Data-Oriented Architectures

Christian Cabrera

University of Cambridge

08/11/2024

Previously...

- The Systems Engineering Approach

Previously...

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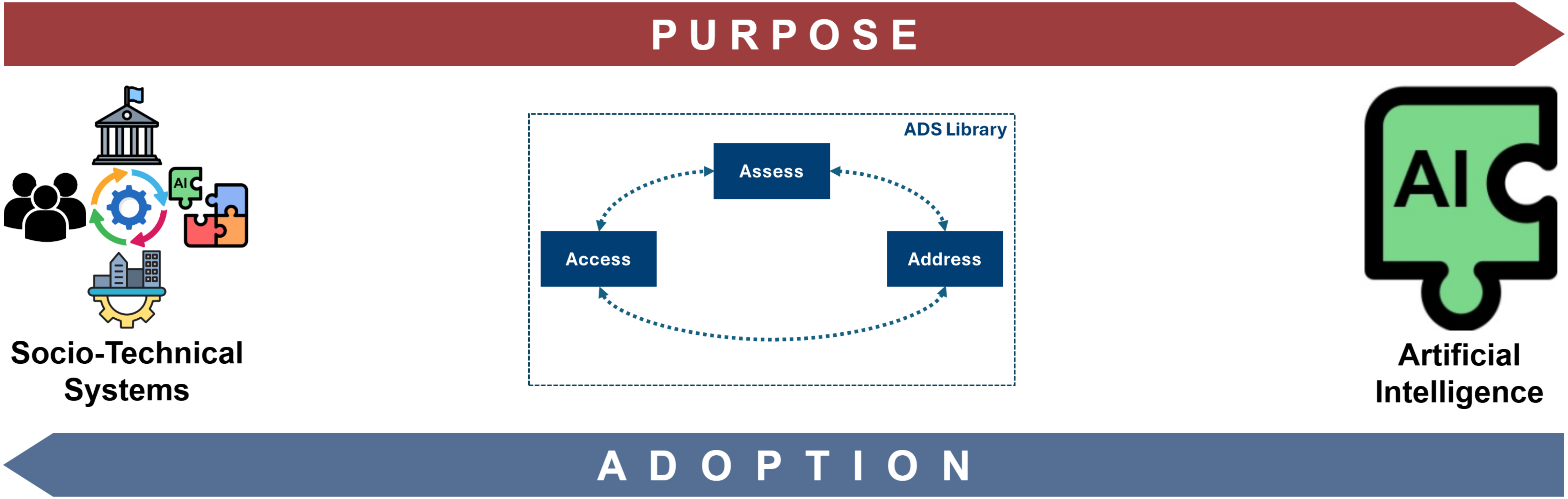
- **Systems Thinking:** System Views, Agility System, and System Dynamics.

- **Process Model**: Top-Down Analysis, Variant Creation and Problem-Solving Cycle.

Previously

- The Systems Engineering Approach



PURPOSE

Socio-Technical Systems

ADS Library

Assess

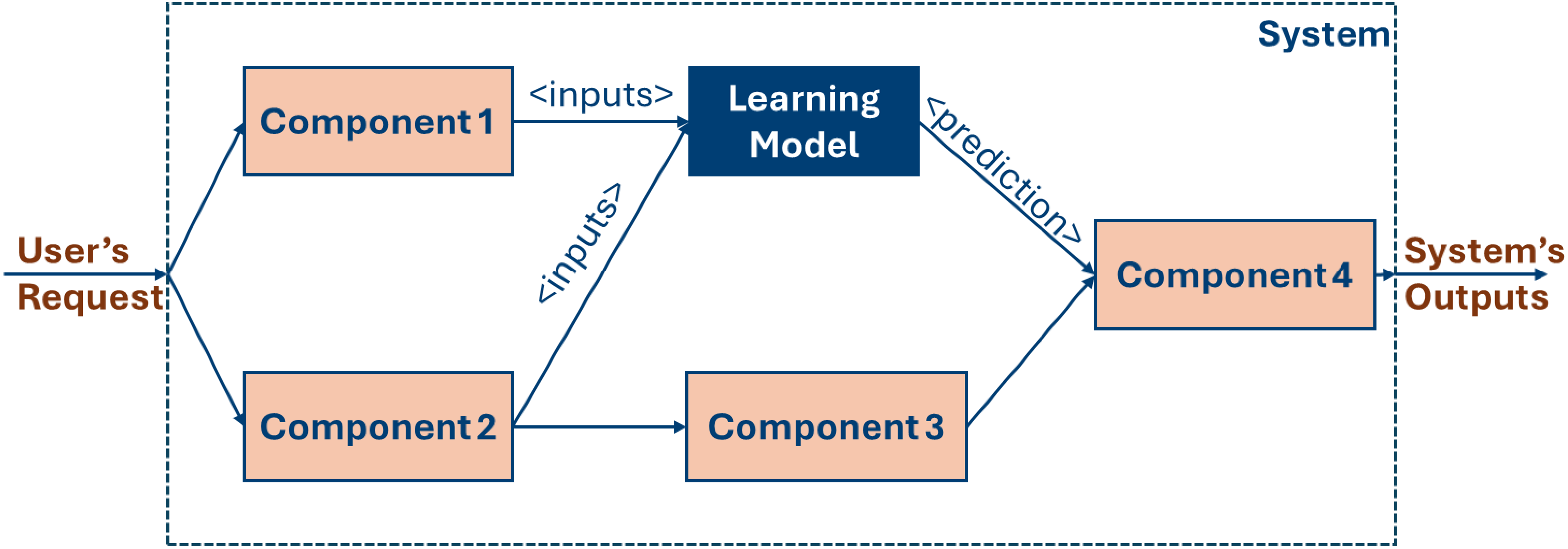
Access

Address

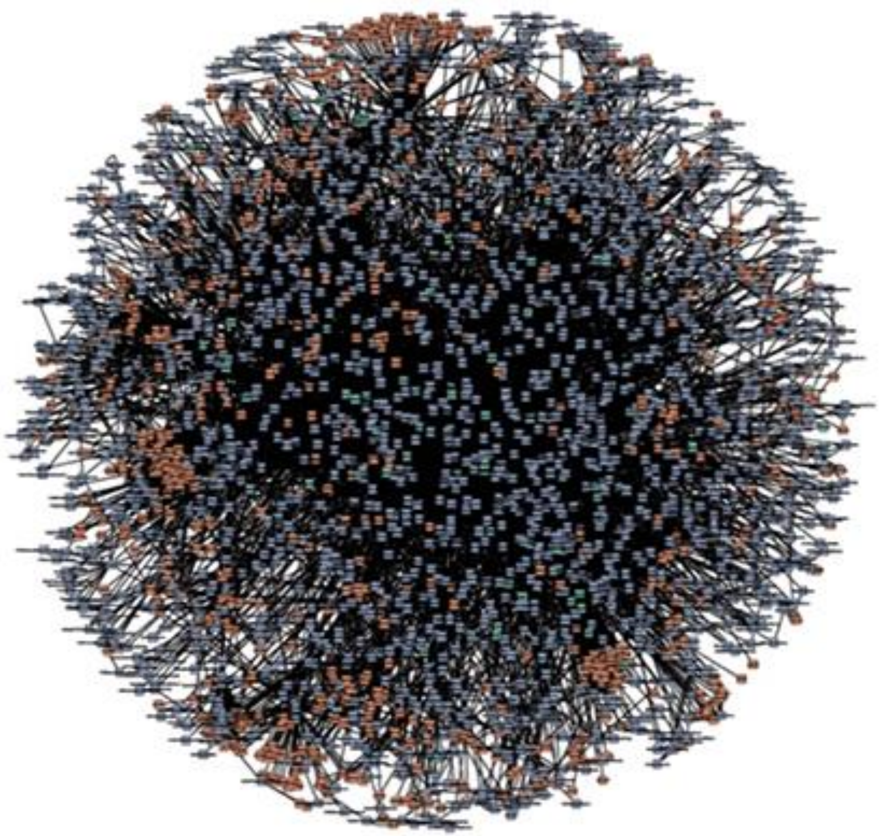
Artificial Intelligence

ADOPTION

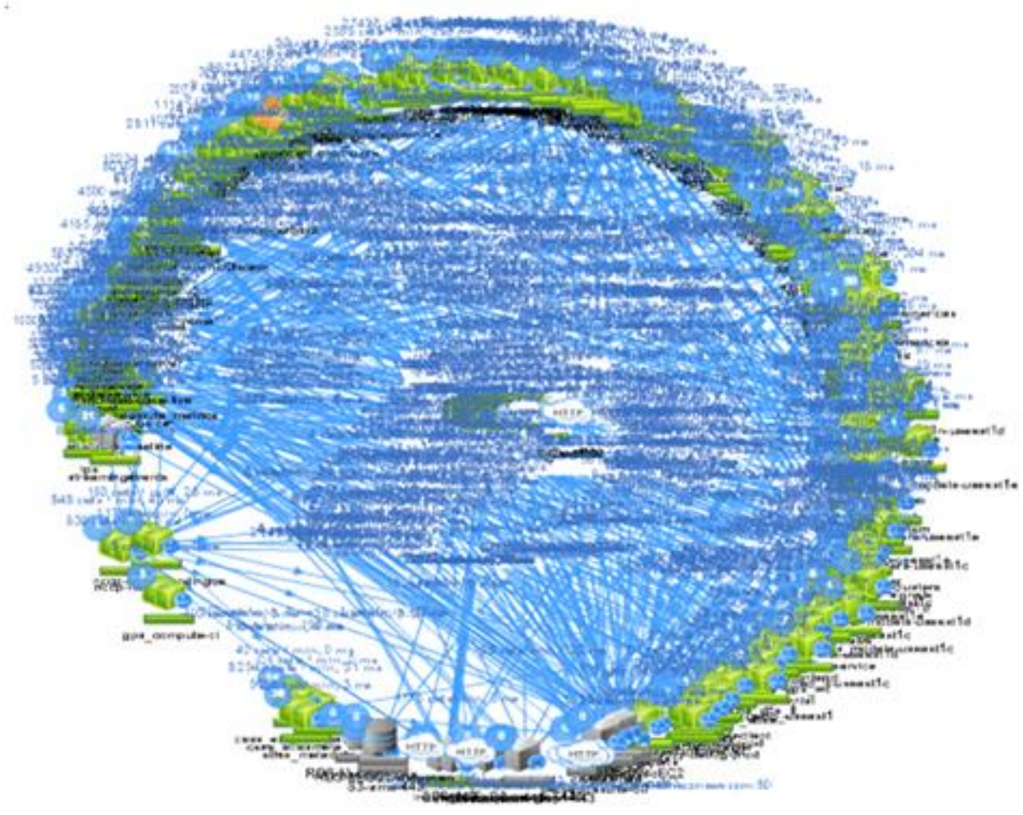
Real-world Deployments



Real-world Deployments



amazon.com



NETFLIX

Source: https://www.divante.com/blog/10-companies-that-implemented-the-microservice-architecture-and-paved-the-way-for-others

Systems Design

Systems’ design decisions change from system to system…

Systems Design

Systems' design decisions change from system to system...

But we can identify common requirements between software systems.

Systems Design

Systems’ design decisions change from system to system...

But we can identify common requirements between software systems.

Based on these commonalities we can define design patterns and systems architectures.

Systems Design

Systems in the age of the Internet required:

- Separation of concerns
- High availability
- Scalability
- Low Latency

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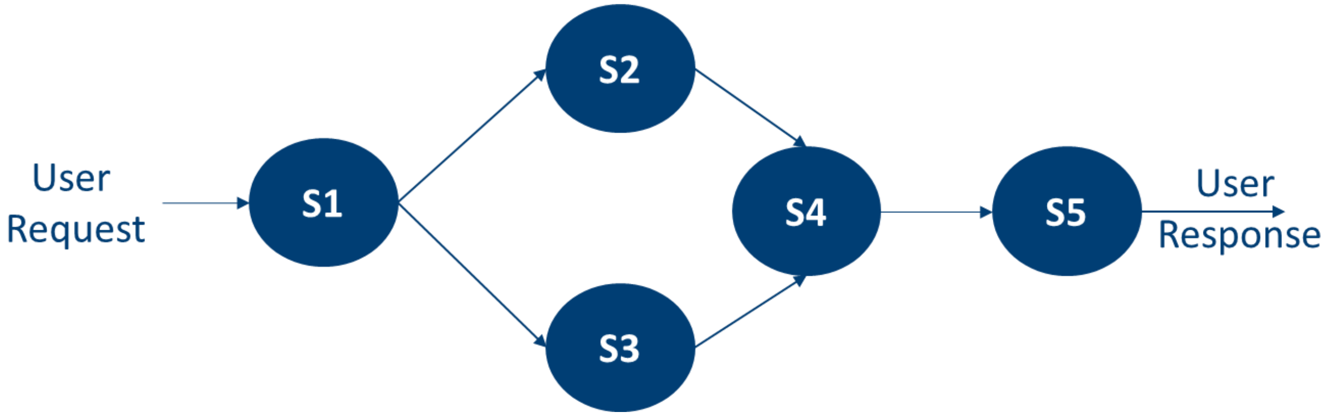
Service-oriented Architectures (SOAs)



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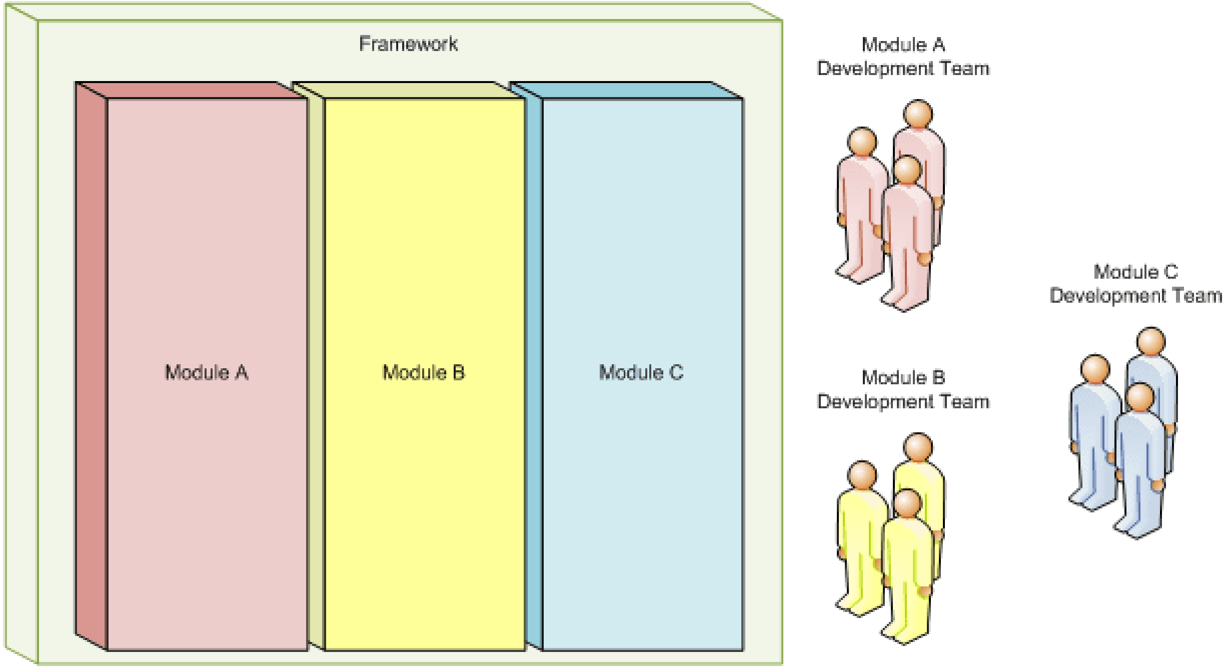
Framework
Module A
Module B
Module C
Module A Development Team
Module B Development Team
Module C Development Team

