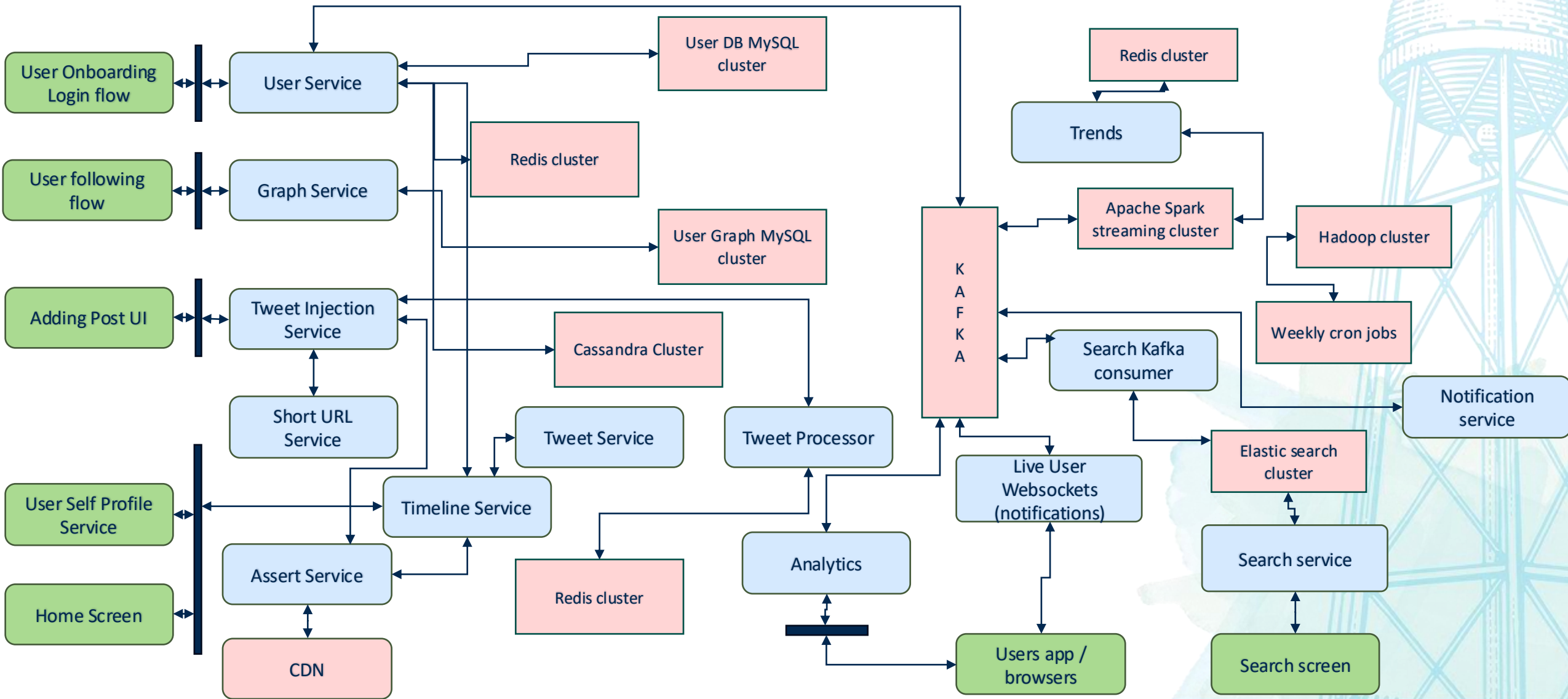


Modern software architectures

Tapti Palit



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!

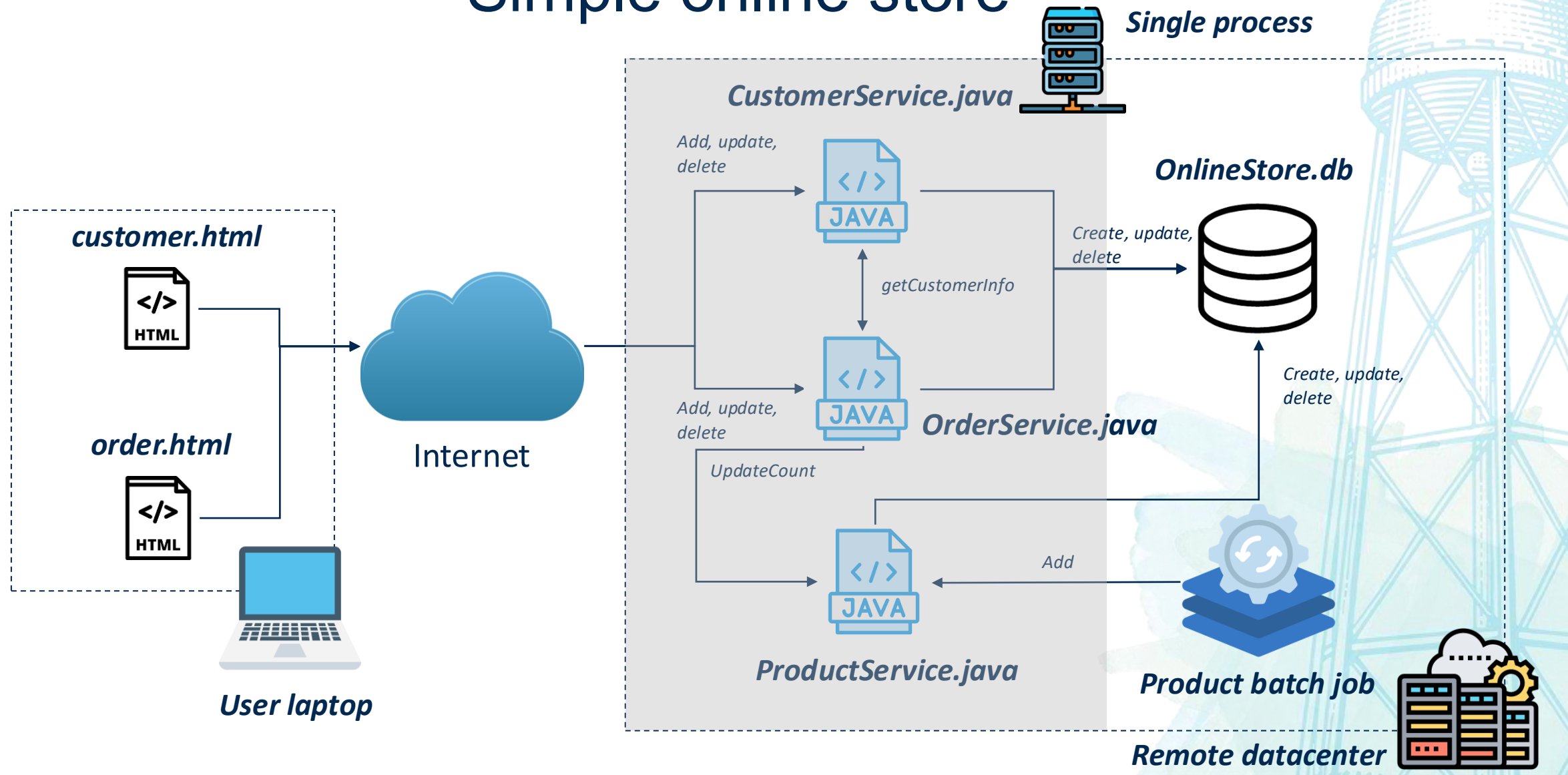
- Modern software architecture is data-intensive
- Primary concerns
 - Who owns data?
 - How to optimally store data?
 - How is data shared?
 - How to limit overhead due to data-sharing?



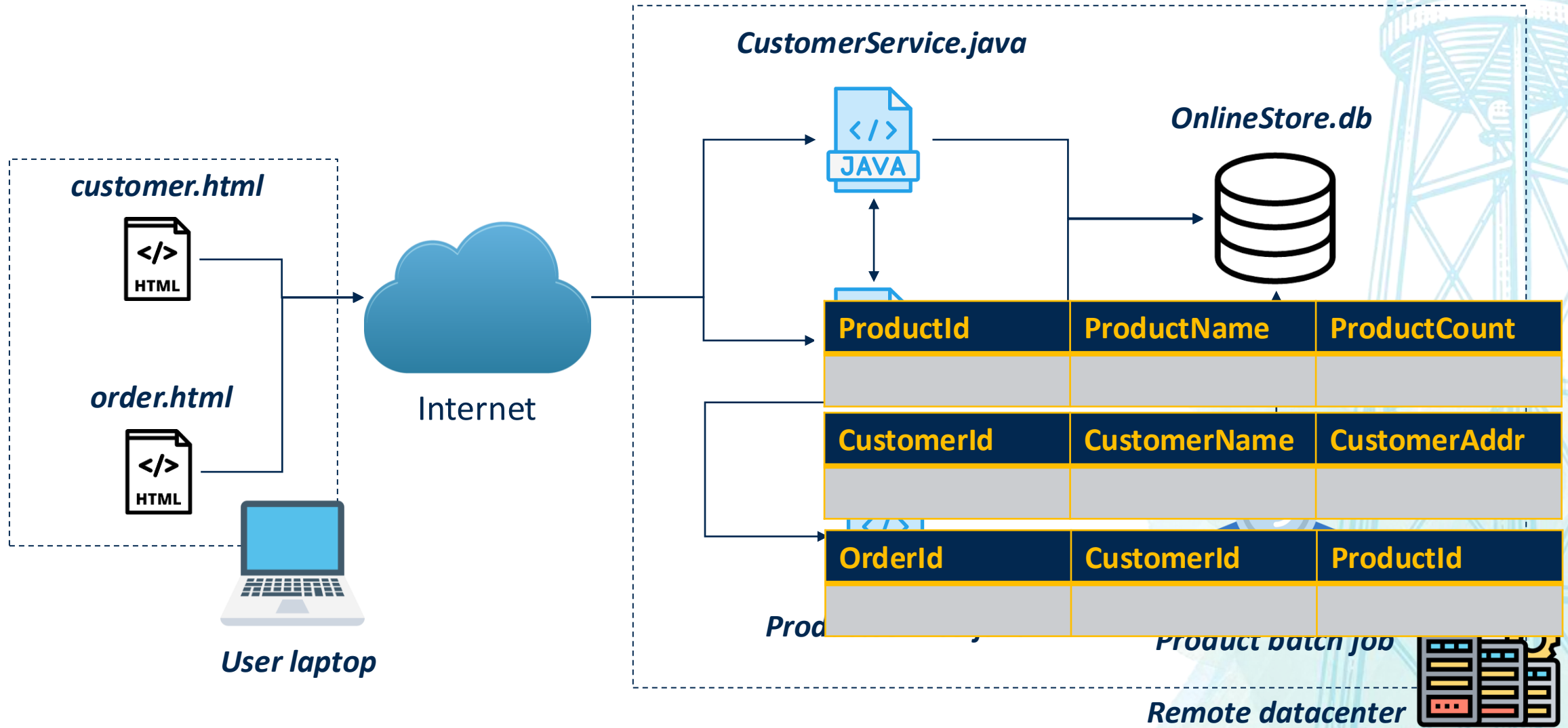
Monolithic software architecture

- 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



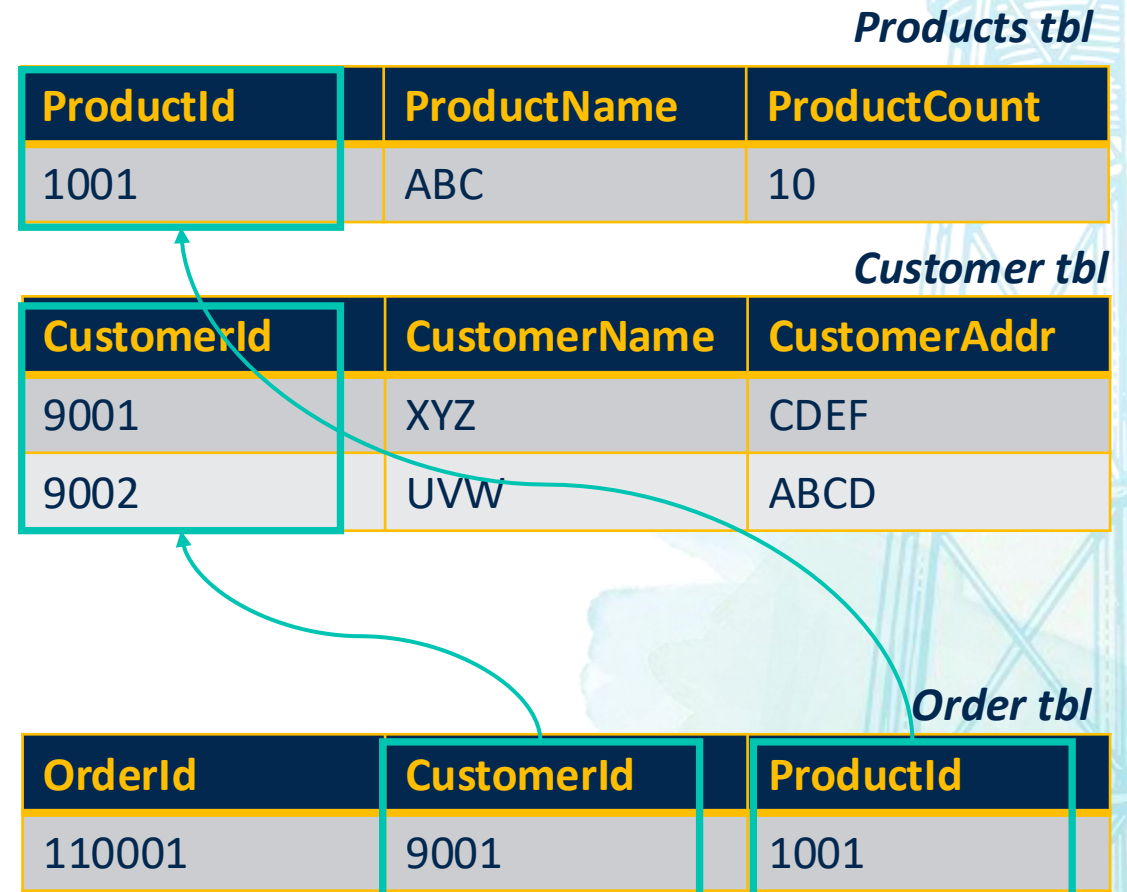
Relational databases

- 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

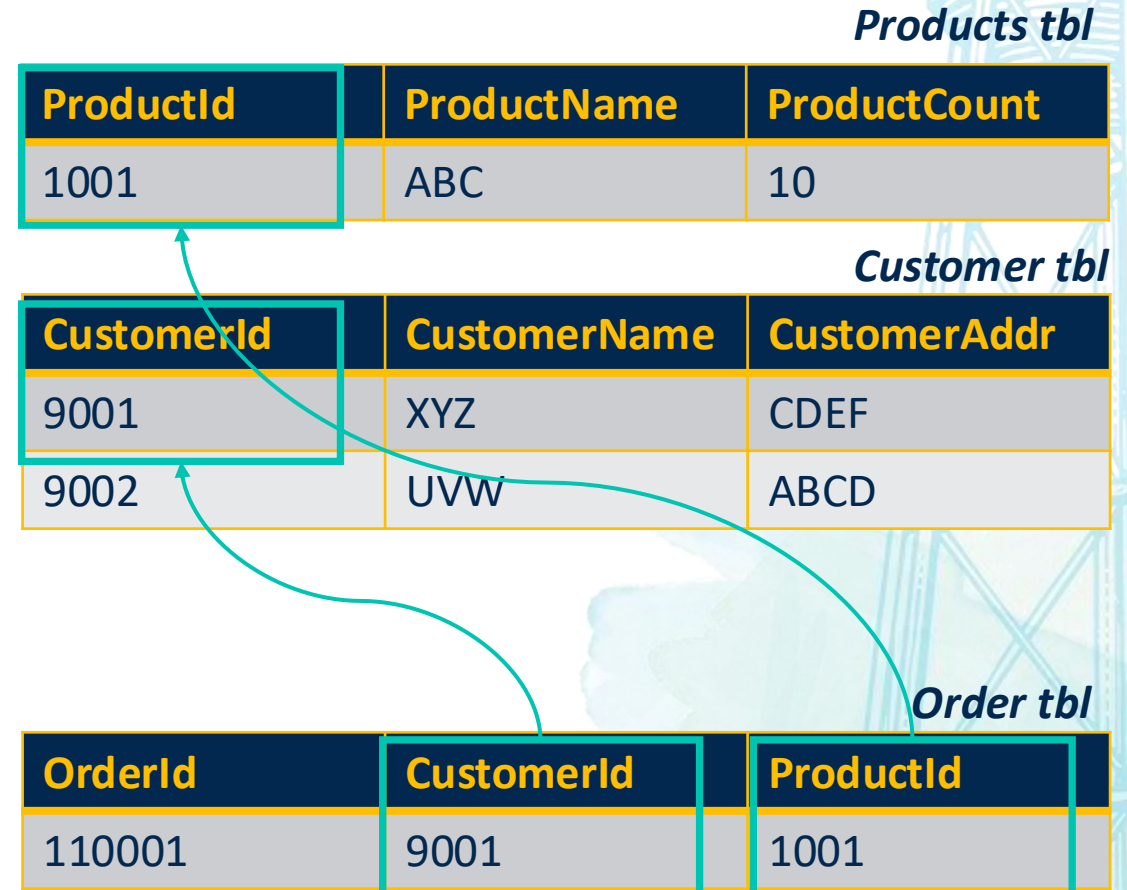


Structured query language (SQL)

- 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



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
10001	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

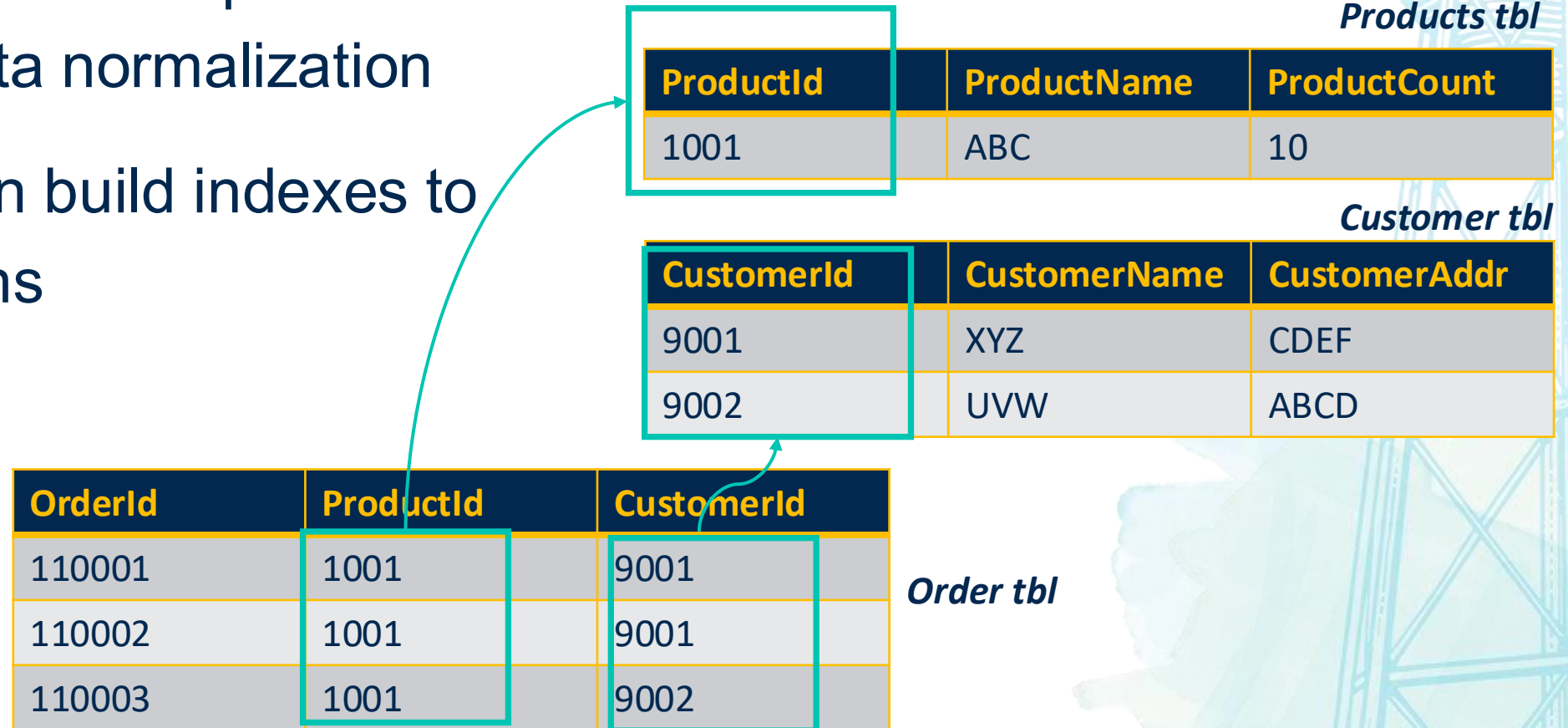
CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

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



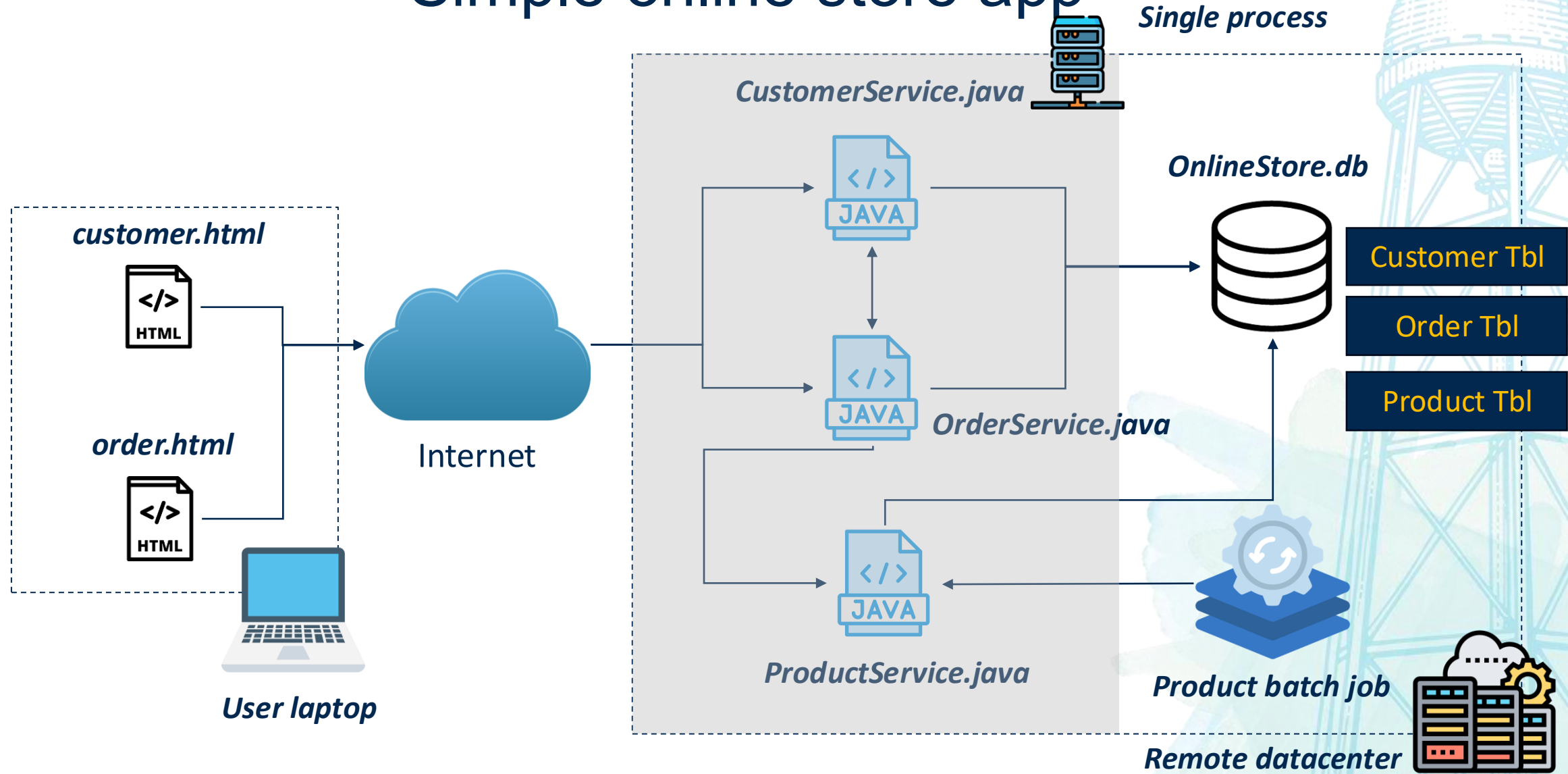
Relational database implications

- 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

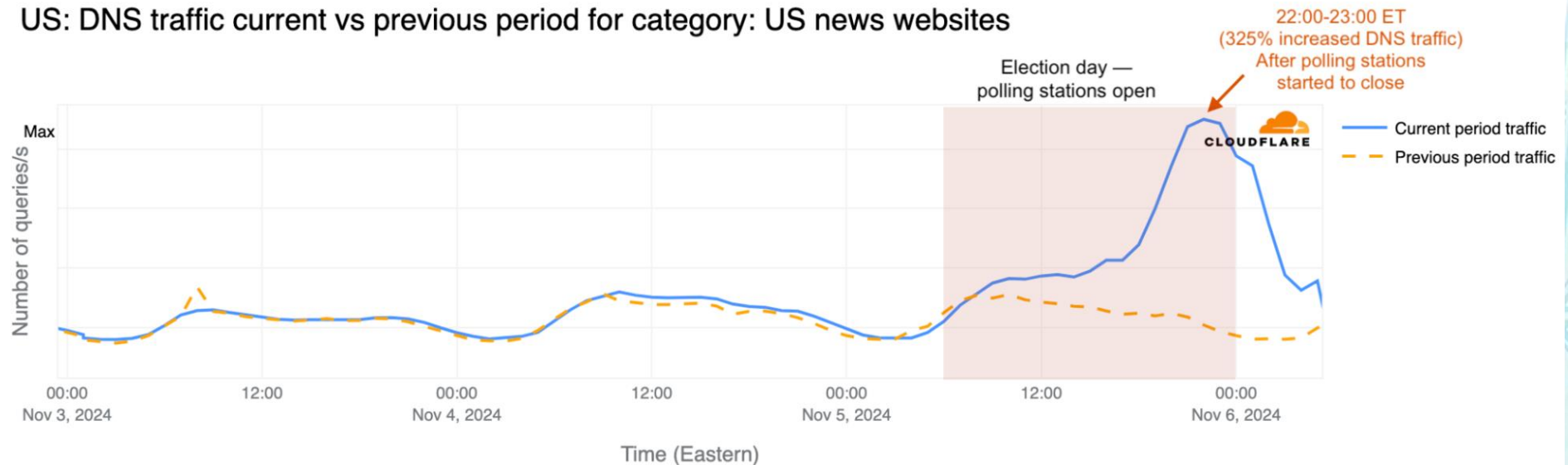


Scalability

- 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/>

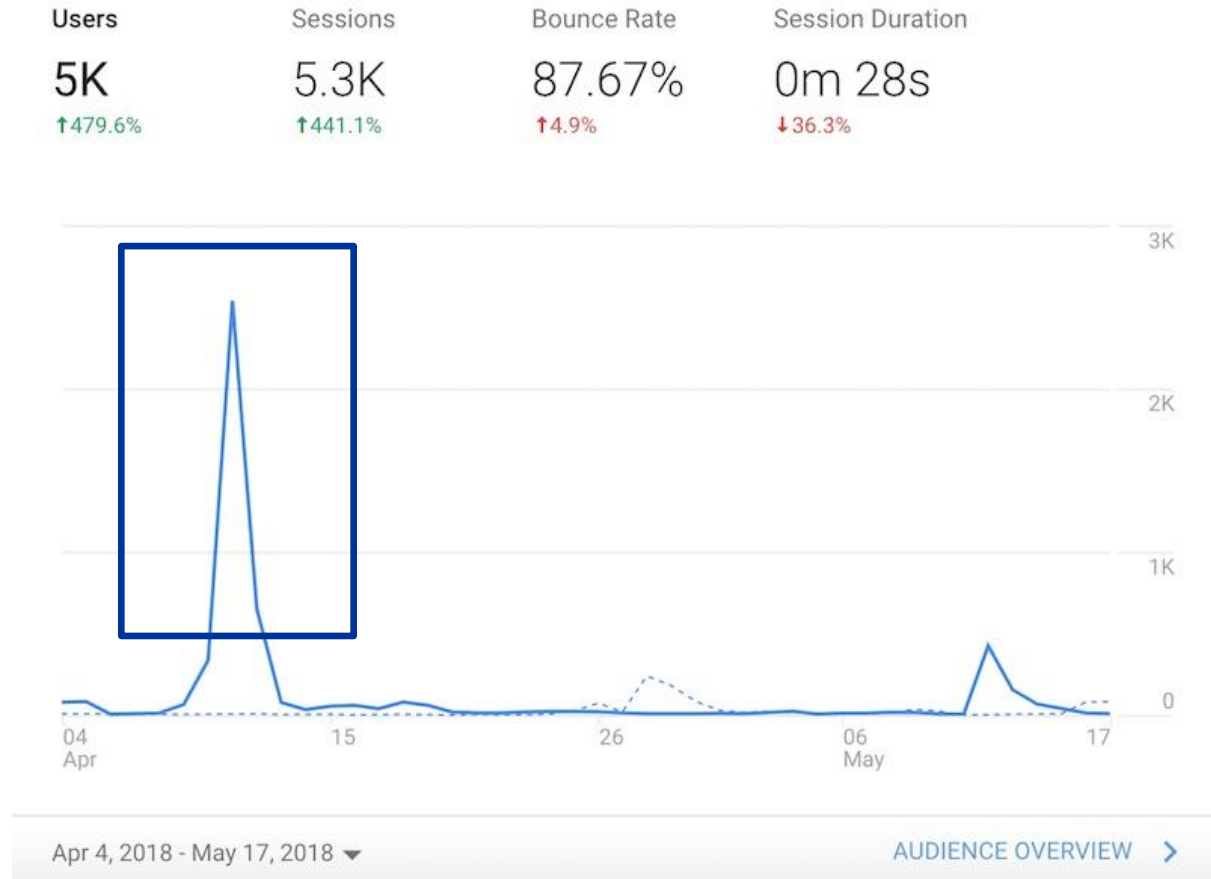
US: DNS traffic current vs previous period for category: US news websites



