Modern software architectures

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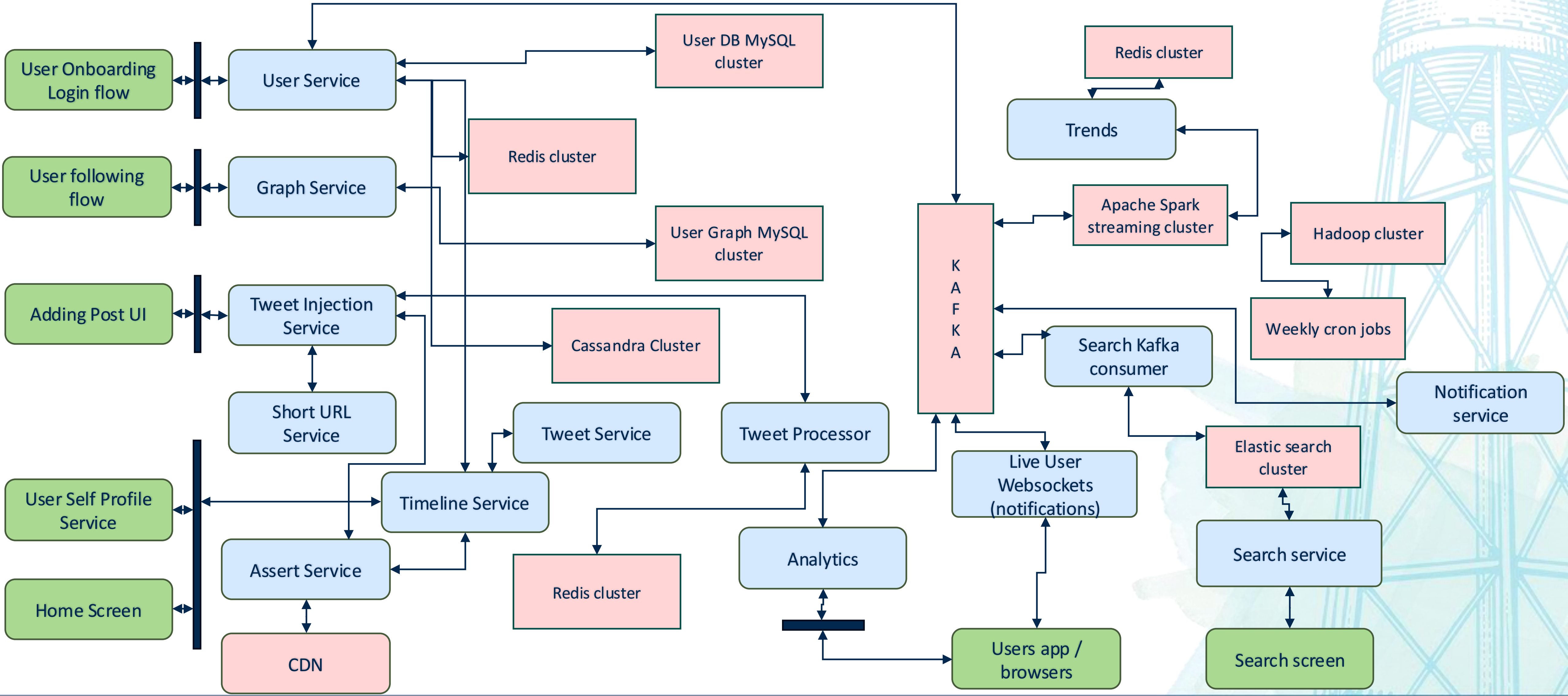
Modern software architecture



Outline

- Microservice architecture and communication
- Event-driven architecture with Kafka
- Kubernetes

Microservices outline

- Monolithic applications
- Microservices and decentralized data
- Data model and storage engine
  - Relational databases, log-structured merge trees (LSM), event logs (more in Kafka section), in-memory cache
- Communication styles
  - Text-based vs binary data exchange formats
  - Synchronous (RPC), asynchronous (MQs), publish-subscribe models

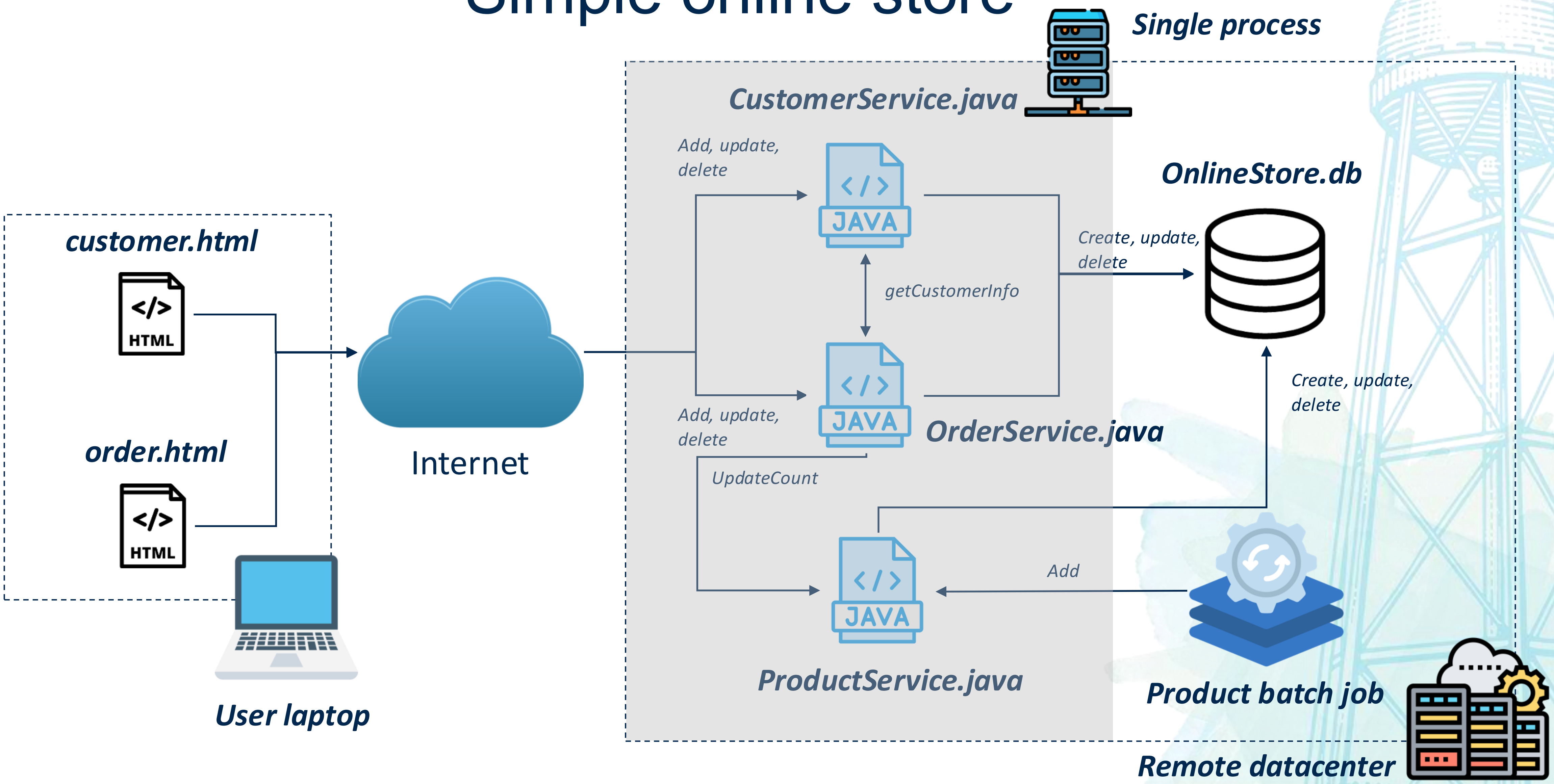
All about the data!

- Modern software architecture is data-intensive
- Primary concerns
  - Who owns data?
  - How to optimally store data?
  - How is data shared?
  - How to limit overhead due to data-sharing?

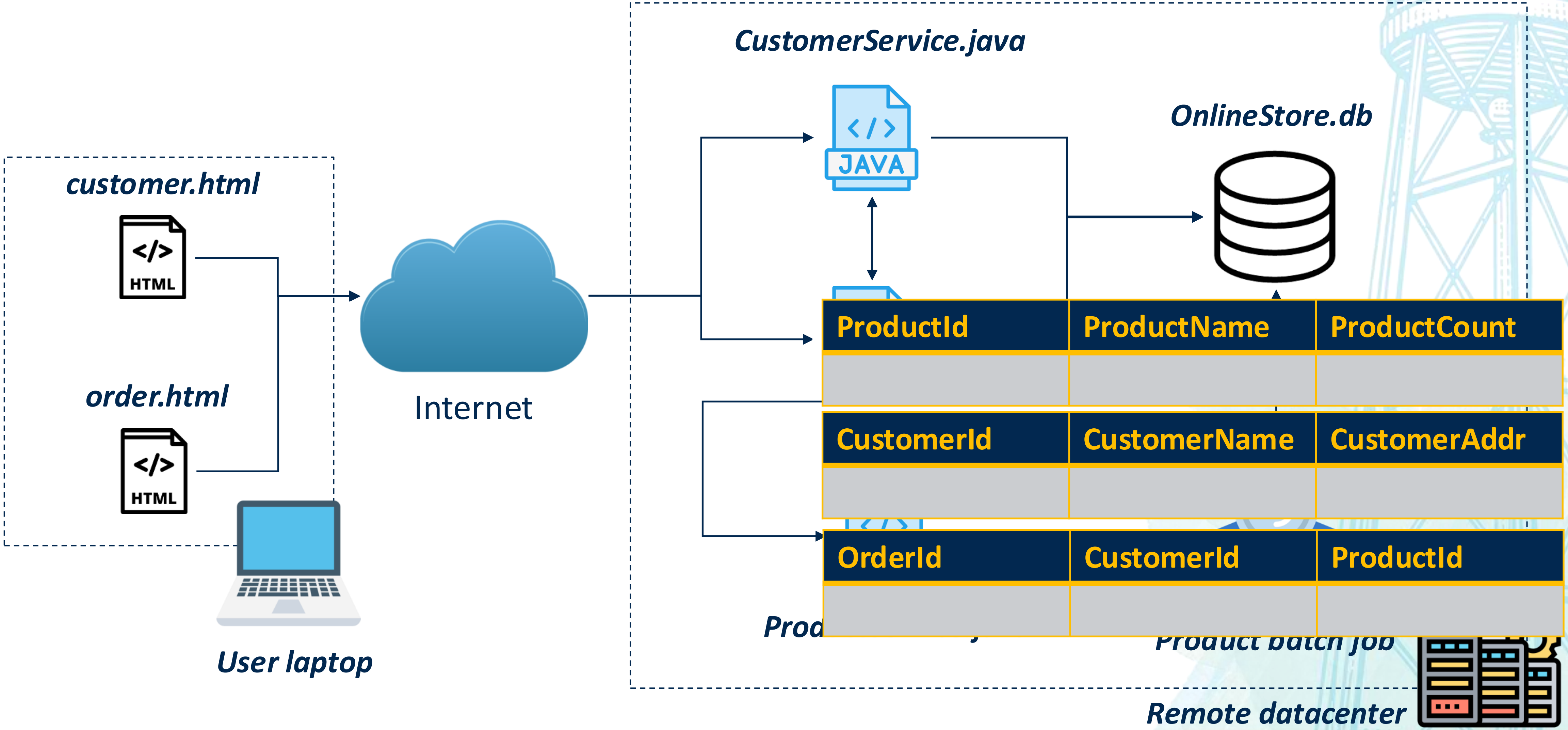
Monolithic software architecture

- Widely used in early, mid 2000s
- All software components are part of the same application
- All software components run on the same machine, in same process
- Typically developed in the same language stack

Simple online store



Simple online store



ProductId	ProductName	ProductCount

CustomerId	CustomerName	CustomerAddr

OrderId	CustomerId	ProductId

Relational databases

- Consists of tables
- Each table contains a primary key
  - Database will not allow insertion of two records with same primary key

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF

Order tbl

OrderId	CustomerId	ProductId
110001	9001	1001

Foreign keys

- Relational databases maintain relations through foreign keys
- Foreign keys ***must refer*** to primary keys of other tables
  - Enforce referential integrity
- A table can contain one or more foreign keys

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Order tbl

OrderId	CustomerId	ProductId
110001	9001	1001

Structured query language (SQL)

- SQL used to interface between application and database
- CREATE TABLE Products (

```
    ProductId INT PRIMARY KEY,
    ProductName VARCHAR(100) NOT NULL,
    ProductCount INT NOT NULL);
```

- INSERT INTO Products (ProductId, ProductName, ProductCount) VALUES (1001, 'ABC', 10);

SQL joins

- Allows table joins
- For e.g. find order details for shipping, including product name, customer name, and address

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Order tbl

OrderId	CustomerId	ProductId
110001	9001	1001

SQL joins

```
SELECT
    o.OrderId,
    p.ProductName,
    c.CustomerName,
    c.CustomerAddr
FROM Orders o
JOIN Products p
    ON o.ProductId = p.ProductId
JOIN Customers c
    ON o.CustomerId =
          c.CustomerId;
```

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Order tbl

OrderId	CustomerId	ProductId
[illegible]0001	9001	1001

o.OrderId	p.ProductName	c.CustomerName	c.CustomerAddr
110001	9001	XYZ	CDEF

Need for joins

- Imagine no support for joins
- Order information must contain product name, customer name, and customer address to ship the order

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Order tbl

OrderId	ProductName	CustomerName	CustomerAddr
110001	ABC	XYZ	CDEF

Need for joins

- Lack of join support increases data duplication
- Data **denormalization**

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

OrderId	ProductName	CustomerName	CustomerAddr
110001	ABC	XYZ	CDEF
110002	ABC	XYZ	CDEF
110003	ABC	UVW	ABCD

Order tbl

Normalization

- Joins reduce data duplication and allow data normalization
- Database can build indexes to speed up joins

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

OrderId	ProductId	CustomerId
110001	1001	9001
110002	1001	9001
110003	1001	9002

Order tbl

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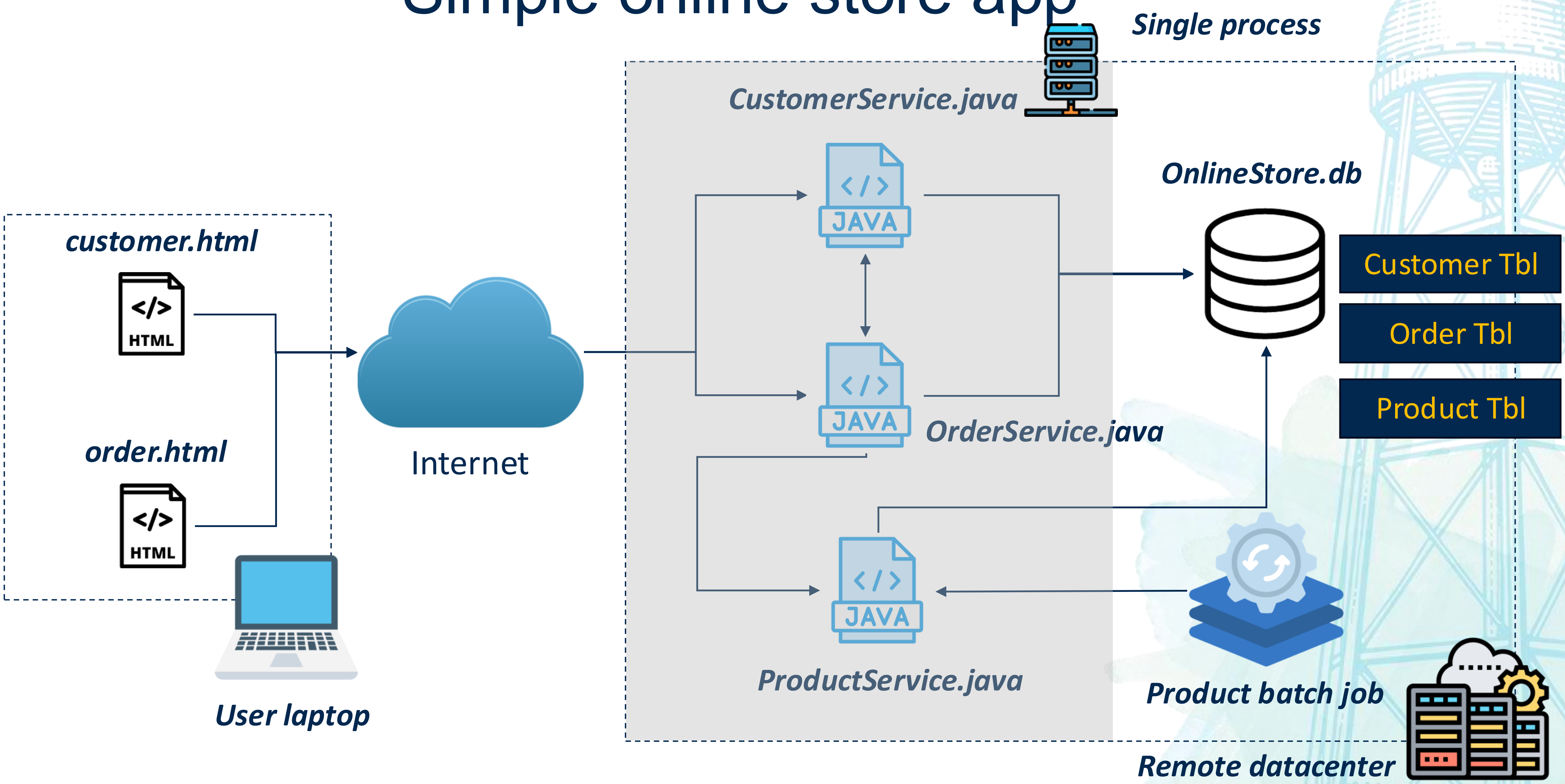
Relational database implications

- Tighter coupling
  - E.g., Customer service cannot alter the Customers table without impacting the Orders service
- Fixed schema
  - E.g., Orders service must know about the schema Customers table

SQL != relational databases

- Note: not quite specific to relational databases
- Apache Cassandra, Apache HBase, Apache Kafka + ksqlDB are not relational databases, but support SQL-like query language

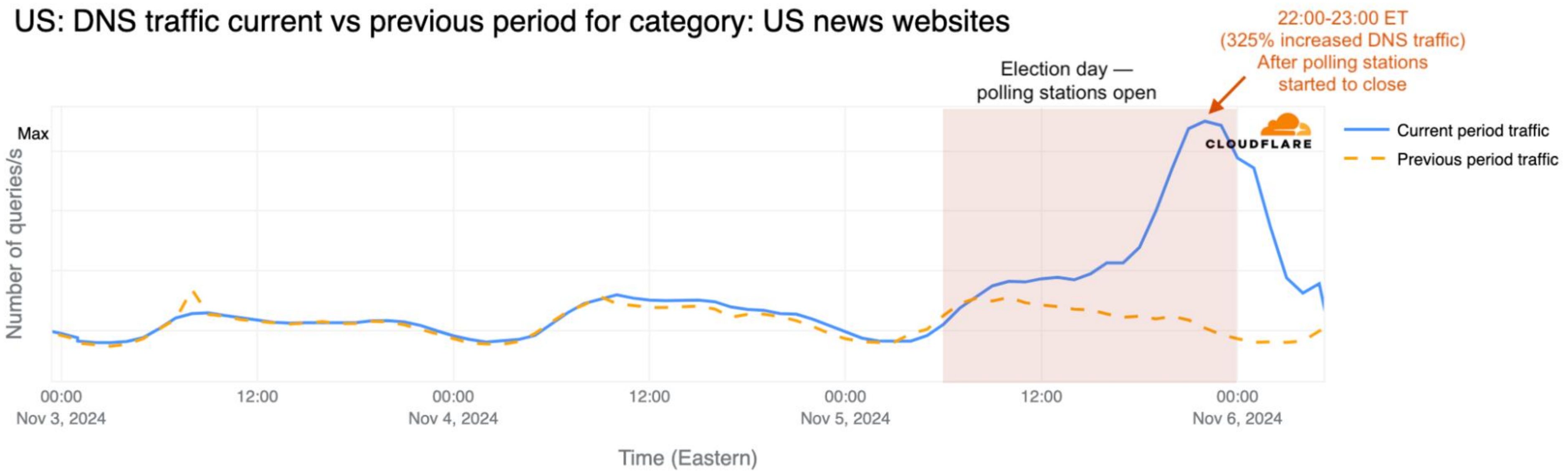
Simple online store app



Scalability

- Online traffic is variable
- Can spike due to planned events
  - Product launches
  - Political events

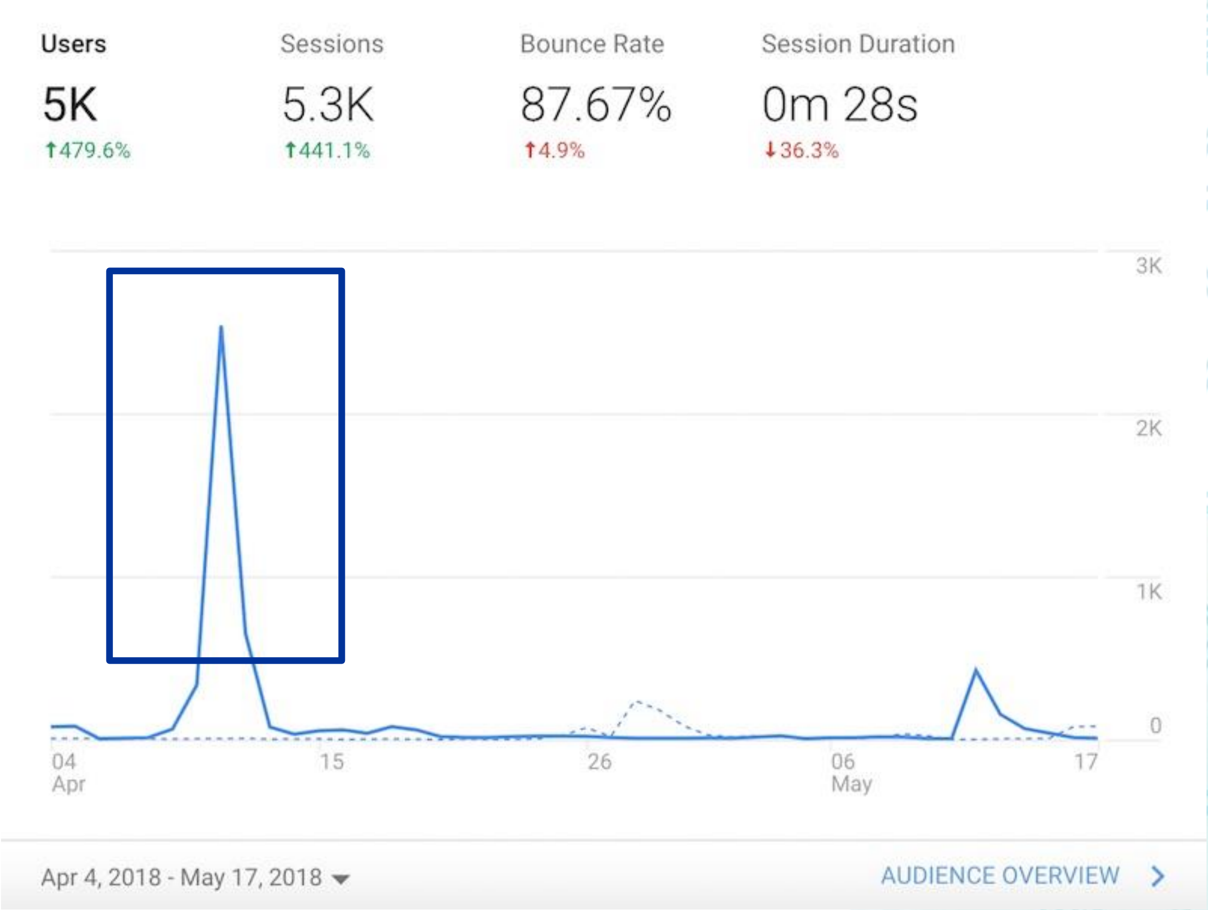
https://blog.cloudflare.com/exploring-internet-traffic-shifts-and-cyber-attacks-during-the-2024-us-election/



