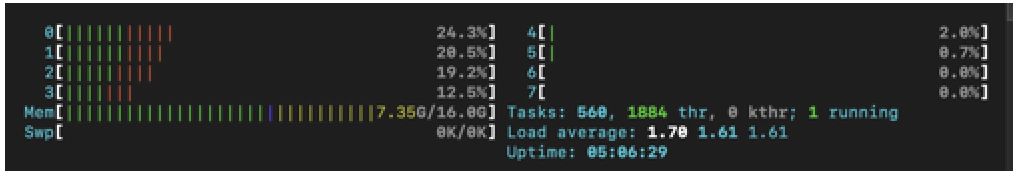
# Einführung

## «Parallele Systeme»

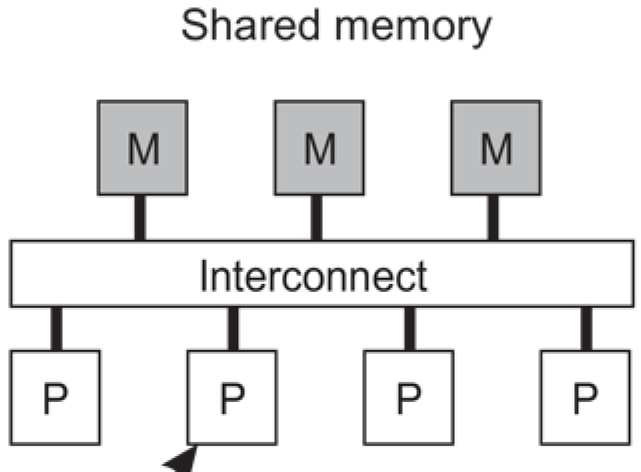
- Eine single core CPU kann nur einen Prozess gleichzeitig ausführen
- Multi-core CPUs entsprechend mehrere gleichzeitig
- Ausser in sehr einfachen Embedded Systemen müssen jedoch immer sehr viele Prozesse «gleichzeitig» ausgeführt werden

können z.B. auf einem Server oder auf einem Desktop Computer

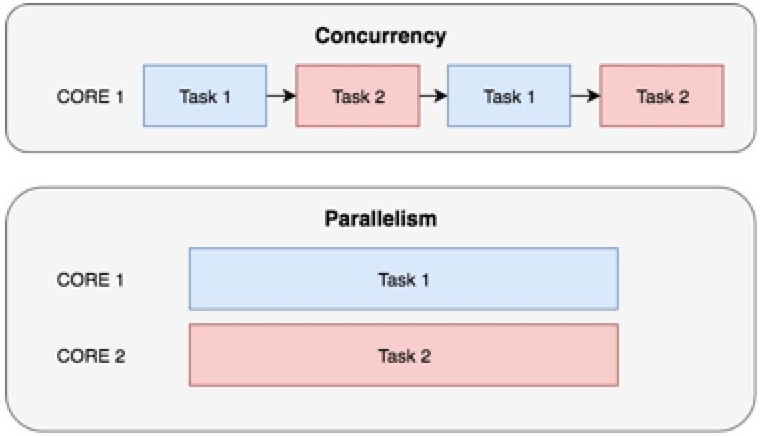


# «Parallele Systeme»

- Viele verschiedene Prozesse (tausende) werden von einem oder mehreren (bis zu dutzenden) Prozessoren ausgeführt
- Ein einzelner Prozessor kann demnach nacheinander mehrere Prozesse bearbeiten
- Die Prozessoren befinden sich auf demselben Chip oder auf dem selben Mainboard
- Sie haben geteilten sowie gemeinsamen Speicher
- Die Verbindung zwischen ihnen (Interconnect) hat geringe Latenz, hohe Bandbreite und ist zuverlässig.



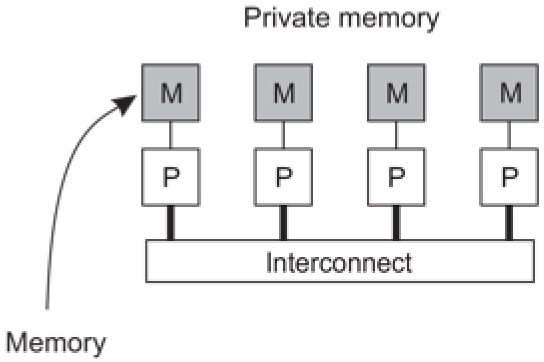
- Parallele Ausführung (parallelism): Mehr als eine Aufgabe wird gleichzeitig ausgeführt
- Nebenläufig (concurrency): Mehr als eine Aufgabe wird abgearbeitet (durch schnelles context switching)



- Eine zentrale Aufgabe von Betriebsystemen ist es, die Prozesse auf die CPUs zu verteilen.
- Dies wird «Scheduling» genannt.

# Verteilte Systeme

> «A distributed system is a collection of independent computers that appears to its users as a single coherent system.»



