Towards Modeling the Modern Distributed Systems Fabric

Keynote at Modelsward 2021

10 Feb 2021

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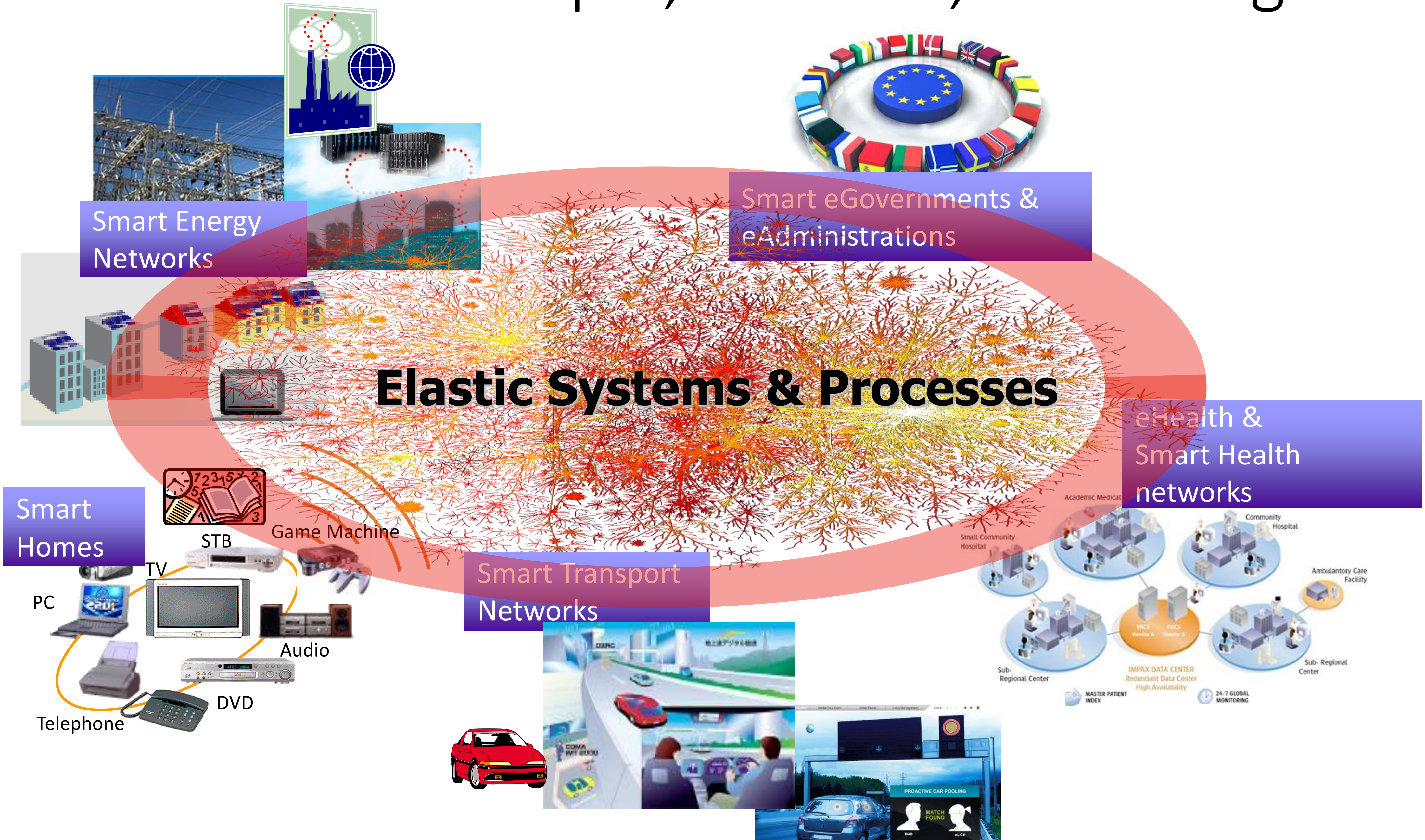
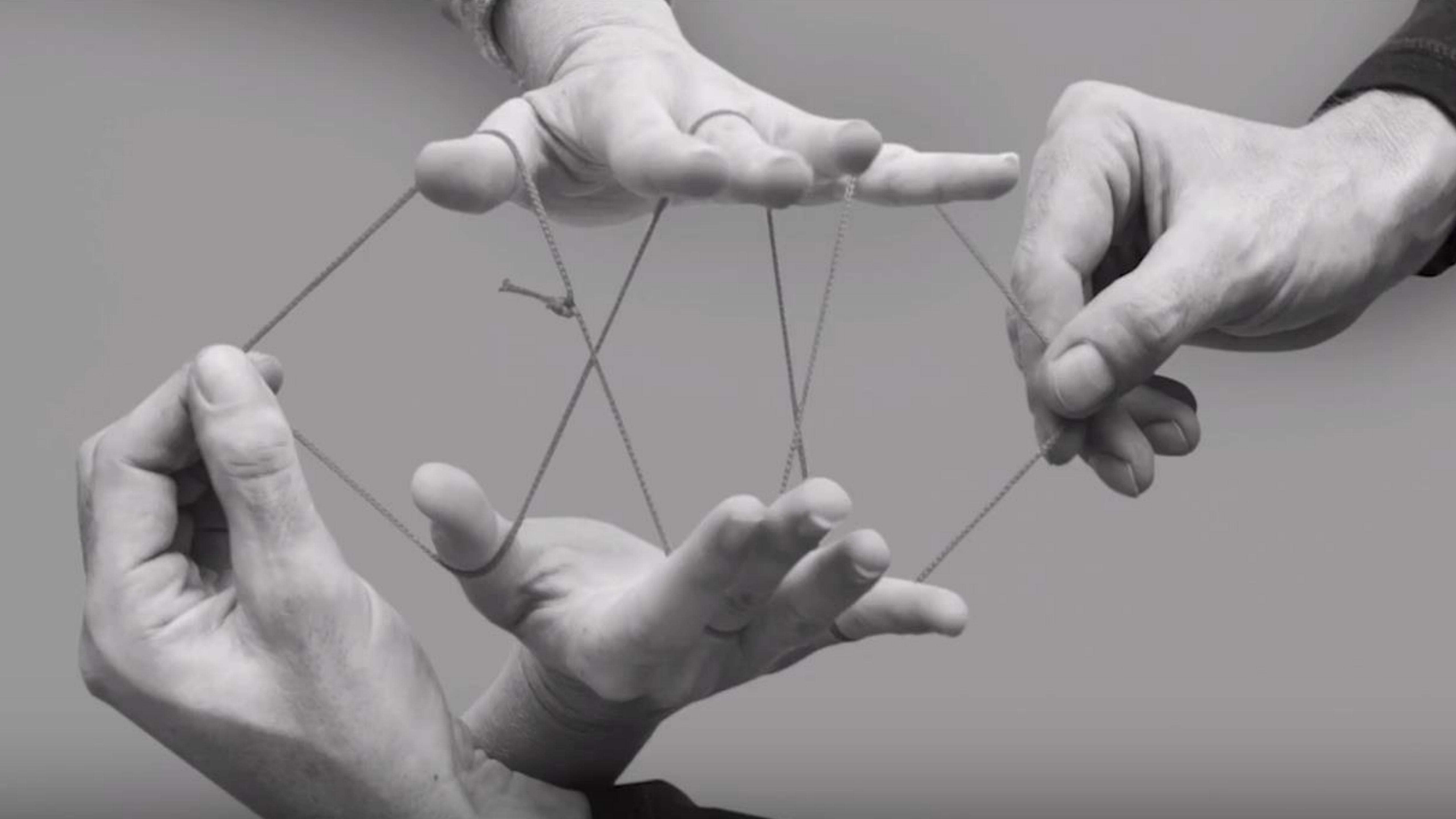
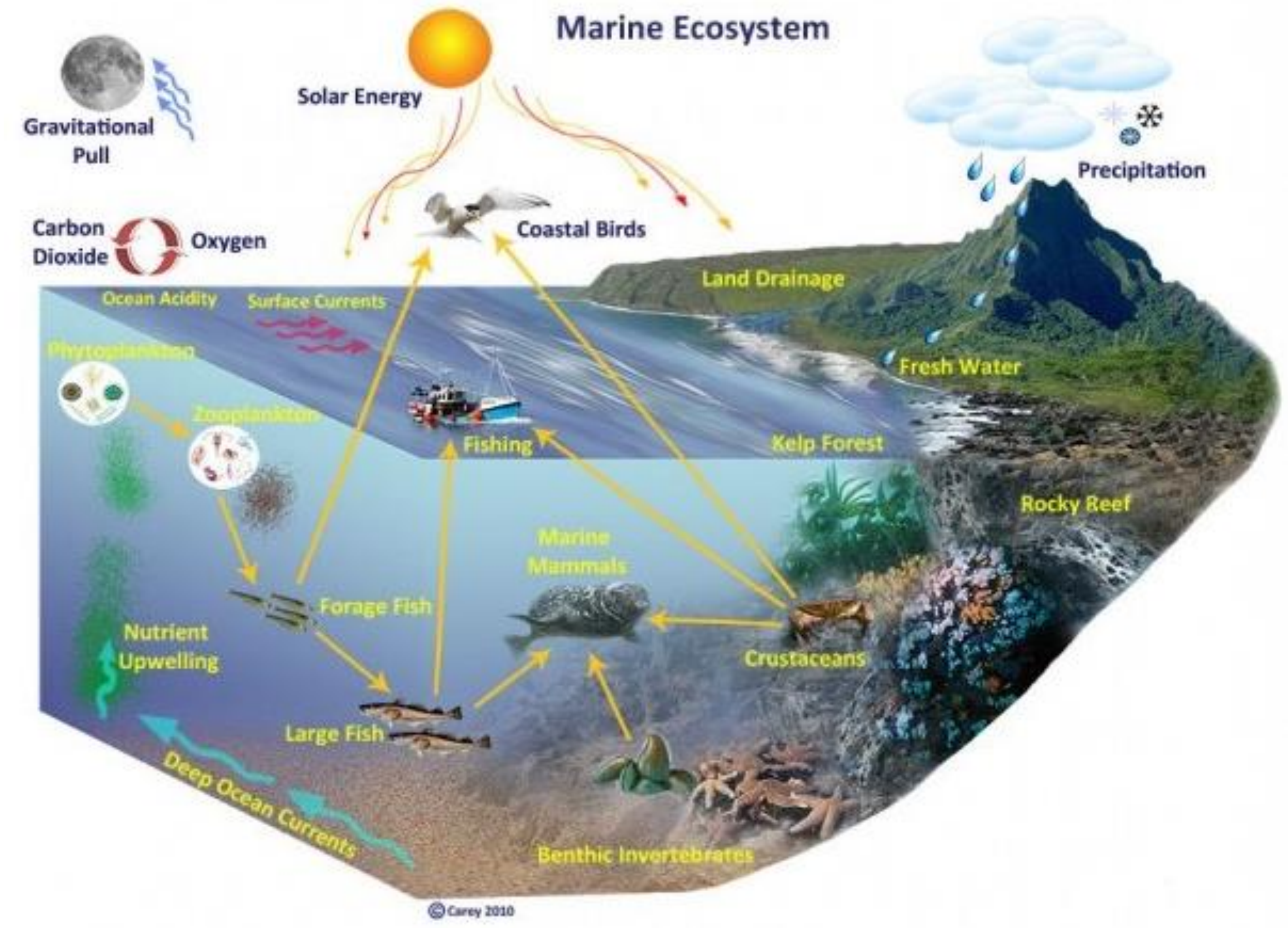
Smart Evolution – People, Services, and Things