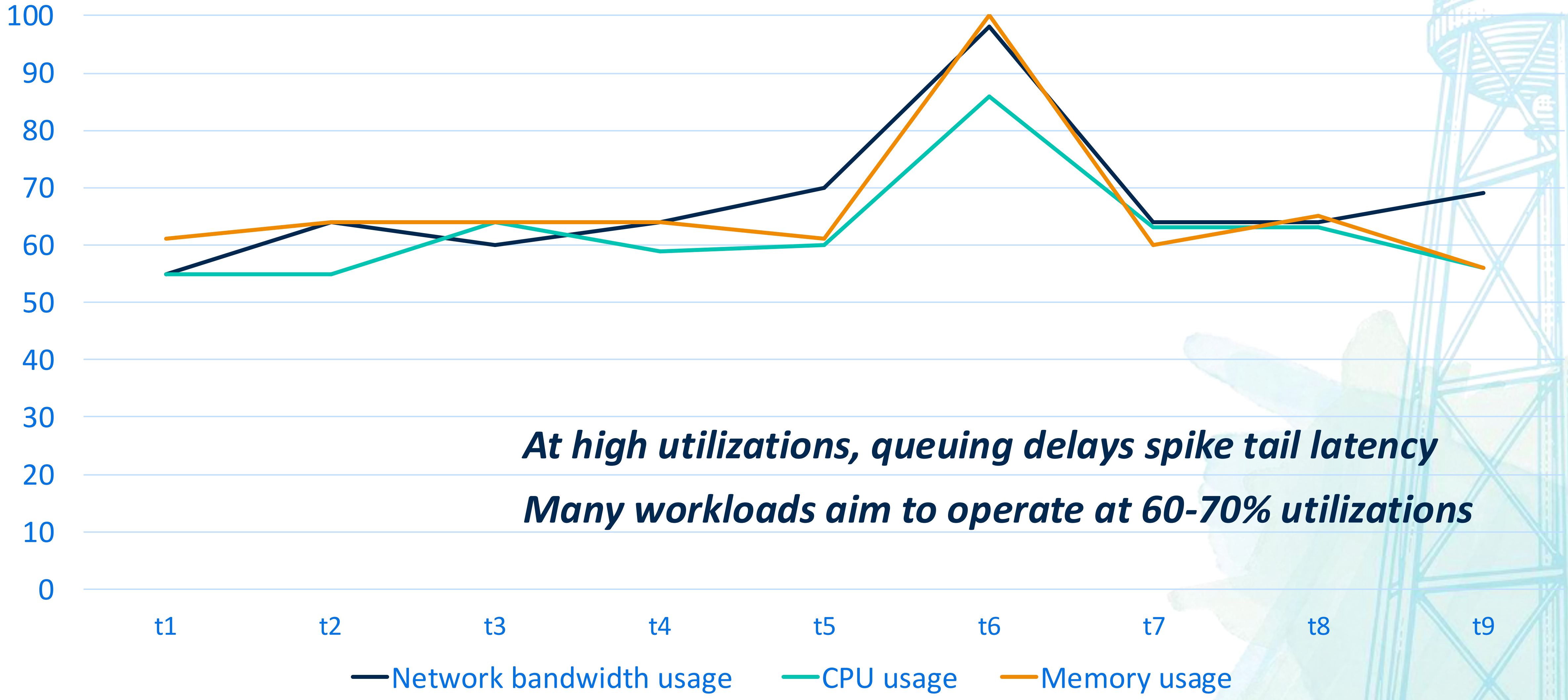
Scalability

- Unplanned events
  - Blog post goes viral
- System design should *adapt* to handle such events

https://www.residualthoughts.com/2018/05/20/traffic-data-from-a-viral-post/



Traffic spike to online store

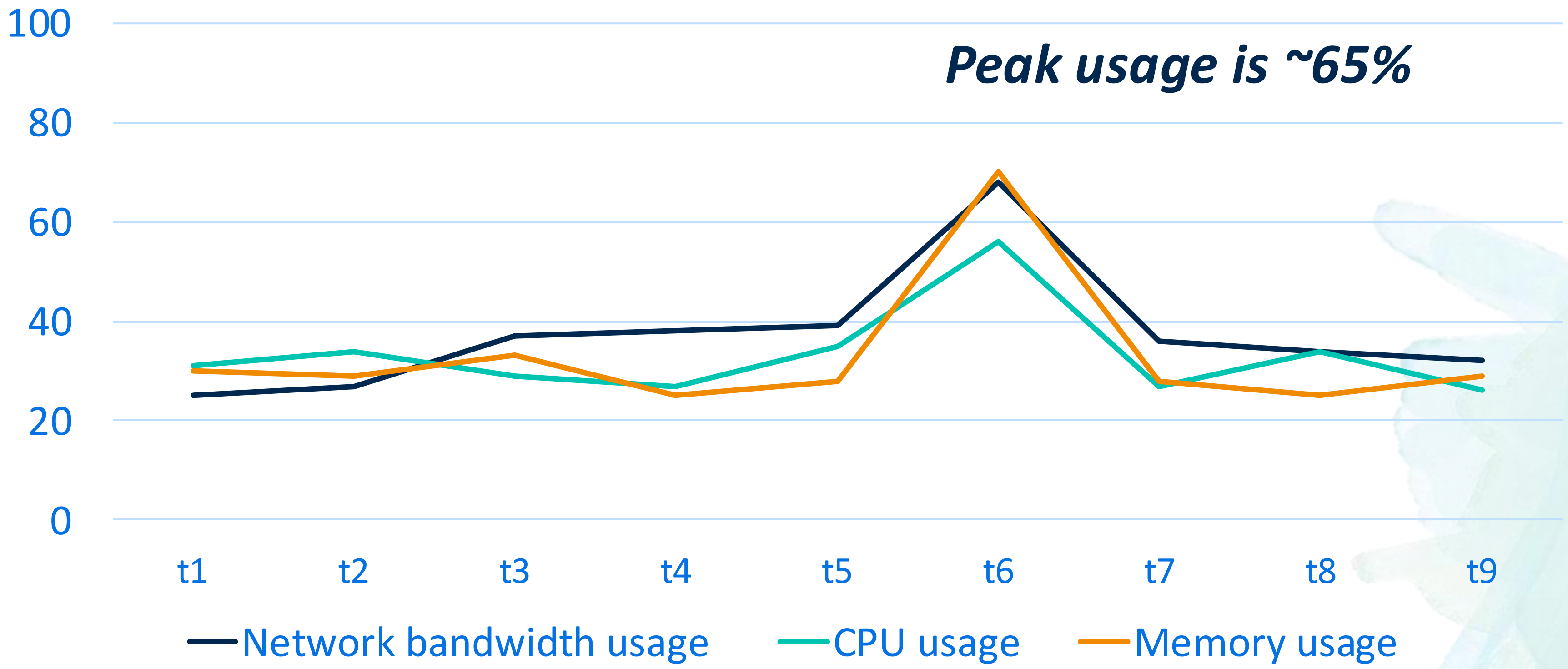


At high utilizations, queuing delays spike tail latency

Many workloads aim to operate at 60-70% utilizations

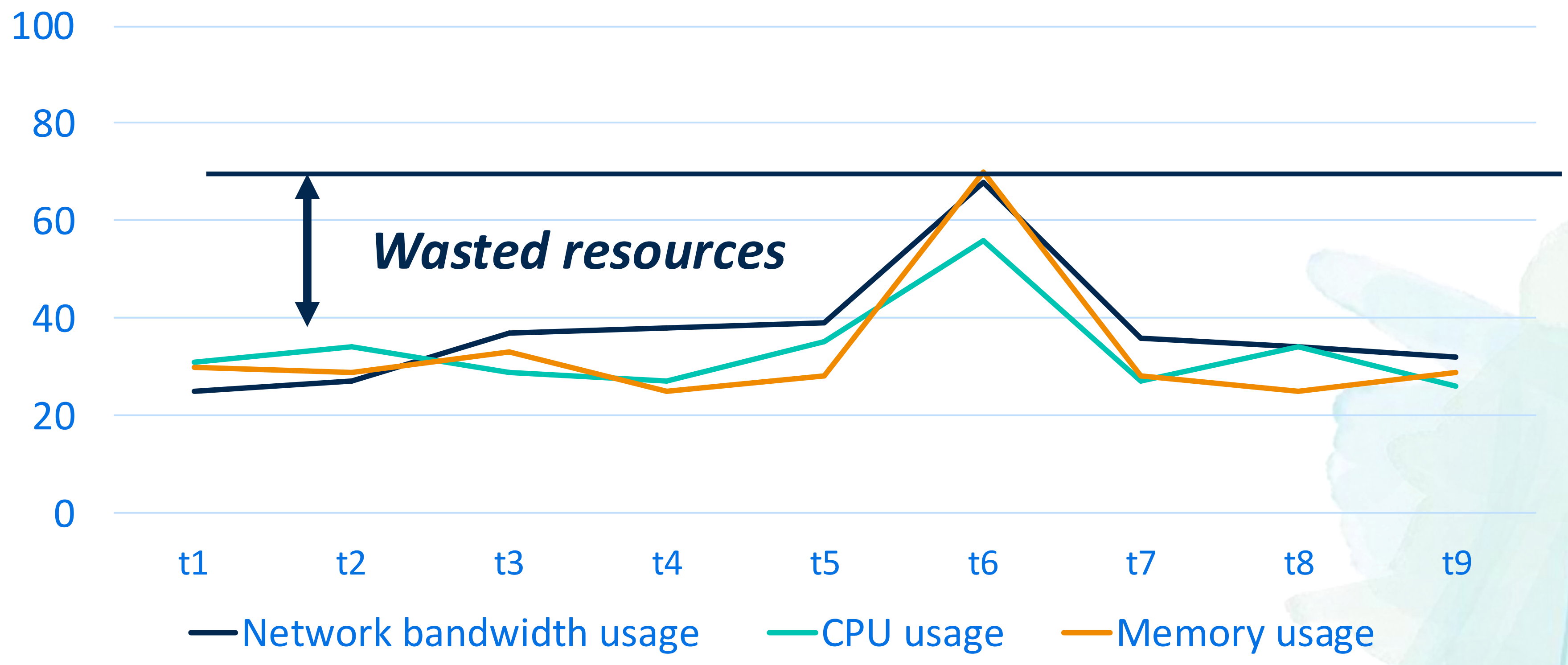
Vertical scaling

- Use more powerful machines
- Add more CPUs, DRAM, network bandwidth



Vertical scaling limitations

Resource wastage when requests are not bursty

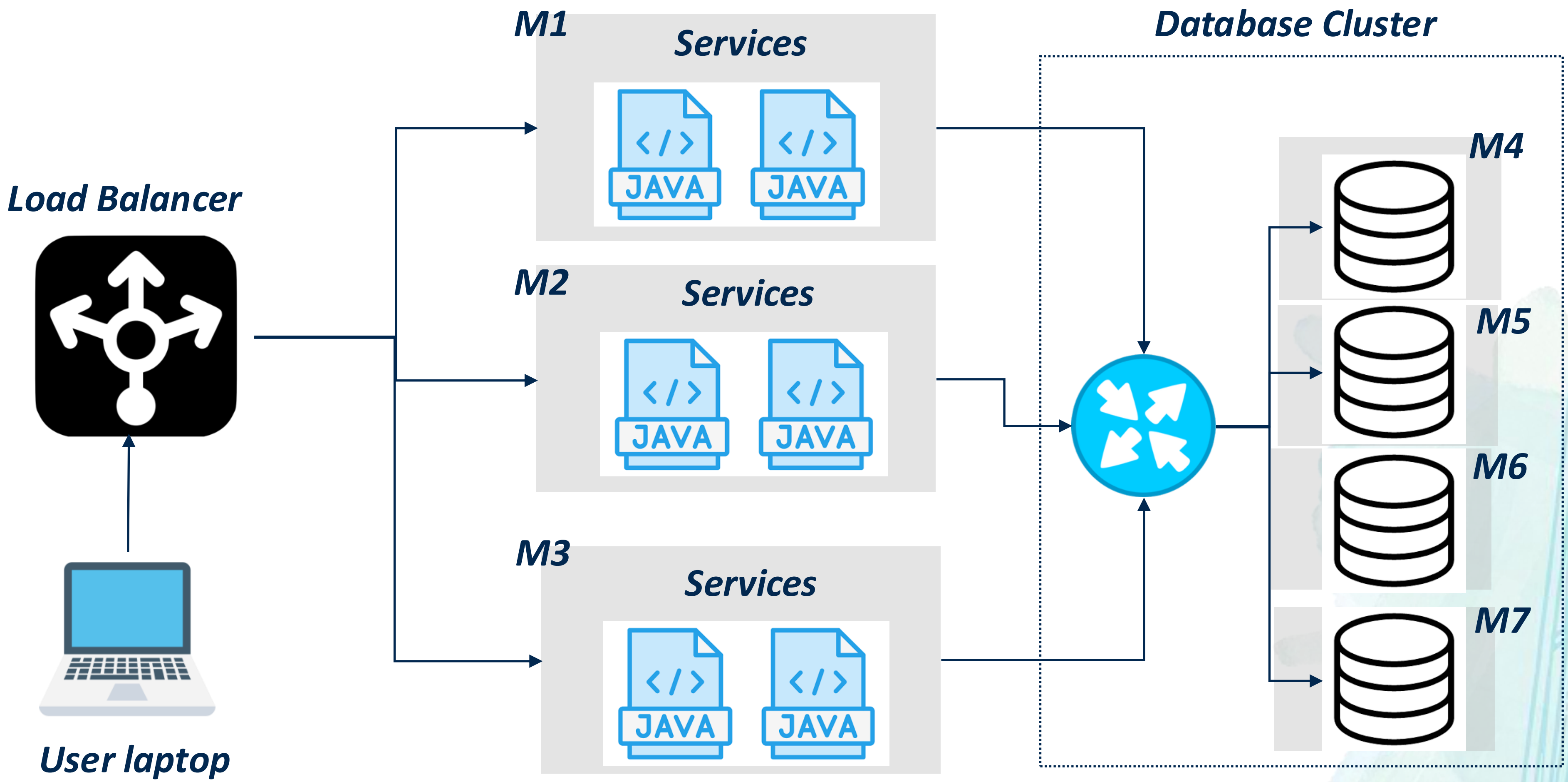


Vertical scaling limitations

- Twitter has 200M-300M active users per day
- No single machine, no matter how powerful, can support such high loads
- Goal: autoscaling
  - **Dynamically** spawn new machines during **high loads**
  - Not possible using vertical scaling alone
  - More in Kubernetes module

Horizontal scaling for monolithic apps

Add more machines and replicate application on each machine



Load balancer

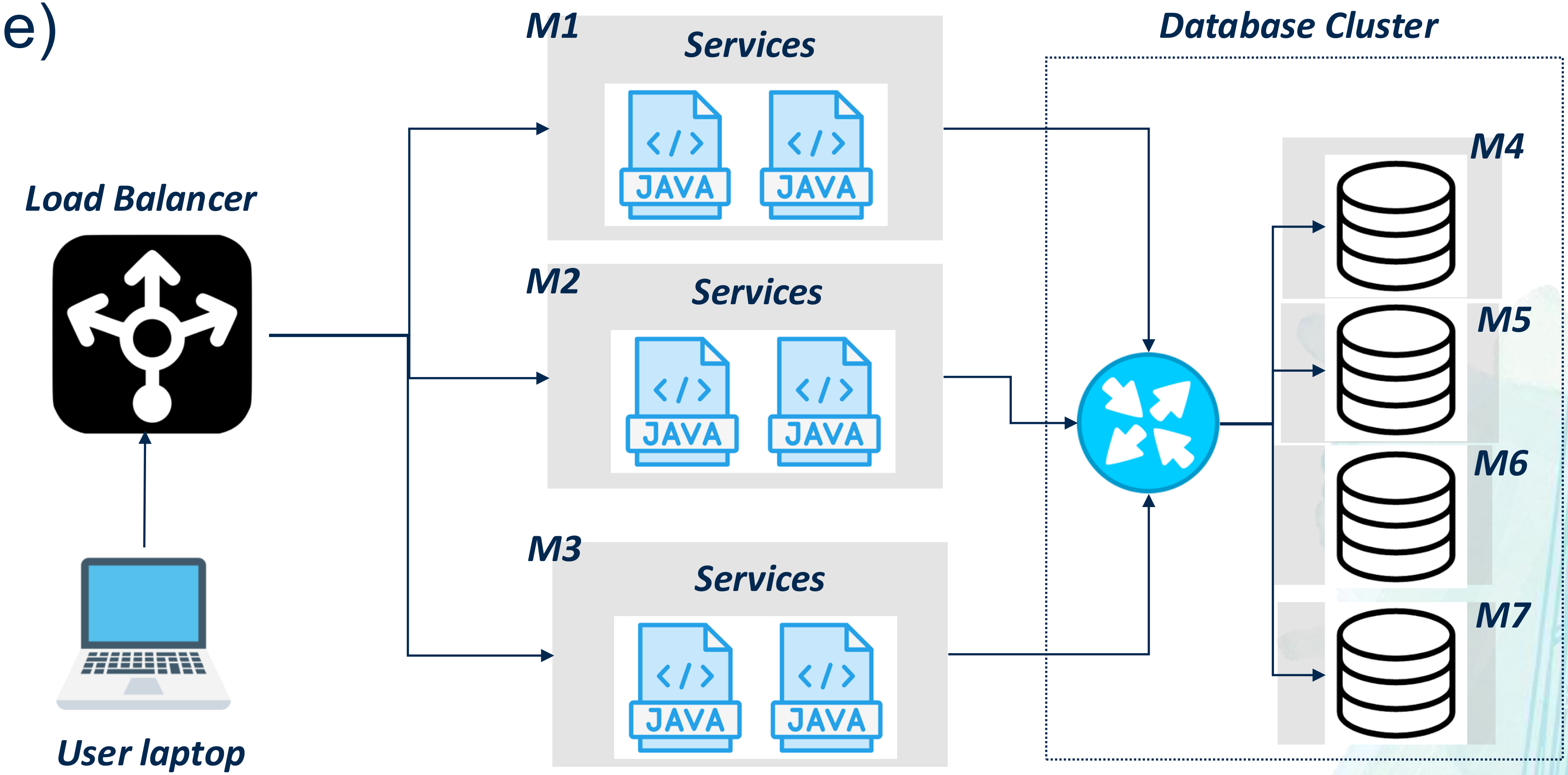
- Distributes incoming requests across multiple servers to improve scalability and availability
- Strategies
  - Round Robin – Sequentially routes requests across servers; simple but doesn’t account for server load
  - Least Connections – Directs traffic to the server with the fewest active connections; adapts well to uneven load
  - Least Response Time – Chooses the server with the fastest response time and fewest connections; performance-oriented
  - Random Policy – Selects servers randomly; useful in stateless, uniform environments
  - Weighted Distribution – Allocates requests based on server capacity (e.g., CPU power, memory)
- Each strategy has tradeoffs
- More details in Kubernetes module

Horizonal scaling is unbounded

- Necessary for applications with high load (like Twitter/X)
  - Can add more machines to support more requests (theoretically unbounded performance)
- Better resource utilization

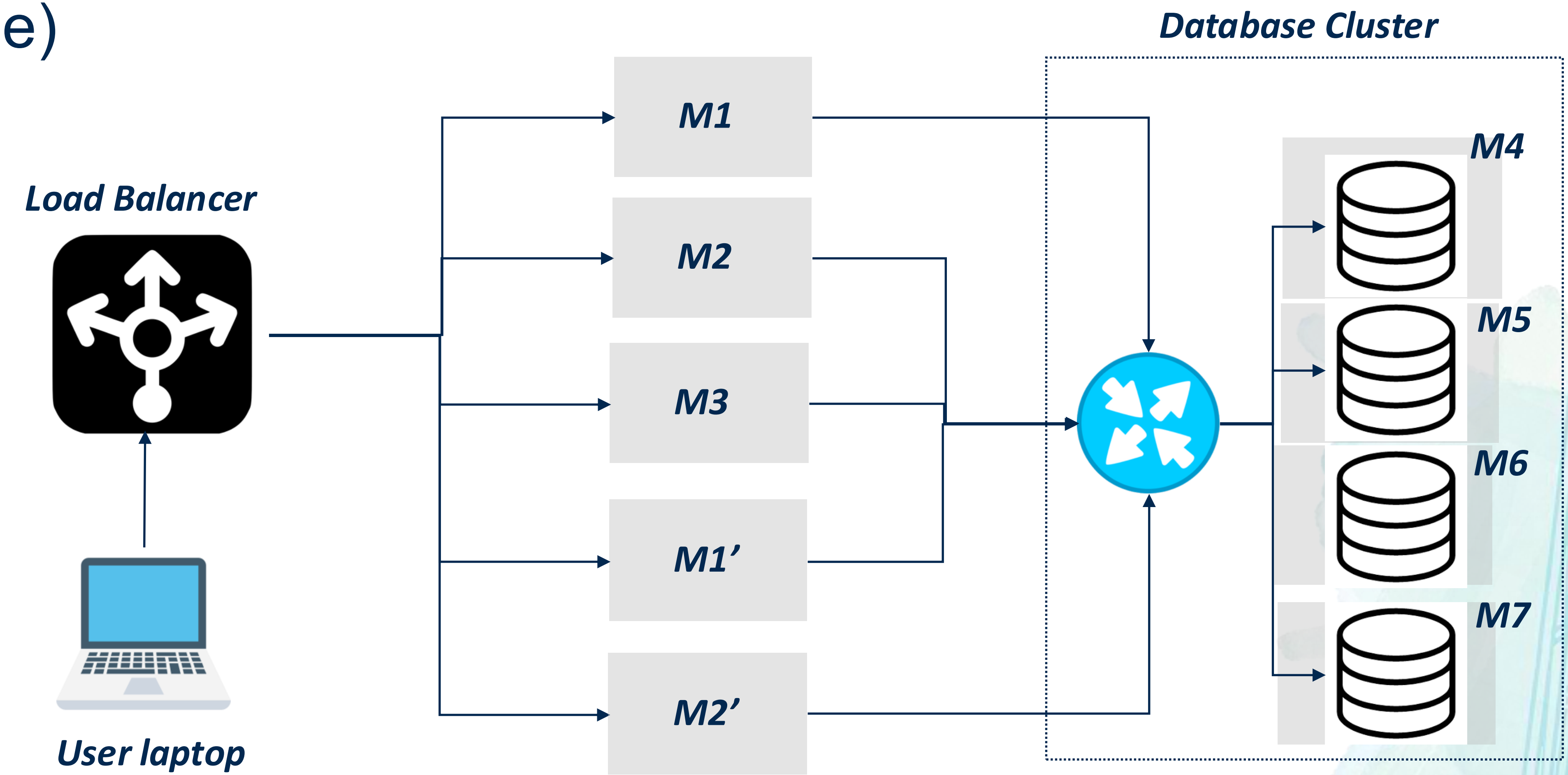
Horizontal scaling is necessary for autoscaling

Auto-scale to more machines during traffic spike (more in Kubernetes module)



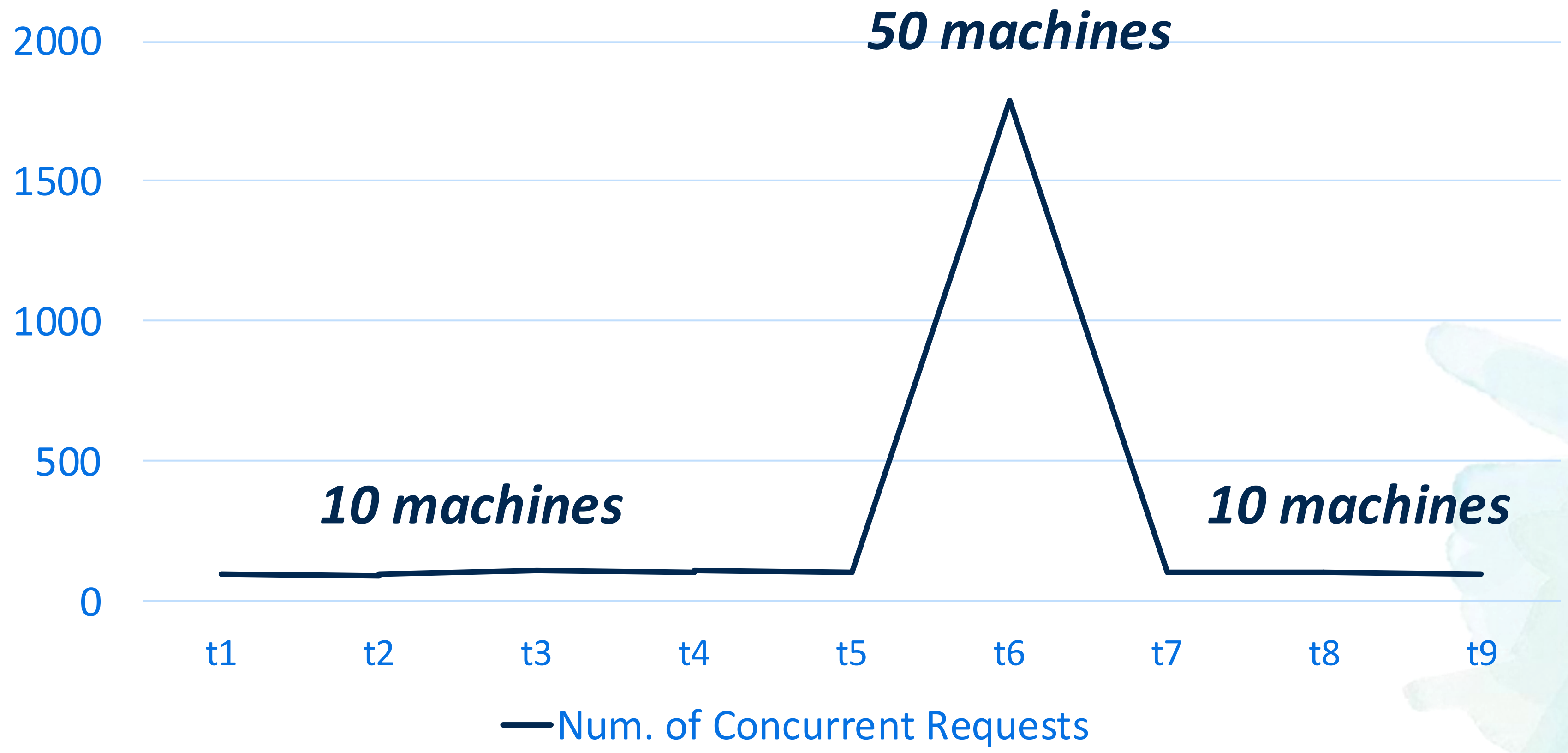
Horizontal scaling is necessary for autoscaling

Auto-scale to more machines during traffic spike (more in Kubernetes module)



Autoscaling

Minimum resource wastage



Horizontal scaling allows autoscaling, but did we solve all problems?