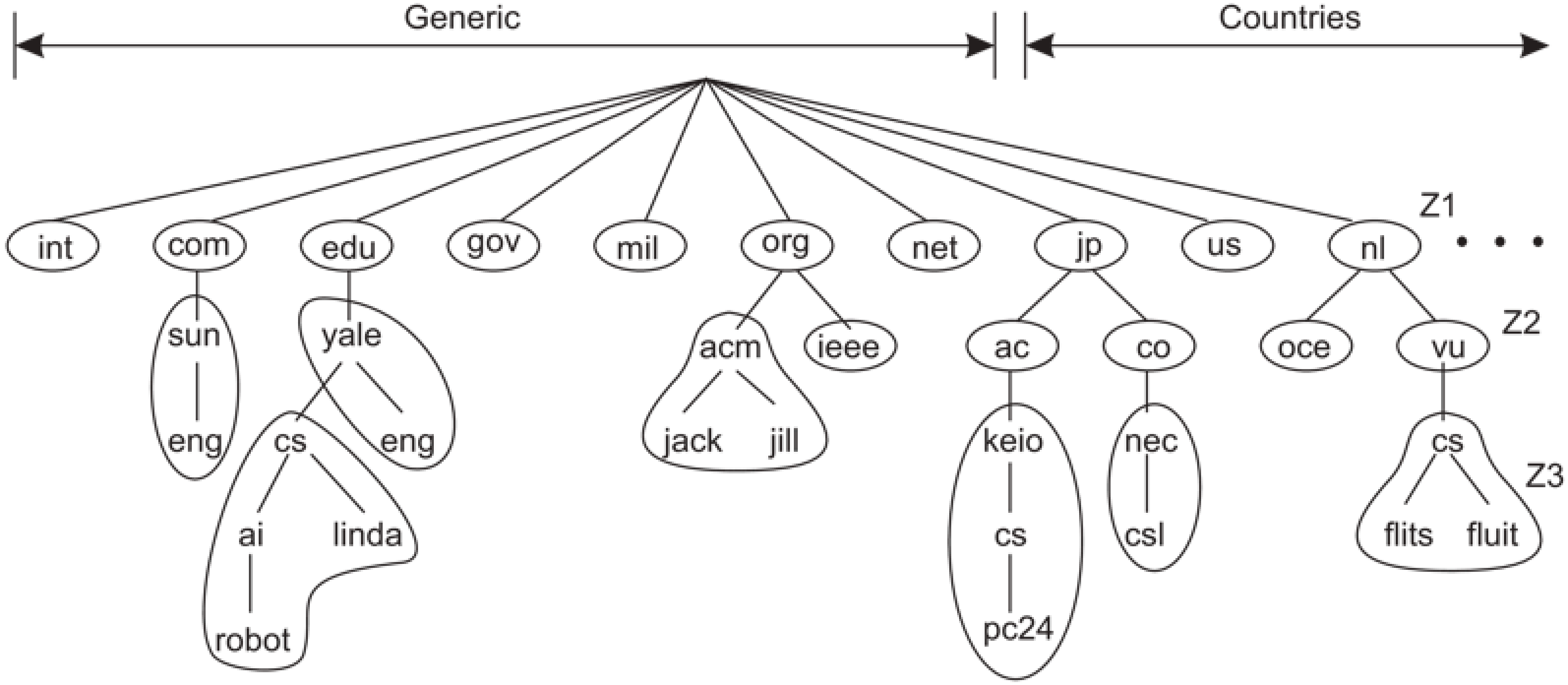

VanSteen, 2017, S. 26

P: Prozessor, Interconnect: Netzwerkverbindung, meistens HTTP, UDP/TCP, IP, Ethernet basiert

## Resource Sharing

- Ressourcen verfügbar machen: Drucker, Computing, Storage, Daten, Netzwerk
- Teure Ressourcen können besser ausgelastet werden und müssen nicht mehrfach angeschafft werden
- Zusammenarbeit

# Domain Name System



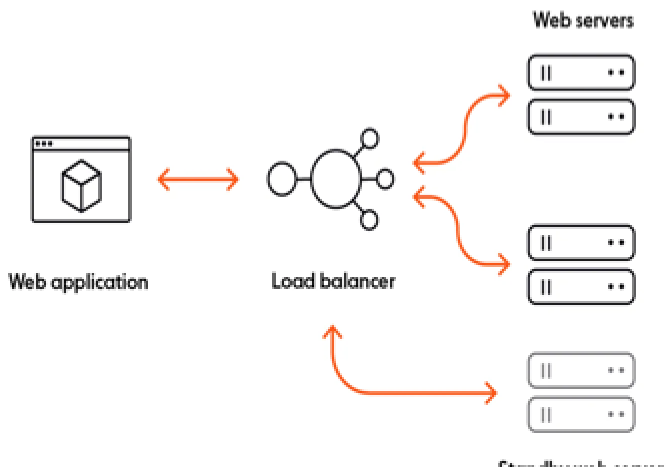

When the cloud leaves the datacenter
Meme-Generator.com

## Anforderungen an moderne Software

- Hohe Verfügbarkeit
- Skalierbarkeit
- Im Katastrophenfall sollen die Systeme schnell wiederhergestellt werden können
- Soll funktionieren, auch wenn Teile des Systems Offline sind (Resilienz)
- Kostengünstig
- Einfach
- Updates müssen einfach eingespielt werden können

# Lösungsansätze

- Replication: Masking Failures
- Tradeoff: Teuer und Komplex



# Populäre verteilte Systeme

- Matrix
- Mastodon
- Nextcloud
- CockroachDB
- Neon
- Ably
- ...

# Koordination

- Tasks können gleichzeitig ausgeführt werden
- Gleichzeitiger Zugriff auf gemeinsame Daten kann in inkonsistenten Daten resultieren

## Mutex

- MUTual EXclusion: wechselseitiger Ausschluss
- Einfachste Möglichkeit, Ressourcen für alle anderen zu blockieren
- Critical Section wird mit acquire() und release() umschlossen
- acquire() und release() müssen atomare Operationen sein (Hardwareunterstützung)

## Mutex

```
acquire() {
  while (!available)
    /* busy wait */
  available = false;;
}

release() {
  available = true;
}
```

```
do {
    acquire lock
       critical section
    release lock
      remainder section
 } while (true);
```

## Semaphore

- Mehr Möglichkeiten als Mutex
- Schützt gemeinsame Ressourcen
- Counting semaphore: Mehrere Ressourcen
- Binary semaphore: Nur eine Ressource
- Ein Zugriff auf eine gemeinsame Ressource wird mit dem Nehmen und Geben umschlossen

# Beispiel

```php
$semaphore = $this->createSemaphore($id);

sem_acquire($semaphore);
try {
    $entityPublishTime = $this->getEntityPublishTime($model, $id);

    if ($entityPublishTime < $messagePublishTime) {
        $returnCode = $this->saveStateToModel($model, $state, $data->timestamp);
    } else {
        $returnCode = 3;
    }
} finally {     // make sure to always release semaphore
    sem_release($semaphore);
}
```

# Time, clocks, and ordering of events

The following slides adapted of Martin Kleppmann's Course at University of Cambridge:

https://www.cl.cam.ac.uk/teaching/2425/ConcDisSys/materials.html

# Clocks and time in distributed systems

Distributed systems often need to measure time, e.g.:

- Schedulers, timeouts, failure detectors, retry timers
- Performance measurements, statistics, profiling
- Log files & databases: record when an event occurred
- Data with time-limited validity (e.g. cache entries)
- Determining order of events across several nodes