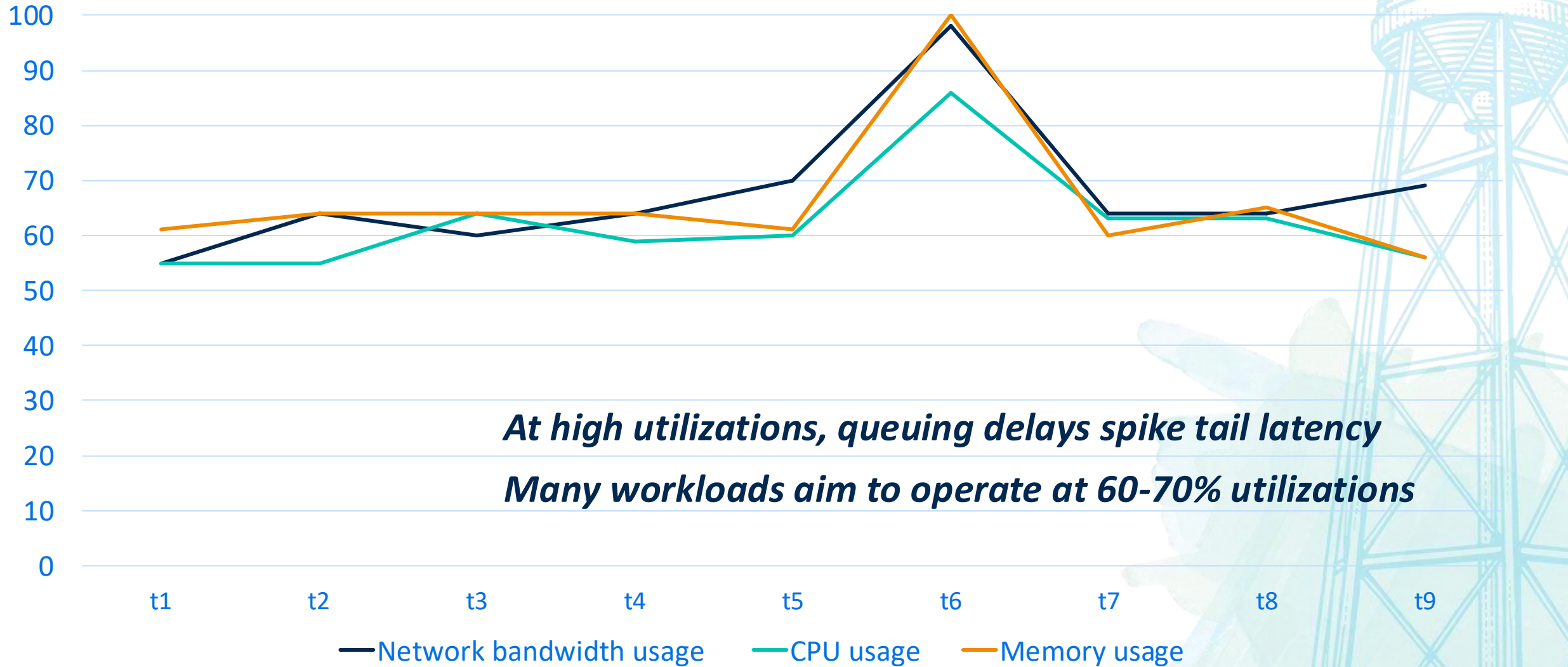
Scalability

- 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/>

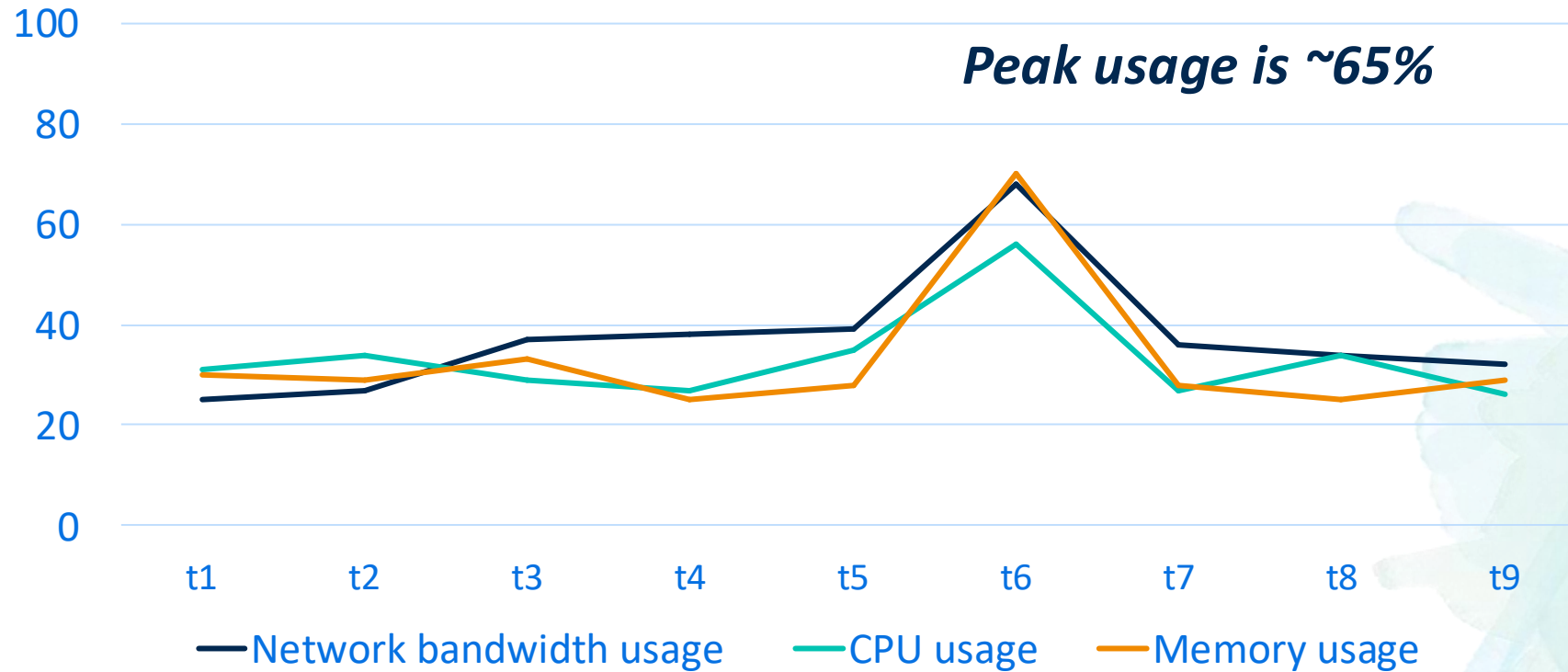


Traffic spike to online store



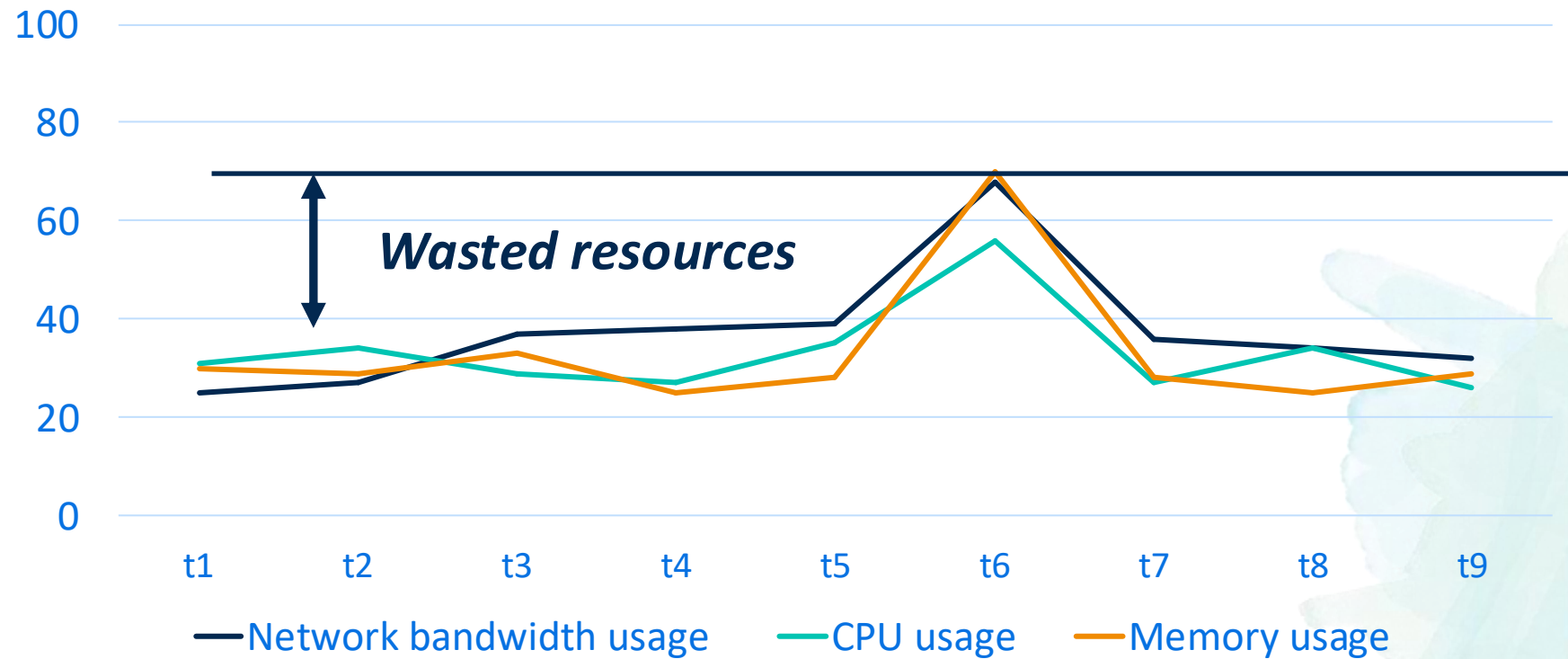
Vertical scaling

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



Vertical scaling limitations

Resource wastage when requests are not bursty

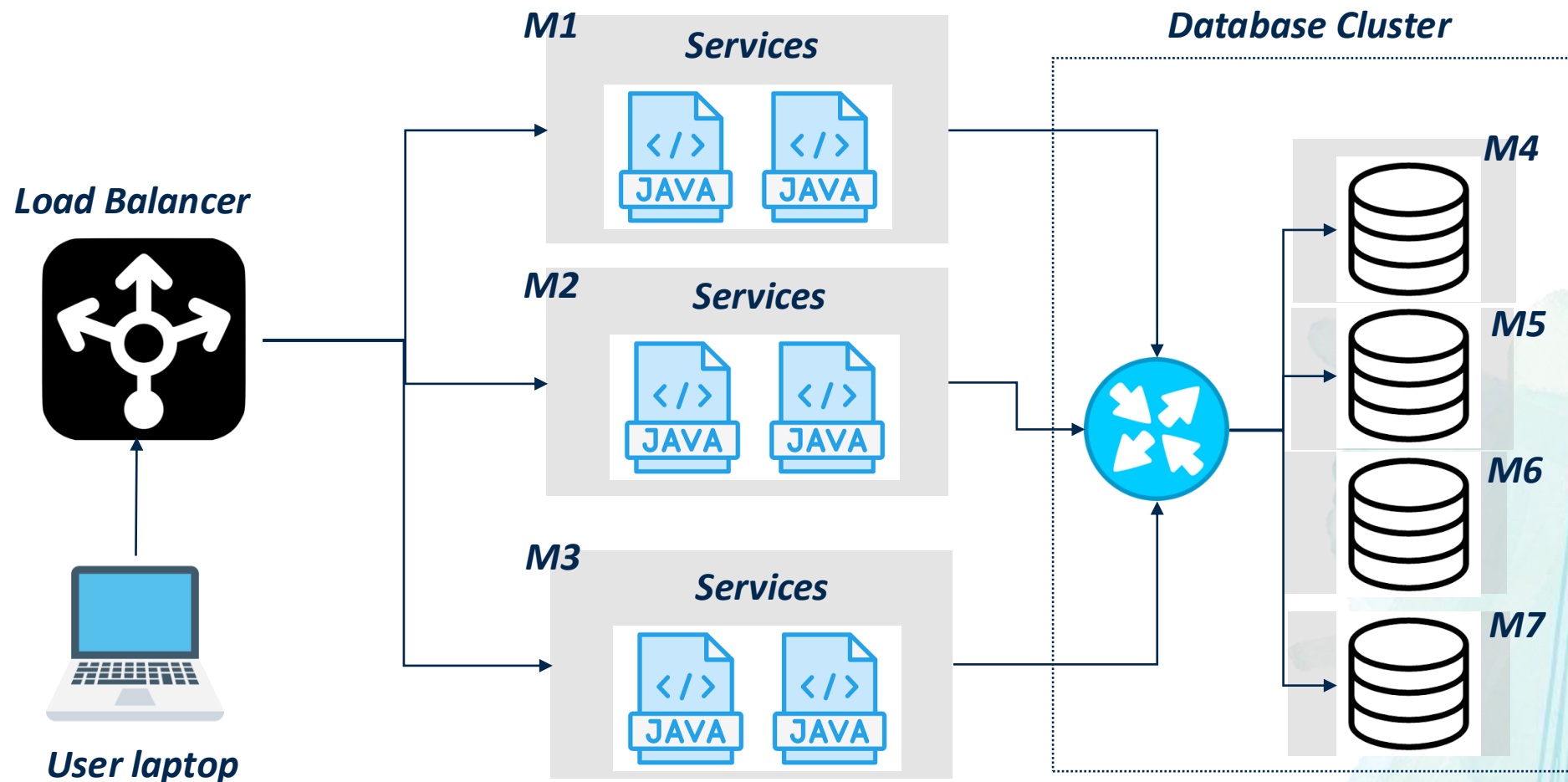


Vertical scaling limitations

- 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

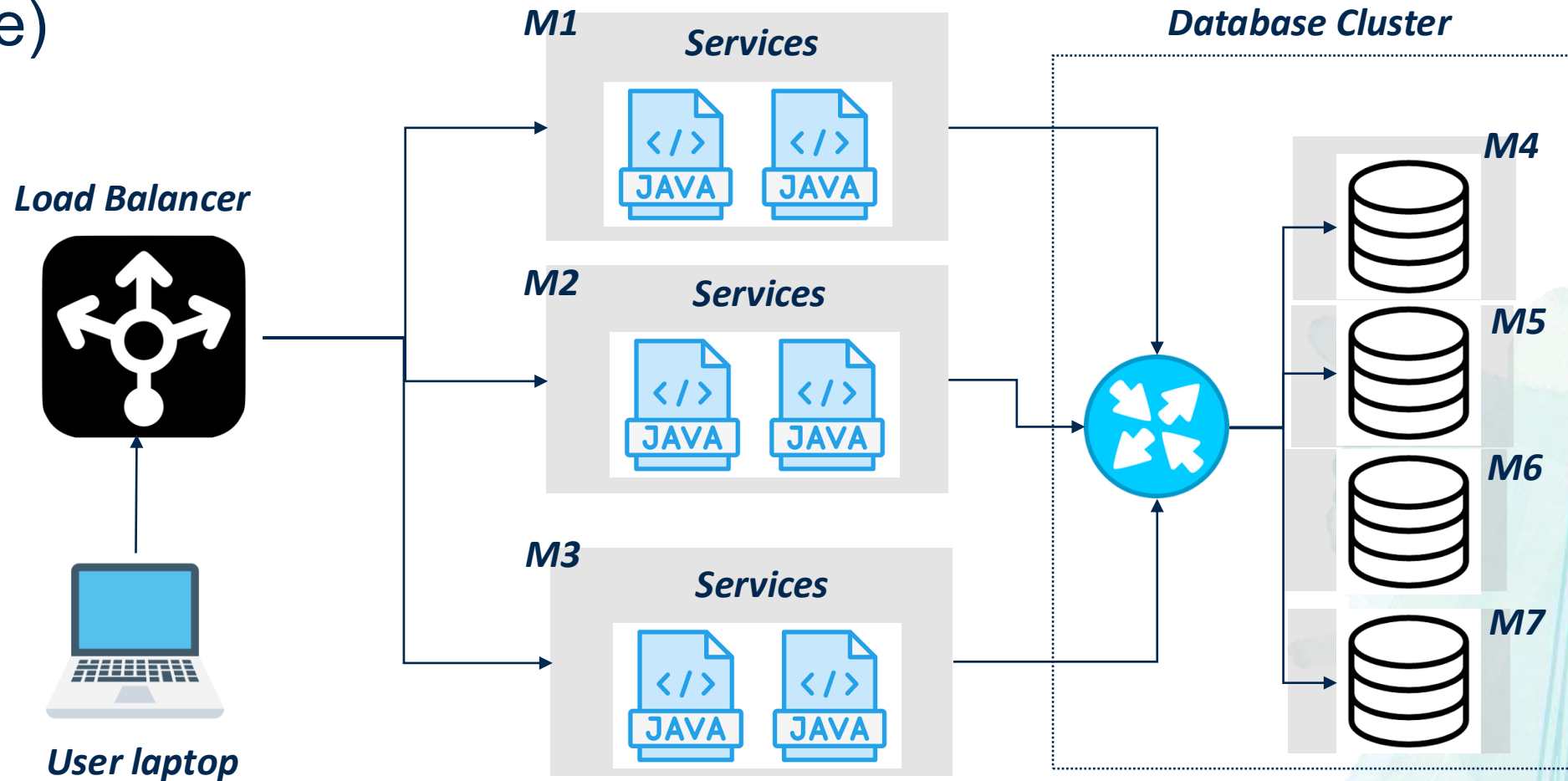
Horizontal scaling is unbounded

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



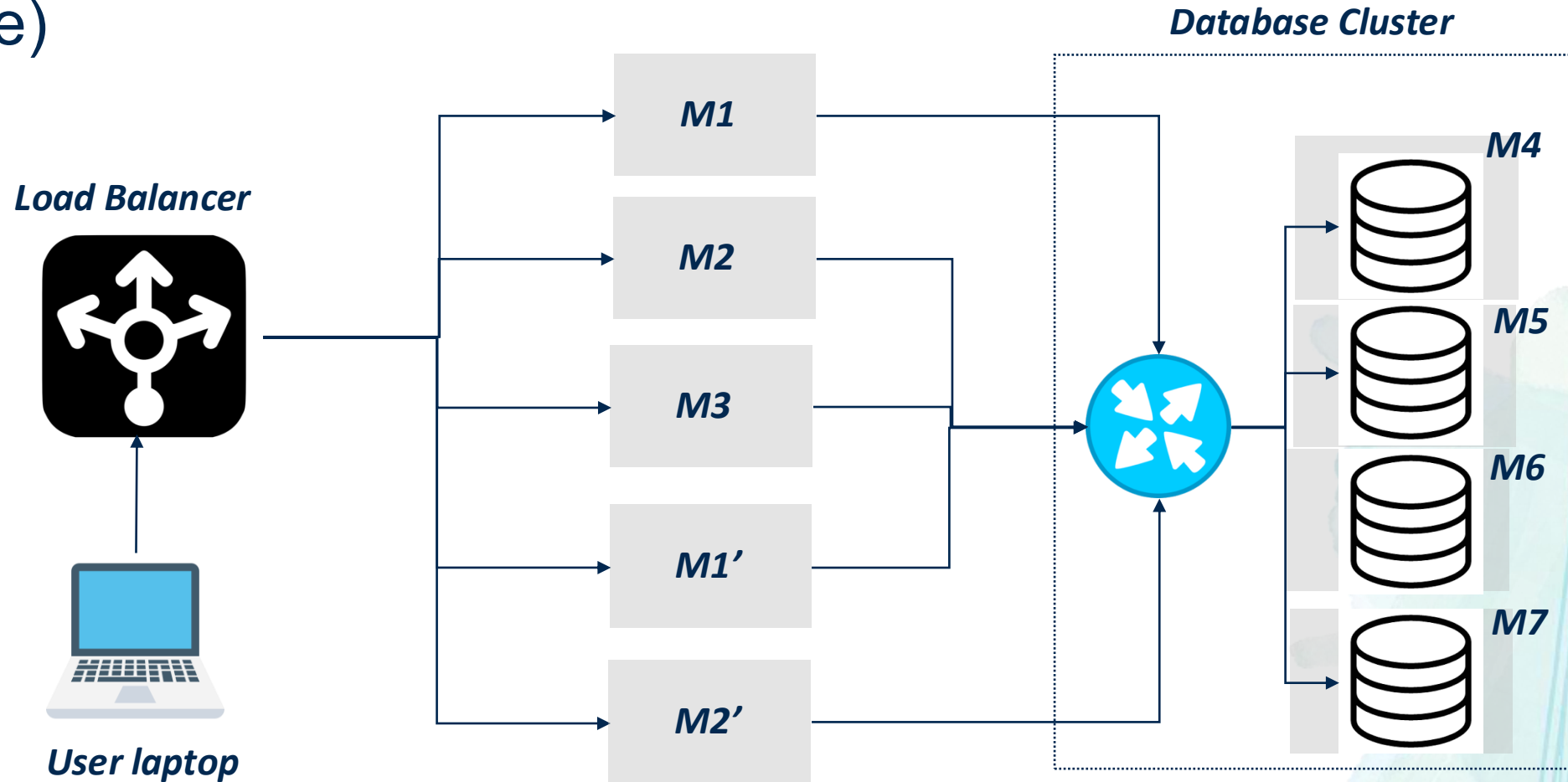
Horizontal scaling is necessary for autoscaling

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



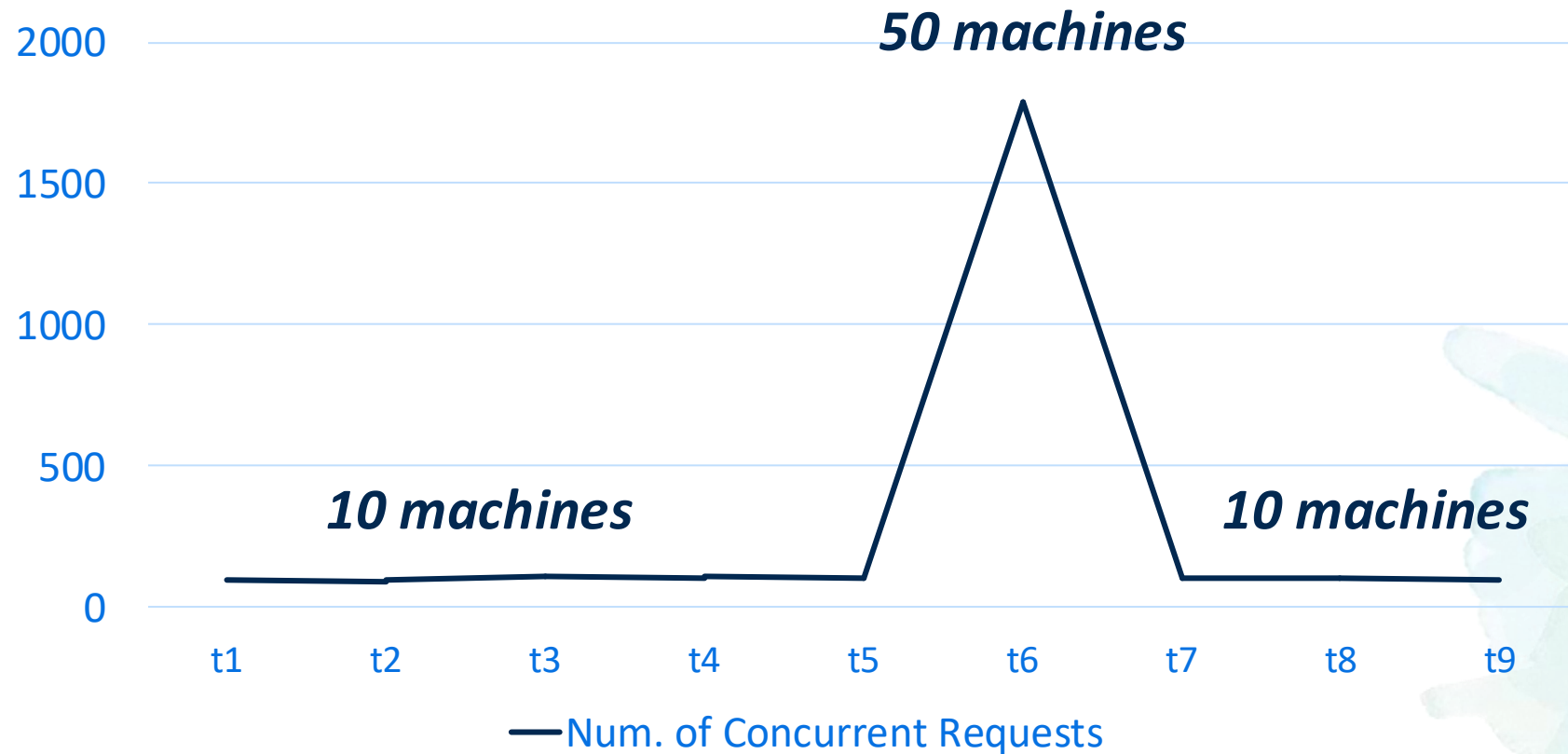
Horizontal scaling is necessary for autoscaling

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

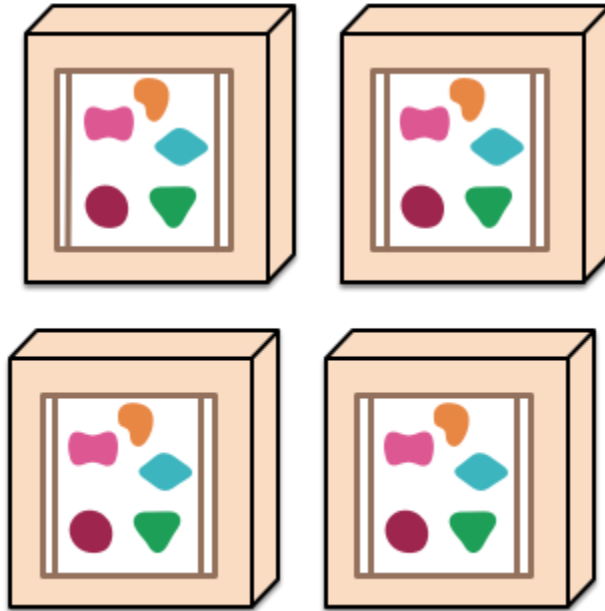
<https://martinfowler.com/articles/microservices.html>

Microservices overview

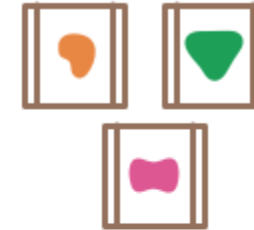
A monolithic application puts all its functionality into a single process...



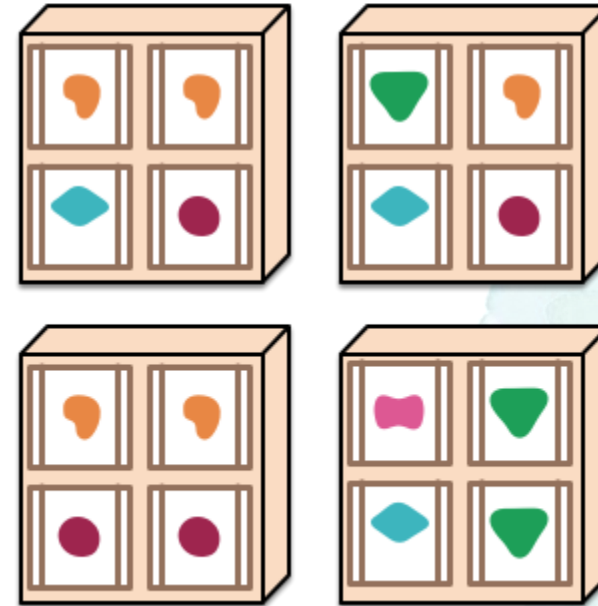
... and scales by replicating the monolith on multiple servers



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

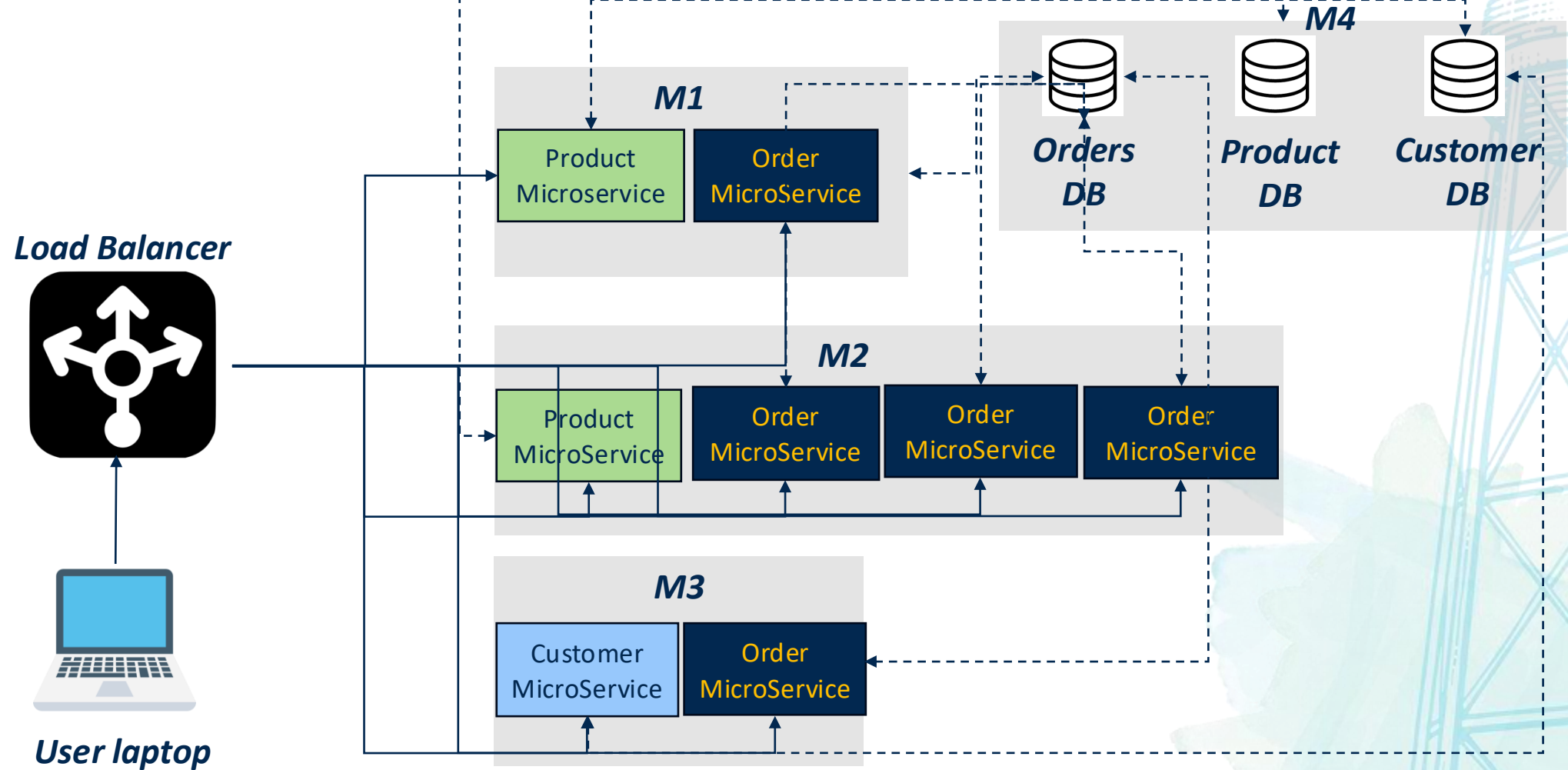


... and scales by distributing these services across servers, replicating as needed.