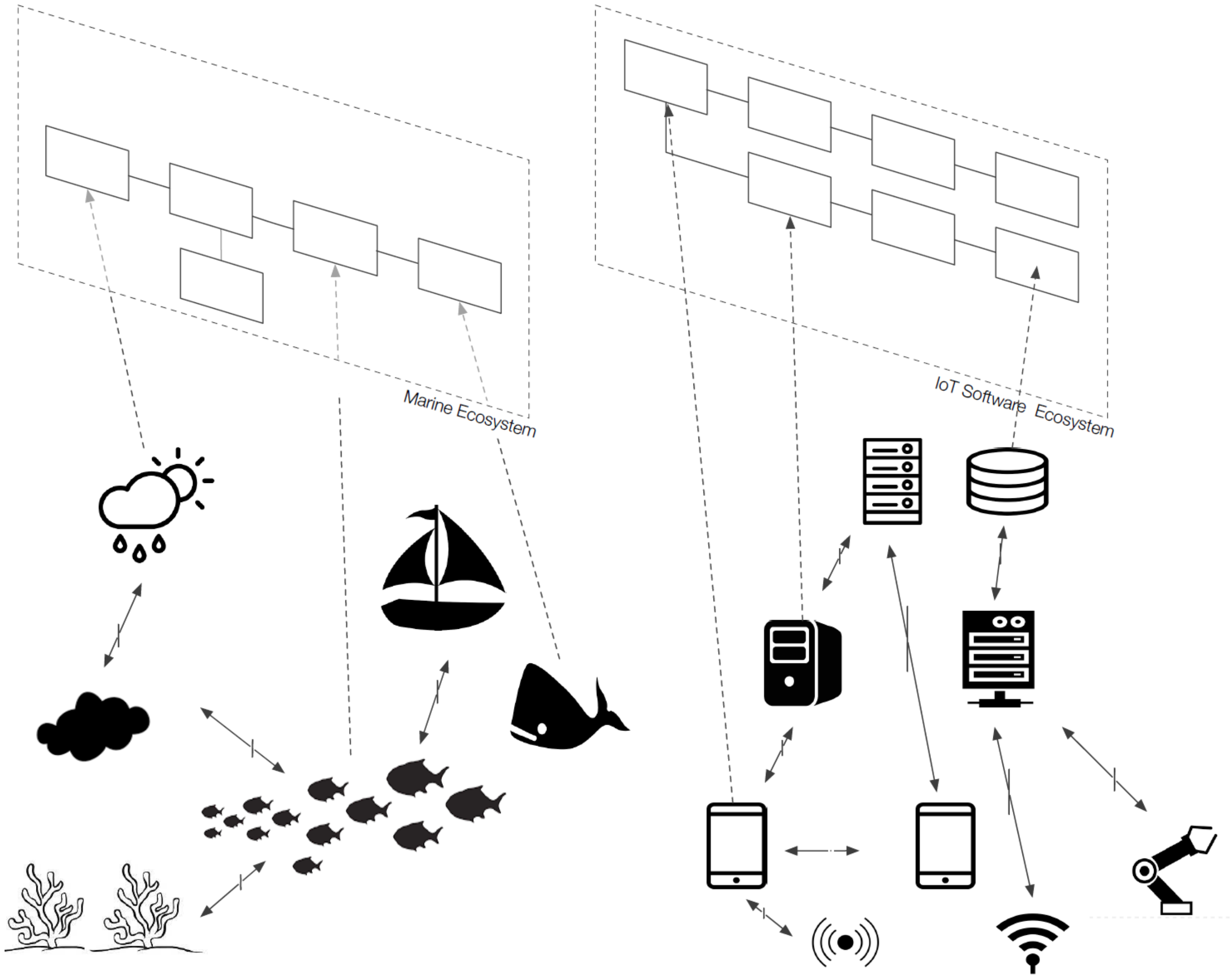
Ecosystems: People, Systems, and Things



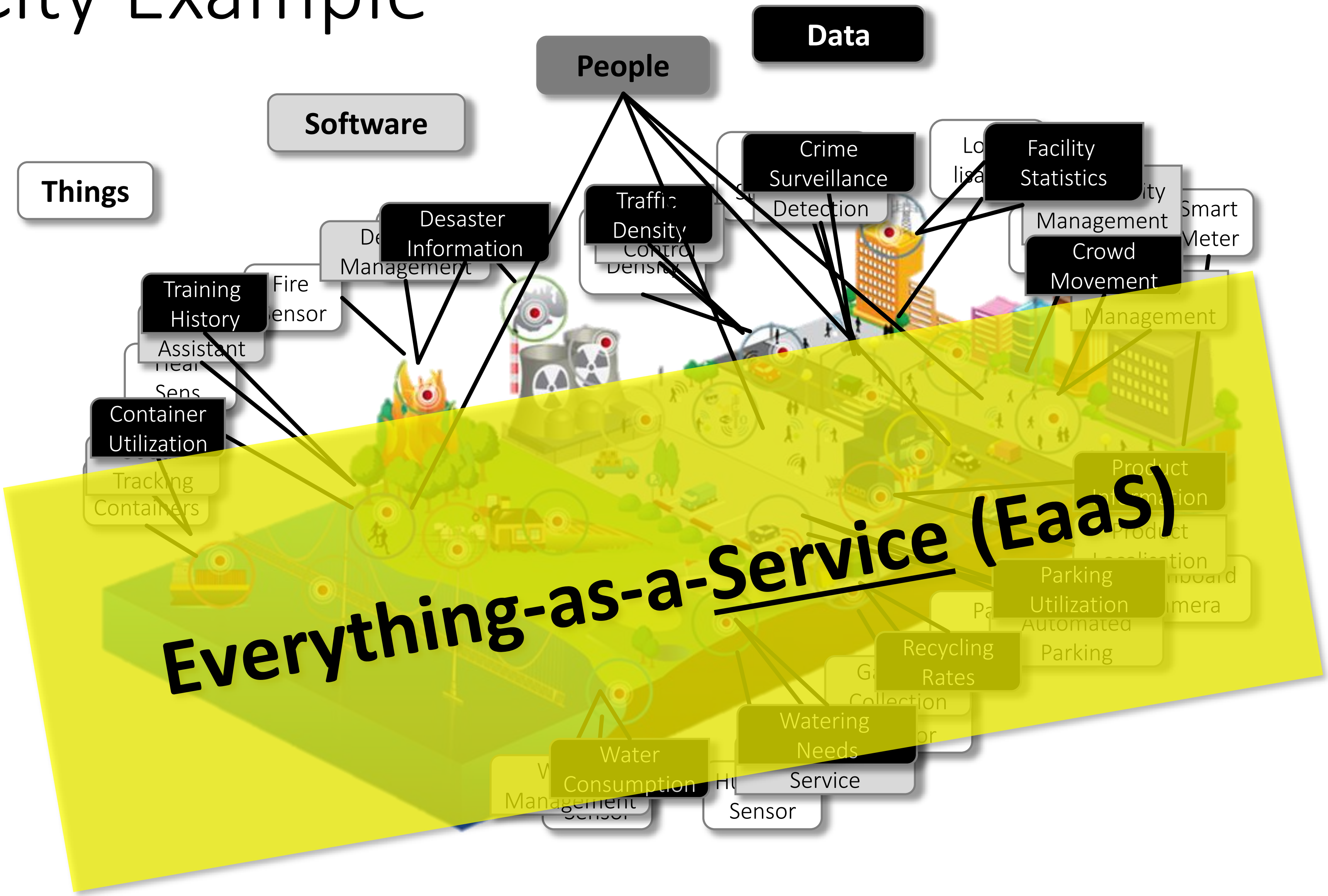
Complex system with networked dependencies and intrinsic adaptive behavior – has:

1. **Robustness & Resilience mechanisms**: achieving stability in the presence of disruption
2. **Measures of health**: diversity, population trends, other key indicators
3. **Built-in coherence**
4. **Entropy-resistence**

Ecosystems for Distributed Systems



Smart City Example

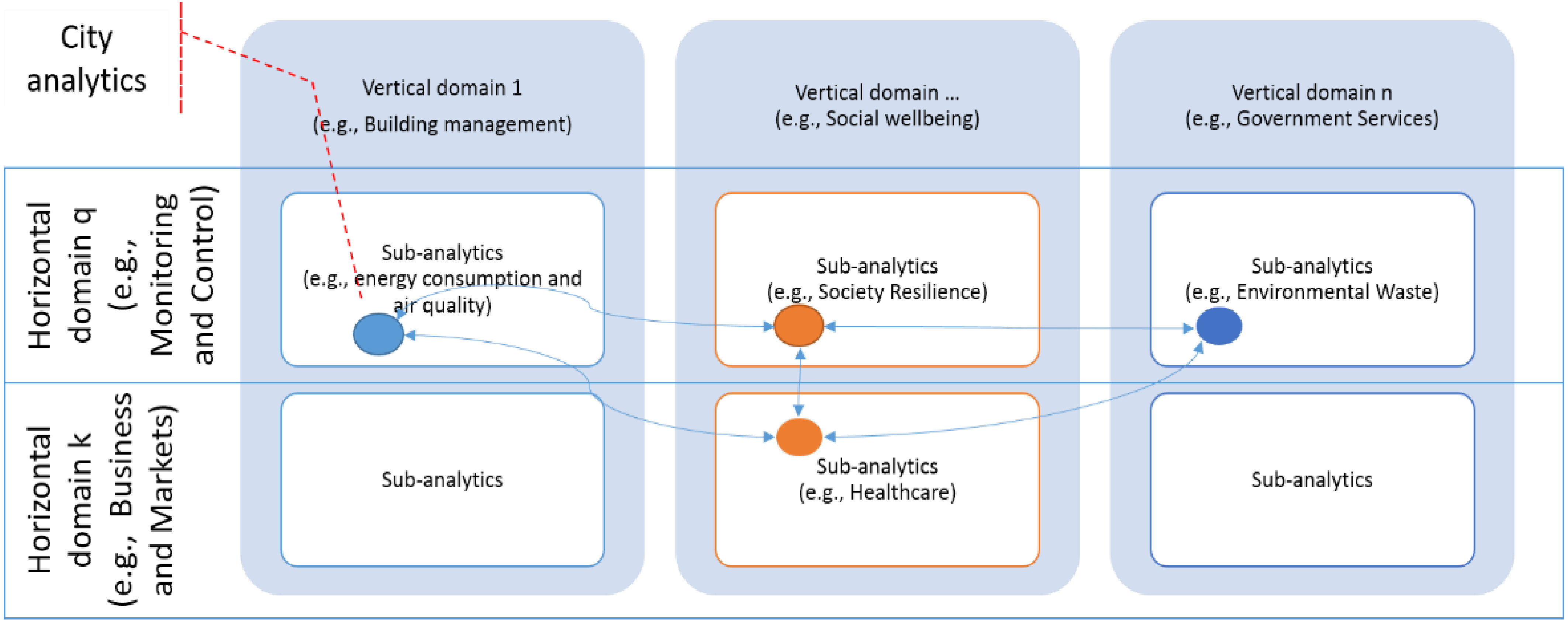


Observation

There are new families of applications that require:

- (Soft) Real-time location-based access to data from the environment at different levels of fidelity
- Appropriate compute and storage resources in close proximity to data producers and consumers

Dynamic Analytics (e.g., Smart City)



Rethinking Divide and Conquer—Towards Holistic Interfaces of the Computing Stack

IEEE Internet Computing, Vol 24., Issue 6, Nov/Dec, pp. 45-57

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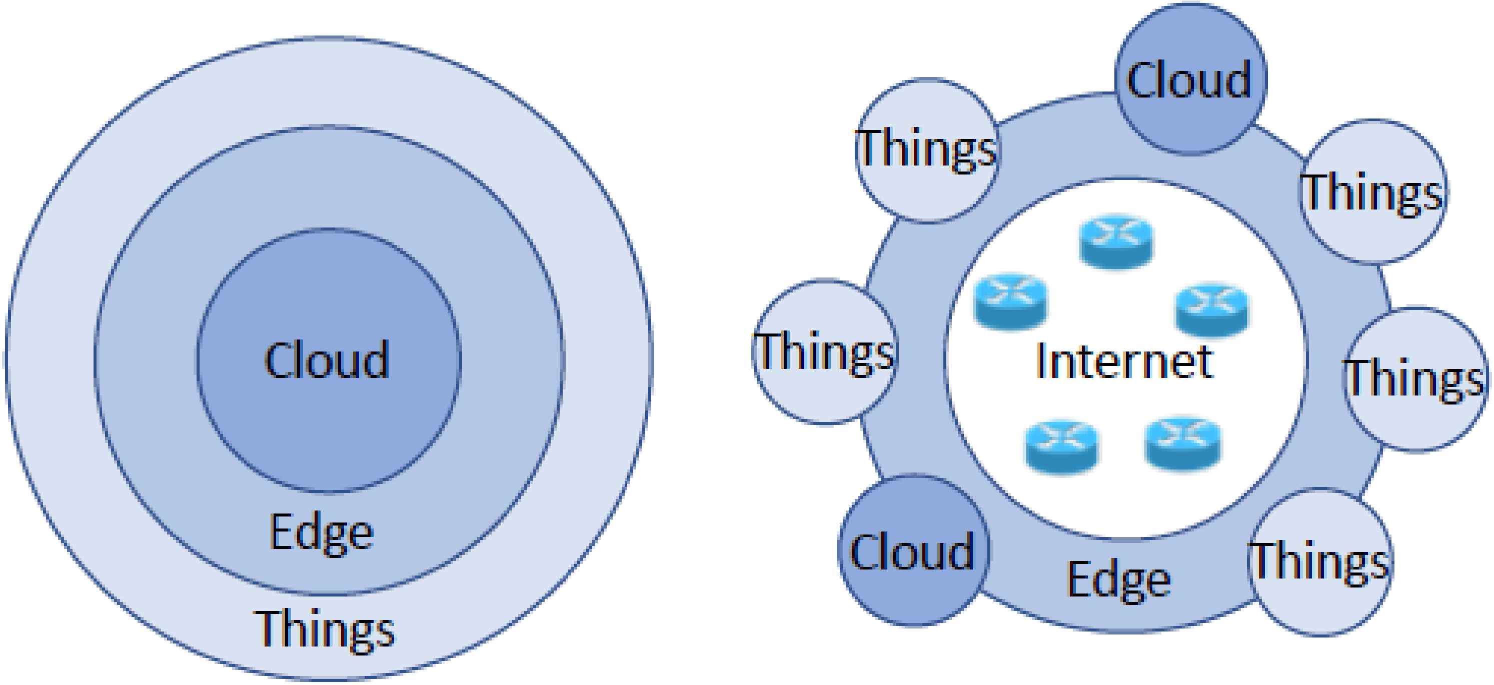
Perspectives on Distributed Systems infrastructures



(a) A cloud-centric perspective:
Edge as "edge of the cloud"

(b) An Internet-centric perspective:
Edge as "edge of the Internet"

Kim, H., Lee, E.A., Dustdar, S. (2019). Creating a Resilient IoT With Edge Computing,
IEEE Computer, 52/8, August 2019

Cloud-centric perspective

Assumptions

- Cloud provides core services; Edge provides local proxies for the Cloud (offloading parts of the cloud's workload)

Edge Computers

- play supportive role for the IoT services and applications
- Cloud computing-based IoT solutions use cloud servers for various purposes including massive computation, data storage, communication between IoT systems, and security/privacy

Missing

- In the network architecture, the cloud is also located at the network edge, not surrounded by the edge
- Computers at the edge do not always have to depend on the cloud; they can operate autonomously and collaborate with one another directly without the help of the cloud

Internet-centric perspective

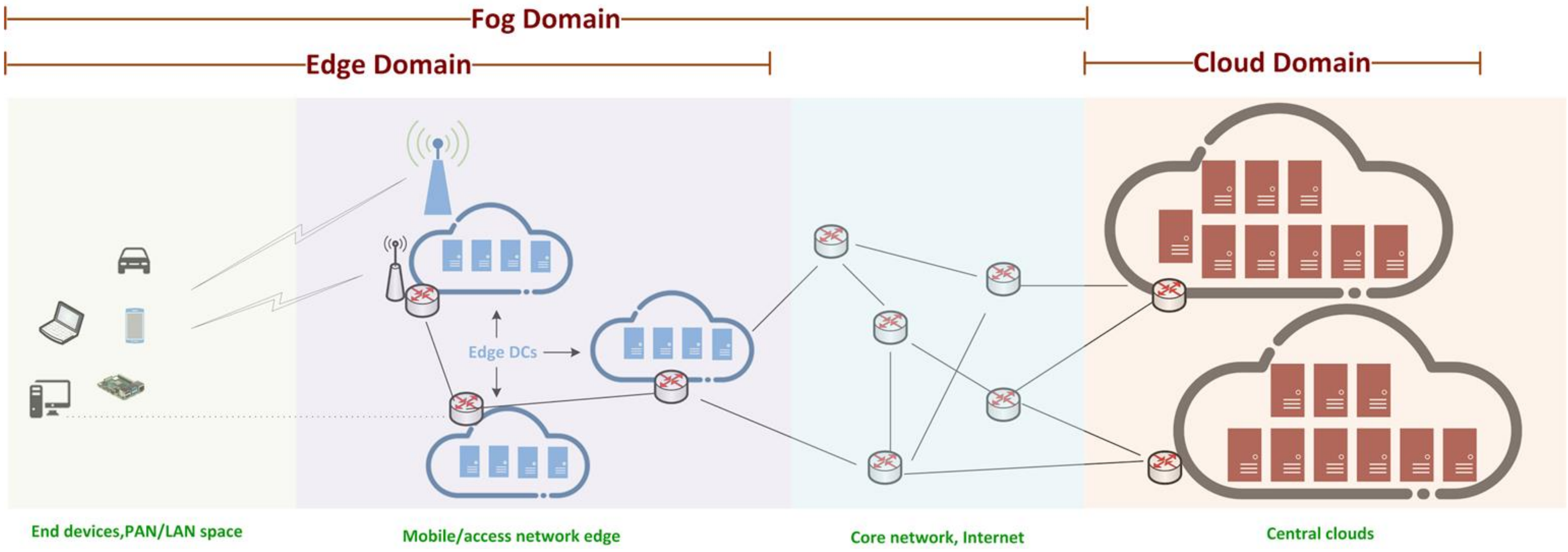
Assumptions

- Internet is center of IoT architecture; Edge devices are gateways to the Internet (not the Cloud)
- Each LAN can be organized around edge devices autonomously
- Local devices do not depend on Cloud

Therefore

- Things belong to partitioned subsystems and LANs rather than to a centralized system directly
- The Cloud is connected to the Internet via the edge of the network
- Remote IoT systems can be connected directly via the Internet. Communications does not have to go via the Cloud
- The Edge can connect things to the Internet and disconnect traffic outside the LAN to protect things -> IoT system must be able to act autonomously