Heterogenous resource requirements across services

- Provisioning is driven by the most resource-hungry service
- Example RAM requirements
  - CustomerService: 32 GB
  - OrderService: 18 GB
  - ProductService: 16 GB
  - Minimum machine RAM? 32 GB

Deployability concerns

- Updating one component requires redeploying the entire application
- Reverting a change requires redeploying the entire application
- Slow, error-prone process

Need for low interdependence

- Software often consists of thousands of components
  - Each component has a dedicated team working on it
- Teams need to work independently
  - E.g., ProductService team should be able to update the Products Tbl schema without consulting other service teams
- Need low coupling between services
- Solution: microservices

Microservices

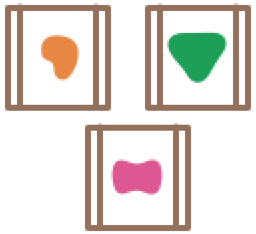
- An approach to developing a single application as a suite of small services, each running in its own process and communicating with lightweight mechanisms, often an HTTP resource API
- Independently deployable by automated processes
- Bare minimum centralized management
- Smart endpoints connected by “dumb” pipes

https://martinfowler.com/articles/microservices.html

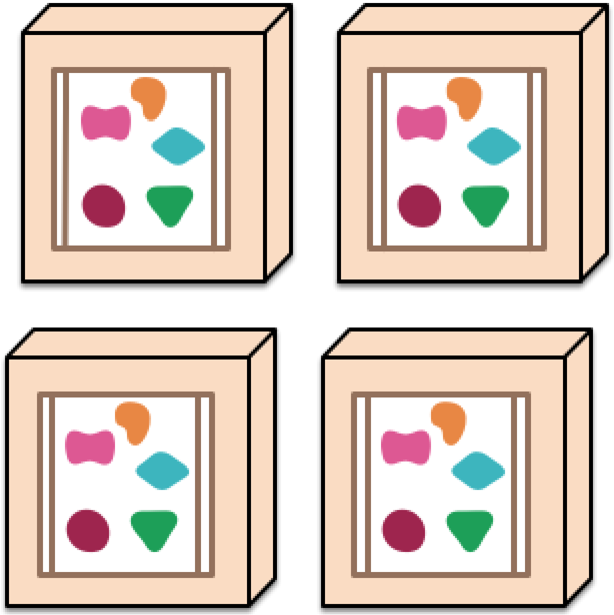
Microservices overview

A monolithic application puts all its functionality into a single process…

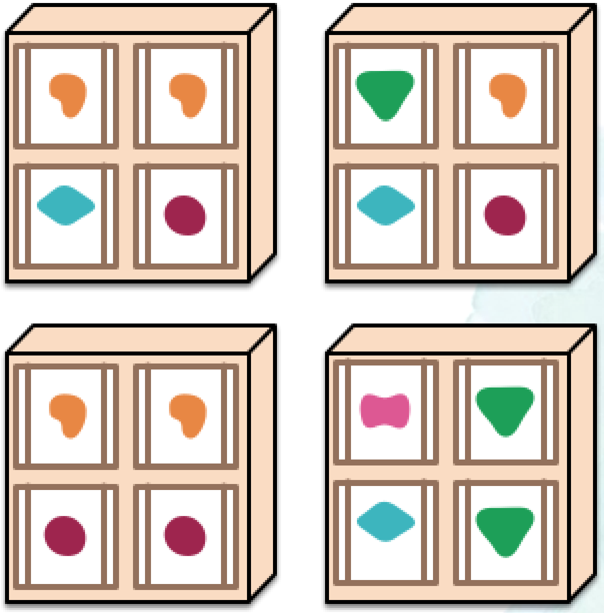
A microservices architecture puts each element of functionality into a separate service…



… and scales by replicating the monolith on multiple servers

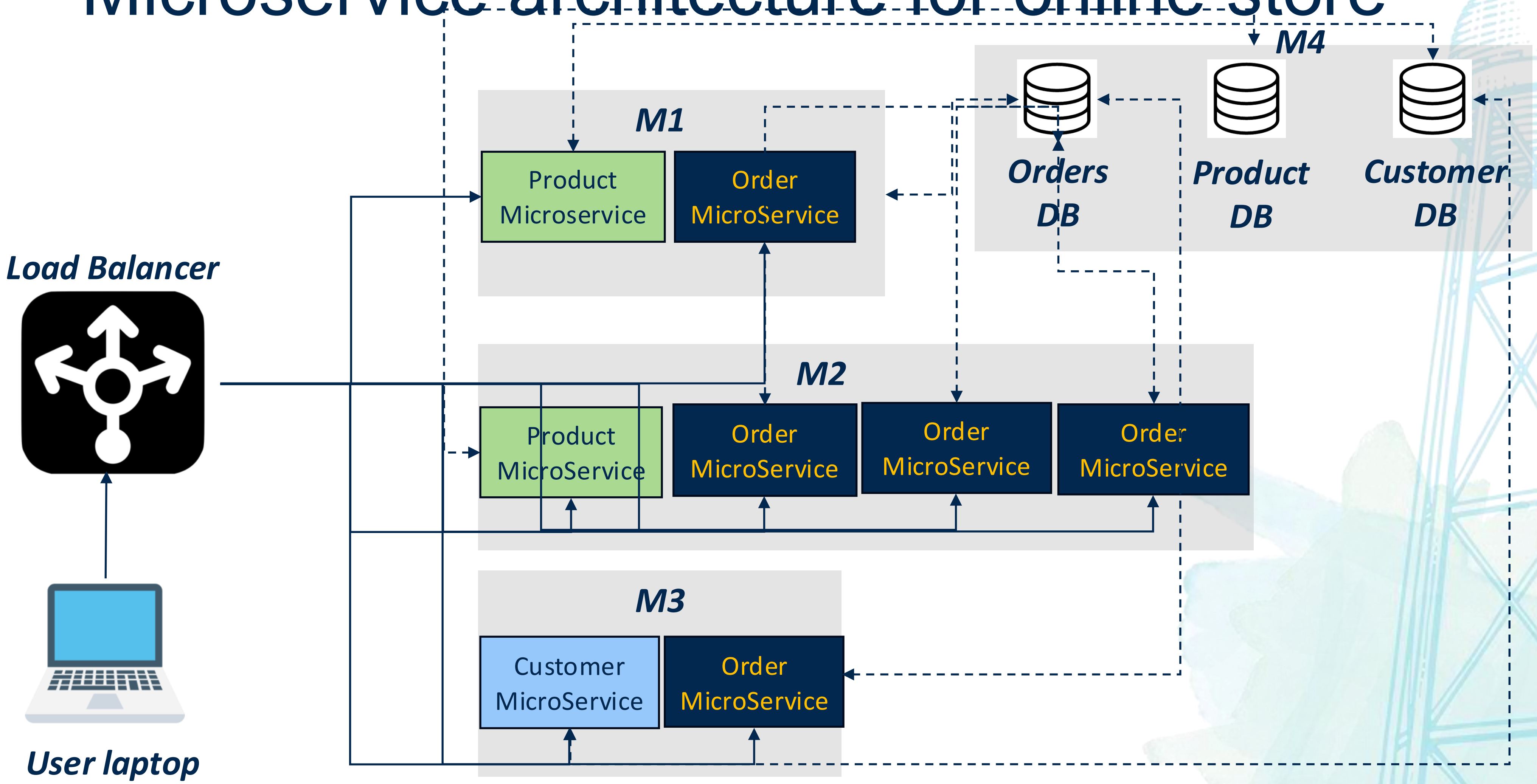


… and scales by distributing these services across servers, replicating as needed.

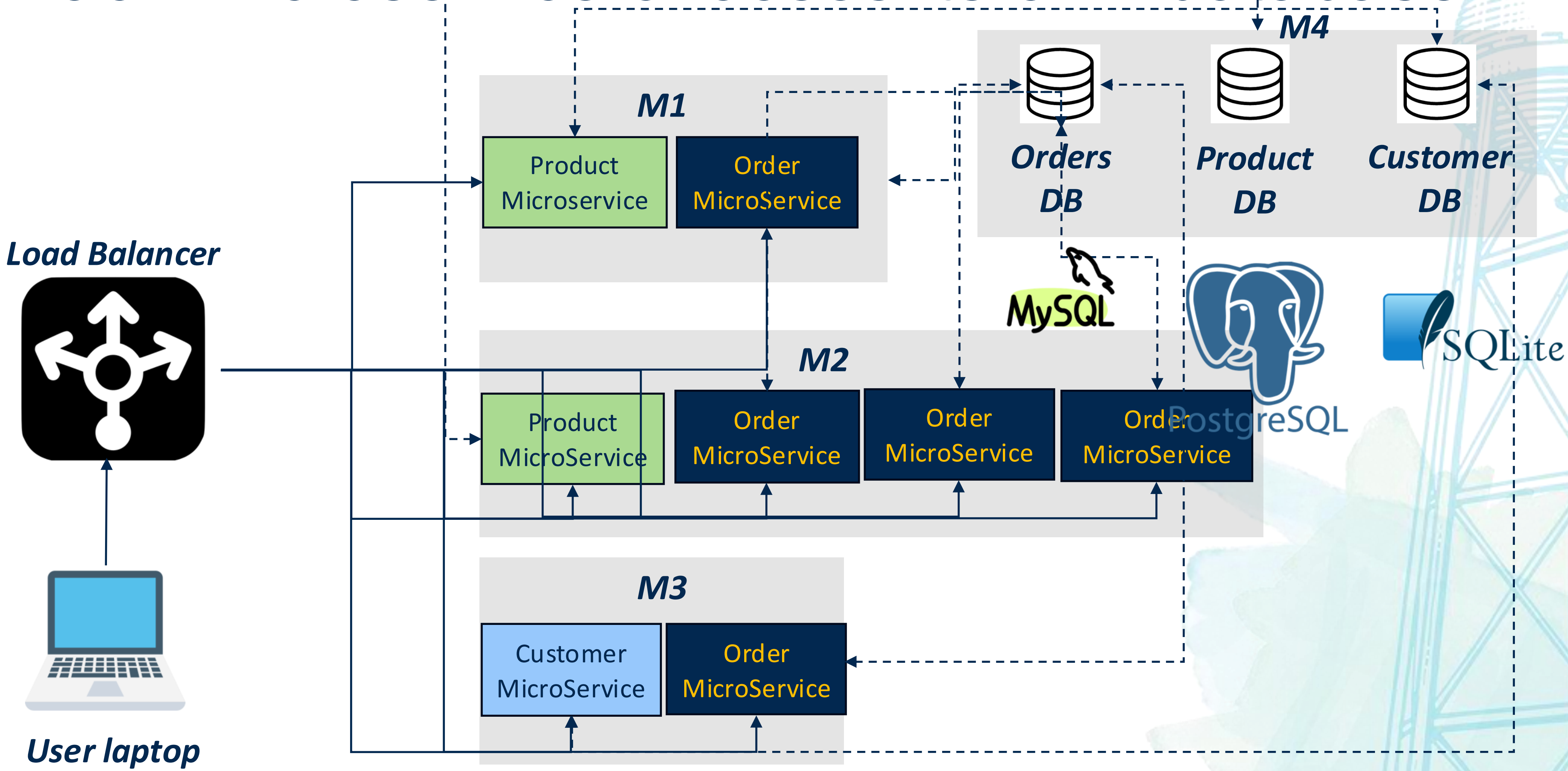


https://martinfowler.com/articles/microservices.html

Microservice architecture for online store



Each microservice chooses its own database



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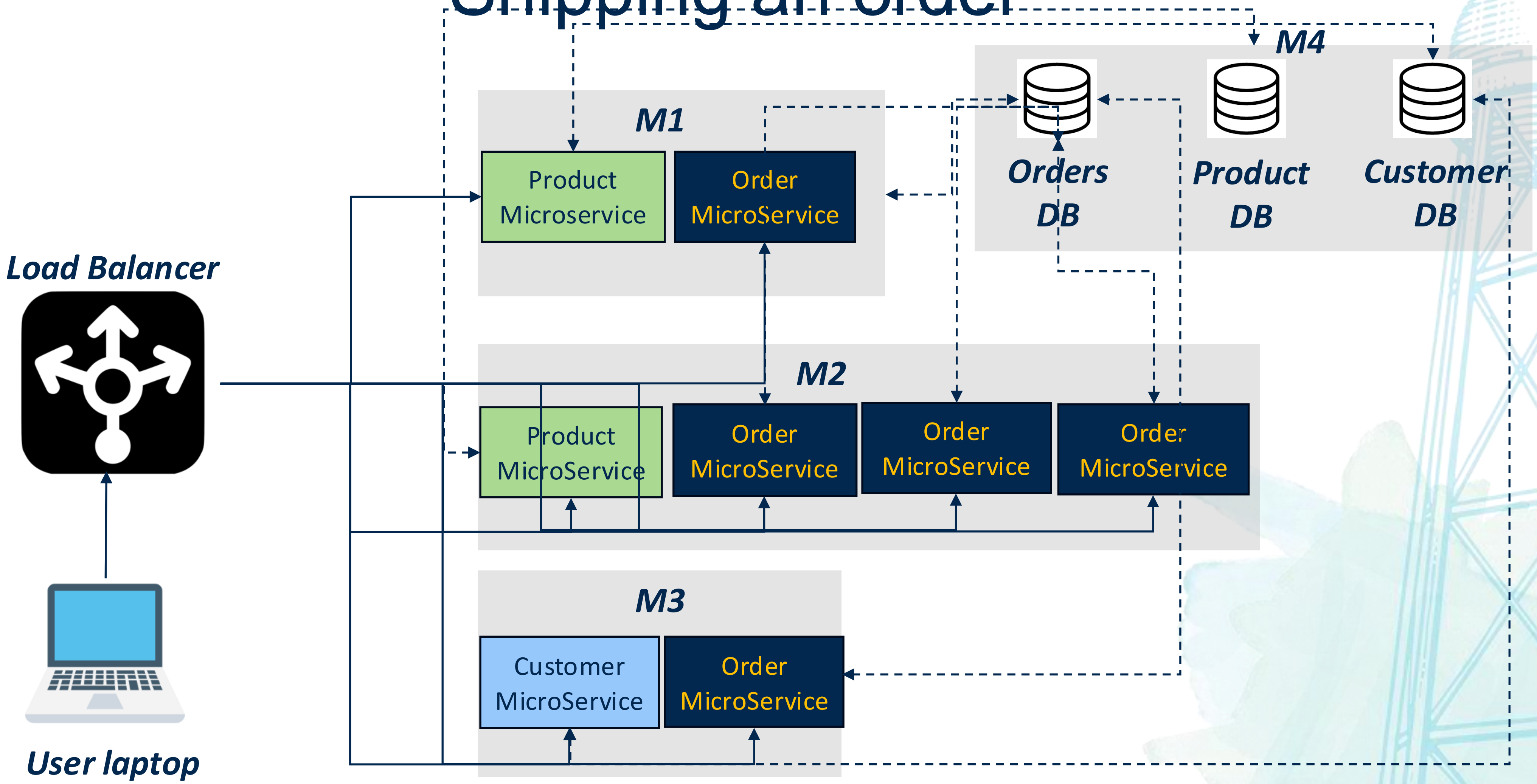
What did we achieve?

- Decompose monolithic app into microservices
- Improve decoupling
  - Each microservice can be scaled independently
  - Each microservice can be deployed independently
  - Each microservice can evolve independently – DB schema, choice of programming languages
- ***Did we solve all problems?***

Shipping an order



Reusing monolithic order schema

Product MicroService

Order MicroService

Customer MicroService

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

MySQL

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

PostgreSQL

Order tbl

OrderId	ProductId	CustomerId
110001	1001	9001

SQLite

Cannot perform joins!

Non-solution

- DO NOT want to query the Customer and Product microservices during shipping
- Will introduce tight coupling and interdependence
  - For example, what if the Customer microservice is down during shipment?

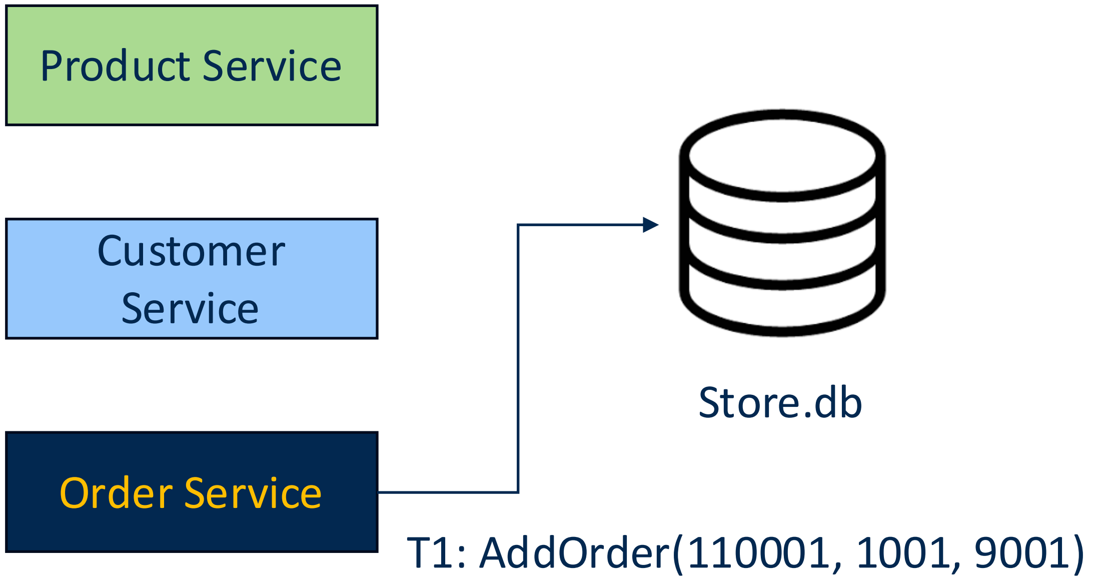
Denormalization

- Must denormalize the data
- Order microservice duplicates and store the customer details in the Order db
- How? (after a few slides)

OrderId	ProductName	CustomerName	CustomerAddr
110001	ABC	XYZ	CDEF
110002	ABC	XYZ	CDEF
110003	ABC	UVW	ABCD

Consistency guarantees

- Consistency property of a system governs how and when updates to shared data become visible to different components of the system
- Monolithic apps typically have strong consistency – updates reflect immediately to subsequent reads



ProductId	ProductName	ProductCount
1001	ABC	10

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

OrderId	ProductId	CustomerId

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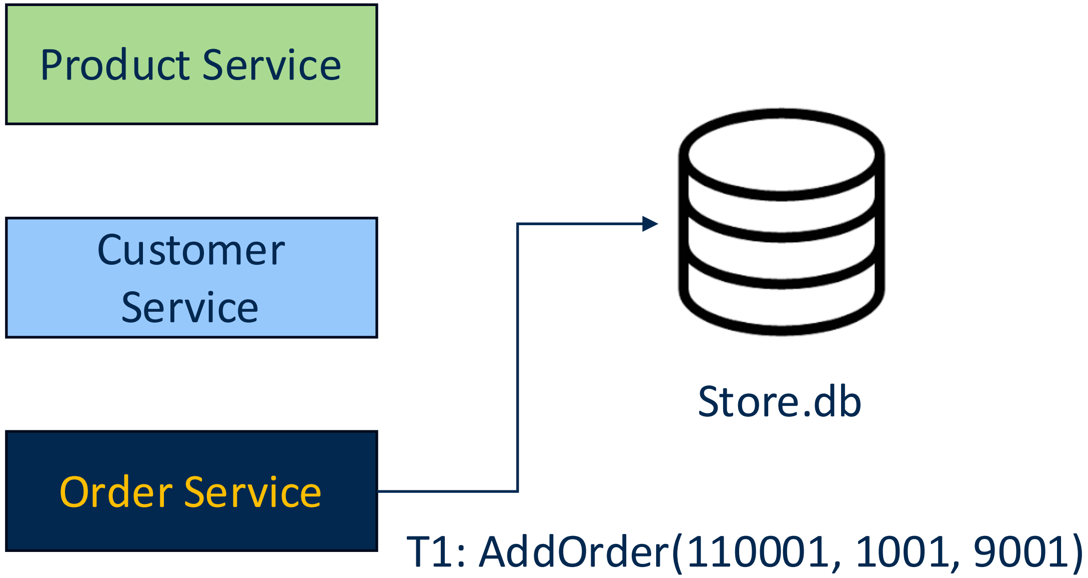

ProductId	ProductName	ProductCount
1001	ABC	10

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

OrderId	ProductId	CustomerId
110001	1001	9001

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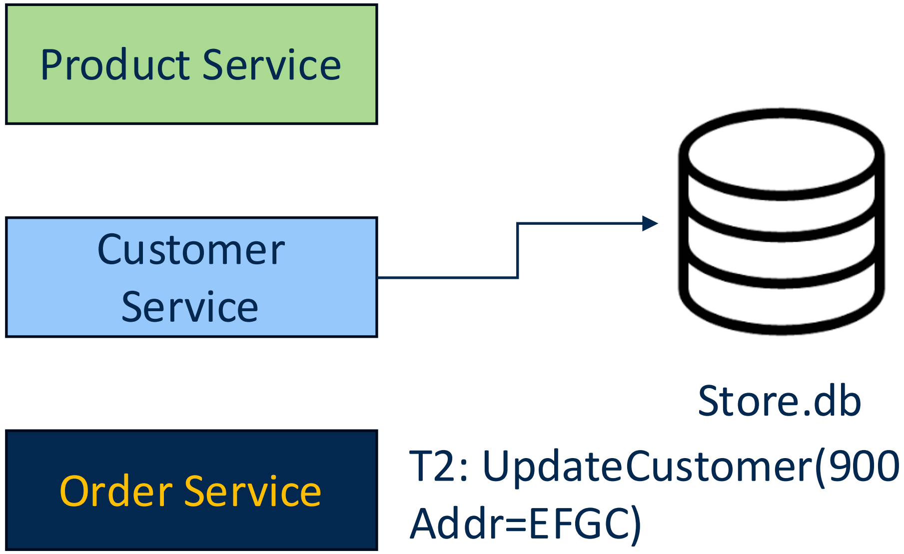

T2: UpdateCustomer(9001, Addr=EFGC)

ProductId	ProductName	ProductCount
1001	ABC	10

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

OrderId	ProductId	CustomerId
110001	1001	9001

Consistency guarantees

- Consistency property of a system governs how and when updates to shared data become visible to different components of the system
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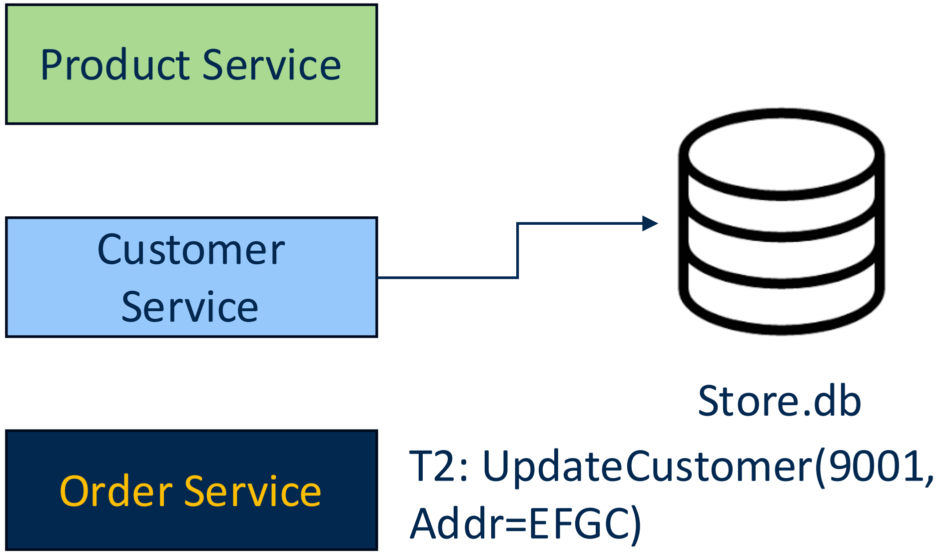

ProductId	ProductName	ProductCount
1001	ABC	10

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	EFGC

OrderId	ProductId	CustomerId
110001	1001	9001

Consistency guarantees

- Consistency property of a system governs how and when updates to shared data become visible to different components of the system
- Monolithic apps typically have strong consistency – updates reflect immediately to subsequent reads

Product Service

Customer Service

Order Service

Store.db

T3: ShipOrder -> JOIN(1001, 9001) -> (ABC, UVW, EFGC)

