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Actionable observability into the emissions of cloud-based software

Vasilios Andrikopoulos

vandriko.github.io

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Takeaways

01 $\mathbb{E}$(software) : non-trivial

02 $\mathbb{E}$() : hard(er) mode

03 $\mathcal{O}^{+}$($\mathbb{E}$()) : essential

Software energy consumption

Establishing the relation between a software system & its consumed energy is non-trivial

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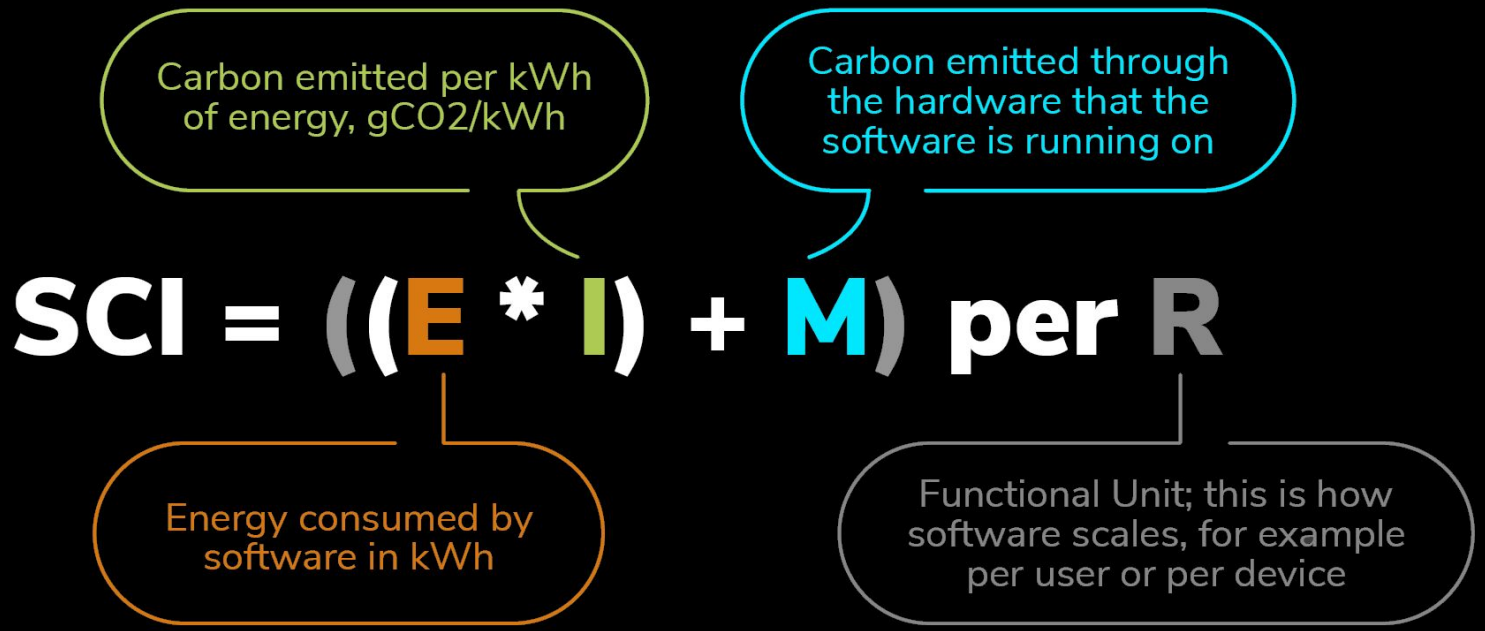
Emissions and energy

Software Carbon Intensity (SCI) [ISO/IEC 21031:2024]



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greensoftware.org

creative commons

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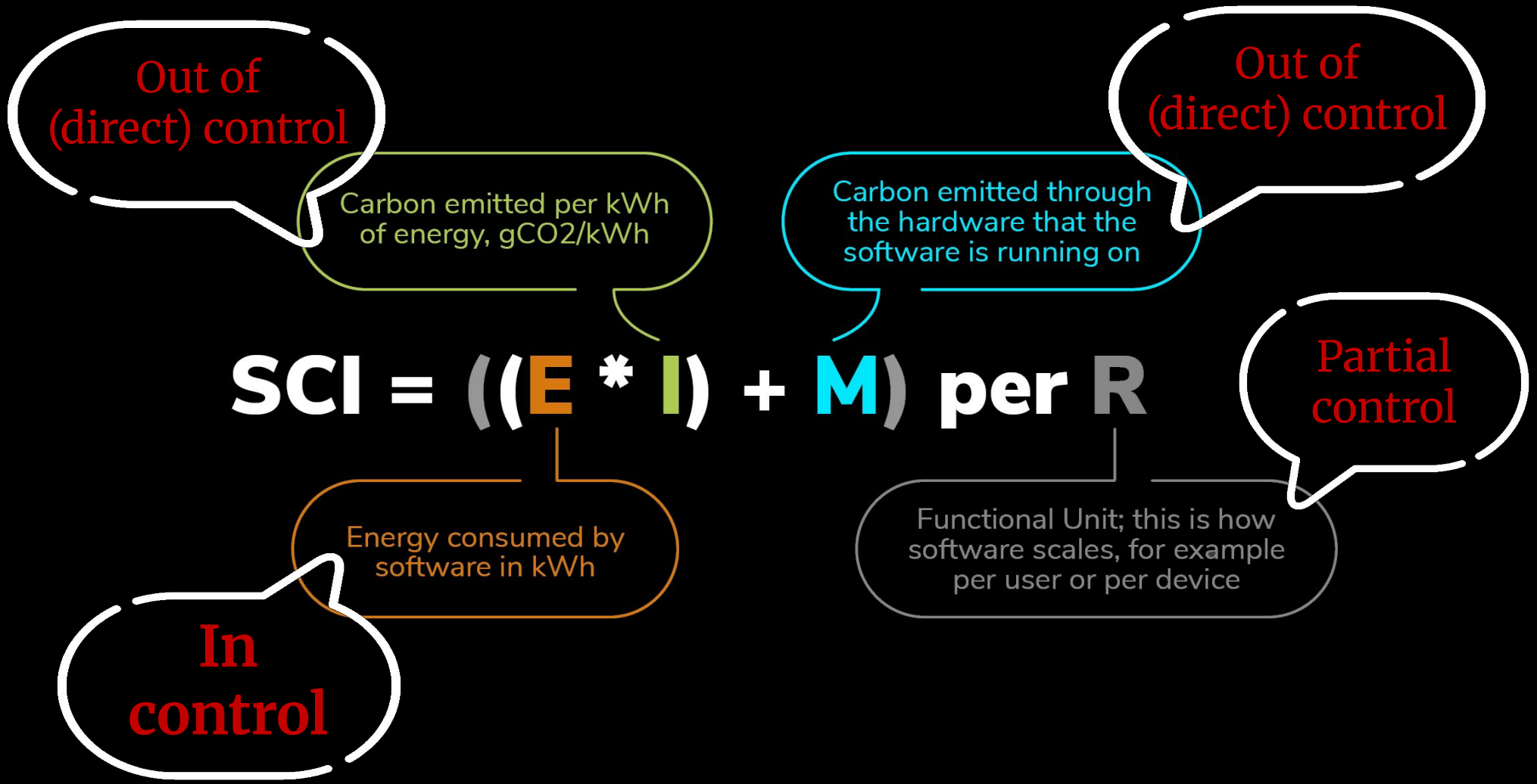
Consumed energy as the optimization target



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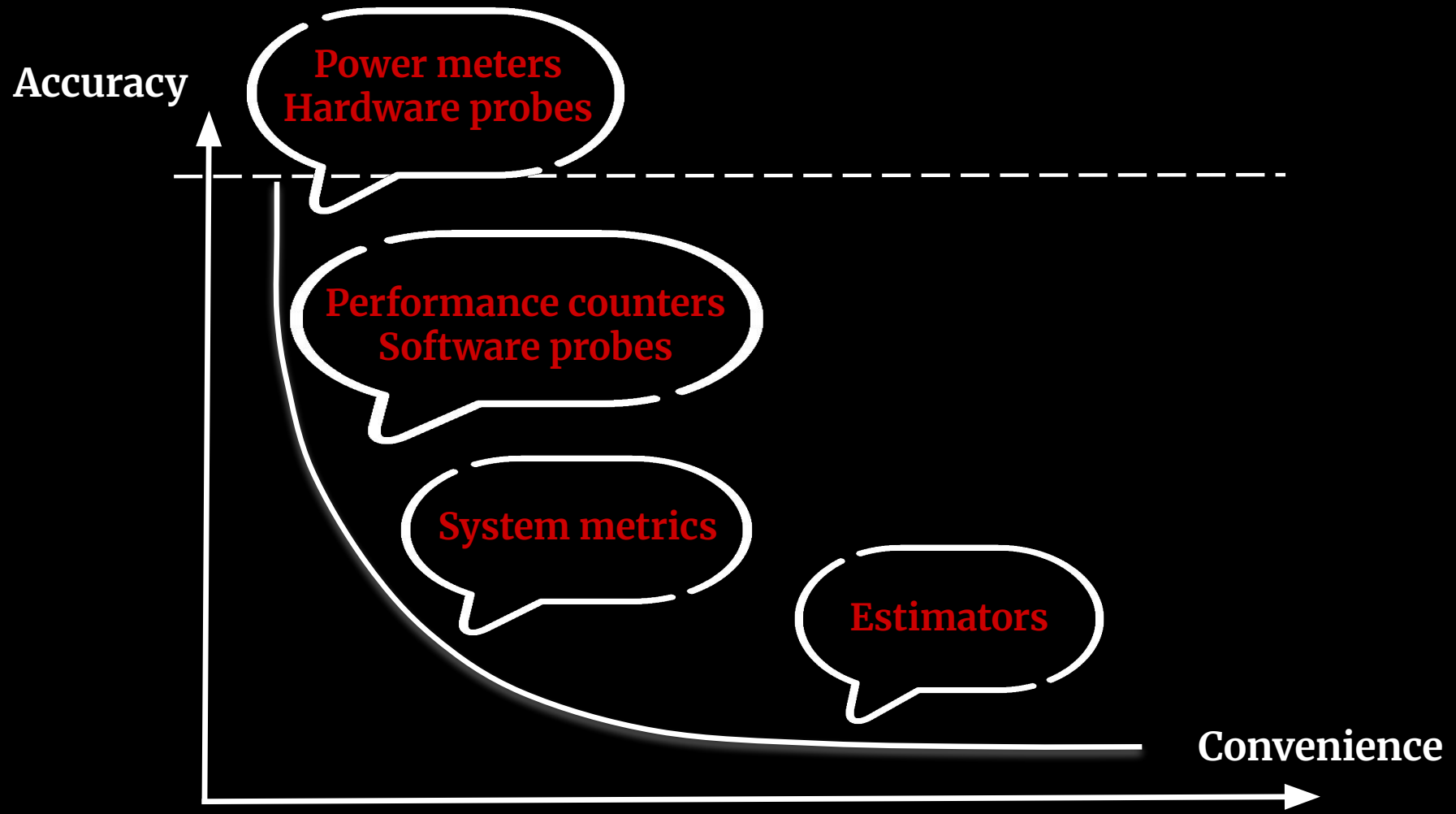
Measuring energy consumption



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Empirical knowledge

We identified three recurring problems in the answers in our base group of questions: (i) misconceptions about software energy consumption and how it can be reduced, (ii) solutions that are applicable in certain contexts being presented as universal, and (iii) lack of tools, in particular, measurement tools.

Mining Questions about Software Energy Consumption

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ABSTRACT

A growing number of software solutions have been proposed to address application-level energy consumption problems in the last few years. However, little is known about how much software developers are concerned about energy consumption, what aspects of energy consumption they consider important, and what solutions they have in mind for improving energy efficiency. In this paper we present the first empirical study on understanding the views of application programmers on software energy consumption problems. Using StackOverflow as our primary data source, we analyze a carefully curated sample of more than 300 questions and 550 answers from more than 800 users. With this data, we observed a number of interesting findings. Our study shows that practitioners are aware of the energy consumption problems: the questions they ask are not only *diverse* – we found 5 main themes of questions – but also often more *interesting* and *challenging* when compared to the control question set. Even though energy consumption-related questions are popular when considering a number of different popularity measures, the same cannot be said about the quality of their answers. In addition, we observed that some of these answers are often flawed or vague. We contrast the advice provided by these answers with the state-of-the-art research on energy consumption. Our summary of software energy consumption problems may help researchers focus on what matters the most to software developers and end users.

1. INTRODUCTION

Nowadays, thanks to the rapid proliferation of mobile phones, tablets, and unwired devices in general, energy efficiency is becoming a key software design consideration where the energy consumption is closely related to battery lifetime. It is also of increasing interest in the non-mobile arena, such as data centers and desktop environments. Energy-efficient solutions are highly sought after across the compute stack, with more established results through innovations in hardware/architecture [2, 14, 28], operating systems [10, 19, 24], and runtime systems [8, 25, 31]. In recent years, there is a growing interest in studying energy consumption from higher layers of the compute stack and most of these studies focus on application software [13, 15, 18, 23, 26, 29]. These approaches complement prior hardware/OS-centric solutions, so that improvements at the hardware/OS level are not cancelled out at the application level, *e.g.*, due to misuses of language/library/application features.

We believe a critical dimension to further improve energy efficiency of software systems is to understand *how software developers think*. The needs of developers and the challenges they face may help energy-efficiency researchers stay focused on the real-world problems. The collective wisdom shared by developers may serve as a practical guide for future energy-aware and energy-efficient software development. The conceptually incorrect views they hold may inspire educators to develop more state-of-the-art curricula.

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Empirical knowledge redux

[...] most practitioners struggle with fundamental energy concepts due to complex API documentation and practical experience required;

Energy-Efficient Software Development: A Multi-dimensional Empirical Analysis of Stack Overflow

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Abstract

Energy consumption of software applications has emerged as a critical concern for developers to contemplate in their daily development processes. Previous studies have surveyed a limited number of developers to understand their viewpoints on energy consumption. We complement these studies by analyzing a meticulously curated dataset of 1,193 Stack Overflow (SO) questions concerning energy consumption. These questions capture real-world energy-related challenges in practice. To understand practitioners' perceptions, we investigate the intentions behind these questions, semantic topics, and associated technologies (e.g., programming languages). Our results reveal that: (i) the most prevalent energy consumption topic is about balancing *Positioning* usage; (ii) efficiently handling data is particularly challenging, with these questions having the longest response times; (iii) practitioners primarily ask questions to understand a concept or API related to energy consumption; and (iv) practitioners are concerned about energy consumption across multiple levels—hardware, operating systems, and programming languages—during energy efficient software development. Our findings raise awareness about energy consumption's impact on software development. We also derive actionable implications for energy optimization at different levels (e.g., optimizing API usage or hardware accesses) during energy-aware software development.