## Quartz clock error: drift

- One clock runs slightly fast, another slightly slow
- Drift measured in parts per million (ppm)
- 1 ppm = 1 microsecond/second = 86 ms/day = 32 s/year
- Most computer clocks correct within ≈ 50 ppm

## Atomic clocks

- Caesium-133 has a resonance
- Tune an electronic oscillator to that resonant frequency
- Accuracy ≈ 1 in 10–14 (1 second in 3 million years)

## GPS as time source

- 31 satellites, each carrying an atomic clock
- satellite broadcasts current time and location
- calculate position from speed-of-light delay between satellite and receiver

## Coordinated Universal Time (UTC)

Greenwich Mean Time (GMT, solar time): it’s noon when the sun is in the south, as seen from the Greenwich meridian

Synonym to GMT: Coordinated Universal Time (UTC)

International Atomic Time (TAI): 1 day is $24 \times 60 \times 60 \times 9{,}192{,}631{,}770$ periods of caesium-133’s resonant frequency

Problem: speed of Earth’s rotation is not constant

Compromise: UTC is TAI with corrections to account for Earth rotation

Time zones and daylight savings time are offsets to UTC

## How computers represent timestamps

Two most common representations:

- Unix time: number of seconds since 1 January 1970 00:00:00 UTC (the "epoch"), not counting leap seconds
- ISO 8601: year, month, day, hour, minute, second, and timezone offset relative to UTC example:
  `2021-11-09T09:50:17+00:00`

## Clock synchronisation

Computers track physical time/UTC with a quartz clock (with battery, continues running when power is off)

Due to clock drift, clock error gradually increases

Clock skew: difference between two clocks at a point in time

Solution: Periodically get the current time from a server that has a more accurate time source (atomic clock or GPS
receiver)

Protocols: Network Time Protocol (NTP), Precision Time Protocol (PTP)

## Ordering of messages

When using Timestamps to order events, order can be inconsistent with expected order!

- Clocks might not be synced
- One message might overtake another message in transit

# Causality

Taken from physics (relativity).

- When $a \to b$, then a might have caused b.
- When $a || b$, we know that a cannot have caused b.

Happens-before relation encodes potential causality.

## Logical vs. physical clocks

- Physical clock: count number of seconds elapsed
- Logical clock: count number of events occurred

Physical timestamps: useful for many things, but may be inconsistent with causality.

Logical clocks: designed to capture causal dependencies.

$$(e1 \rightarrow e2) \Rightarrow (T(e1) < T(e2))$$

- Lamport clocks
- Vector clocks

## Lamport clocks in words

- Each node maintains a counter t, incremented on every local event e
- Attach current t to messages sent over network
- Recipient moves its clock forward to timestamp in the message (if greater than local counter), then increments

Properties of this scheme:

- If $a \rightarrow b$ then $L(a) < L(b)$ (Let L(e) be the value of t after that increment)
- However, $L(a) < L(b)$ does not imply $a \rightarrow b$

# Replication

- Keeping a copy of the same data on multiple nodes: Databases, filesystems, caches, …
- A node that has a copy of the data is called a replica
- If some replicas are faulty, others are still accessible
- Spread load across many replicas
- Easy if the data doesn't change: just copy it
- We will focus on data changes

# Idempotence

A function f is idempotent if $f(x) = f(f(x))$.

Choice of retry behaviour:

- **At-most-once semantics:** send request, don’t retry, update may not happen
- **At-least-once semantics:** retry request until acknowledged, may repeat update
- **Exactly-once semantics:** retry + idempotence or deduplication

# "Consistency"

A word that means many different things in different contexts!

- **ACID**: a transaction transforms the database from one “consistent” state to another
  - Here, “consistent” = satisfying application-specific invariants e.g. “every course with students enrolled must
    have at least one lecturer”
- **Read-after-write consistency**
- **Replication**: replica should be “consistent” with other replicas
  - “consistent” = in the same state? (when exactly?)
  - “consistent” = read operations return same result?
- Consistency model: many to choose from

Recall atomicity in the context of ACID transactions:

- A transaction either commits or aborts
- If it commits, its updates are durable
- If it aborts, it has no visible side-effects
- ACID consistency (preserving invariants) relies on atomicity

## Strong Consistency: Linearizability

- Informally: every operation takes effect atomically sometime after it started and before it finished
- All operations behave as if executed on a single copy of the data (even if there are in fact multiple replicas)
- Consequence: every operation returns an “up-to-date” value, a.k.a. “strong consistency”

Linearizability advantages:

- Makes a distributed system behave as if it were non-distributed
- Simple for applications to use

Downsides:

- Performance cost: lots of messages and waiting for responses

## Eventual Consistency

- Eventual consistency: a weaker model than linearizability. Different trade-off choices.
- Replicas process operations based only on their local state.
- If there are no more updates, eventually all replicas will be in the same state.
- No guarantees how long it might take