ProductId	ProductName	ProductCount
1001	ABC	10

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	EFGC

OrderId	ProductId	CustomerId
110001	1001	9001

Microservice consistency guarantees

- Core idea: a microservice ***owns*** some data
  - ***Notifies*** dependent microservices of change
  - ***Soft guarantees*** on when the updates synchronize

Microservice consistency guarantees

- Microservice-oriented apps are distributed
- Enforcing strong consistency guarantees in distributed systems is very hard
  - Network overhead, network partition, node failures
- Typically have **eventual consistency** guarantees – updates are **eventually** visible to all components
- System must work around these limitations

Working with eventual consistency

Product MicroService

Products.db

ProductId	ProductName	ProductCount
1001	ABC	10

Products tbl

Customer MicroService

Customer.db

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF

Customer tbl

CustomerMicroservice owns the customer data

Order MicroService

Orders.db

OrderId	ProductName	CustomerAddr

Order tbl

CustomerId	CustomerName	CustomerAddr

Customer Cache tbl

OrderMicroservice maintains a cache of the customer information

Working with eventual consistency

Product MicroService

T1: AddCustomer(9002, UVW, ABCD)

Customer MicroService

Order MicroService

Products.db

Customer.db

Orders.db

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Order tbl

OrderId	ProductName	CustomerAddr

Customer Cache tbl

CustomerId	CustomerName	CustomerAddr

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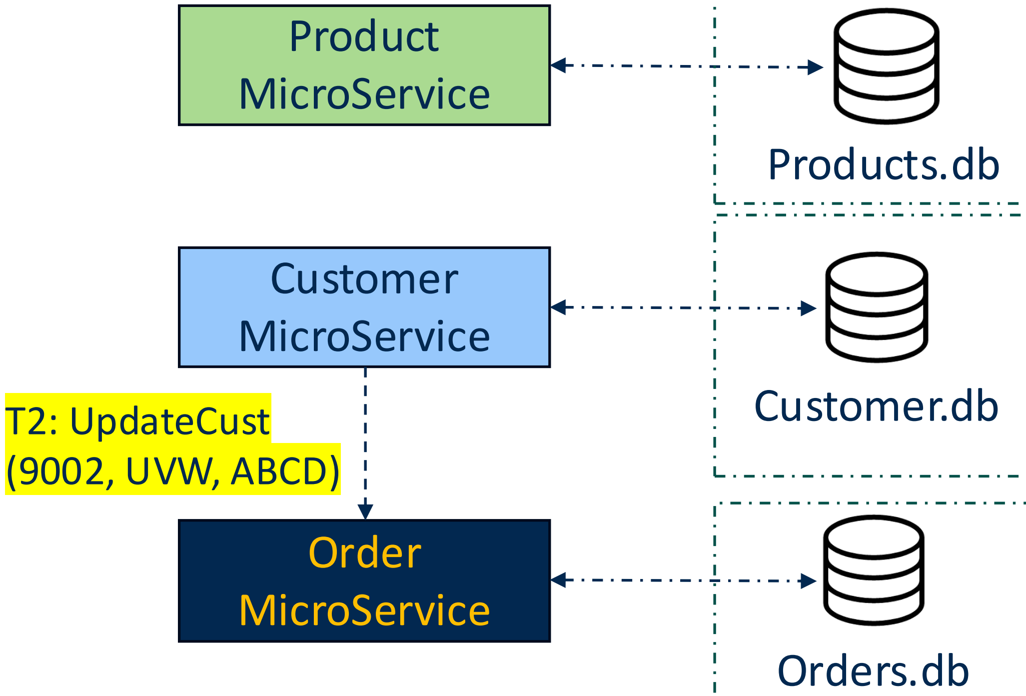
Working with eventual consistency



Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Order tbl

OrderId	ProductName	CustomerAddr

Customer Cache tbl

CustomerId	CustomerName	CustomerAddr
9002	UVW	ABCD

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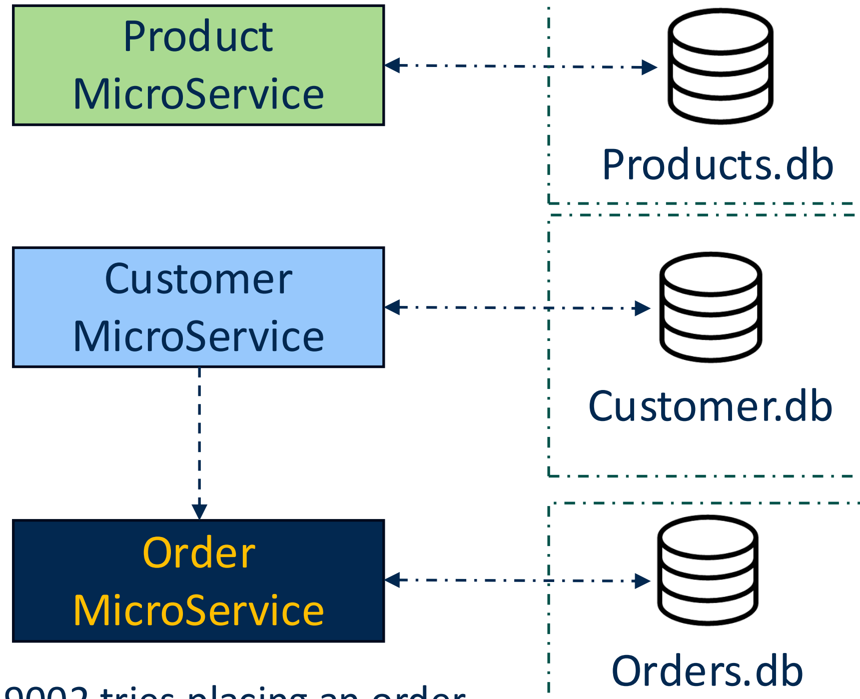
Working with eventual consistency



User 9002 tries placing an order

T3: FetchOrderAddrForConfirm() -> (9002, UWV, ABCD)

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Order tbl

OrderId	ProductName	CustomerAddr

Customer Cache tbl

CustomerId	CustomerName	CustomerAddr
9002	UVW	ABCD

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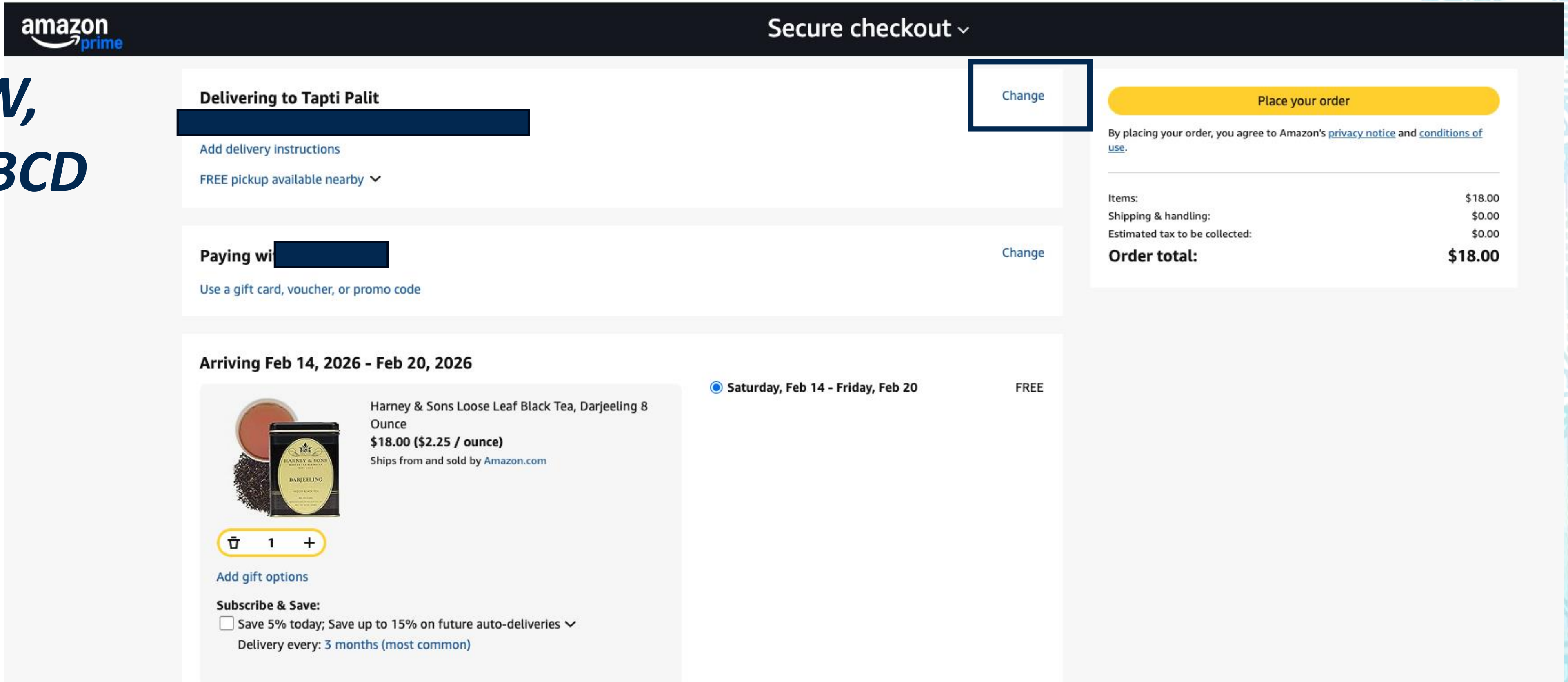
Working with eventual consistency

Name: UVW,
Address: ABCD



Working with eventual consistency

Product MicroService

Products.db

ProductId	ProductName	ProductCount
1001	ABC	10

Products tbl

Customer MicroService

Customer.db

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Customer tbl

Order MicroService

T4: AddOrder(110001, ABC, ABCD)

Orders.db

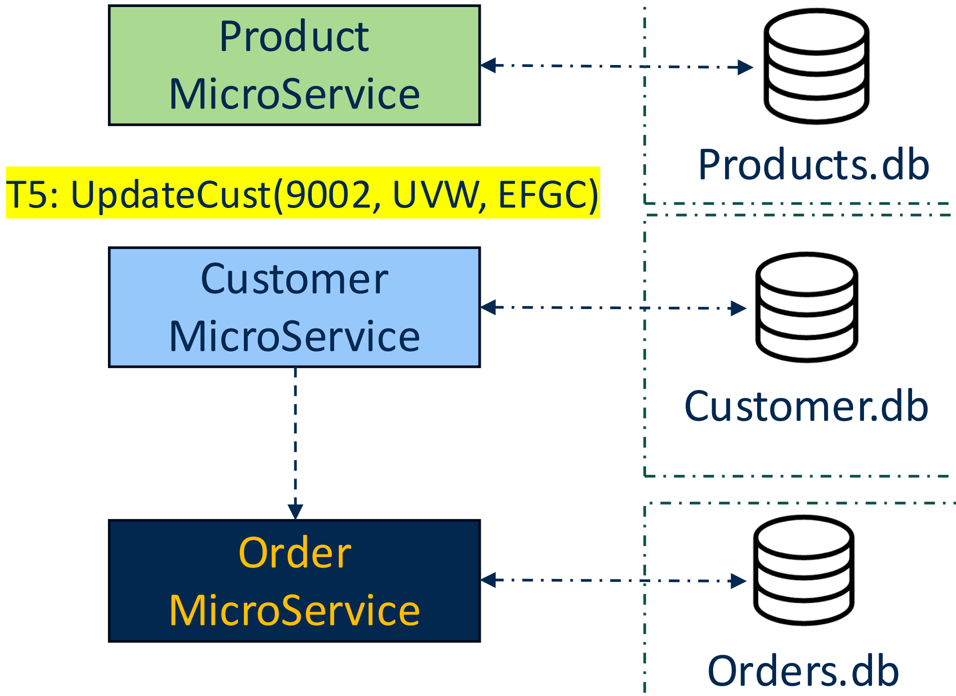
OrderId	ProductName	CustomerAddr
110001	ABC	ABCD

Order tbl

CustomerId	CustomerName	CustomerAddr
9002	UVW	ABCD

Customer Cache tbl

Working with eventual consistency



Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	EFGC

Order tbl

OrderId	ProductName	CustomerAddr
110001	ABC	ABCD

Customer Cache tbl

CustomerId	CustomerName	CustomerAddr
9002	UVW	ABCD

Working with eventual consistency

Product MicroService

Products.db

ProductId	ProductName	ProductCount
1001	ABC	10

Products tbl

Customer MicroService

Customer.db

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	EFGC

Customer tbl

Order MicroService

Orders.db

OrderId	ProductName	CustomerAddr
110001	ABC	ABCD

Order tbl

CustomerId	CustomerName	CustomerAddr
9002	UVW	ABCD

Customer Cache tbl

T6: ShipOrder(11001, ABC, ABCD)

Working with eventual consistency

Product MicroService

Products.db

ProductId	ProductName	ProductCount
1001	ABC	10

Products tbl

Customer MicroService

T7: UpdateCustCache(9002, UVW, EFGC)

Customer.db

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	EFGC

Customer tbl

Order MicroService

Orders.db

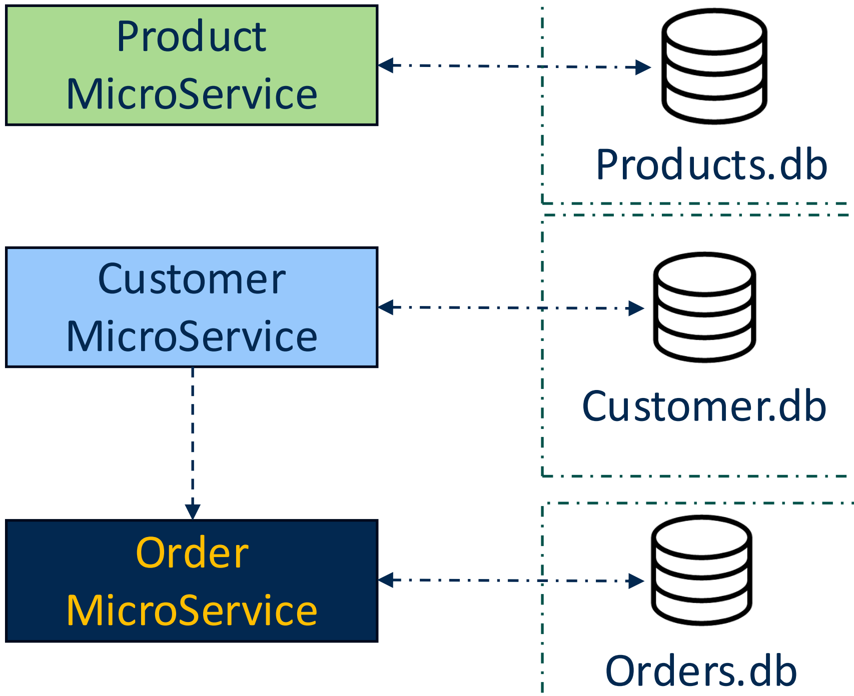
OrderId	ProductName	CustomerAddr
110001	ABC	ABCD

Order tbl

CustomerId	CustomerName	CustomerAddr
9002	UVW	EFGC

Customer Cache tbl

Working with eventual consistency



ProductId	ProductName	ProductCount
1001	ABC	10

Products tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	EFGC

Customer tbl

OrderId	ProductName	CustomerAddr
110001	ABC	ABCD

Order tbl

CustomerId	CustomerName	CustomerAddr
9002	UVW	EFGC

Customer Cache tbl

Subsequent orders load updated customer address

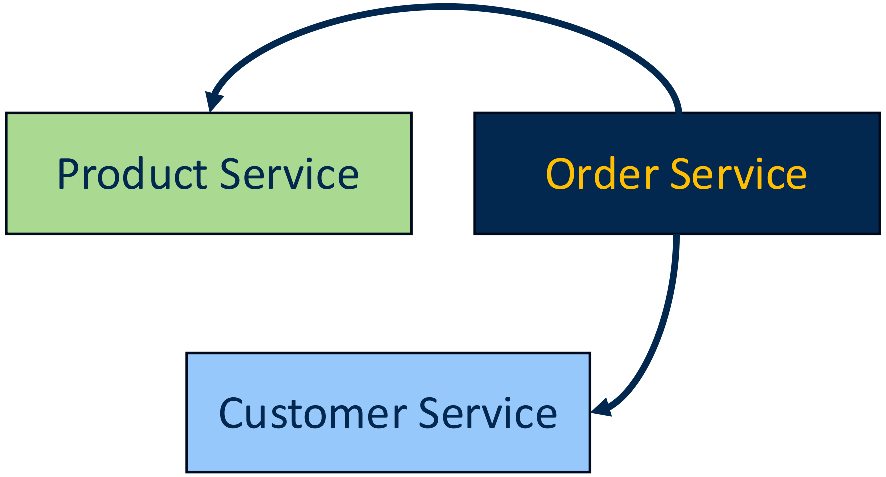
Microservice design concerns

- Solution for eventual consistency is generally use-case dependent
- Reduce tight coupling
  - A microservice should not know the internal DB schema of another microservice
  - A microservice should not depend on another to be running to perform its task
- Limit network communication

Network communication cost

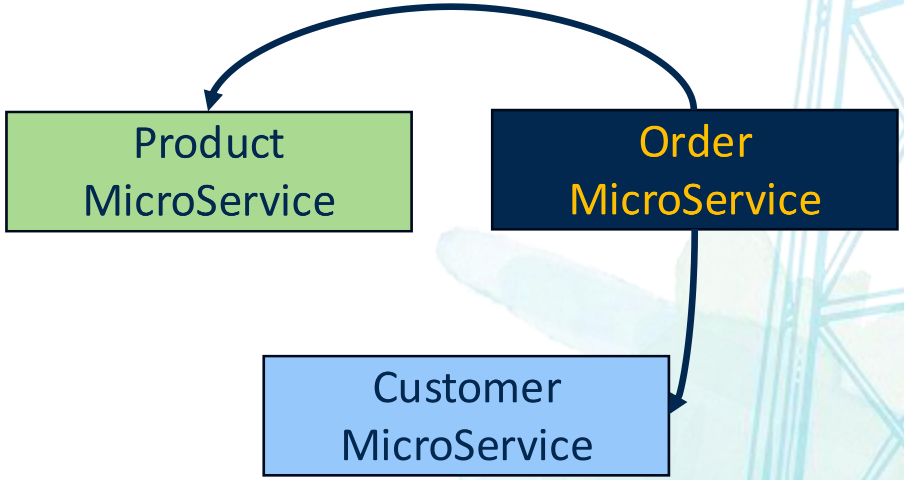
Monolithic applications

Function calls (few nanoseconds)



Microservices

Network RPC calls (few microseconds)

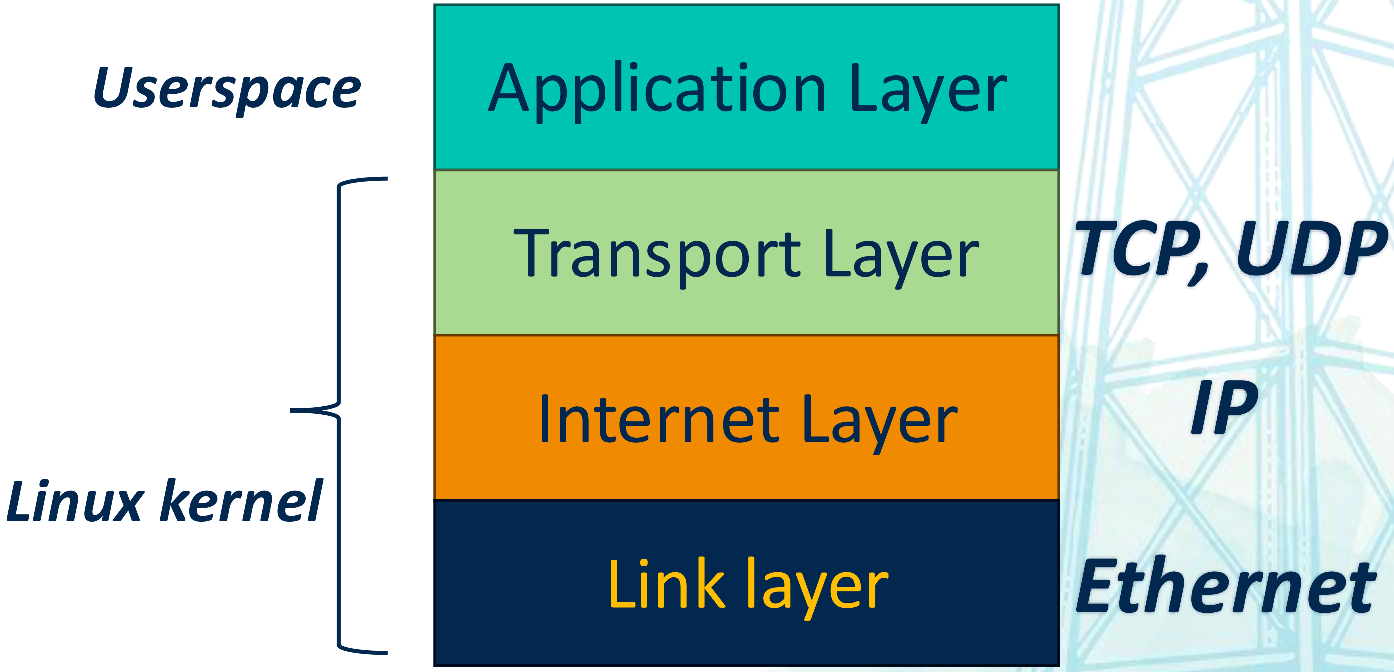


Network overhead decomposition

- Network latency
  - Datacenters use fast network connections
    - Latest technology - Infiniband has ~1-2 microsecond latency, 400+ Gbps bandwidth
    - Network communication is still over ethernet in most data centers
  - Still not as fast as a local function call
- OS kernel overhead

Kernel overhead for network comm. (Not in syllabus)

- The OS kernel contains the networking code
- TCP-IP is the most common networking stack
- It is organized in layers
- Every layer has a ***protocol***

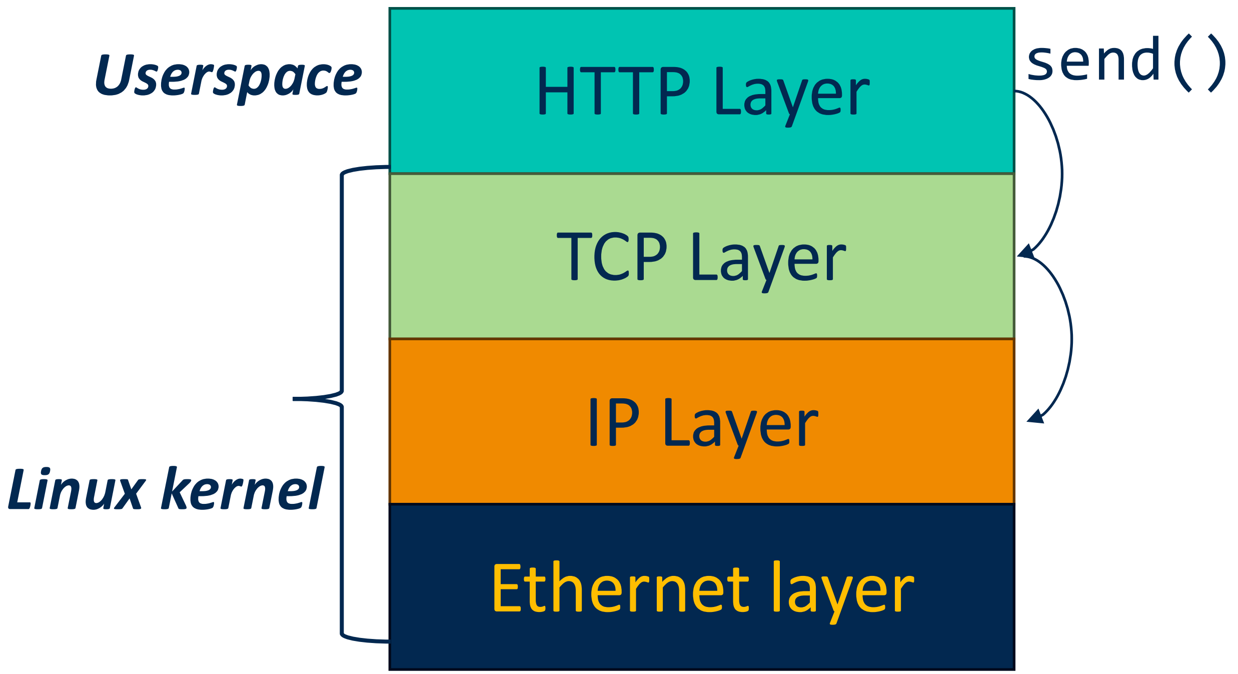


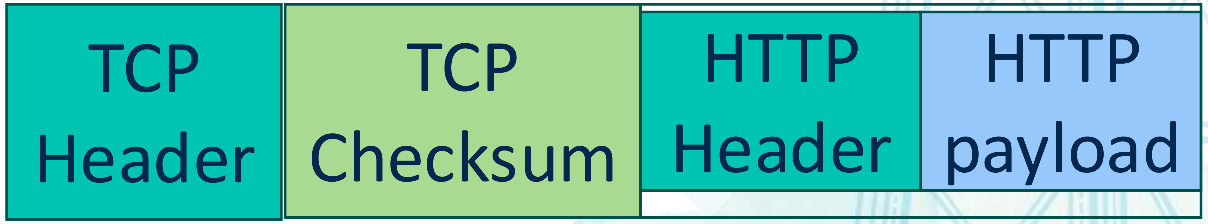
Each layer has a protocol (Not in syllabus)