Source: https://dev.to/suspir0n/soc-separation-of-concerns-5ak7

Systems Design

Systems in the age of the Internet required:

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- **High availability**
- **Scalability**
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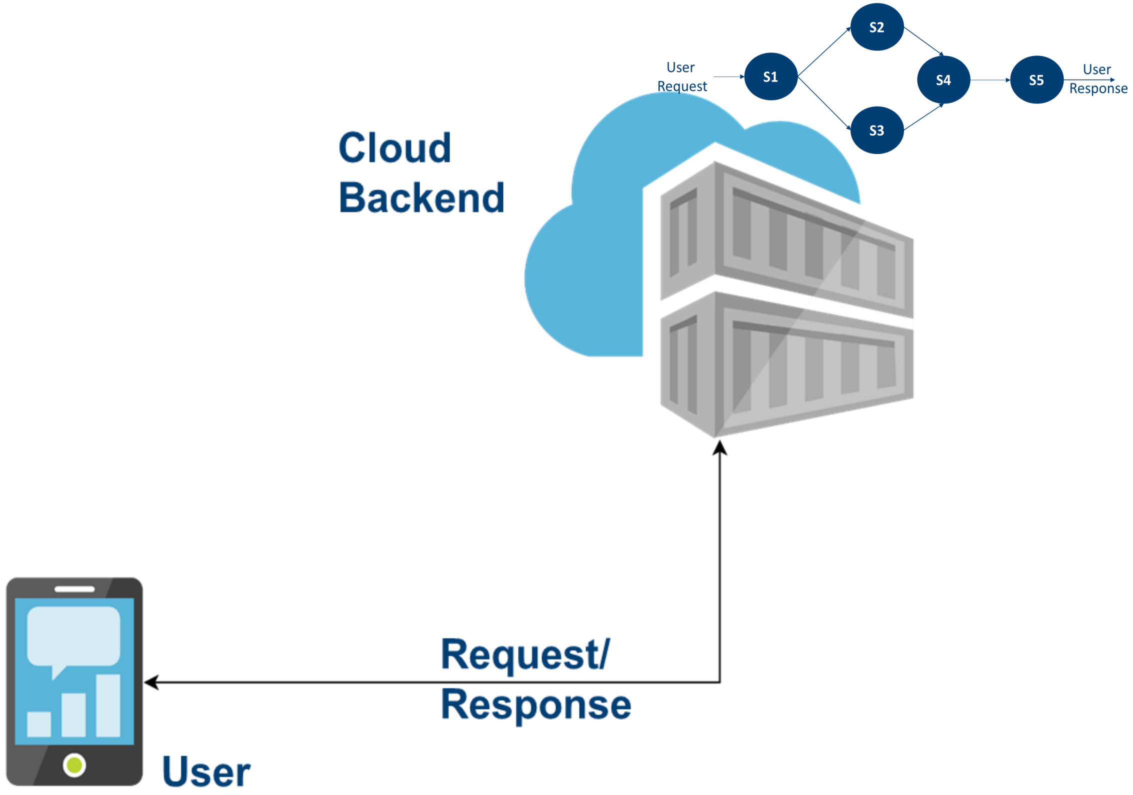
Service-oriented Architectures (SOAs)



AI Systems Design

Systems in the age of AI are data-driven:

- Data availability
- Data ownership
- Data traceability and monitoring
- Super-low latency requirements
- Sustainability

AI Systems Design

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Service-oriented Architectures (SOAs)

The Data Dichotomy:

“While data-driven systems are about exposing data, service-oriented architectures are about hiding data.” [1]

[1] Stopford B., The Data Dichotomy: Rethinking the Way We Treat Data and Services. https://www.confluent.io/en-gb/blog/data-dichotomy-rethinking-the-way-we-treat-data-and-services

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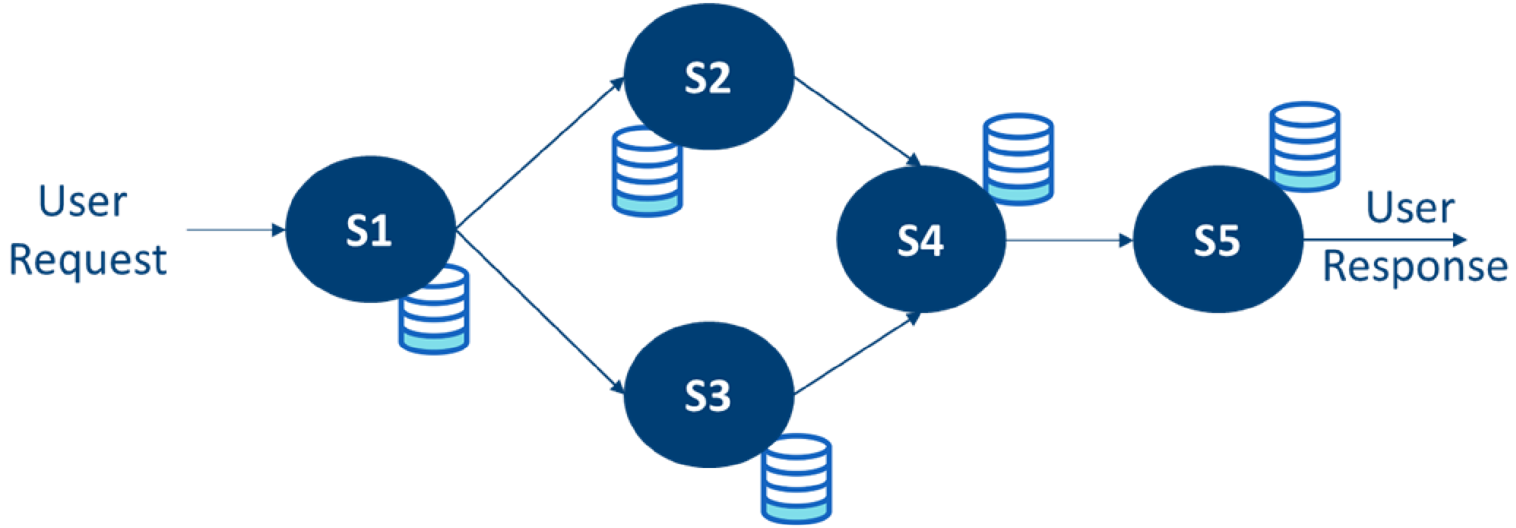

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AI Systems Design

The Data Dichotomy:

“While data-driven systems are about exposing data, service-oriented architectures are about hiding data.” [1]

We need to design systems prioritising data!

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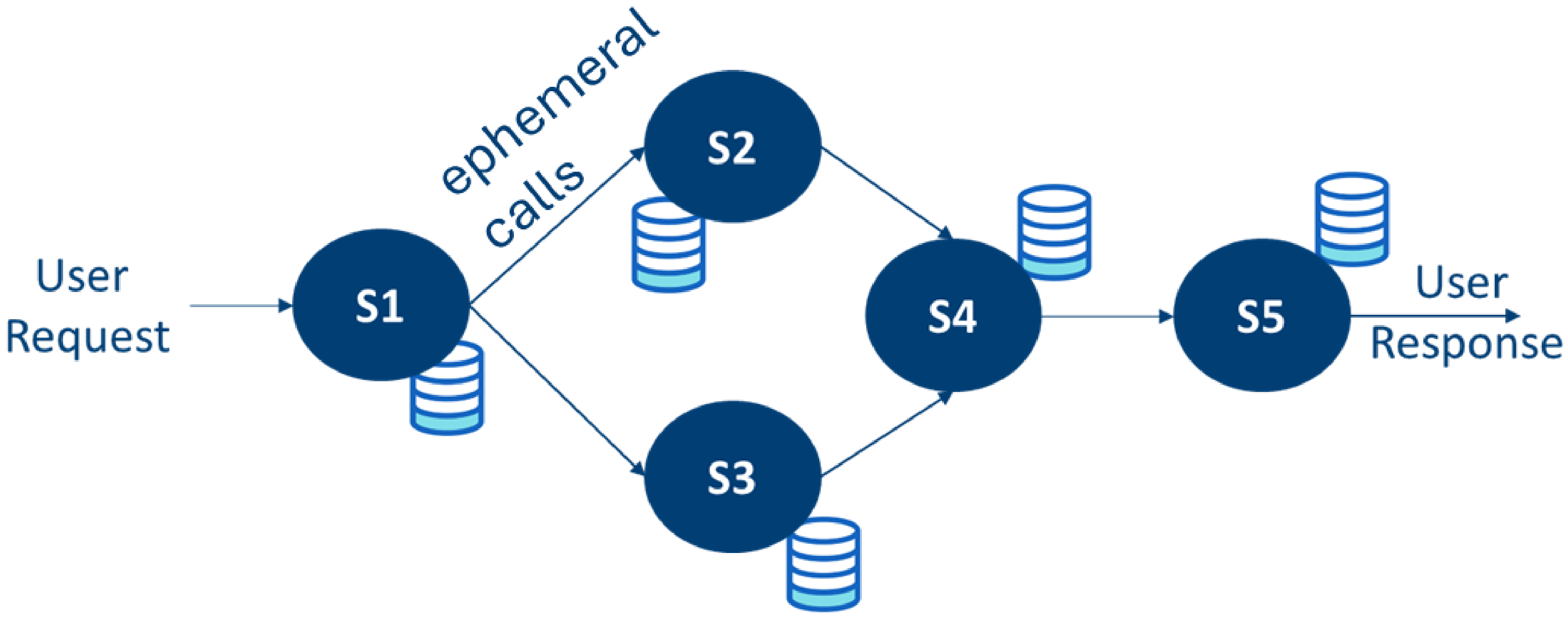
Data-Oriented Architectures