# Local-first software

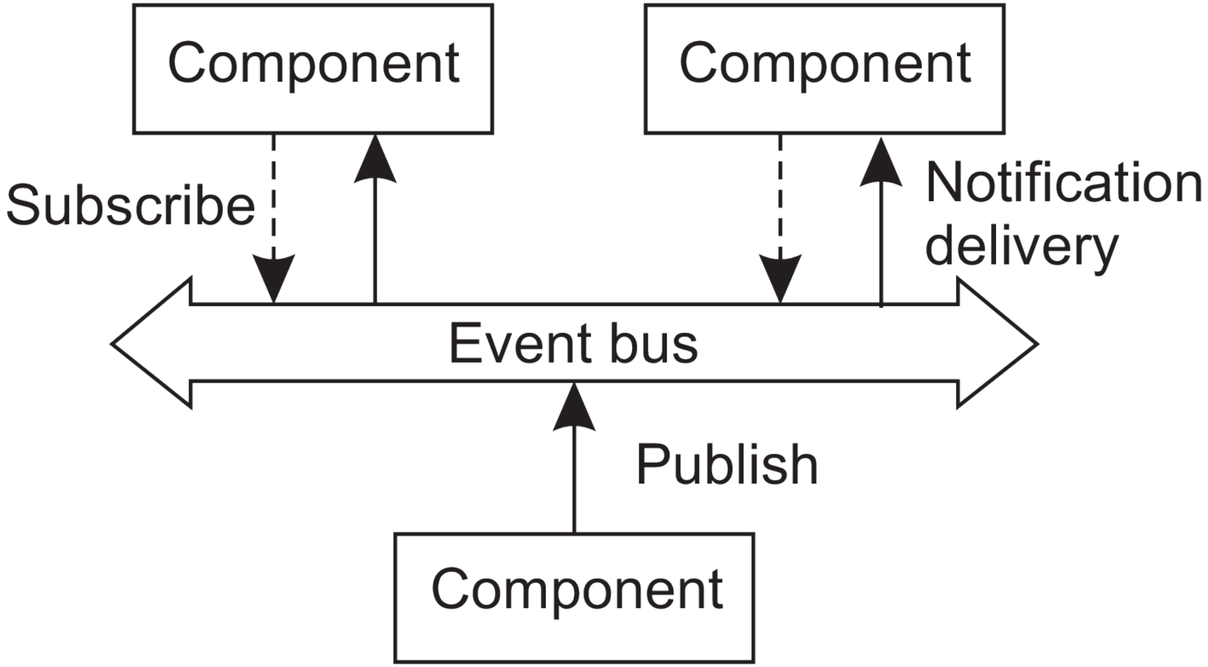
End-user device is a full replica; servers are just for backup. “Local-first”: a term introduced by me (Martin Kleppmann) and my colleagues https://www.inkandswitch.com/local-first/

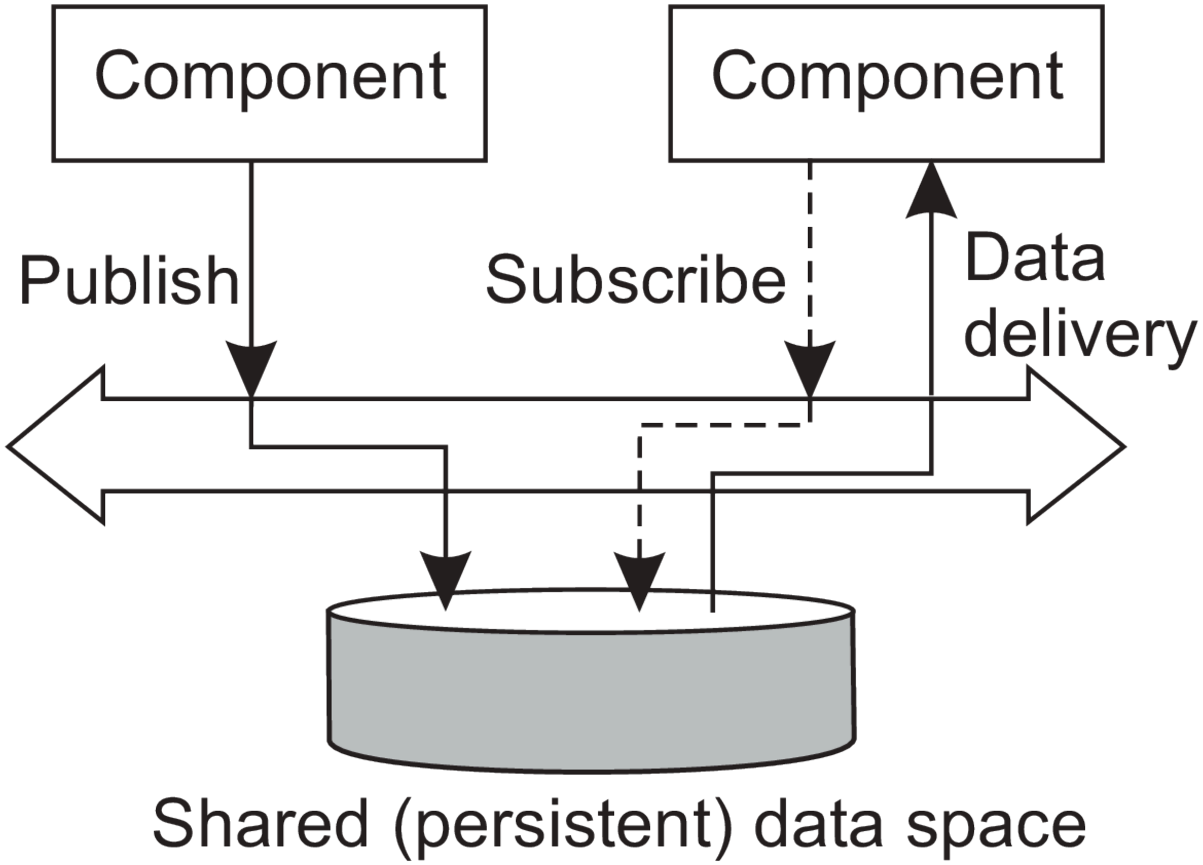
Calendar app with cross-device sync as an example:

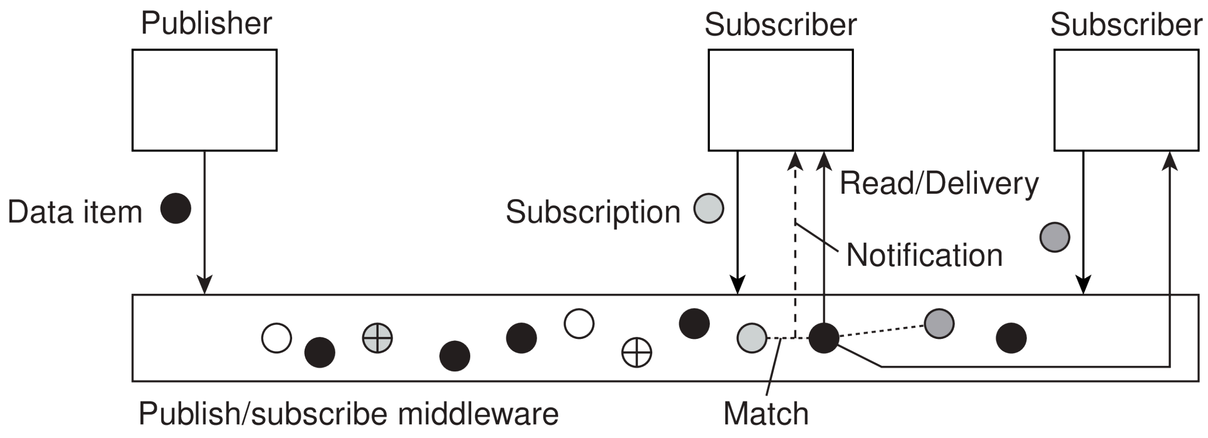
- App works offline (can both read and modify data)
- Fast: no need to wait for network round-trip
- Sync with other devices when online
- Real-time collaboration with other users
- Longevity: even if cloud service shuts down, you have a copy of your files on your own computer
- Supports end-to-end encryption for better security

