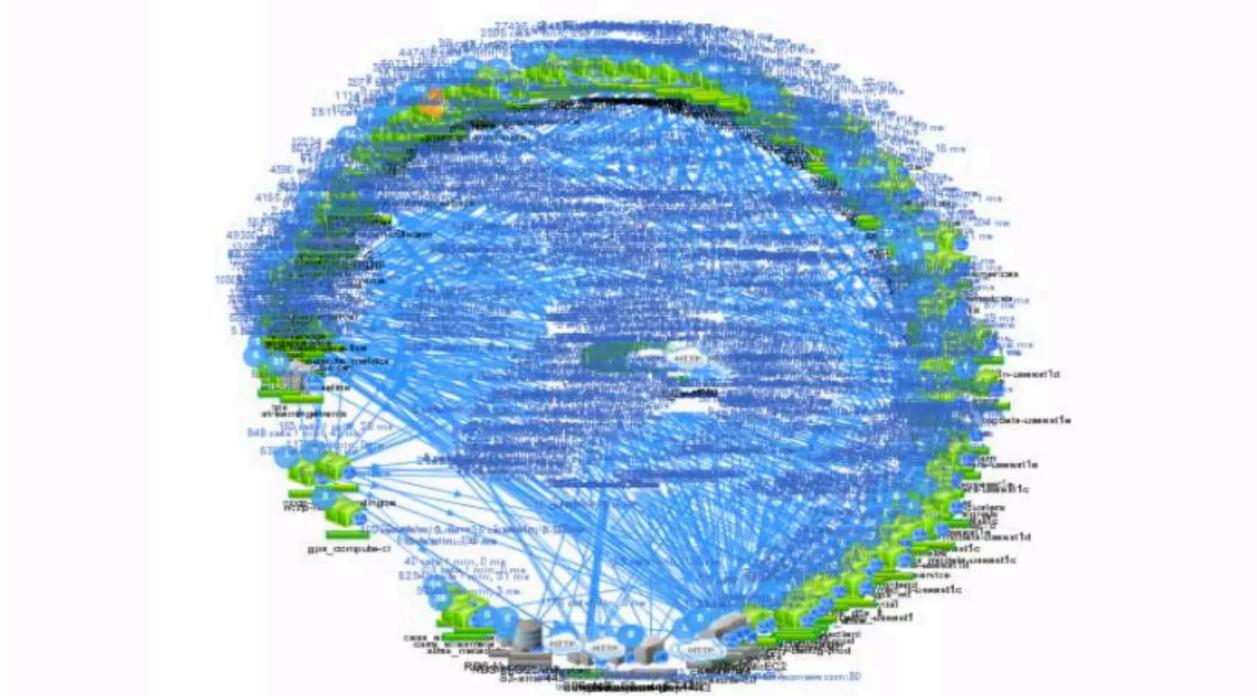
Naturally, you don't get all the benefits, but it's not a demanding investment



*"The smaller the service, the more you
maximize the benefits and downsides of
microservice architecture."*

Sam Newman

Netflix & Micro-Services



author: Bruce Wong

Netflix: 2000 engineers

Applying the high scalability tips from Google and Netflix software architectures to your trivial project.



However, don't be fooled by the size of those microservices, because a lot of those so-called microservices at Netflix are a lot larger, just looking at the code base, than the big monoliths that I've worked at, at many other companies.