ACM Reference Format:
Bihui Jin, Heng Li, Pengyu Nie, and Ying Zou. 2026. Energy-Efficient Software Development: A Multi-dimensional Empirical Analysis of Stack Overflow. In *2026 IEEE/ACM 48th International Conference on Software Engineering (ICSE '26), April 12–18, 2026, Rio de Janeiro, Brazil.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3744916.3773177

including design, implementation, testing, and maintenance [29]. Energy-efficient software can save energy, extend battery life, and enhance user experience [80], helping mitigate the growing trend of global electricity consumption. Practitioners now view energy efficiency as a key software property and have demonstrated willingness to learn about energy issues in software development [64].

A few empirical studies have been conducted to understand practitioners' perceptions of energy consumption. For instance, prior studies [64, 80] conduct online surveys with 122 and 464 practitioners, respectively, who self-identify as experienced developers and testers across various application domains. The studies find that 65% of practitioners on Reddit recognize energy usage as a crucial factor in software quality [80], and many are willing to sacrifice other requirements to reduce energy consumption [64]. However, these studies only survey opinions rather than the concrete barriers practitioners face when developing energy-efficient software. The most similar work to ours is by Pinto et al. [84], who study 325 Stack Overflow (SO) questions from 2008 to 2013 and identify five primary themes of energy-related questions (e.g., measurements and code design). Given rapid technological changes (e.g., IoT devices), practitioners likely face different challenges today than a decade ago, making the earlier studies less relevant to current practitioners.

We follow the same methodology outlined in Pinto et al. [84] to collect energy-related posts. Through keyword search followed by manual verifications, we curated a dataset of 1,193 energy-related SO questions, which contains **larger and more recent** questions compared to the work by Pinto et al. (325 questions by 2013). Inspired by recent work on analyzing SO posts [16, 91, 109, 112], we perform **LDA topic modeling instead of thematic analysis** to

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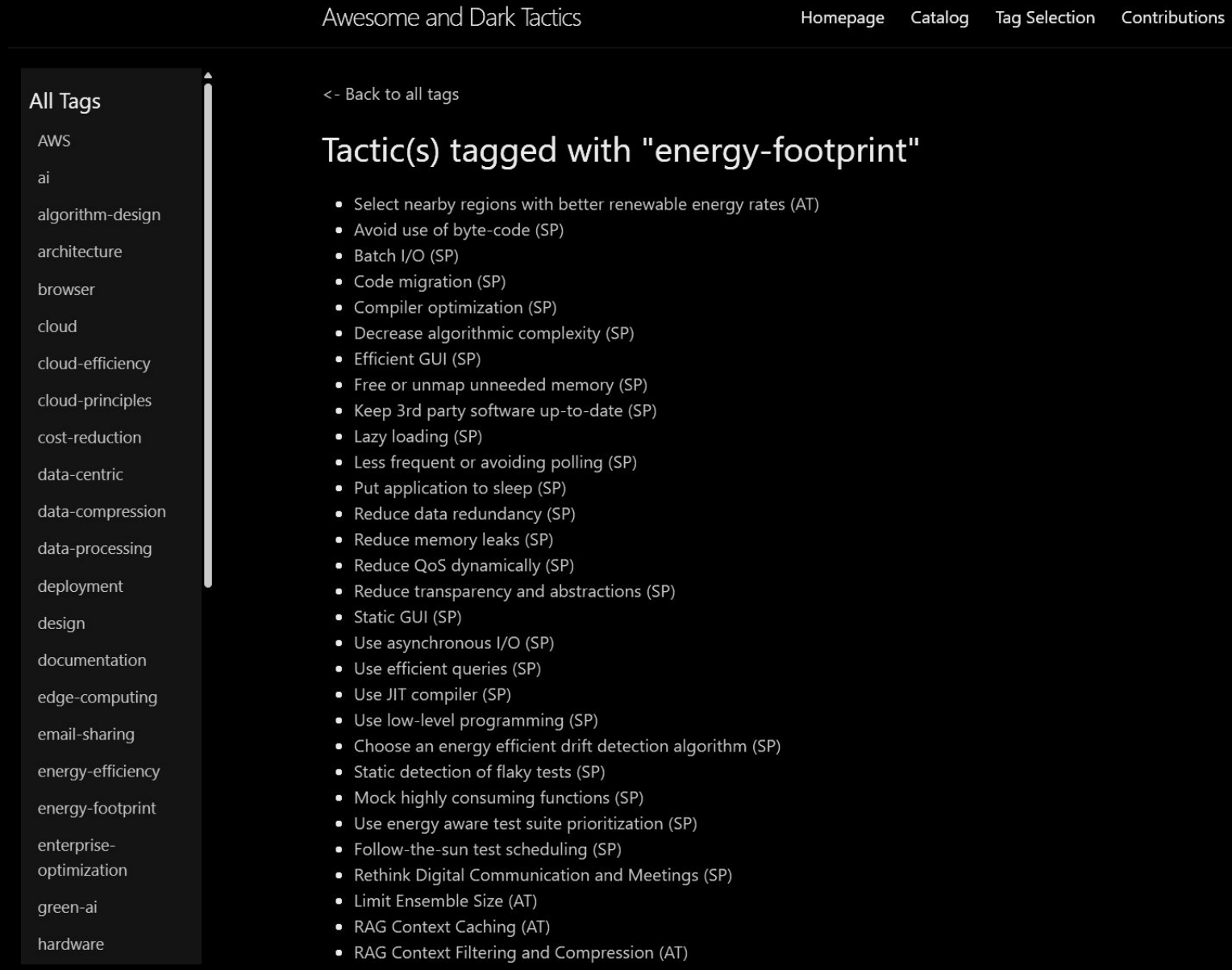
Tactics



SOFTWARE AND SUSTAINABILITY
S2 RESEARCH GROUP

https://s2group.cs.vu.nl/AwesomeAndDarkTactics/

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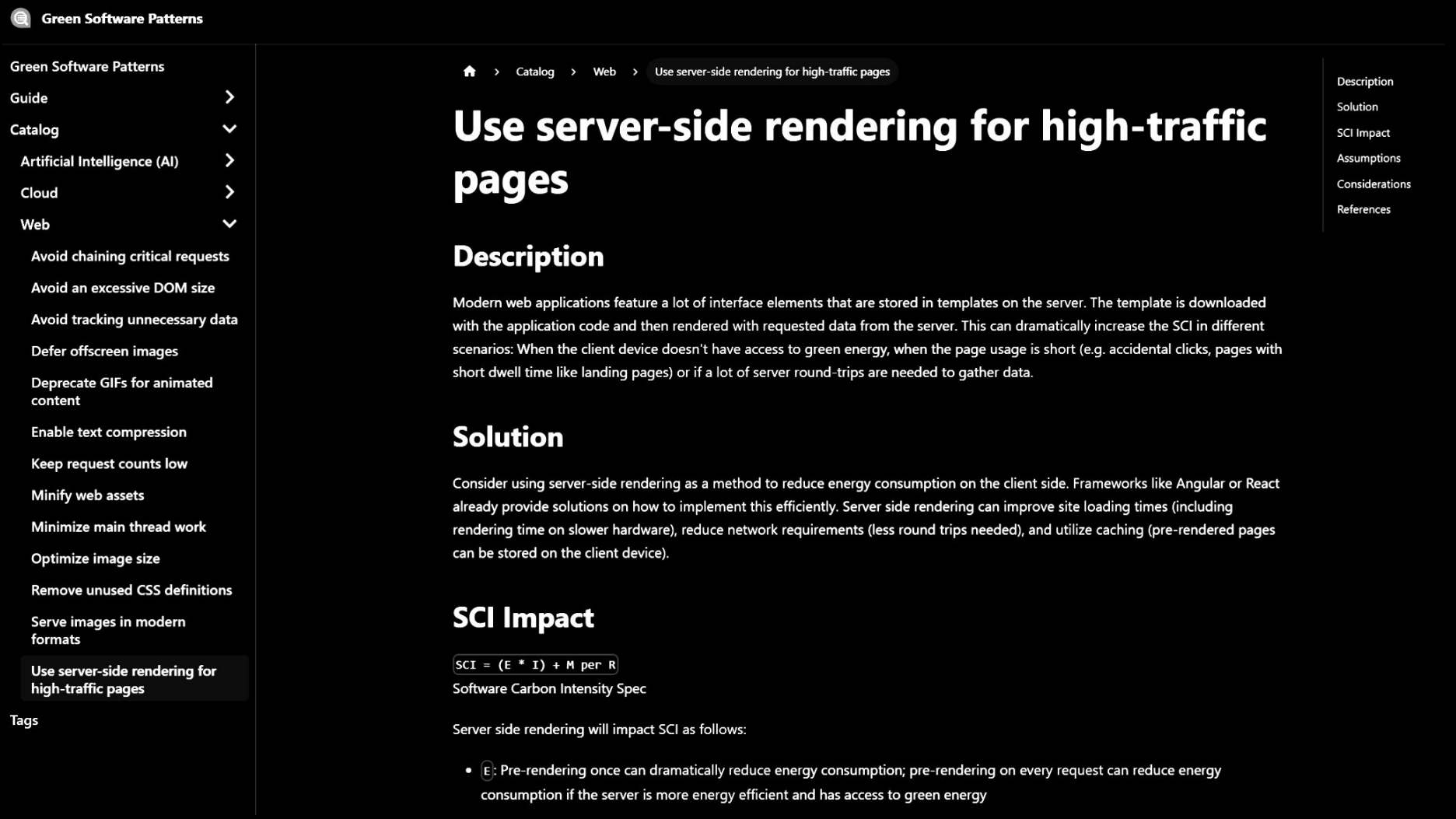
Patterns

https://patterns.greensoftware.foundation/



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Smells

Environmental Code Smells

Name	Detailed Description
Optimized API	
Fused Location	The fused location provider is one of the location APIs in Google Play services which combines signals from GPS, Wi-Fi, and cell networks, as well as accelerometer, gyroscope, magnetometer and other sensors. It is officially recommended to maximize battery life. Thus, developer has to set up Google Play Service in her gradle file with a dependency to `com.google.android.gms:play-services-location:x.y.z`, and then to import from `com.google.android.gms.location` instead of the `android.location` package of the SDK.
Bluetooth Low-Energy	In contrast to classic Bluetooth, Bluetooth Low Energy (BLE) is designed to provide significantly lower power consumption. Its purpose is to save energy on both paired devices but very few developers are aware of this alternative API. From the Android client side, it means append `android.bluetooth.le.*` imports to `android.bluetooth.*` imports in order to benefits from low-energy features.
Lazy Loading	When displaying scrollable data on screen, the new Jetpack Compose API introduced lazy views instead of `ListView`, `GridView` and even `RecycleView`. These components use the technique of lazy loading, which consists of loading data only when it arrives at the display area. Import `androidx.compose.foundation.lazy.*` to benefit from objects like `LazyColumn`, `LazyRow`, `LazyVerticalGrid` or `LazyHorizontalGrid`.
Leakage	
Media Leak	Creation of a Media Recorder object with `new MediaRecorder()` is used to record audio and video, while creation of a Media Player object with `new MediaPlayer()` can be used to control playback of audio/video files and streams. Both classes own a `release()` method. In addition to unnecessary resources (such as memory and instances of codecs) being held, failure to call this method immediately if a media object is no longer needed may also lead to continuous battery consumption for mobile devices.

https://github.com/cnumr/best-practices-mobile

Energy consumption in the cloud

If the software is living in the cloud, the problem is in hard(er) mode

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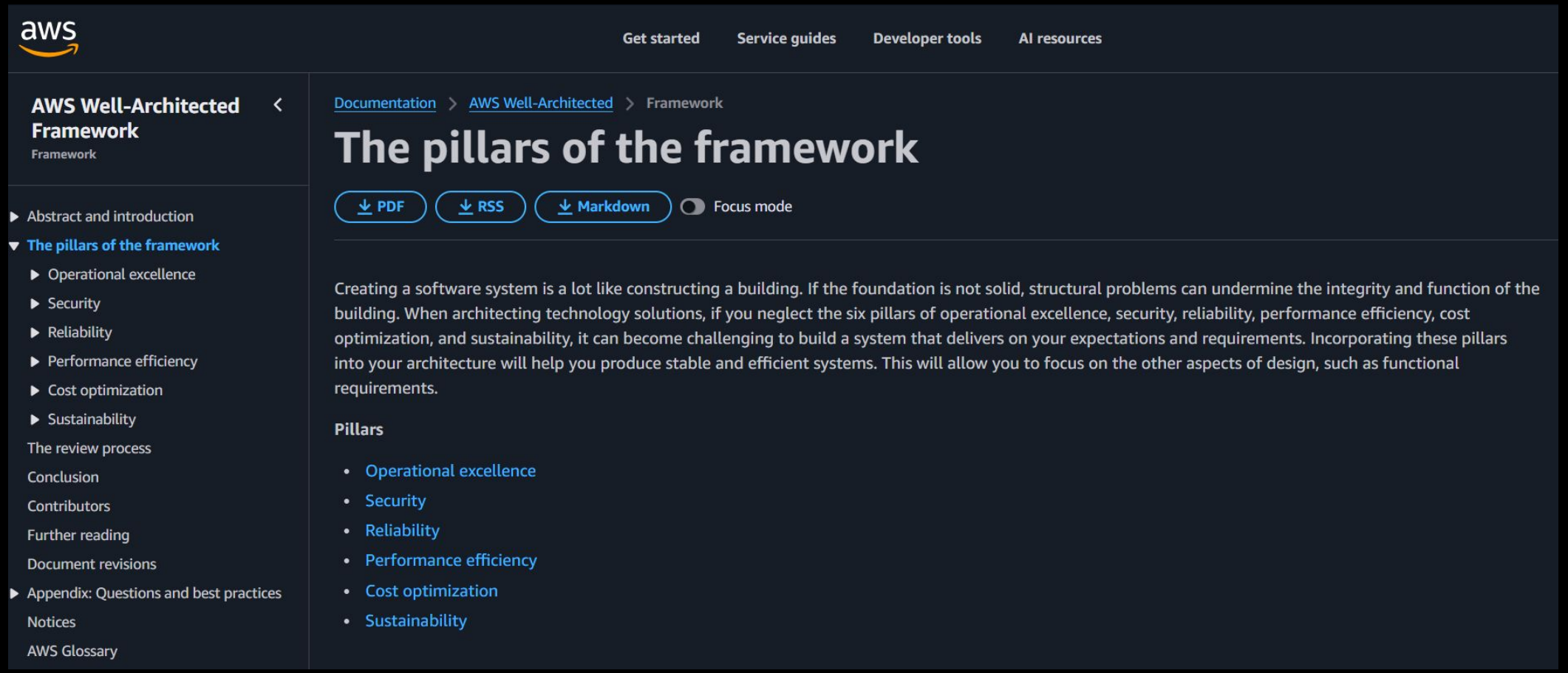
Software energy optimization in the cloud