- Every layer/protocol has a fixed message format
  - Header
  - Payload
  - [optional] Checksum

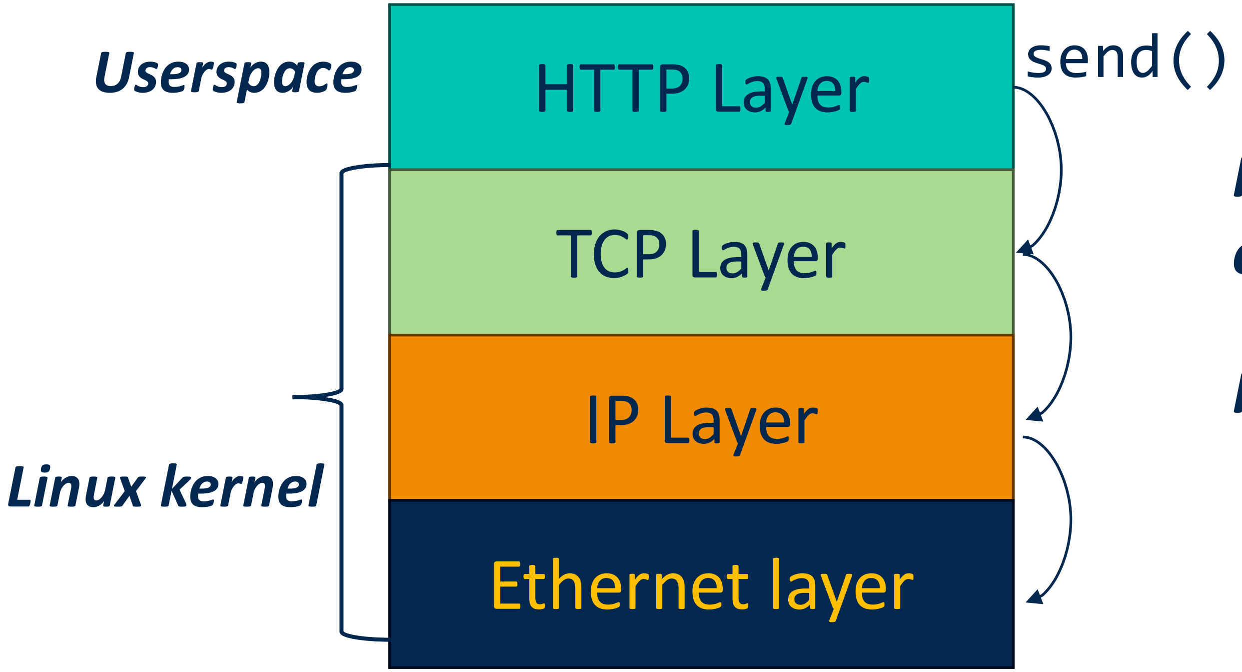
- As the packet traverses through the layers, packets are rewrapped

Life of a packet (Not in syllabus)





Life of a packet (Not in syllabus)



Packet encapsulation process + kernel context switch can take 100+ microseconds

Reading 6 will discuss alternative solutions

Ethernet Header	Ethernet Checksum	IP Header	IP Checksum	TCP Header	TCP Checksum	HTTP Header	HTTP payload

Microservice pros

- Stronger decoupling and lower interdependence
- Improved scalability
- Easer deployment

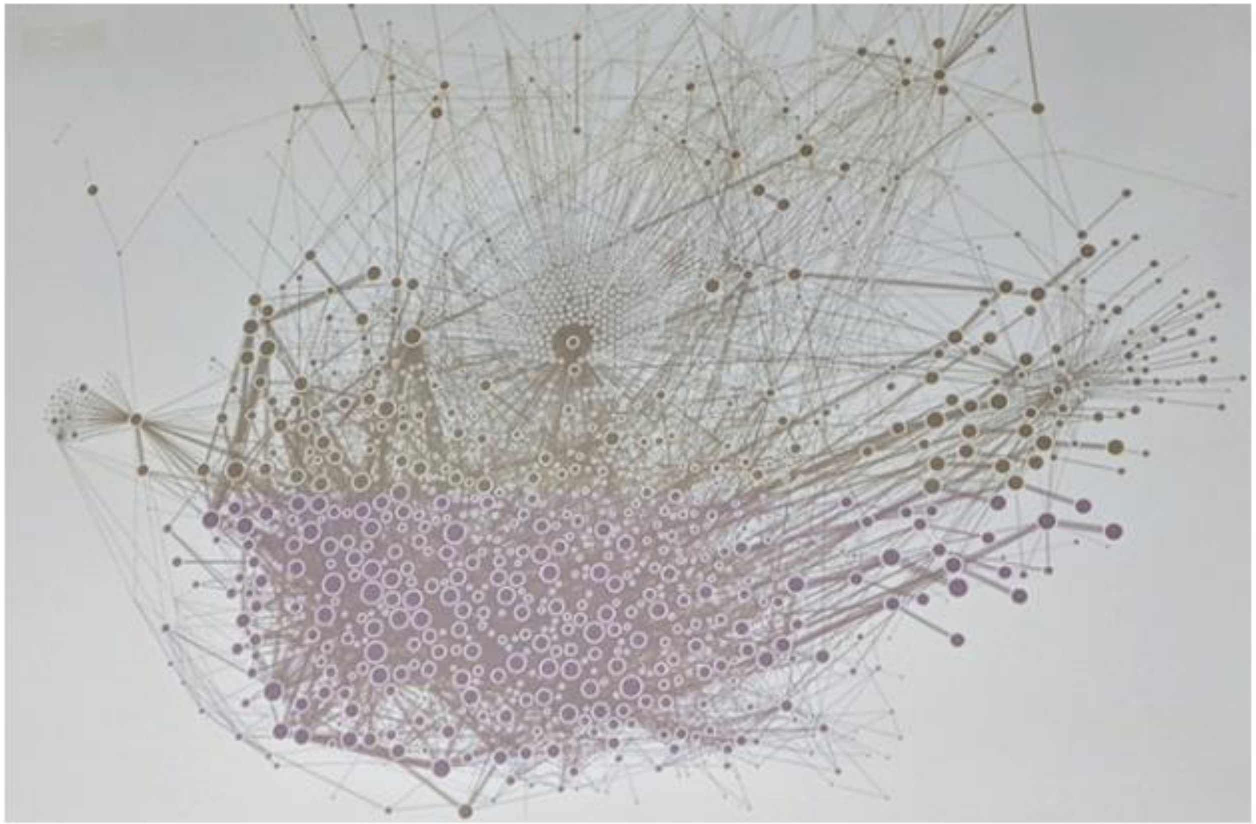
Microservice cons

- Causes data denormalization
- Network overhead
- Higher complexity
- Debugging complex interactions is harder

Latency vs throughput

- Latency – time taken for one operation
  - Measured in seconds, milliseconds, microseconds, etc
  - Service Level Objectives/Agreements (SLO/SLA)
    - Example: 95% of all requests should be served in under 2 ms
- Throughput – number of operations performed in unit time (requests/sec)
- Microservices increase latency compared to monolithic operation, but improve throughput

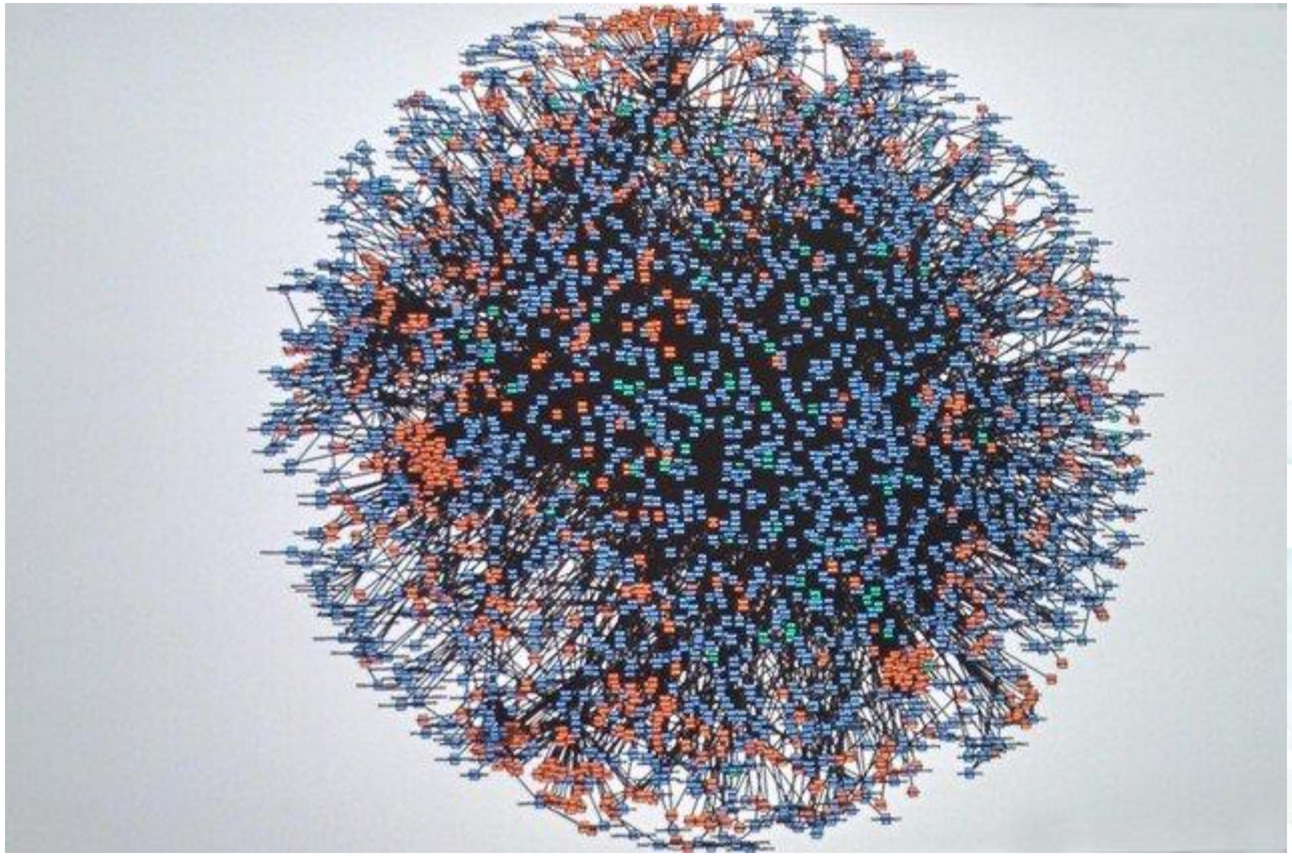
Microservices at Uber (2019)



https://x.com/msuriar/status/1110244877424578560

Microservices at Amazon (2008)

- Code-named “Deathstar”



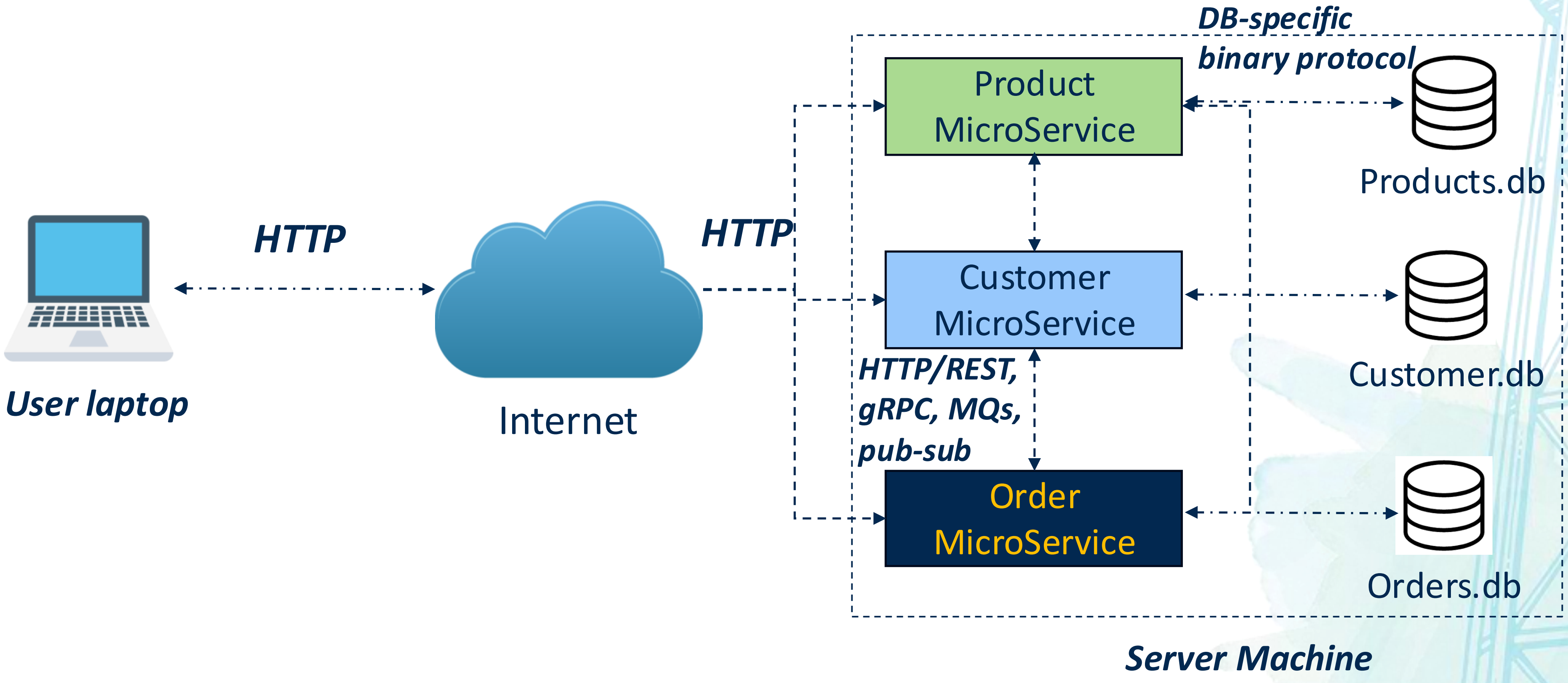
https://x.com/Werner/status/741673514567143424

Data management and communication

- Once data and computation are split across services, two problems remain
  - How is data stored?
  - How services communicate?
- First, Spring Boot overview

Spring Boot with REST API overview

Microservices over HTTP



HTTP GET and POST request

- GET request - Used to retrieve data from the server
  - `GET /index.html HTTP/1.1`

    URL
  - `GET /index.html?name=ECS160&data=02132025`

    Request parameters

HTTP GET and POST request

- POST request - used to send data to the server

URL

```
POST /users HTTP/1.1
Content-Type: application/json{
   "name": "John Doe",
   "email": john.doe@example.com
}
```

Post "body"

Spring Boot Overview

- Framework for creating RESTful microservices
- Reduces boilerplate configuration code
- Embedded server (Tomcat/Jetty)
- Simplifies microservice creation through annotations
- Built-in support for REST APIs

RESTful microservices with Spring Boot

- Create classes that can act as REST endpoints
- Uses annotations to denote REST endpoint URLs
  - Allows complete decoupling from the boilerplate code
- Types of requests
  - @GetMapping, @PostMapping, @PutMapping, and so on… for all HTTP methods
- @PathVariable – extract variable from GET request
- @RequestBody – extract the post request body

```
class MyRequest {
    private String postDate;
    private String postContent;
    // .. Getters and setters
}

@RestController
@RequestMapping("/myservice")
public class MyController {
    @PostMapping("/sayhello")
    public String sayHello(@RequestBody MyRequest
request) {
        return "";
    }
}
```

Effective URL: http://[serverip:port]/myservice/sayhello

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Spring Boot Framework

- Uses reflection to first look up all classes with @RestController annotation
- Then automatically creates Servlets out of the methods annotated with @GetMapping, @PostMapping, etc.
- Uses reflection to parse the request parameters into class objects annotated with @RequestBody
- Generates the WAR file and launches the Apache Tomcat server
  - Simply execute `mvn spring-boot:run`

```
class MyRequest {
    private String postDate;
    private String postContent;
    // .. Getters and setters
}

@RestController
@RequestMapping("/myservice")
public class MyController {
    @PostMapping("/sayhello")
    public String sayHello(@RequestBody MyRequest
request) {
        return "";
    }
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```
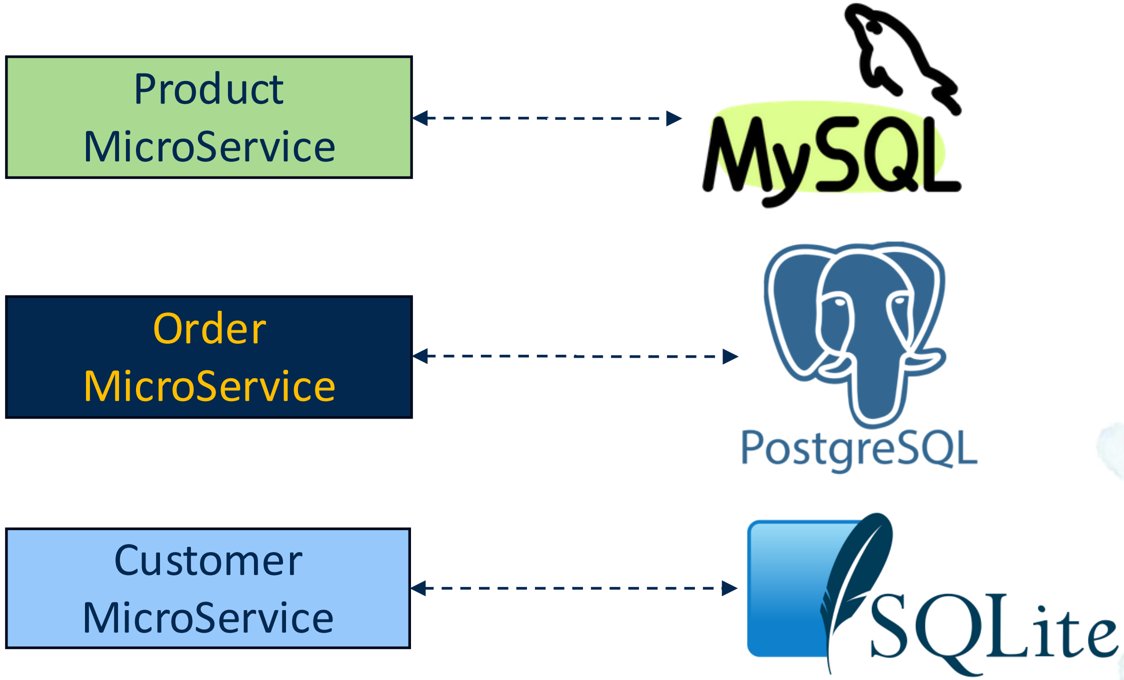

Data management and communication

- Once data and computation are split across services, two problems remain
  - How is data stored?
  - How services communicate?

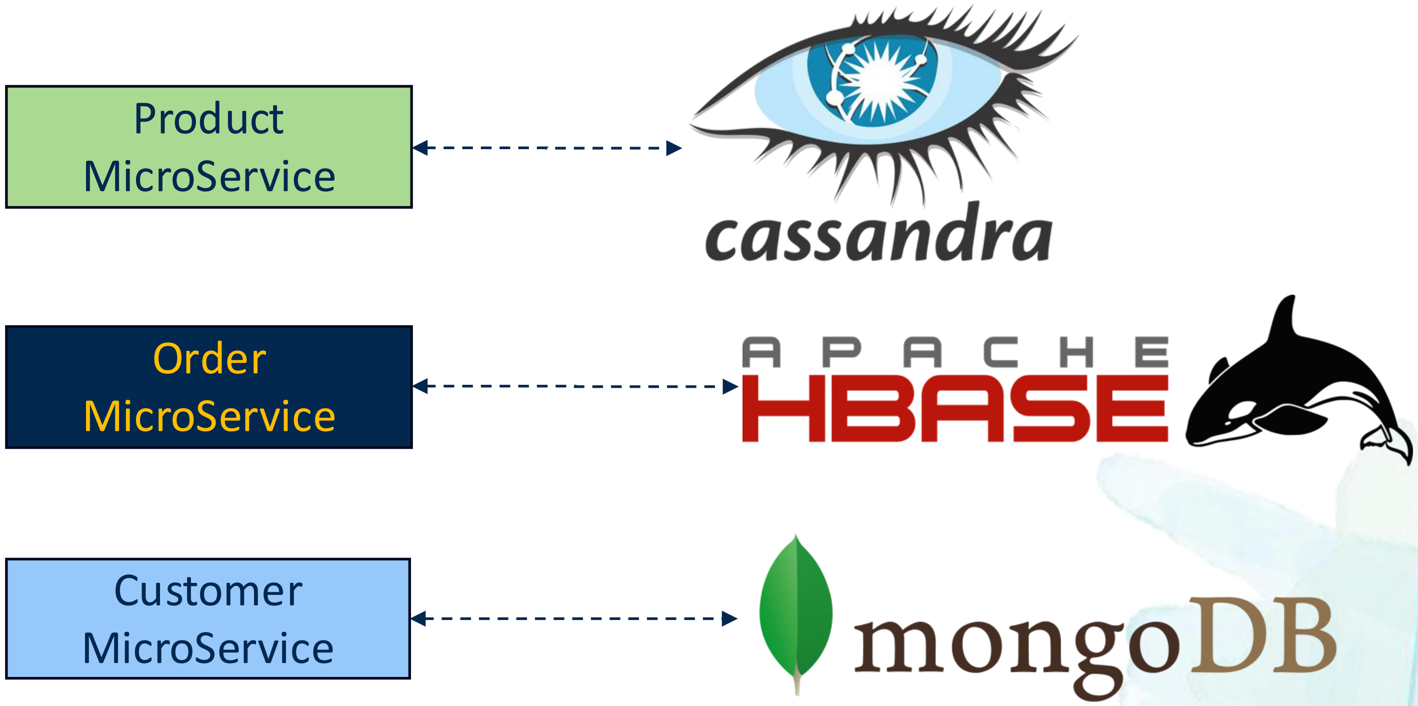
Databases

Microservices can have individual DBs



MySQL, PostgreSQL, SQLite are relational databases

Microservices can have individual DBs



Non-relational, NoSql databases

How to select which database to use?

MySQL

PostgreSQL

cassandra

APACHE HBASE

SQLite

mongoDB

redis

Database choice dimensions

- Data model
  - Format of data user gives to the database
  - Examples - relational, document, graph, key-value
  - Shapes query semantics (joins, traversals, etc.)
    - Mechanism through which you can retrieve the data
- Storage engine
  - How data is physically stored and indexed
  - B-Trees, SSTables and LSM-Trees, Hash Indexes
  - Impacts performance tradeoffs (read vs. write performance, range scans, etc)

Data models and query languages

- Relational databases
- Document model
- Key-value stores

Relational databases

- Stores data as tables
- Supports relations using foreign keys and joins
- Fixed schema

Products tbl

ProductId	ProductName	ProductCount
1001	ABC	10

Customer tbl

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

Order tbl

OrderId	CustomerId	ProductId
110001	9001	1001

Document model

- Data is a document!
  - JSON, XML
  - E.g. MongoDB
- The database maintains this document
  - Provides a query language to inspect the contents
- Flexible schema

MongoDB BSON format

- BSON is binary-encoded JSON
- String that represents an object
- Objects consists of key-value pairs
- Values can be primitives, arrays, or nested JSON objects
- Naturally supports hierarchical and semi-structured data

JSON object

Nested JSON object

JSON array

```
[
  {
        "id": "usr123",
        "username": "coder_gal",
        "details": {
          "age": 28,
          "city": "San Francisco”
        },
        "skills": [
              "JavaScript",
              "Python",
              "JSON",
              "APIs"]
  }
]
```

MongoDB

- MongoDB insert, find, update, delete operations

```
> db.createCollection(“posts”)

> db.posts.insertOne({
      title: “First post!”,
      body: “Hello world!”,
      likes: 3,
      category: “News”,
      tags: [“news”, “events”],
       author: “ABC”})

> db.posts.find( {category:
“news”} )
```

MongoDB BSON format

- Fields are accessed using dot notation
  - `post.id`
  - `post.category`
- Arrays are accessed using index notation
  - `post.tags[0]`

```
> db.posts.findOne( {category: "news"} )