IoT/Edge/Fog/Cloud Continuum: A high level view



Low reliability

Volatility

Mobility

(Mostly) Wireless connectivity

Small form factor

Battery constraints

Mobile, IoT, smart home, vehicles, …

User/Service provider controlled

Edge of the (mobile) network

Low latency to end device

Close to/collocated with 4G/5G base stations

General purpose compute infrastructure

Standards-based architectures & management/orchestration stacks

Telecom operator controlled

“Unlimited” compute/storage resources

Full spectrum of cloud services

High availability

Lower cost

Higher latency vs. edge/fog

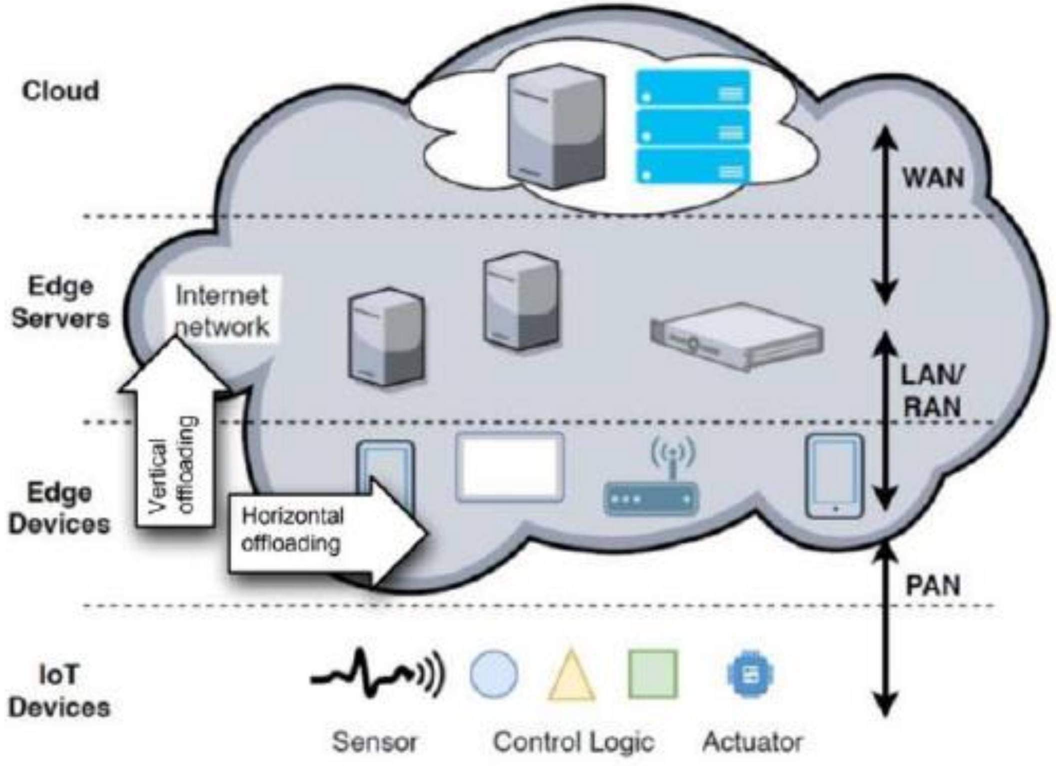
Cloud provider controlled

Vertical vs. Horizontal Edge/Fog/Cloud Architecture

Cloud Computing

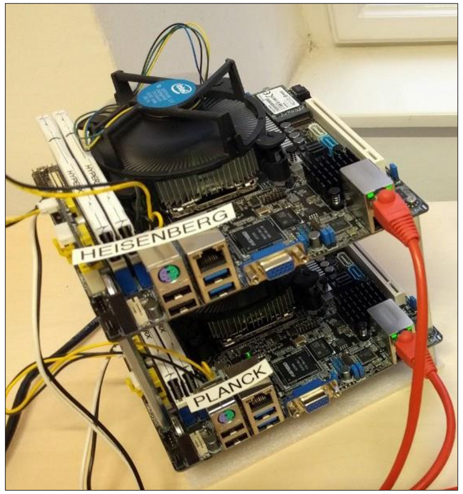
Fog Computing

Edge Computing



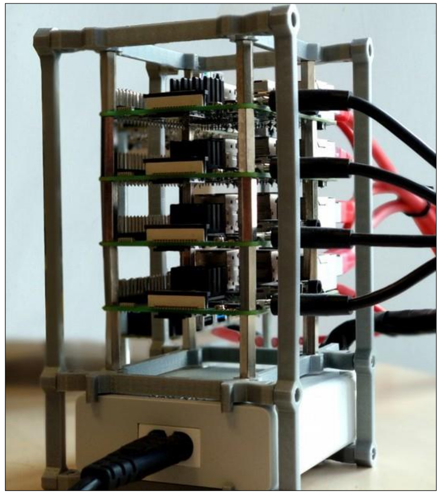
Computing Continuum (horizontal | vertical)

Sun Modular Datacenter



Mini-ITX Servers [1]

Ubuntu Orange Box
(Intel NUC cluster)



“Micro Clouds” [2]

Server Computers

SOC & Single Board Computers

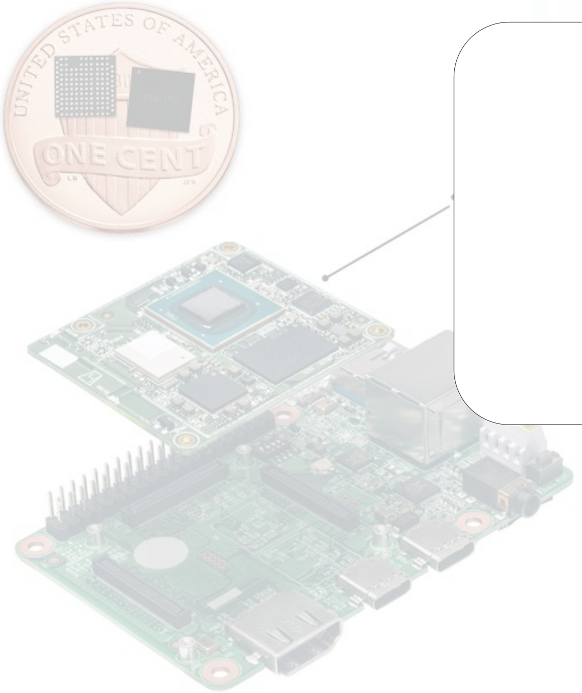
1. Rausch T., Avasalcai C., Dustdar S. (2018). Portable Energy-Aware Cluster-Based Edge Computers. 3rd ACM/IEEE Symposium on Edge Computing (SEC 2018), October 25-27, 2018, Bellevue, WA, USA
2. Elkhatib et al., 2017, “On Using Micro-Clouds to Deliver the Fog”

Specialized Compute Platforms

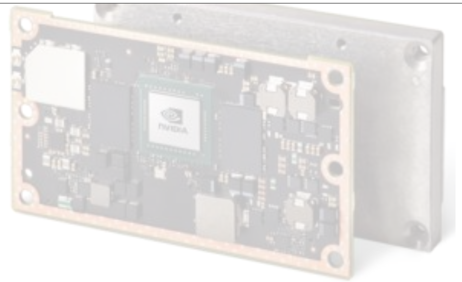
Baidu Kunlun

Microsoft
ject BrainWave

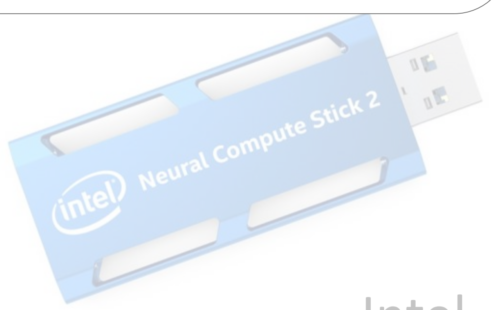
Write once run anywhere™ ?



Google Edge TPU

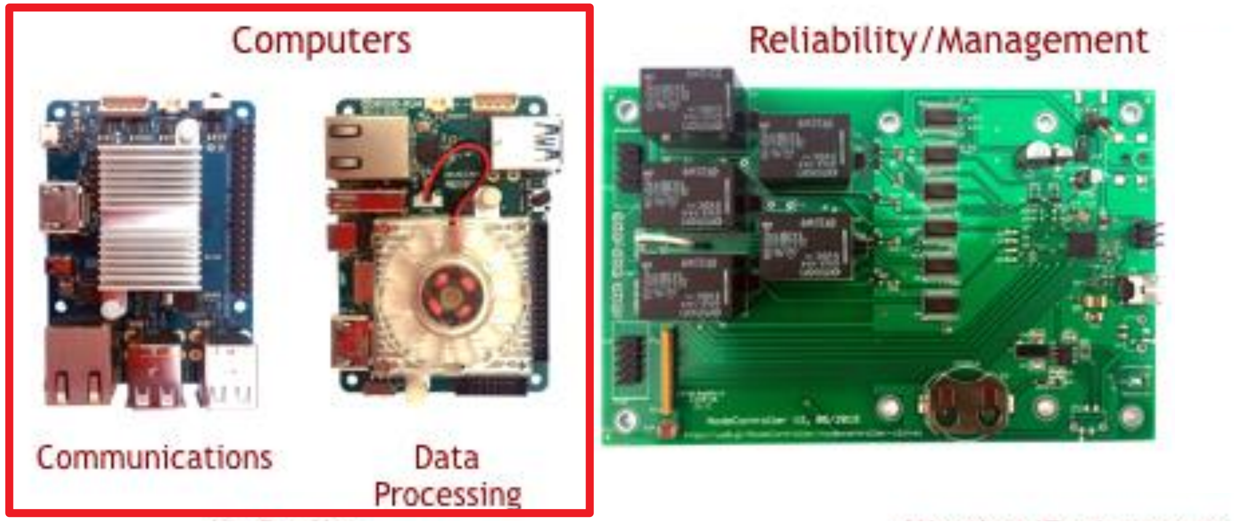


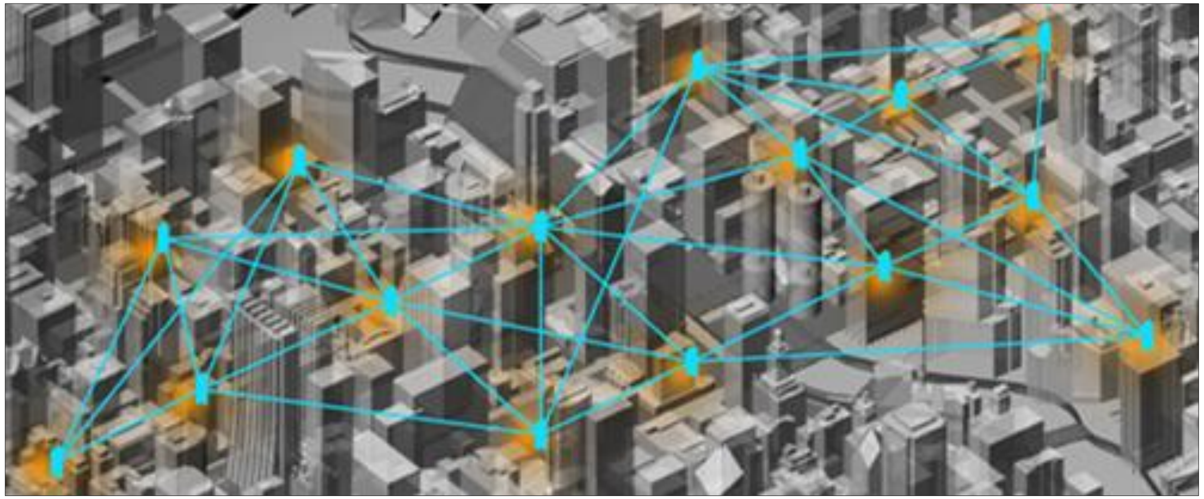
NVIDIA Jetson



Intel
Neural Compute Stick

City-Scale Edge Computing Fabric





https://arrayofthings.github.io

URBAN CENTER FOR COMPUTATION AND DATA

Huawei PoleStar2.0

Software-intensive Edge Systems

Total rethink necessary to support design and operation in an environment that changes

Fundamental conflicting system factors critical to system requirements satisfaction include:

- Latency, as delays of data or control command transfers is a factor arising from the platform and networks heterogeneity and the inherent traditional division of Cloud-IoT, and may affect timeliness and performance;

- Computation as an Edge resource, traditionally performed on cloud infrastructures now may be located closer to end devices, raising an abundance of complex issues associated with distributed systems such as safety, and security;

- Locality and mobility within administrative domains introduces novel challenges with respect to privacy, software configuration and system evolution

Question

Which characteristics of edge computing systems should be abstracted as first-class citizens into the underpinning model?

