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Harnessing Untapped Potentials in the Internet of Things: Retrofitting and Upgradeability

Public Lecture Series: Sustainability in Computer Science

Kaspar Lebloch

Intro

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Agenda

1. UN SDG 12: Responsible Production and Consumption
2. Product Obsolescence and the legal Framework in the EU
3. Domain Specific Challenges of IoT Retrofitting
4. SerIoT: An Interface for Upgradeability-by-Default
5. Towards a Right to Improve

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1. UN SDG 12: Responsible Production and Consumption
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https://sdgs.un.org/goals

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11 Targets

https://sdgs.un.org/goals

11 Targets

Target **12.5:** “By 2030, substantially reduce waste generation through **prevention**, **reduction**, recycling and **reuse**”*

*https://sdgs.un.org/goals/goal12#targets_and_indicators

E-Waste

"In 2019, the amount of e-waste generated was **7.3 kg** per capita, with only 1.7 kg per capita documented to be managed in an environmentally sustainable manner. […]*"

https://sdgs.un.org/goals/goal12#progress_and_info

E-Waste

"[…] E-waste generation is expected to grow by 0.16 kg per capita annually to reach **9 kg** per capita in 2030."*

*https://sdgs.un.org/goals/goal12#progress_and_info

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Prevention, Reduction, Recycling and Reuse

- Design for durability
- Favor repair over replacement
  - In Design
  - In Use
- Beyond repair: **Improvement**
  - Upgrade
  - Retrofit
- Anticipate and encourage **repurposing**

- How are these goals currently enforced?

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2. **Product Obsolescence and the legal Framework in the EU**
3. Domain Specific Challenges of IoT Retrofitting
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Product Obsolescence in Household Appliances

- Obsolescence: ”The process or fact of becoming obsolete or outdated, or of falling into disuse.”*
- Product obsolescence is **inevitable**
  - Durability of materials and parts
  - Technological advancement: Safety, efficiency, features, …
  - Fashion

→ Design for obsolescence: efficient use of resources

- Planned obsolescence: premature failure due to deliberate design flaws
- New phenomenon: Software-based obsolescence
  - Lack of (security) updates