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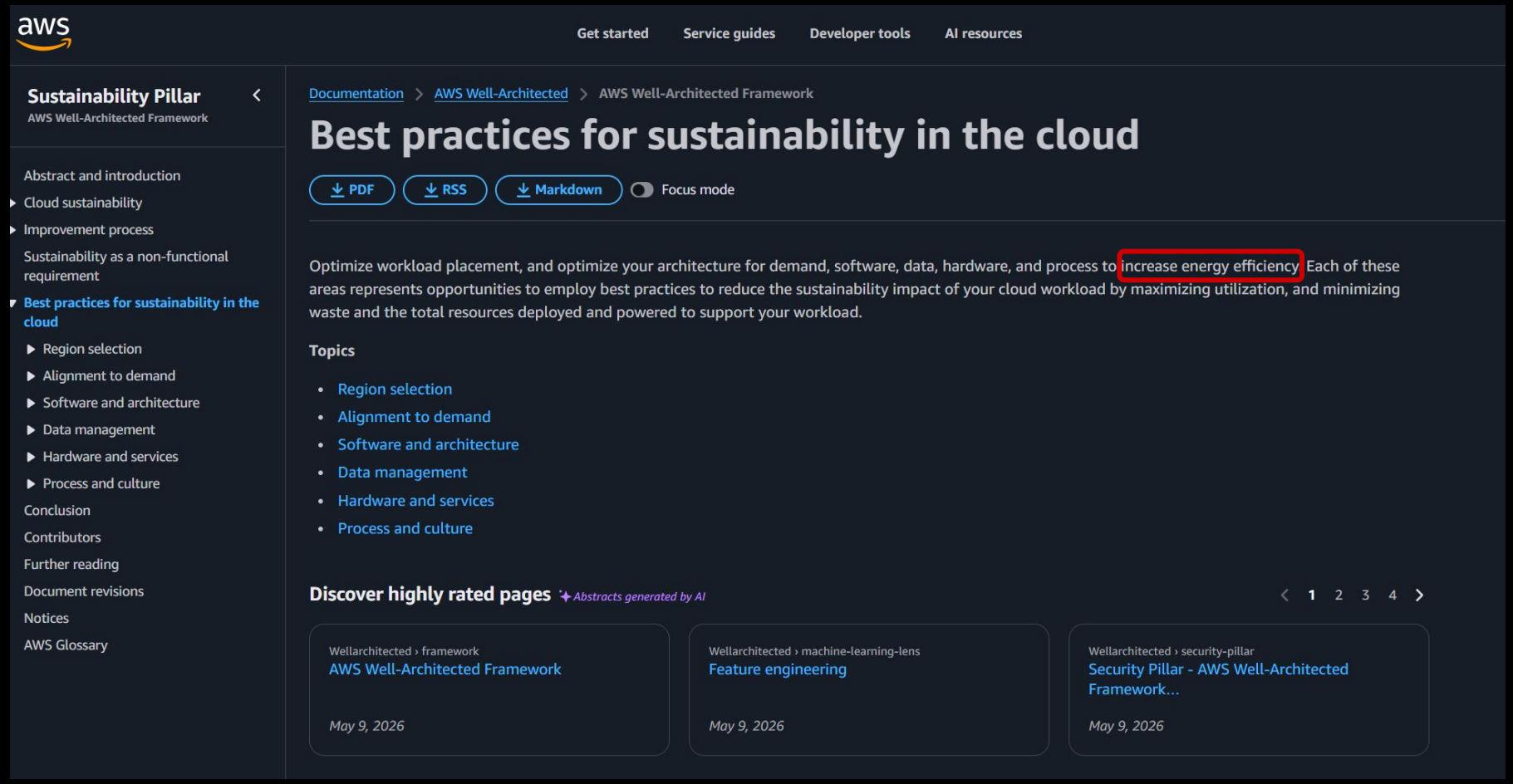
Software energy optimization in the cloud



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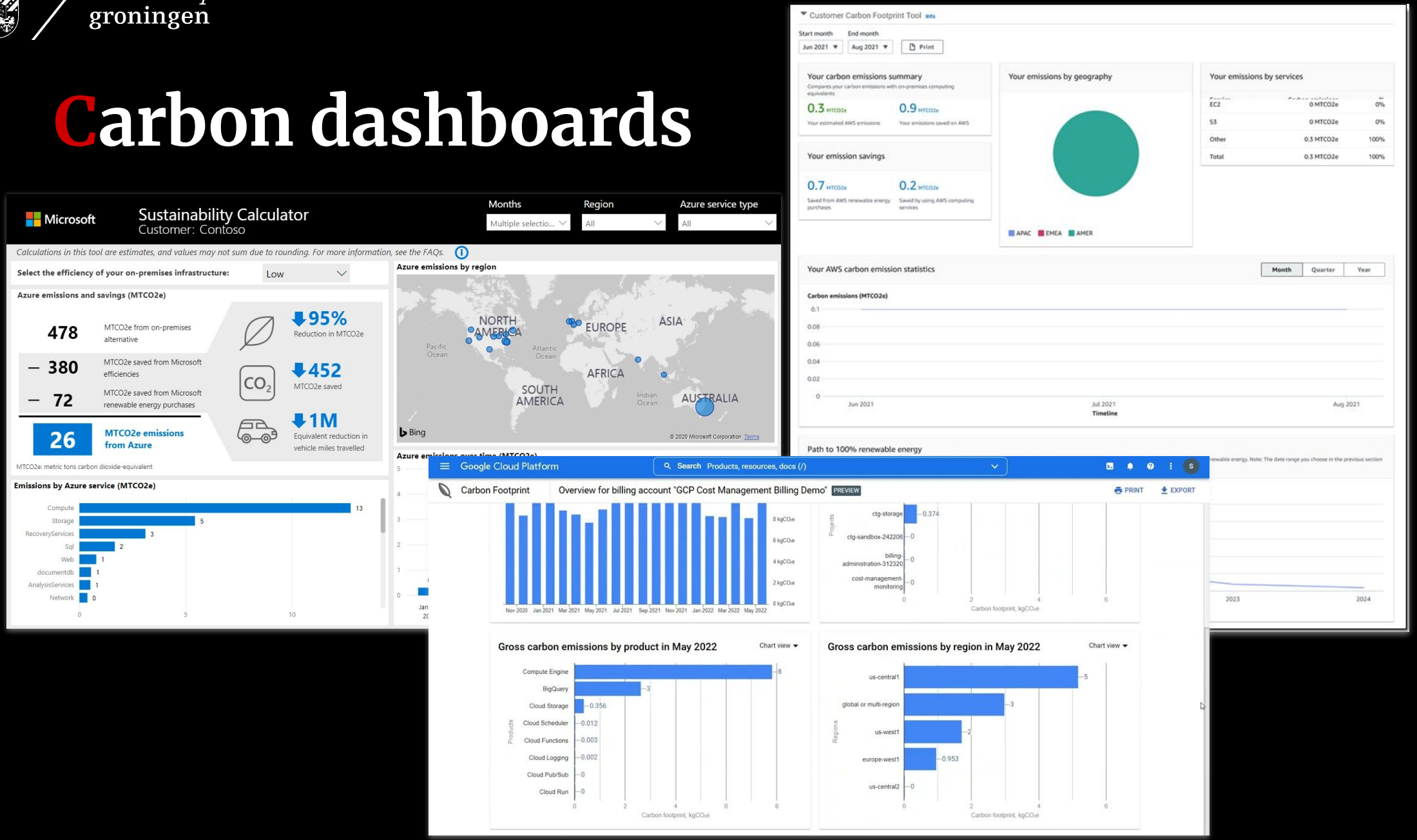
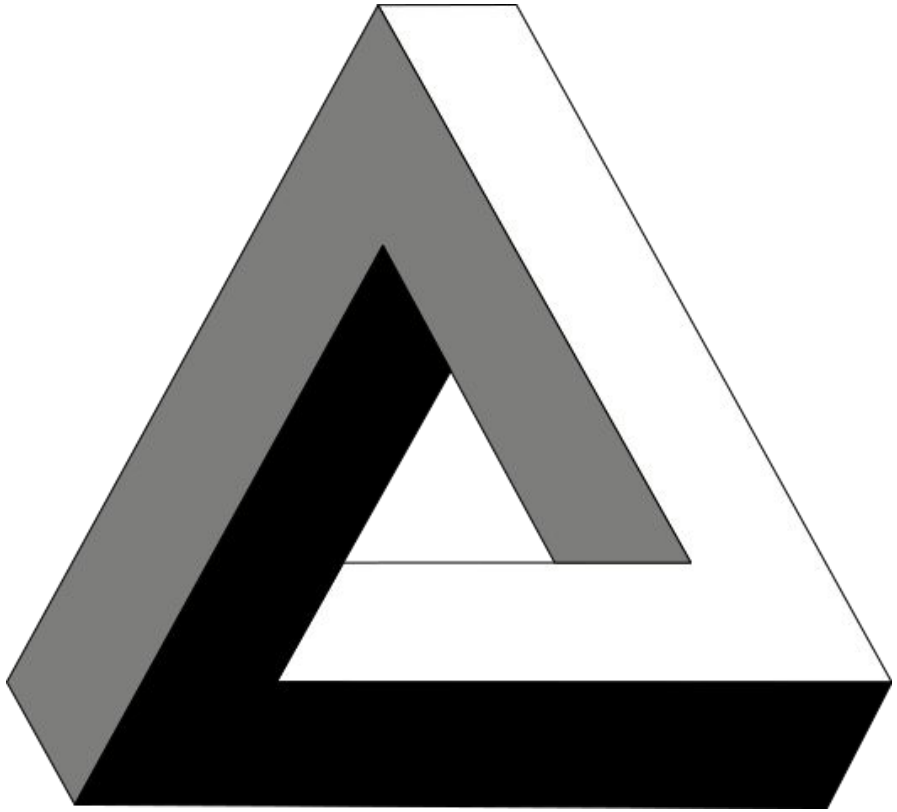
Carbon dashboards