Hypothesized Answer

- Proximity
- Context
- Capabilities
- Energy

- **Elastic diffusion**
- Intelligent resource allocation
- Efficient operations

Elasticity (Resilience)

(Physics) The property of returning to an initial form or state following deformation

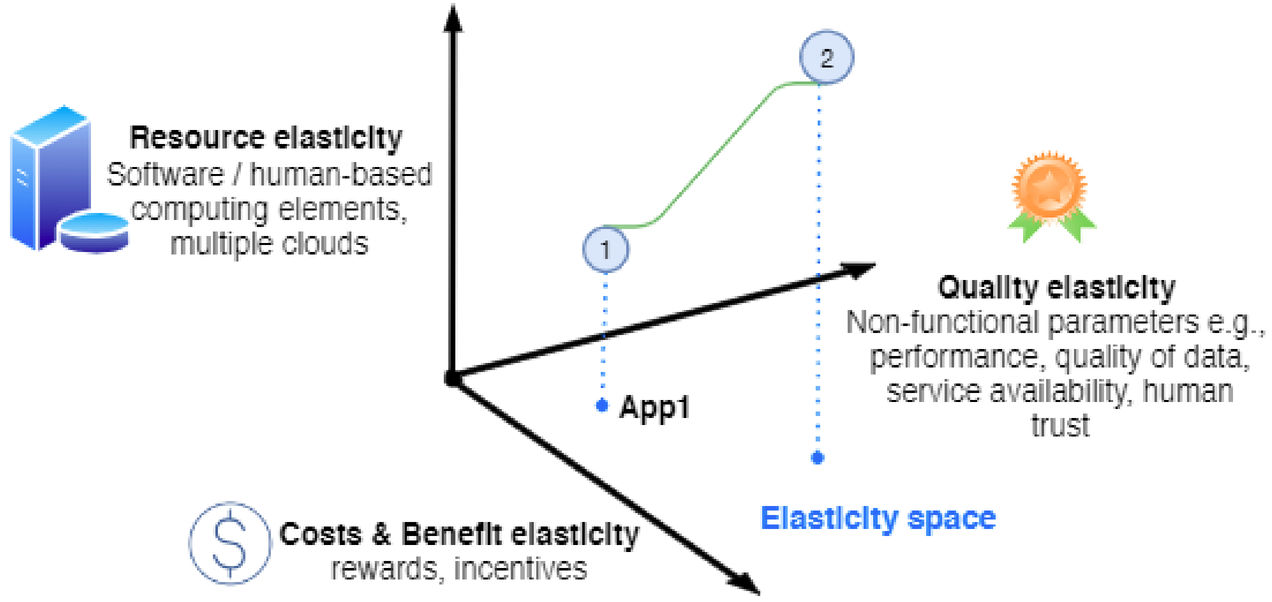
stretch when a force stresses them

e.g., ***acquire*** *new resources,* ***reduce*** *quality*

shrink when the stress is removed

e.g., ***release*** *resources,* ***increase*** *quality*

Elastic Computing > Scalability



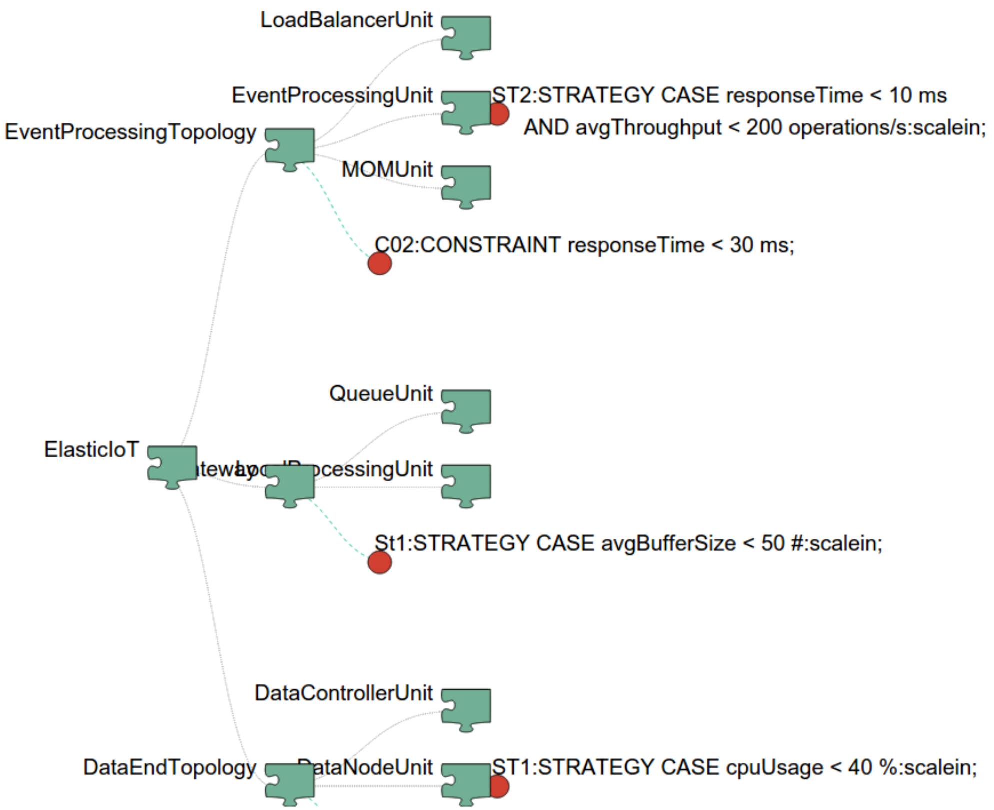
Dustdar S., Guo Y., Satzger B., Truong H. (2012) Principles of Elastic Processes, IEEE Internet Computing, Volume: 16, Issue: 6, Nov.-Dec. 2012

High level elasticity control

#SYBL.CloudServiceLevel
Cons1: CONSTRAINT responseTime < 5 ms
Cons2: CONSTRAINT responseTime < 10 ms
WHEN nbOfUsers > 10000
Str1: STRATEGY CASE fulfilled(Cons1) OR fulfilled(Cons2): minimize(cost)

#SYBL.ServiceUnitLevel
Str2: STRATEGY CASE ioCost < 3 Euro : maximize(dataFreshness)

#SYBL.CodeRegionLevel
Cons4: CONSTRAINT dataAccuracy>90% AND cost<4 Euro



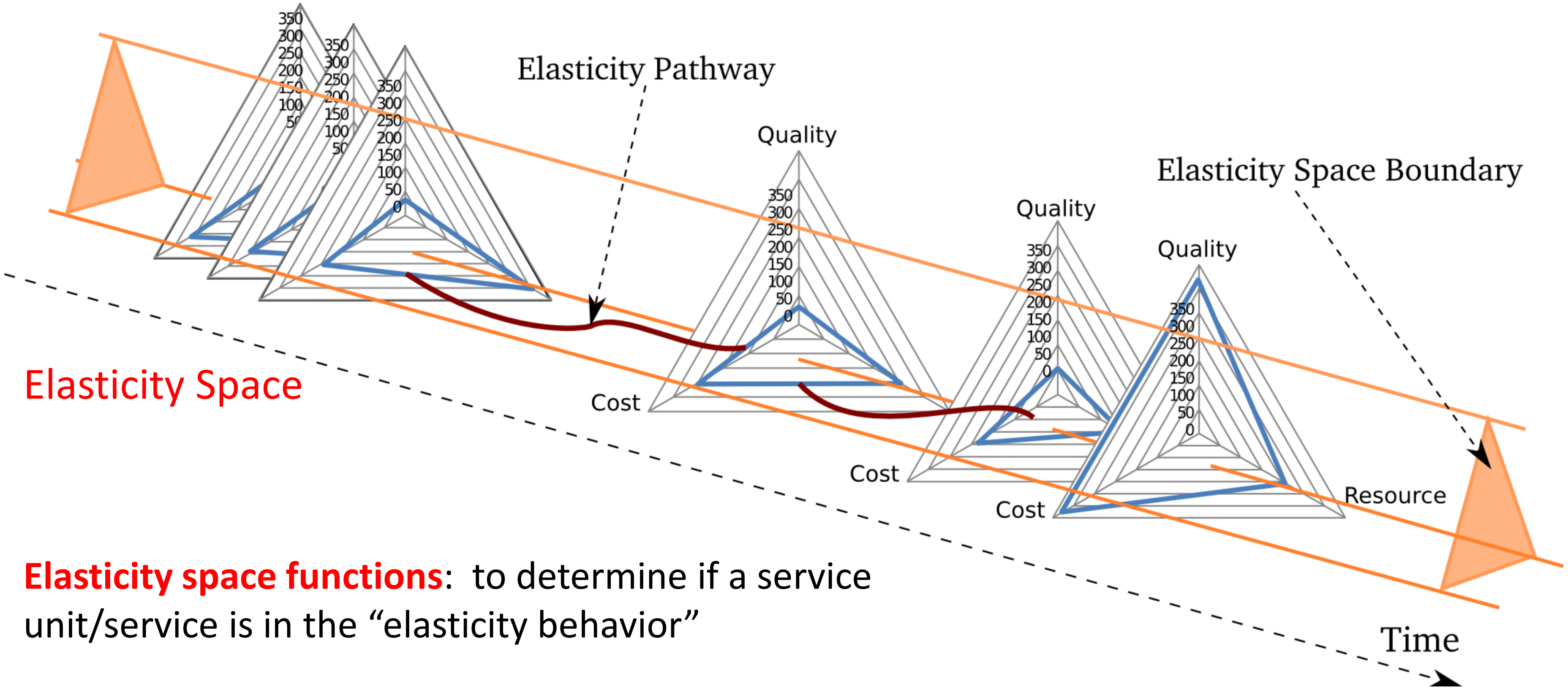
Georgiana Copil, Daniel Moldovan, Hong-Linh Truong, Schahram Dustdar, **"SYBL: an Extensible Language for Controlling Elasticity in Cloud Applications",** 13th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid), May 14-16, 2013, Delft, Netherlands

Copil G., Moldovan D., Truong H.-L., Dustdar S. (2016). **rSYBL: a Framework for Specifying and Controlling Cloud Services Elasticity**. *ACM Transactions on Internet Technology*

Elasticity Model for Edge & Cloud Services

Moldovan D., G. Copil,Truong H.-L., Dustdar S. (2013). **MELA: Monitoring and Analyzing Elasticity of Cloud Service. CloudCom 2013**

Elasticity Pathway functions: to characterize the elasticity behavior from a general/particular view