Paul Bakker

source: <https://www.infoq.com/presentations/netflix-java/>

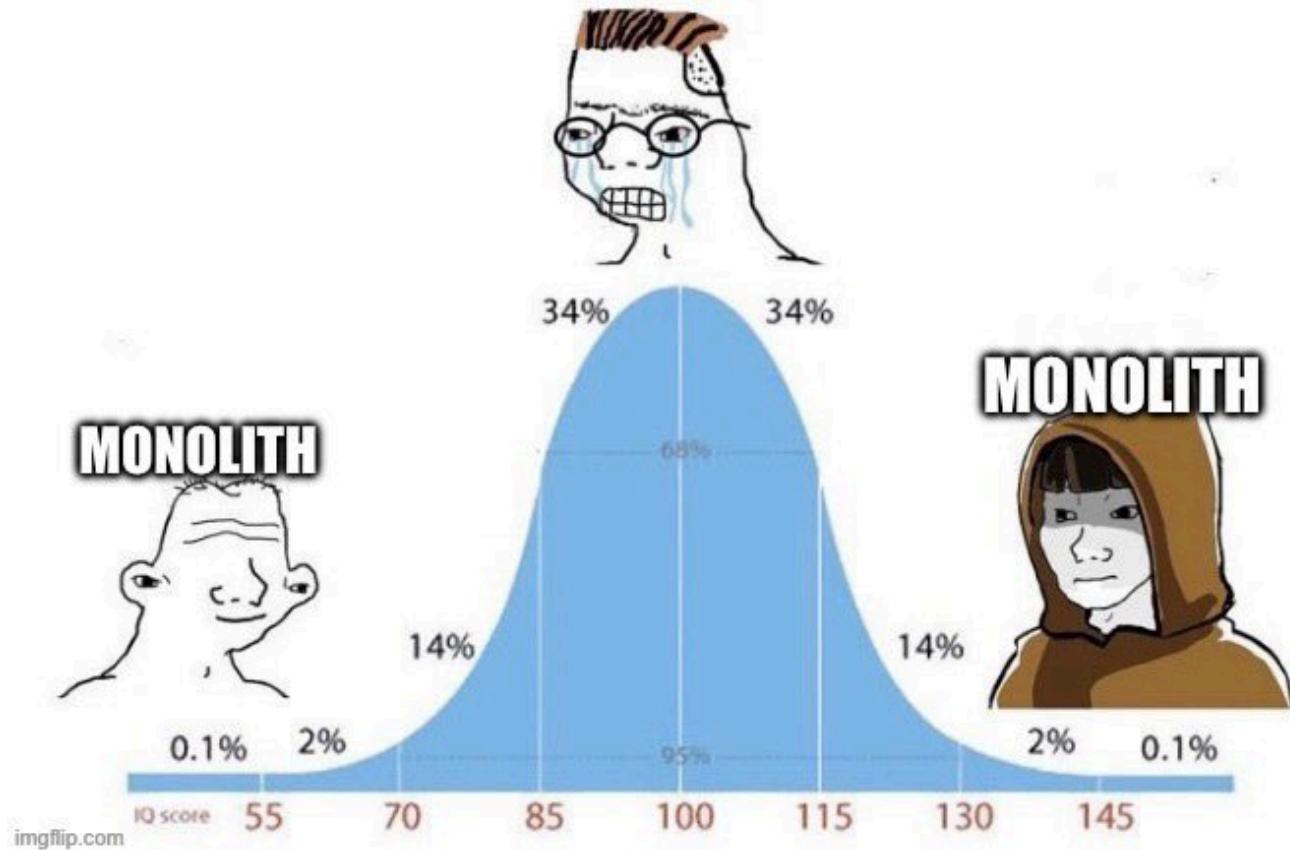
Do not ask about the max size, but when to split

So... when do we split?

When it hurts too much

The #1 rule of distributed systems: don't do it until you have
to

EVENT-DRIVEN MICROSERVICES



The Pragmatic Default

DHH  @dhh · Apr 7, 2020

The amount of pain that's been inflicted by the overeager adoption of microservices is immense.

Gergely Orosz  @GergelyOrosz · Apr 6, 2020

For the record, at Uber, we're moving many of our microservices to what @copyconstruct calls macroservices (wells-sized services).

Exactly b/c testing and maintaining thousands of microservices is not only hard - it can cause more trouble long-term than it solves the ...

Show more

36 204 826

DHH  @dhh

In addition to the Majestic Monolith, someone should write up the pattern of The Citadel: A single Majestic Monolith captures the majority mass of the app, with a few auxiliary outpost apps for highly specialized and divergent needs.