> db.posts.findOne( {category: "news"}).likes # prints 3

> db.posts.findOne( {category: "news"}).tags[0] # print news
```

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Key-value stores

- Simple key-value pairs
- Redis, Memcached
- Typically operate in-memory only
- Usages
  - Cache expensive queries
  - Communication (PUBLISH and SUBSCRIBE primitives) (later)

Key	Value	
10279811	**Field**	**Value**
	Name	ABC
	Age	22
	GPA	3.8
	Credits	45
10279812	**Field**	**Value**
	Name	DEF
	Age	21
	GPA	3.9
	Credits	60

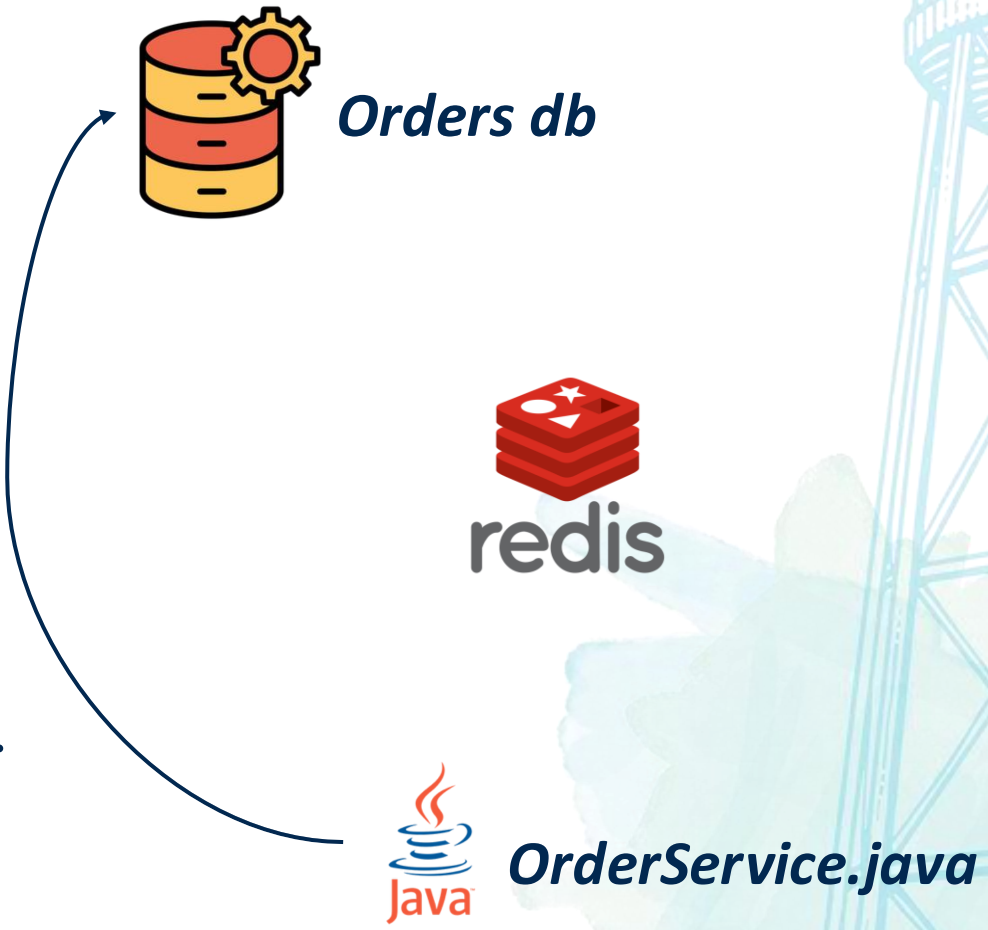
Students Redis DB

Key-value stores

- Cache results of expensive operations

- For e.g. caching the results of API requests, or expensive database queries

```
SELECT * FROM
T1 JOIN T2
JOIN T3
ON T1.id = ...
```



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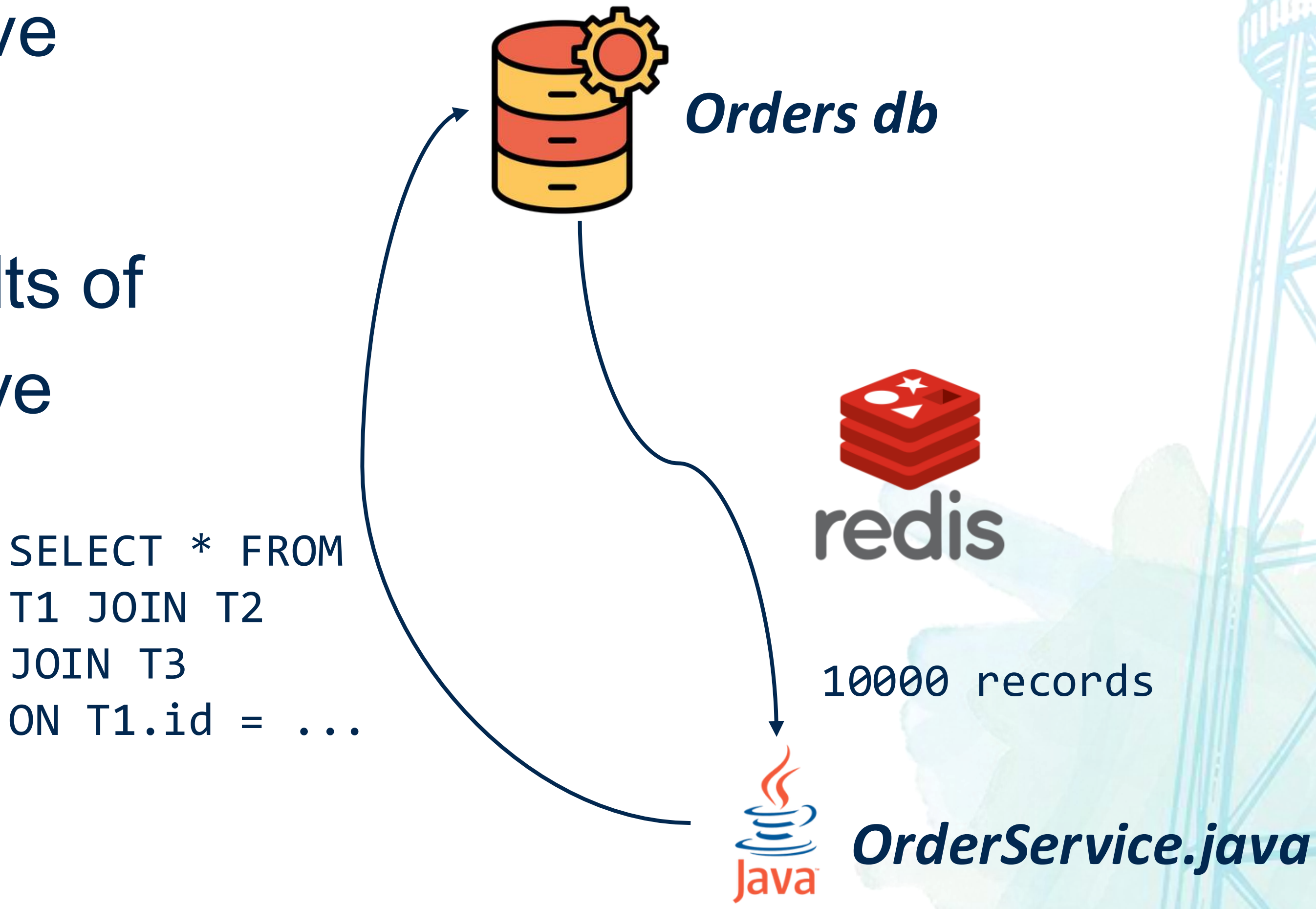

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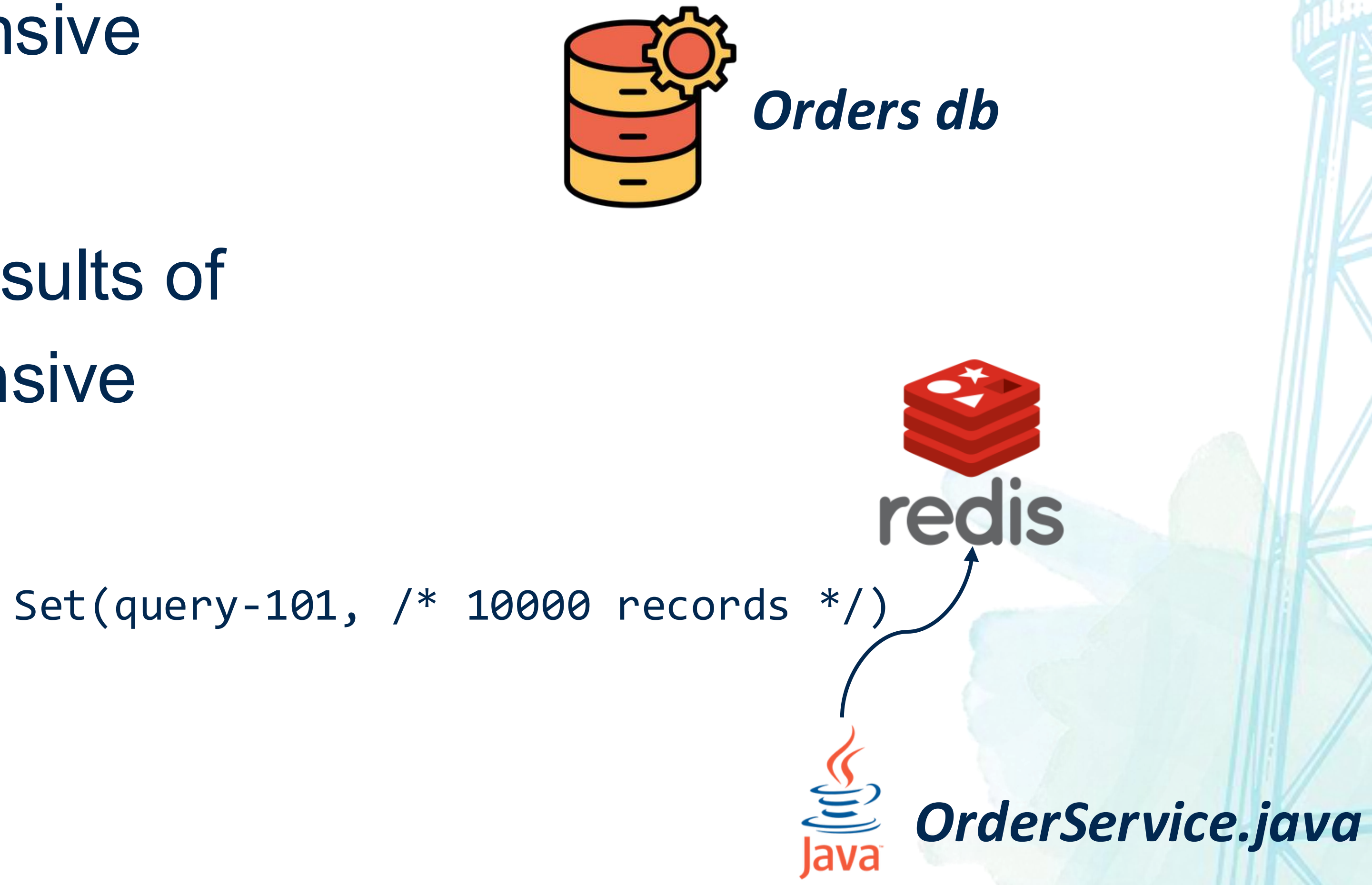

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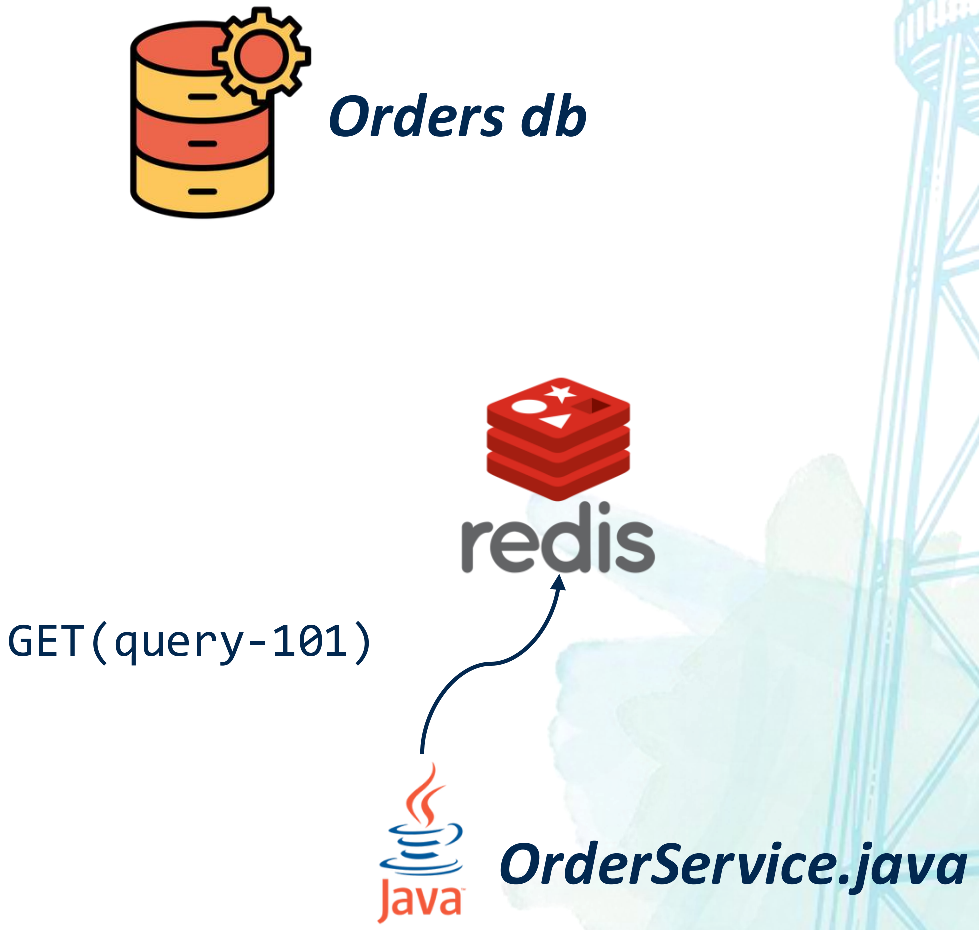

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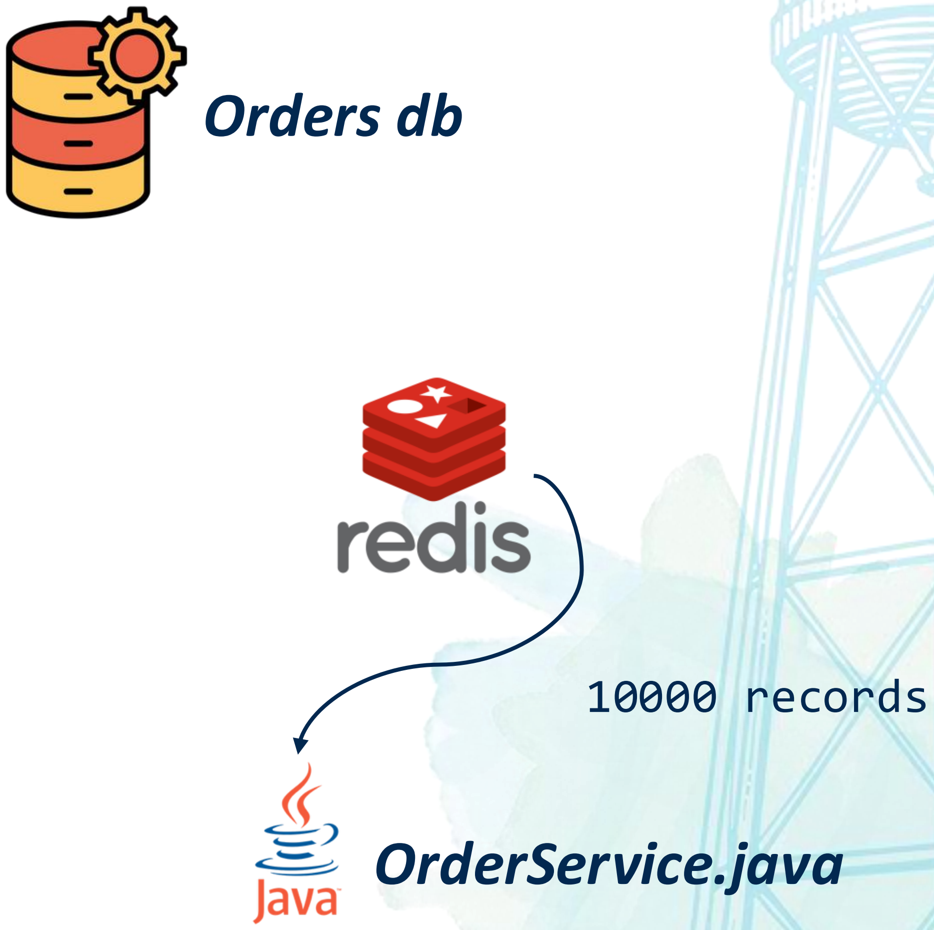

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  - Impacts performance tradeoffs (read vs. write performance, range scans, etc)

Storage engines

- Log-structured storage engines
  - Bitcask (for Riak distributed system)
  - Apache Cassandra, LevelDB, RocksDB
- Page-oriented storage engines
  - Most relational databases – MySQL, Postgresql, etc.

Database as an immutable log

- A log is an append-only data structure
- Example, store JSON as a log
- Access complexities
  - Insert/update is append is O(1)
  - Search is O(n)