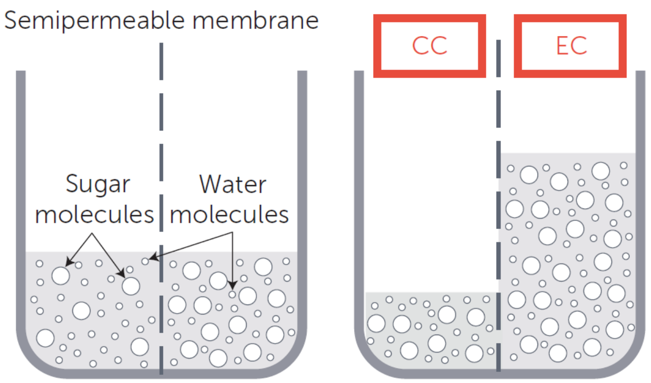
Elasticity Space

Elasticity space functions: to determine if a service unit/service is in the "elasticity behavior"

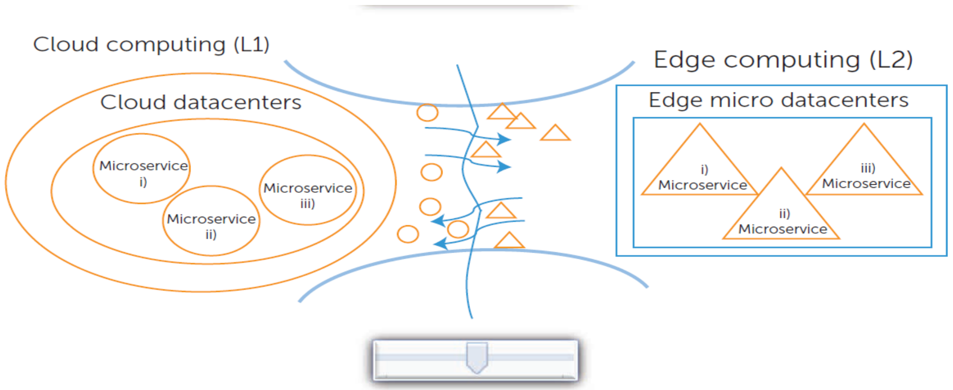
Elastic Diffusion, aka Osmotic Computing

osmotic.org

- In chemistry, “osmosis” represents the seamless diffusion of molecules from a higher to a lower concentration solution.



- Dynamic management of (micro)services across cloud and edge infrastructures
  - deployment, networking, and security, …
  - providing reliable IoT support with specified levels of QoS.



Villari M., Fazio M., Dustdar S., Rana O., Ranjan R. (2016). [Osmotic Computing: A New Paradigm for Edge/Cloud Integration]. *IEEE Cloud Computing*, Volume 3, Issue 6, pp. 76-83

Towards Edge Intelligence

Computational Fabric

- dispersed resources allow training, monitoring, serving of models
- Heterogeneity of applications and models requires
    - (1) flexible and modular **infrastructure** and
    - (2) intelligent operations **mechanisms** (due to the scale of the infrastructure)

Operationalization

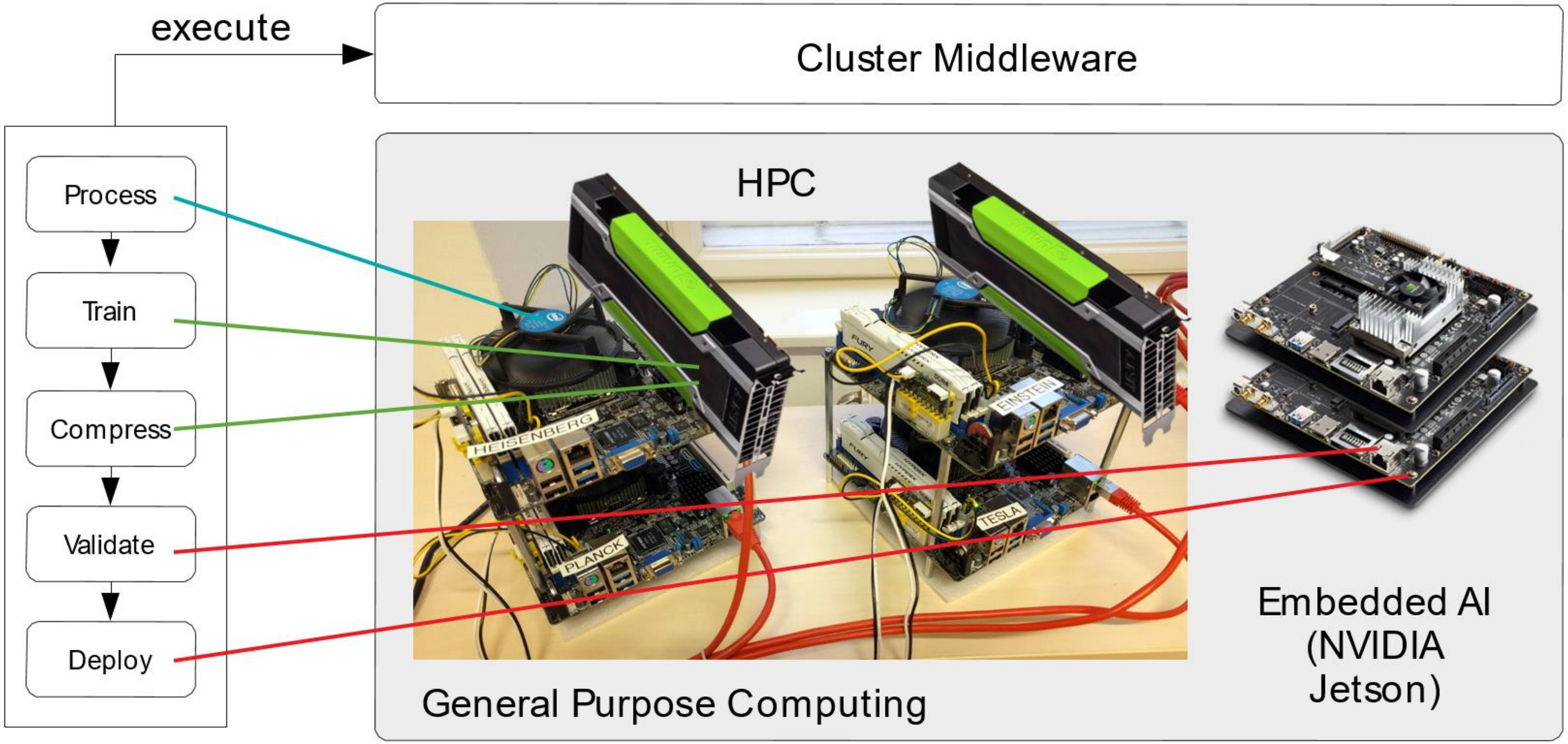
- Automated AI application lifecylce management to the Edge

Rausch, T., Dustdar, S. (2019). Edge Intelligence: The Convergence of Humans, Things, and AI. In *IEEE International Conference on Cloud Engineering (IC2E) 24-27 June 2019*.

Fabric for Edge Intelligence

1. **Sensing (Sensor Data as a Service)**
   - Large number, dynamic and mobile nature of publishers/subscribers of sensor data + QoS requirements of edge intelligence
     ->> rethink centralized messaging services such as AWS IoT or MS Azure IoT Hub
   - Management and governance of such a distributed/decentralized sensing infrastructure
2. **Edge computer network with modular AI capabilities**
   - New AI accelarators for edge devices (e.g., Google Edge TPU with an aplication specific integrated circuit; MS BrainWave with field-programmable gate arrays (FPGAs); Intel Neural Compute Stick; Baidu Kunlun, Huawei Atlas AI Platform
3. **Intelligent orchestration mechanisms for decentralized and distributed infrastructure**

Edge Intelligence Fabric



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Nastic S., Rausch T., Scekic O., Dustdar S., Gusev M., Koteska B., Kostoska M., Jakimovski B., Ristov S., Prodan R. (2017). [A Serverless Real-Time Data Analytics Platform for Edge Computing](). IEEE Internet Computing, Volume 21, Issue 4, pp. 64-71

Rausch T., Dustdar S., Ranjan R. (2018). [Osmotic Message-Oriented Middleware for the Internet of Things](). *IEEE Cloud Computing*, Volume 5, Issue 2, pp. 17-25

Federated learning in Distributed Systems

- Training on data **directly on remote devices**...
- ...**without revealing** the data themselves
- Sending the outcome of local training to server (**local updates**)
- Server aggregates these updates into a **global model**
- Makes the model available to devices

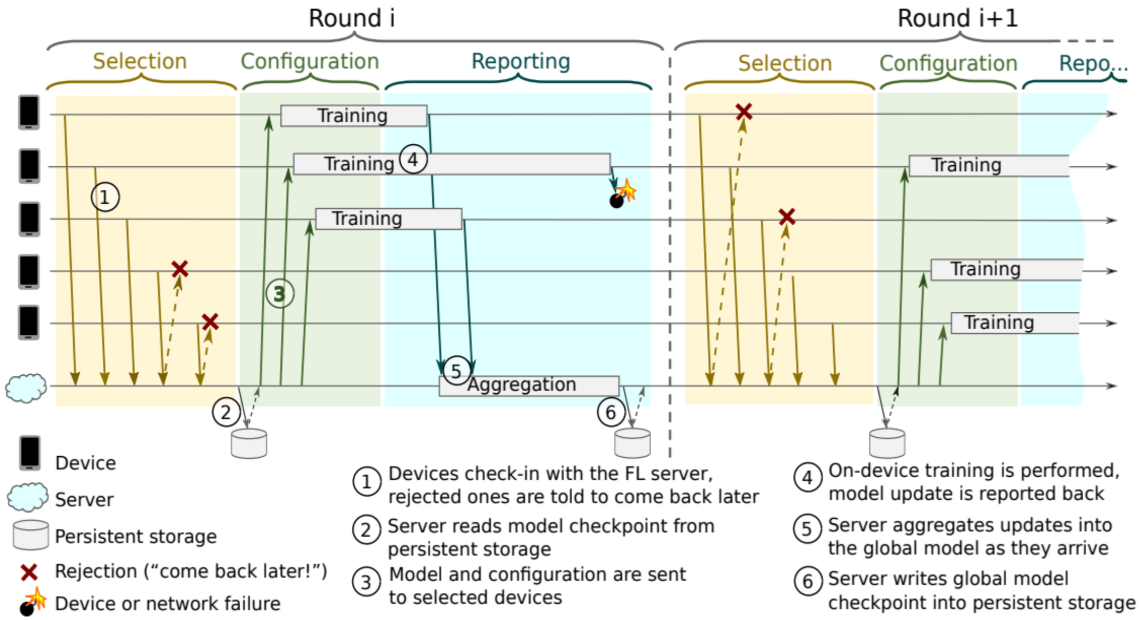


Figure source & further reading: K. Bonawitz et al., "Towards Federated Learning at Scale: System Design," arXiV:1902.01046, March 2019. Available: https://arxiv.org/pdf/1902.01046.pdf

Applications

- For mobile devices
  - Next-word prediction, face detection, voice recognition
  - Train on data from smartphone text editors, cameras, mics
  - Users do not wish to reveal their messages, photos, and videos
  - Also, they don’t want to waste bandwidth and MBs from their data plan

- For organizations
  - Organizations such as hospitals have data, but should not expose them
  - Federating such data in a private way to apply ML for medical and other research

- For environmental, transportation, smart home, and other applications
  - Measurement devices with sensors (e.g., for air pollution) mounted on cars
  - Sensors in a smart home
  - Pushing data to servers for centralized training might leak driver patterns, daily habits, etc.