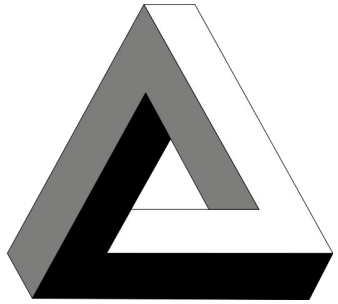
The Devil's triangle in the cloud

Virtualization

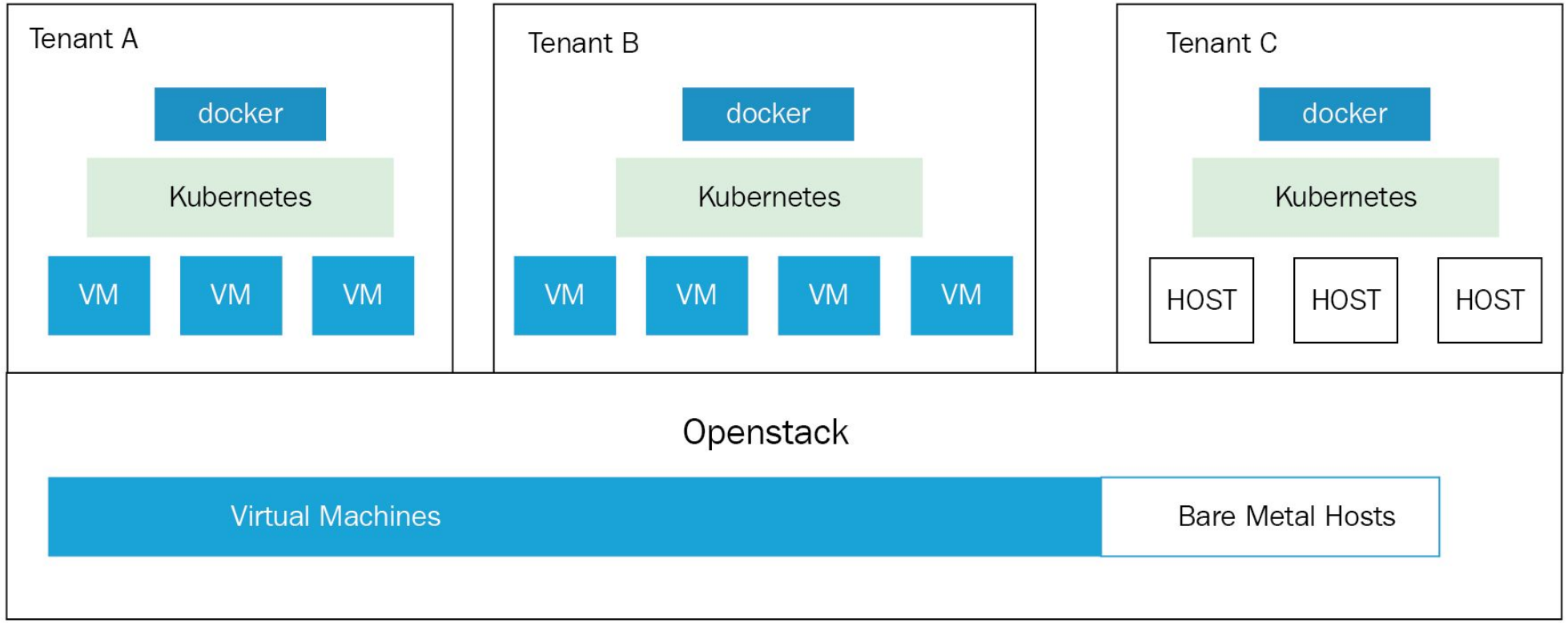


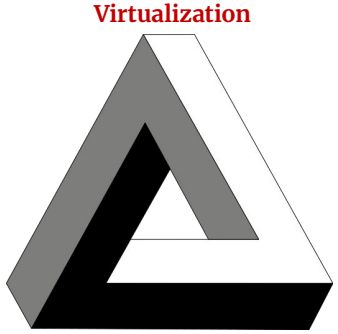
Multitenancy

Servitization

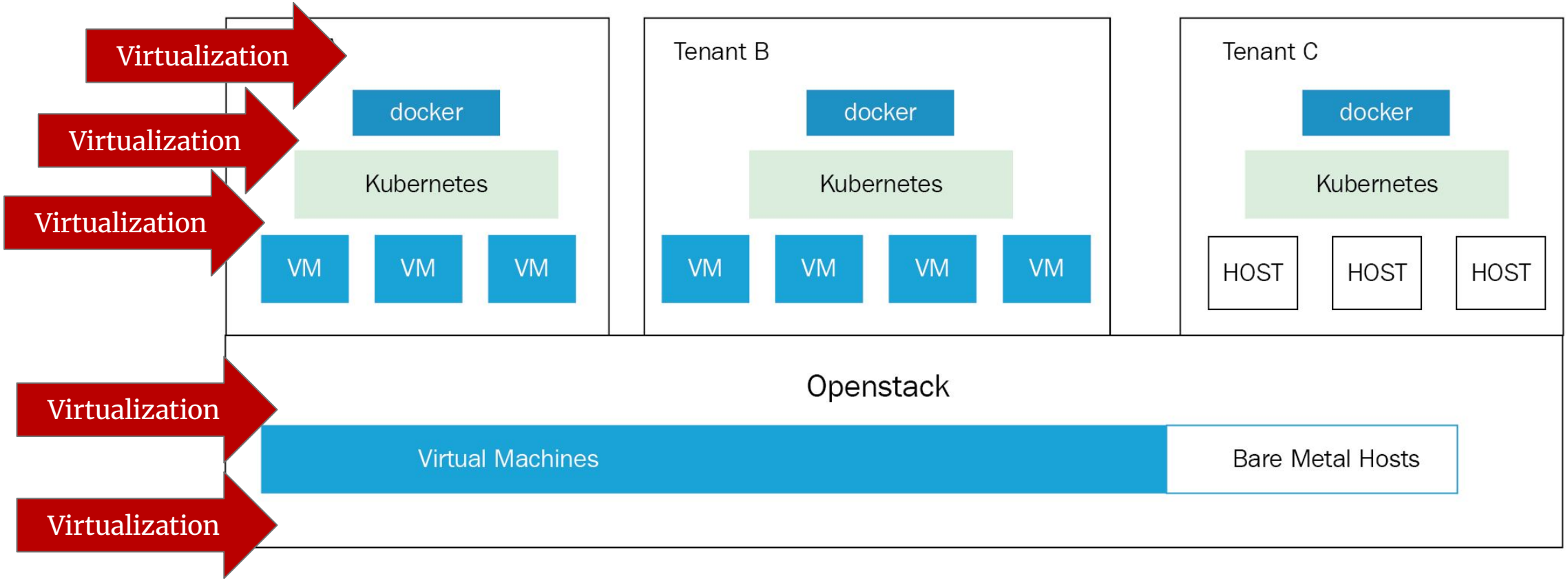


Virtualization layers





Virtualization layers



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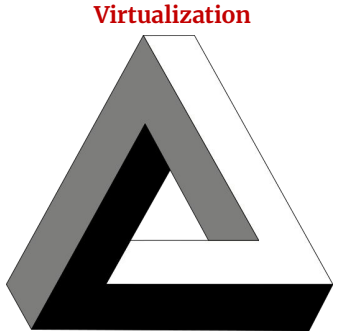

Monitoring energy in a cloud-native application

https://doi.org/10.1145/3676151.3719371

Application	OpenTelemetry (demo app)
Kubernetes	cAdvisor + Kepler
Virtual Machine	Scaphandre
Bare metal	node_exporter + RAPL
Physical	PowerPlug

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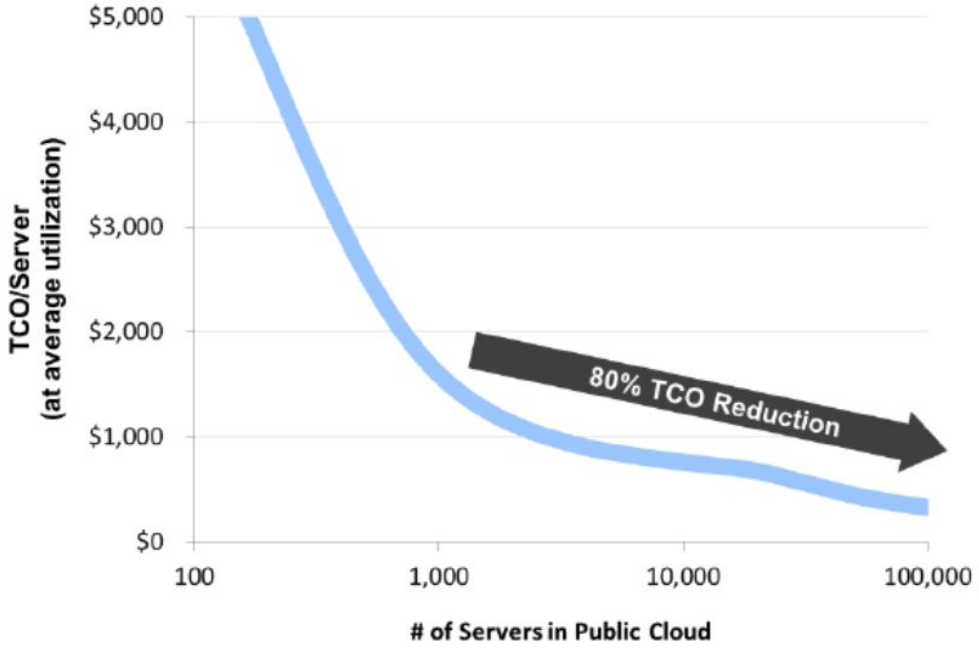
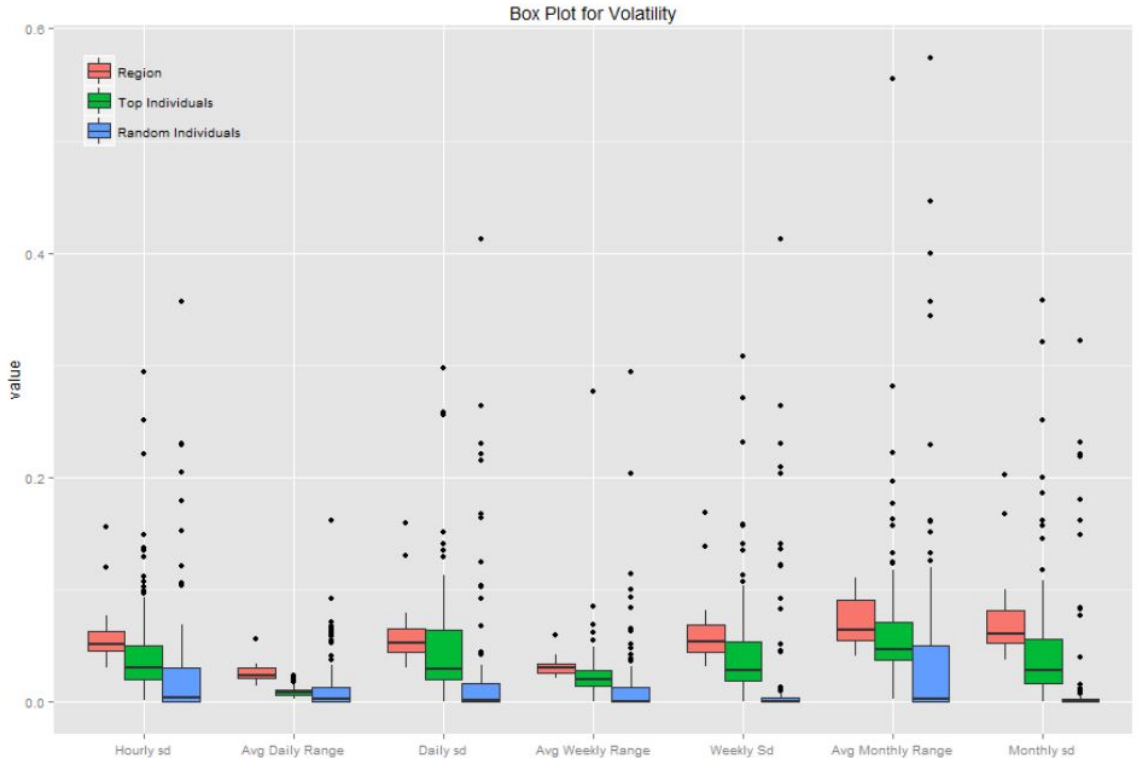
Economies of Scale

Multitenancy





https://doi.org/10.1145/3038912.3052707

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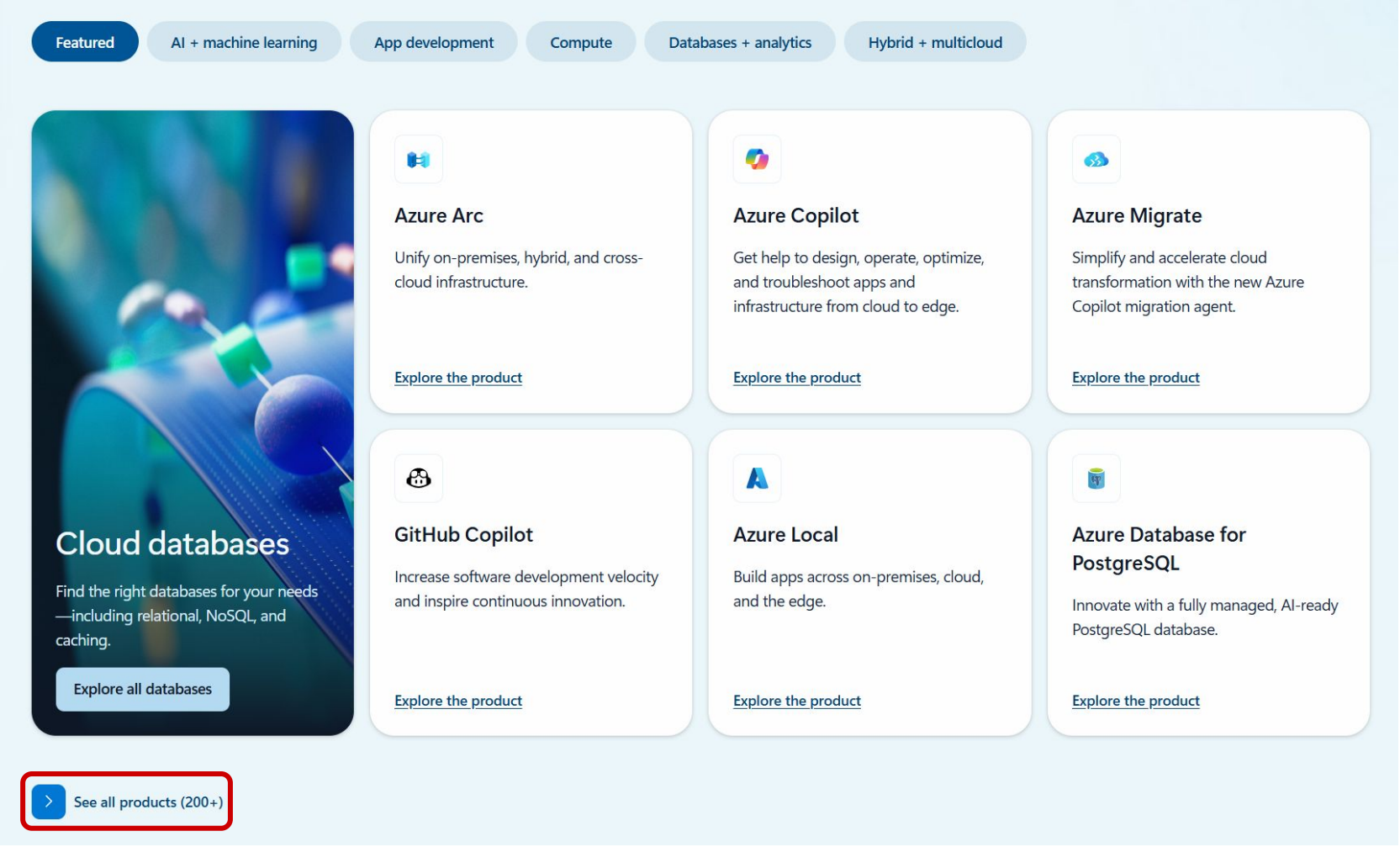
Everything as a Service



Servitization

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Implications of the Devil's triangle

- Existing tooling fails in at least one of three points
- Need to treat the system as a (semi-)black box

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Observability of energy consumption

Making sense using available data

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Observability

Control theory: *a measure of how well internal states of a system can be inferred from knowledge of its external outputs* (Kalman, 1960)

$$\mathcal{O} = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{n-1} \end{bmatrix}$$

Observability

Control theory: *a measure of how well internal states of a system can be inferred from knowledge of its external outputs*

$$\mathcal{O} = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{n-1} \end{bmatrix}$$

Software systems: *how well a system's state can be understood from the obtained telemetry*