- Data-first systems
- Prioritise decentralisation
- Openness

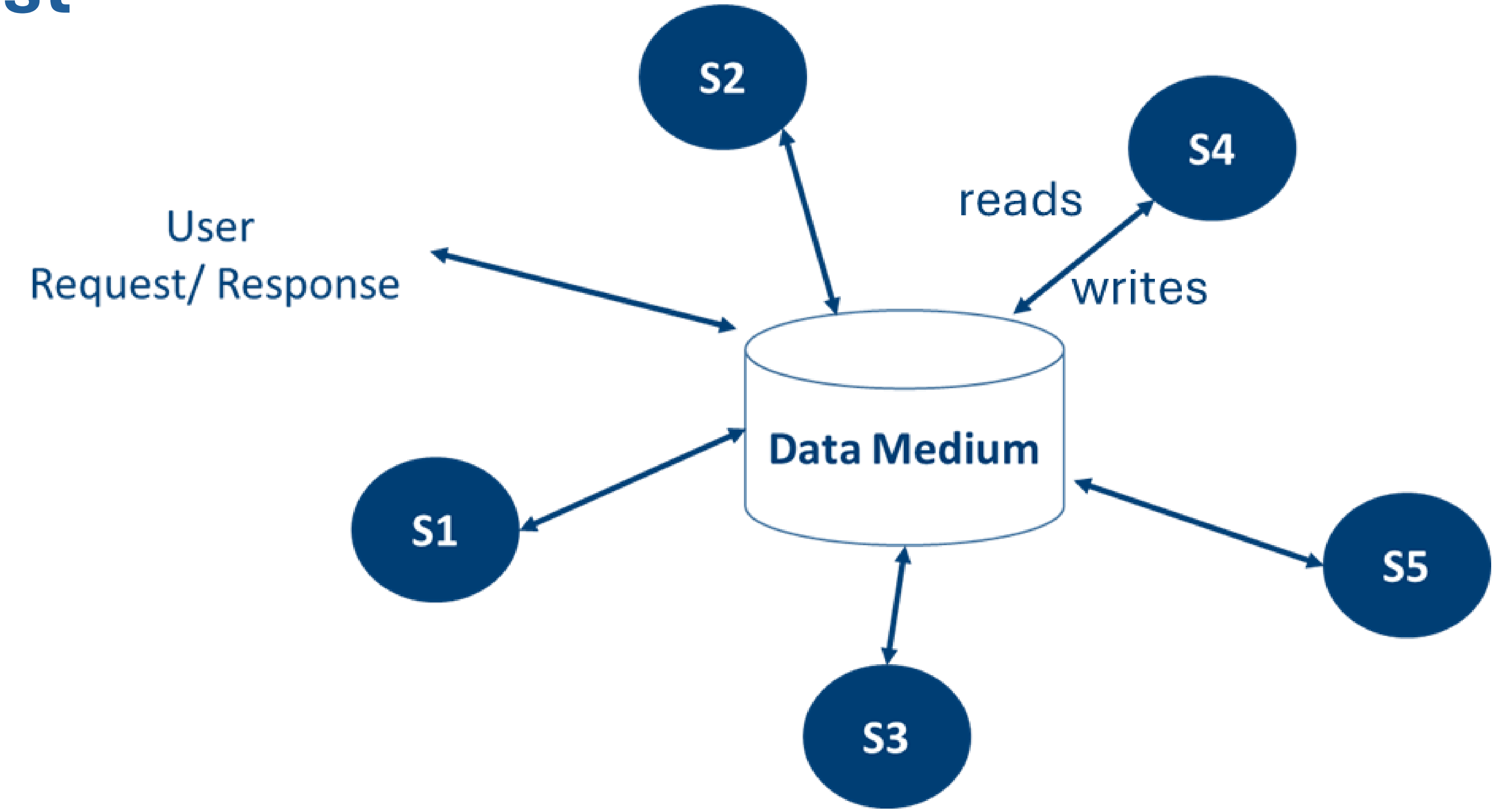
Data-Oriented Architectures

Data-First



Data-Oriented Architectures

Data-First



Data-Oriented Architectures

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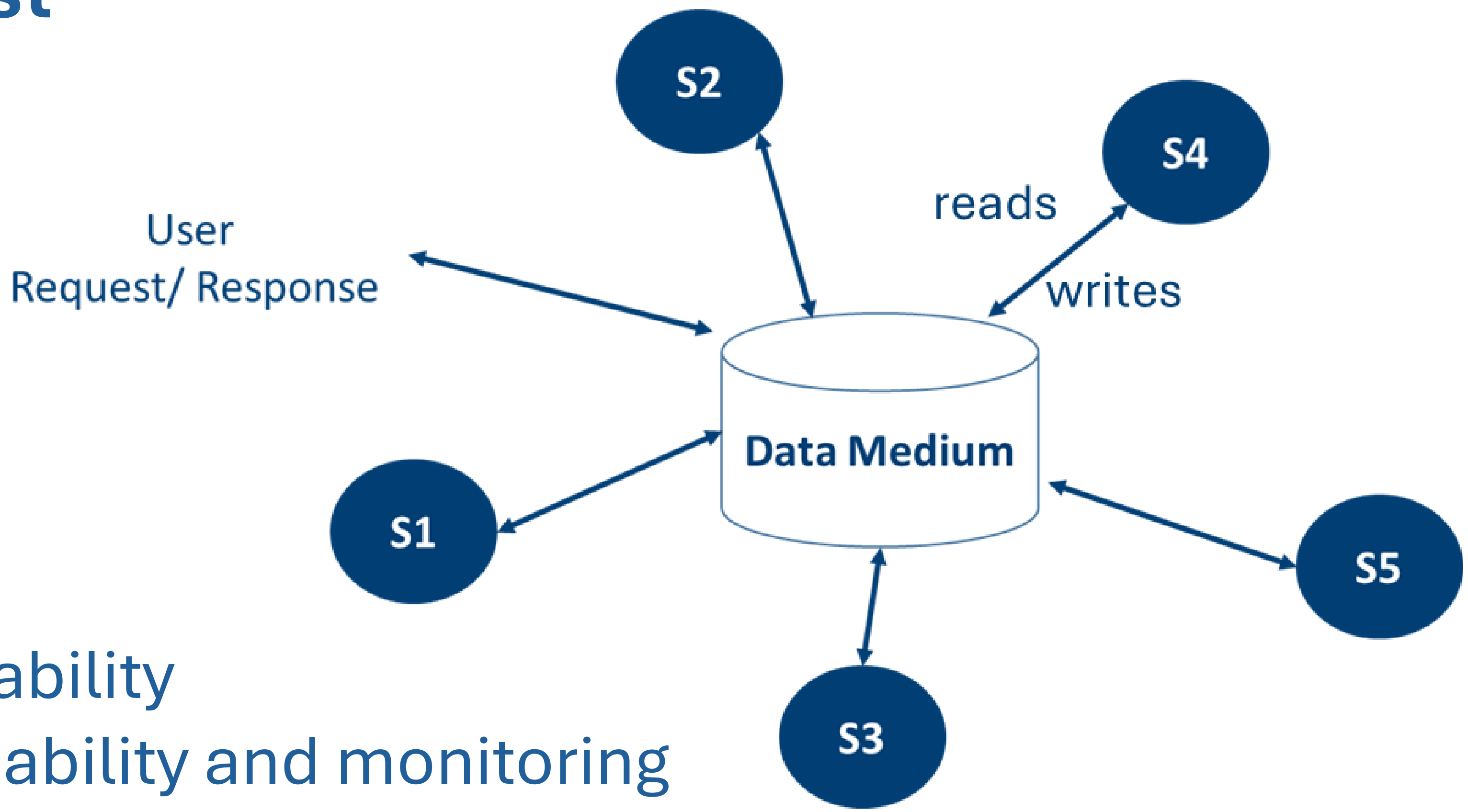
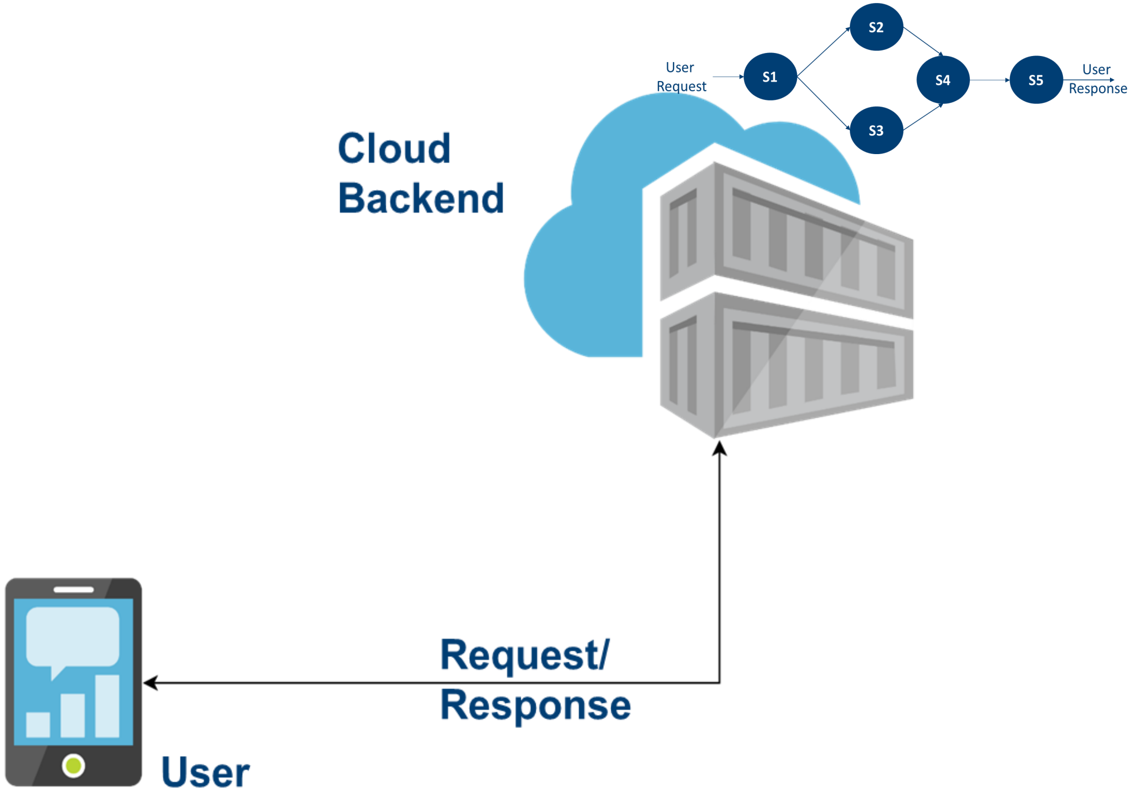