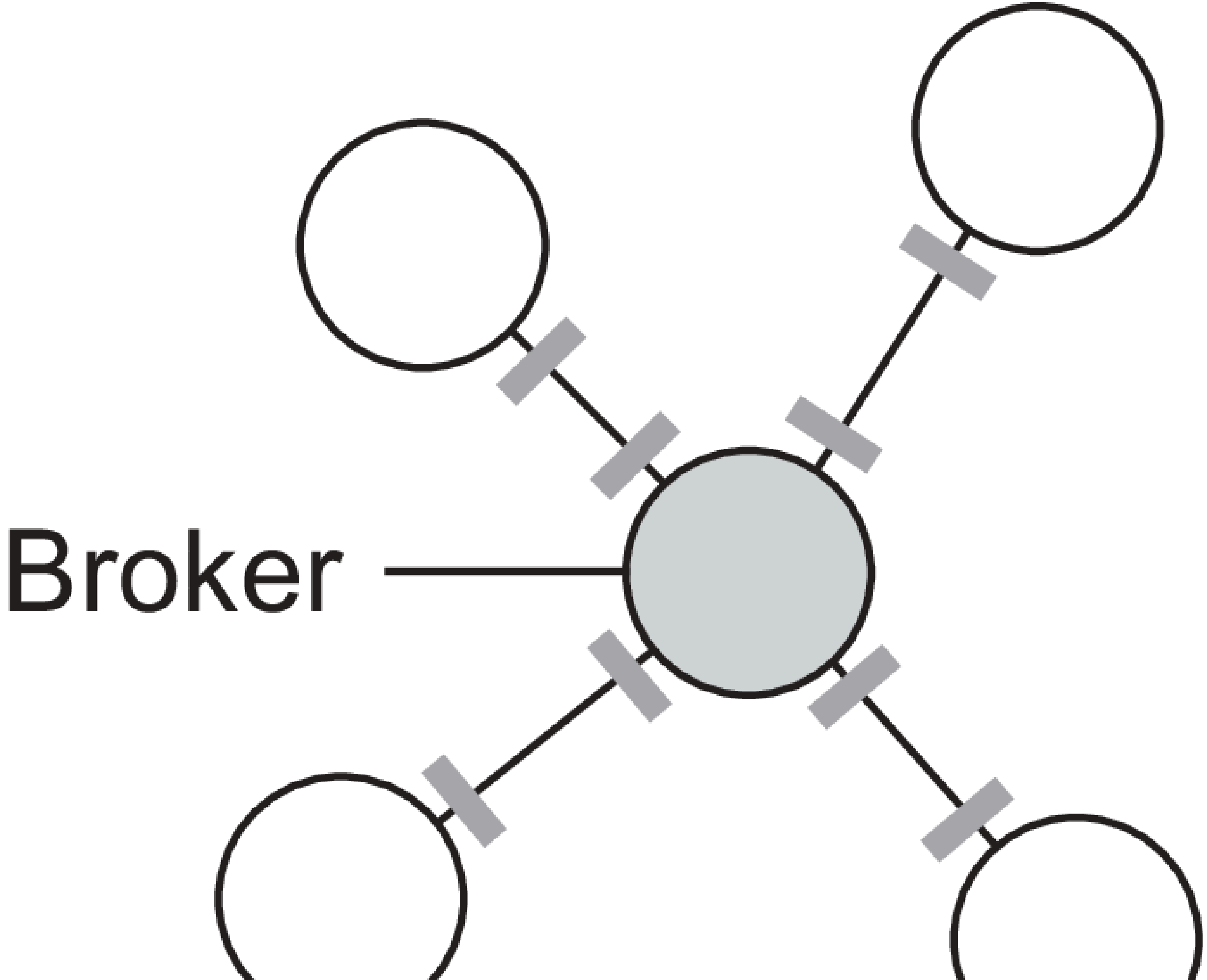
# Publish-subscribe Architekturen

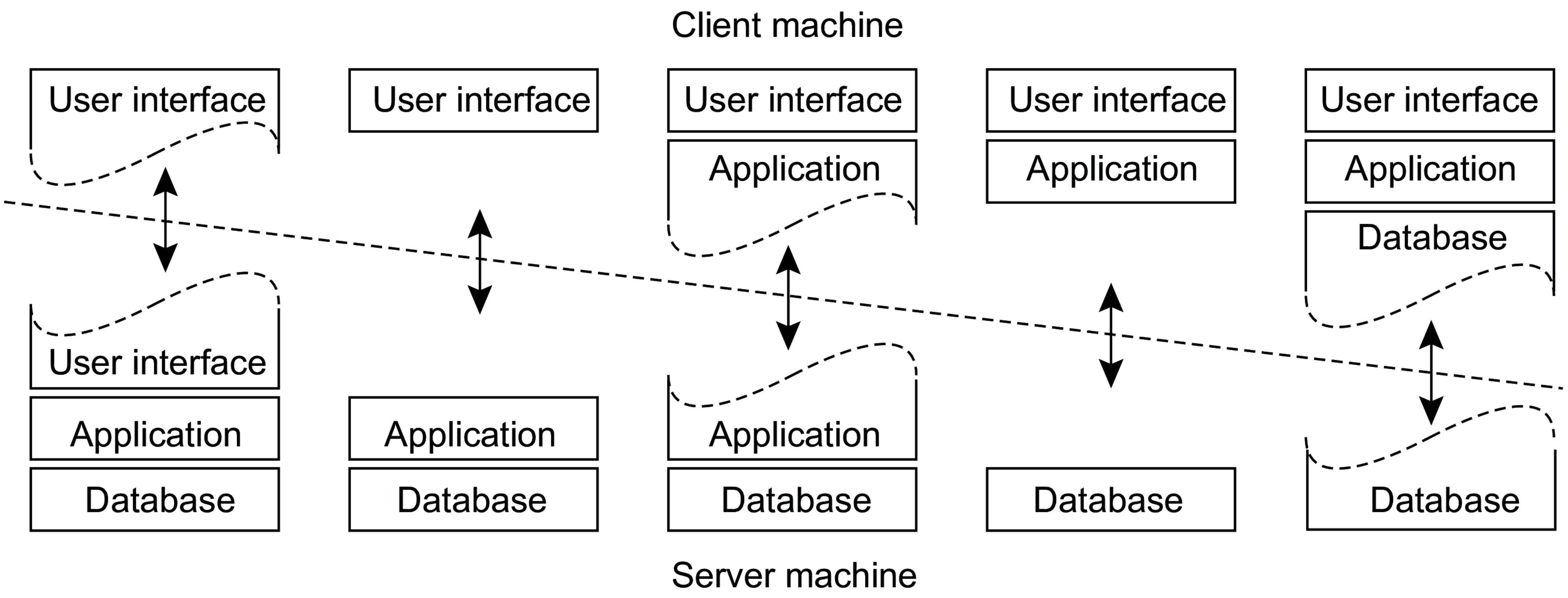
| | Temporally coupled | Temporally decoupled |
|---|---|---|
| **Referentially coupled** | Direct | Mailbox |
| **Referentially decoupled** | Event-based | Shared data space |