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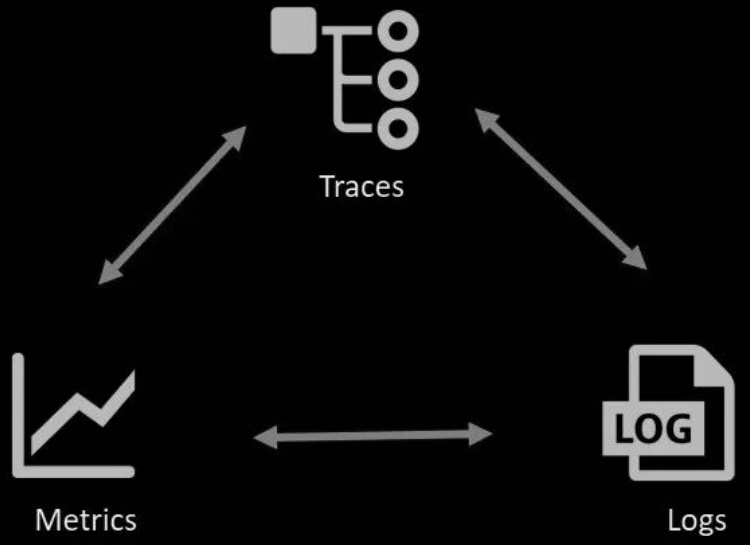
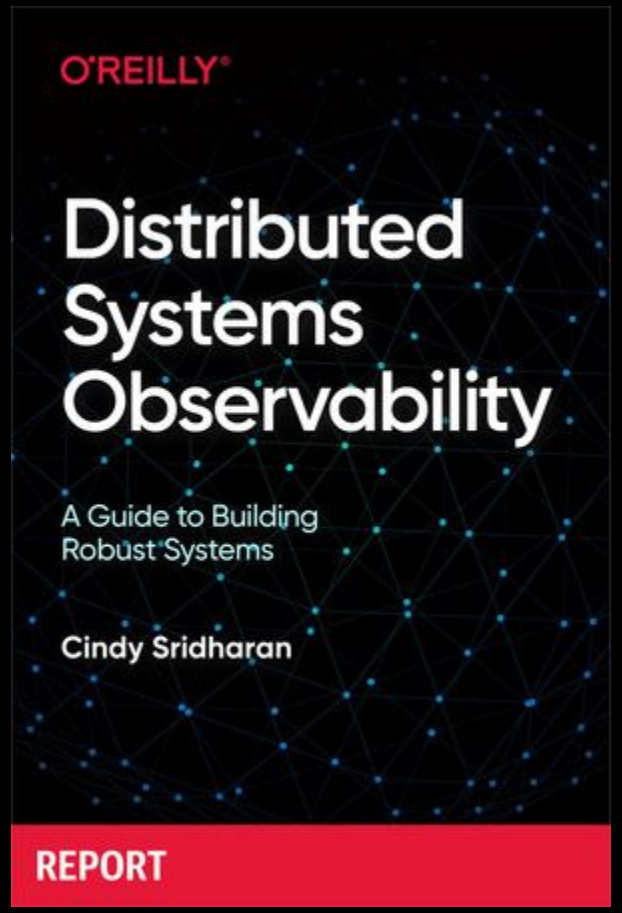
Pillars of observability

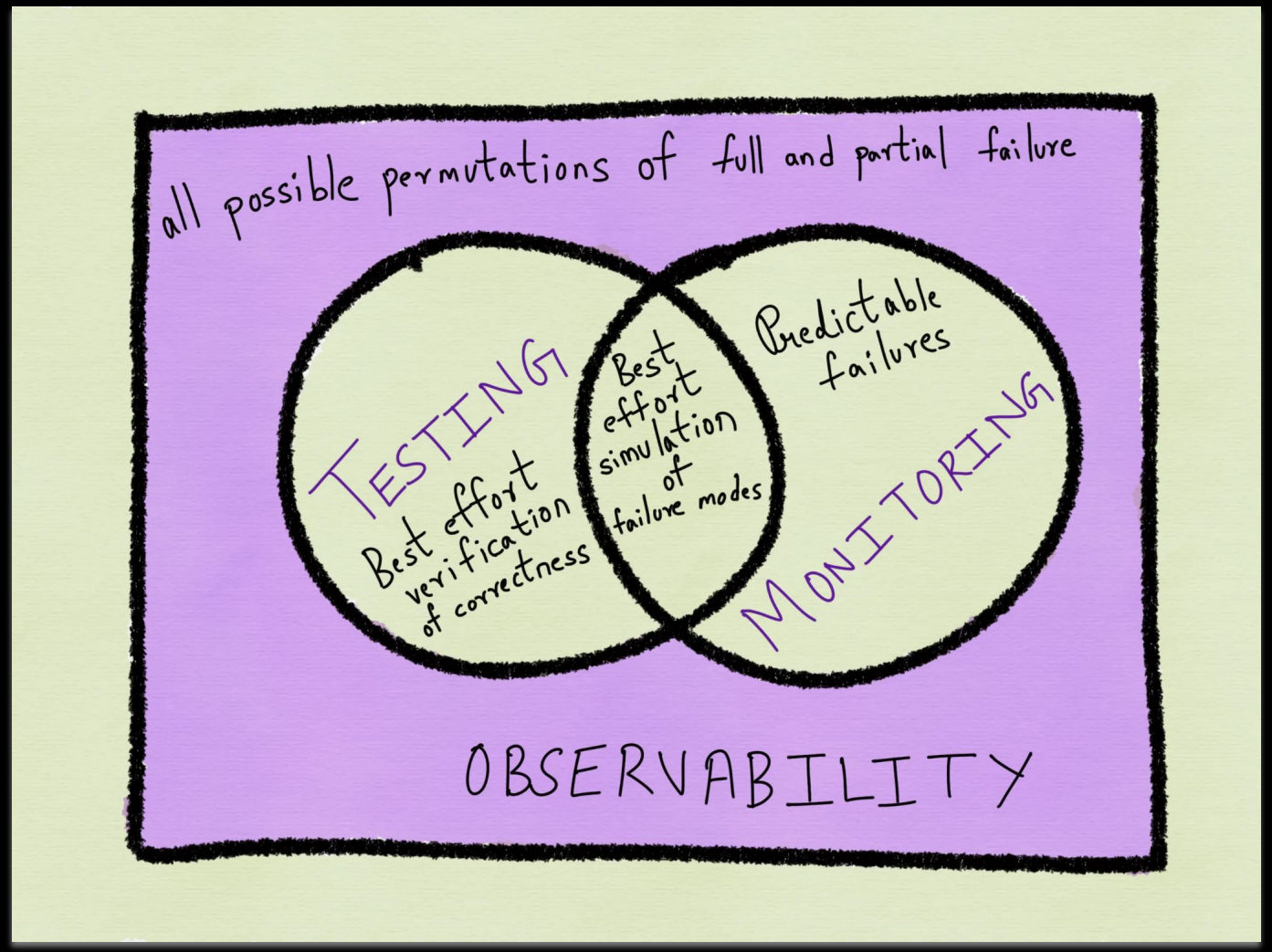
Three data silo



Three pillars of observability, in context

Source: dynatrace





https://copyconstruct.medium.com/monitoring-and-observability-8417d1952e1c

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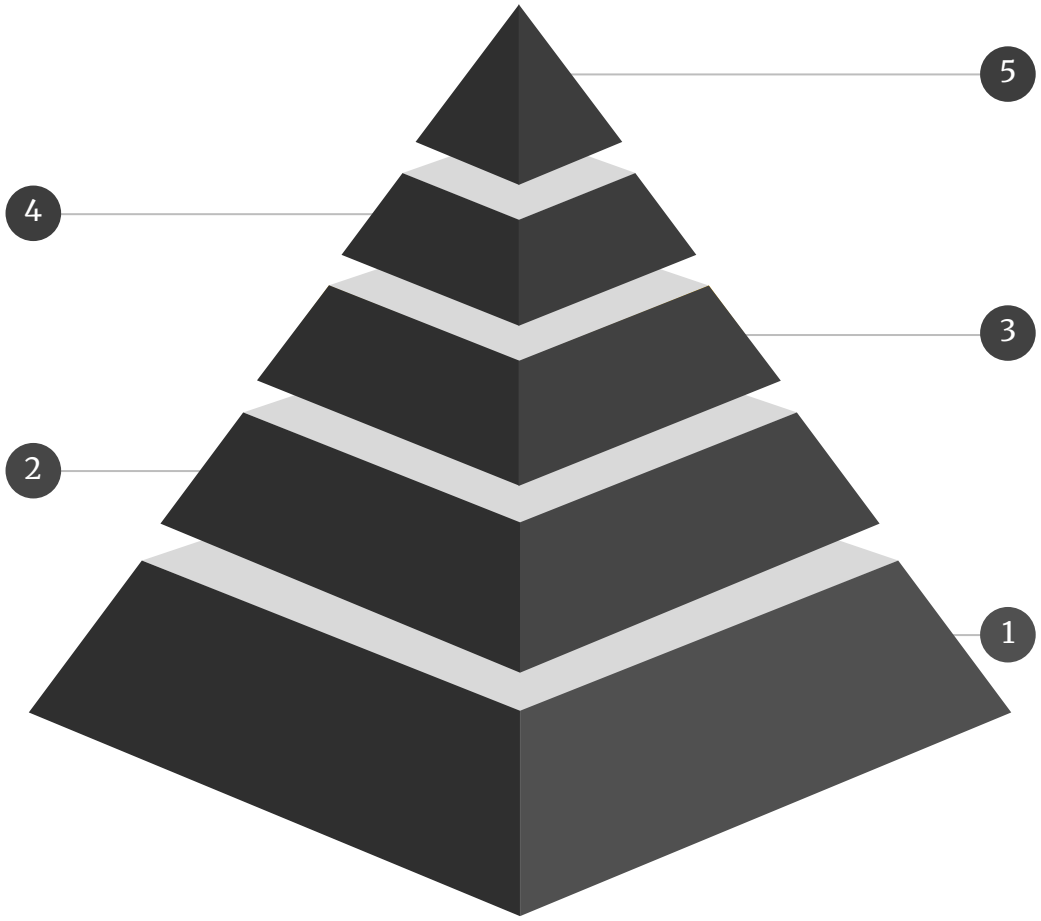
Observability solutions: literature landscape



Analysis (5)
Visualization [18 studies]
Diagnostics [16 studies]

Preprocessing (3)
Stream broker [3 studies]
Aggregator [18 studies]

Instrumentation (1)
Sidecars/Proxies [4 studies]
Probes [5 studies]
Instrumentation libraries [10 studies]

Storage (4)
Time-series DBs [14 studies]
Non Time-series DBs [24 studies]

Collection (2)
Agent [19 studies]
Collector [25 studies]

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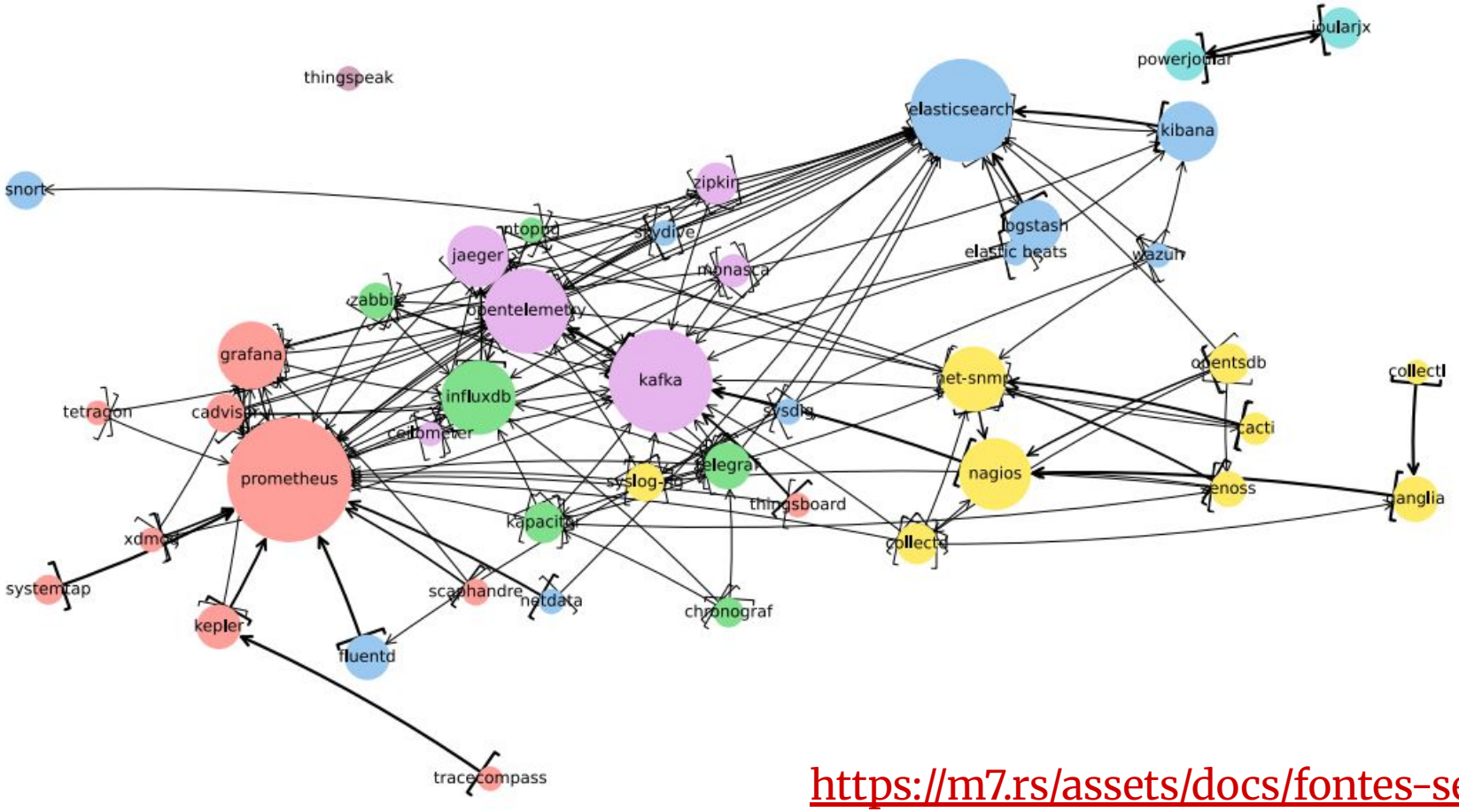
Observability solutions: open source landscape