Data availability
Data traceability and monitoring

Data-Oriented Architectures

Prioritise decentralisation



User Request

S1

S2

S3

S4

S5

User Response

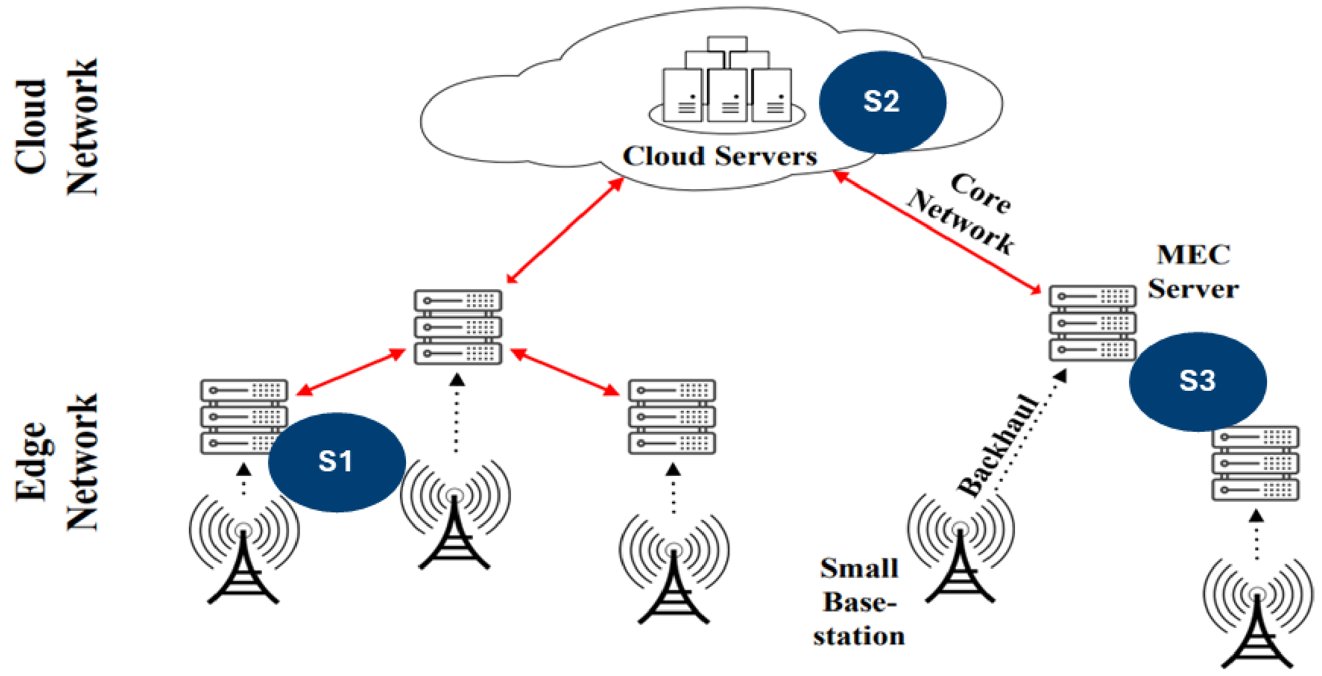
Cloud Backend

Request/ Response

User

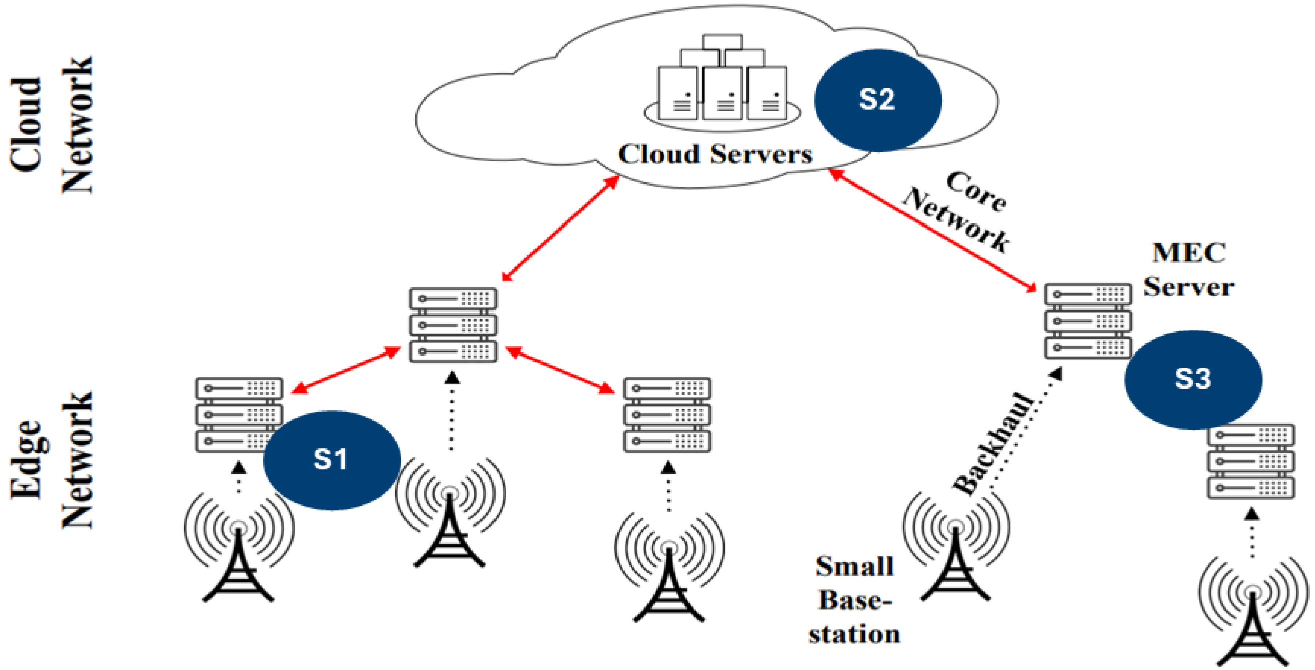
Data-Oriented Architectures

Prioritise decentralisation



Data-Oriented Architectures

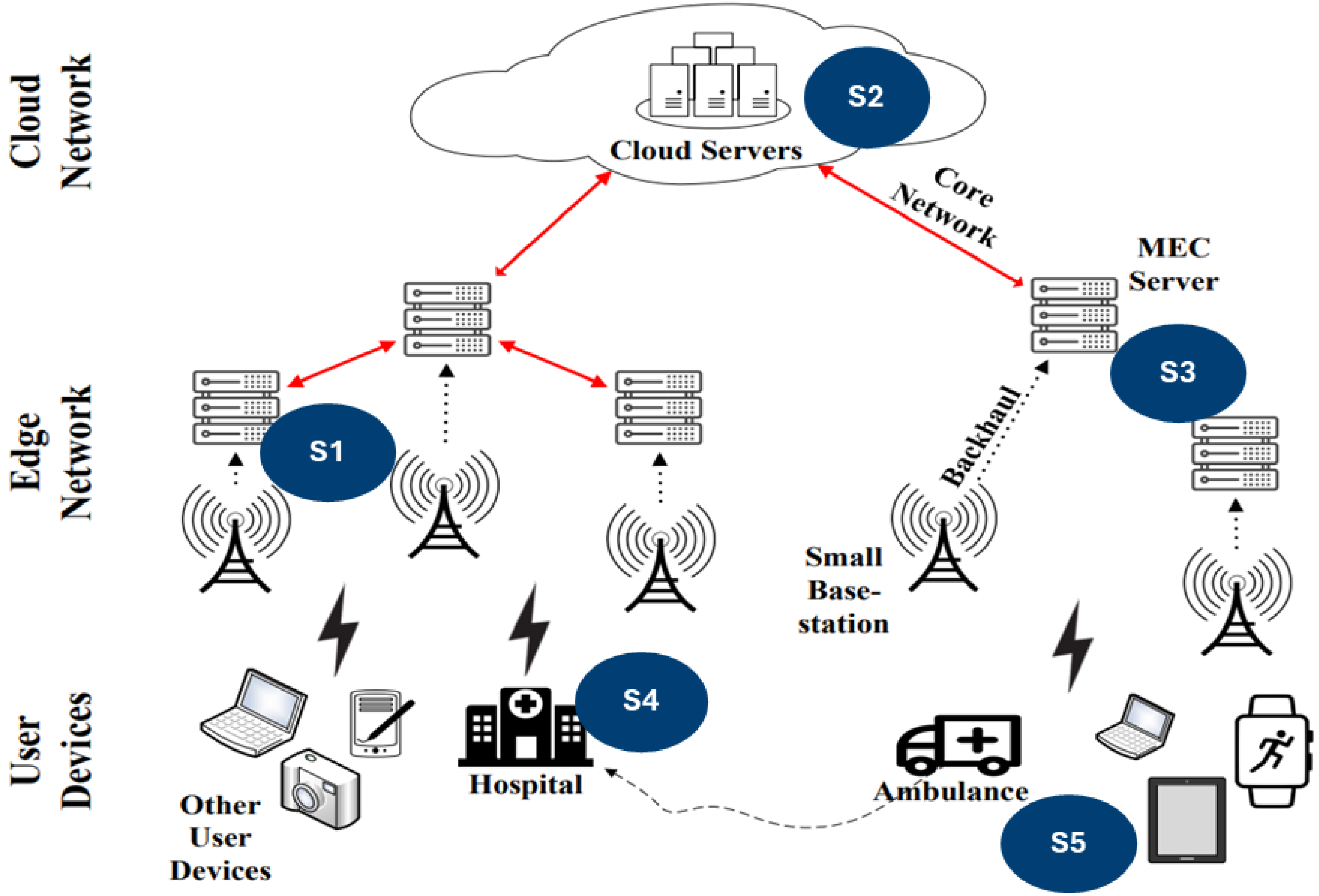
Prioritise decentralisation



Super-low latency requirements

Data-Oriented Architectures

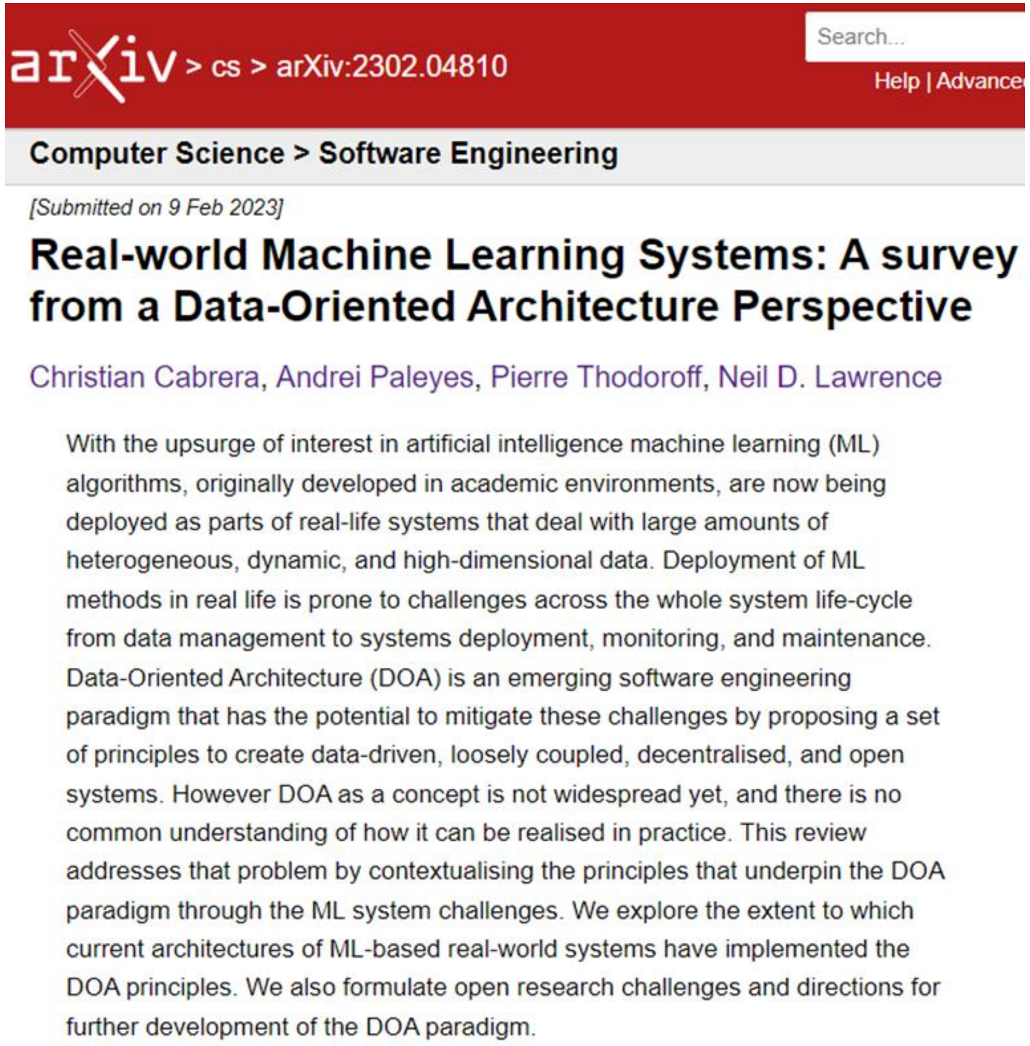
Openness



Data ownership

Sustainability

Data-Oriented Architectures



arXiv > cs > arXiv:2302.04810

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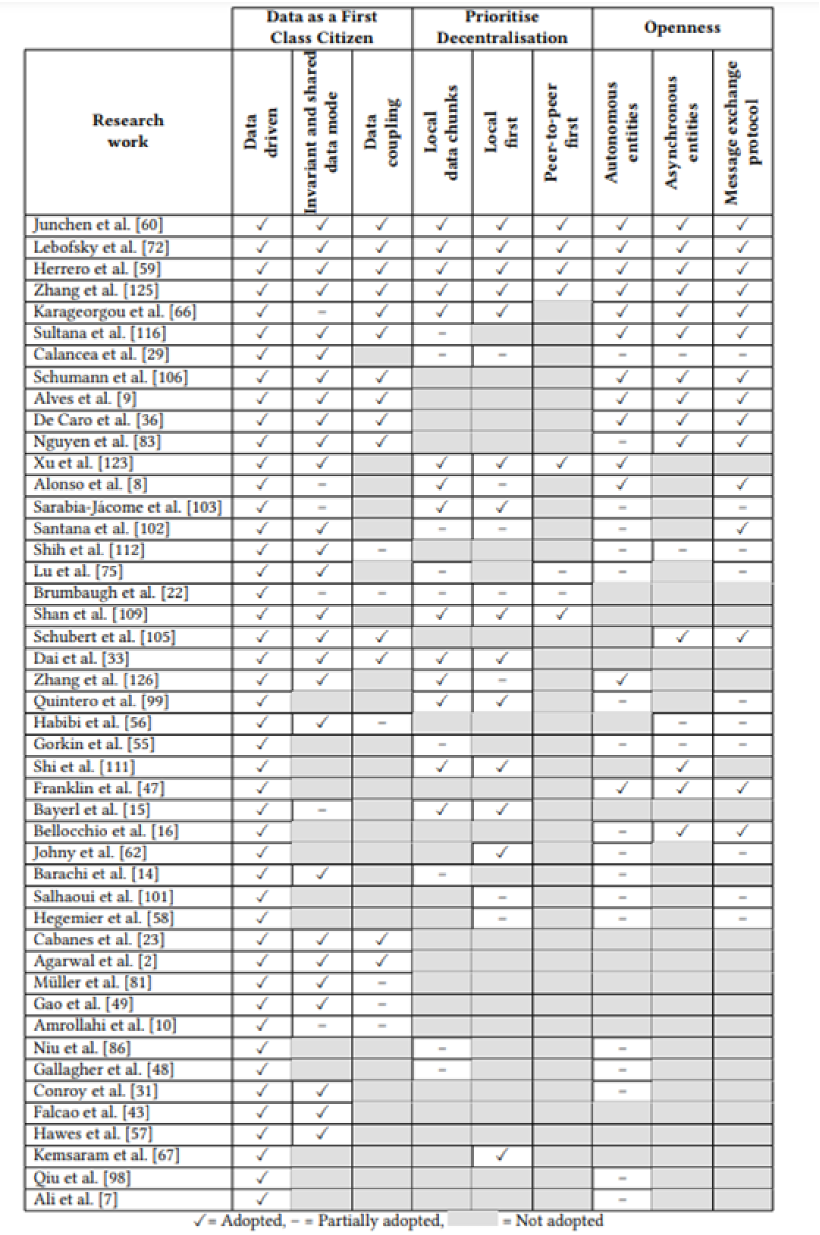
Computer Science > Software Engineering

[Submitted on 9 Feb 2023]

Real-world Machine Learning Systems: A survey from a Data-Oriented Architecture Perspective

Christian Cabrera, Andrei Paleyes, Pierre Thodoroff, Neil D. Lawrence

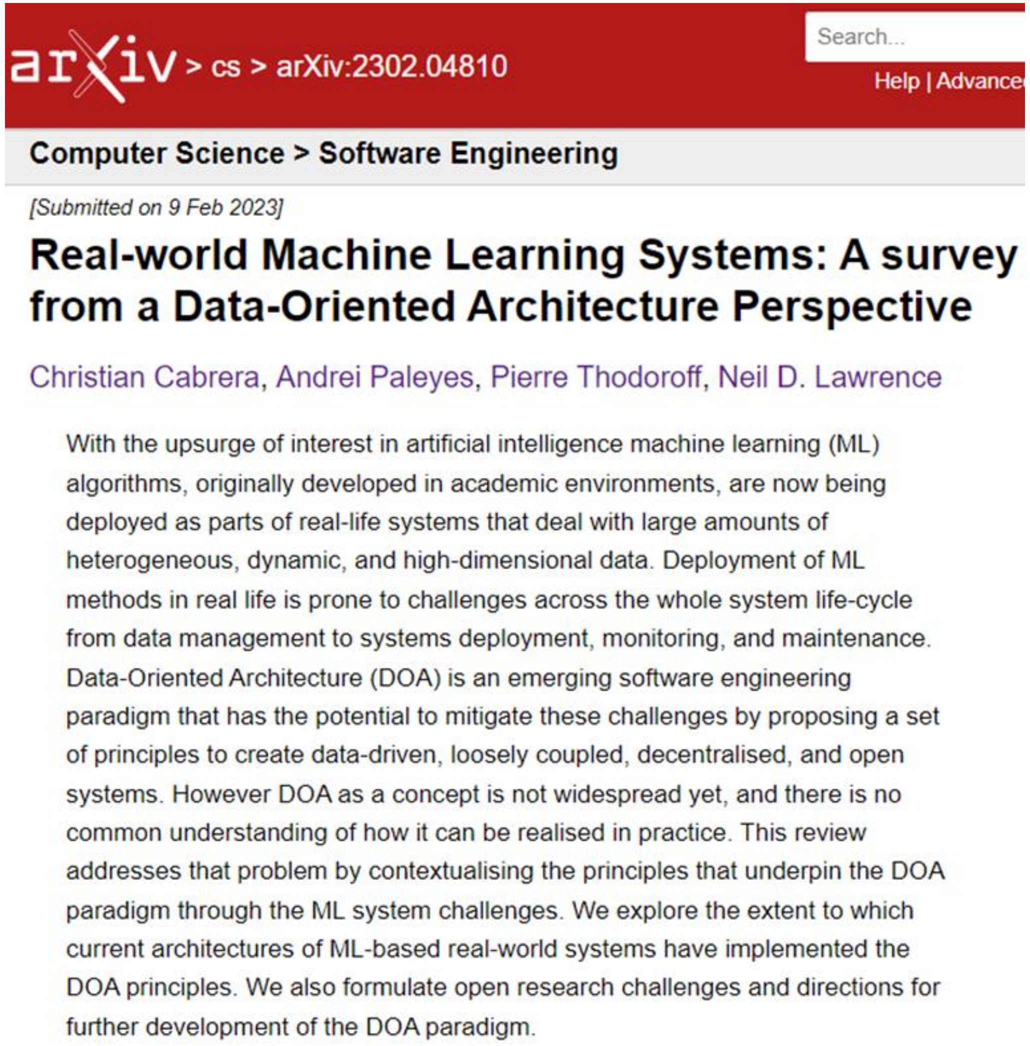
With the upsurge of interest in artificial intelligence machine learning (ML) algorithms, originally developed in academic environments, are now being deployed as parts of real-life systems that deal with large amounts of heterogeneous, dynamic, and high-dimensional data. Deployment of ML methods in real life is prone to challenges across the whole system life-cycle from data management to systems deployment, monitoring, and maintenance. Data-Oriented Architecture (DOA) is an emerging software engineering paradigm that has the potential to mitigate these challenges by proposing a set of principles to create data-driven, loosely coupled, decentralised, and open systems. However DOA as a concept is not widespread yet, and there is no common understanding of how it can be realised in practice. This review addresses that problem by contextualising the principles that underpin the DOA paradigm through the ML system challenges. We explore the extent to which current architectures of ML-based real-world systems have implemented the DOA principles. We also formulate open research challenges and directions for further development of the DOA paradigm.