Component
Component
Subscribe
Notification delivery
Event bus
Publish
Component


Component
Component
Publish
Subscribe
Data
delivery
Shared (persistent) data space


Publisher
Subscriber
Subscriber
Data item
Subscription
Read/Delivery
Notification
Publish/subscribe middleware
Match


Broker

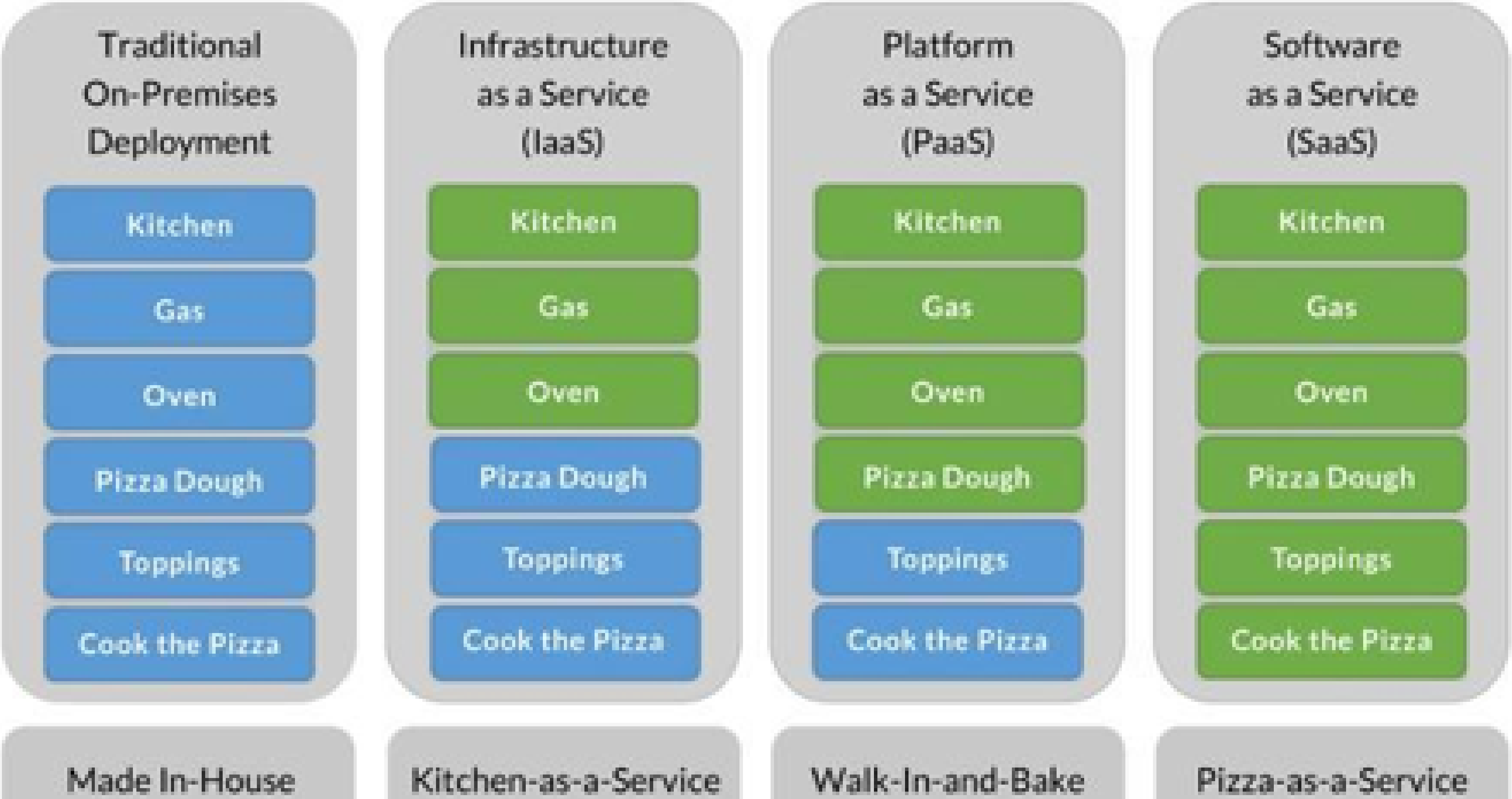

Client machine
User interface
User interface
User interface
Application
User interface
Application
User interface
Application
Database
User interface
Application
Database
Application
Database
Application
Database
Database
Database
Server machine