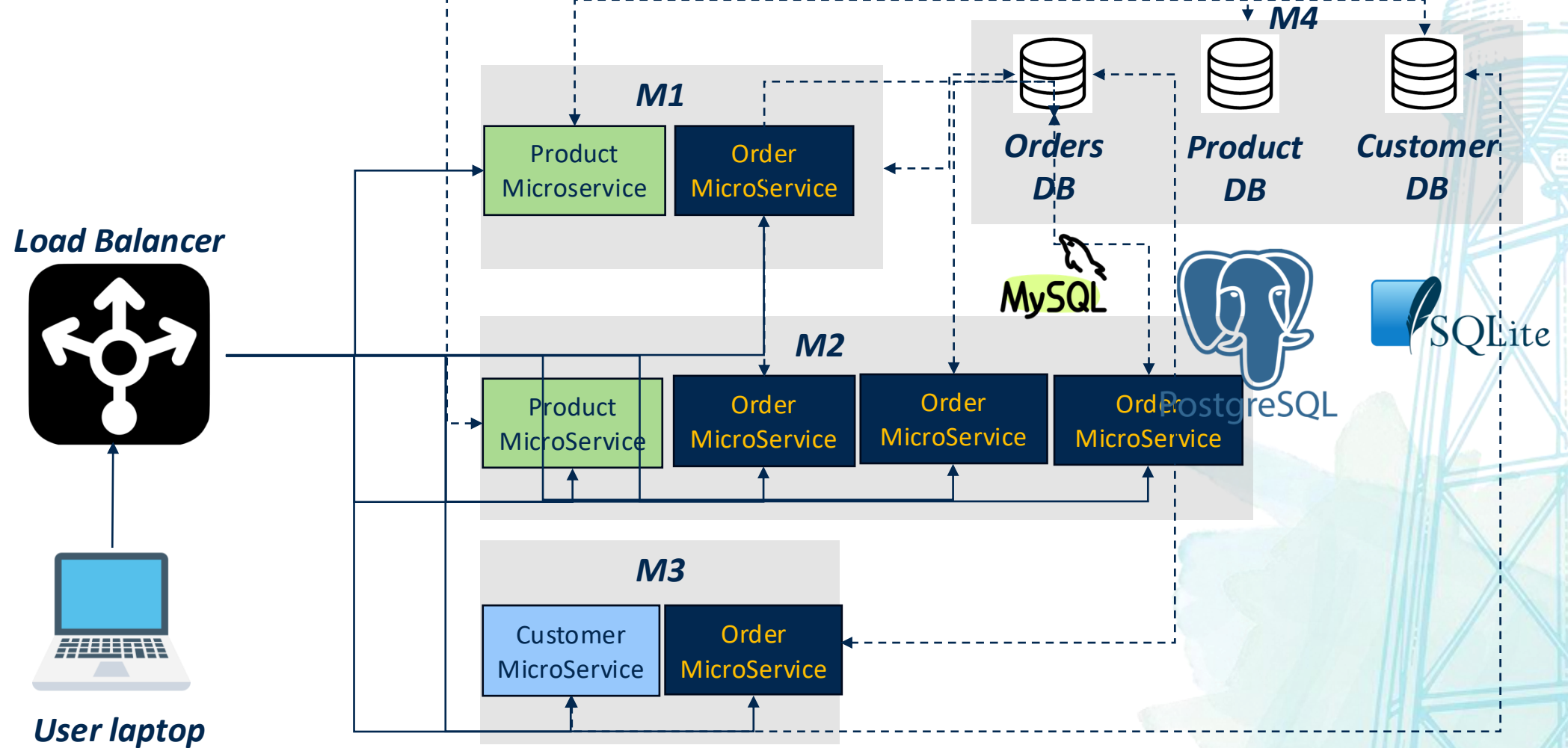


<https://martinfowler.com/articles/microservices.html>

Microservice architecture for online store



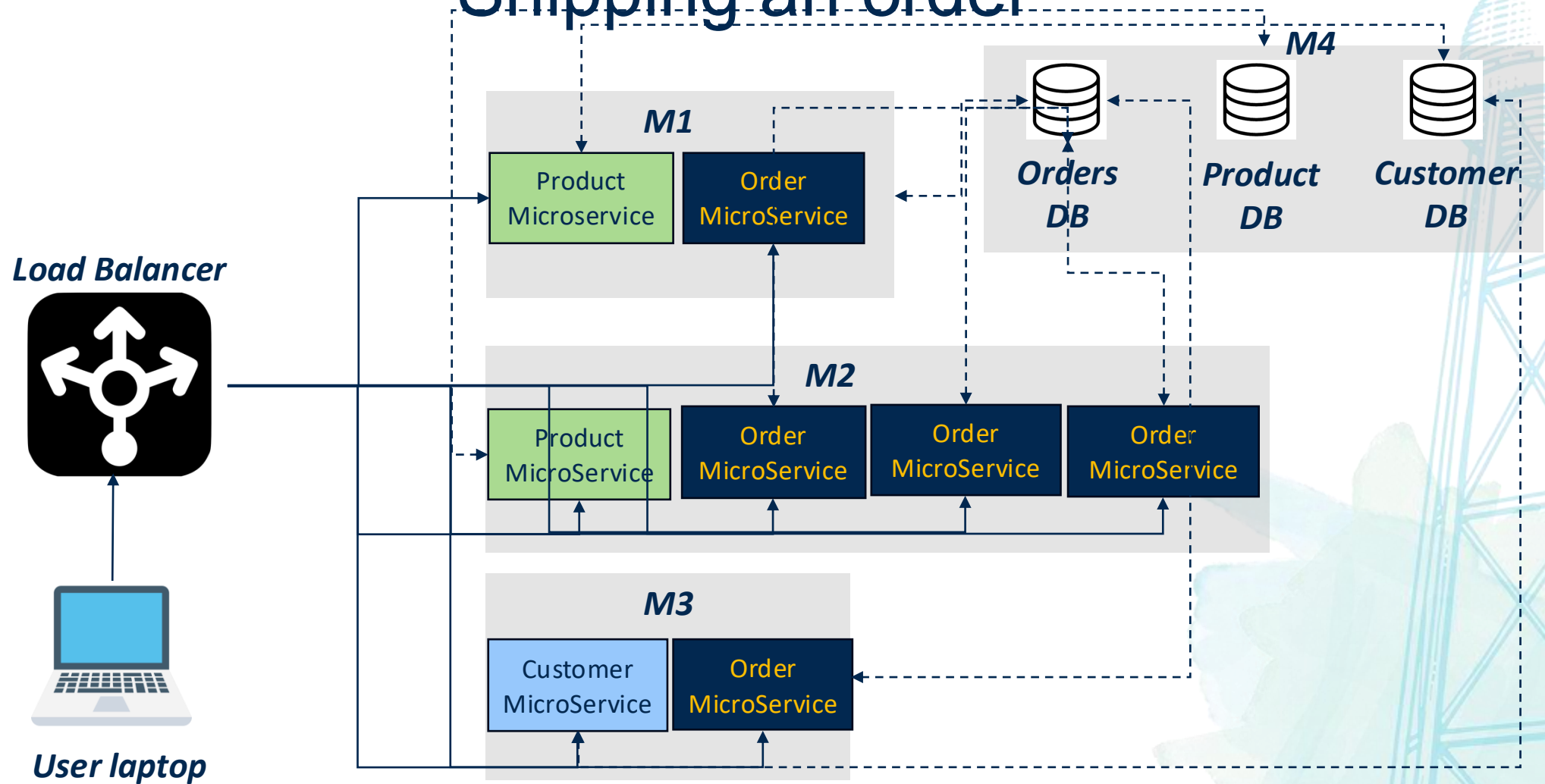
Each microservice chooses its own database



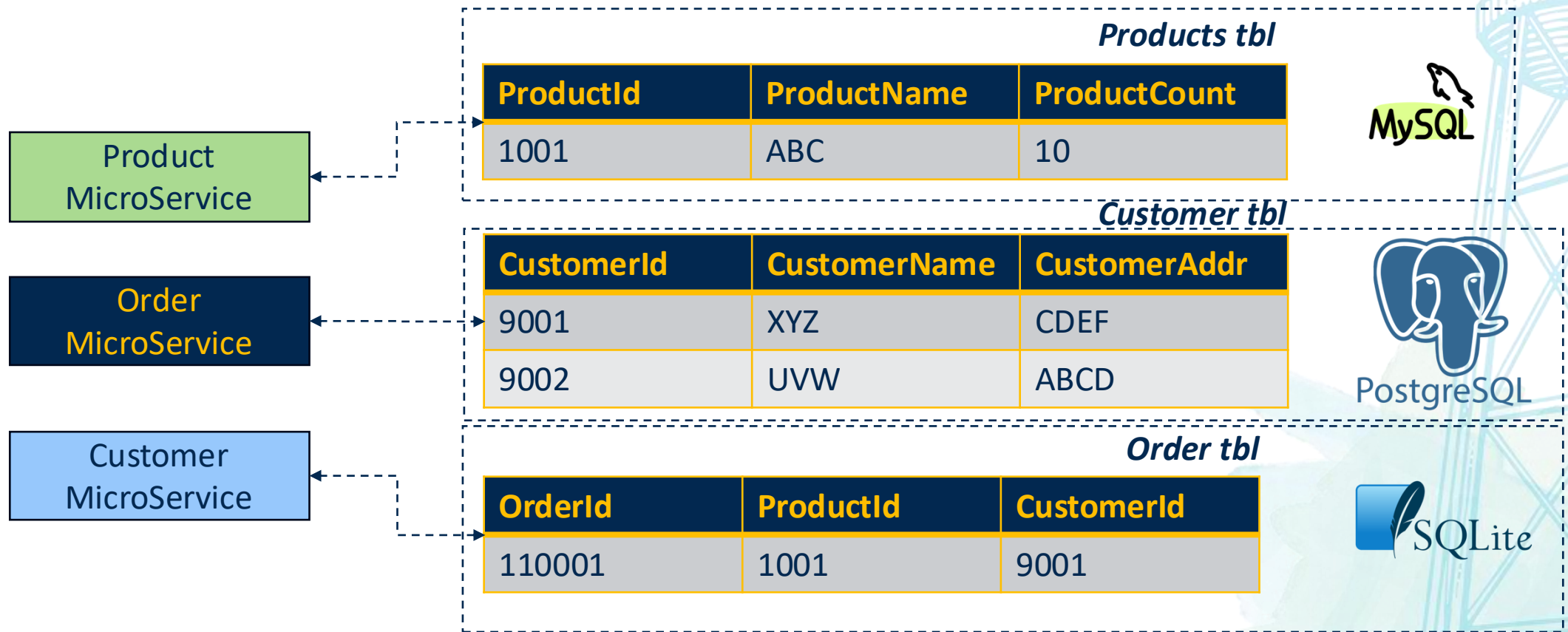
What did we achieve?

- 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



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?

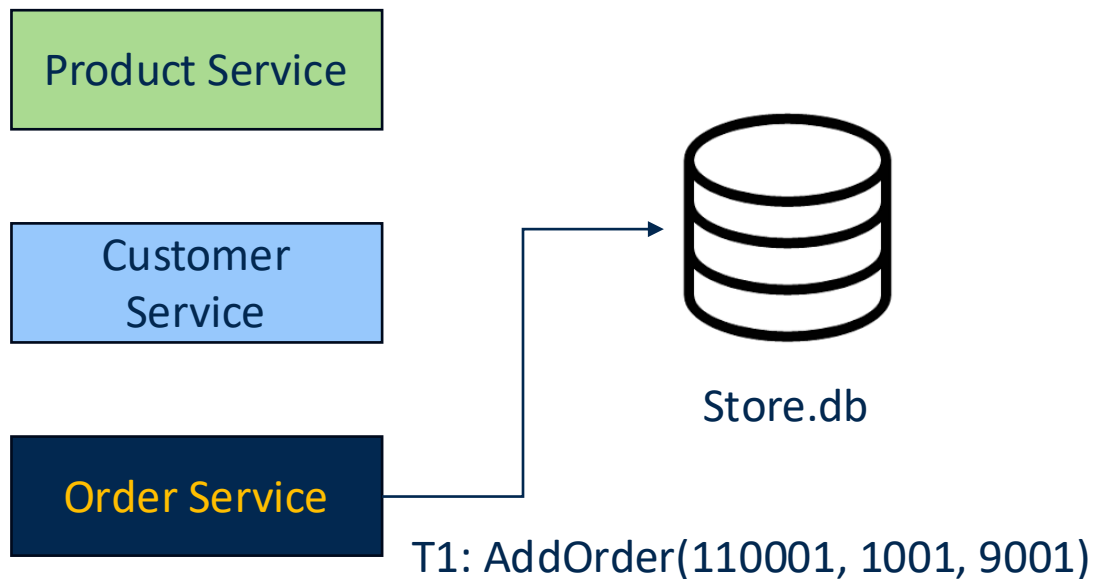
Denormalization

- 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



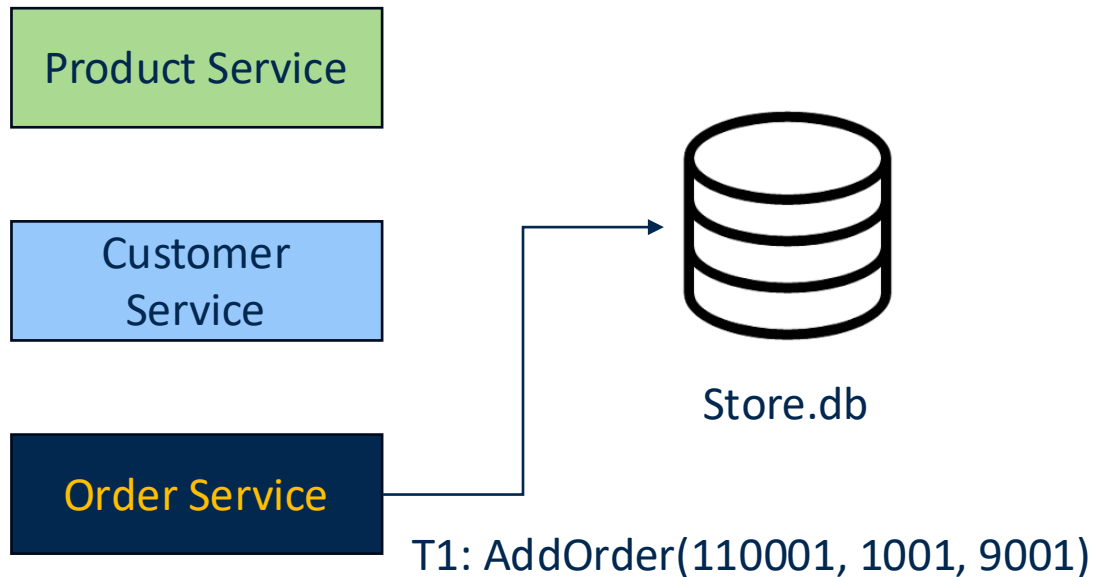
ProductId	ProductName	ProductCount
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CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

OrderId	ProductId	CustomerId

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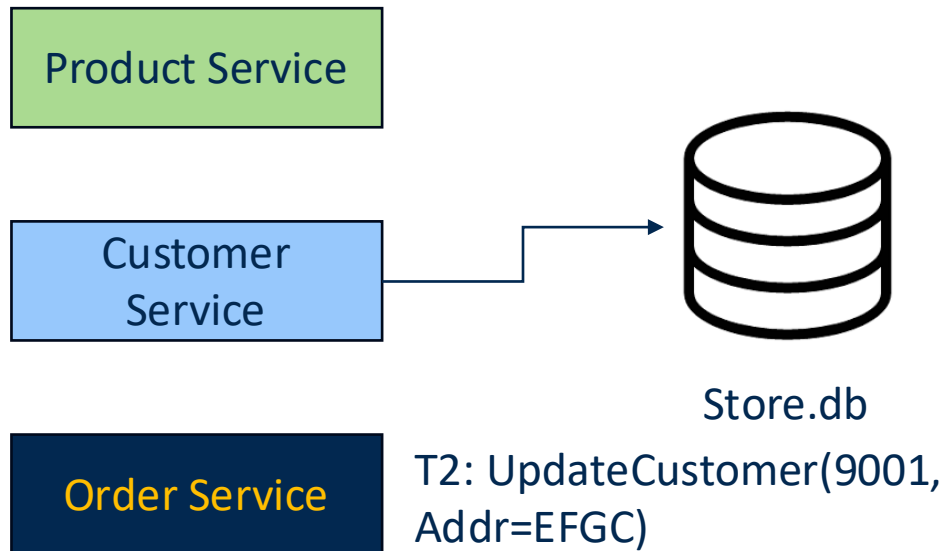
ProductId	ProductName	ProductCount
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CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

OrderId	ProductId	CustomerId
110001	1001	9001

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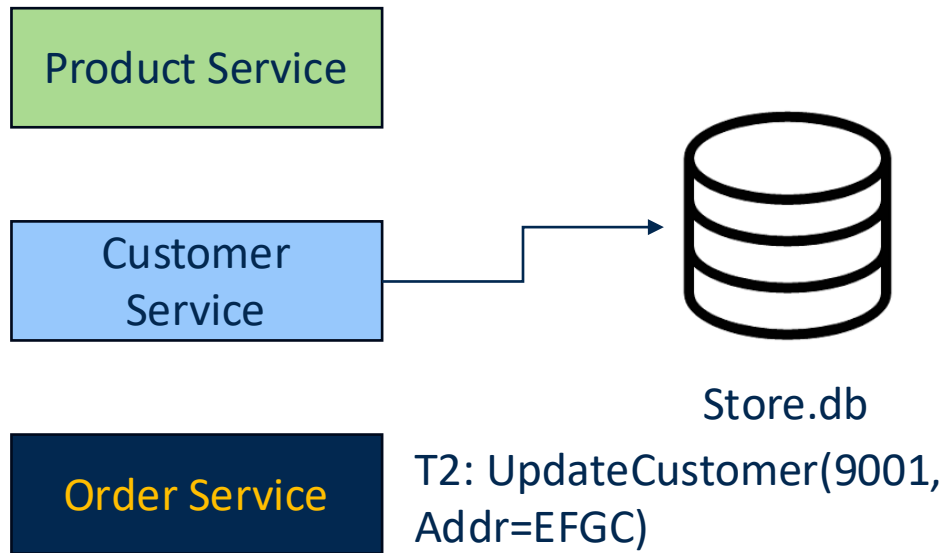
ProductId	ProductName	ProductCount
1001	ABC	10

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	ABCD

OrderId	ProductId	CustomerId
110001	1001	9001

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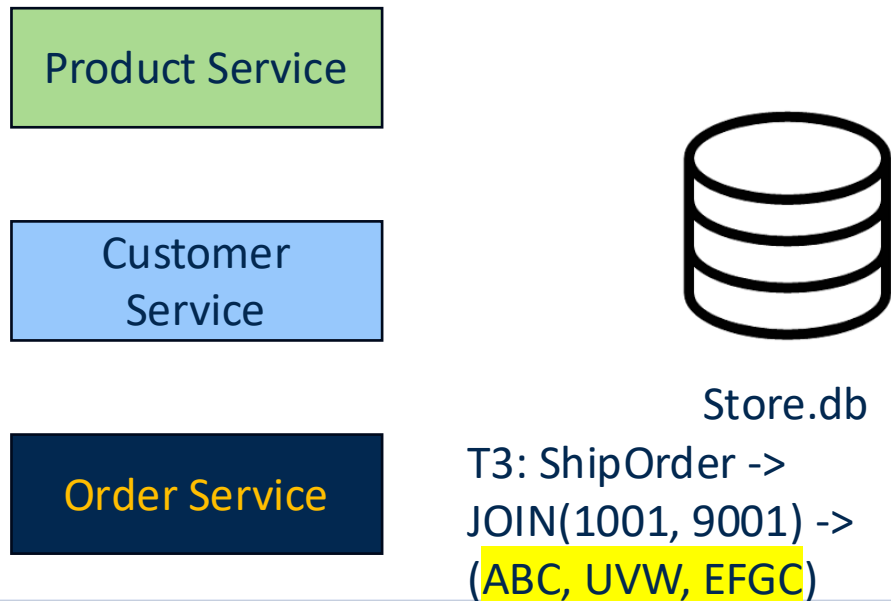
ProductId	ProductName	ProductCount
1001	ABC	10

CustomerId	CustomerName	CustomerAddr
9001	XYZ	CDEF
9002	UVW	EFGC

OrderId	ProductId	CustomerId
110001	1001	9001

Consistency guarantees

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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

Microservice consistency guarantees

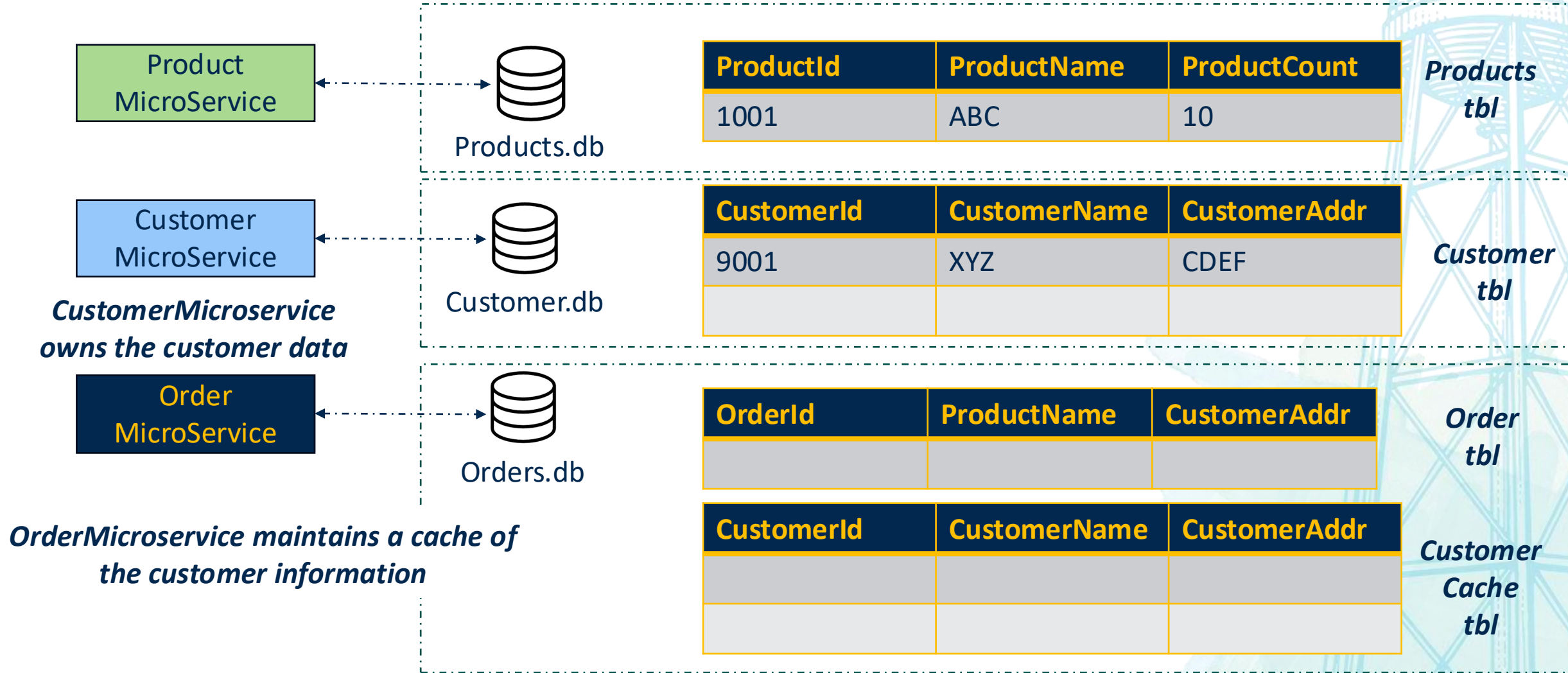
- Core idea: a microservice ***owns*** some data
 - ***Notifies*** dependent microservices of change
 - ***Soft guarantees*** on when the updates synchronize