<https://twitter.com/dhh/status/1247522358908215296>

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Our server app is a monolith, one big codebase of several million lines and a few thousand Django endpoints [1], all loaded up and served together. A few services have been split out of the monolith, but we don't have any plans to aggressively break it up.

<https://instagram-engineering.com/static-analysis-at-scale-an-instagram-story-8f498ab71a0c>

Reliability in an unreliable world

When sending a message over unreliable channels, how to
guarantee delivery?

(...thought experiment...)

Definition

An operation is **idempotent** if performing it multiple times produces the *same effect* as performing it once.

$$f(f(x)) = f(x)$$

Examples

- Setting a user's status to "active" → 
- Incrementing a counter → 

In a distributed system
Failures and retries are inevitable.

- Network retries may cause duplicate requests
- Clients or load balancers might resend operations
- Idempotency prevents unwanted side effects

Exactly-once delivery?

A fairy tale.

Reality: You only ever get:

- **at-most-once** → messages may be lost
- **at-least-once** → messages may be duplicated

Exactly-once doesn't exist

- Networks can fail between *send* and *acknowledge*
- Clients can retry
- Servers can crash mid-processing

Exactly-once *effect*

We can't guarantee *exactly-once delivery*,
but we can design for **exactly-once effect** using
idempotency.

```
at-least-once delivery + idempotency = exactly-once
```

PACELC Theorem

Daniel Abadi extended CAP to include trade-offs when
no partition occurs:

If P (partition) $\rightarrow A$ or C

Else (ok) \rightarrow Latency or Consistency

Even without partitions, there's another trade-off

Waiting for consensus takes time

This is the “ELC” part of PACELC.

Imagine two coffee shops sharing an order system

- network failure → choice: *keep taking orders (A) or pause until synced (C)*
- no failure → each order can be: *fast but maybe outdated (L) or slow but always accurate (C)*

Real-world examples

- **Amazon Dynamo / Cassandra** → prioritize *Availability + Low Latency*
- **Google Spanner** → prioritize *Consistency*, accept more latency

temporal coupling

when all your services need to responsive at the same time

False Dichotomy: Consistent vs. Inconsistent

Different consistency levels

- **Strong consistency** → Data converges immediately
- **Eventual consistency** → Data converges... eventually
- **Accidental consistency** → Data converges... maybe

All are “consistent” – just in different ways.

Eventual consistency

If no new updates occur, all replicas will eventually converge to the same state.

It's a trade-off: we get **availability and speed** at the cost of temporary disagreement.

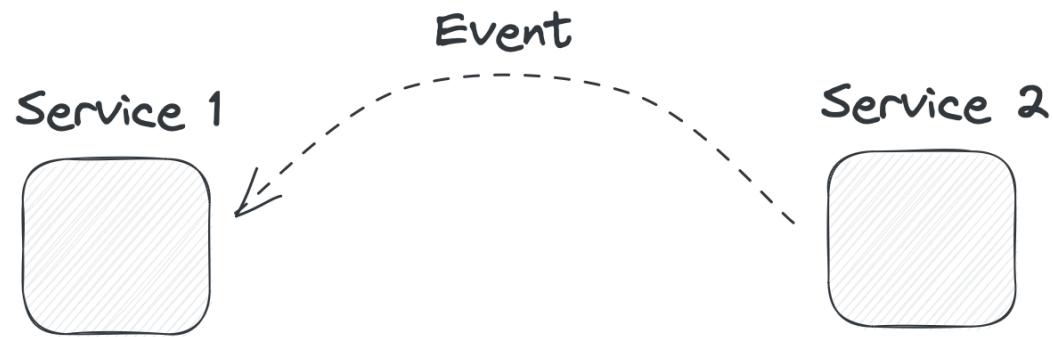
Why this makes sense

- Networks are slow and unreliable
- Waiting for everyone to agree slows everything down
- So we let nodes respond now and sync later
 - **Fast now, consistent later**

synchronous communication



asynchronous communication



From HTTP calls...

```
OrderService -> PaymentService -> NotificationService
```

Each service calls another directly...