```
{
    “title”: “ABC”,
    “tags”: [“S”, “T”],
    “author”: “X”
}
```

0	1	:	{	“	t	i	t	l	e	“	:
“	A	B	C	“	,	“	t	a	g	s	“
:	[	”	S	“	,	“	T	“	]	,	“
a	u	t	h	o	r	“	:	“	X	“	}

Log

Hash indices

- Naive design: in-memory hash map stores key and log-offset as value
- O(1) insert, update, and search

Key	Value
01	
03	

0	1	:	{	“	t	i	t	l	e	“	:
“	A	B	C	“	,	a	u	t	h	o	r
“	:	“	X	“	}	\n	0	3	:	{	“
t	i	t	l	e	“	:	“	X	Y	Z	“
,	“	a	u	t	h	o	r	“	:	“	Y
”	}										

Log

Hash indices – update operation

- Update operation consists of an append and an update of the hash index
  - Previous records immutable
- E.g. update(03)

Key	Value
01	■
03	■

0	1	:	{	“	t	i	t	l	e	“	:
“	A	B	C	“	,	a	u	t	h	o	r
“	:	“	X	“	}	\n	0	3	:	{	“
t	i	t	l	e	“	:	“	X	Y	Z	“
,	“	a	u	t	h	o	r	“	:	“	Y
”	}	0	3	:	{	“	t	i	t	l	e
“	:	“	P	Q	R	“	,	“	a	u	t
h	o	r	“	:	“	Y	“	}			

Log

Compaction of hash indices

- Divide log into segments
- Reduce disk usage by periodically removing duplicates
- Compaction generates a new segment
- Used by Bitcask DB

Key	Value
01	
03	

0	1	:	{	“	t	i	t	l	e	“	:
“	A	B	C	“	,	a	u	t	h	o	r
“	:	“	X	“	}	\n	0	3	:	{	“
t	i	t	l	e	“	:	“	P	Q	R	“
,	“	a	u	t	h	o	r	“	:	“	Y
”	}										

Compacted Log Segment

Compaction of hash indices

- Compaction runs in a background thread
- Compaction needs to ”remember” the latest value of a key
- Compaction is expensive

Key	Value
01	
03	

0	1	:	{	“	t	i	t	l	e	“	:
“	A	B	C	“	,	a	u	t	h	o	r
“	:	“	X	“	}	\n	0	3	:	{	“
t	i	t	l	e	“	:	“	P	Q	R	“
,	“	a	u	t	h	o	r	“	:	“	Y
”	}										

Log Segment

Hash indices limitations

- High memory usage for large logs
  - A sparse hash index can overcome this limitation, but needs sorting
- Range queries are not natively supported
  - Find all records with id in range [02 – 20] must scan all records
  - Sorting the records can solve this limitation, too
- Compaction is expensive
- Solution: SSTables (memtable) and LSM trees

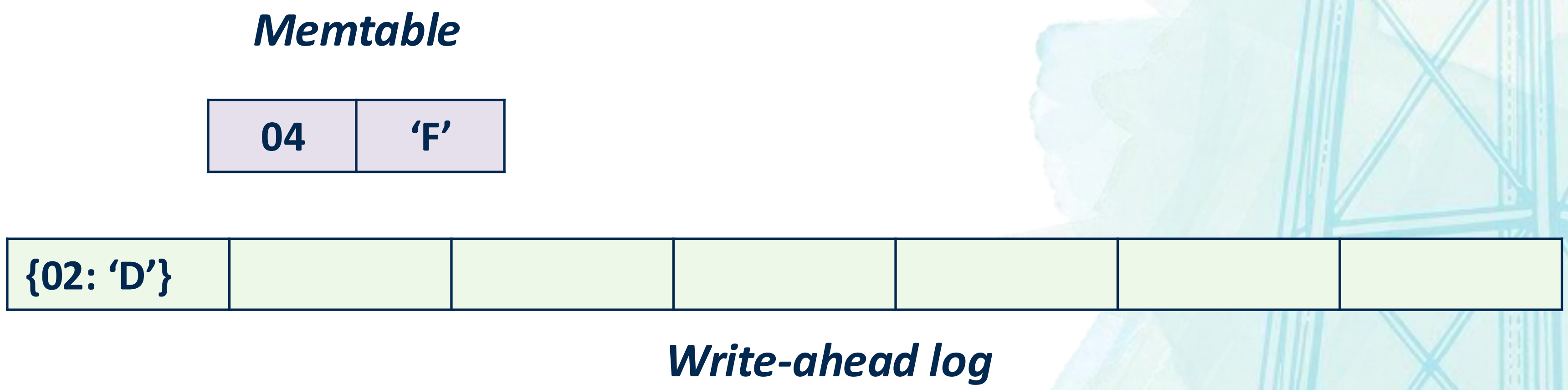
Log structured merge tree (LSM tree)

- Designed by Google as part of their distributed database BigTable
  - Chang, Fay, et al. "Bigtable: A distributed storage system for structured data." *ACM Transactions on Computer Systems (TOCS)* 26.2 (2008)
- Adopted by many recent databases (distributed or single-machine)
- LSM tree components
  - On-disk write-ahead log (WAL)
  - In-memory sorted tree (memtable)
  - Immutable on-disk sorted string table (SSTable)

LSM tree operations

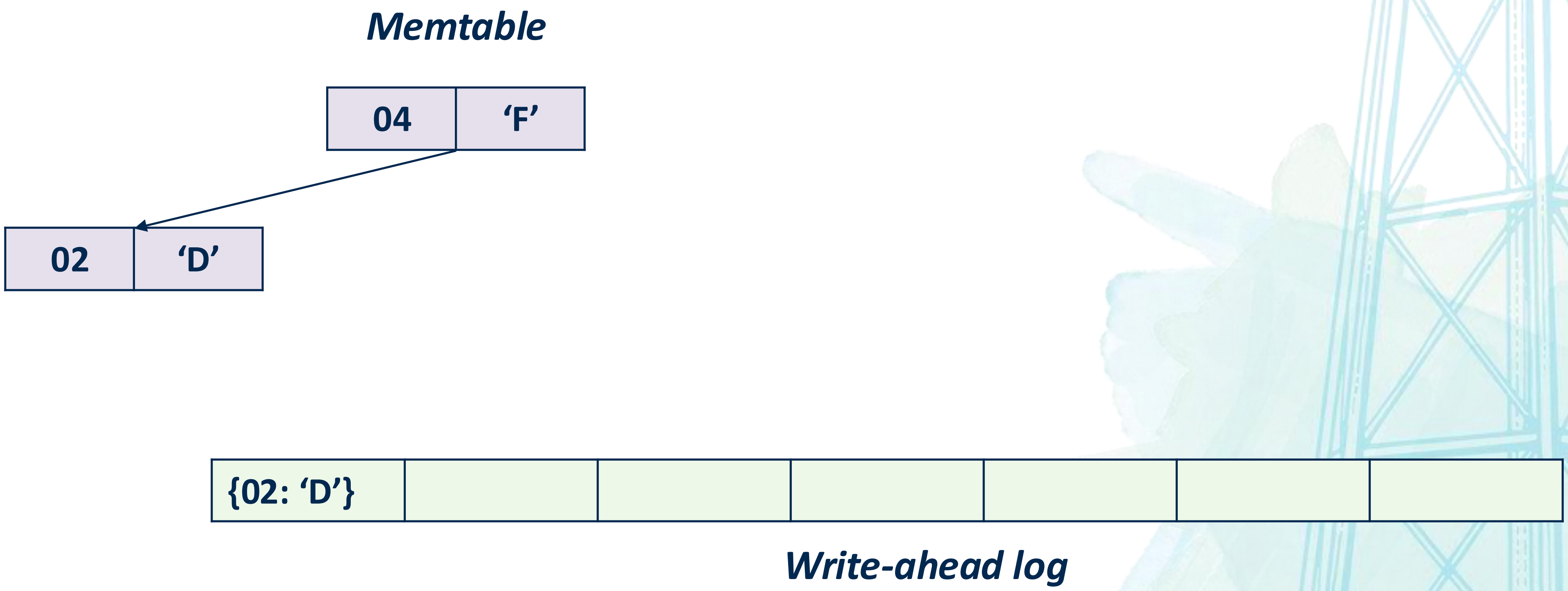
Write-ahead log

- On-disk log that provides crash recovery abilities
  - System crashes can delete the in-memory sorted tree
  - Solution: write out the updates to a log on the disk before inserting into tree
- During crash recovery replay the write-ahead log



Memtable

- Maintain a sorted in-memory tree (AVL or red-black tree)
- Writes update the in-memory tree



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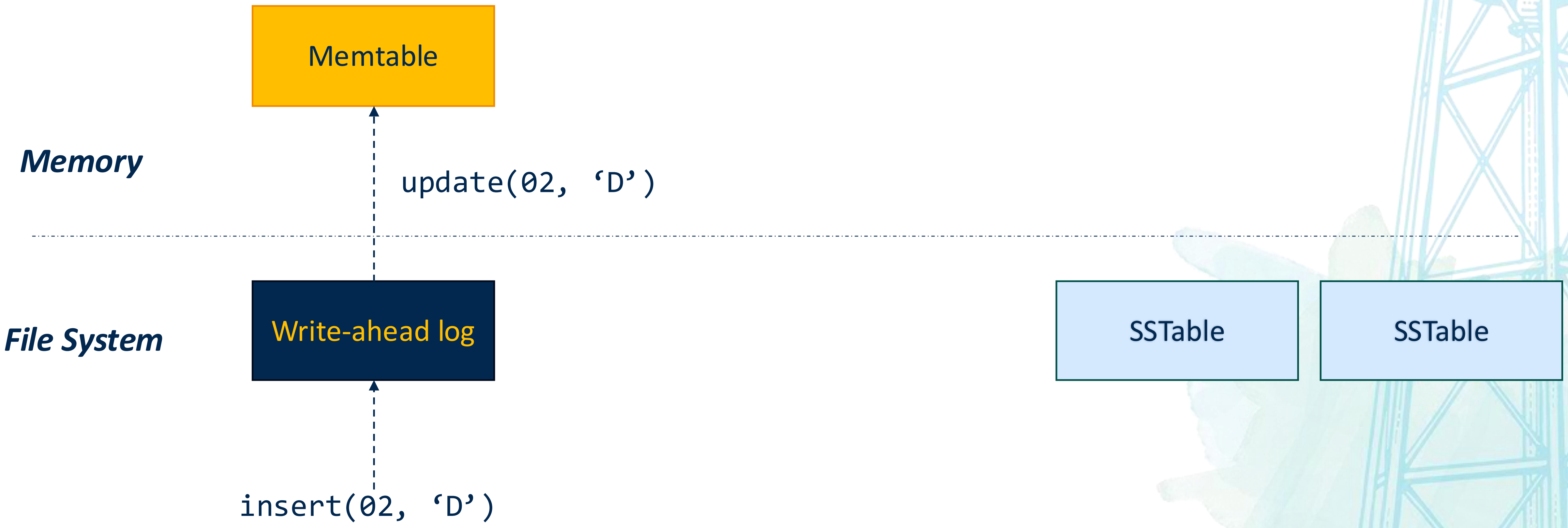
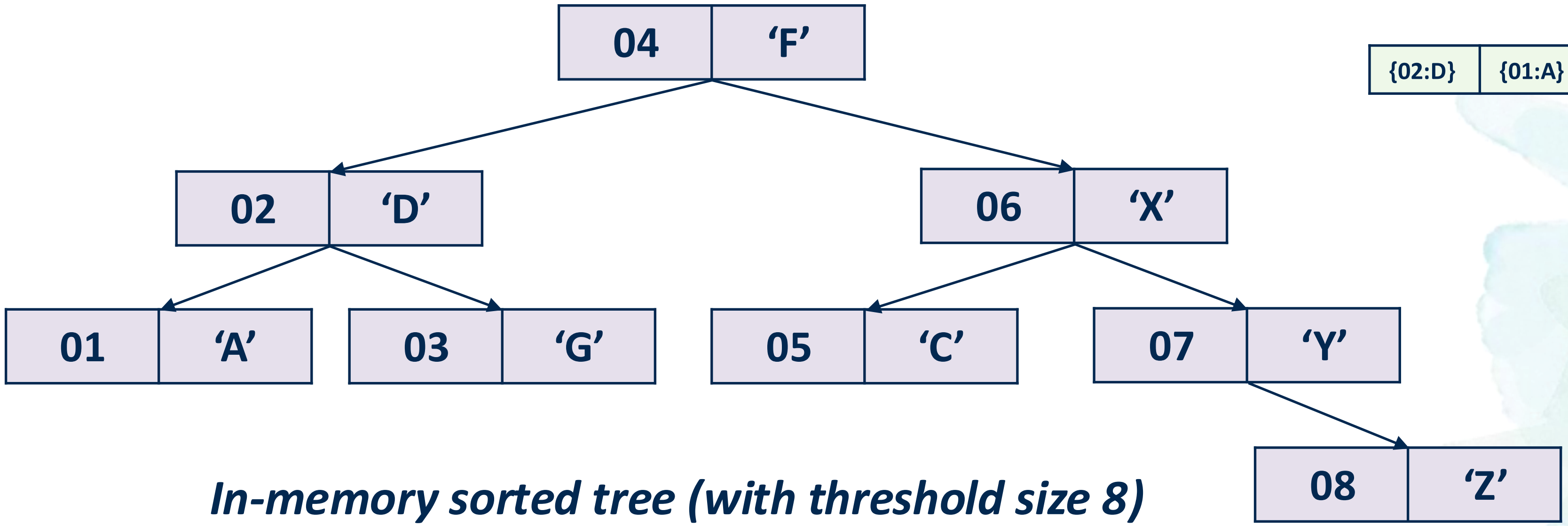
LSM tree write operation



Memtable

- Write contents to log segment (SSTable) when tree size reaches threshold
- Threshold is typically a few MB



In-memory sorted tree (with threshold size 8)

Write-ahead log

Memtable

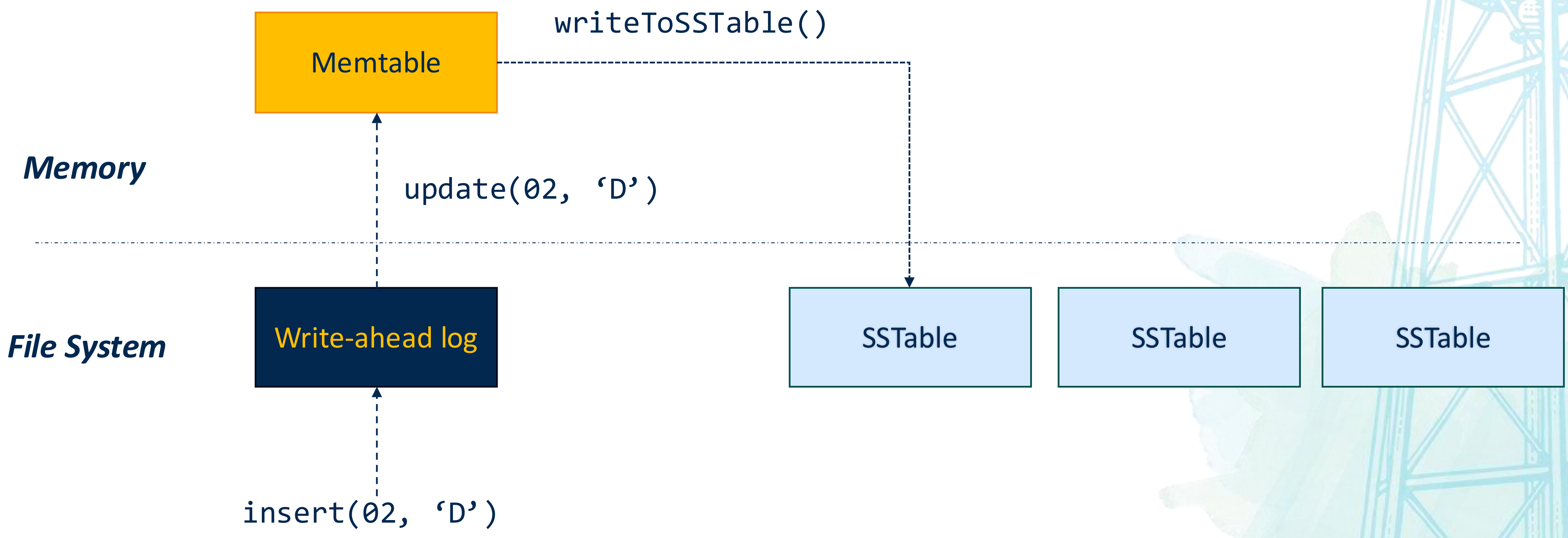
- Write sorted contents from Memtable to log segment (SSTable) when tree size reaches threshold
- Clear the WAL

0	1	:	{	‘A’	}	\n	0	2	:	{	‘D’
}	\n	0	3	:	{	‘G’	}	\n	0	4	:
{	‘F’	}	\n	0	5	:	{	‘C’	}	\n	0
6	:	{	‘X’	}	\n	0	7	:	{	‘Y’	}
0	8	:	{	‘Z’	}						

Sorted segment file (on disk)

Write-ahead log

LSM tree write operation



SSTables compaction

- Recall: SSTables are immutable
- Updates insert new records with same key
- Needs compaction to reduce on-disk storage size

0	1	:	{	'A'	}	\n	0	4	:	{	'B'	*Segment 1*
}	\n	0	5	:	{	'C'	}	…				

0	2	:	{	'D'	}	\n	0	3	:	{	'E'	*Segment 2*
}	\n	0	4	:	{	'F'	}	…				

0	3	:	{	'G'	}	\n	0	4	:	{	'H'	*Segment 3*
}												

SSTables compaction

- Recall: SSTables are immutable
- Updates insert new records with same key
- Needs compaction to reduce on-disk storage size

0	1	:	{	‘A’	}	\n	0	2	:	{	‘D’
}	\n	0	3	:	{	‘G’	}	\n	0	4	:
{	‘F’	}	\n	0	5	:	{	‘C’	}	\n	

Merged Segment

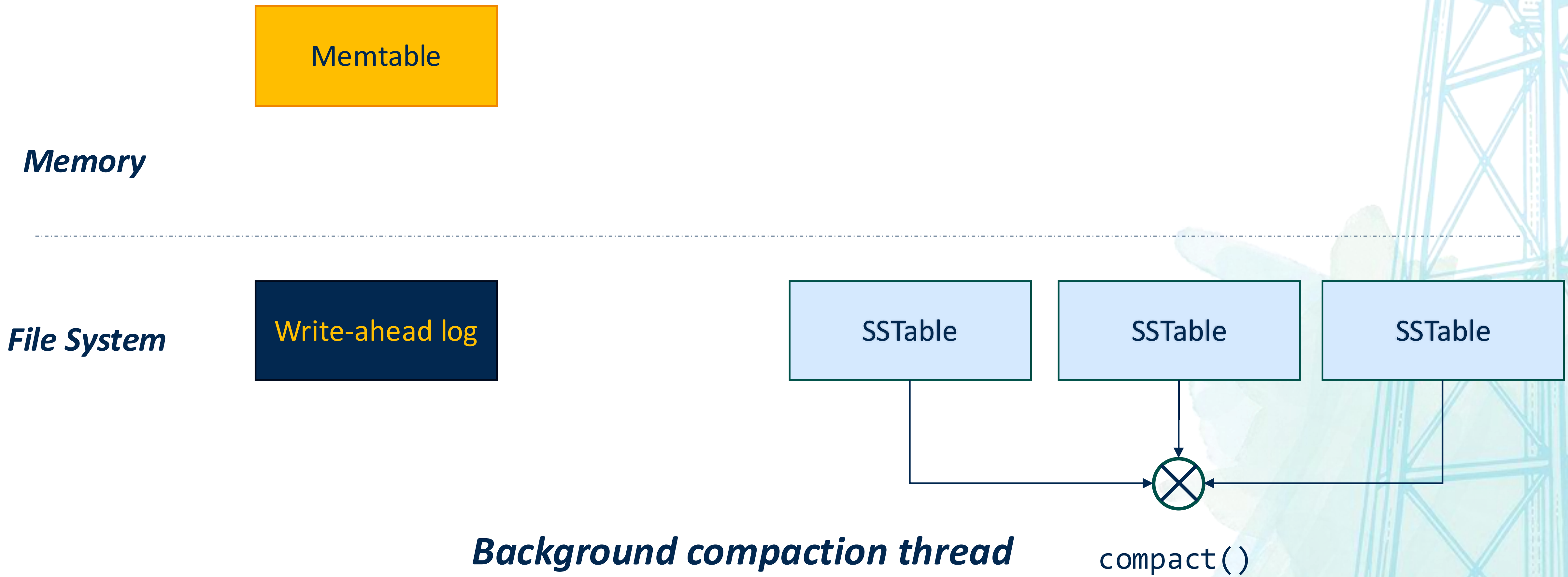
SSTables compaction

- The records in each log segment is sorted by key
- Advantages: compaction is faster (essentially the ”merge phase” of a merge-sort algorithm)

0	1	:	{	‘A’	}	\n	0	2	:	{	‘D’
}	\n	0	3	:	{	‘G’	}	\n	0	4	:
{	‘F’	}	\n	0	5	:	{	‘C’	}	\n	

Merged Segment

LSM tree compaction operation



LSM tree compaction operation

Memtable

Memory

File System

Write-ahead log

New Merged
SSTable

New merged SSTable can participate in further compactions

UCDAVIS

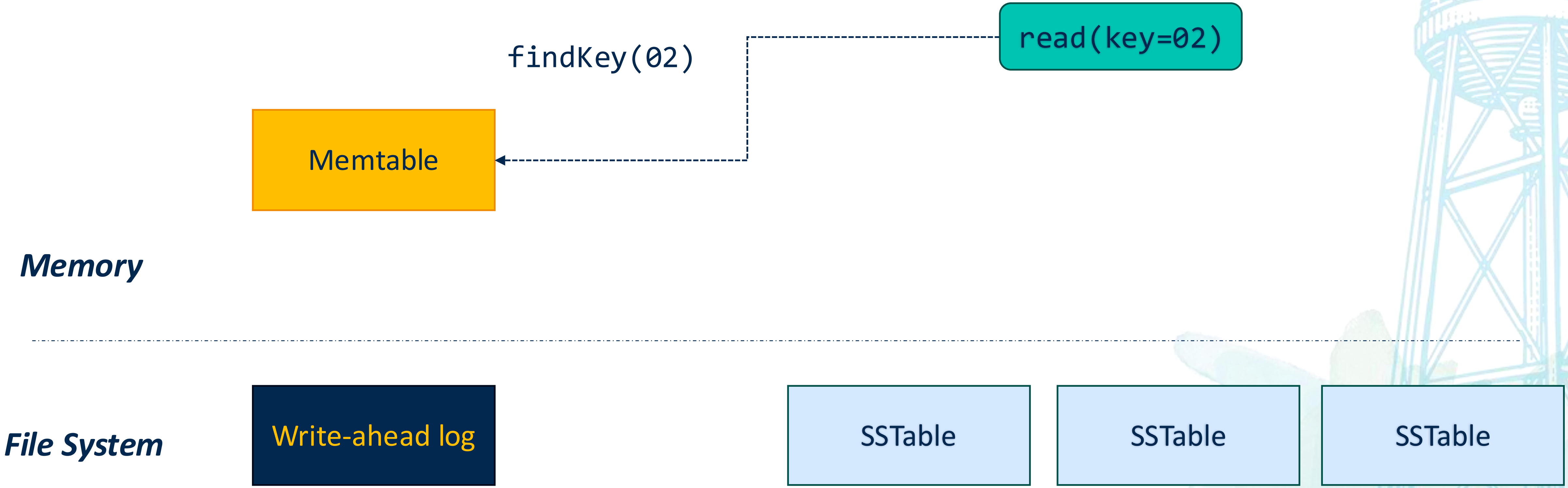
Typical overheads of LSM write path

- Append to ***on-disk*** WAL has O(1) complexity
- Insert into ***in-memory*** memtable (AVL tree) has O(log(n)) complexity
- Eventually, append to ***on-disk*** SSTable has O(1) complexity per-key
  - Bulk write amortizes the disk overhead
- ***On-disk*** log compaction and merging runs in a background thread
- Generally, writes are fast compared to alternatives
- Still, at least 3x write amplification

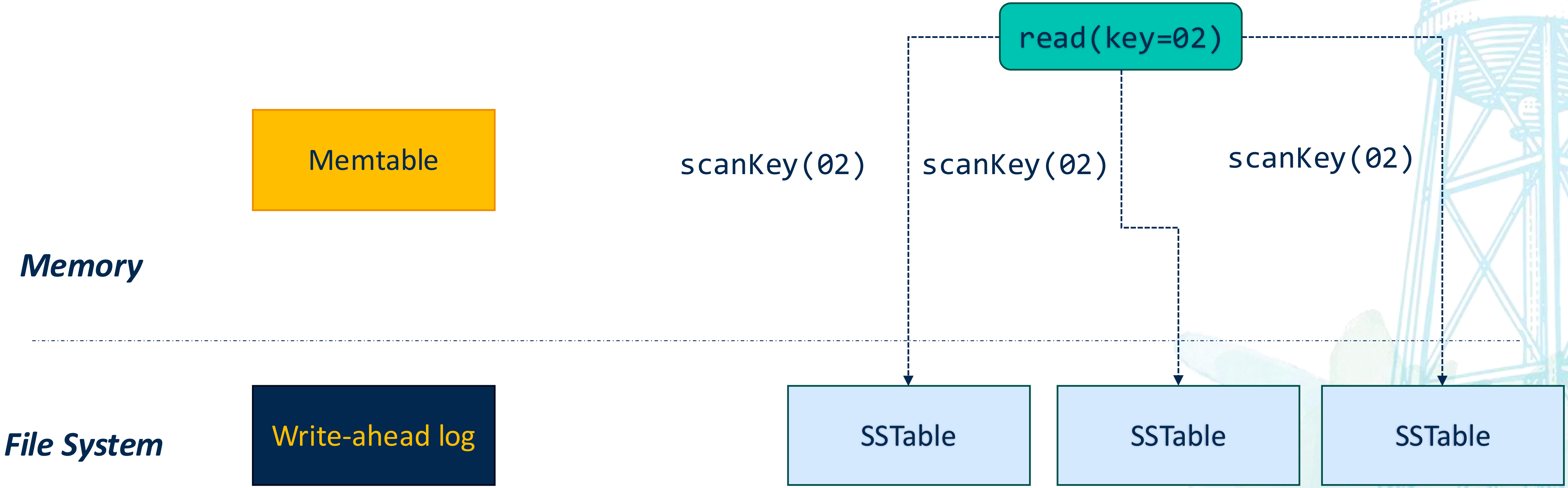
LSM tree read operation

- Check if the key is in the ***in-memory*** memtable
  - Typically, O(log(n)) complexity
- If not, scan each of the ***on-disk*** SSTables has the key
  - Typically, O(n) complexity
- Generally, reads are slower than writes

LSM tree read operation



LSM tree read operation



Block index for read optimization

- Each SSTable is divided into blocks
- Each SSTable has a block index which maps keys to block offsets inside the SSTable

Block Index

Key	Offset
01	
06	

Block-0

Block-1

SSTable segment

0	1	:	{	'A'	}	\n	0	2	:	{	'D'
}	\n	0	3	:	{	'G'	}	\n	0	4	:
{	'F'	}	\n	0	5	:	{	'C'	}	\n	
0	6	:	{	'X'	}	\n	0	7	:	{	'Y'
}	0	8	:	{	'Z'	}					

Block index for read optimization

- When scanning SSTable for reads, load block index into memory
- Use block index to index into SSTable

Block Index

Key	Offset
01	
06	

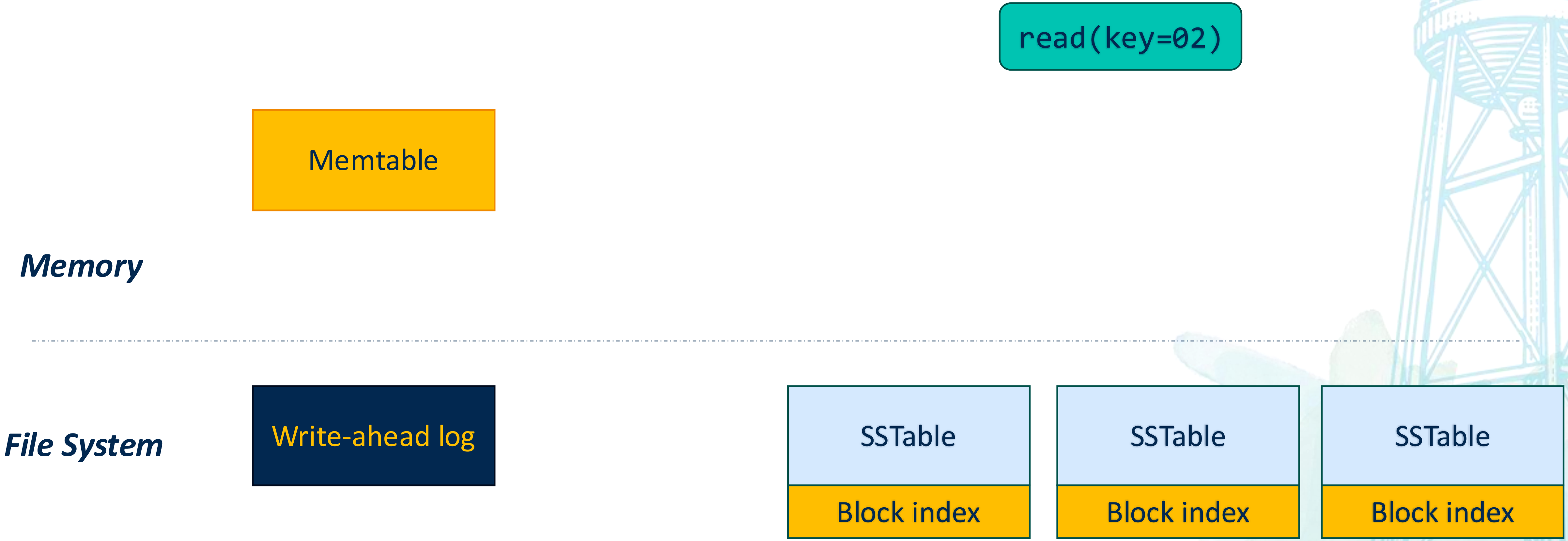
Block-0

Block-1

SSTable segment

0	1	:	{	'A'	}	\n	0	2	:	{	'D'
}	\n	0	3	:	{	'G'	}	\n	0	4	:
{	'F'	}	\n	0	5	:	{	'C'	}	\n	
0	6	:	{	'X'	}	\n	0	7	:	{	'Y'
}	0	8	:	{	'Z'	}					

LSM tree read path with block index



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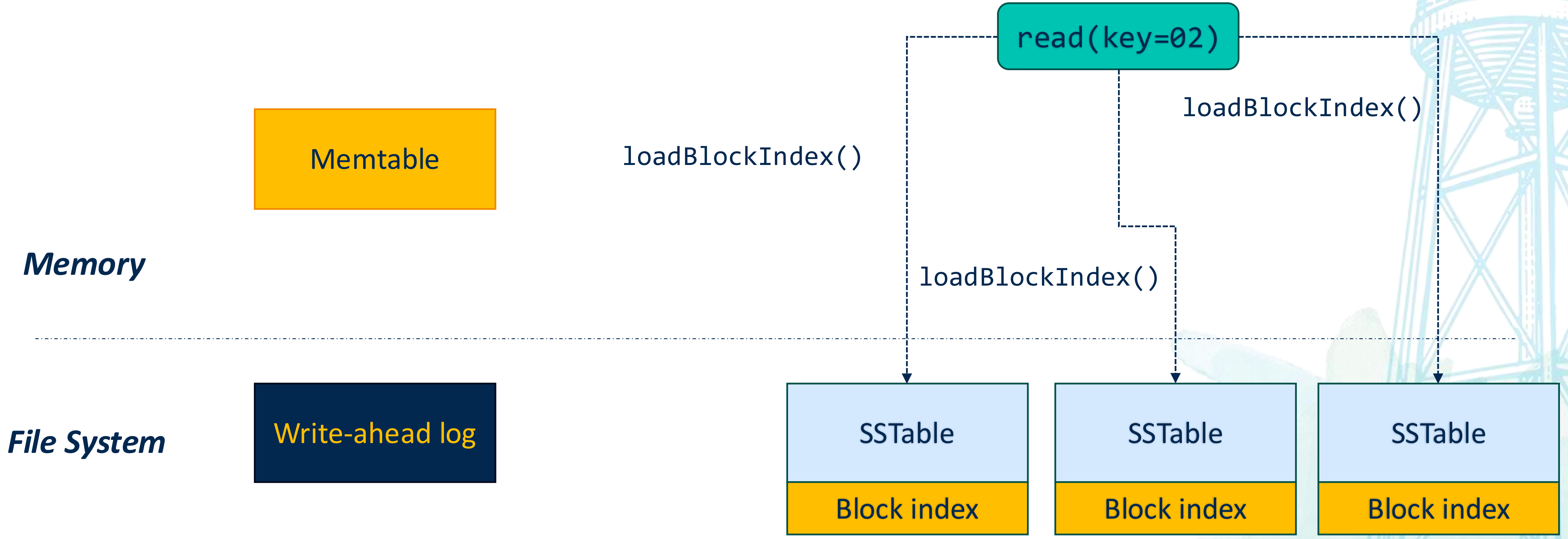

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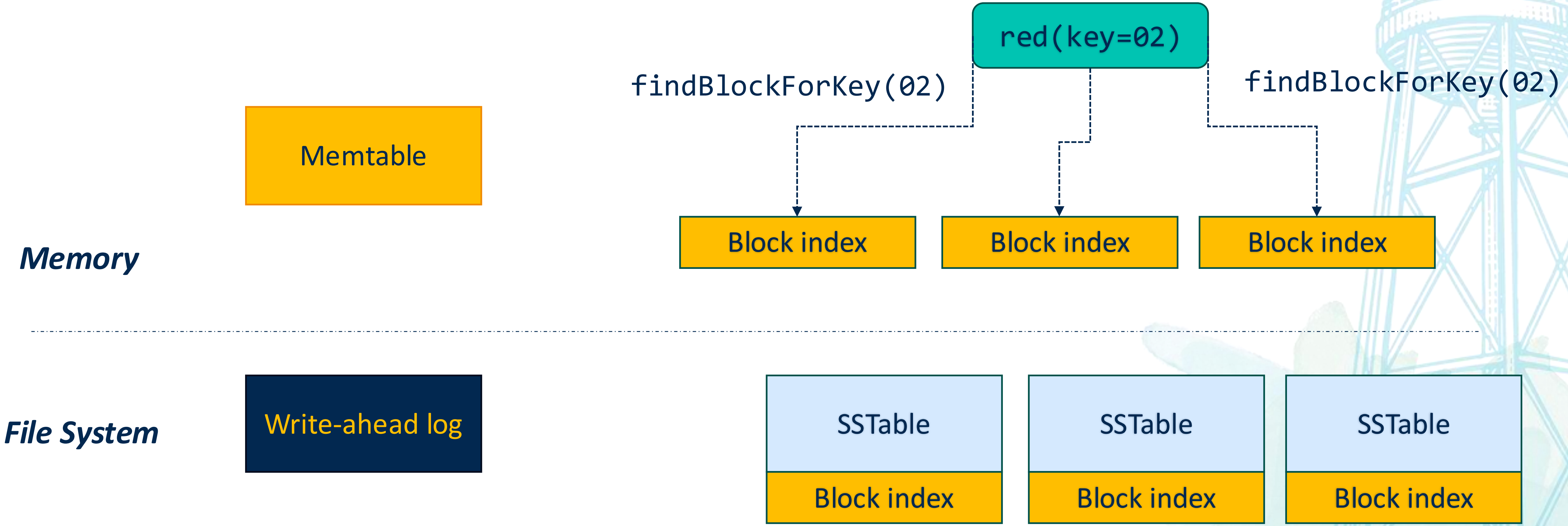
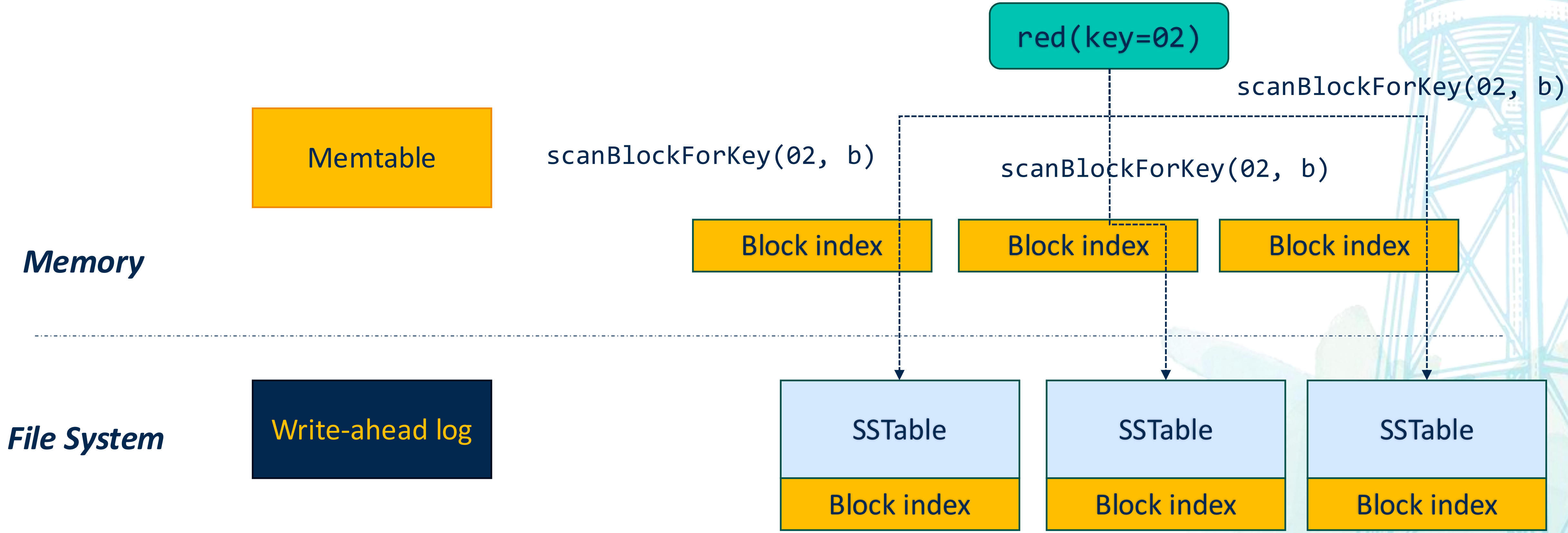


Scan the block indices to find the corresponding SSTable blocks where the key could potentially be located

LSM tree read path with block index



Scan only the selected blocks in each SSTable

Page-oriented storage engine (B+ trees)

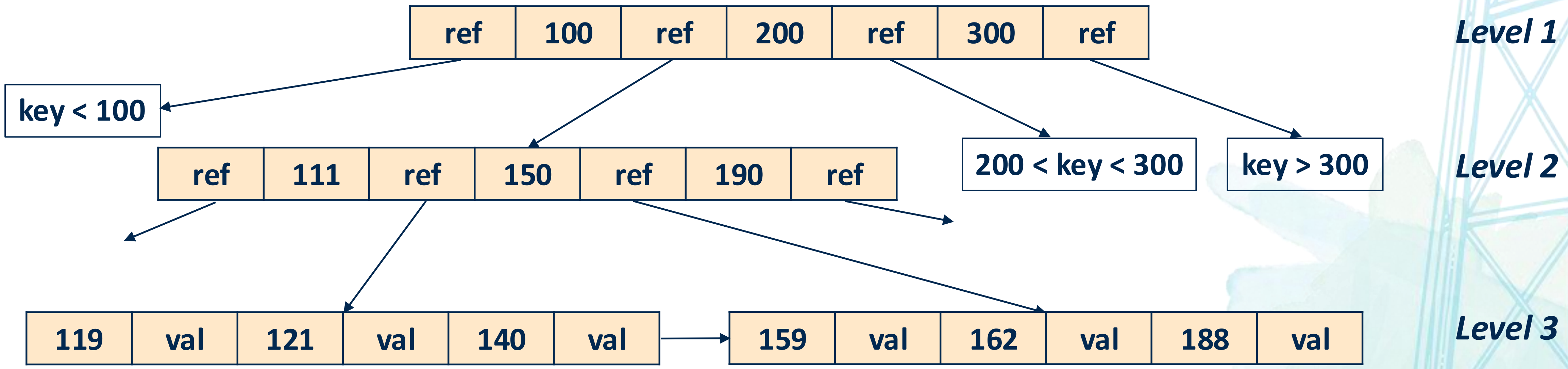
- Used to implement primary key indexes in traditional relational databases
- On-disk data structure that keeps key-value pairs sorted by key
- Supports random accesses
- Writes are performed directly on this on-disk sorted tree, unlike in LSM trees which operated on the in-memory Memtable

B+ tree

- Recall: B+ trees are ”inspired” by binary search tree
  - B+ trees have multiple branches
- Each node has a max and minimum number of keys
  - Branching factor – how many children each internal node has
- Data only lives in the leaf nodes, intermediary nodes help navigation
- Leaf nodes maintain a linked list for better range scans
- Each node is stored on a “page” of 4 KB size

B+ tree

- Example B+ tree with three levels and branching factor of 4



B+ tree read path

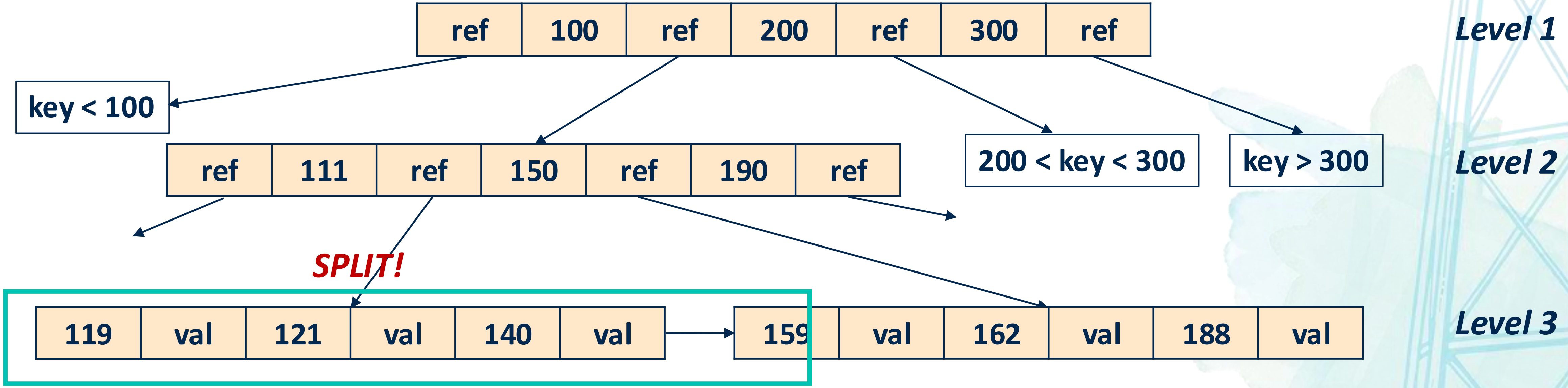
- Traverse the tree following the branches based on the key value
  - Start at the root
  - At each node: search the sorted keys (e.g., binary search) to find the correct child pointer
  - Follow the pointer to the next node and repeat until you reach the leaf
- Complexity is O(log(n))

B+ tree write path

- Recall – every B+ tree has a max number of keys per node
- If insertion exceeds this max number, the node must be split and tree rebalanced
- Node splitting and tree balancing are expensive operations performed on disk

B+ tree node splitting

- Assume max number of keys is 3
- insert(152)

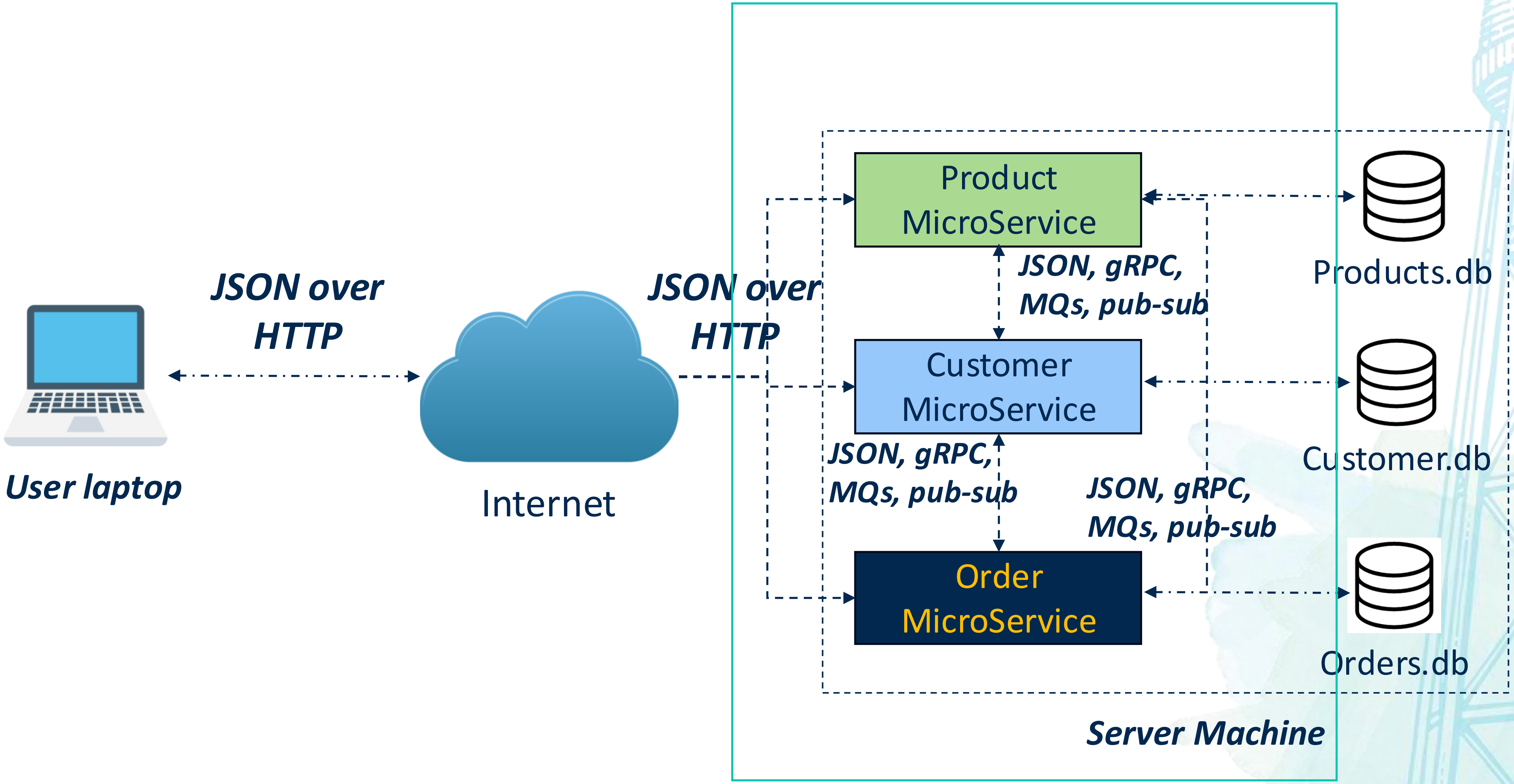


LSM tree vs B+ tree

- LSM trees typically have higher write throughput
- LSM trees can compress better, B+ trees can cause fragmentation
- B-trees typically have better read performance
  - The key can exist at only one place, unlike LSM trees which involve scanning multiple SSTables
- No clear winner – requires empirical testing on a per use-case basis

Communication styles

Intra-service communication



Communication choice dimensions

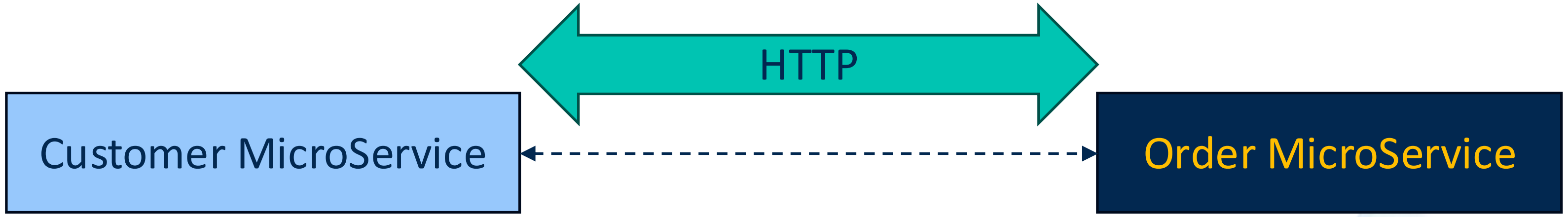
- Synchronous request/response (RPC/HTTP)
- Asynchronous request/response (message queues - RabbitMQ)
- Event-driven publish/subscribe models (Kafka – next module)

Synchronous request/response

- Designed to make a remote call feel like a local function call
- Same programming model as local function calls
  - Caller sends a request, waits for a response
  - Typically, it is a blocking call
- JSON over HTTP, gRPC
- Note: the “synchronous” here refers to the communication paradigm or interaction pattern, not how the programmer *uses* the paradigm
  - Programmer can use async programming primitives to communicate with synchronous communication substrates

JSON over HTTP