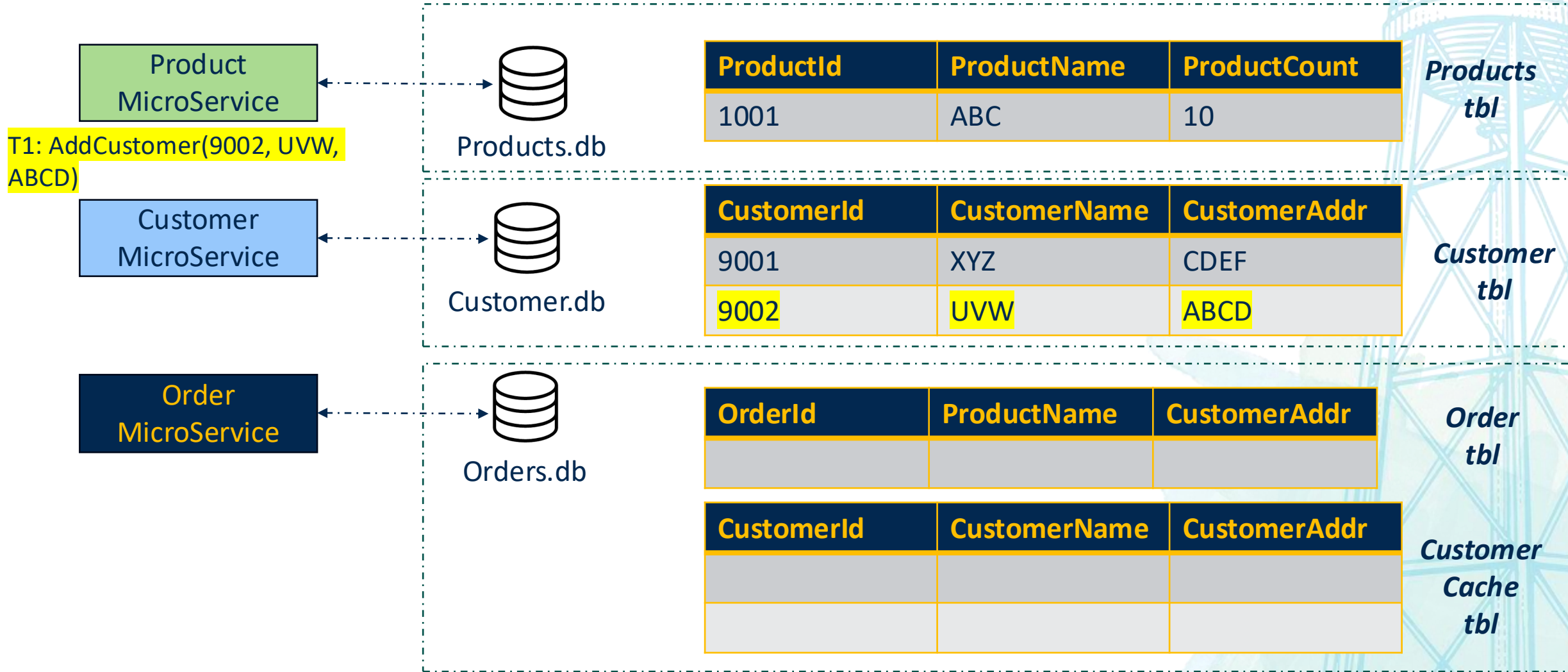
Microservice consistency guarantees

- 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

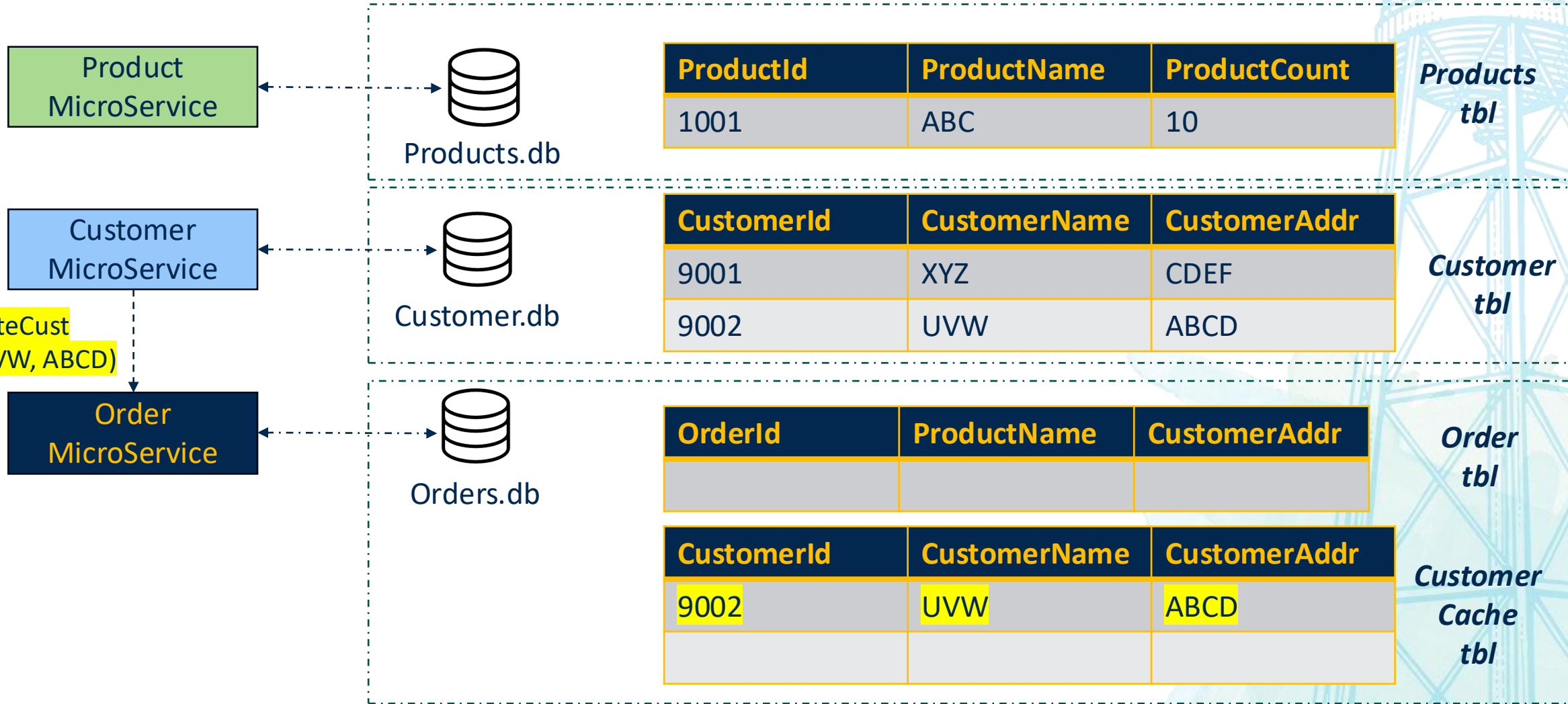
Working with eventual consistency



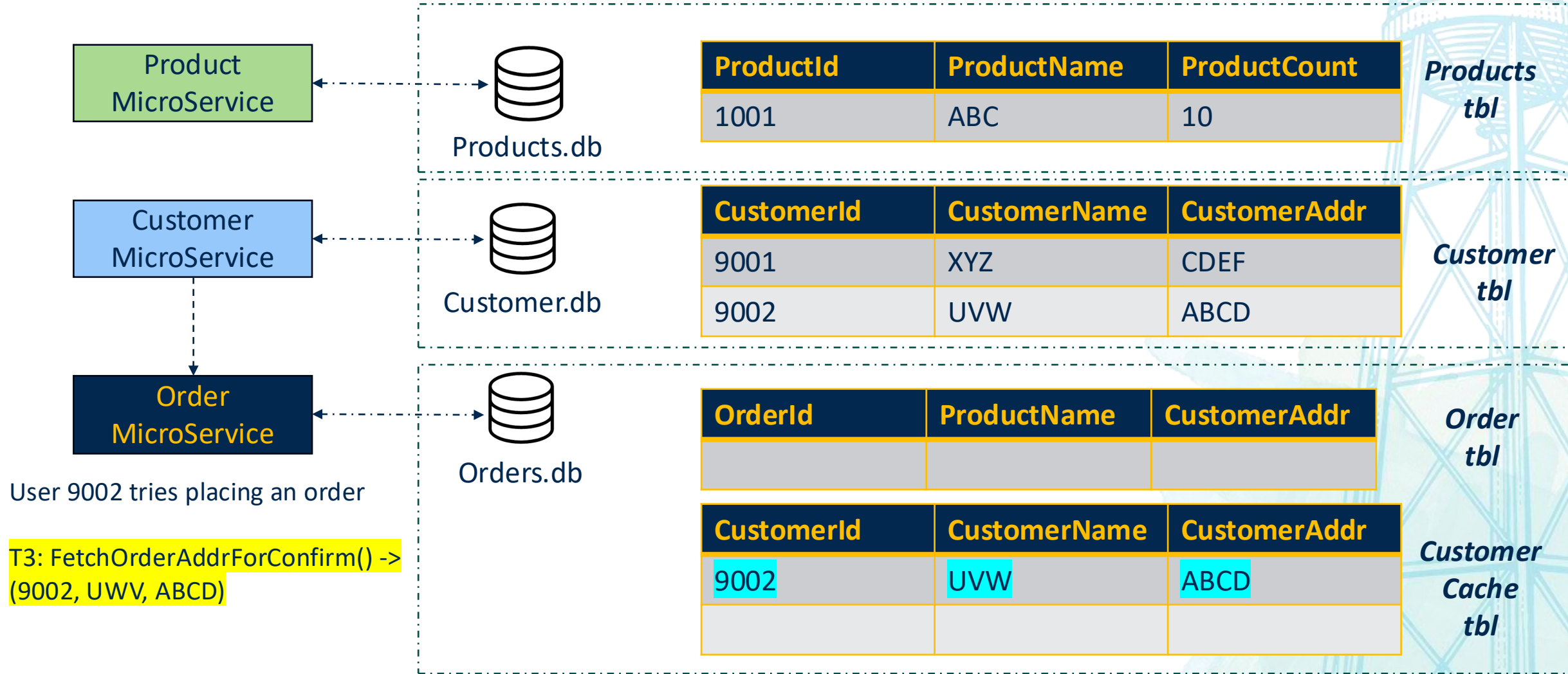
Working with eventual consistency



Working with eventual consistency



Working with eventual consistency



Working with eventual consistency

*Name: UVW,
Address: ABCD*

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Items:

Shipping & handling:

Estimated tax to be collected:

Order total:

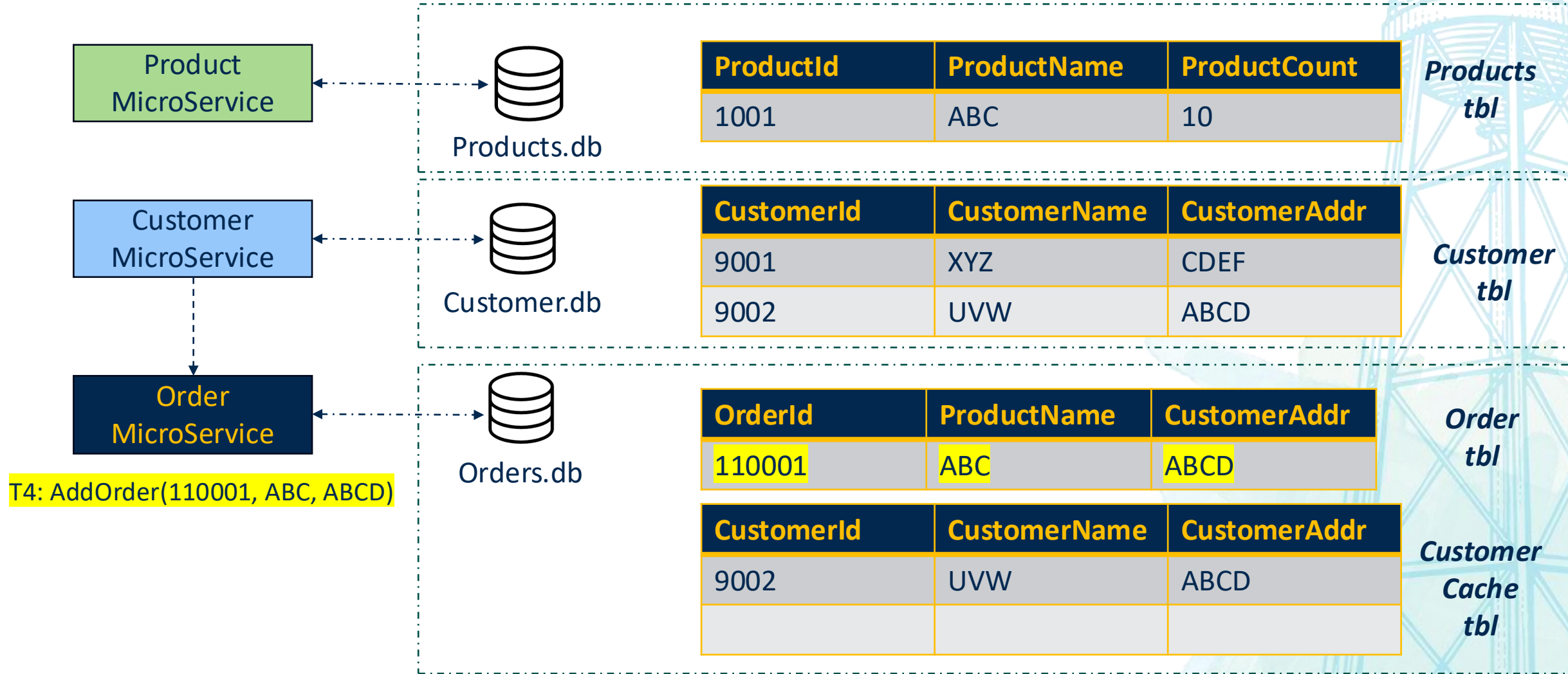
\$18.00

\$0.00

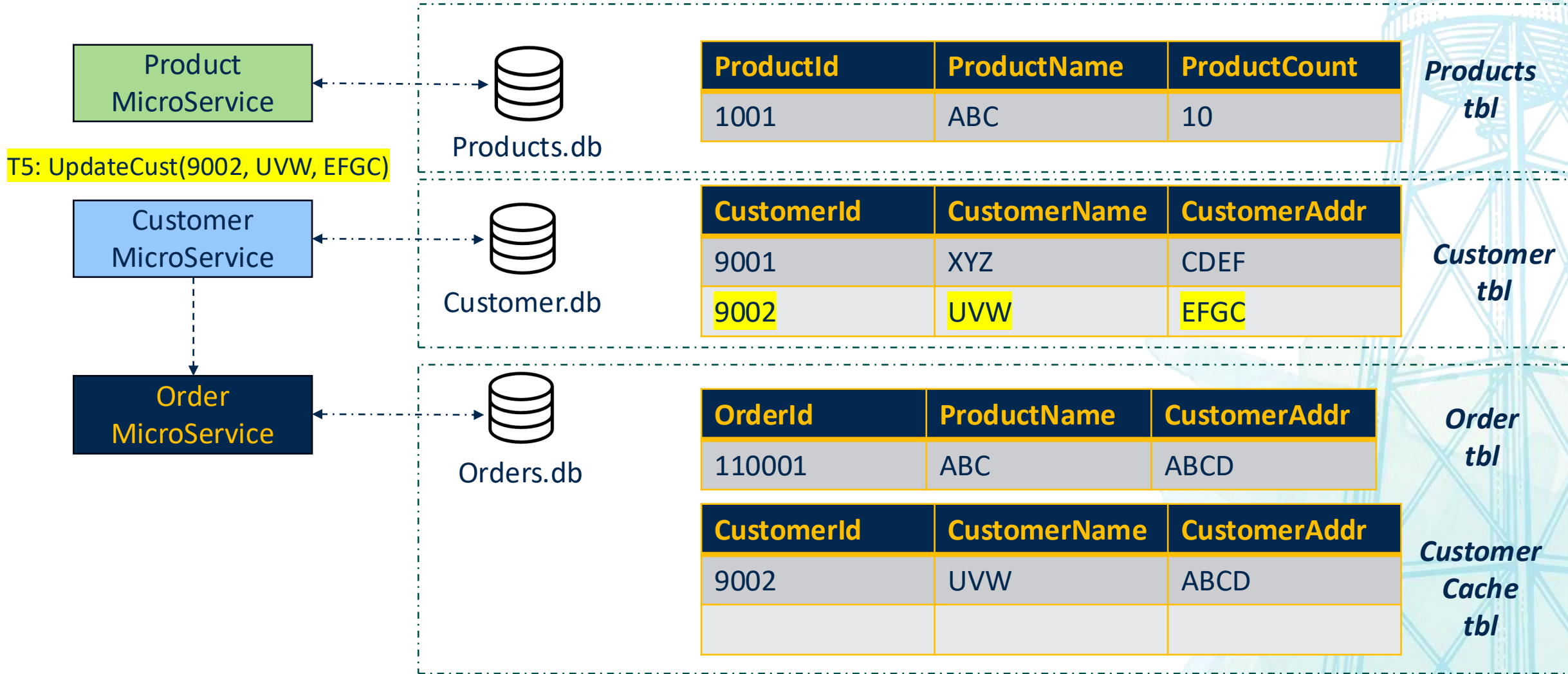
\$0.00

\$18.00

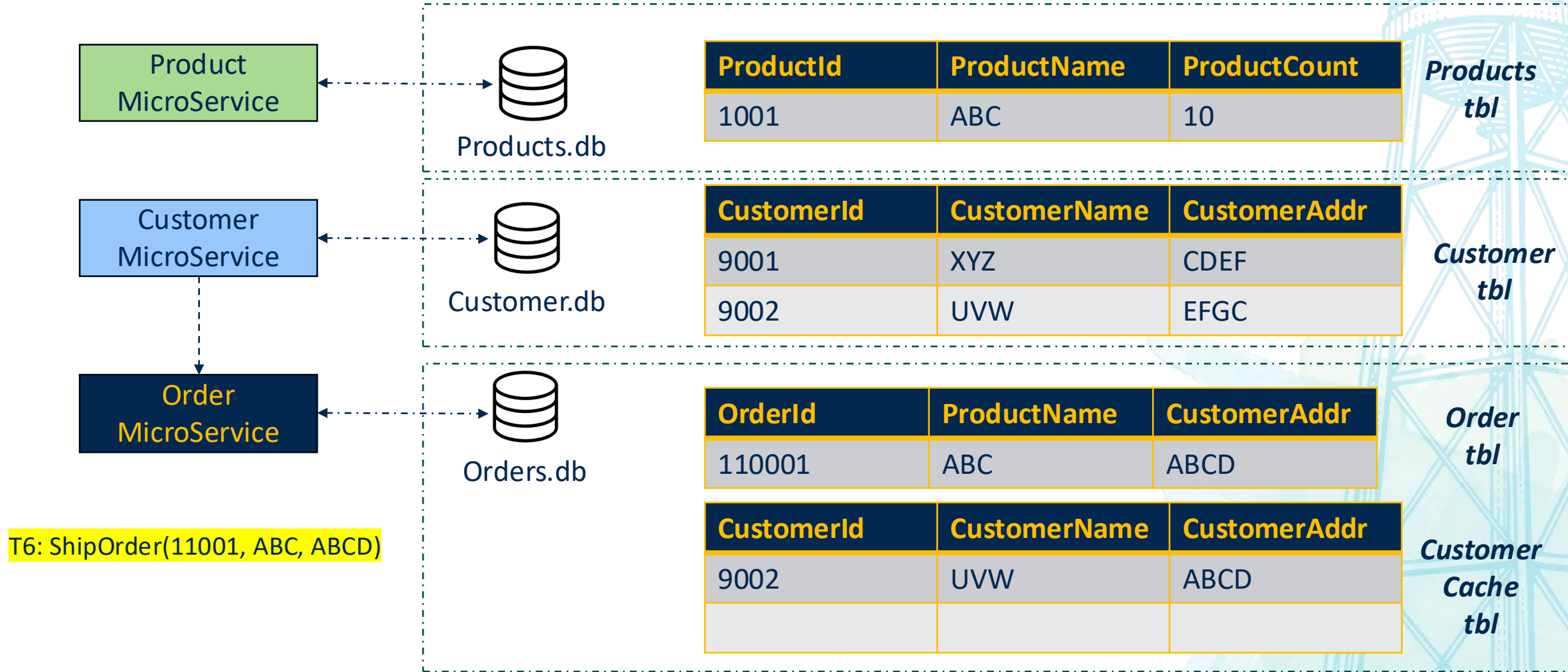
Working with eventual consistency



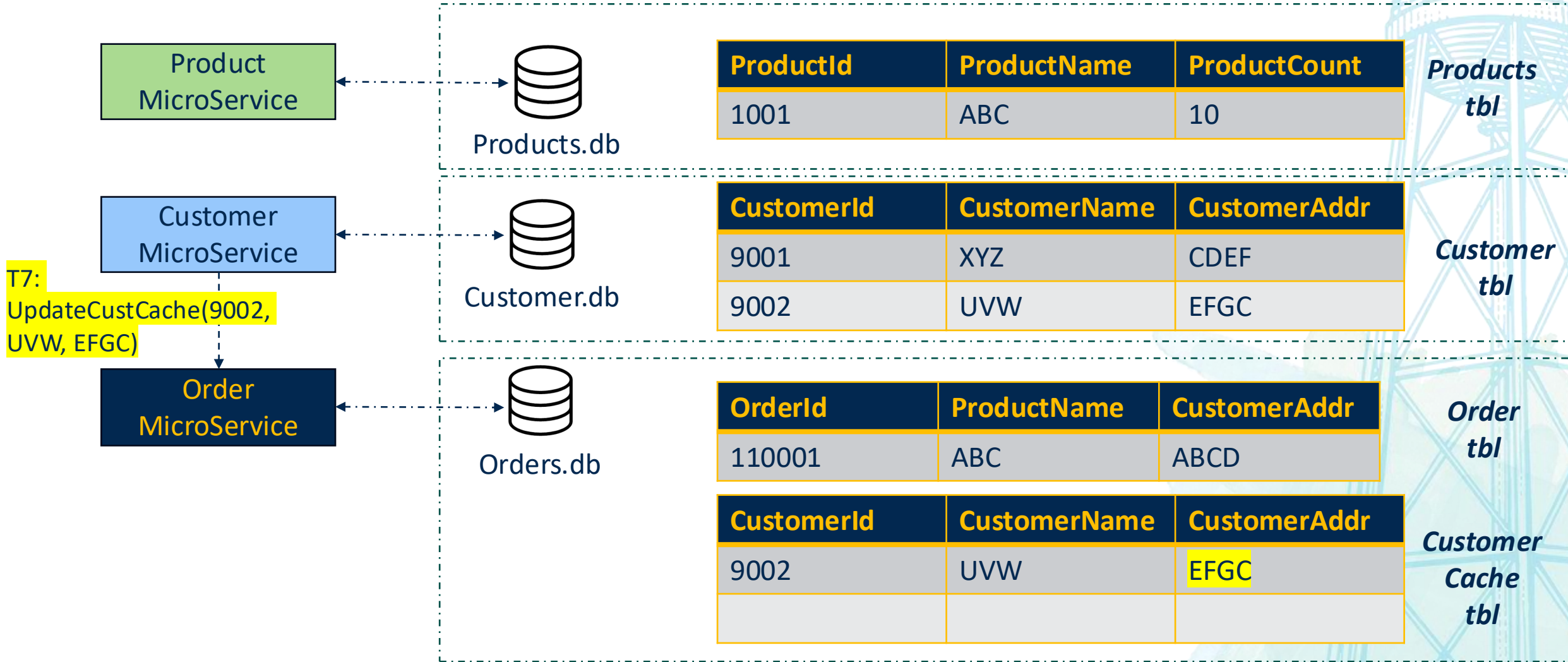
Working with eventual consistency



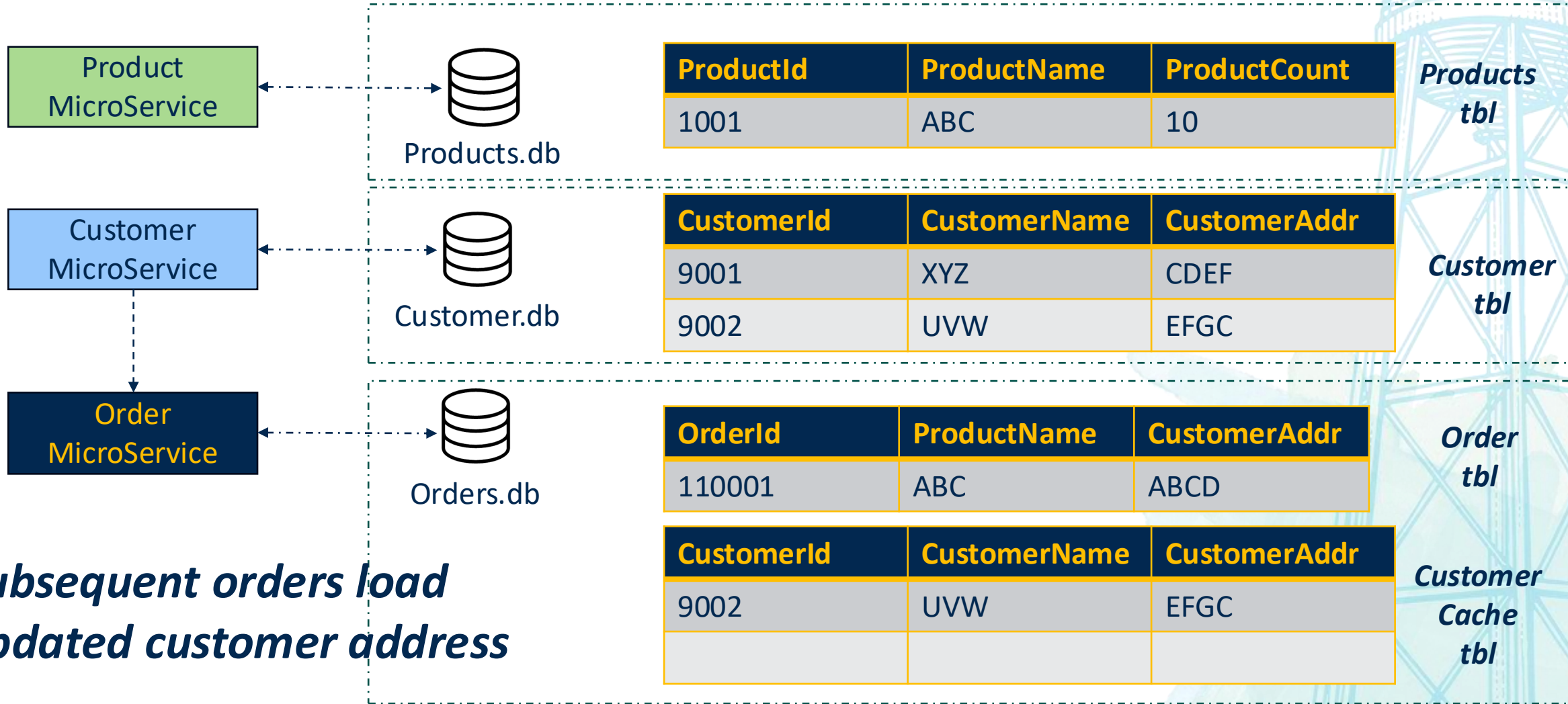
Working with eventual consistency



Working with eventual consistency



Working with eventual consistency

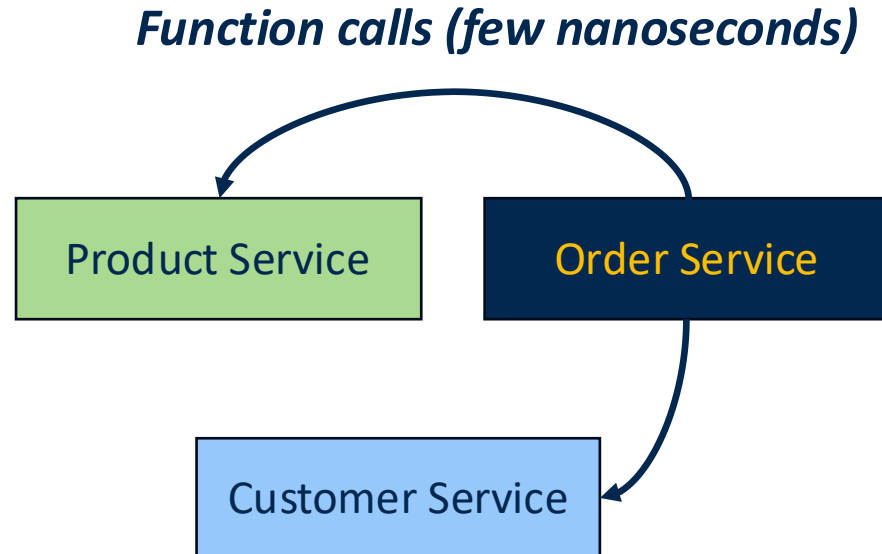


Microservice design concerns

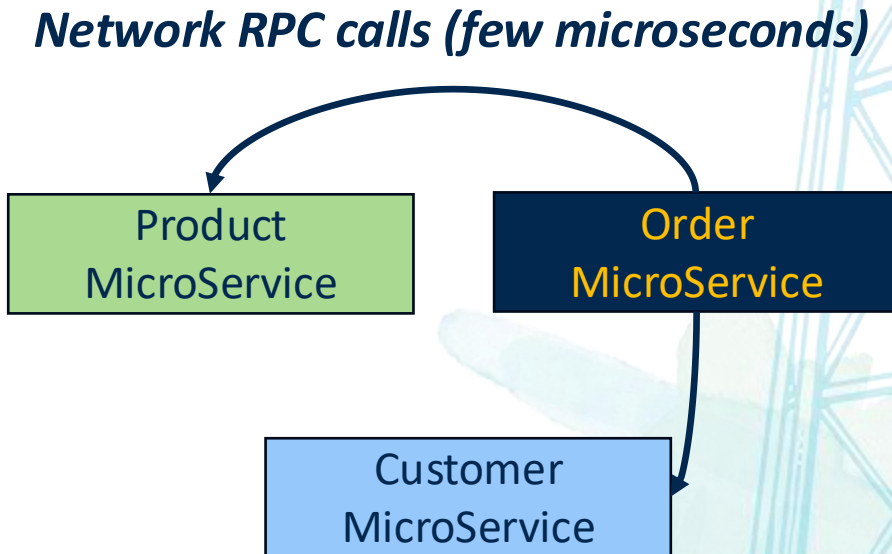
- Solution for eventual consistency is generally use-case dependent
- Reduce tight coupling
 - A microservice should not know the internal DB schema of another microservice
 - A microservice should not depend on another to be running to perform its task
- Limit network communication

Network communication cost

Monolithic applications



Microservices



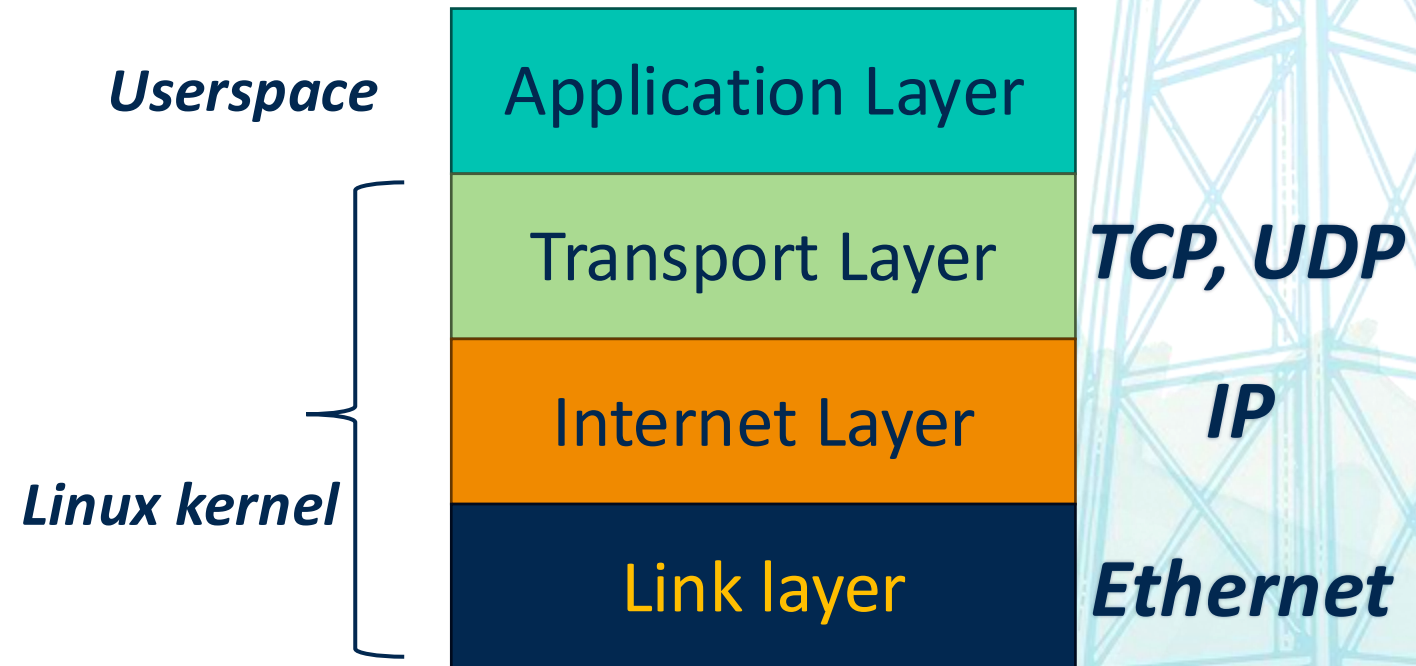
Network overhead decomposition

- 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



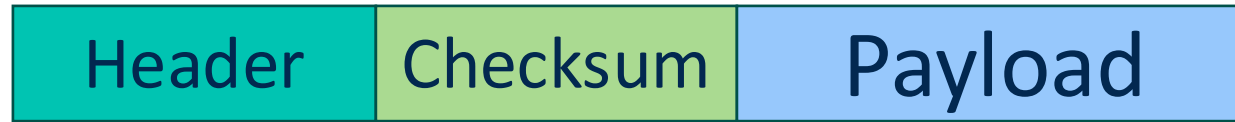
Kernel overhead for network comm. (Not in syllabus)