...tight coupling, dependencies, and failure chains.

...to Events

```
OrderService --> publishes OrderCreatedEvent
```

```
PaymentService --> consumes OrderCreatedEvent
```

```
NotificationService --> consumes PaymentConfirmedEvent
```

Services react to **events** instead of making direct calls.

Local Read Models

Each service maintains its own **local view** of data it needs.

```
@EventListener  
void on(PaymentConfirmedEvent event) {  
    orderReadModel.updateStatus(event.orderId(), "PAID");  
}
```

This enables fast, local reads - no cross-service queries needed

...but it eventually consistent

Why Local Read Models?

- No need to call other services for data
- Improves reliability - service can operate even if others are down

Time



```
var first = Instant.now();  
var second = Instant.now();
```

first <= second?

A monotonic clock always moves forward - never backward.

But most system clocks are not monotonic.

Why clocks go backwards

- NTP (Network Time Protocol) adjustment
- Virtual machines paused and resumed
- Leap seconds
- Manual time correction by an admin

Monotonic clocks to the rescue

- In Java: `System.nanoTime()`
- In Linux: `CLOCK_MONOTONIC`

They never go backward, but don't represent "real" time.

Measuring time: from Java to kernel and back

In distributed systems, time is... an illusion.

The problem with clocks

- Each machine has its own clock
- Clocks drift - even if synced
- Network delays make “now” ambiguous

So: there is no single, global “current time.”

Example

Two servers record an event:

- Server A: event at 12:00:00.100
- Server B: event at 12:00:00.090

Which happened first? 🤔

Why this matters

- Event ordering affects state changes
- Conflicts appear when we can't tell "what came first"
- Replication, logs, and causality all depend on time

Happened-before relationship

Instead of wall-clock time, we use **causal order**:

$A \rightarrow B$ if *A happened before B (causally)*

We care about *ordering* of events, not their timestamps.

Logical clocks

- **Lamport clocks** → simple counters to track causal order
- **Vector clocks** → richer structure to detect concurrent events

They don't measure real time - they measure **cause and effect**.

Real time vs. logical time

- **Real time** → what your watch shows
- **Logical time** → what the system can *prove* happened first

Distributed systems live in **logical time**.

Google's Spanner uses special hardware clocks
(TrueTime API) 

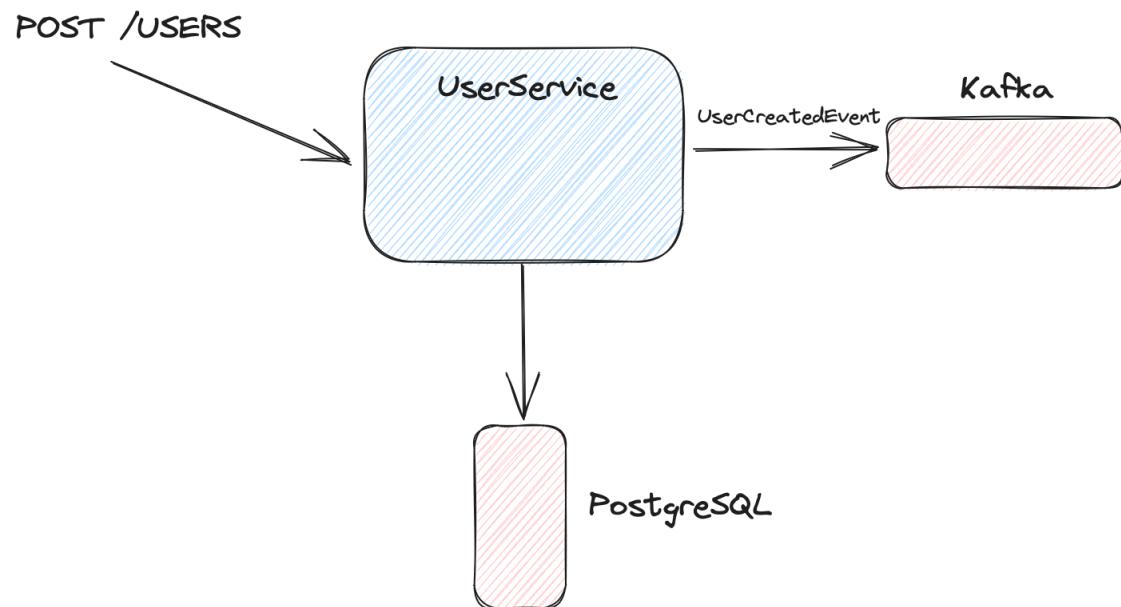
But even then, they include an **uncertainty window** -
because perfect time doesn't exist.