	Data as a First Class Citizen			Prioritise Decentralisation			Openness		
Research work	Data driven	Invariant and shared data mode	Data coupling	Local data chunks	Local first	Peer-to-peer first	Autonomous entities	Asynchronous entities	Message exchange protocol
Junchen et al. [60]	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lebofsky et al. [72]	✓	✓	✓	✓	✓	✓	✓	✓	✓
Herrero et al. [59]	✓	✓	✓	✓	✓	✓	✓	✓	✓
Zhang et al. [125]	✓	✓	✓	✓	✓	✓	✓	✓	✓
Karageorgou et al. [66]	✓	–	✓	✓	✓	▨	✓	✓	✓
Sultana et al. [116]	✓	✓	✓	–	▨	▨	✓	✓	✓
Calancea et al. [29]	✓	✓	▨	–	–	▨	–	–	–
Schumann et al. [106]	✓	✓	✓	▨	▨	▨	✓	✓	✓
Alves et al. [9]	✓	✓	✓	▨	▨	▨	✓	✓	✓
De Caro et al. [36]	✓	✓	✓	▨	▨	▨	✓	✓	✓
Nguyen et al. [83]	✓	✓	✓	▨	▨	▨	–	✓	✓
Xu et al. [123]	✓	✓	▨	✓	✓	✓	✓	▨	▨
Alonso et al. [8]	✓	–	▨	✓	–	▨	✓	▨	✓
Sarabia-Jácome et al. [103]	✓	–	▨	✓	✓	▨	–	▨	–
Santana et al. [102]	✓	✓	▨	–	–	▨	–	▨	✓
Shih et al. [112]	✓	✓	–	▨	▨	▨	–	–	–
Lu et al. [75]	✓	✓	▨	–	▨	–	–	▨	–
Brumbaugh et al. [22]	✓	–	–	–	–	–	▨	▨	▨
Shan et al. [109]	✓	✓	▨	✓	✓	✓	▨	▨	▨
Schubert et al. [105]	✓	✓	✓	▨	▨	▨	▨	✓	✓
Dai et al. [33]	✓	✓	✓	✓	✓	▨	▨	▨	▨
Zhang et al. [126]	✓	✓	▨	✓	–	▨	✓	▨	▨
Quintero et al. [99]	✓	▨	▨	✓	✓	▨	–	▨	–
Habibi et al. [56]	✓	✓	–	▨	▨	▨	▨	–	–
Gorkin et al. [55]	✓	▨	▨	–	▨	▨	–	–	–
Shi et al. [111]	✓	▨	▨	✓	✓	▨	▨	✓	▨
Franklin et al. [47]	✓	▨	▨	▨	▨	▨	✓	✓	✓
Bayerl et al. [15]	✓	–	▨	✓	✓	▨	▨	▨	▨
Bellocchio et al. [16]	✓	▨	▨	▨	▨	▨	–	✓	✓
Johny et al. [62]	✓	▨	▨	▨	✓	▨	–	▨	–
Barachi et al. [14]	✓	✓	▨	–	▨	▨	–	▨	▨
Salhaoui et al. [101]	✓	▨	▨	▨	–	▨	–	▨	–
Hegemier et al. [58]	✓	▨	▨	▨	–	▨	–	▨	–
Cabanes et al. [23]	✓	✓	✓	▨	▨	▨	▨	▨	▨
Agarwal et al. [2]	✓	✓	✓	▨	▨	▨	▨	▨	▨
Müller et al. [81]	✓	✓	–	▨	▨	▨	▨	▨	▨
Gao et al. [49]	✓	✓	–	▨	▨	▨	▨	▨	▨
Amrollahi et al. [10]	✓	–	–	▨	▨	▨	▨	▨	▨
Niu et al. [86]	✓	▨	▨	–	▨	▨	–	▨	▨
Gallagher et al. [48]	✓	▨	▨	–	▨	▨	–	▨	▨
Conroy et al. [31]	✓	✓	▨	▨	▨	▨	–	▨	▨
Falcao et al. [43]	✓	✓	▨	▨	▨	▨	▨	▨	▨
Hawes et al. [57]	✓	✓	▨	▨	▨	▨	▨	▨	▨
Kemsaram et al. [67]	✓	▨	▨	▨	✓	▨	▨	▨	▨
Qiu et al. [98]	✓	▨	▨	▨	▨	▨	–	▨	▨
Ali et al. [7]	✓	▨	▨	▨	▨	▨	–	▨	▨

✓ = Adopted, – = Partially adopted, ▨ = Not adopted

Data-Oriented Architectures



Computer Science > Software Engineering

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Few projects fully follow DOA principles.

Most of the solutions are centralised and cloud-based.

Databases, streams and message queues enable the data first principle.

Distributed storage and computing technologies for decentralisation.

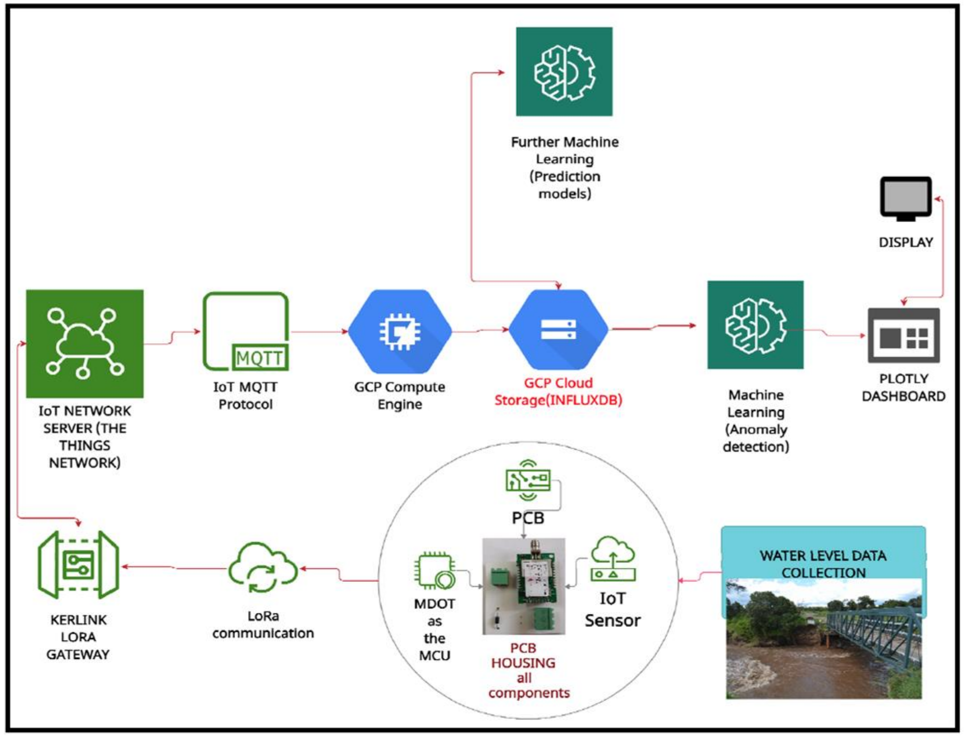
Asynchronous communication for openness.

Data-Oriented Architectures

Source: https://en.wikipedia.org/wiki/Ewaso_Ng%27iro

Ewaso Nyiro River - Kenya

Water level monitoring project at DeKUT [1]


Further Machine Learning (Prediction models)
DISPLAY
IoT NETWORK SERVER (THE THINGS NETWORK)
MQTT
IoT MQTT Protocol
GCP Compute Engine
GCP Cloud Storage(INFLUXDB)
Machine Learning (Anomaly detection)
PLOTLY DASHBOARD
PCB
MDOT as the MCU
IoT Sensor
PCB HOUSING all components
WATER LEVEL DATA COLLECTION
KERLINK LORA GATEWAY
LoRa communication

[1] Kabi, Jason, and Ciira Maina. "Leveraging IoT and machine learning for improved monitoring of water resources-a case study of the upper ewaso nyiro river." *2021 IST-Africa Conference (IST-Africa)*. IEEE, 2021.

Data-Oriented Architectures

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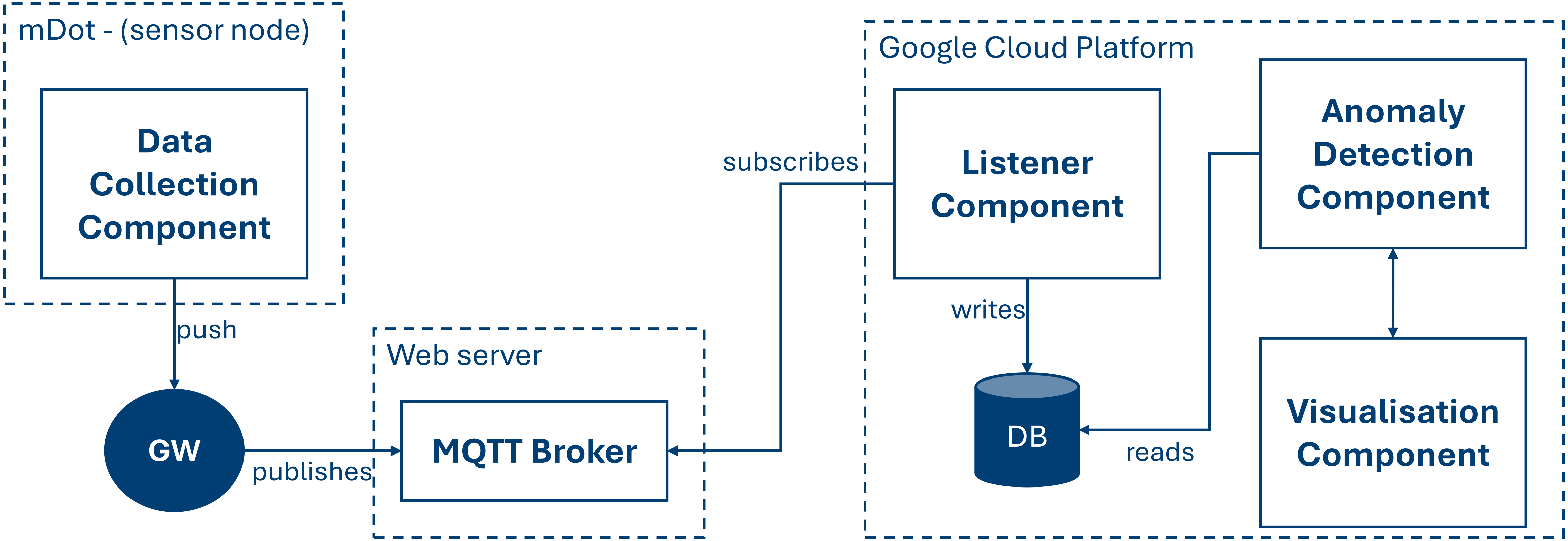

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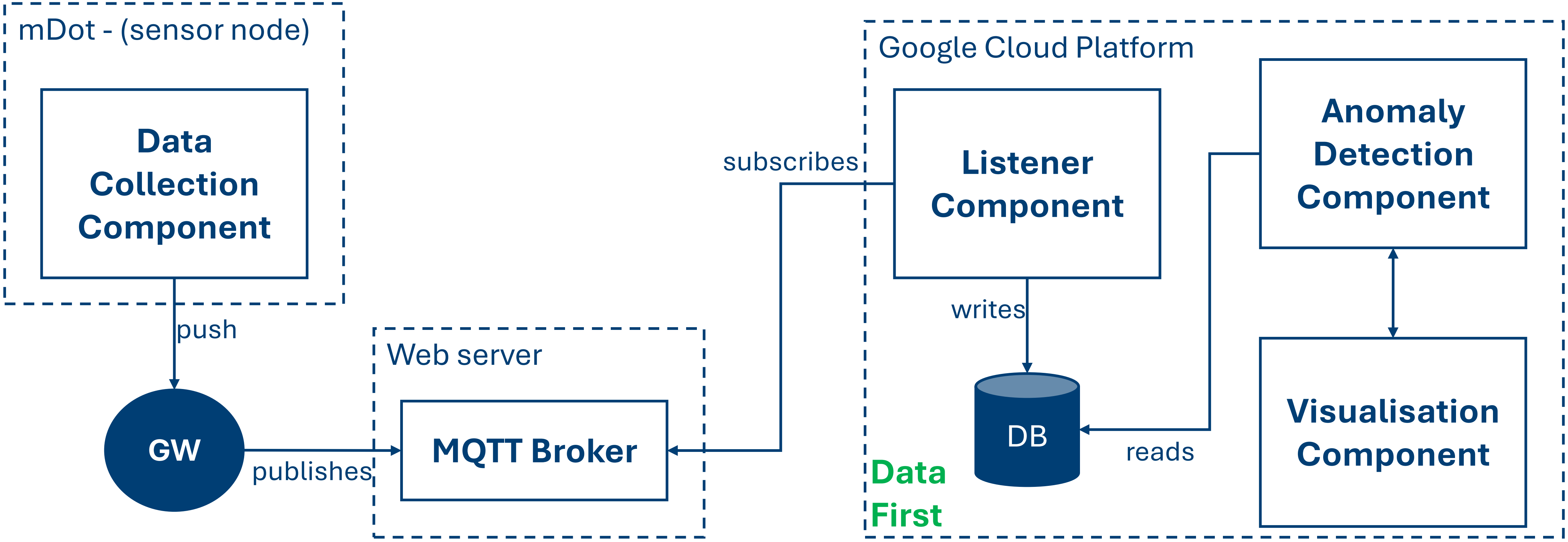

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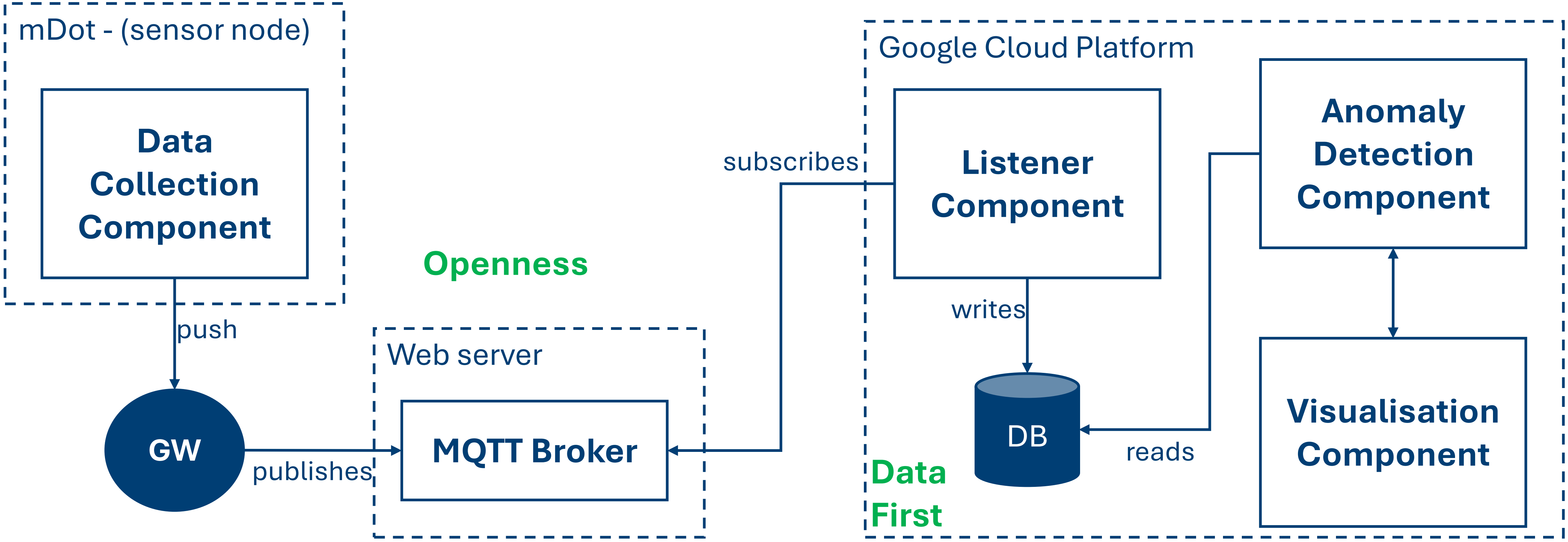

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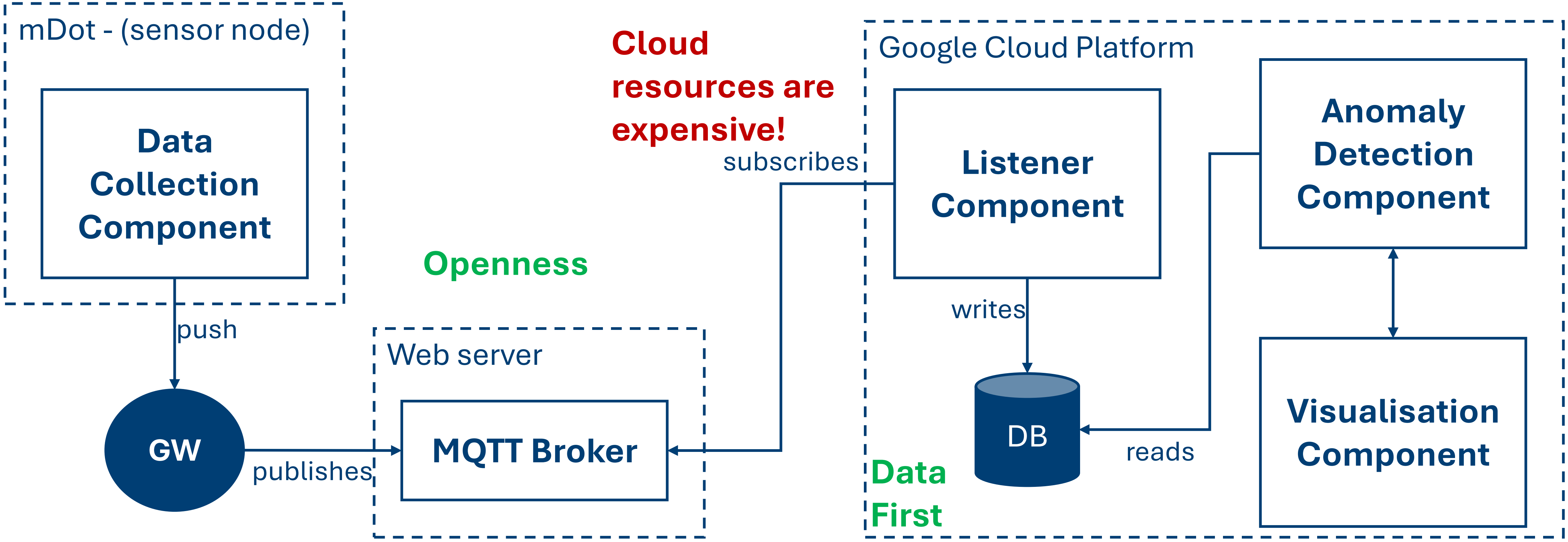

Cloud resources are expensive!