* Per the Oxford Dictionary

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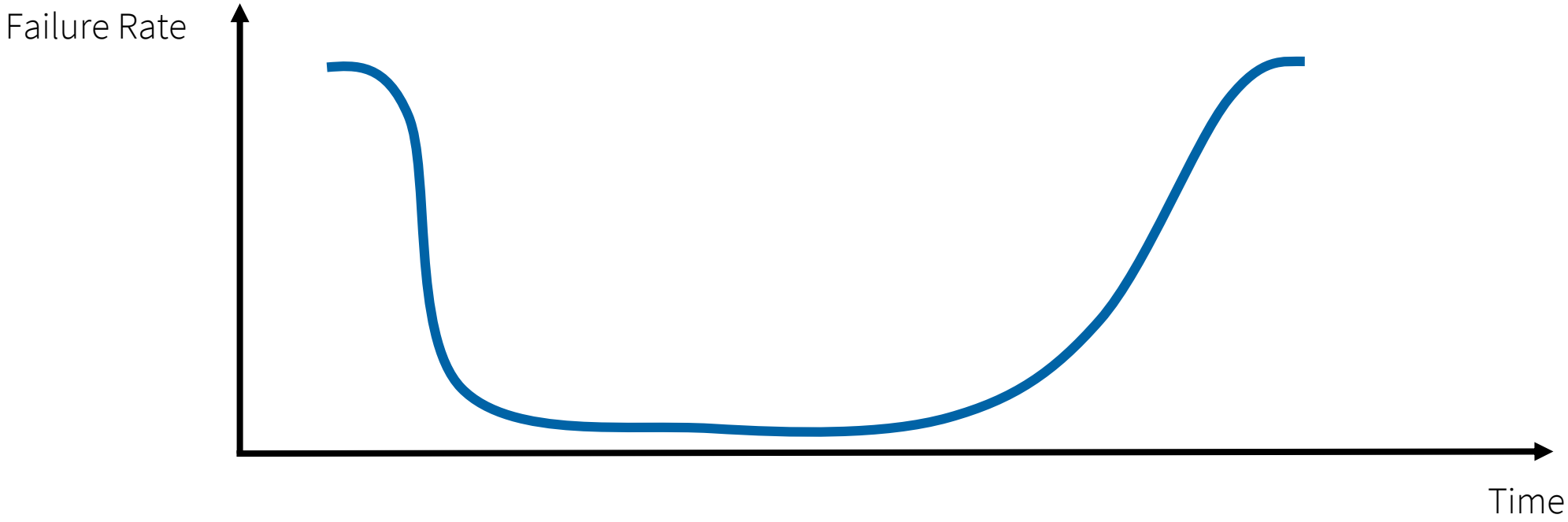
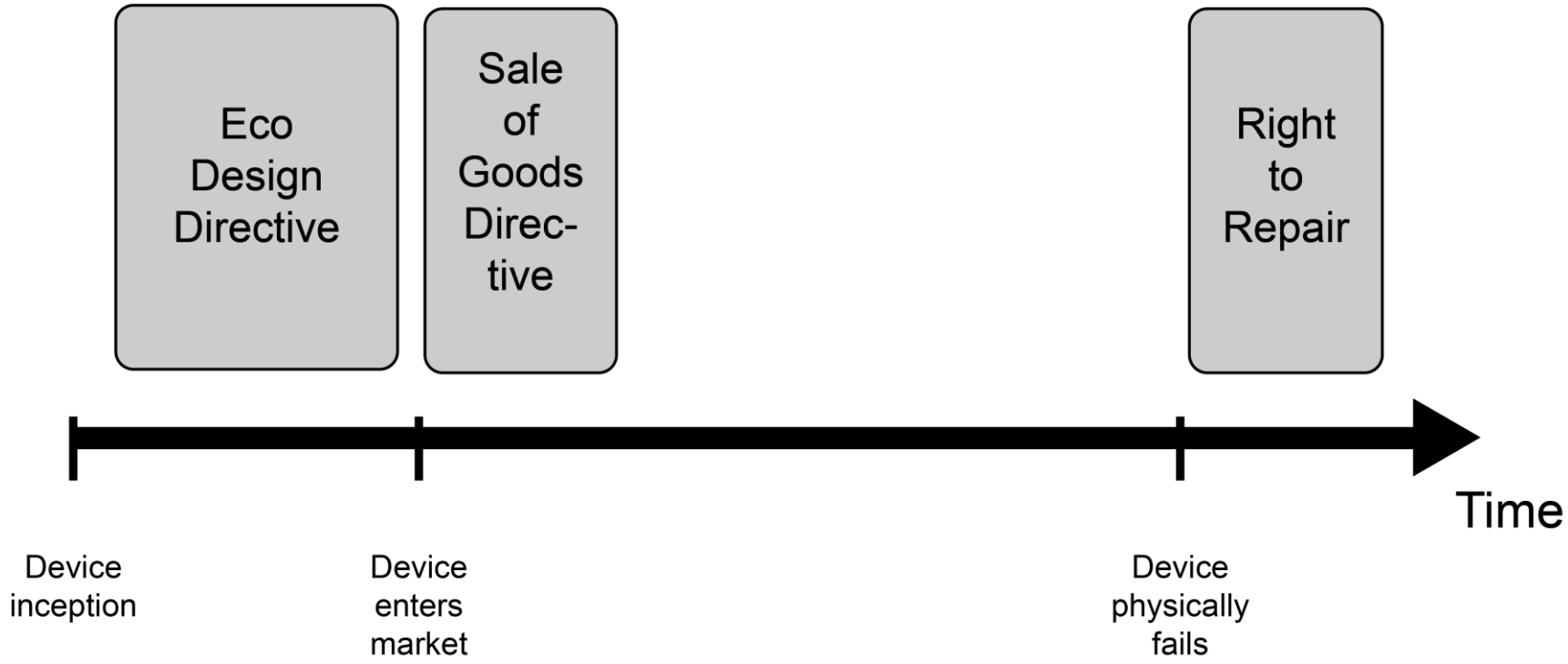
The Bathtub Curve of Device Failure Rate over Time