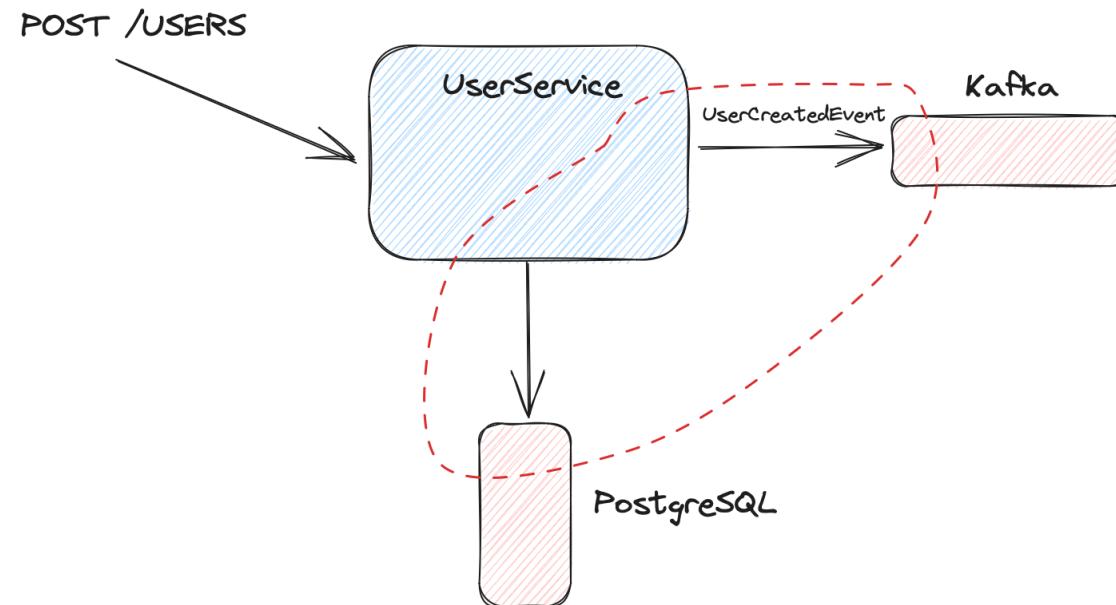
Summary

- Each node has its own imperfect sense of time
- We can't rely on timestamps for ordering
- We use **logical or causal time** to reason safely