Openness

Data First

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Data-Oriented Architectures

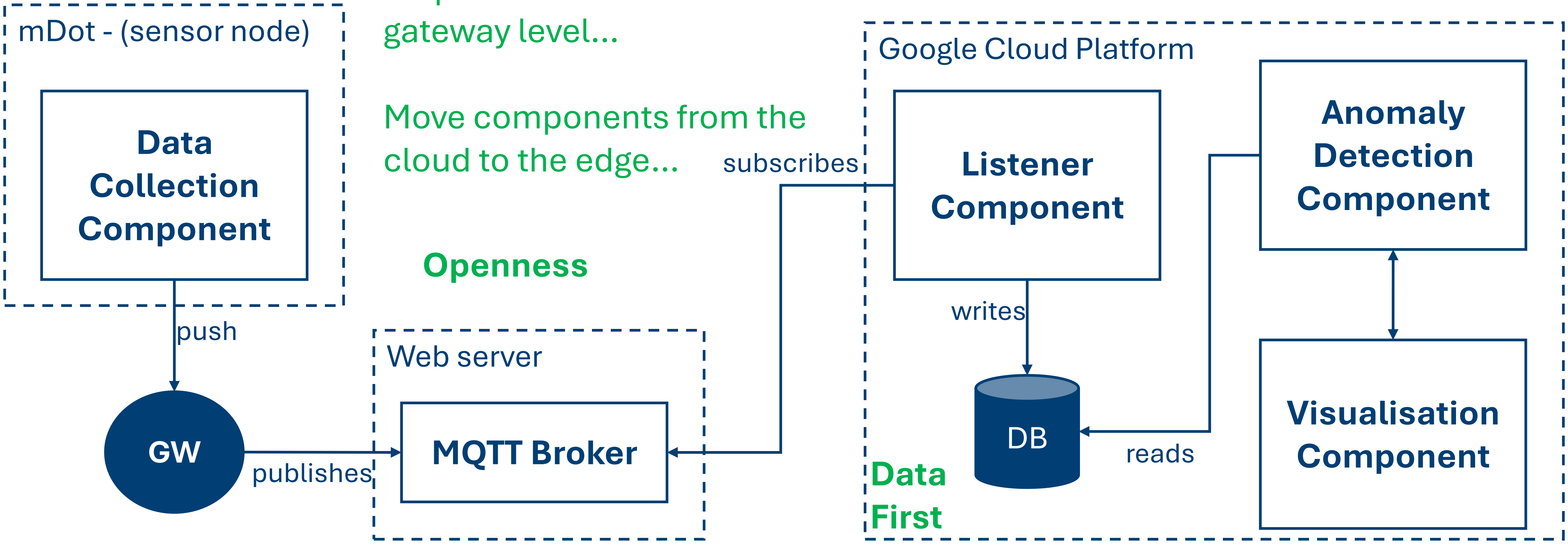
Water level monitoring project at DeKUT [1]

Decentralisation

Preprocess data at the gateway level…

Move components from the cloud to the edge…

Openness



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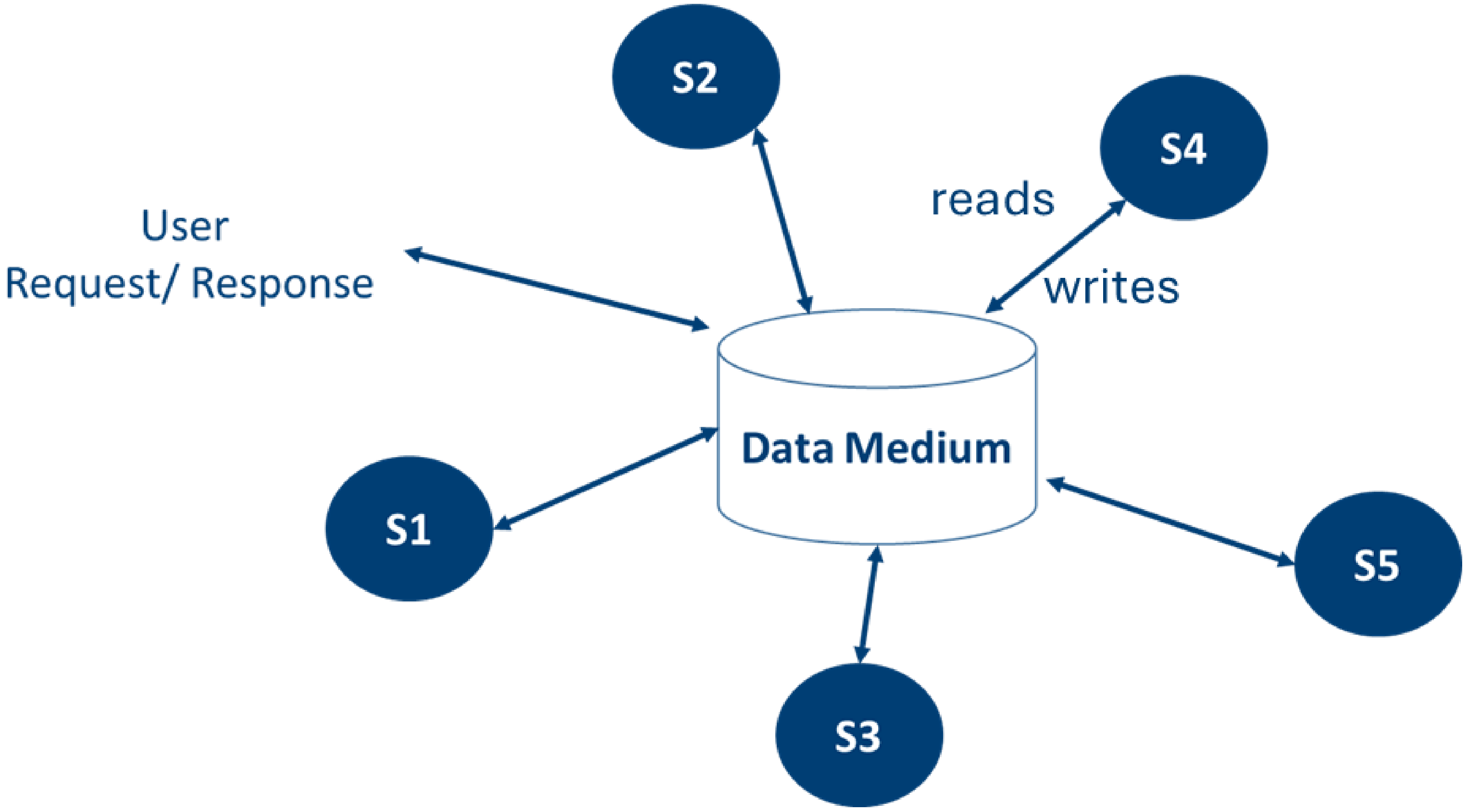
Data-First Principle



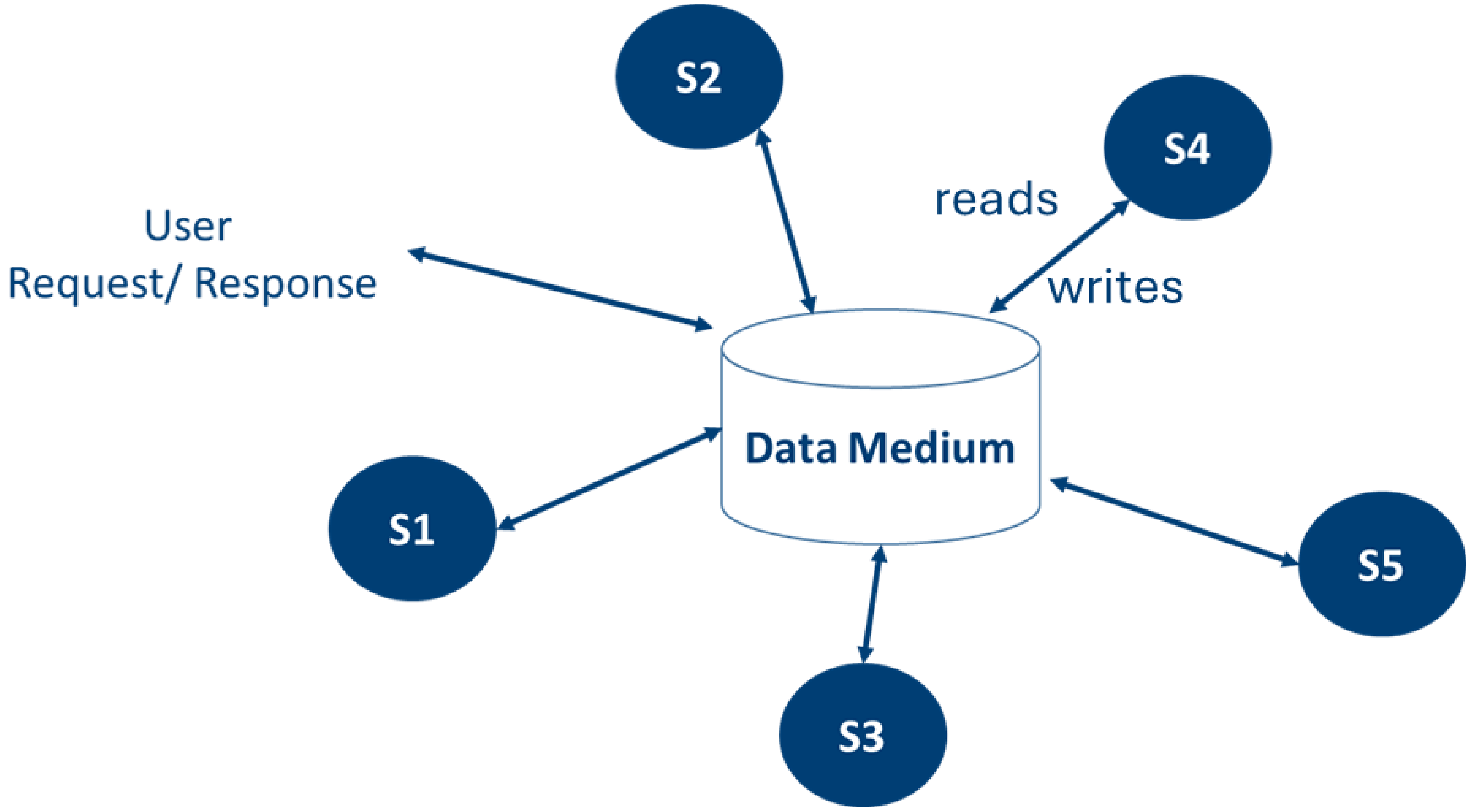
Data-First Principle

Facilitates data collection processes.

Asynchronous communication fits better when manipulating large data sets.

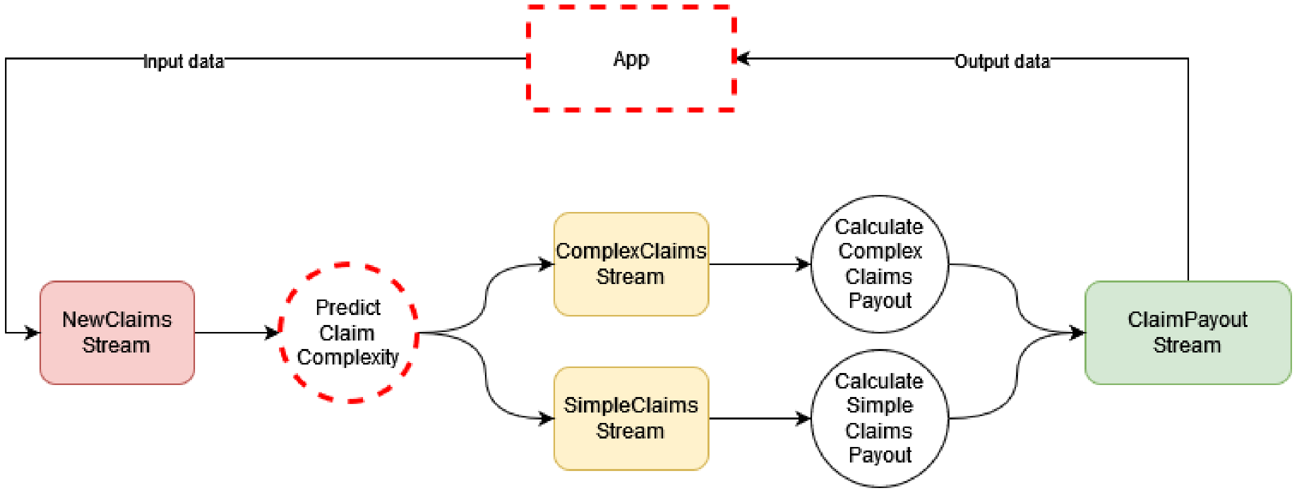
The Data Medium is a shared model that facilitates monitoring tasks.