```
{
  "id": 123,
   "name": "John Doe",
   "email": john.doe@example.com
}
```



REST APIs

- Representational State Transfer (REST) is an architectural style for web services
- Application/microservice exposes an URL
- Uses HTTP methods (GET, POST, PUT, DELETE) to perform operations on resources
- Commonly paired with JSON for data exchange

```
// GET Request to Fetch a User denoted by ID

> GET https://api.github.com/users/123

// Response

{
    "id": "123",
    "name": "John Doe",
    "email": john.doe@example.com

}
```

HTTP JSON client

- Example Java HTTP client communicating with GitHub API endpoint

```
HttpClient client = HttpClient.newHttpClient();

String jsonBody =
    {"title":"Found a bug",
     "body":"Steps to reproduce..."};

HttpRequest req = HttpRequest.newBuilder()
    .uri(URI.create(
    "http://api.github.com/repos/ecs160/issues"))
    .header("Content-Type", "application/json”).
    .POST(jsonBody).build();

HttpResponse<String> resp = client.send(req, ..);

System.out.println("Status: " +
resp.statusCode());

System.out.println("Body: " + resp.body());
```

JSON implications

- JSON message contains the schema
- What happens if the receiver receives a message with the `email` field missing?
  - Receiver can still make sense of the rest of the fields
  - Receiver can ”handle” missing or extra fields

```
// expected
{
    "id": "123",
    "name": "John Doe",
    "email": john.doe@example.com
}

// received
{
    "id": "123",
    "name": "John Doe",
}
```

JSON implications

- JSON is text-based
- Text-based protocols are less efficient than binary protocols

```
{
    "id": "123",
    "name": "John",
}
```

Text-based representation

{	“	i	d	“	:	1	2	3	,	“	n
a	m	e	“	:	“	J	O	H	N	“	}

Binary-based representation

123	J	O	H	N

* Assume each box is 8 bits, chars are 8 bits, integers are 32 bits

JSON implications

- Protocol efficiency: low
- Type safety (schema adherence): low
- What about ease of debugging?
  - Can view exactly the message contents on the wire
- Ease of debugging: high

Remote procedure call (RPC)

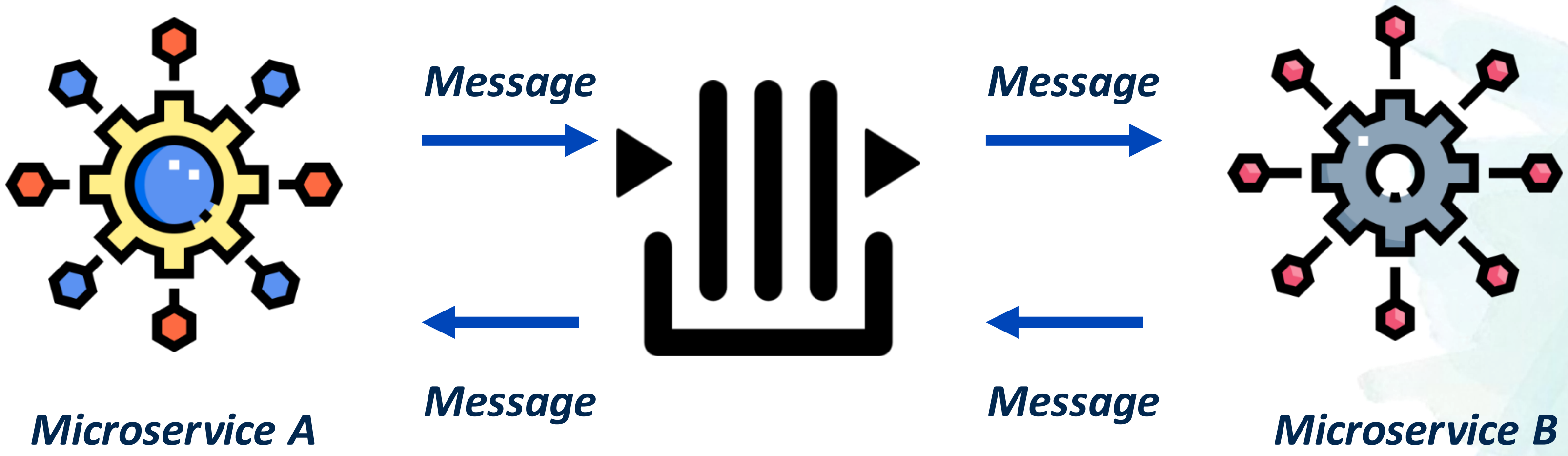
- Library/framework gives the illusion that the other microservice is running locally
- Protocol that allows a program to execute a procedure on a remote server as if it were local

RPC key features

- Language agnostic: the RPC itself does not depend on the service language
- Abstracts network details
- Typically, over HTTP

Message queuing (MQ)

- Asynchronous communication model
  - Messages sent to a queue and processed by consumers independently of the producer
- Stronger decoupling



Open source and paid MQ services

RabbitMQ

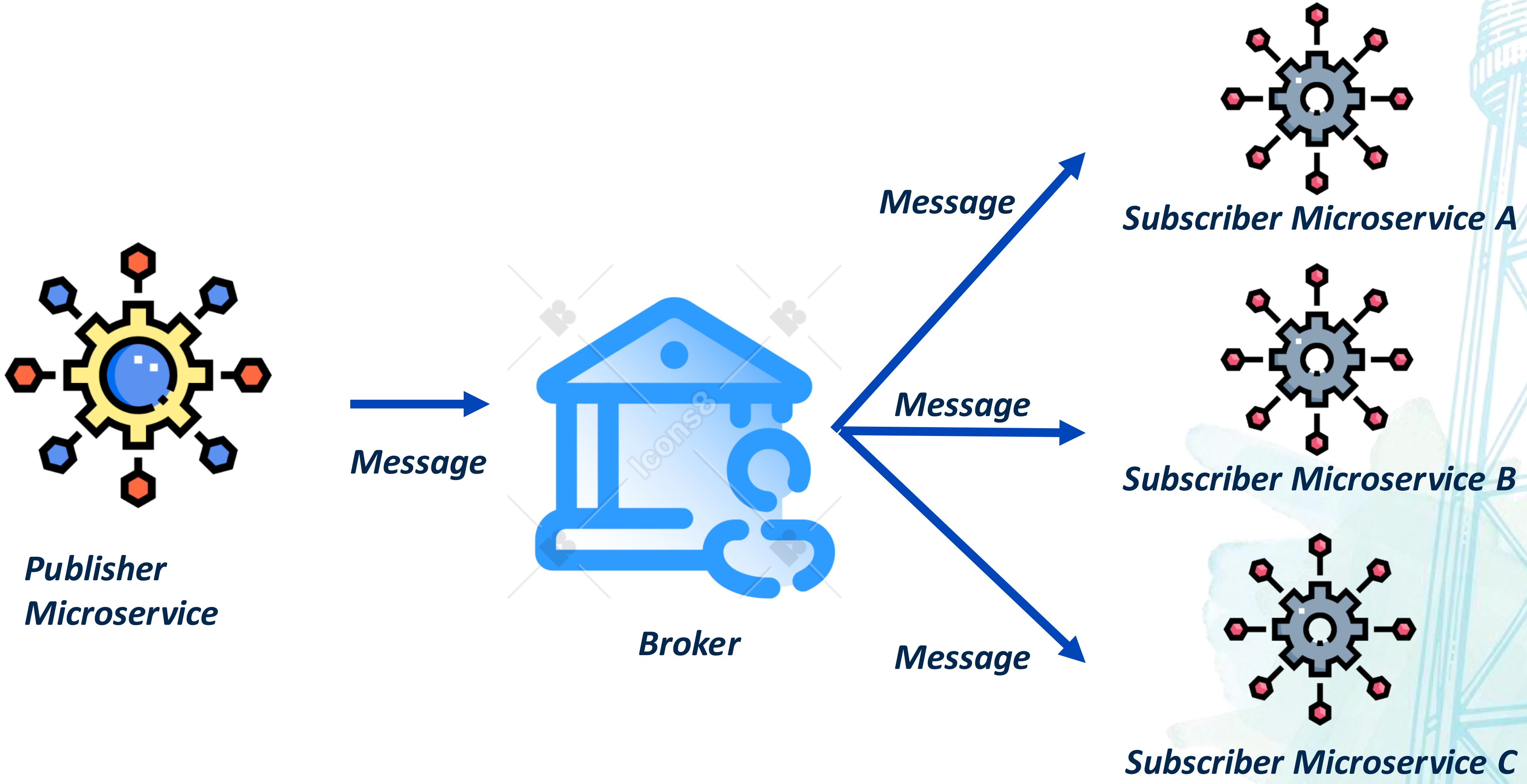
APACHE ACTIVEMQ®

amazon SQS

Pub-sub architecture

- Asynchronous messaging pattern where **publishers** send messages to a central **message broker** or **topic**, and **subscribers** receive messages based on their subscriptions
- Broadcasting: messages can be sent to multiple subscribers
- Typically, messages are persistent at the broker and must be explicitly deleted
- Same frameworks often can act as both MQ or Pub-Sub depending on configuration

Pub-sub architecture



Pub-sub frameworks

Google Cloud Pub/Sub

Redis Pub Sub