Current research challenges

Device recruitment strategies: Which subset of the devices to assign a learning task at any given round? Processing, storage, battery, trustworthiness, data quality and other criteria to consider

Volatility: Devices can "disappear" or join at any time

Asynchrony: Algorithms face challenges when end devices do not submit their data in a timely manner

Non independent and identically distributed data: inaccuracies, personalization lost

Heterogeneity in the volume of training data per device: A device that contributes a lot may lead to a biased model

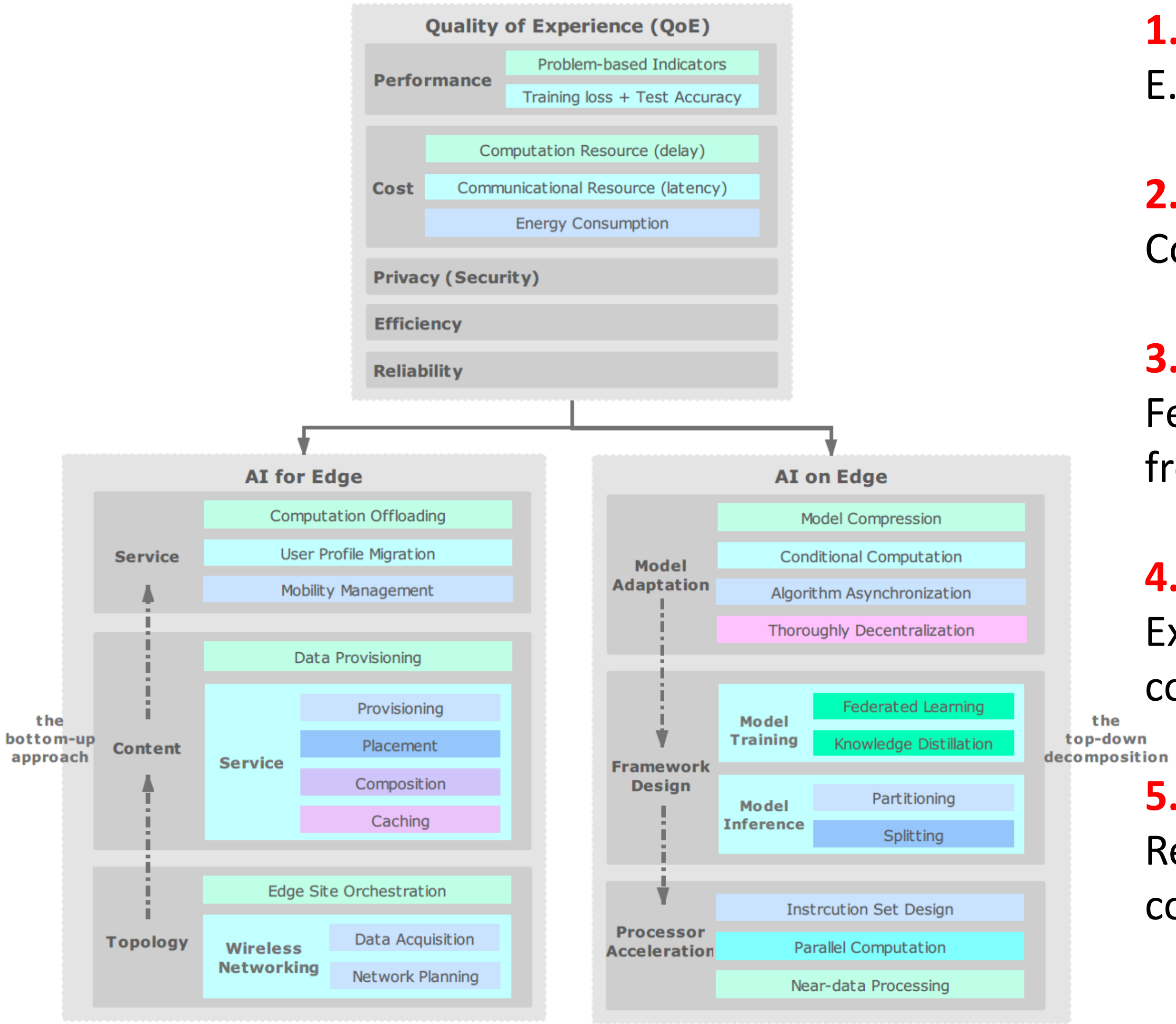
Preventing privacy leaks: Some private information may be inferred even if devices do not transmit the actual data

Incentives to misbehave: Why waste battery when I can let the others do all the work?

Further reading: T. Li at al., "Federated Learning: Challenges, Methods, and Future Directions," arXiv:1908.07873, August 2019. Available: https://arxiv.org/pdf/1908.07873.pdf

Research Roadmap – Quality of Experience

Edge Intelligence: The Confluence of Edge Computing and Artificial Intelligence,
IEEE Internet of Things Journal, Volume 7, Issue 8, pp. 7457-7469



1. Performance
E.g., the ratio of computation offloading

2. Cost
Computation|Communication|Energy consumption costs

3. Privacy & Security
Federated learning, i.e., aggregating local machines models from distributed edge devices

4. Efficiency
Excellent performance with low overhead, e.g., model compression, conditional computation

5. Reliability
Relates to model upload and download and wireless network congestion

AI *for* Edge

1. Topology

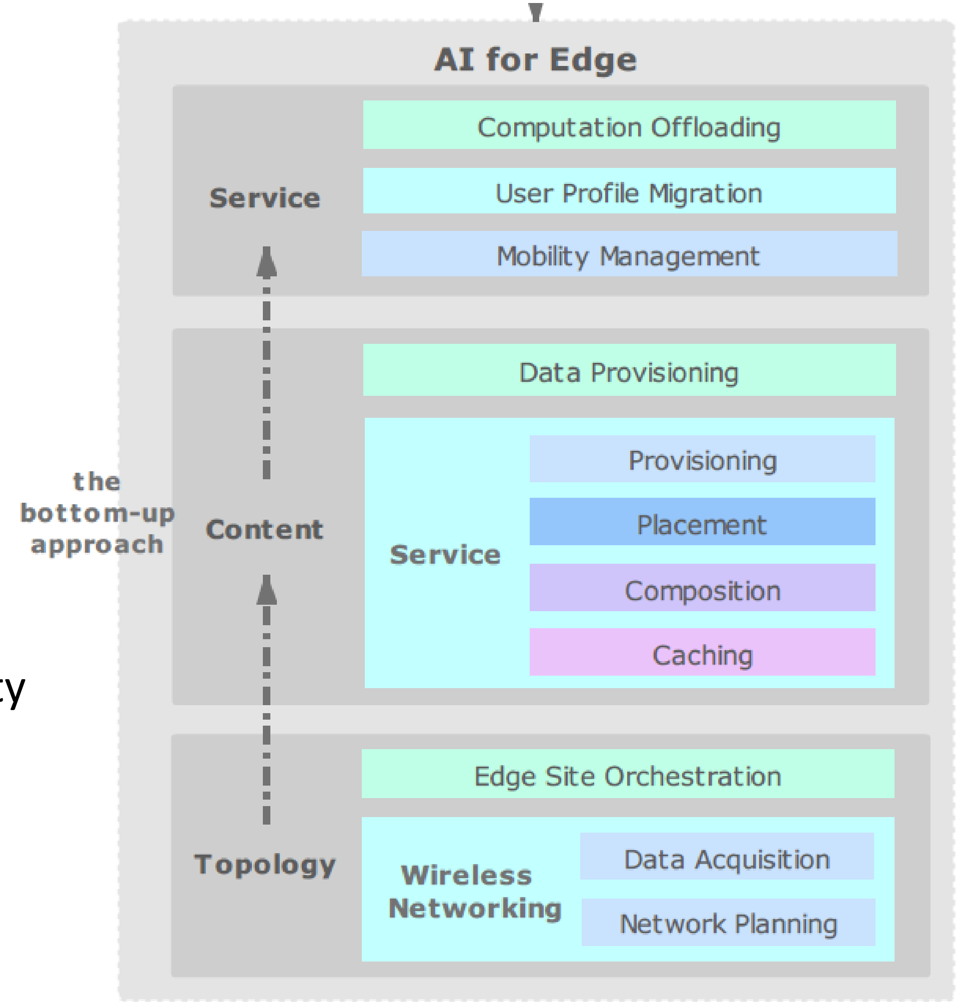
- Edge orchestration and coordination with small base stations
- Unmanned Aerial Vehicles (UAVs) and access points

2. Content

Lightweight service frameworks for QoS-aware services, e.g., on mobile devices

3. Service

Computation offloading, User profile migration and mobility management



Edge Intelligence: The Confluence of Edge Computing and Artificial Intelligence, *IEEE Internet of Things Journal*, Volume 7, Issue 8, pp. 7457-7469

Grand Challenges – AI *for* Edge

- **Model Establishment – restraining the optimization model**
  - Stochastic Gradient Descent (SGD)
  - MBGD (Mini-Batch Gradient Descent)