https://m7.rs/assets/docs/fontes-sesos-2026.pdf

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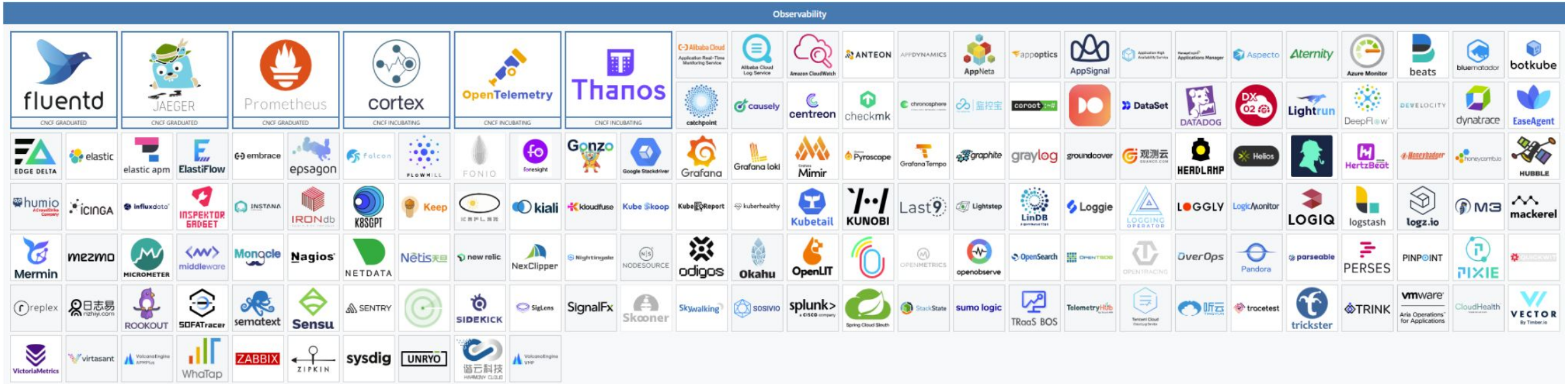
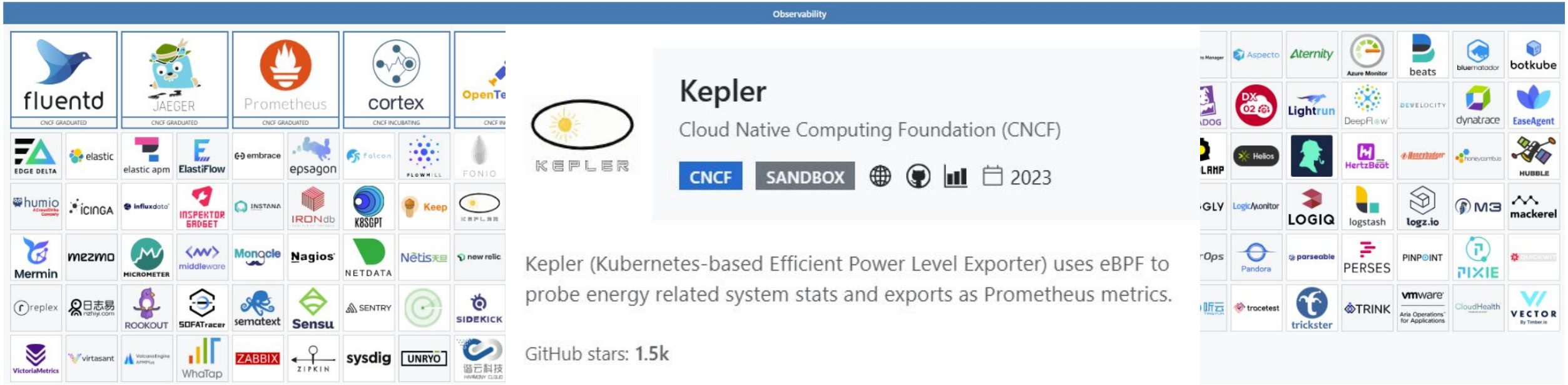
Observability solutions: CNCF landscape

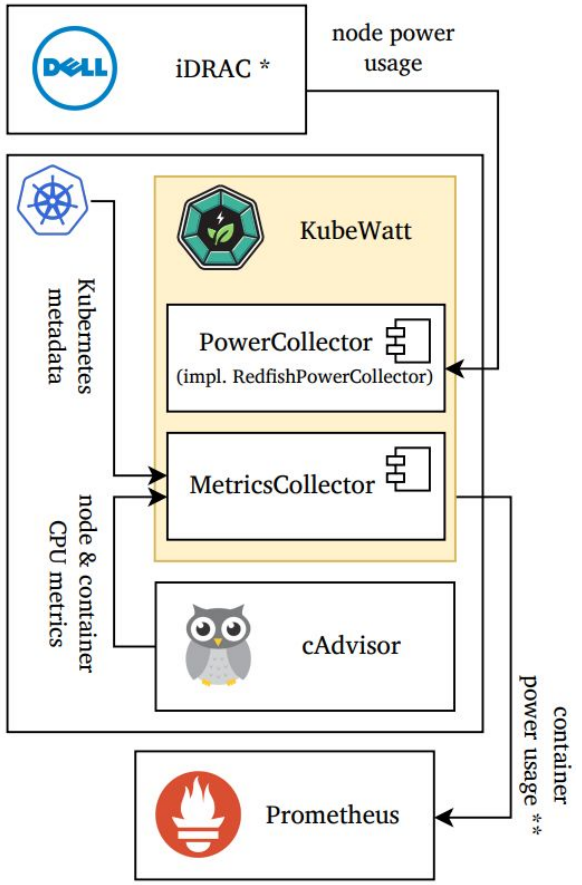


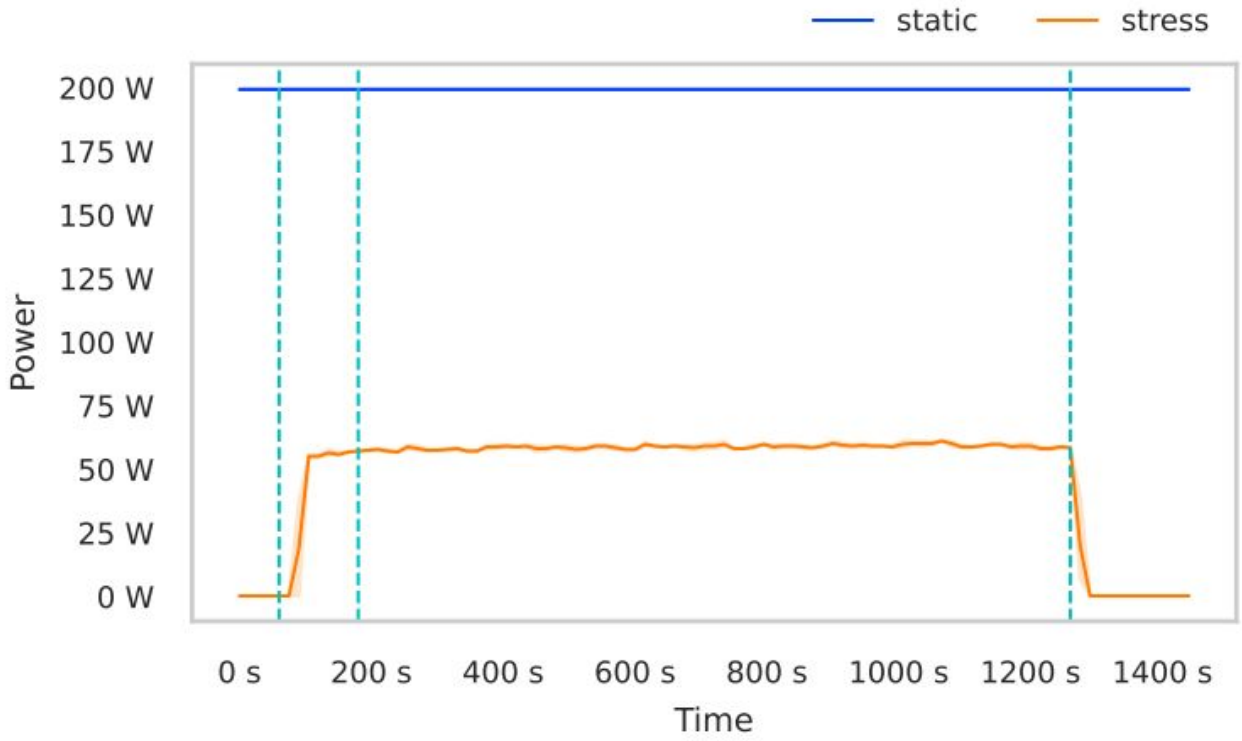
Observability solutions: CNCF's Kepler



https://sustainable-computing.io/

KubeWatt





https://doi.org/10.1109/ICT4S68164.2025.00016

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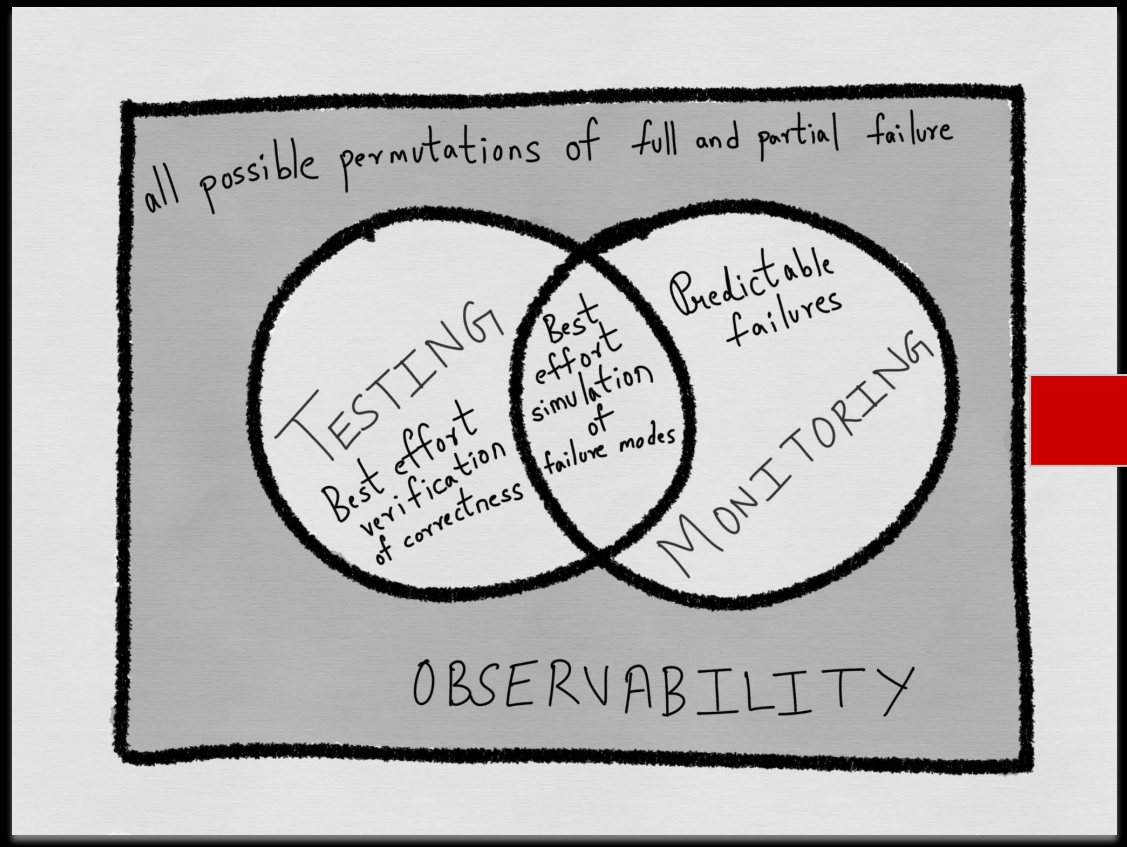
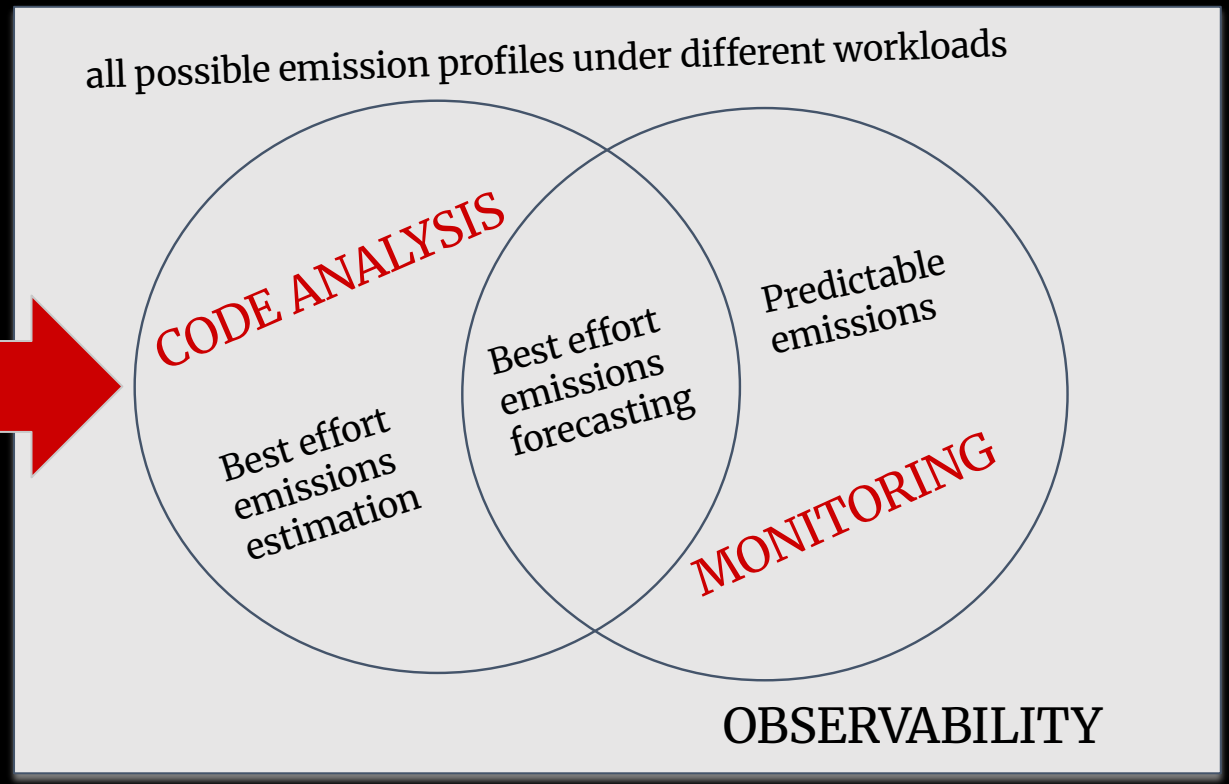
Energy & carbon observability





Beyond observability

Is observability *enough* to understand how to reduce software-generated emissions?

Beyond observability

Is observability enough to understand how to reduce software-generated emissions?

Does establishing observability solve reliability problems?

Beyond observability

Is observability enough to understand how to reduce software-generated emissions?

Does establishing observability solve reliability problems?

Do we need something *more* than simply understanding system state?