- 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***

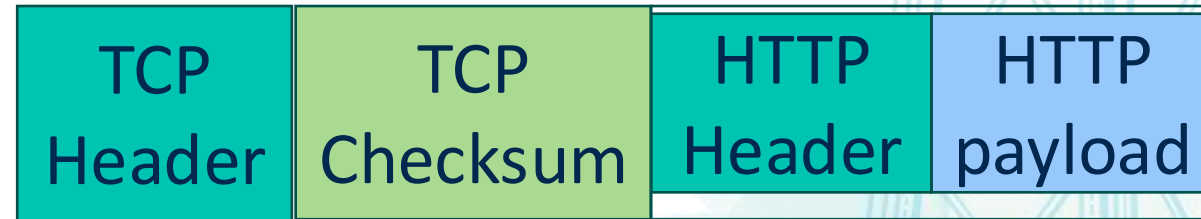
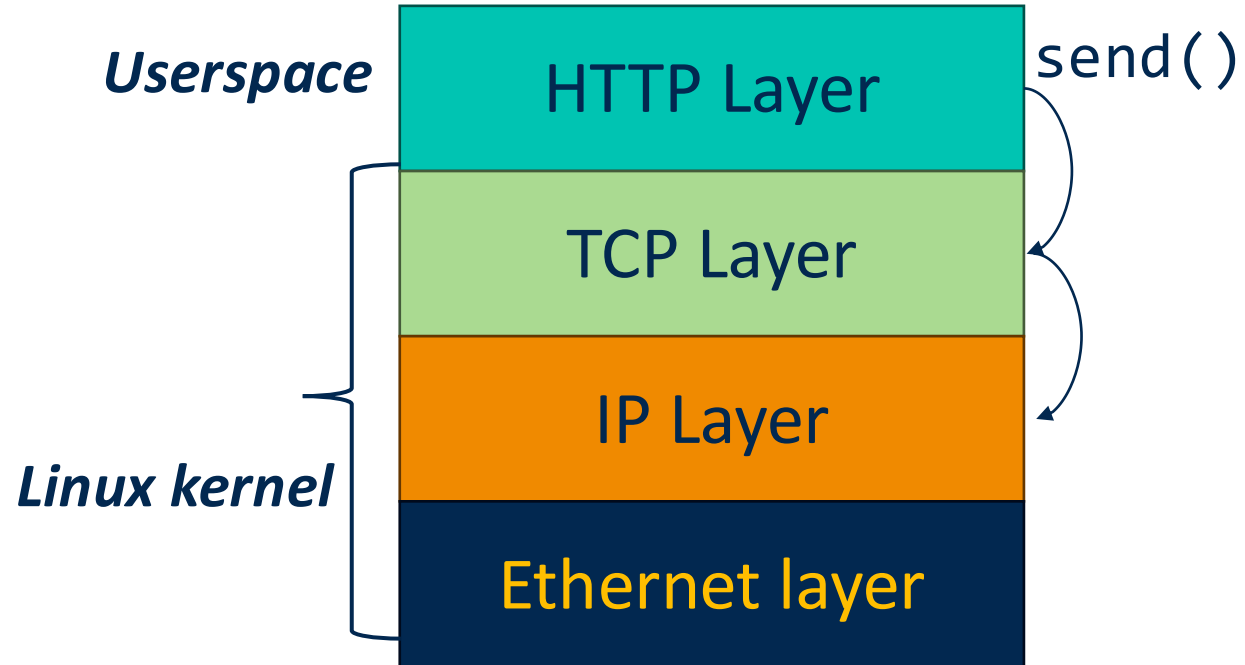


Each layer has a protocol (Not in syllabus)

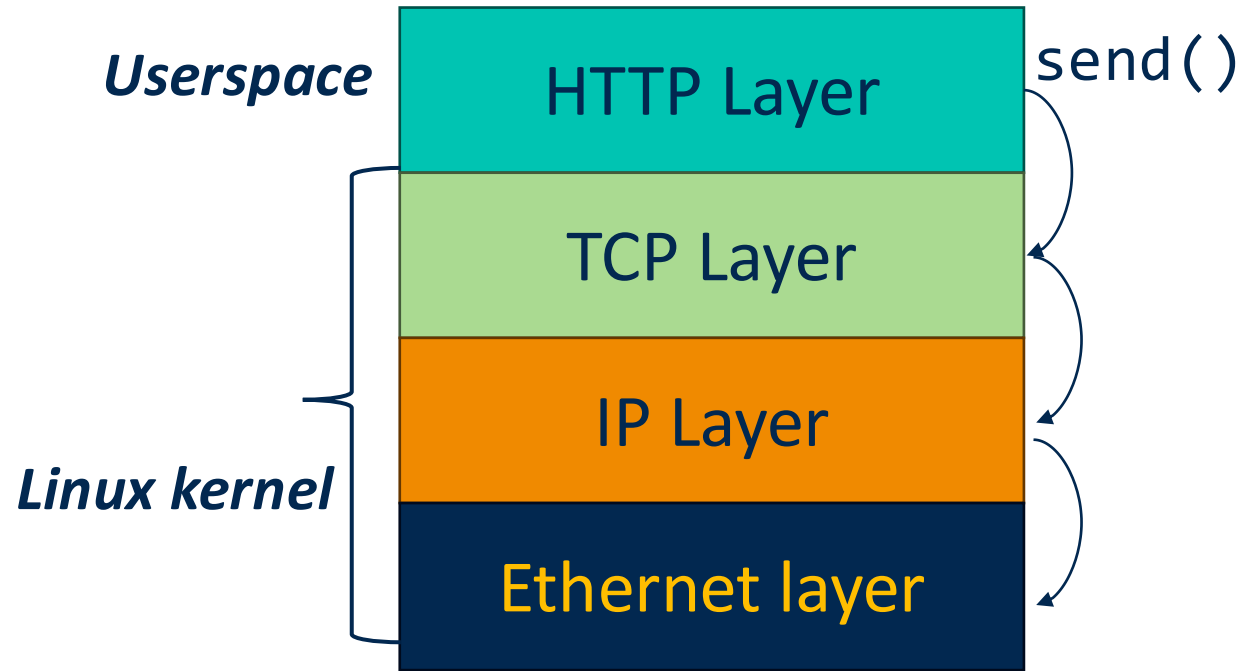
- Every layer/protocol has a fixed message format
 - Header
 - Payload
 - [optional] Checksum
- As the packet traverses through the layers, packets are rewrapped



Life of a packet (Not in syllabus)

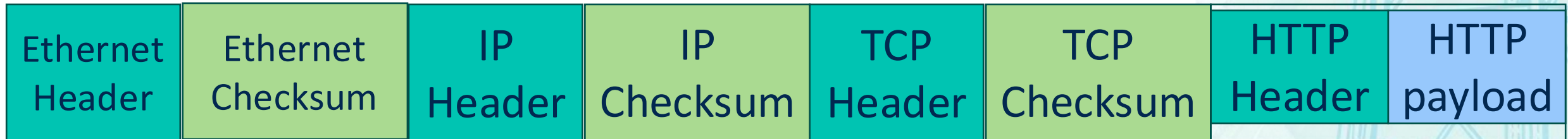


Life of a packet (Not in syllabus)



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

Reading 6 will discuss alternative solutions



Microservice pros

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



Microservice cons

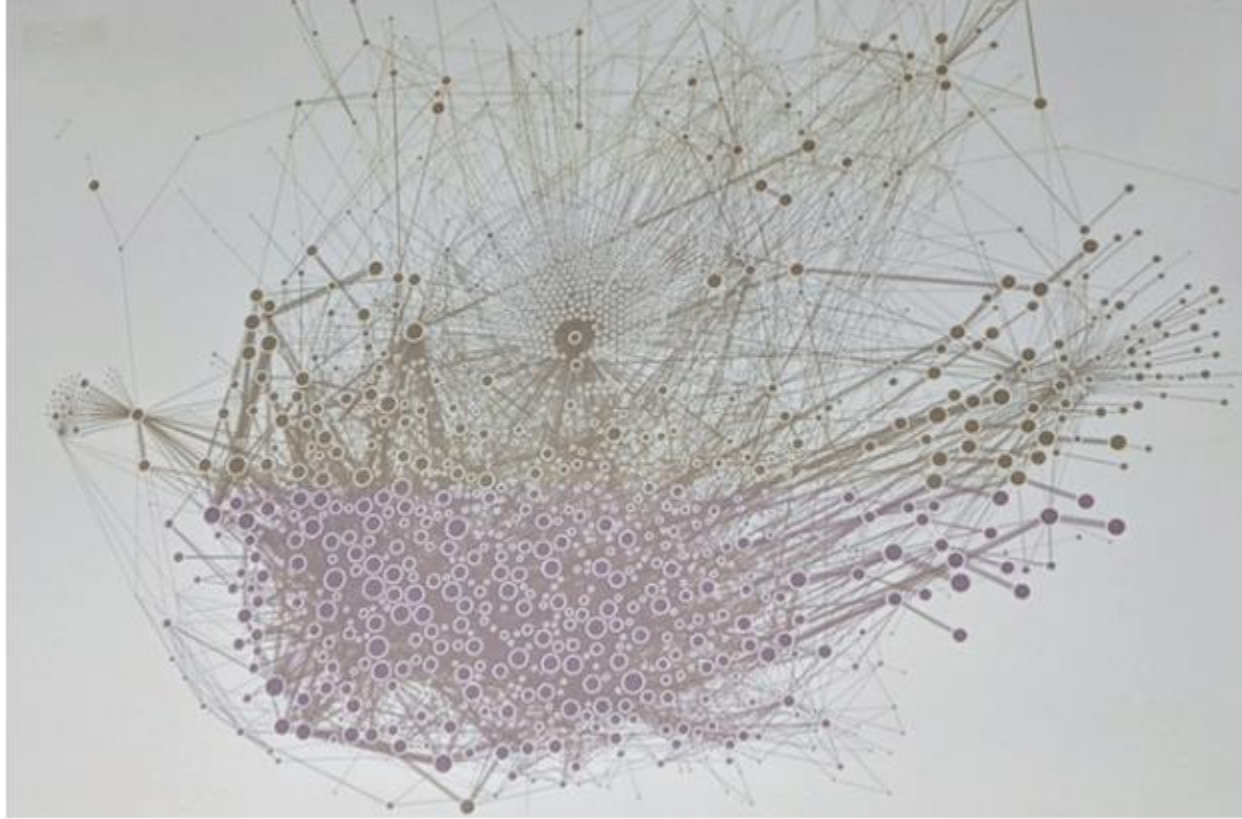
- Causes data denormalization
- Network overhead
- Higher complexity
- Debugging complex interactions is harder



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

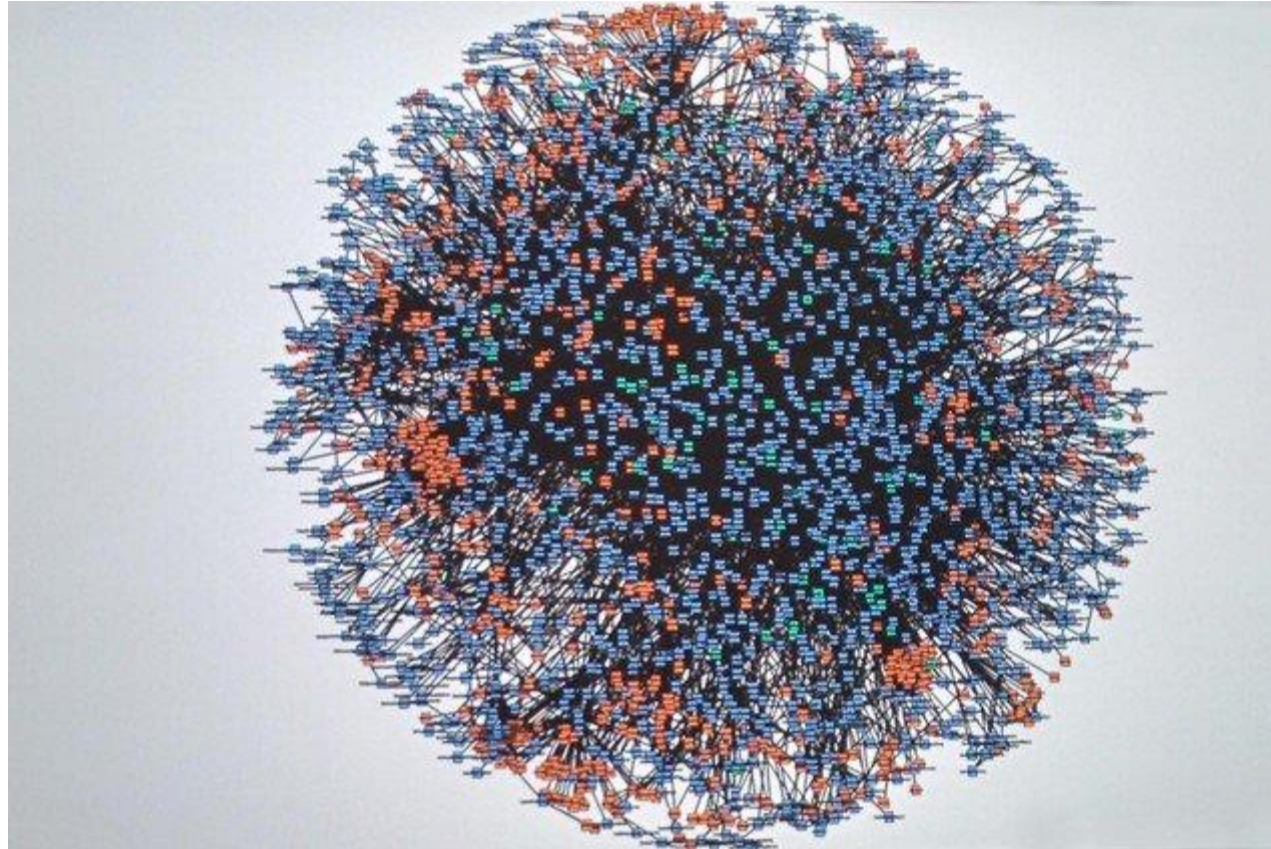
Microservices at Uber (2019)



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

Microservices at Amazon (2008)

- Code-named “Deathstar”



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

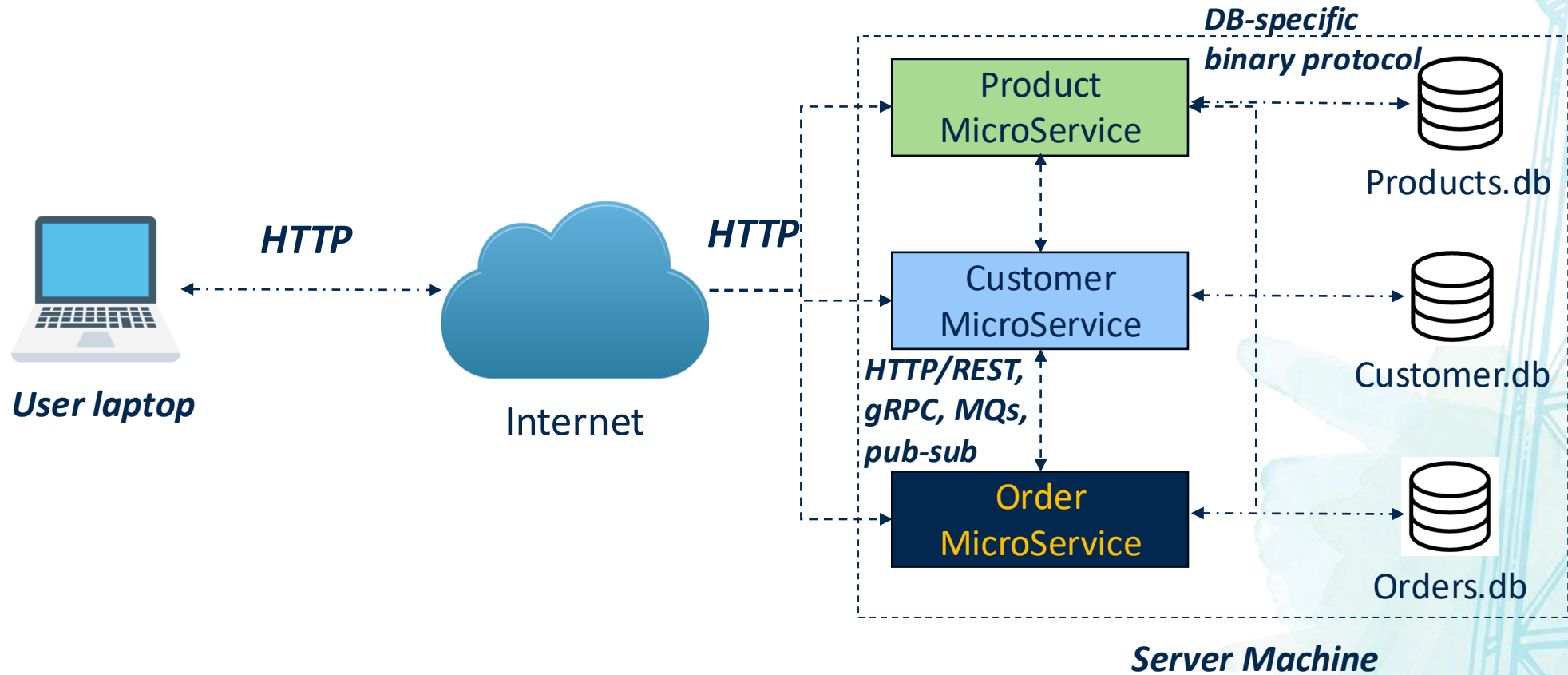
Data management and communication

- 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?id=ECS160&count=10`

Request parameters



HTTP GET and POST request

- POST request - used to send data to the server

- POST **URL** `/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) {  
        // do something  
        return "";  
    }  
}
```

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

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 "";  
    }  
}
```

Data management and communication

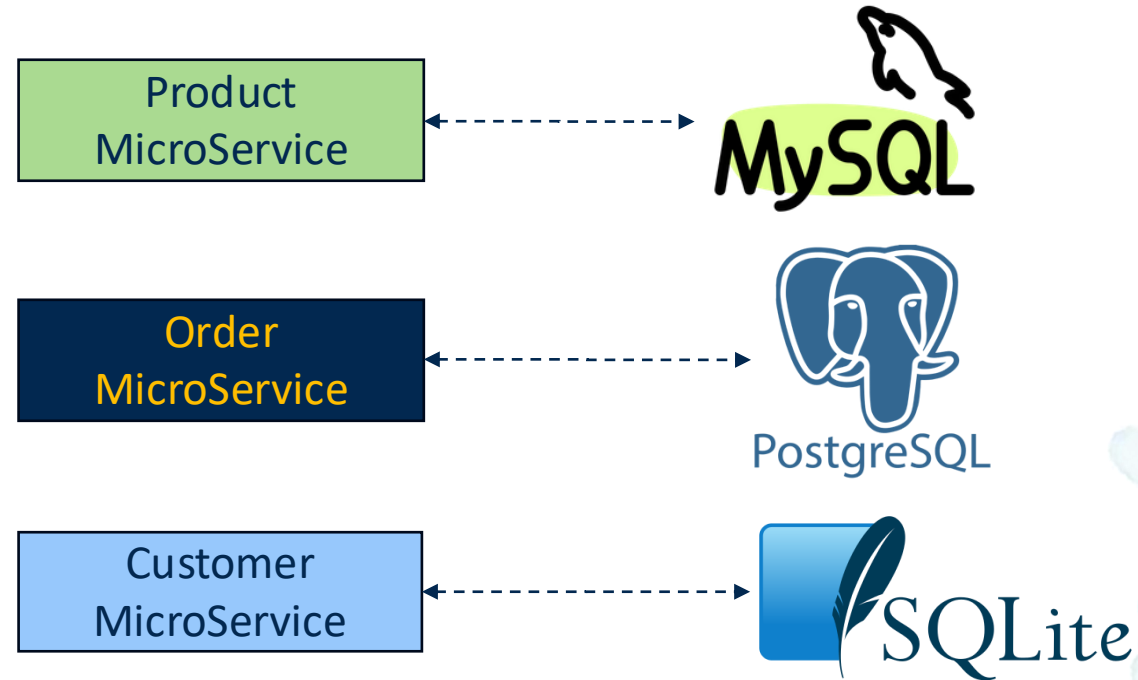
- Once data and computation are split across services, two problems remain
 - How is data stored?
 - How services communicate?



Databases

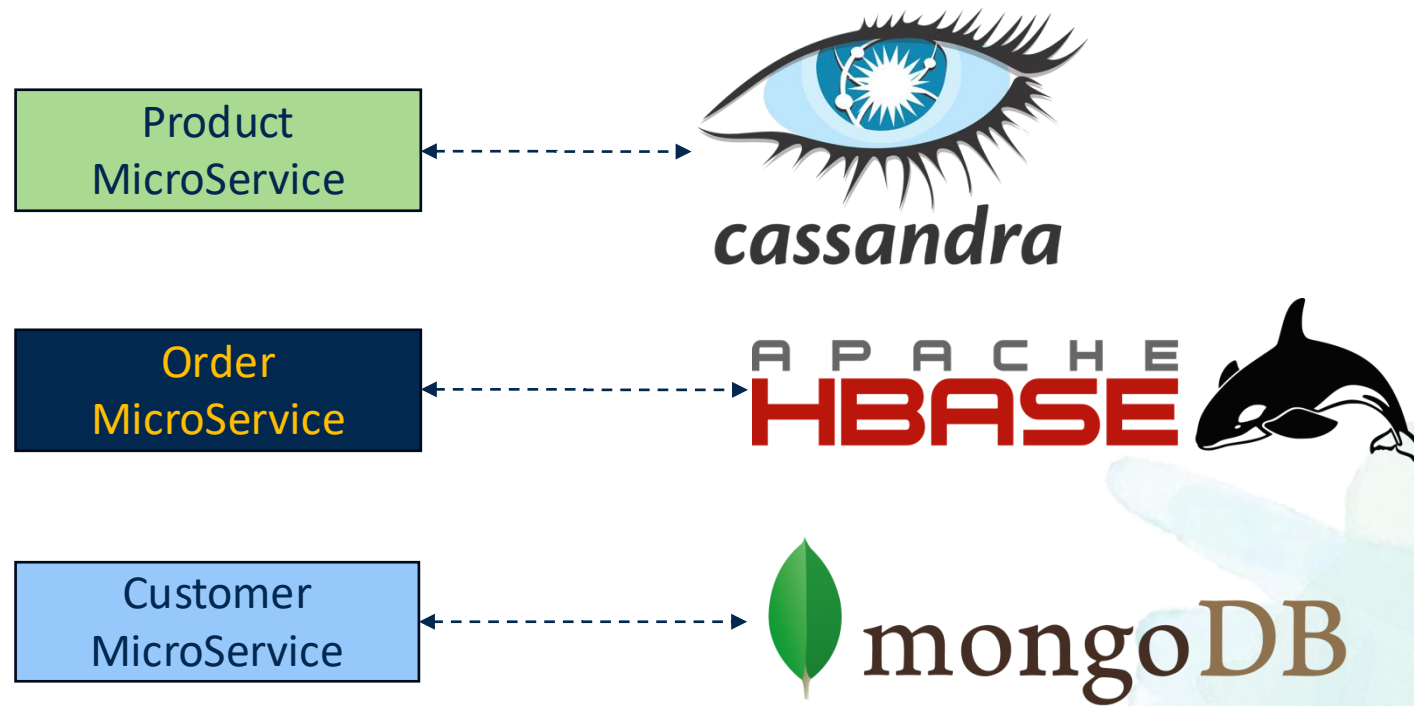


Microservices can have individual DBs



MySQL, PostgreSQL, SQLite are relational databases

Microservices can have individual DBs



Non-relational, NoSql databases

How to select which database to use?



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)

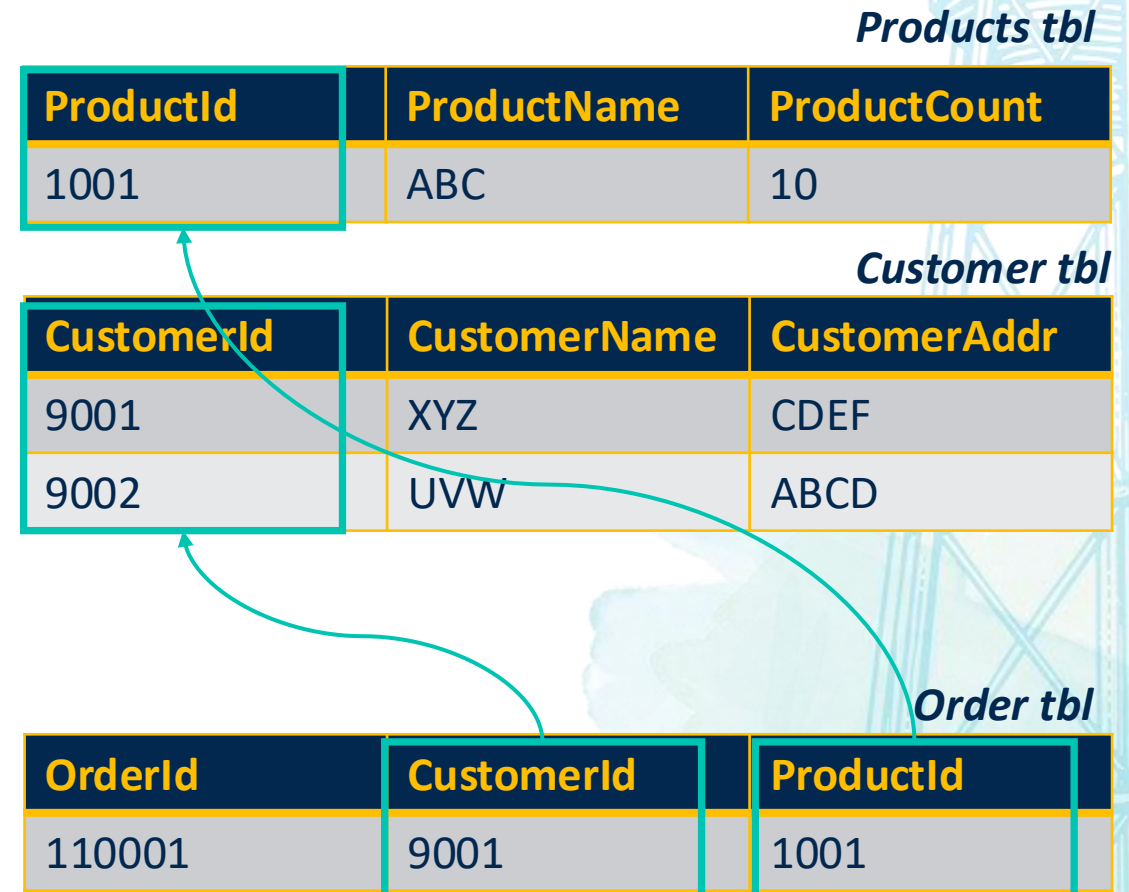
Data models and query languages

- Relational databases (discussed earlier)
- Document model
- Key-value stores (discussed earlier in Redis discussion)



Relational databases

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



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

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

JSON object

Nested JSON object

JSON array

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
```


Key-value stores

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

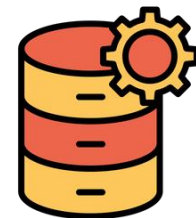
Key	Value	
	Field	Value
10279811	Name	ABC
	Age	22
	GPA	3.8
	Credits	45
10279812	Name	DEF
	Age	21
	GPA	3.9
	Credits	60

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 = ...
```