Time is relative - especially in distributed systems 

Eventual Consistency != Accidental Consistency

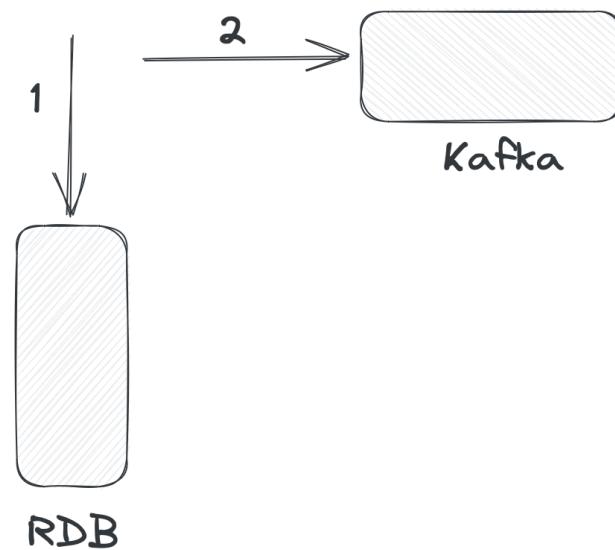




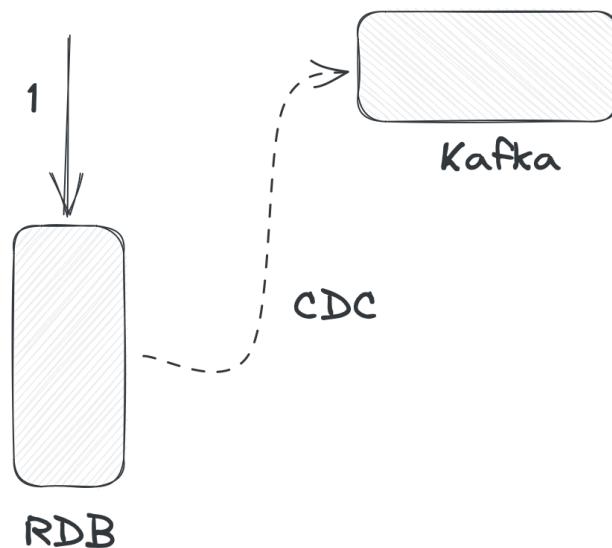
```
@Transactional  
public void createUser(CreateUserCommand command) {  
    var user = from(command);  
  
    persist(user); // 1  
    send(UserCreatedEvent.from(user)); // 2  
}
```

`@Transactional` won't save you in the distributed world

Dual-Write (distributed transaction)



Singe-Write with async propagation



Transactional Outbox Pattern

Change Data Capture

Transactional Outbox Pattern

Write the event to a local **outbox table** as part of the same transaction.

```
@Transactional  
public void createOrder(Order order) {  
    orderRepository.save(order);  
    outboxRepository.save(new OutboxEvent("OrderCreated", order.i  
})
```

Then a separate process reads the outbox and publishes the events

Trivial Publisher

```
while (true) {  
    for (OutboxEvent event : outboxRepository.findUnpublished())  
        eventBus.publish(event.toDomainEvent());  
        event.markAsPublished();  
    }  
}
```

Reliable, asynchronous, and decoupled event publishing.

Change Data Capture (CDC)

Instead of polling the outbox table manually...

We can let the database **stream its own changes**.

CDC in Action

- Tools like **Debezium** rely on db replication protocols
- Each committed change becomes an event
- No need to modify application logic

```
-- Database change -->
INSERT INTO outbox (....) VALUES (....)

-- Debezium -->
Produces Kafka event: OrderCreated { orderId: 42 }
```

Outbox + CDC Combo

Most robust solution:

- Use the **outbox table** for atomic writes
- Use **CDC** to stream events out automatically
- No dual writes, no lost events, no external transactions

Trade-offs

- Increased complexity (extra tables/processes)
- Possible duplication → requires idempotency

Distributed Transactions

When one business operation spans multiple services or databases.

- Each service has its own local data and transaction boundaries.
- We still want **atomicity** across them.

But... there's no global transaction manager in distributed systems.

Example

Booking a trip:

- Reserve a flight 
- Book a hotel 
- Charge a credit card 

If one step fails, the others must be reverted.

Two-Phase Commit (2PC)

Classic protocol to coordinate distributed commits.

1. **Prepare phase** - coordinator asks all participants if they can commit.
2. **Commit phase** - if all say “yes”, everyone commits; otherwise, all roll back.

2PC Pros and Cons

-  Guarantees atomicity across systems.
-  Introduces a single point of failure – the coordinator.
-  Participants must lock data until the commit is decided.
-  Doesn't scale well under high latency or partial failures.

When 2PC Fails

If the coordinator crashes between phases...

- Some participants may have committed.
- Others may still be waiting.
- System enters an **uncertain state**.