# Cloud und Edge Computing

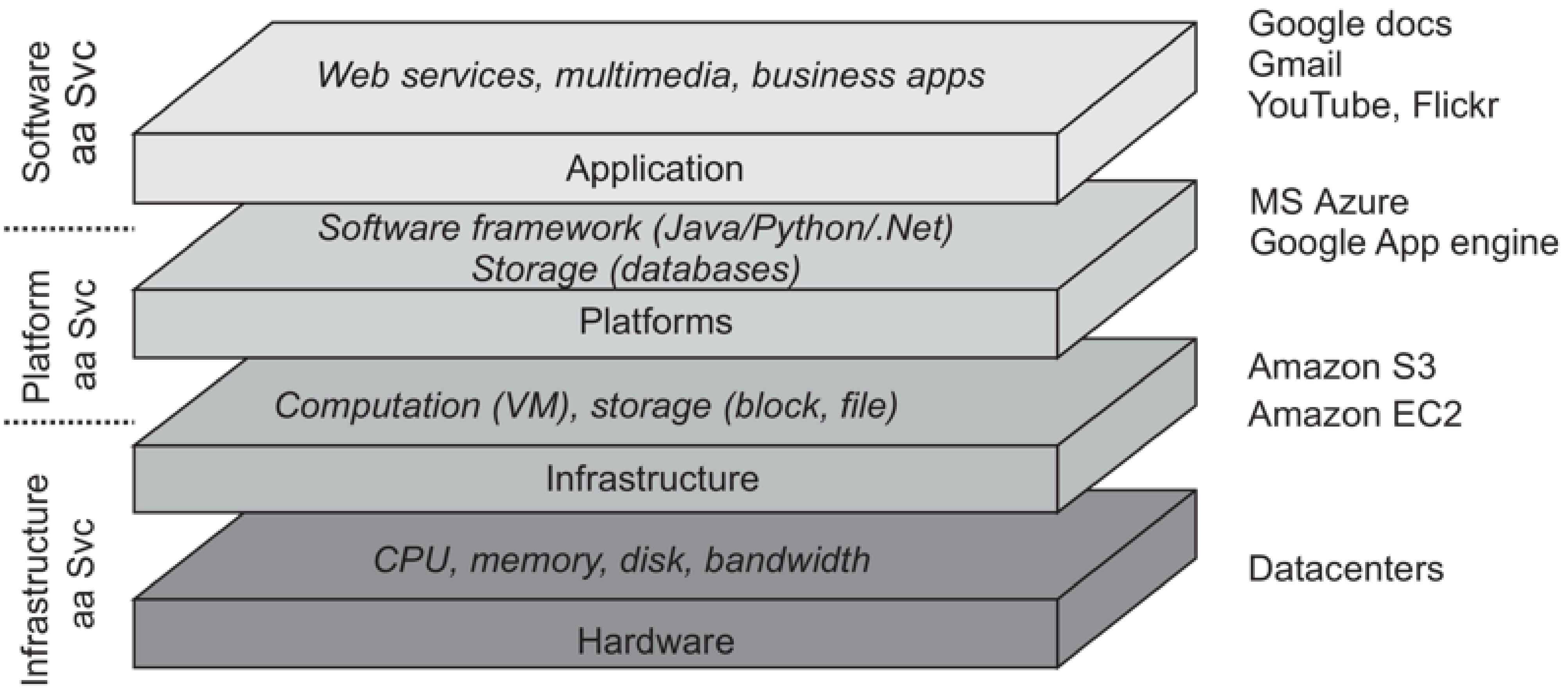
> The entire history of software engineering is that of the rise in levels of abstraction.