Orders db



redis

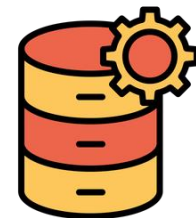


OrderService.java

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 = ...
```



Orders db



redis

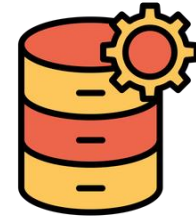
10000 records



OrderService.java

Key-value stores

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



Orders db



redis

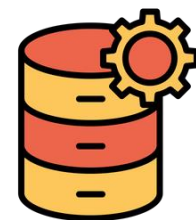
`Set(query-101, /* 10000 records */)`



OrderService.java

Key-value stores

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



Orders db



redis

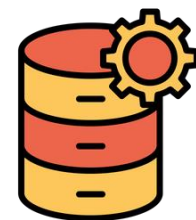
GET(query-101)



OrderService.java

Key-value stores

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



Orders db



redis

10000 records



OrderService.java

Database choice dimensions

- Data model
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 - Mechanism through which you can retrieve the data
- Storage engine
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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 $O(n)$

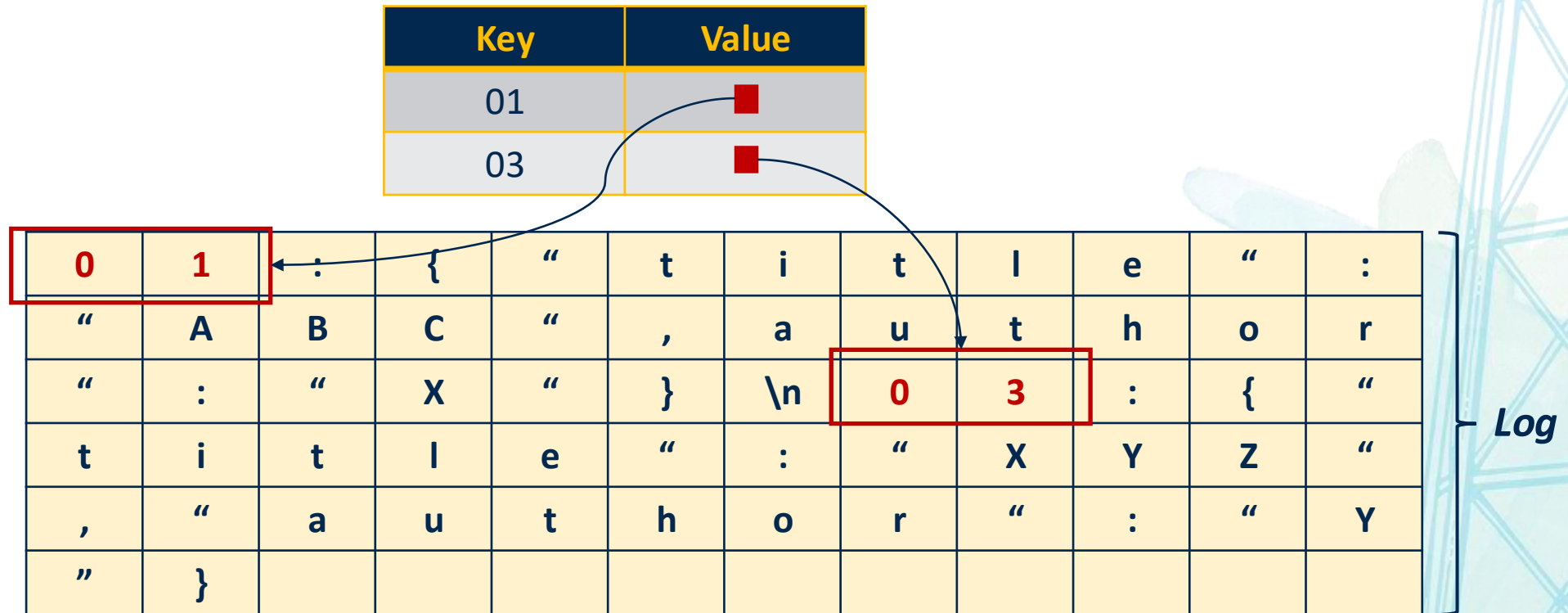
```
{  
  "title": "ABC",  
  "tags": ["S", "T"],  
  "author": "X"  
}
```

0	1	:	{	"	t	i	t	l	e	"	:
"	A	B	C	"	,	"	t	a	g	s	"
:	["	S	"	,	"	T	"]	,	"
a	u	t	h	o	r	"	:	"	X	"	}
0	2	:	{	...							

Log

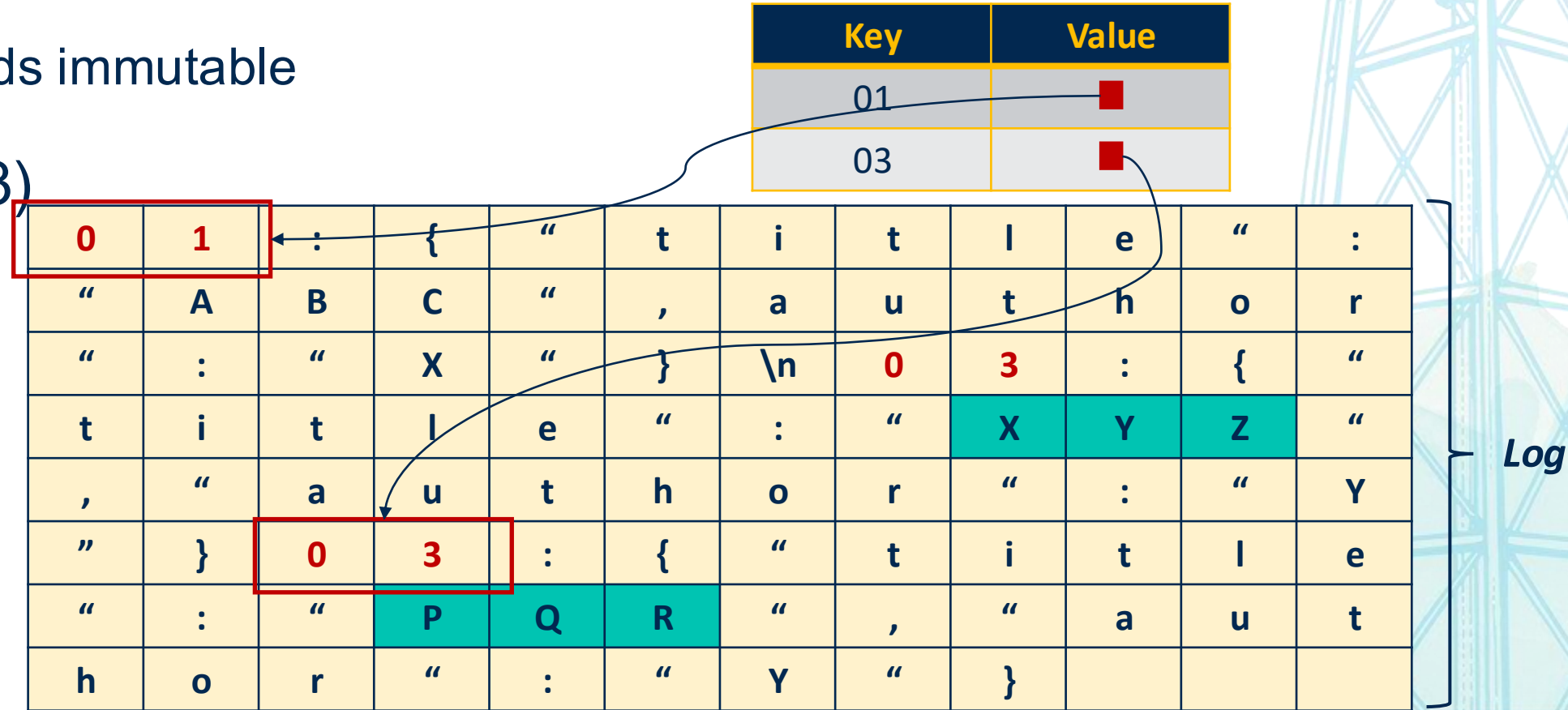
Hash indices

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





Hash indices – update operation

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



Compaction of hash indices

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

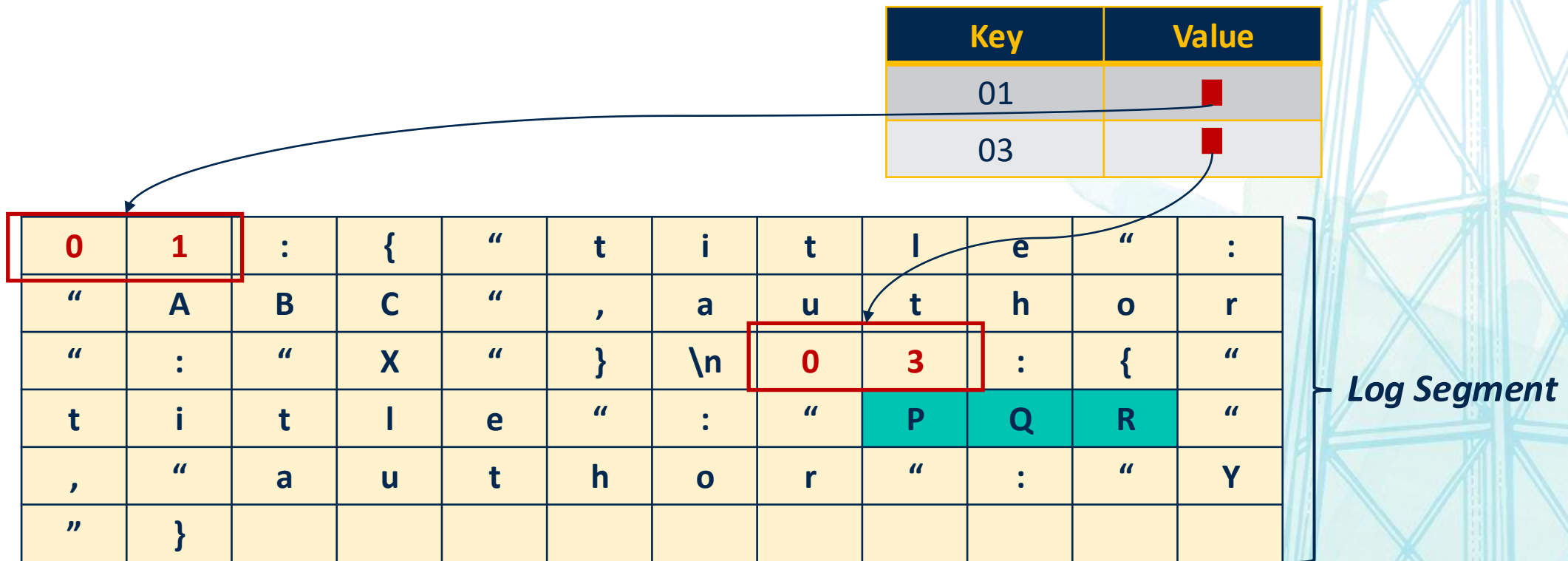
Key	Value
01	
03	

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 can be expensive



Limitations of approach

- High memory usage for large logs
 - A sparse hash index can overcome this limitation, but needs **sorting**
- Hash indices typically maintained only for the latest log segment
- 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 can be 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)

Log structured merge tree (LSM tree)

- LSM tree components
 - On-disk write-ahead log (WAL)
 - In-memory sorted tree (memtable)
 - Immutable on-disk sorted string table (SSTable)
- **Core idea:** sort in-memory before storing on disk



LSM tree operations

Memtable

Memory

File System

Write-ahead log

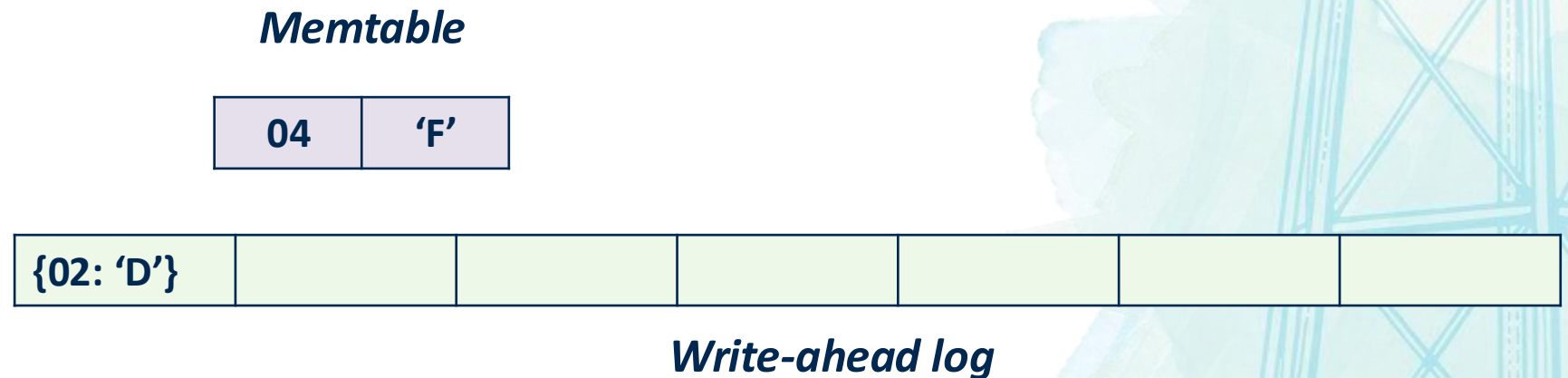
`insert(02, 'D')`

SSTable

SSTable

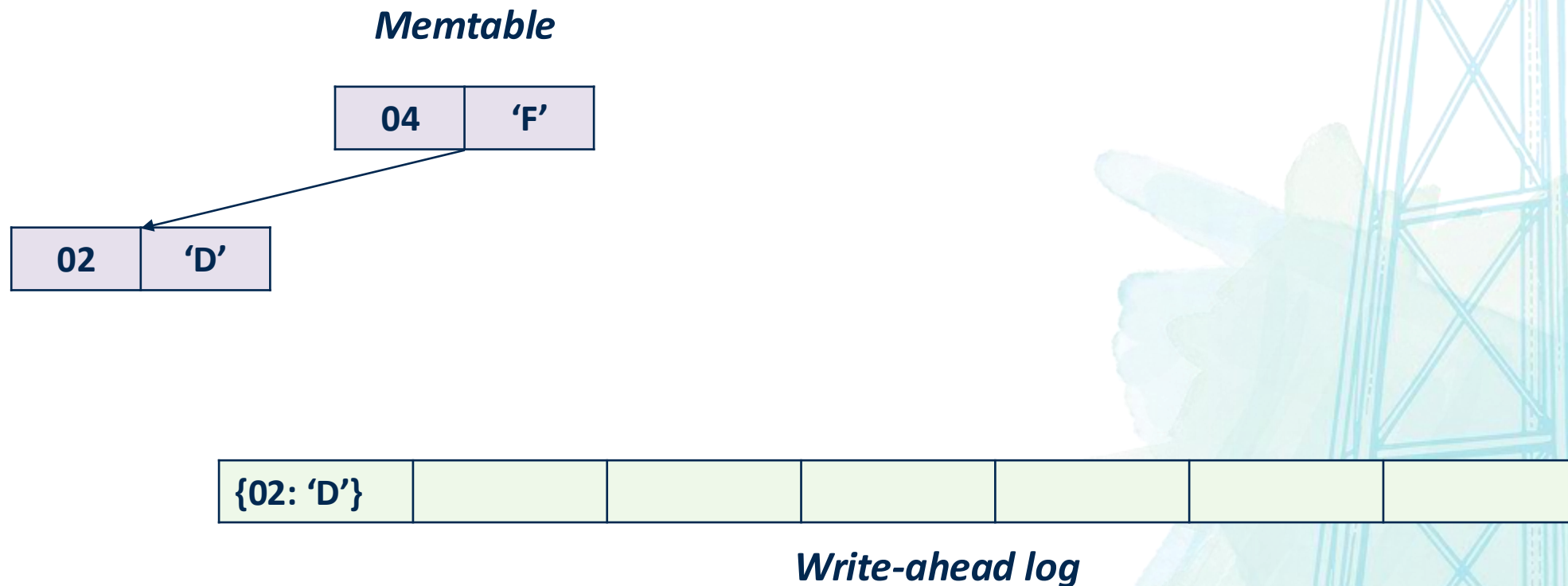
Write-ahead log

- 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

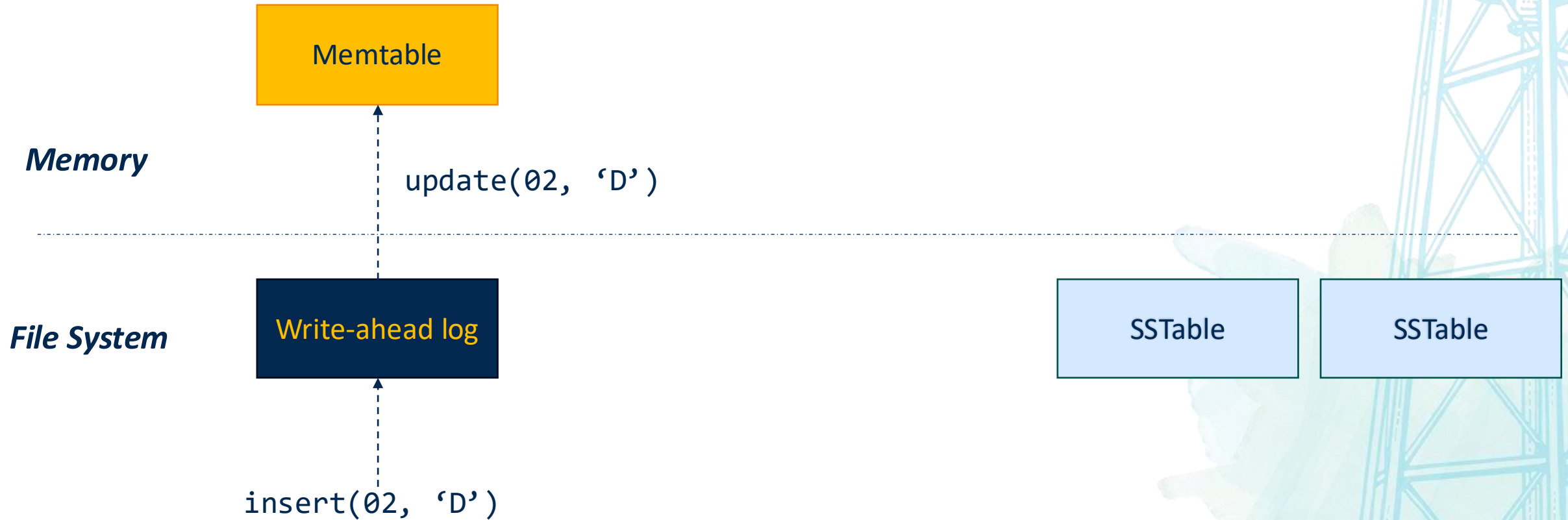


Memtable

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

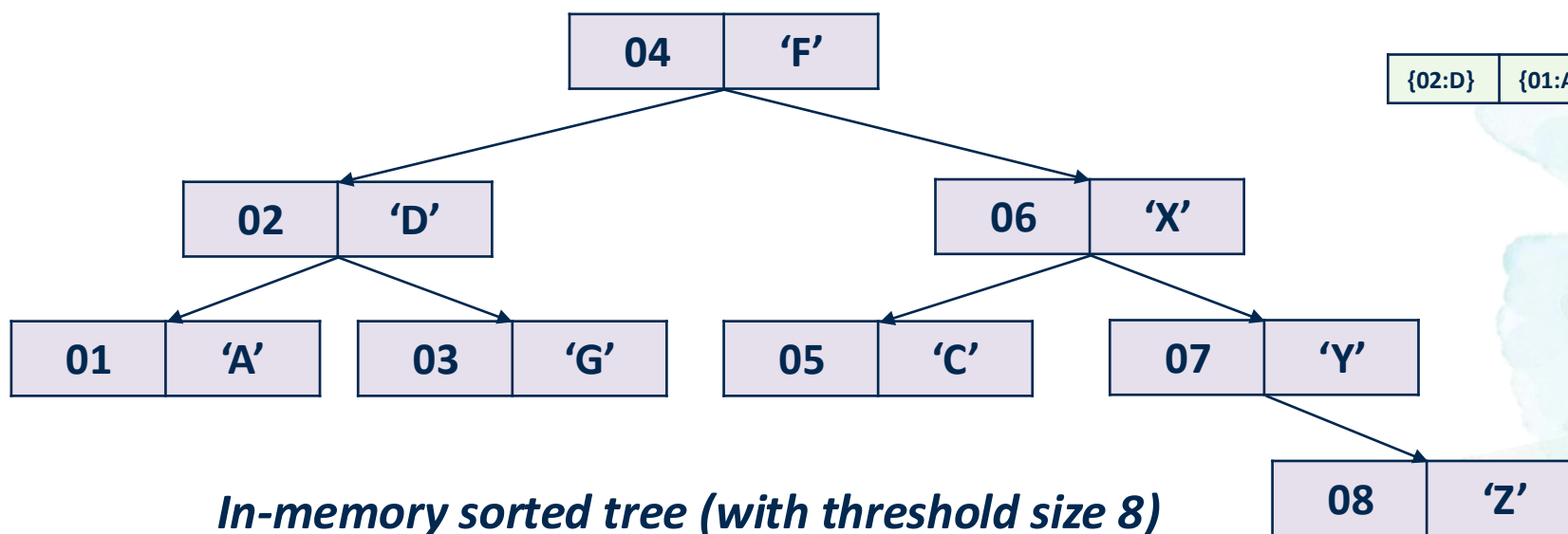


LSM tree write operation



Memtable

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



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)*

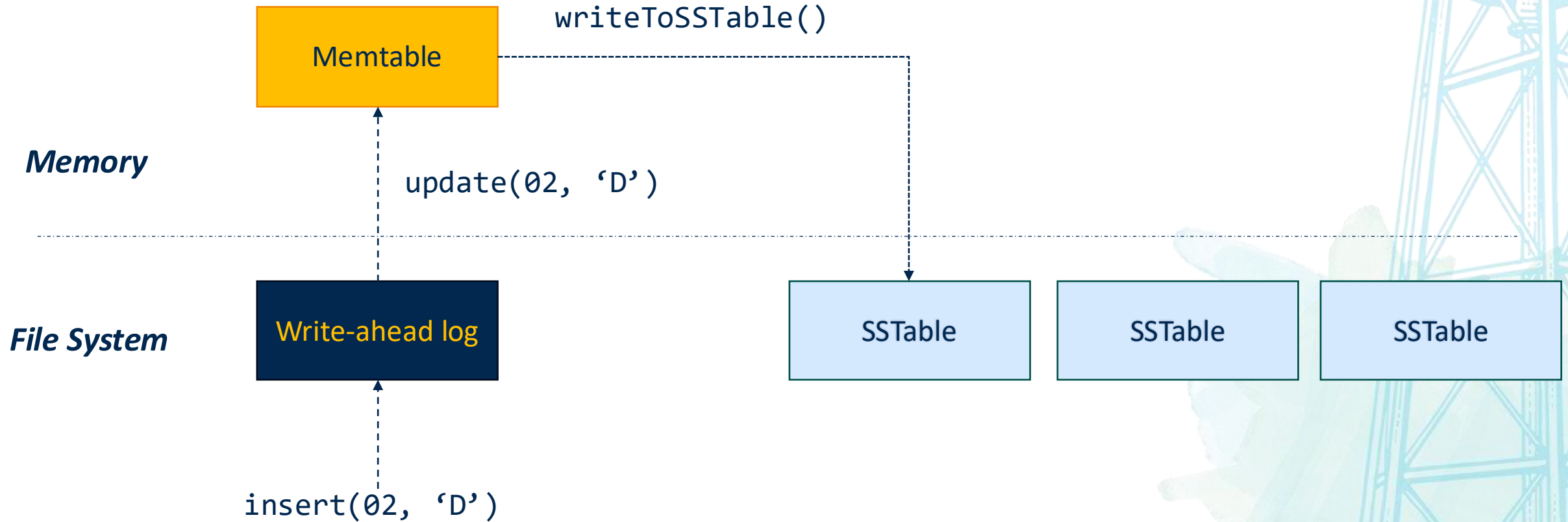
--	--	--	--	--	--	--

Write-ahead log

Memtable crash recovery

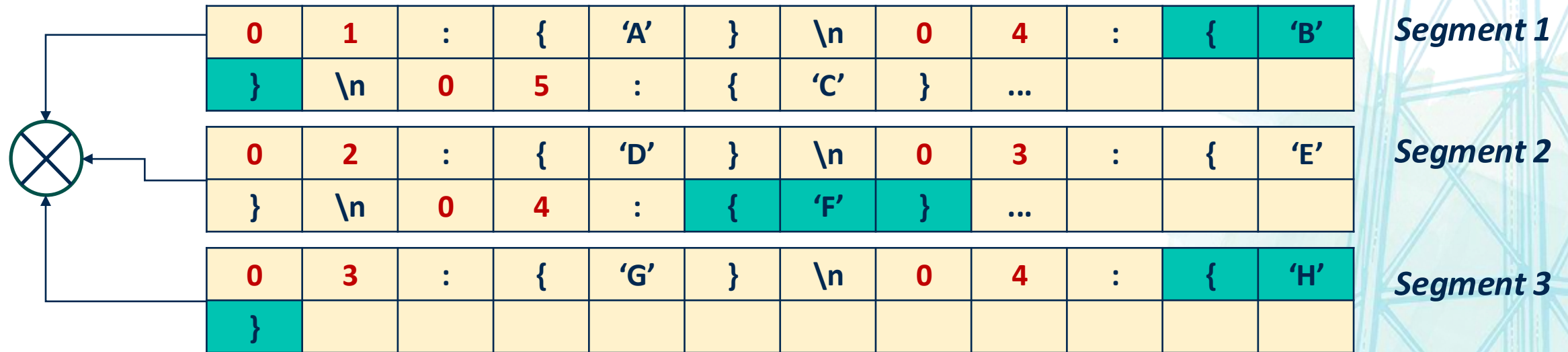
- Memtable lives in memory
 - System crashes/reboots lose its contents
- WAL provides crash recovery if system crashes before Memtable written to disk
- On reboot, replay the WAL records

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



SSTables compaction

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

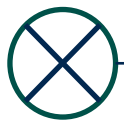


0	1	:	{	'A'	}	\n	0	2	:	{	'D'
}	\n	0	3	:	{	'G'	}	\n	0	4	:
{	'F'	}	\n	0	5	:	{	'C'	}	\n	

*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

Memtable

Memory

Write-ahead log

File System

SSTable

SSTable

SSTable

Background compaction thread

compact()

LSM tree compaction operation

Memtable

Memory

Write-ahead log

File System

New Merged
SSTable

New merged SSTable can participate in further compactions

Typical overheads of LSM write path

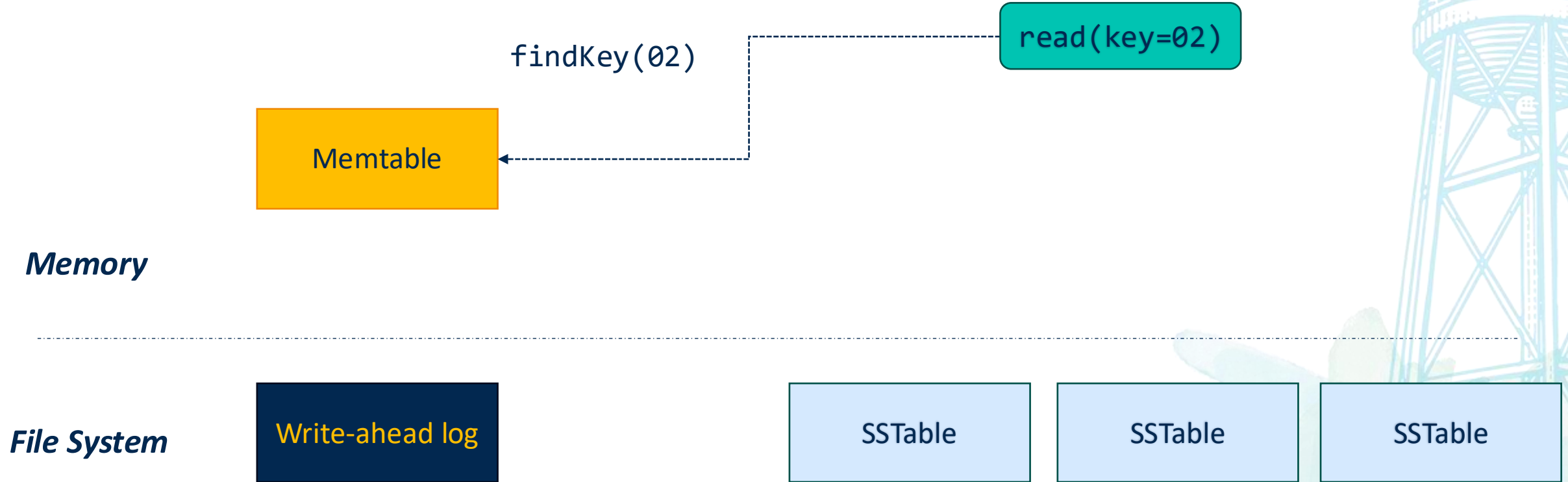
- Append to ***on-disk*** WAL has $O(1)$ complexity
- Insert into ***in-memory*** memtable (AVL tree) has $O(\log(n))$ complexity
- Eventually, append to ***on-disk*** SSTable has $O(1)$ complexity per-key
 - Bulk write amortizes the disk overhead
- ***On-disk*** log compaction and merging runs in a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

LSM tree read operation

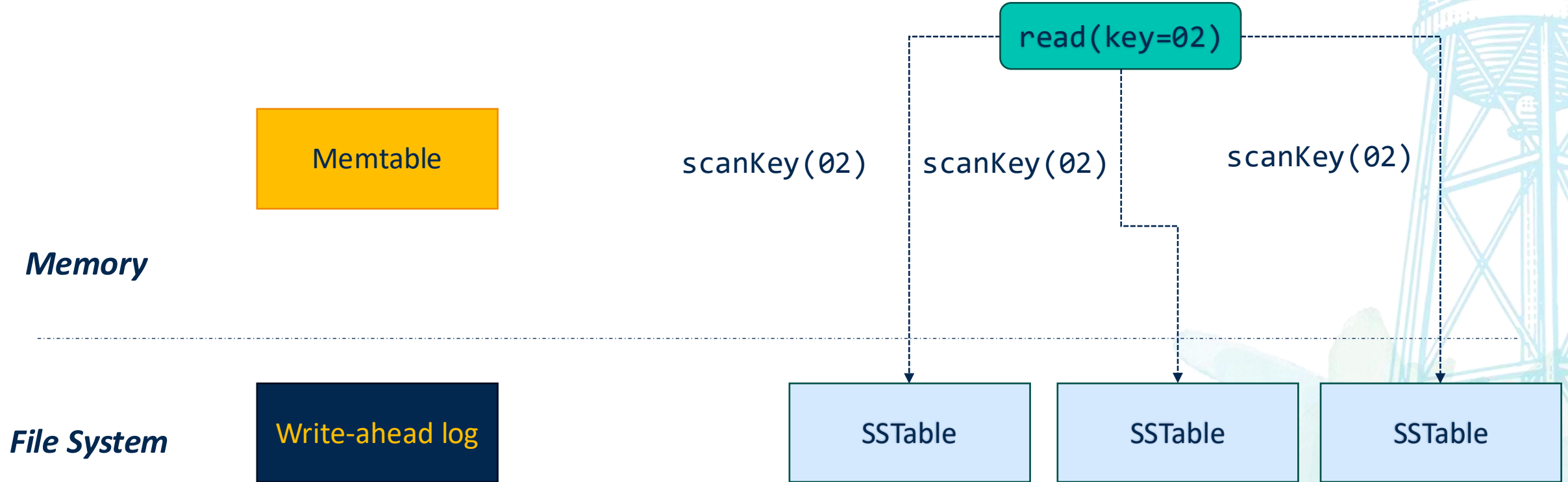
- Check if the key is in the ***in-memory*** memtable
 - Typically, $O(\log(n))$ complexity
- If not, scan each of the ***on-disk*** SSTables has the key
 - Typically, $O(n)$ complexity
- Generally, reads are slower than writes



LSM tree read operation

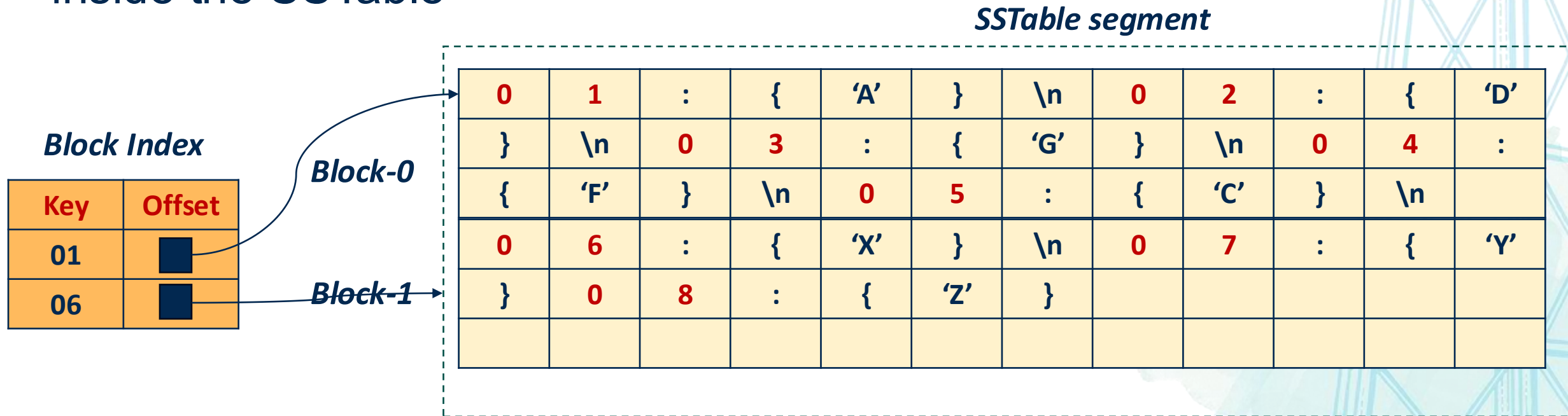


LSM tree read operation



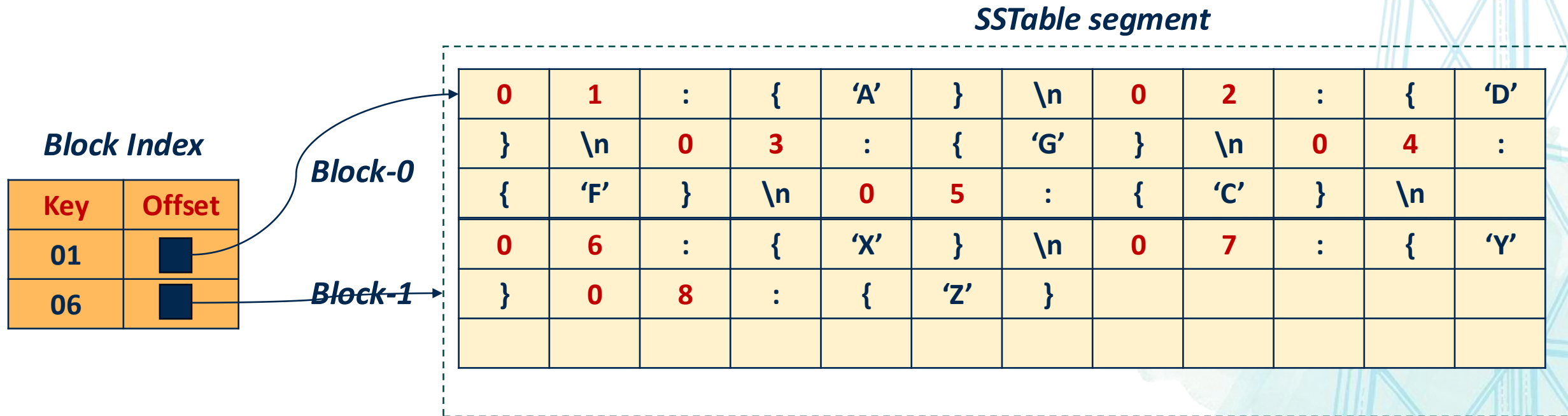
Block index for read optimization

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

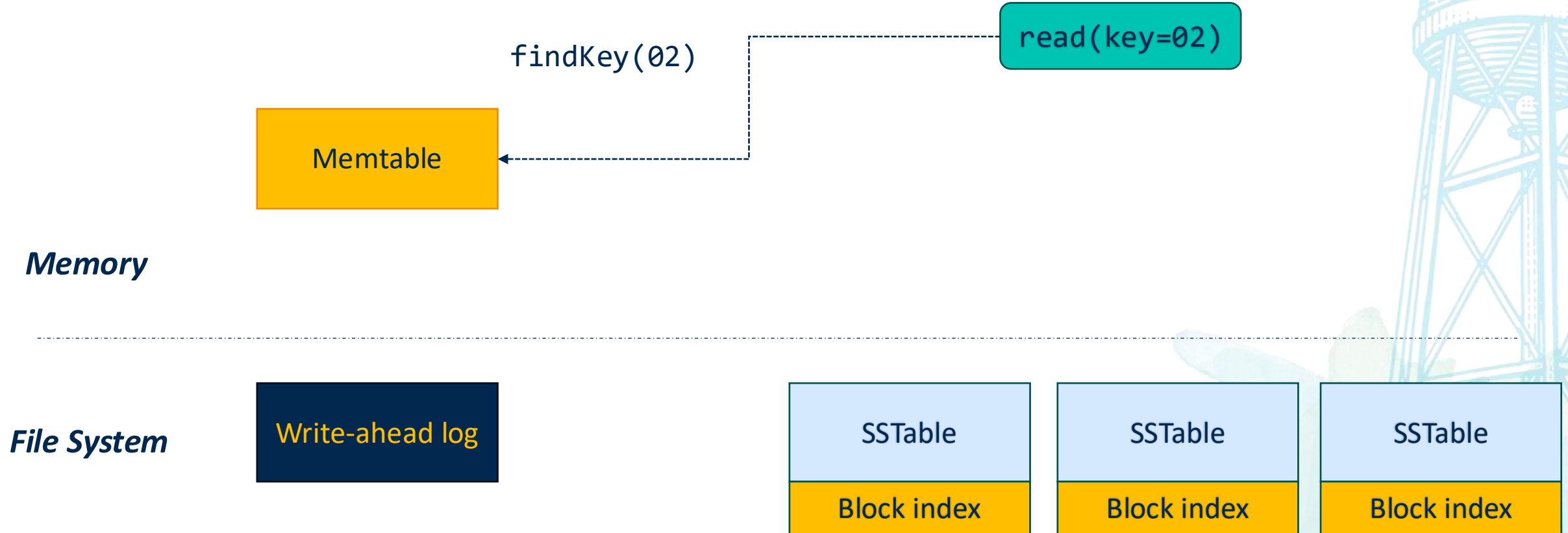


Block index for read optimization

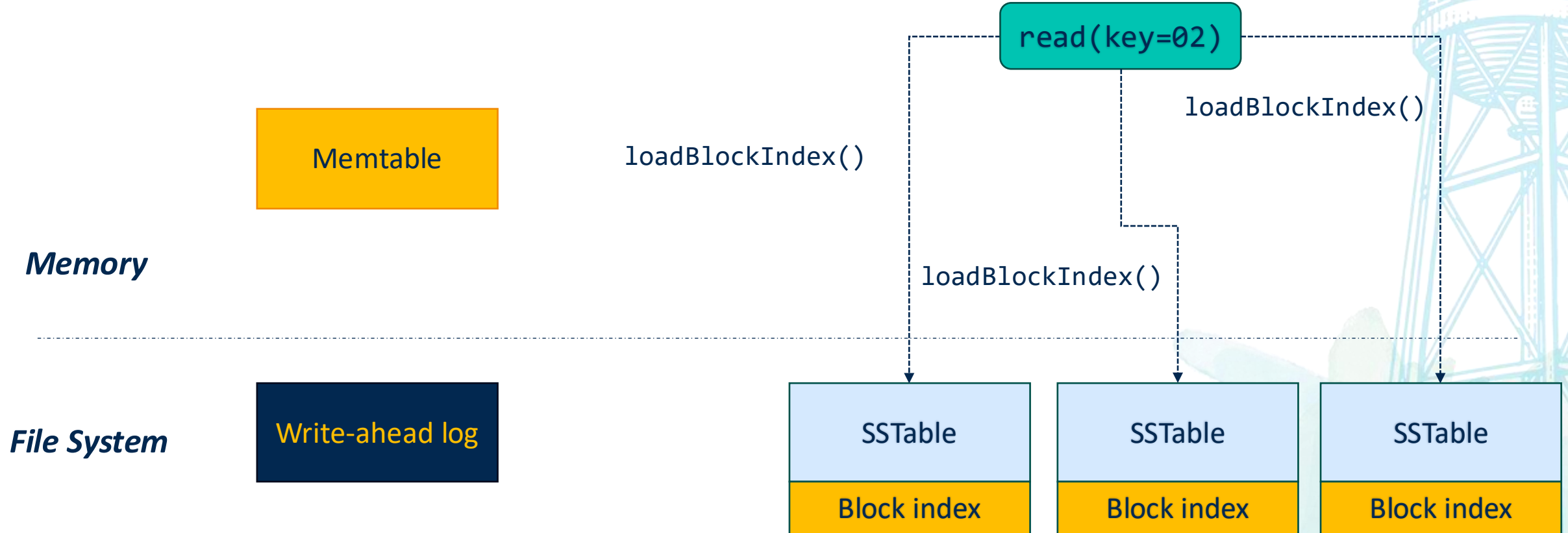
- When scanning SSTable for reads, load block index into memory
- Use block index to index into SSTable



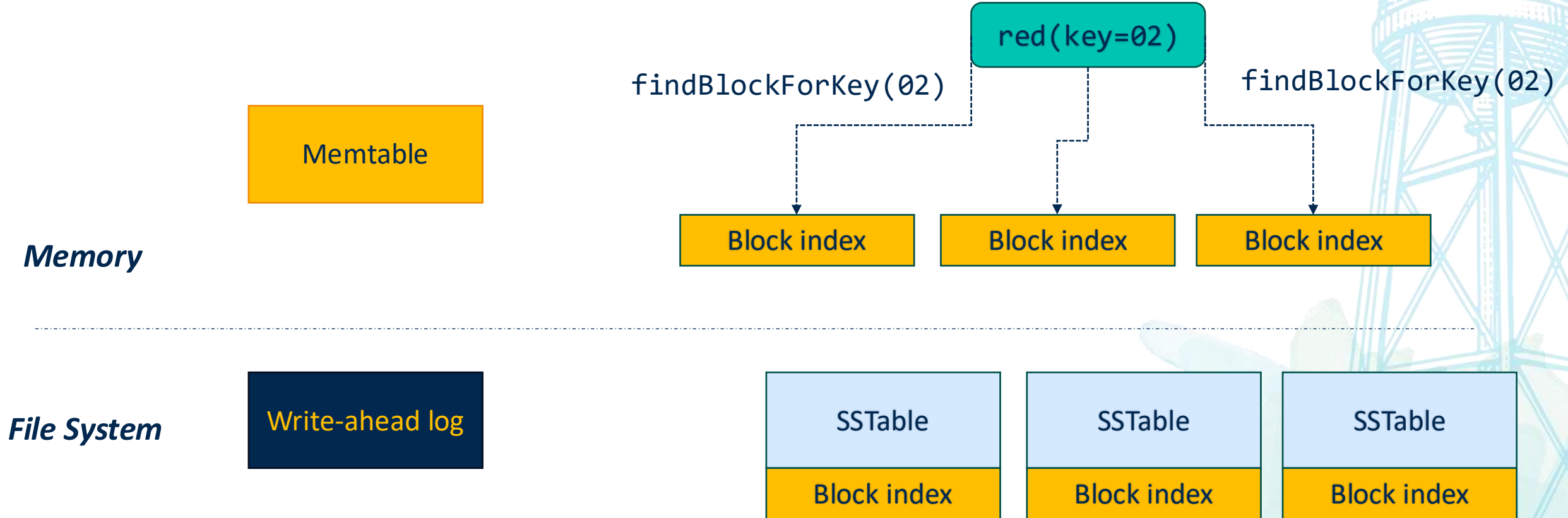
LSM tree read path with block index



LSM tree read path with block index

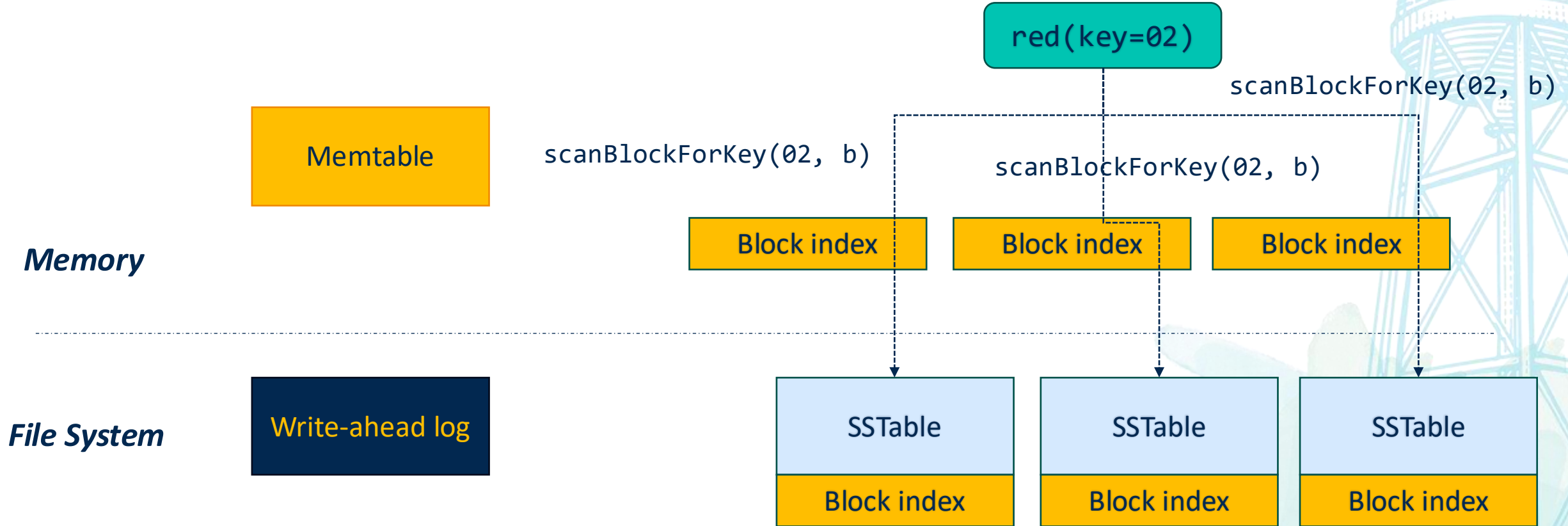


LSM tree read path with block index



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)

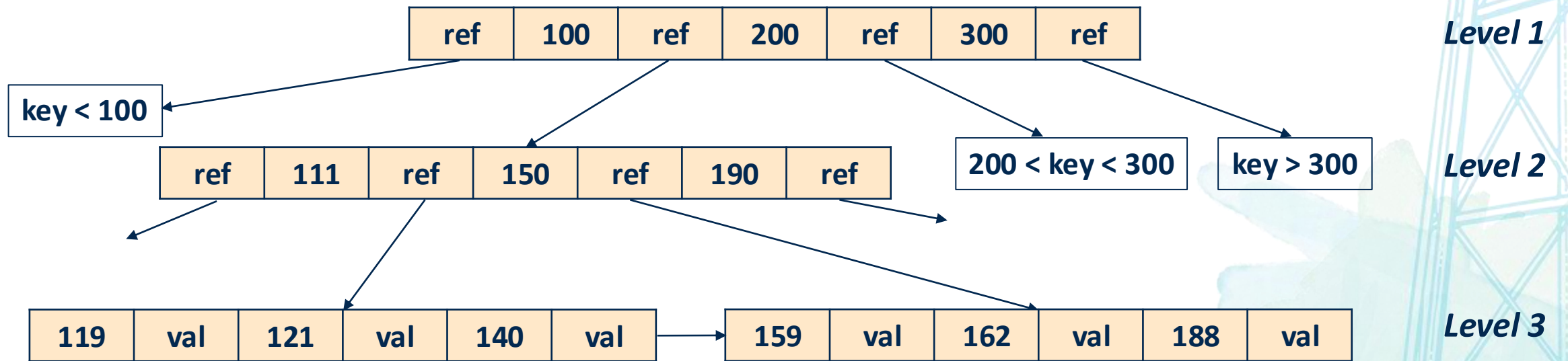
- Used to implement primary key indexes in traditional relational databases
- On-disk data structure that keeps key-value pairs sorted by key
- Supports random accesses
- Writes are performed directly on this on-disk sorted tree, unlike in LSM trees which operated on the in-memory Memtable

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

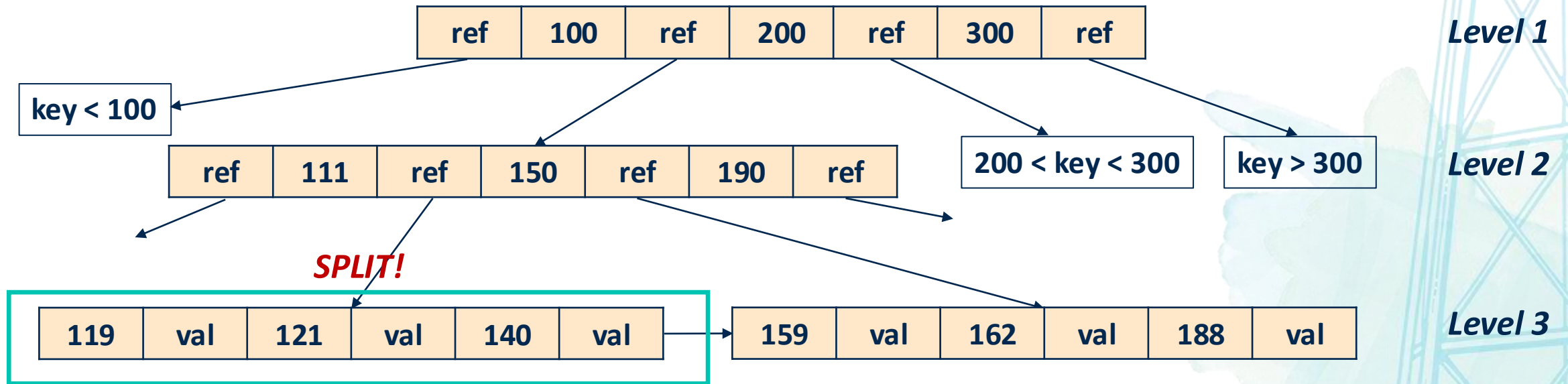
- Traverse the tree following the branches based on the key value
 - Start at the root
 - At each node: search the sorted keys (e.g., binary search) to find the correct child pointer
 - Follow the pointer to the next node and repeat until you reach the leaf
- Complexity is $O(\log(n))$

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 per node 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

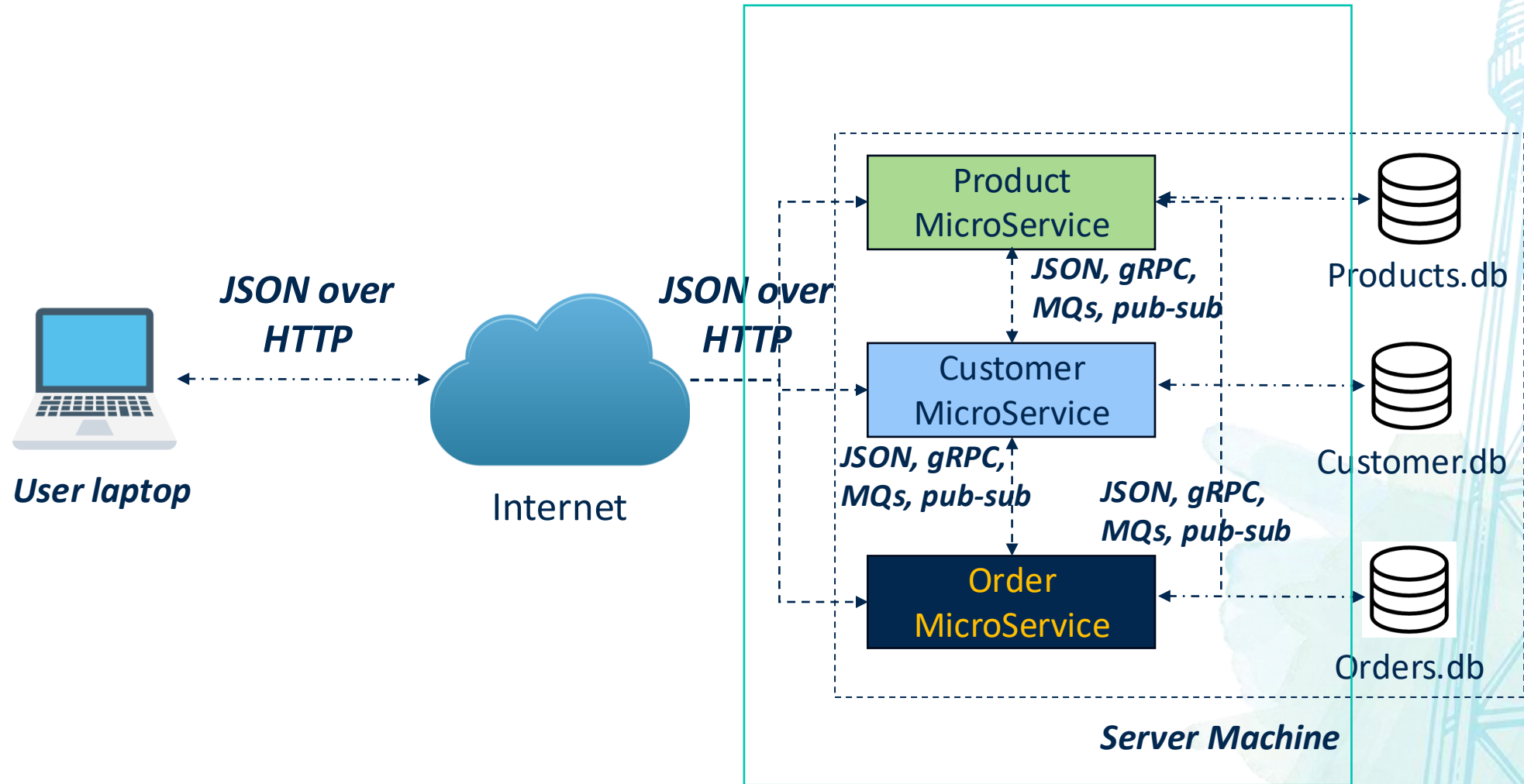
Summary

- Decomposing monolithic apps into microservices allows per-microservice database selection
- Read-heavy and write-heavy microservices can choose which db to use according to its needs

Communication styles



Intra-service communication

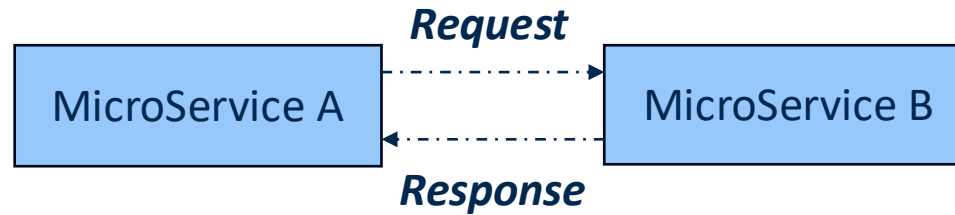


Communication choice dimensions

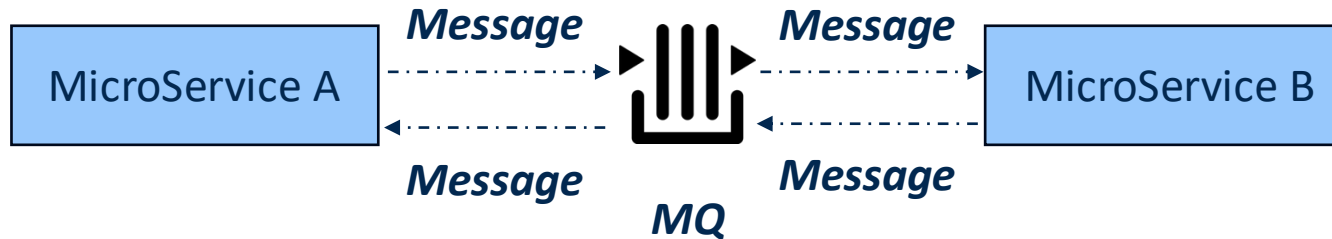
- Synchronous request/response (JSON over HTTP, gRPC)
- Asynchronous request/response (message queues - RabbitMQ)
- Event-driven publish/subscribe models

Communication choices

- Synchronous request/response (JSON over HTTP, gRPC)

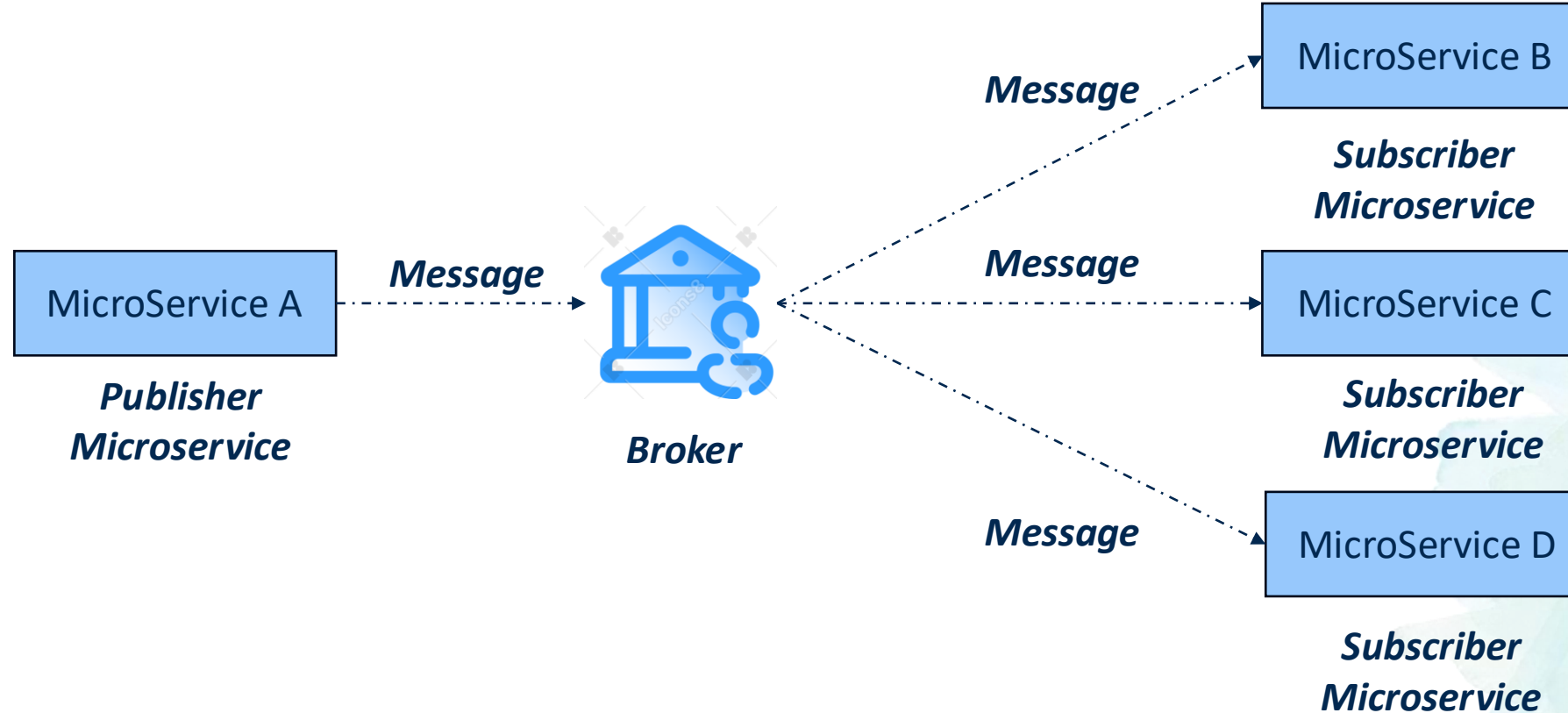


- Asynchronous request/response (message queues - RabbitMQ)



Communication choices

- Event-driven publish/subscribe models

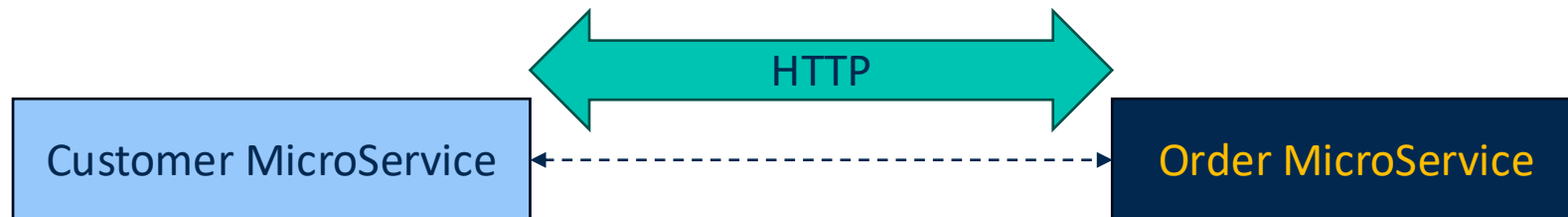


Synchronous request/response

- 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

- 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());
```