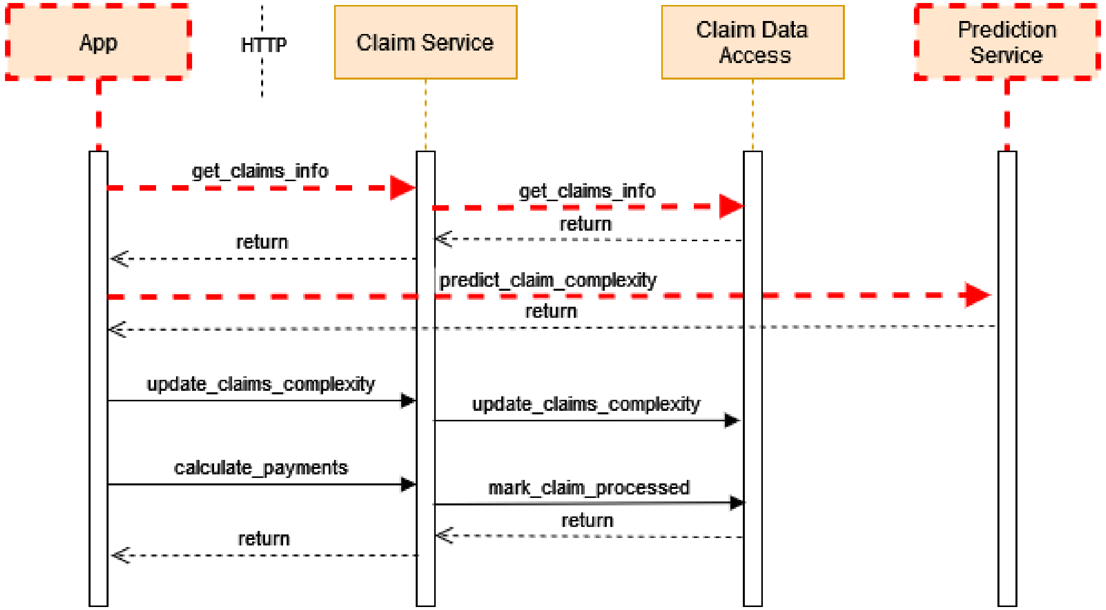
The historical state of the systems is available by design.



Data-First Principle

DOA vs SOA

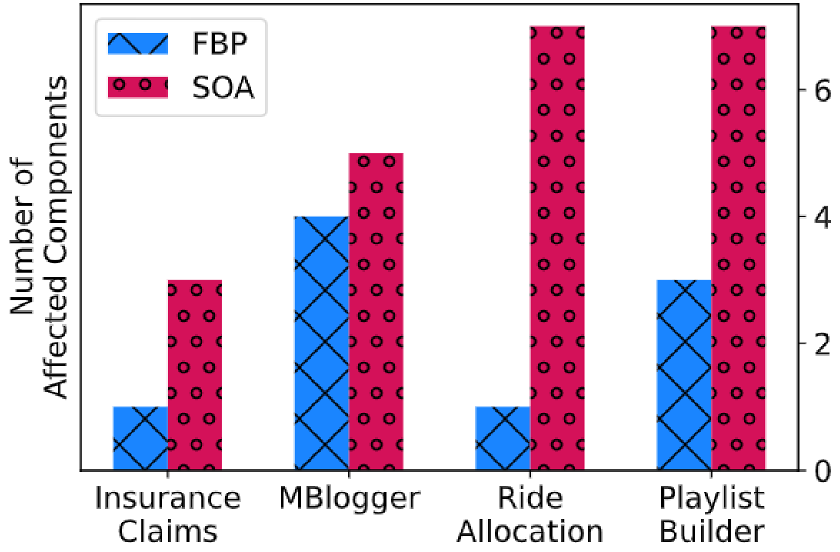




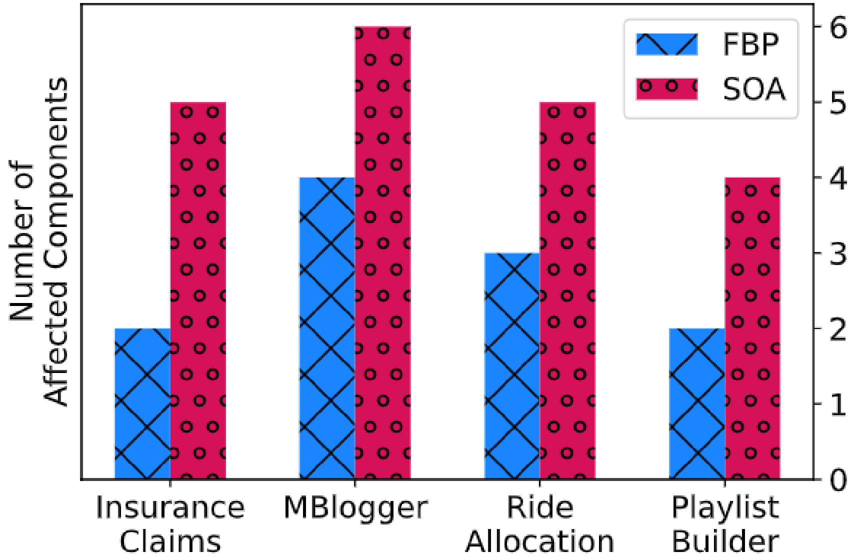
Paleyes, Andrei, Christian Cabrera, and Neil D. Lawrence. "An empirical evaluation of flow based programming in the machine learning deployment context." *Proceedings of the 1st International Conference on AI Engineering: Software Engineering for AI*. 2022.

Data-First Principle

DOA vs SOA – Number of Affected Components



From Baseline to Data Collection



From Data Collection to ML

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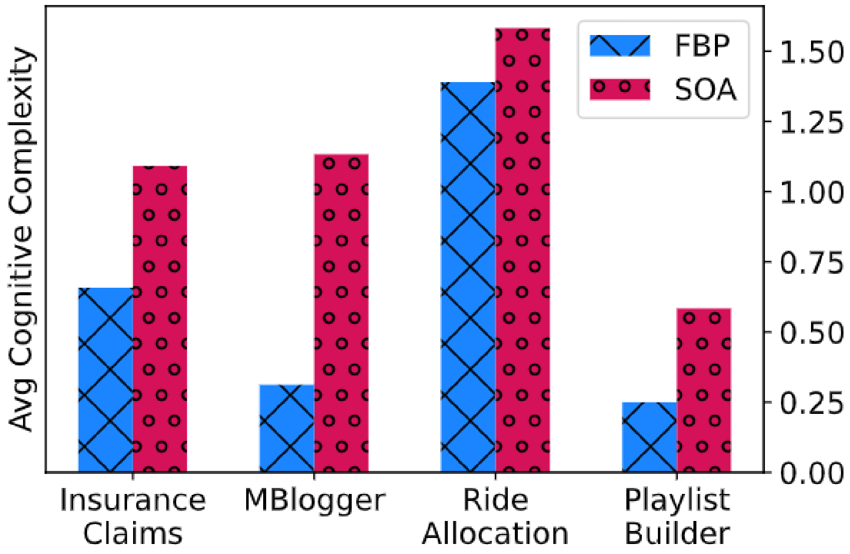
Data-First Principle

DOA vs SOA – Cognitive Complexity



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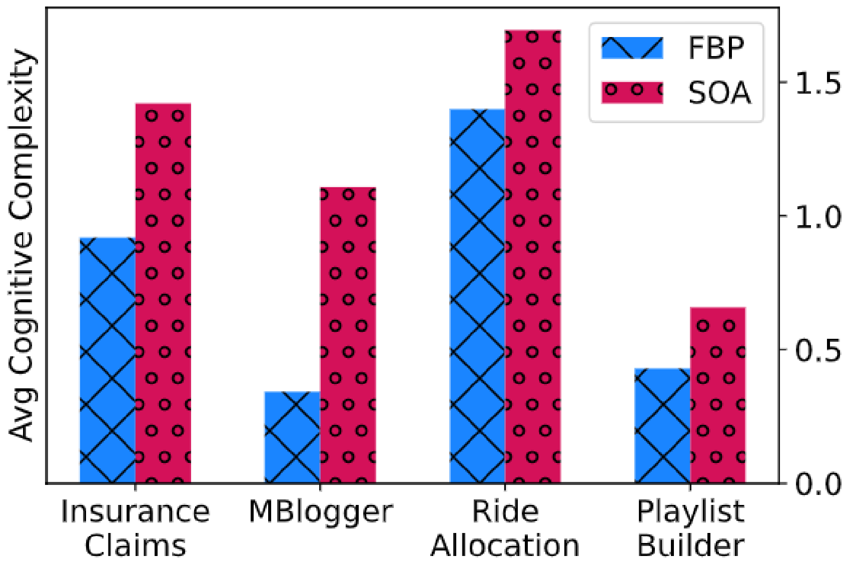

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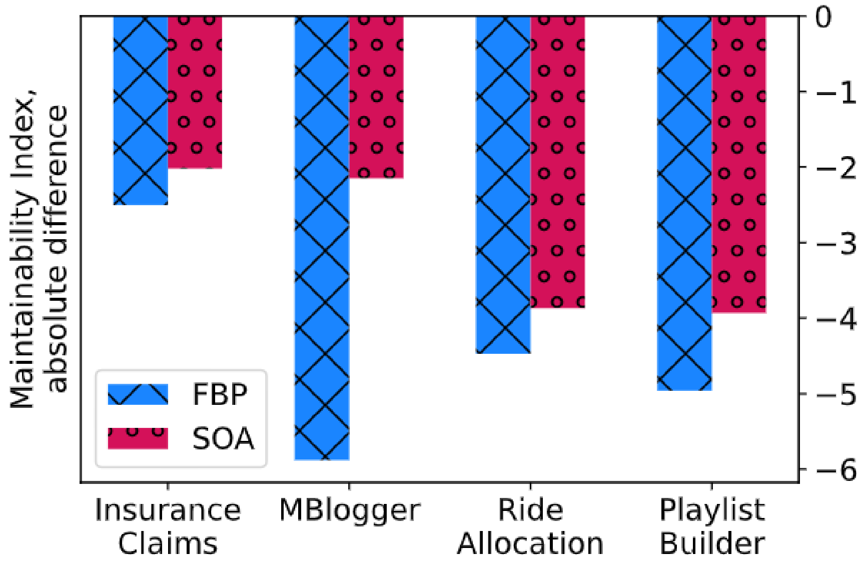
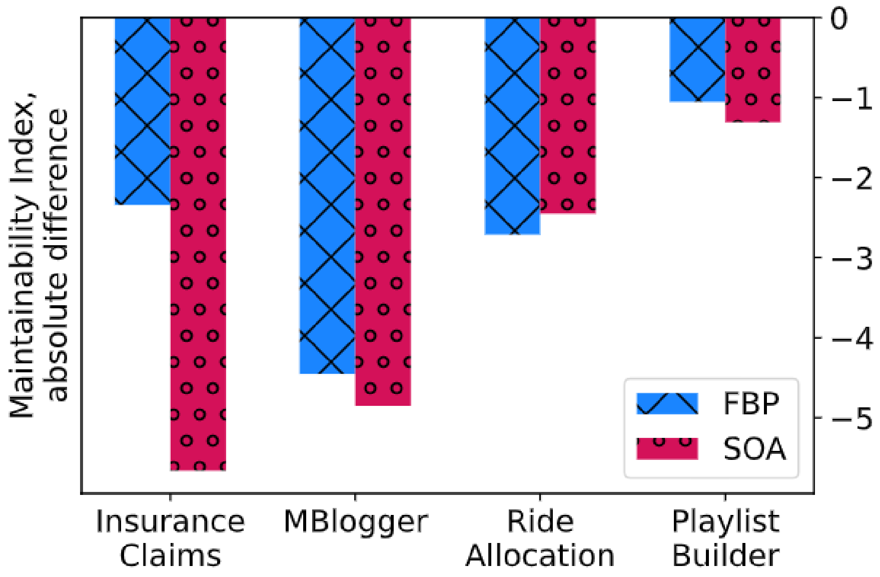
Data-First Principle

DOA vs SOA – Maintainability Index



From Baseline to Data Collection

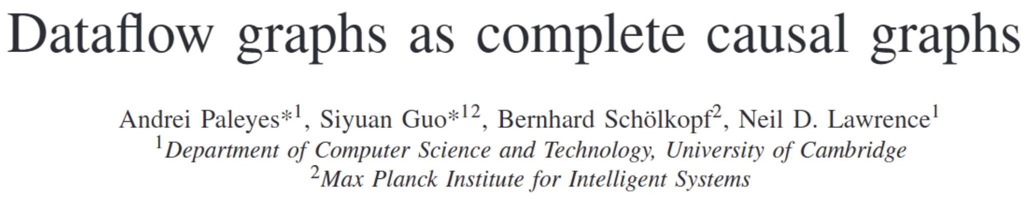


From Data Collection to ML

Paleyes, Andrei, Christian Cabrera, and Neil D. Lawrence. "An empirical evaluation of flow based programming in the machine learning deployment context." *Proceedings of the 1st International Conference on AI Engineering: Software Engineering for AI*. 2022.