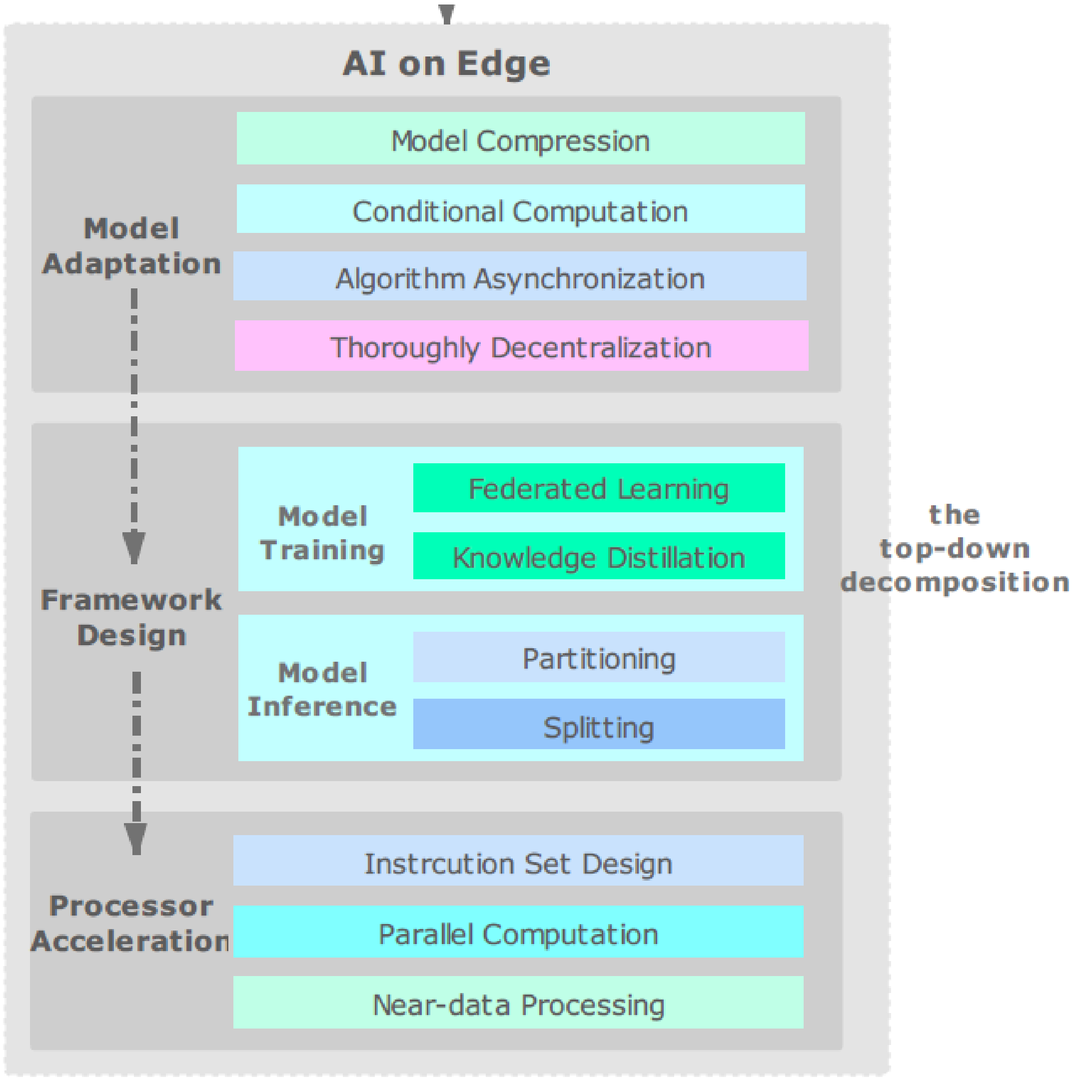
- **Algorithm Development**
  - Selection of *which* edge device should be responsible for deployment and execution in an online manner
  - SOTA formulates combinatorial and NP-hard optimization problems with high computational complexity

- **Trade-off between optimality and efficiency**
  - Consider resource constraint devices

Edge Intelligence: The Confluence of Edge Computing and Artificial Intelligence, *IEEE Internet of Things Journal*, Volume 7, Issue 8, pp. 7457-7469

AI *on* Edge

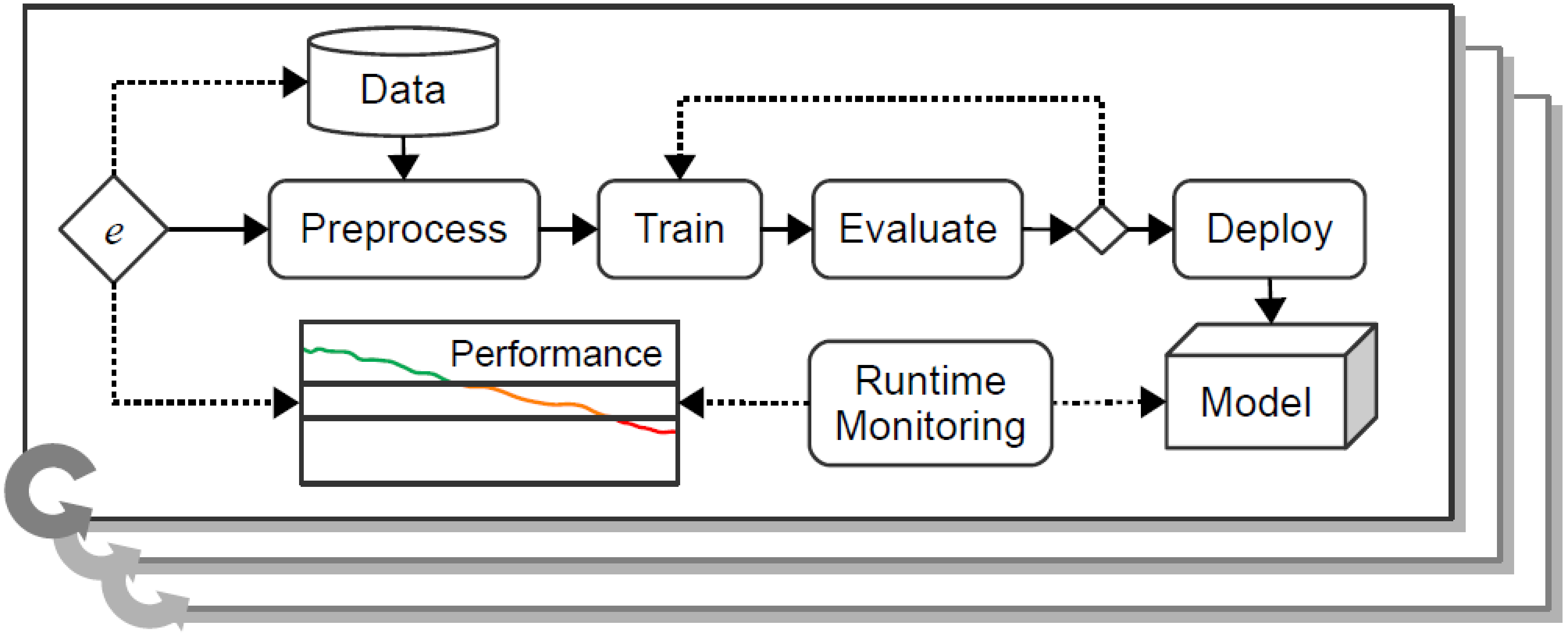
- **Data Availability**
  - Challenge of lack of availability and usability of raw training data for model training and inference
  - Bias of raw data from various end user/mobile devices
- **Model Selection**
  - SOTA requires selection of need-to-be trained AI models has challenges
  - Threshold of learning accuracy and scale of AI models for quick deployment and delivery
  - Selection of probe training frameworks and accelerator architectures under limited resources
- **Coordination Mechanisms**
  - Cordination between heterogeneous edge devices, cloud, and various middlewares and APIs



Edge Intelligence: The Confluence of Edge Computing and Artificial Intelligence, *IEEE Internet of Things Journal*, Volume 7, Issue 8, pp. 7457-7469

Managing the AI Lifecycle

AI lifecycle pipeline with a rule-based trigger *e* that monitors available data and runtime performance data to form an automated retraining loop



AI Operations Workflows – Edge to Cloud

	Data characteristics	Model characteristics	Enabling technologies	Example use cases
C2C	- Training data is centralized - Massive data sets	- Models are large - Huge number of inferencing requests need to be load balanced	- Scalable learning infrastructure [39] - Data warehousing	- Image search - Recommender systems
C2E	- Training data is centralized - Inferencing data may be sensitive	- Inferencing may need to happen in near-real time - Large number of model deployments - Models run on specialized hardware	- Model compression [42] - Latency/accuracy tradeoff [43] - Distributed inferencing [44] - Transfer learning [45]	- Surveillance systems - Self driving cars - Fieldwork assistants
E2C	- Training data is distributed - Training data may be sensitive	- Models can be centralized - Huge number of inferencing requests need to be load balanced	- Decentralized/federated learning [41]	- Volunteer computing - Novel Smart City use cases
E2E	- Training data is distributed - Training and inferencing data may be sensitive	- Inferencing may need to be near-real time	- Decentralized/federated learning - Distributed inferencing	- Industrial IoT (e.g., predictive maintenance) - Privacy-aware personal assistants - Novel IoT use cases

Rausch, T., Dustdar, S. (2019). Edge Intelligence: The Convergence of Humans, Things, and AI. In *IEEE International Conference on Cloud Engineering (IC2E) 24-27 June 2019*.

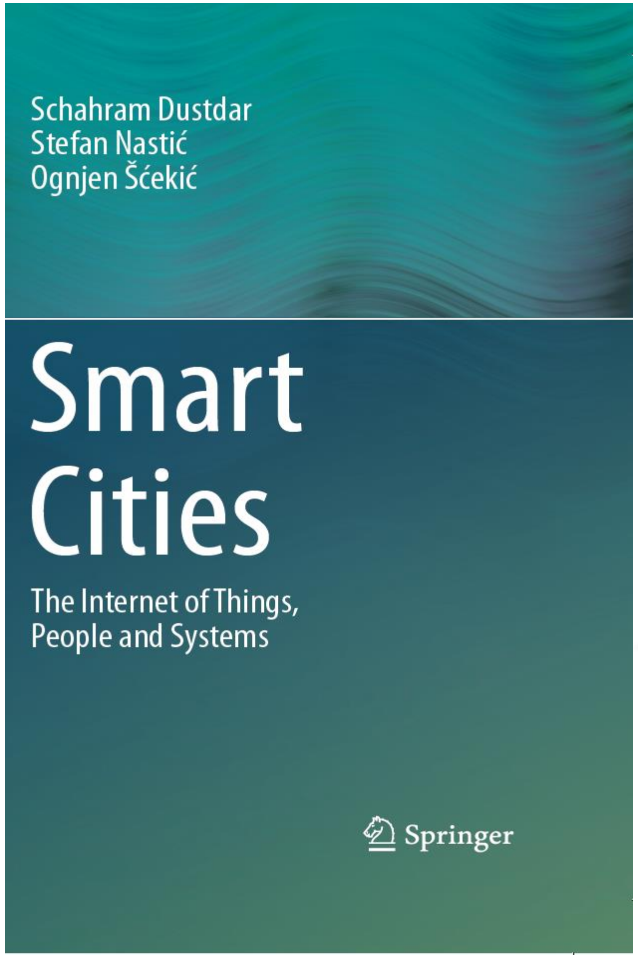
Conclusions

- Leverage the Computing “Continuum“ from IoT->Edge->Fog->Cloud

- Differentiate between AI *for* Edge and AI *on* Edge. Both bring their distinct research challenges

- Need for an Edge Intelligence AI Fabric and a “clear“ distributed systems ecosystems understanding

Thanks for your attention



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ACM Distinguished Speaker

IEEE TCSVC Outstanding Leadership Award in Services Computing

IEEE TCSC Award for Excellence in Scalable Computing

IBM Faculty award

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