Async HTTP JSON client (Not in syllabus)

- Can use language-level async primitives with synchronous communication mechanisms
- Python, Rust, and other languages provide async I/O through coroutines
- Java provides "futures"

```
import asyncio
```

```
async def fetch(url: str) -> str:  
    # Simulate network I/O  
    await asyncio.sleep(1)  
    return f"fetch: {url}"
```

```
async def main():
```

```
    # Start multiple coroutines concurrently  
    tasks = [asyncio.create_task(fetch(u)) for u in  
             ["a", "b", "c"]]
```

```
    # Do other work while they run  
    for i in range(3):  
        print("doing other work", i)  
        some_other_long_running_task()
```

```
    # Await results (does not block the OS thread)  
    results = await asyncio.gather(*tasks)  
    print(results)
```

```
asyncio.run(main())
```

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



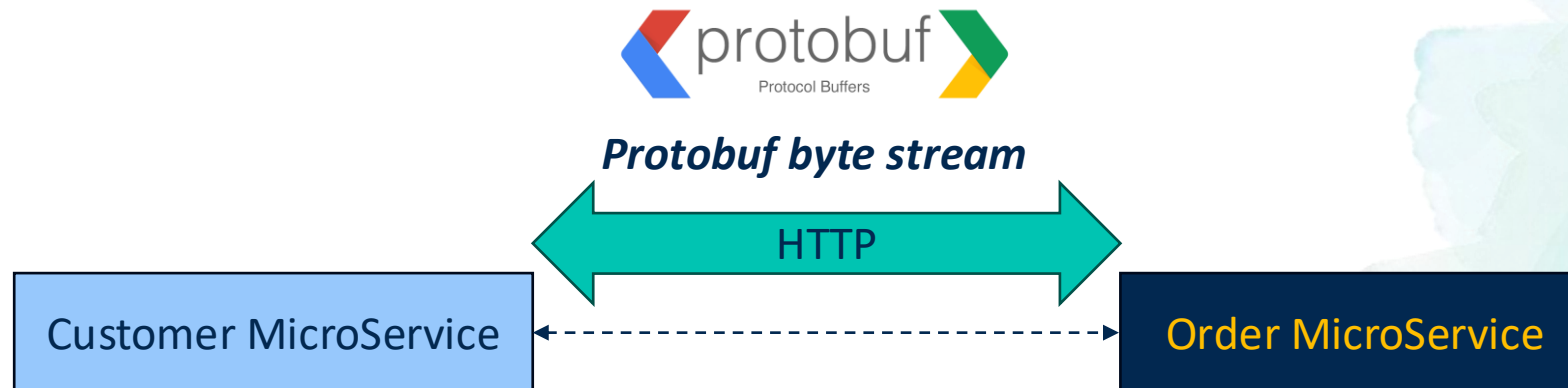
gRPC

<https://martin.kleppmann.com/2012/12/05/schema-evolution-in-avro-protocol-buffers-thrift.html>

Google Remote Procedure Call

```
Person(  
  userName: "Martin",  
  favouriteNumber: 1337,  
  interests: ["daydreaming", "hacking"]  
)
```

0a	4d	61	72	74	69	6e	10	b9	0a	1a	0b
64	61	61	79	64	72	65	61	6d	69	6e	67
1a	07	68	61	63	6b	6e	67				



Protobuf

- Google's binary encoding format
- User must define schema in a .proto file
- protoc compiler generates typed data classes and service stubs across many languages
 - C++, C#, Java, Kotlin, Objective-C, PHP, Python, Ruby

Protobuf

- Define schema in .proto file
- Protobuf defines standard data types
- Tags are the field's numeric identifier used in the binary format
- Fields are encoded as (tag, wire-type, value)

```
Person(  
  userName: "Martin",  
  favouriteNumber: 1337,  
  interests: ["daydreaming", "hacking"]  
)
```

```
// myservice.proto  
message Person {  
  required string user_name  
  optional int64  favourite_number  
  repeated string interests  
}
```

	Tag
required string user_name	= 1;
optional int64 favourite_number	= 2;
repeated string interests	= 3;