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Actionable Observability

*To provide tangible outcomes we need to connect what we **observe** with what we **build***

Actionable Observability $\mathcal{O}^+$

How well the need for specific interventions on an existing software system can be inferred from obtained telemetry

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Actionable Observability

- Dealing with *engineered* and not *natural* systems
- Closing the loop between *intended* and *observed* behavior
- Bridging *design-* and *run-time* to avoid further debt

see also https://doi.org/10.1145/3643657.3643909

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Actionable Observability roadmap

Signals	Elements	Knowledge	Action
What we observe	*Where* we need to intervene	*How* we intervene	*How* we use it in practice

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Actionable Observability roadmap

Signals → Elements → Knowledge → Action

- Define *correct* granularity of information
- Connect signals to KPIs/NFRs/QAs
- Avoid data overload

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Data overload

Data availability paradox: too much data leading to paralysis

Can We Ever Escape from Data Overload? A Cognitive Systems Diagnosis

D. D. Woods[1], E. S. Patterson[1] and E. M. Roth[2]

[1]*Institute for Ergonomics, Ohio State University, Columbus, Ohio, USA;* [2]*Roth Cognitive Engineering, Inc., Brookline, Massachusetts, USA*

Abstract: Data overload is a generic and tremendously difficult problem that has only grown with each new wave of technological capabilities. As a generic and persistent problem, three observations are in need of explanation: Why is data overload so difficult to address? Why has each wave of technology exacerbated, rather than resolved, data overload? How are people, as adaptive responsible agents in context, able to cope with the challenge of data overload? In this paper, first we examine three different characterisations that have been offered to capture the nature of the data overload problem and how they lead to different proposed solutions. As a result, we propose that (a) data overload is difficult because of the context sensitivity problem – meaning lies, not in data, but in relationships of data to interests and expectations and (b) new waves of technology exacerbate data overload when they ignore or try to finesse context sensitivity. The paper then summarises the mechanisms of human perception and cognition that enable people to focus on the relevant subset of the available data despite the fact that what is interesting depends on context. By focusing attention on the root issues that make data overload a difficult problem and on people's fundamental competence, we have identified a set of constraints that all potential solutions must meet. Notable among these constraints is the idea that organisation precedes selectivity. These constraints point toward regions of the solution space that have been little explored. In order to place data in context, designers need to display data in a conceptual space that depicts the relationships, events and contrasts that are informative in a field of practice.

Keywords: Agent; Alarm; Context; Data overload; Information Visualisation; Workload

1. DATA OVERLOAD IS A GENERIC, DIFFICULT PROBLEM

> Information is not a scarce resource. Attention is. (Herbert Simon)[1]

Each round of technical advances, whether in artificial intelligence, computer graphics or electronic connectivity, promises to help people better understand and manage a whole host of activities, from financial analysis to monitoring data from space missions to controlling the national air space. Certainly, this ubiquitous computerisation of the modern world has tremendously advanced our ability to collect, transmit and transform data, producing unprecedented levels of access to data.

However, our ability to interpret this avalanche of data, i.e., to extract meaning from artificial fields of data, has expanded much more slowly, if at all. In studies across multiple settings, we find that practitioners are bombarded with computer-processed data, especially when anomalies occur. We find users lost in massive networks of computer-based displays, options and modes. For example, one can find a version of the following statement in most accident investigation reports:

> although all of the necessary data was physically available, it was not operationally effective. No one could assemble the separate bits of data to see what was going on. (Joyce and Lapinski 1983)

The challenge has become finding what is informative given our interests and needs in a very large field of available data.

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Observability

Observability as the desired property *beyond* data availability

Can We Ever Escape from Data Overload?

4. ***Observability*** *is more than mere data availability.*

> The greatest value of a picture is when it *forces* us to notice what we never expected to see. (Tukey 1977, p. vi)

There are significant differences between the available data and the meaning or information that a person extracts from that data. *Observability* is the technical term that refers to the cognitive work needed to extract meaning from available data (Rasmussen 1985). This term captures the relationship among data, observer and context of observation that is fundamental to effective feedback.

Observability is distinct from data availability, which refers to the mere presence of data in some form in some location. For human perception, 'it is not sufficient to have something in front of your eyes to see it' (O'Regan 1992, p. 475). Recent studies on visual perception emphasise the role of attention in the perception of suprathreshold stimuli (Resnick et al 1997; Simons and Levin 1997) – 'there seems to be no conscious perception without attention' (Mack and Rock 1998, p. ix).

Data overload

⇨ Context-sensitive treatment of data collection

- Fundamental models as *conceptual spaces*
- Artificial intelligence to support observers

Can We Ever Escape from Data Overload? A Cognitive Systems Diagnosis

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Abstract: Data overload is a generic and tremendously difficult problem that has only grown with each new wave of technological capabilities. As a generic and persistent problem, three observations are in need of explanation: Why is data overload so difficult to address? Why has each wave of technology exacerbated, rather than resolved, data overload? How are people, as adaptive responsible agents in context, able to cope with the challenge of data overload? In this paper, first we examine three different characterisations that have been offered to capture the nature of the data overload problem and how they lead to different proposed solutions. As a result, we propose that (a) data overload is difficult because of the context sensitivity problem – meaning lies, not in data, but in relationships of data to interests and expectations and (b) new waves of technology exacerbate data overload when they ignore or try to finesse context sensitivity. The paper then summarises the mechanisms of human perception and cognition that enable people to focus on the relevant subset of the available data despite the fact that what is interesting depends on context. By focusing attention on the root issues that make data overload a difficult problem and on people's fundamental competence, we have identified a set of constraints that all potential solutions must meet. Notable among these constraints is the idea that organisation precedes selectivity. These constraints point toward regions of the solution space that have been little explored. In order to place data in context, designers need to display data in a conceptual space that depicts the relationships, events and contrasts that are informative in a field of practice.

Keywords: Agent; Alarm; Context; Data overload; Information Visualisation; Workload

1. DATA OVERLOAD IS A GENERIC, DIFFICULT PROBLEM

> Information is not a scarce resource. Attention is. (Herbert Simon)[1]

Each round of technical advances, whether in artificial intelligence, computer graphics or electronic connectivity, promises to help people better understand and manage a whole host of activities, from financial analysis to monitoring data from space missions to controlling the national air space. Certainly, this ubiquitous computerisation of the modern world has tremendously advanced our ability to collect, transmit and transform data, producing unprecedented levels of access to data.

However, our ability to interpret this avalanche of data, i.e., to extract meaning from artificial fields of data, has expanded much more slowly, if at all. In studies across multiple settings, we find that practitioners are bombarded with computer-processed data, especially when anomalies occur. We find users lost in massive networks of computer-based displays, options and modes. For example, one can find a version of the following statement in most accident investigation reports:

> although all of the necessary data was physically available, it was not operationally effective. No one could assemble the separate bits of data to see what was going on. (Joyce and Lapinski 1983)

The challenge has become finding what is informative given our interests and needs in a very large field of available data.

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Actionable Observability roadmap

Signals | **Elements** | Knowledge | Action

- Identify pertinent architectural elements at *right* level of abstraction
- Attribute observed information to elements
- Identify hotspots as optimization/refactoring targets

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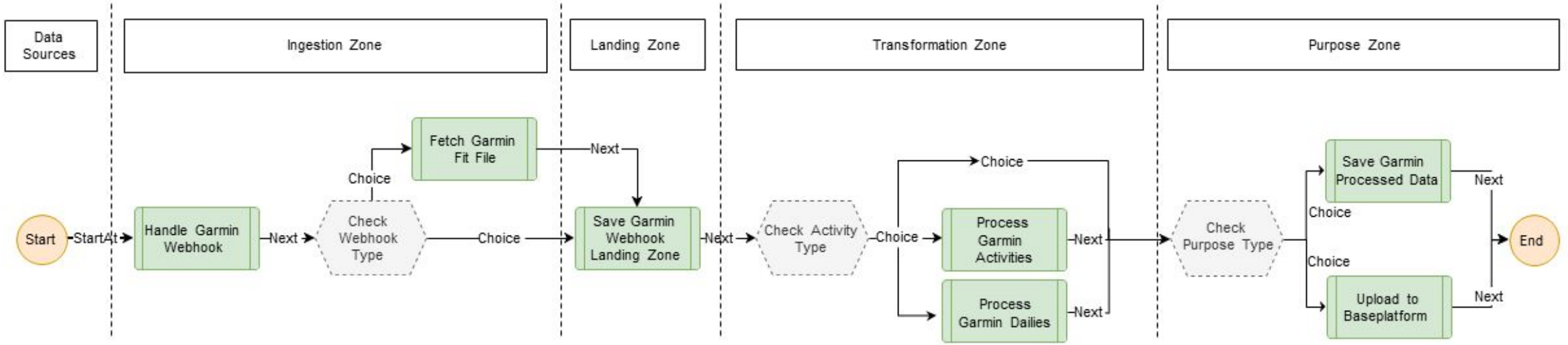
The Researchable case study

RESEARCHABLE



https://doi.org/10.3390/fi15010037

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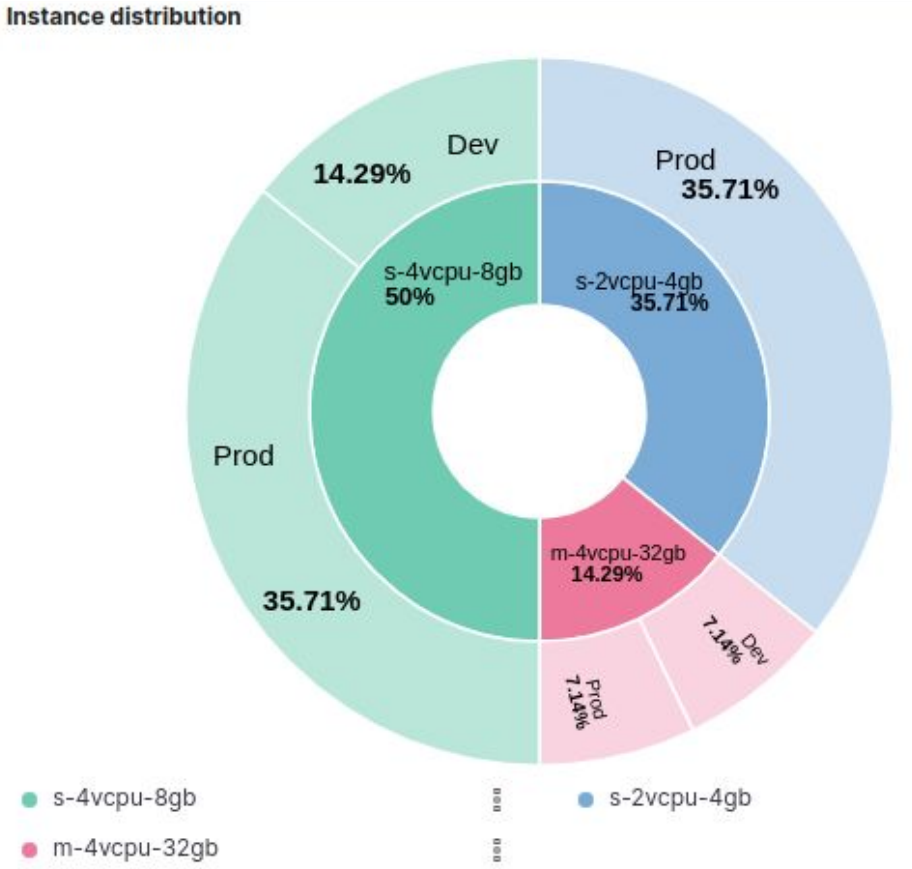
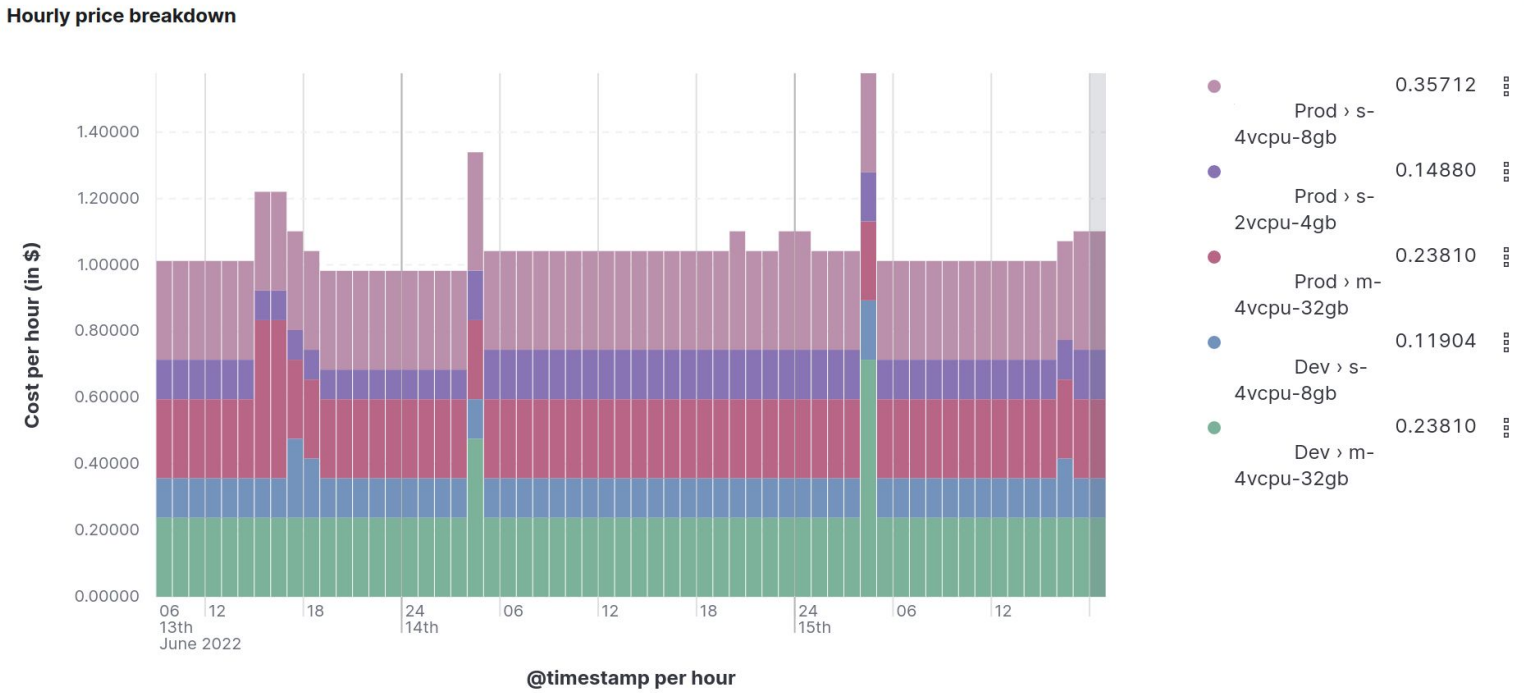
Cost observability dashboard