Recovery requires manual intervention or a timeout heuristic.

The Saga Pattern

An alternative to distributed transactions.

- Each step is a **local transaction**.
- On failure, execute **compensating actions**.

Two Saga Coordination Styles

- **Choreography** - services react to each other's events.
- **Orchestration** - a central orchestrator tells each participant what to do.

Both achieve eventual consistency, but with different trade-offs.

Saga Example

```
BookTripSaga:  
  1. FlightService.reserve(flight)  
  2. HotelService.book(hotel)  
  3. PaymentService.charge(user)
```

```
If step 3 fails:  
  -> HotelService.cancelBooking()  
  -> FlightService.releaseSeat()
```

Transaction Isolation

Even inside a single database, transactions can interfere with each other.

Isolation defines **how visible** one transaction's changes are to others.

Remember PACELC?

ACID Refresher

- Atomicity - all or nothing
- Consistency - valid state transitions
- Isolation - no interference
- Durability - once committed, it stays

Why Isolation Matters

Concurrent transactions may cause anomalies:

- **Dirty Read** - see uncommitted data
- **Non-repeatable Read** - unexpected data changes
- **Phantom Read** - new rows appear unexpectedly
- **Lost Update** - two transactions overwrite each other

Dirty Read Example

```
T1: UPDATE accounts SET balance = balance - 100 WHERE id=1;  
T2: SELECT balance FROM accounts WHERE id=1; -- sees uncommitted  
T1: ROLLBACK;
```

T2 read something that never really existed.

Non-Repeatable Read Example

```
T1: SELECT * FROM orders WHERE id = 1; -- sees "status = NEW"
T2: UPDATE orders SET status = 'PAID' WHERE id = 1; COMMIT;
T1: SELECT * FROM orders WHERE id = 1; -- sees "status = PAID"
```

Same query, different result - during one transaction.

Phantom Read Example

```
T1: SELECT * FROM orders WHERE status = 'NEW'; -- returns 3 rows
T2: INSERT INTO orders (status) VALUES ('NEW'); COMMIT;
T1: SELECT * FROM orders WHERE status = 'NEW'; -- now 4 rows
```

New “phantom” data appears mid-transaction.

Write Skew Anomaly

Occurs when two concurrent transactions read overlapping data and make **non-conflicting writes** based on those reads.

Even though each transaction is consistent on its own, the *combined result* breaks an invariant.

Classic Example

Hospital rule: at least one doctor must be on call.

```
CREATE TABLE doctors (
    id INT,
    on_call BOOLEAN
);
-- Initially:
-- Dr. Alice: on_call = true
-- Dr. Bob:   on_call = true
```

Step 1 - Two Transactions Start

```
T1: SELECT * FROM doctors WHERE on_call = true;  
-- sees Alice + Bob
```

```
T2: SELECT * FROM doctors WHERE on_call = true;  
-- sees Alice + Bob
```

Both see that someone else is on call.

Step 2 - Both Decide to Go Off Call

```
T1: UPDATE doctors SET on_call = false WHERE name = 'Alice';  
T2: UPDATE doctors SET on_call = false WHERE name = 'Bob';
```

Each assumes the other doctor stays on call.

Step 3 - Both Commit

```
T1: COMMIT;  
T2: COMMIT;
```

Invariant broken: nobody is on call anymore 

Why It Happens

- Both transactions read the same initial state
- Each makes a decision that was valid at that moment
- No direct conflict → no locking → no blocking
- Combined result violates a business rule

Isolation Levels and Write Skew

Isolation Level	Prevents Write Skew?
Read Committed	
Repeatable Read	(in most DBs)
Serializable	

Only Serializable prevents it, e.g. via predicate locks or SSI (Serializable Snapshot Isolation).

Serializable \neq Simple

Serializable isolation **simulates sequential execution.**

But it comes at a cost:

- Higher contention and locking
- Deadlocks
- Lower throughput

Using common sense is the ultimate Best Practice™.

Thank You!

Need help? Reach out! It's free.

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