Protobuf binary format

<https://martin.kleppmann.com/2012/12/05/schema-evolution-in-avro-protocol-buffers-thrift.html>

```
// myservice.proto
message Person {
  required string user_name      = 1;
  optional int64  favourite_number = 2;
  repeated string interests      = 3;
}
```

```
Person(
  userName: "Martin",
  favouriteNumber: 1337,
  interests: ["daydreaming", "hacking"]
)
```

Protocol Buffers

field tag = 1 type 2 (string)

0 0 0 0 1 0 1 0

field tag = 2 type 0 (varint)

0 0 0 1 0 0 0 0

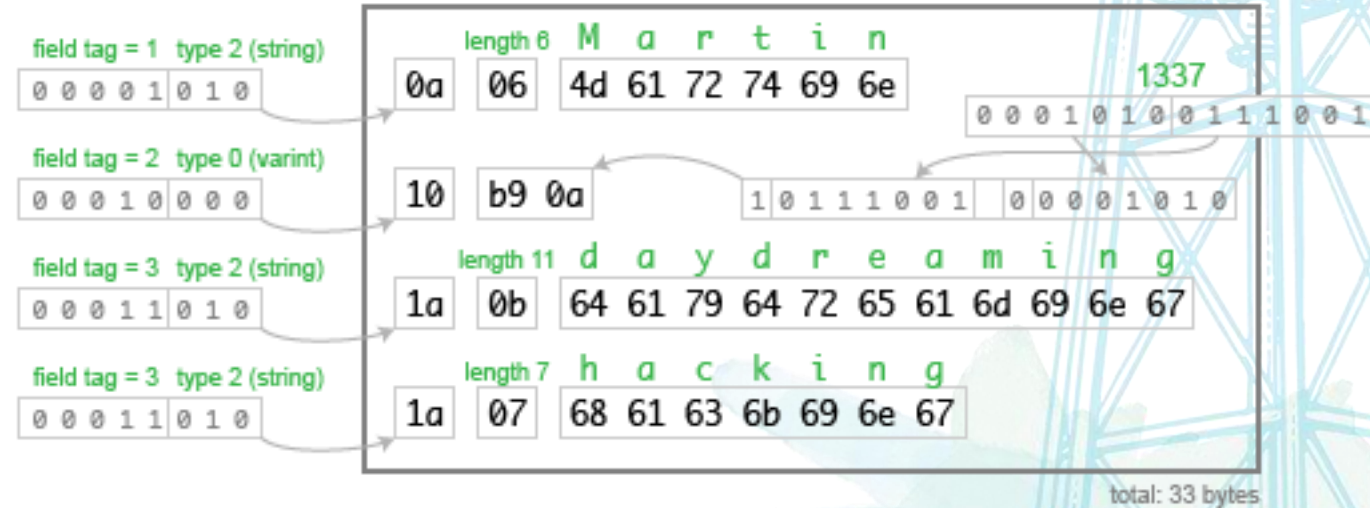
field tag = 3 type 2 (string)

0 0 0 1 1 0 1 0

field tag = 3 type 2 (string)

0 0 0 1 1 0 1 0

Binary representation

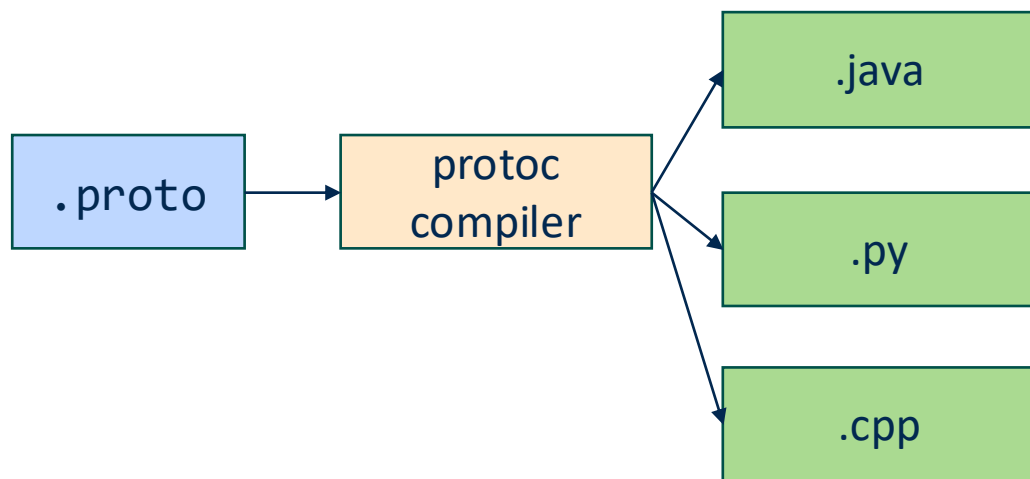


Binary data on the wire

0a	4d	61	72	74	69	6e	10	b9	0a	1a	0b
64	61	61	79	64	72	65	61	6d	69	6e	67
1a	07	68	61	63	6b	6e	67				

Codegen with protoc

- Invoke protoc to generate classes and service stubs
- `protoc -I . myservice.proto --java_out=./gen`



```
{  
  "userName": "Martin",  
  "favouriteNumber": 1337,  
  "interests": ["daydreaming", "hacking"]  
}  
  
// Proto schema  
message Person {  
  required string user_name = 1;  
  optional int64 favourite_number = 2;  
  repeated string interests = 3;  
}
```


Java codegen with protoc

- protoc generates Java code
 - Person class
 - Code to build the binary representation (serialization)
 - Parse a Person object from the binary representation (deserialization)
- Classes can be used by both the server and client

```
// PSEUDOCODE (protobuf version 2)

public final class Person {
    // -- snip (fields)
    // -- snip (getters and setters)

    // Serialization
    public byte[] toByteArray() { ... }
    public void writeTo(OutputStream out) { ... }
    public int getSerializedSize() { ... }

    // --- Deserialization (Des) ---
    public Person parseFrom(byte[] data) { ... }
    public Person parseFrom(InputStream in) { ... }
}
```

Generating gRPC endpoints

- Define the interface for service endpoints in .proto file
- The method name (SayHello) is the endpoint
 - Note: no URLs – gRPC is not HTTP
- Run protoc with --grpc-java_out=gen

```
// myservice.proto  
syntax = "proto3";
```

```
service Greeter {  
    rpc SayHello(HelloRequest) returns (HelloReply);  
}
```

```
message HelloRequest { string name = 1; }  
message HelloReply   { string msg  = 1; }
```

Generating gRPC endpoints

- Define the service endpoints in .proto file
- Run protoc with --grpc-java_out=gen

// Server code generated by protoc

```
public final class GreeterGrpc {  
    static final String SERVICE_NAME = "demo.Greeter";  
  
    public abstract static class GreeterImplBase  
        implements io.grpc.BindableService {  
  
        public void sayHello(HelloRequest req,  
            io.grpc.stub.StreamObserver<HelloReply>  
resp) {  
            resp.onError(... EXCEPTION ...);  
        }  
    }  
}
```

Generating gRPC endpoints

- Define the service endpoints in .proto file
- Run protoc with --grpc-java_out=gen
- Extend GreeterImplBase to provide functionality

```
public final class GreeterImpl extends  
GreeterGrpc.GreeterImplBase {
```

```
    @Override
```

```
    public void sayHello(  
        HelloRequest req,
```

```
        io.grpc.stub.StreamObserver<HelloReply> resp) {
```

```
        resp.onNext(  
            HelloReply.newBuilder().setMsg("hi " +  
                req.getName()).build());  
        resp.onCompleted();  
    }
```

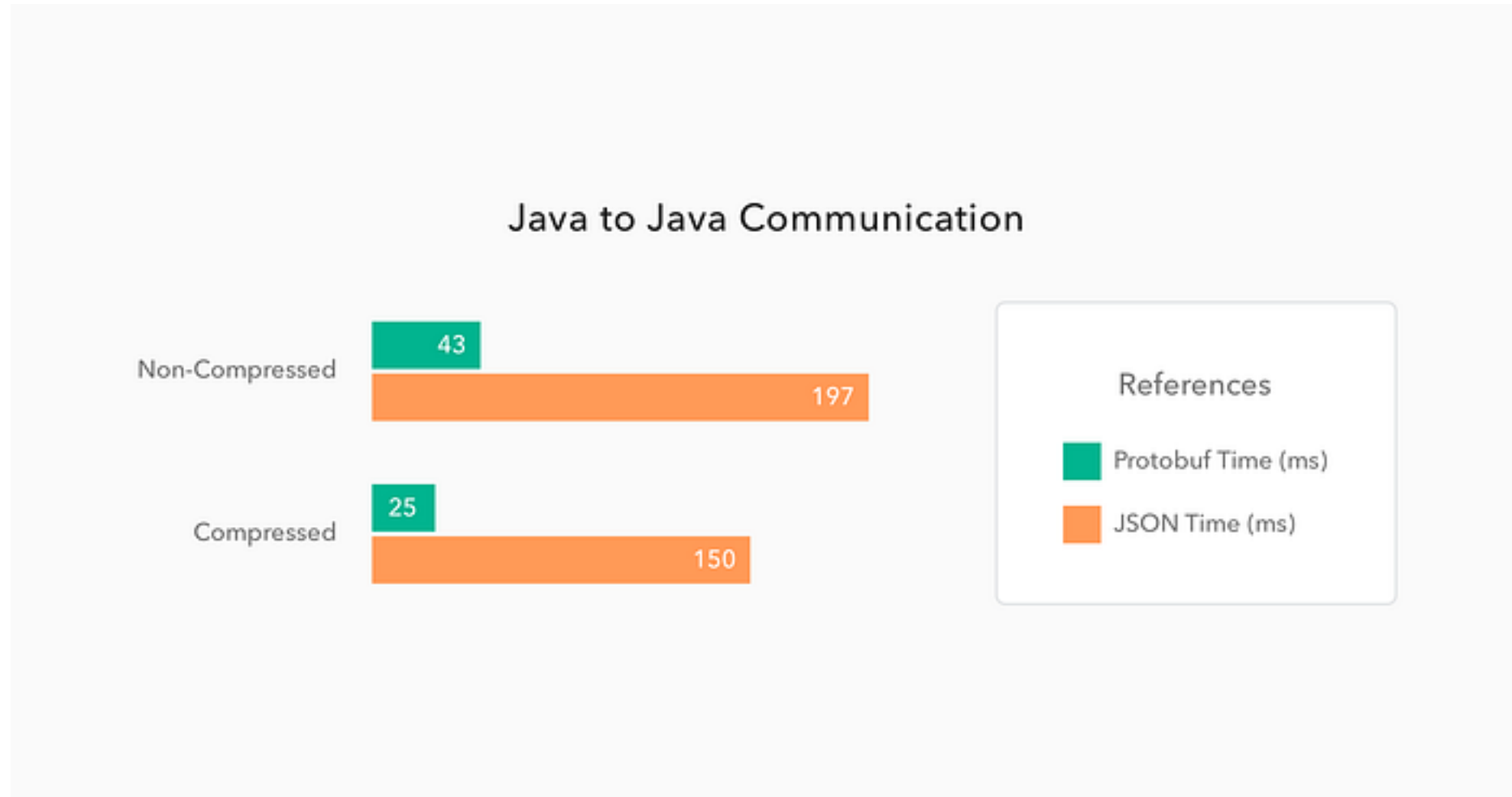
```
}
```

gRPC implications

- Protocol efficiency: high
- Type safety (schema adherence): high
 - If a field is missing, the ser-des logic will detect it and raise an Exception
- What about ease of debugging?
 - Ease of debugging: low

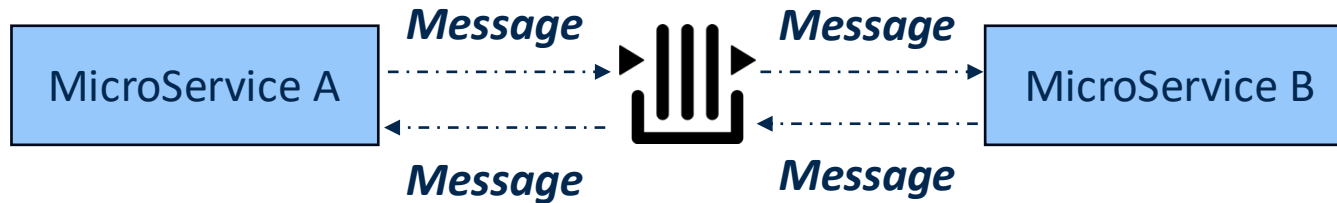
gRPC efficiency

<https://itnext.io/a-minimalist-guide-to-grpc-e4d556293422>



Message queuing (MQ)

- Asynchronous communication model
 - Messages sent to a queue and processed by consumers independently of the producer
 - Message queue is persistent (saved on disk)
- Stronger decoupling

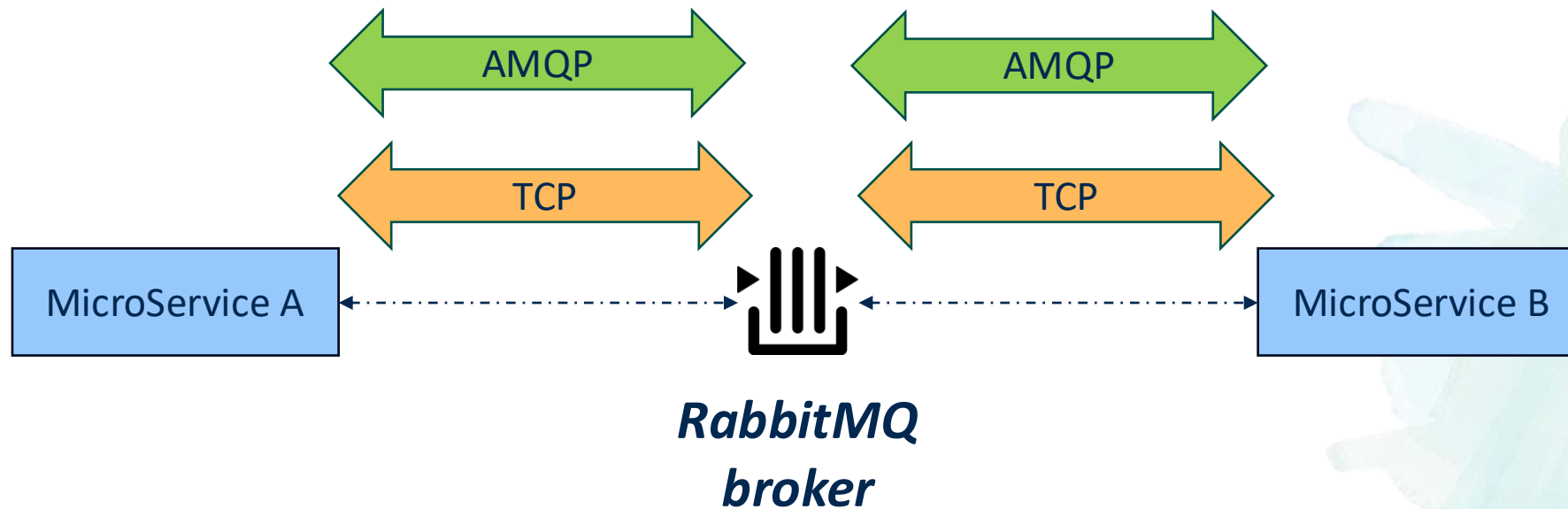


Message queuing (MQ)

- Application must be aware of asynchronicity
- Message sent not necessarily message delivered
- Publisher can request acks
 - When the message exchange has received the message and saved it durably

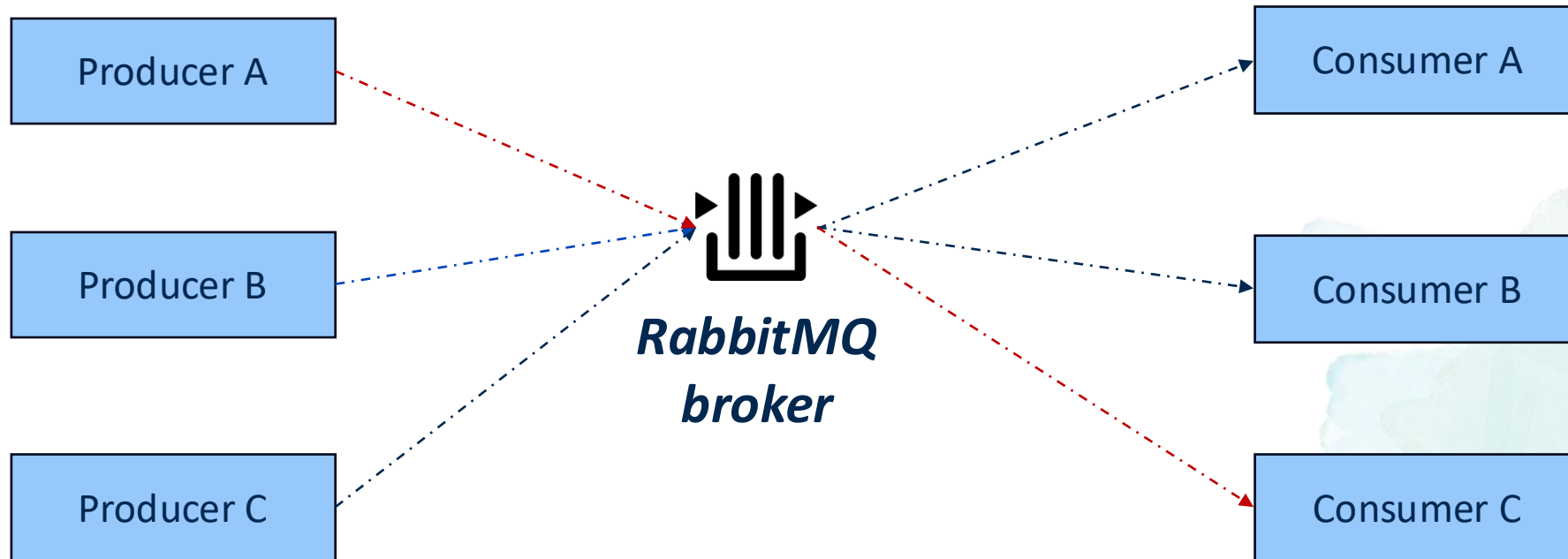
RabbitMQ

- Advanced Message Queuing Protocol (AMQP)
- Binary protocol running on TCP



AMQP model

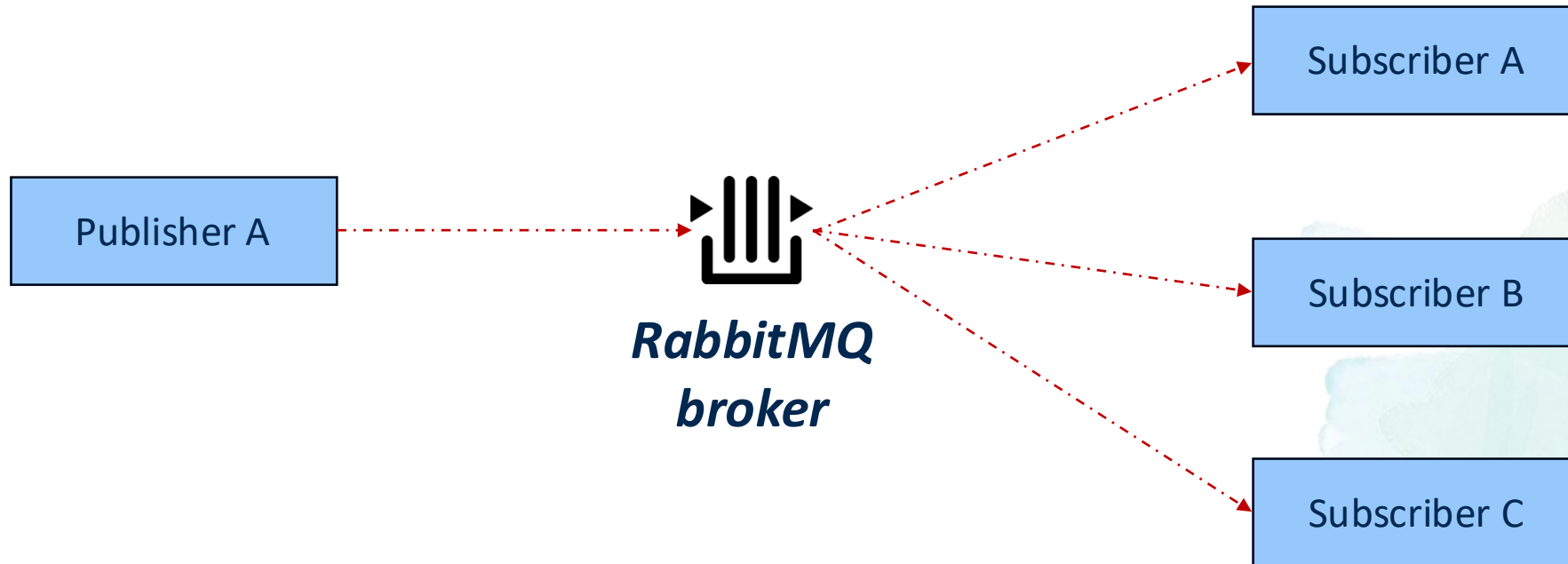
- The broker receives messages from publishers and route them to subscribers



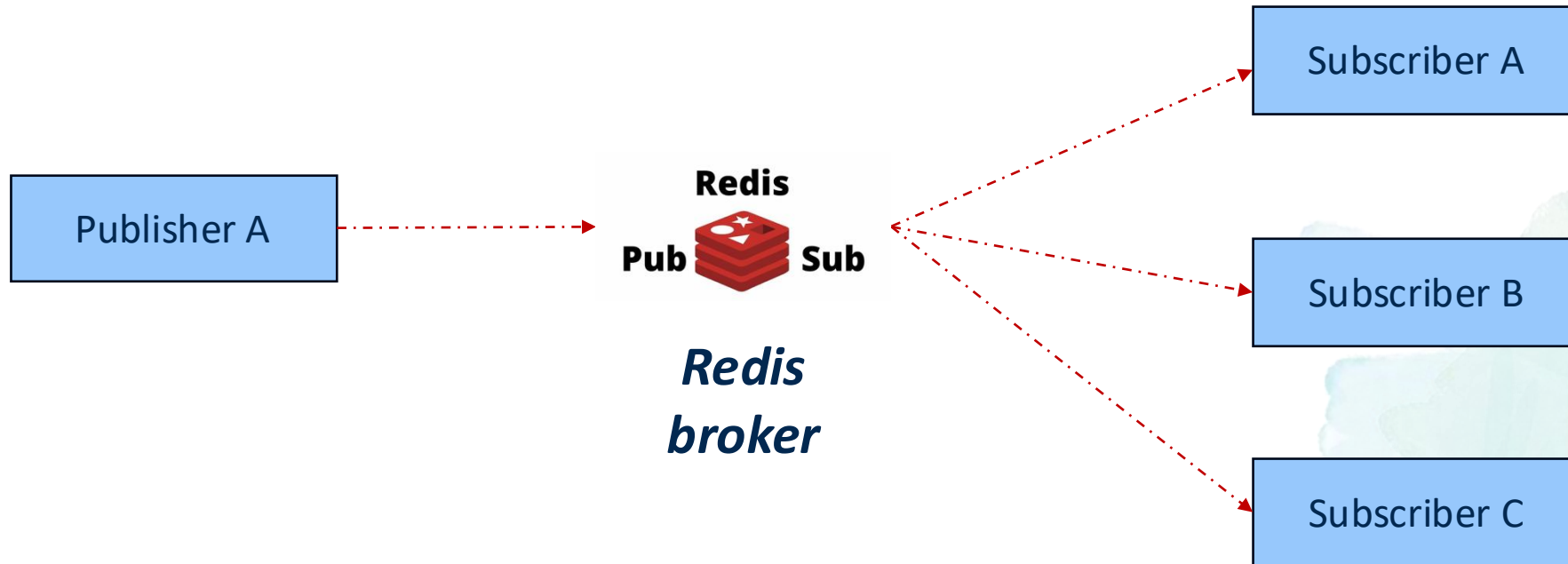
Pub-sub architecture

- 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

RabbitMQ as message broker

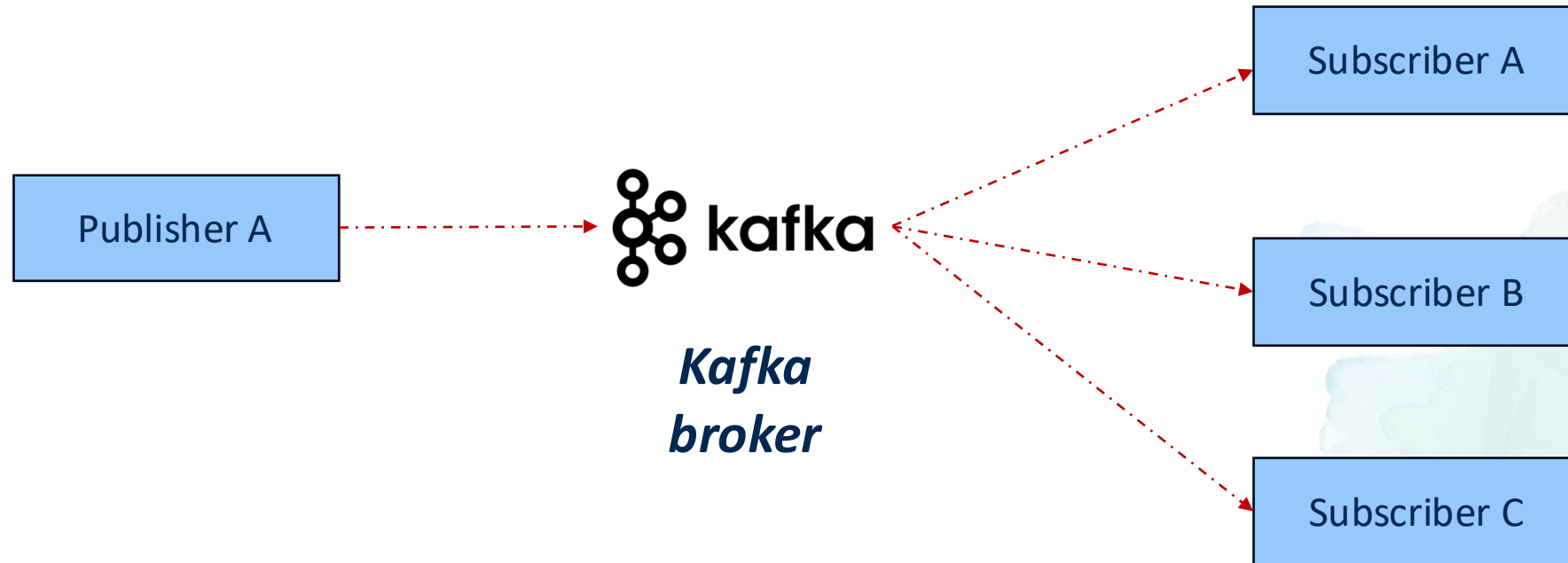


Redis as message broker



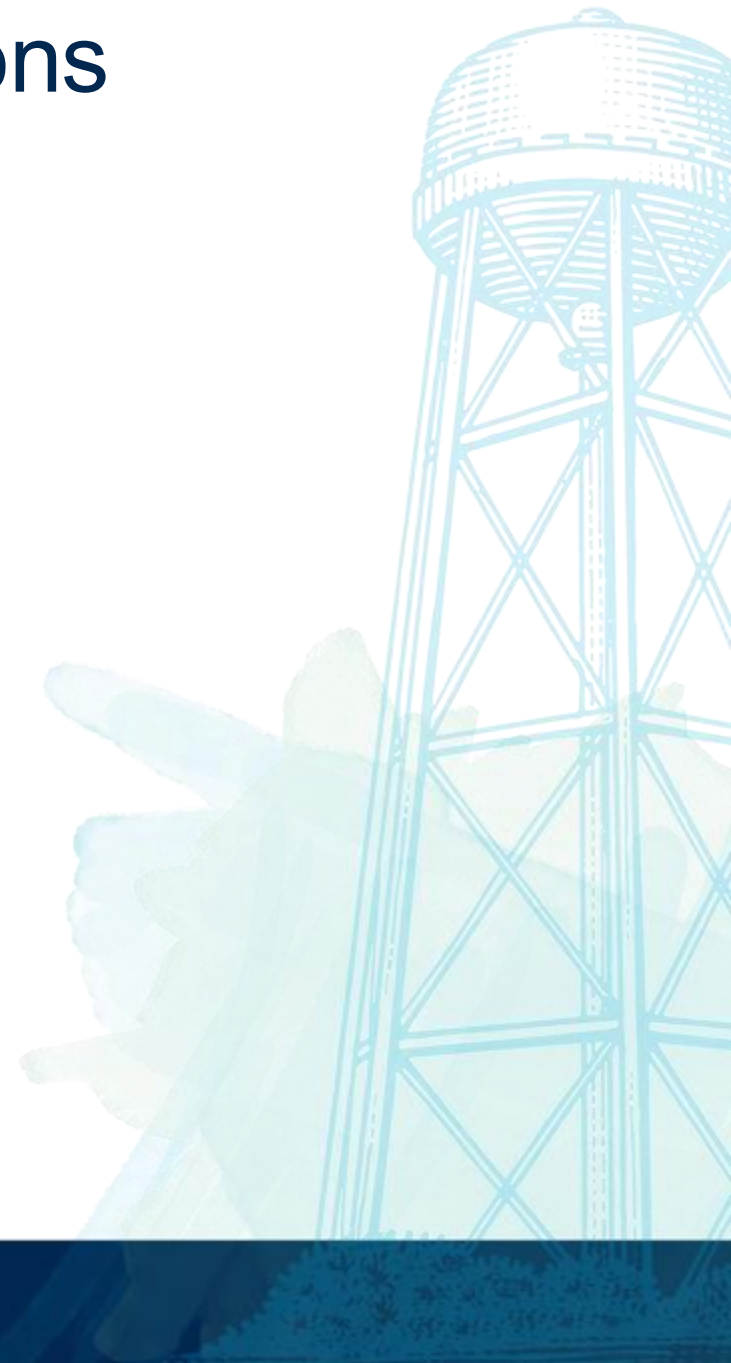
Kafka as message broker

[More in next module]



Message queues implications

- Strong decoupling
 - Consumer does not have to be running
 - Message persisted in the message queue
- Potentially increased latency
 - Increased number of hops
 - Overhead for persisting the message



Summary

- Microservices improve throughput
- Microservices allow each service to have its own database
 - Data models – relational, document model, key-value store
 - Storage engine – log-based and B-tree based
- Microservices can communicate
 - Synchronously (JSON over HTTP, gRPC)
 - Asynchronously (Message queues)
 - Event-driven pub/sub (Kafka – next module)