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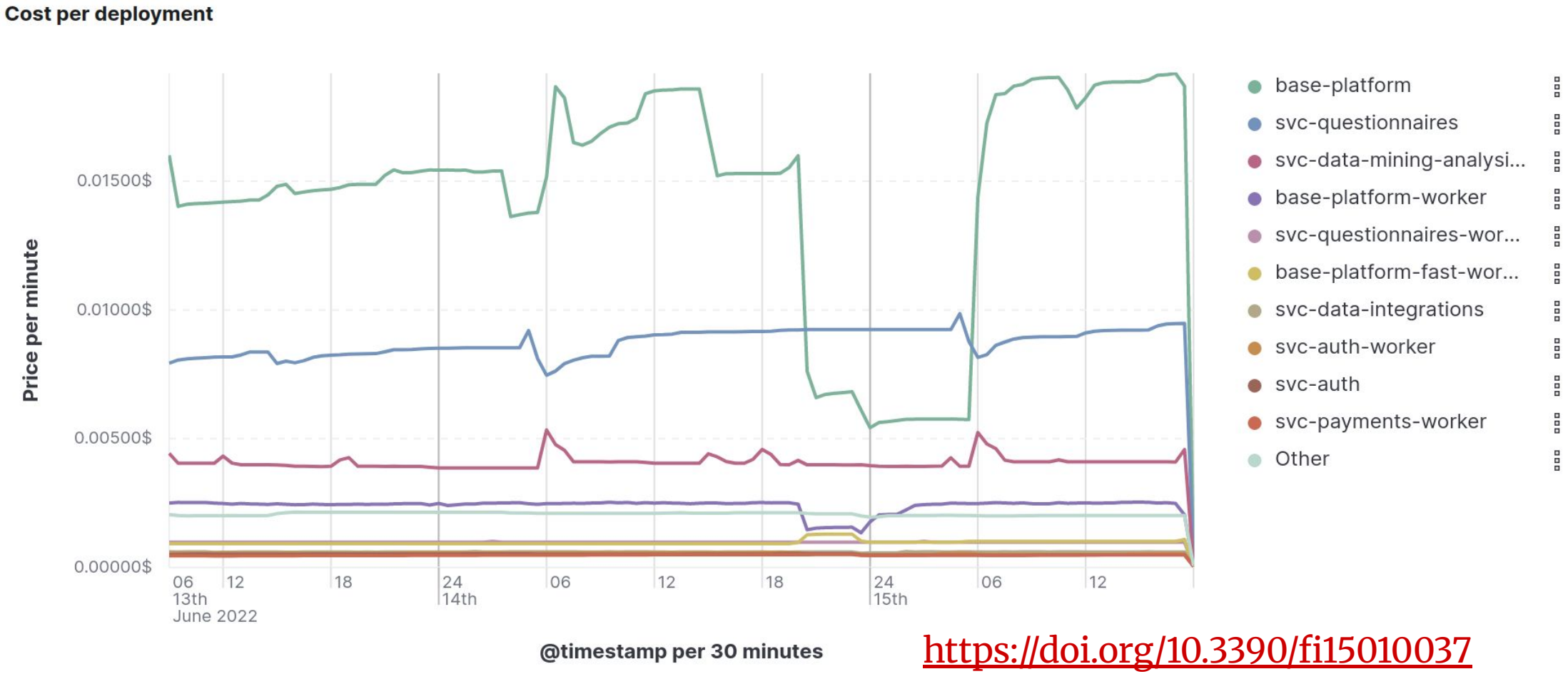
Cost allocation per microservice



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Actionable Observability roadmap

Signals | Elements | **Knowledge** | Action

- Decide which best practices/tactics/patterns to apply
- Decide when, where, and how to apply them
- Deal with heterogeneity of infrastructure over time and space

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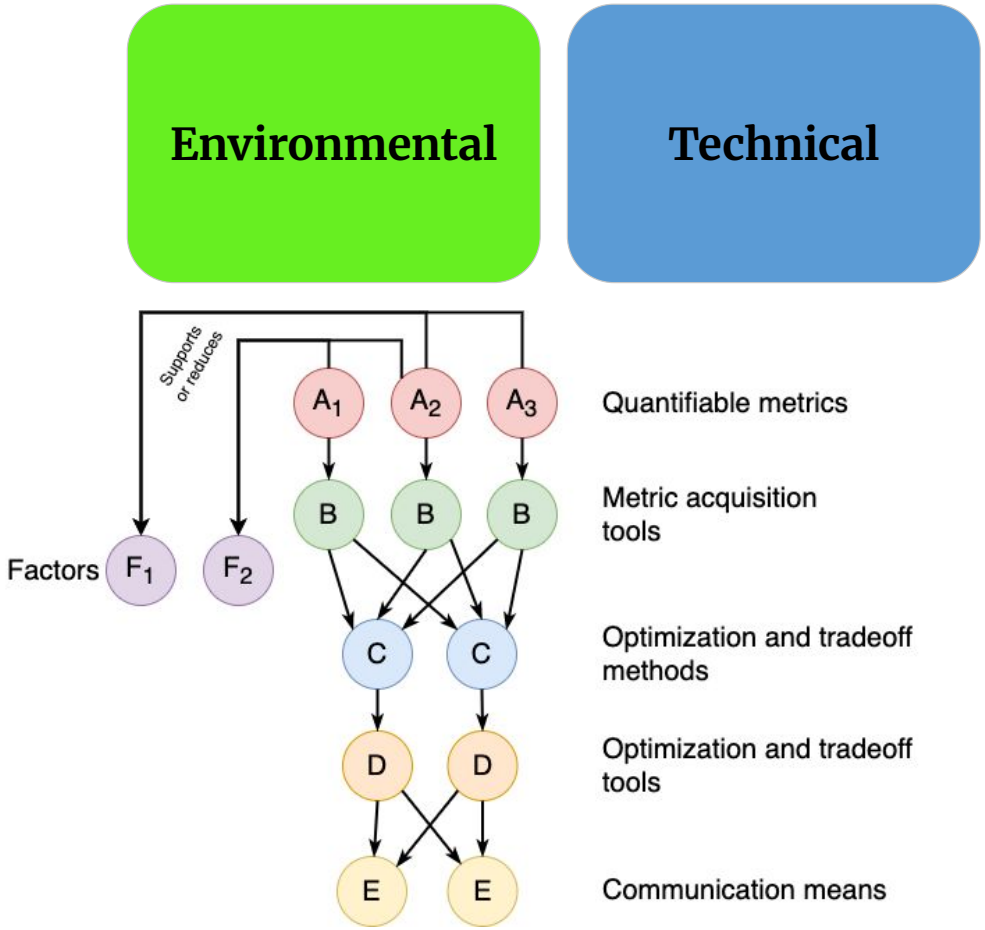
Actionable Observability roadmap

Signals → Elements → Knowledge → **Action**

- Rationalize & automate refactoring
- Integrate into development pipelines & practices
- Manage tradeoffs between affected QAs
- Enable sustainability across dimensions

MAST ITEA4 project



MAST
Managing Sustainability Tradeoffs

http://itea-mast.org/

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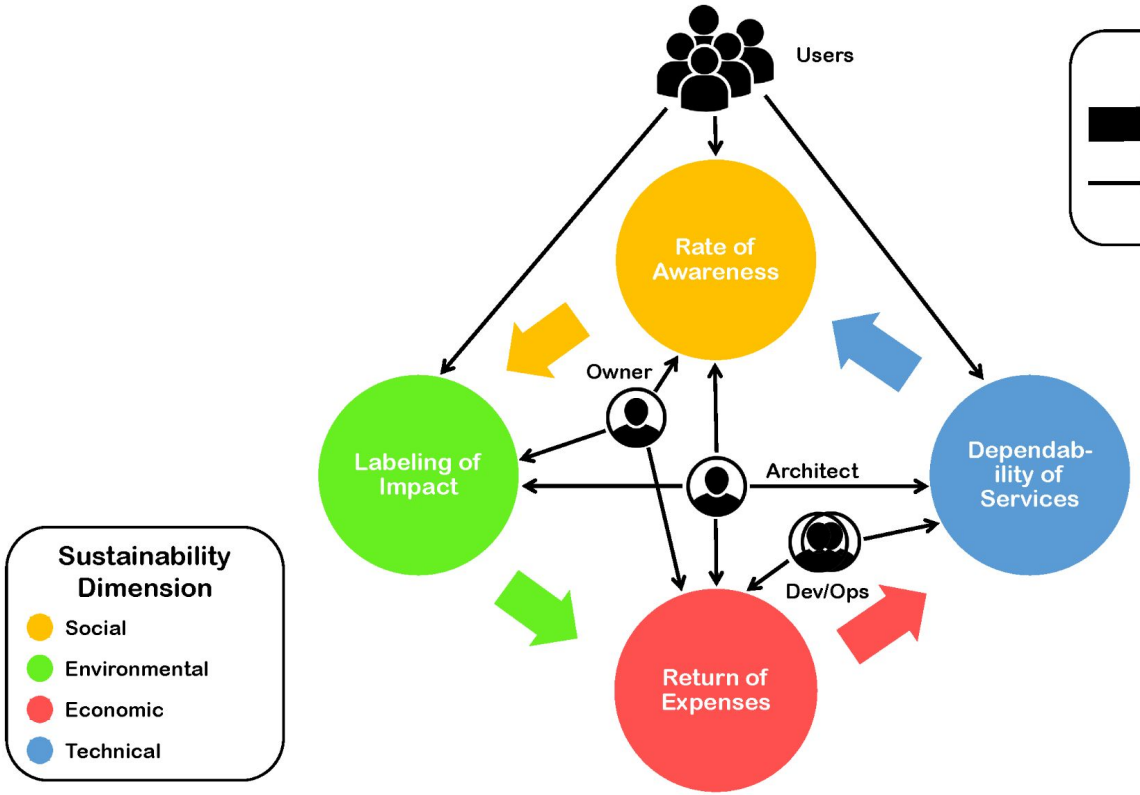
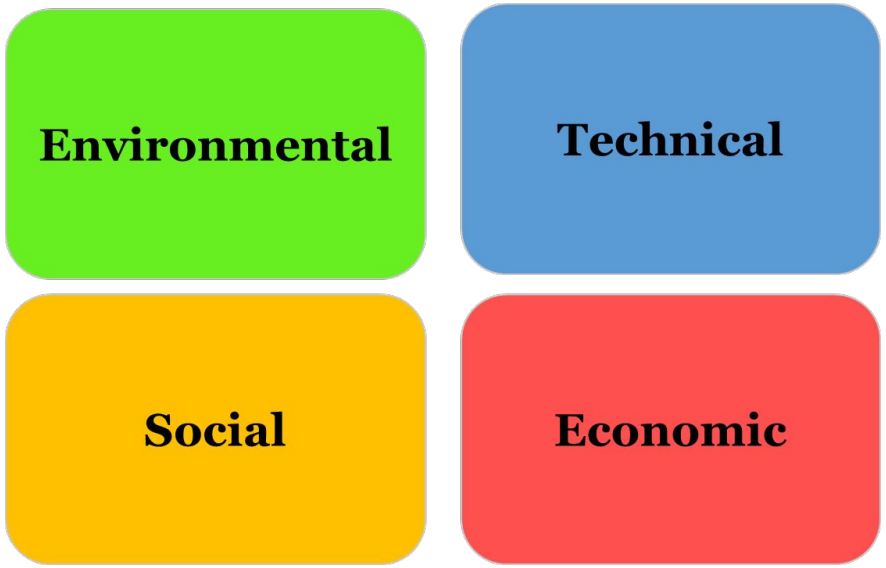
SustainableCloud





https://s2group.cs.vu.nl/sustainablecloud/

Coda

In music, a passage that brings a piece (or a movement) to an end

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Takeaways (revisited)

01	$\mathbb{E}$(software)	*Be aware and beware of the tools*
02	$\mathbb{E}$()	*Requires reverting a few decades worth of design decisions*
03	$\mathcal{O}^{+}(\mathbb{E}($  $))$	*Actionable observability, not just observability*

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Colophon

In publishing, a brief statement containing information about the publication

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It takes a village






https://vandriko.github.io/







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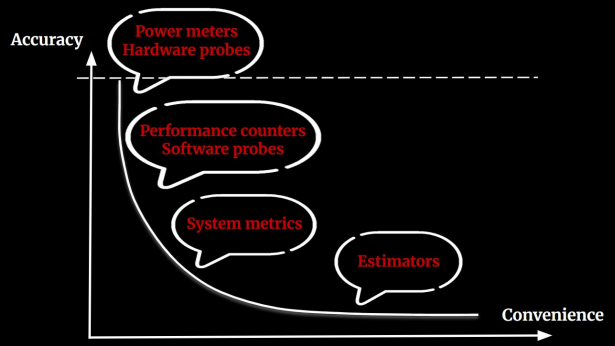
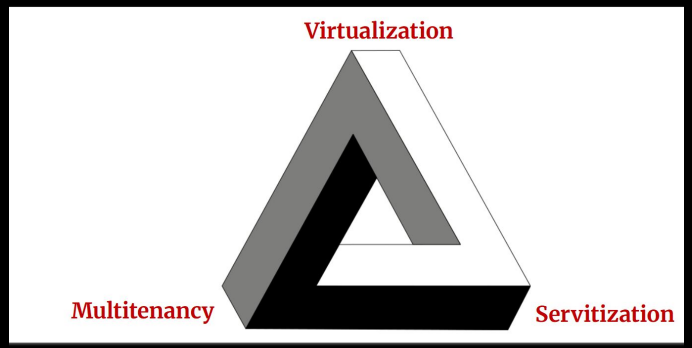
Thank you

Measuring energy consumption



The **D**evil's triangle in the cloud



Actionable **O**bservability roadmap

Signals	Elements	Knowledge	Action
What we observe	*Where* we need to intervene	*How* we intervene	*How* we use it in practice