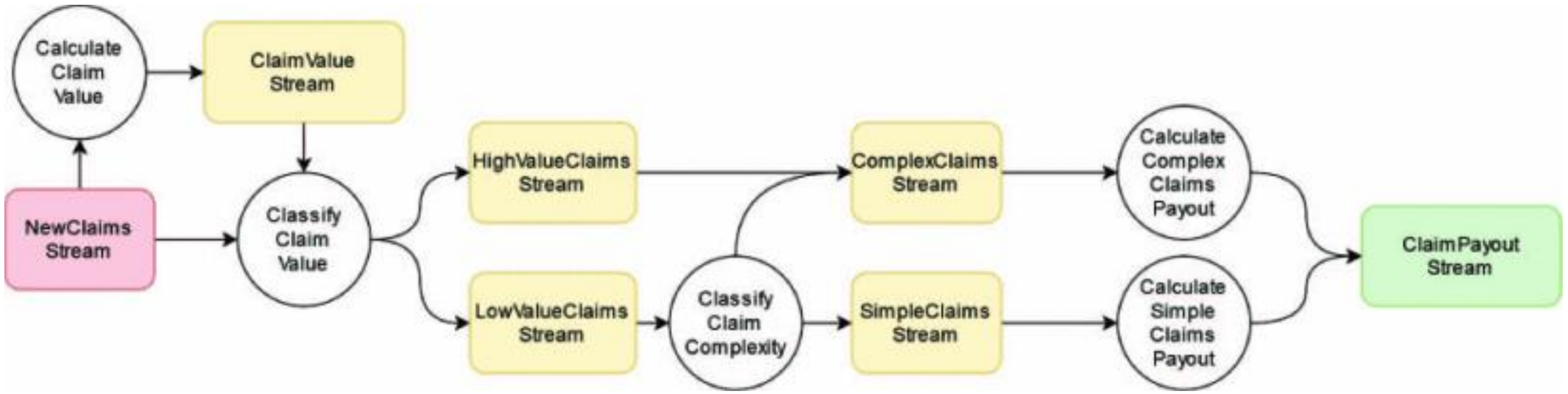
Data-First Principle

DOA and Causality Analysis



Dataflow graphs as complete causal graphs

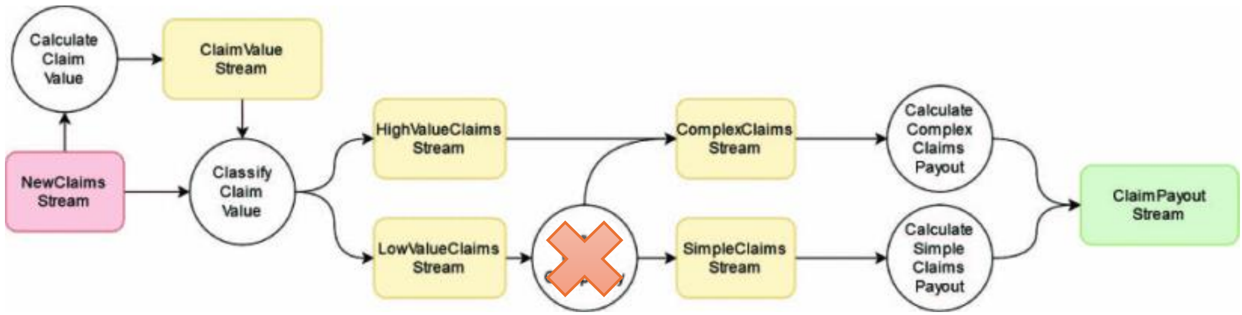
Andrei Paleyes*[1], Siyuan Guo*[1][2], Bernhard Schölkopf[2], Neil D. Lawrence[1]
[1]*Department of Computer Science and Technology, University of Cambridge*
[2]*Max Planck Institute for Intelligent Systems*

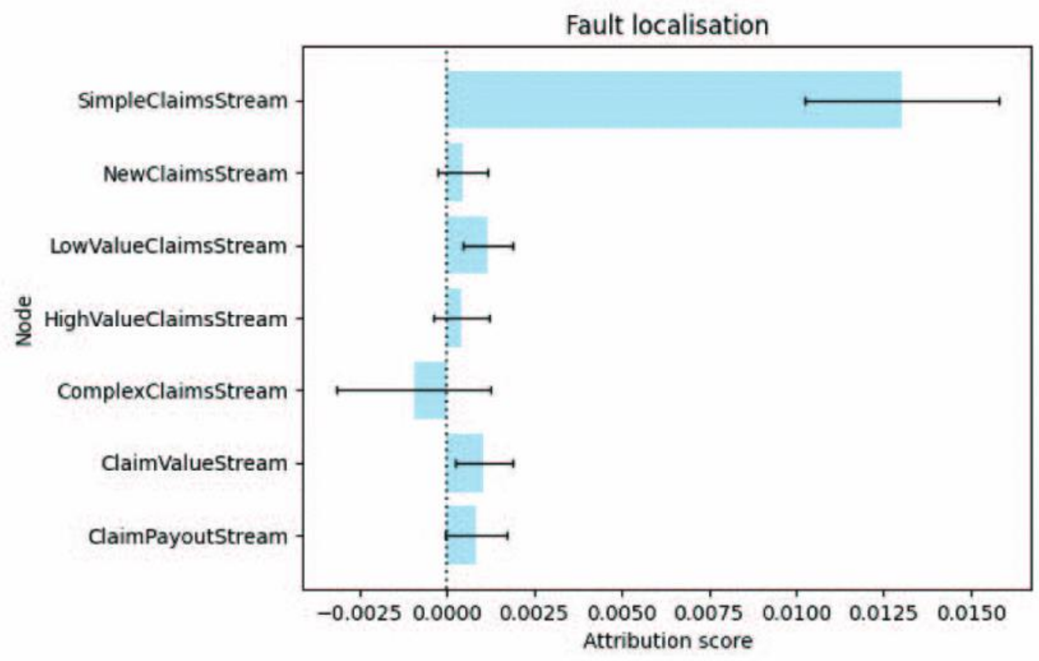


Paleyes, Andrei, et al. "Dataflow graphs as complete causal graphs." *2023 IEEE/ACM 2nd International Conference on AI Engineering–Software Engineering for AI (CAIN)*. IEEE, 2023.

Data-First Principle

DOA and Causality Analysis – Fault localisation

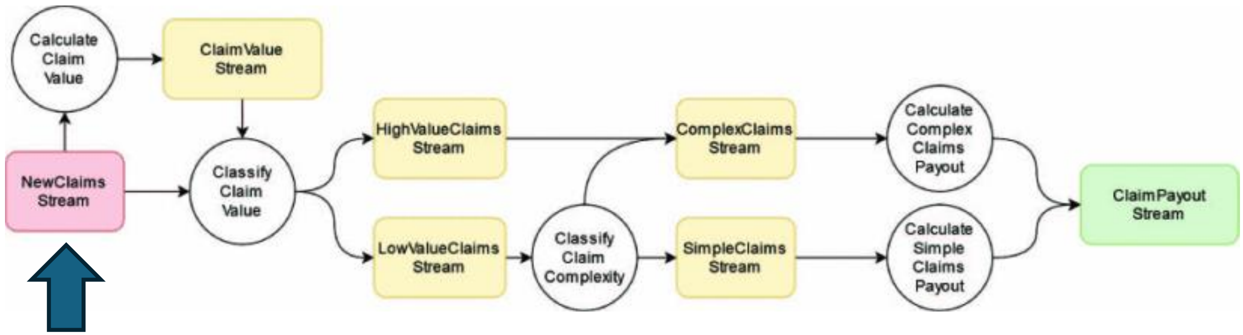




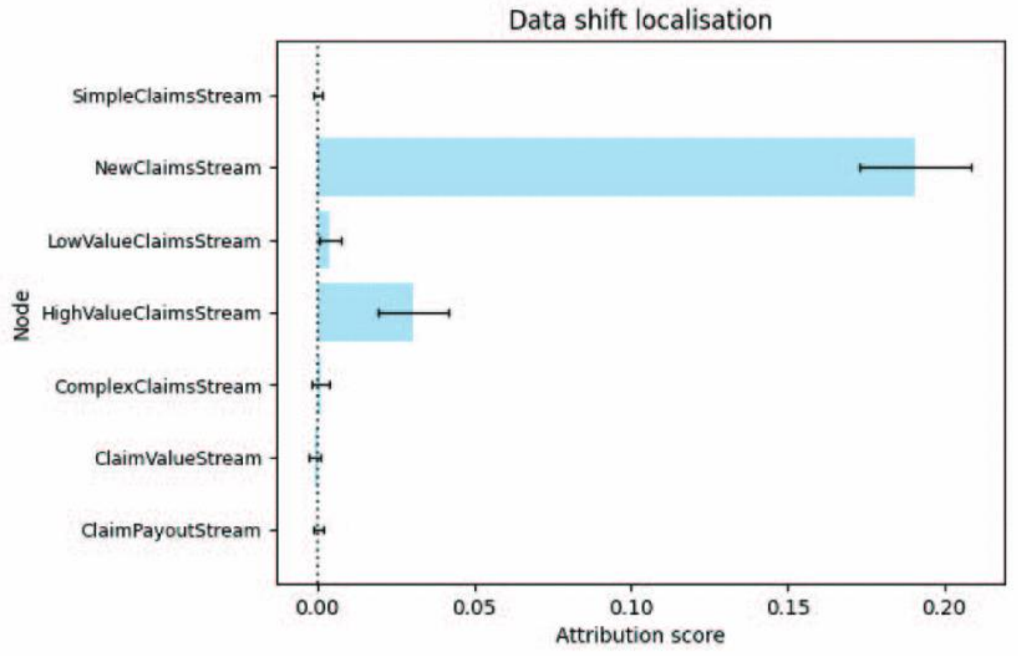
Paleyes, Andrei, et al. "Dataflow graphs as complete causal graphs." *2023 IEEE/ACM 2nd International Conference on AI Engineering–Software Engineering for AI (CAIN)*. IEEE, 2023.

Data-First Principle

DOA and Causality Analysis – Identifying data shifts

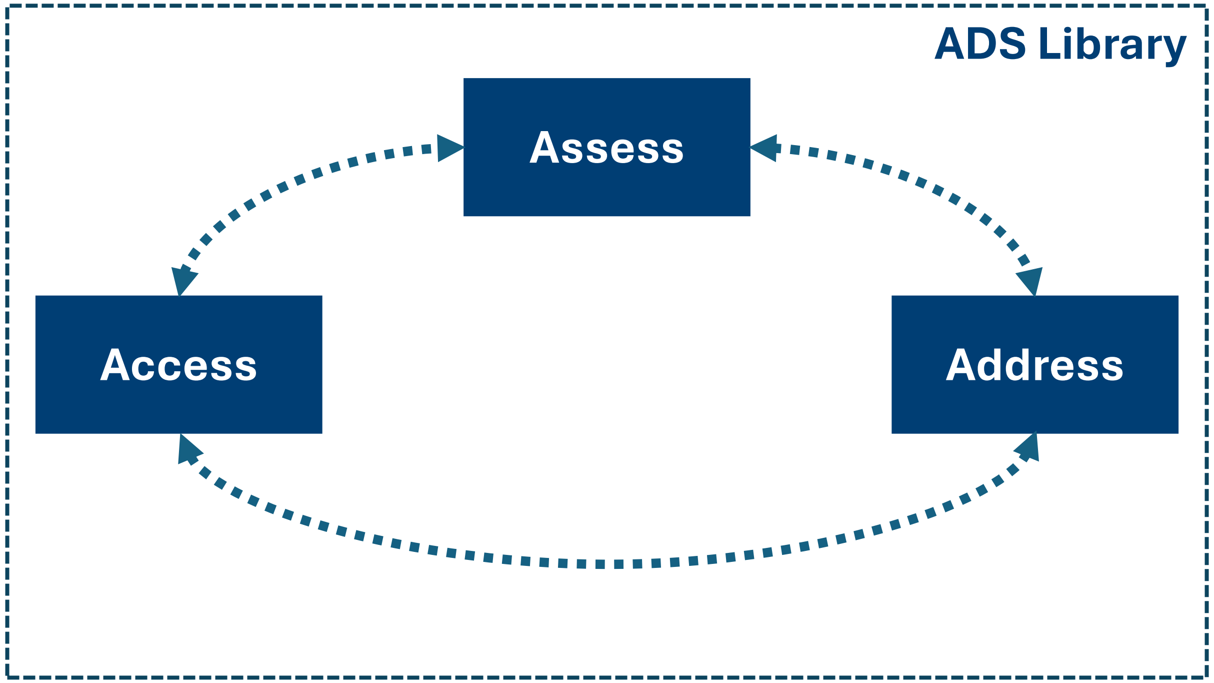


50% up on the originally claimed amount.

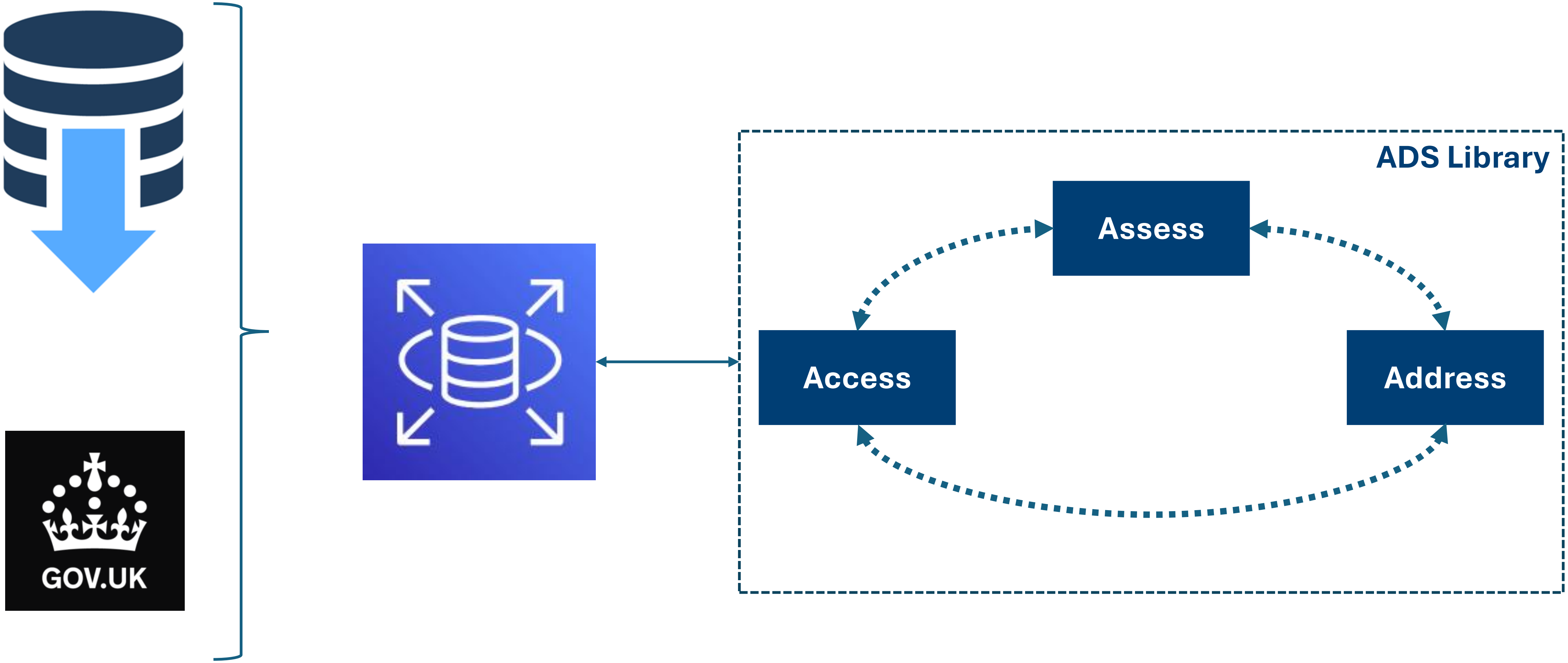


Paleyes, Andrei, et al. "Dataflow graphs as complete causal graphs." *2023 IEEE/ACM 2nd International Conference on AI Engineering–Software Engineering for AI (CAIN)*. IEEE, 2023.

Data-First Principle



Data-First Principle



Summary

- Systems design decisions change between systems, but these usually share requirements.
- Similar requirements can be addressed following similar solutions.
- Data-driven systems demand to design systems that prioritise data.
- Data-Oriented Architectures is a useful paradigm to design data-driven systems.
- The Data-First principle is particularly relevant for our data science pipelines.

Many thanks!