-- Grady Booch

# New Pizza as a Service

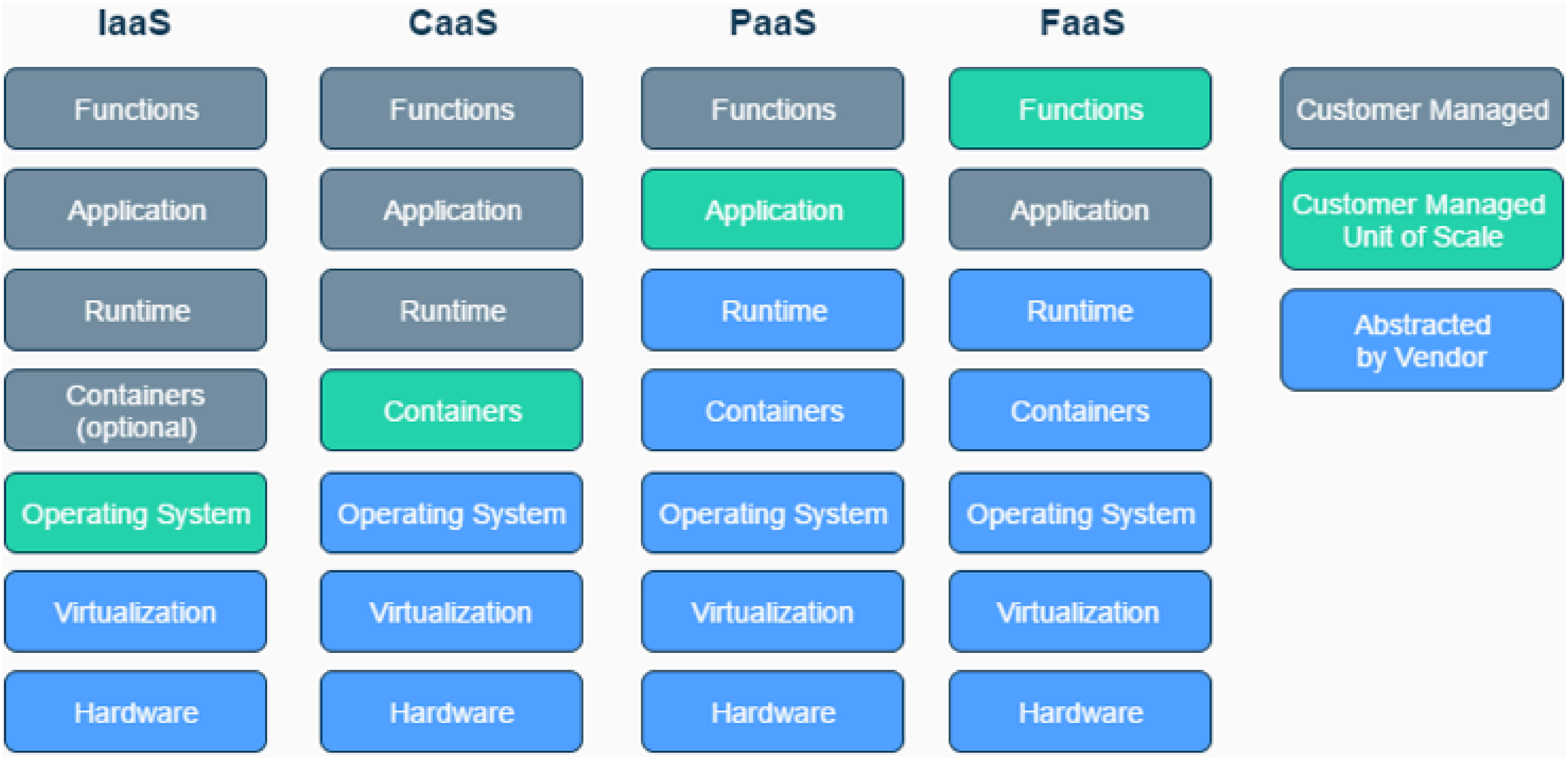


# Abstractions



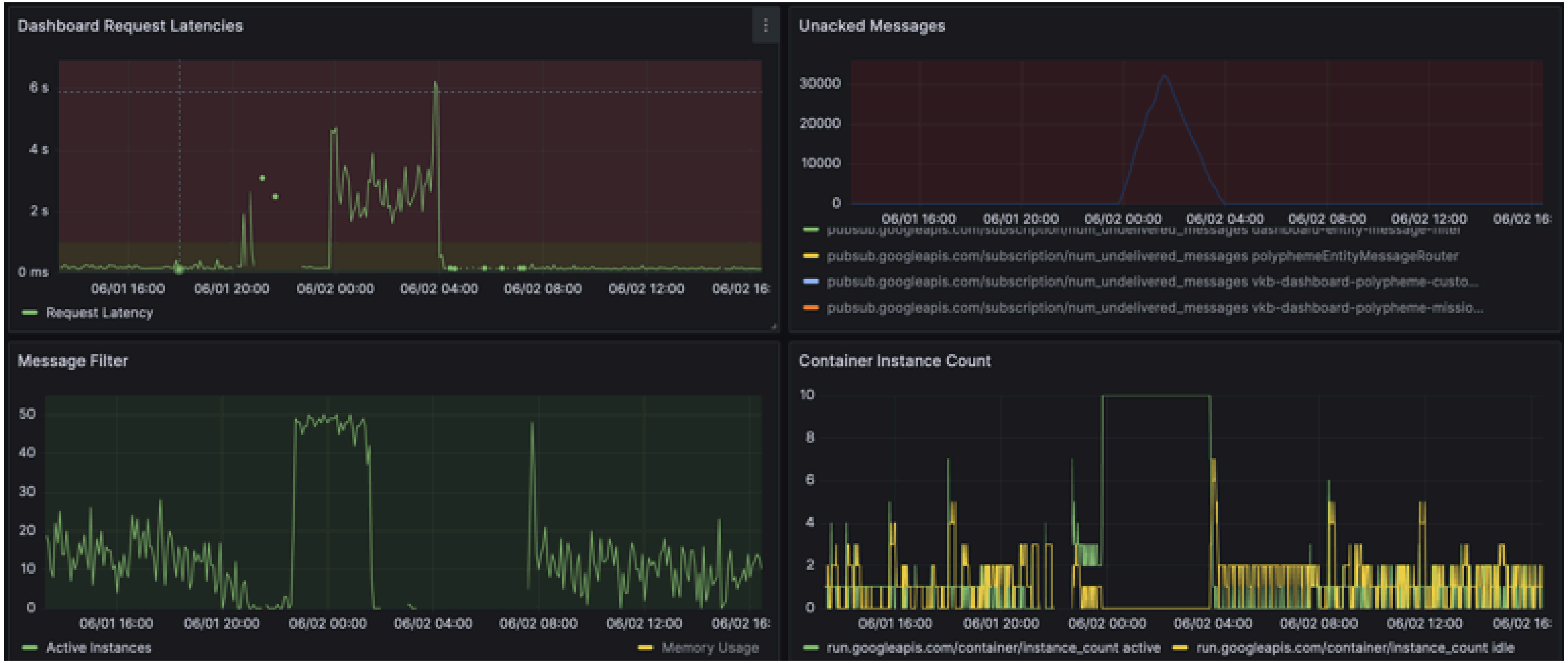

(VanSteen, 2017, S. 30)

# XaaS



IaaS
CaaS
PaaS
FaaS
Functions
Functions
Functions
Functions
Customer Managed
Application
Application
Application
Application
Customer Managed Unit of Scale
Runtime
Runtime
Runtime
Runtime
Abstracted by Vendor
Containers (optional)
Containers
Containers
Containers
Operating System
Operating System
Operating System
Operating System
Virtualization
Virtualization
Virtualization
Virtualization
Hardware
Hardware
Hardware
Hardware

# Fallstudie


Dashboard Request Latencies
6 s
4 s
2 s
0 ms
06/01 16:00
06/01 20:00
06/02 00:00
06/02 04:00
06/02 08:00
06/02 12:00
06/02 16:
Request Latency
Unacked Messages
30000
20000
10000
0
06/01 16:00
06/01 20:00
06/02 00:00
06/02 04:00
06/02 08:00
06/02 12:00
06/02 16:
pubsub.googleapis.com/subscription/num_undelivered_messages polyphemeEntityMessageRouter
pubsub.googleapis.com/subscription/num_undelivered_messages vkb-dashboard-polypheme-custo...
pubsub.googleapis.com/subscription/num_undelivered_messages vkb-dashboard-polypheme-missio...
Message Filter
50
40
30
20
10
0
06/01 16:00
06/01 20:00
06/02 00:00
06/02 04:00
06/02 08:00
06/02 12:00
06/02 16:
Active Instances
Memory Usage
Container Instance Count
10
8
6
4
2
0
06/01 16:00
06/01 20:00
06/02 00:00
06/02 04:00
06/02 08:00
06/02 12:00
06/02 16:
run.googleapis.com/container/instance_count active
run.googleapis.com/container/instance_count idle

# Edge Computing