The Legal Framework in the EU



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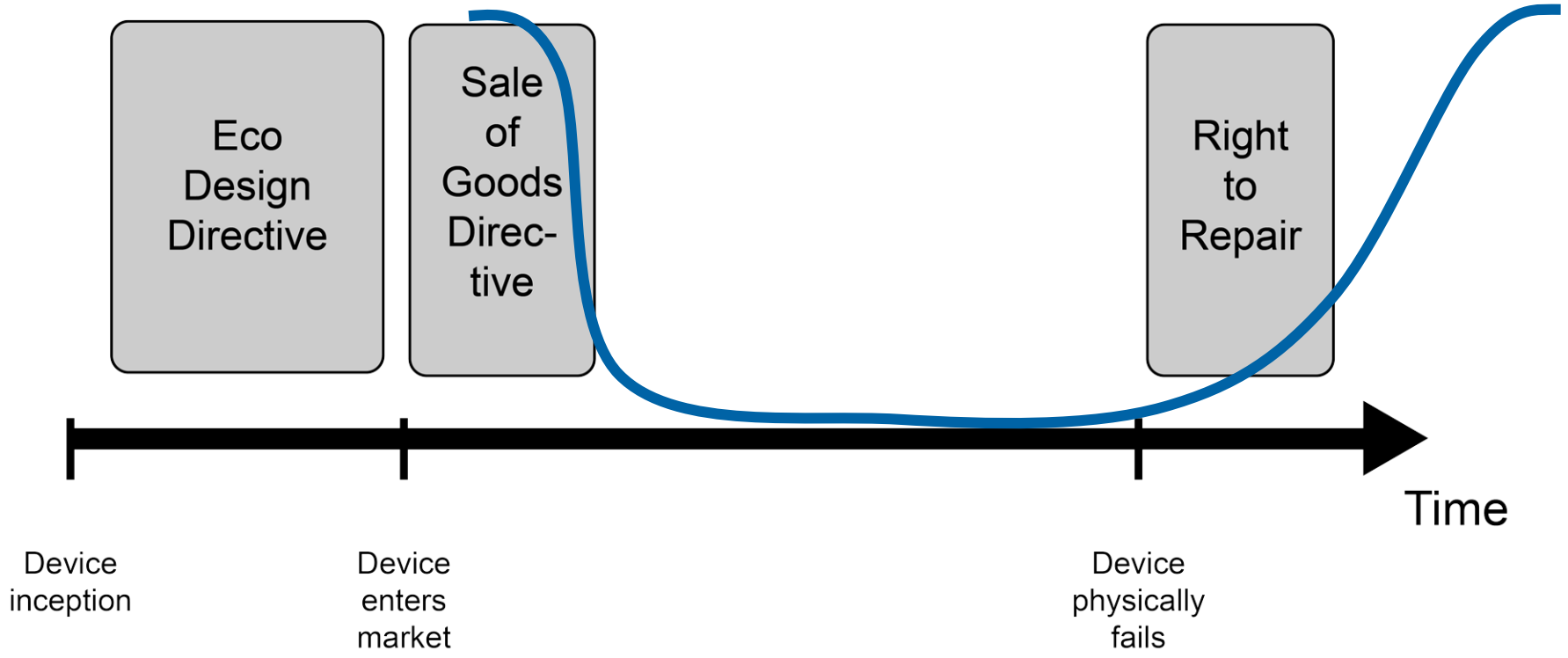

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Takeaways

- Obsolescence is inevitable and designed for
  - Failure rates / obsolescene incidence can be modeled with the „Baththub curve“
- The Ecodesign Directive
  - Mandates parameters for appliance design
  - Applies to specific product categories only
- The Sale of Goods Directive
  - Protects consumers for two years after a sale
  - Concerns vendors, not manufacturers
- The Right to Repair
  - Is yet to come and will only apply to Ecodesign Directive categories
  - Entitles consumers to receive a repair service

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The legal framework handles product obsolescence in the EU. How can Computer Science contribute beyond that?

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The (Residential) Internet of Things

- „Network of physical objects—“things”—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet”*
- Residential IoT: Smart Home
  - „Smart“ Household appliances
  - Remote control and monitoring
  - Home automation
  - Competing standards
  - Competing manufacturers
  - Selective cross-integrations

*https://www.oracle.com/internet-of-things/what-is-iot/#:~:text=What%20is%20IoT%3F,and%20systems%20over%20the%20internet.

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IoT Retrofitting – what is it, and why?

- Outfitting existing, often unprepared appliances with IoT Technology
  - Network modules
  - Sensors
  - Actuators
- Observed mostly in Industrial context
  - Fabrication machinery
  - Industry 4.0
  - Appliances are significant investment
  - Delaying obsolescence motivated from economic view
- Consumer-grade IoT retrofitting
- Goal: **Prolong the use phase** of an appliance as opposed to replacing it with a new, smart one

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Domain Specific Challenges of IoT Retrofitting: Three Case Studies

- Domains:
  1. Physical
  2. Electronic
  3. Digital

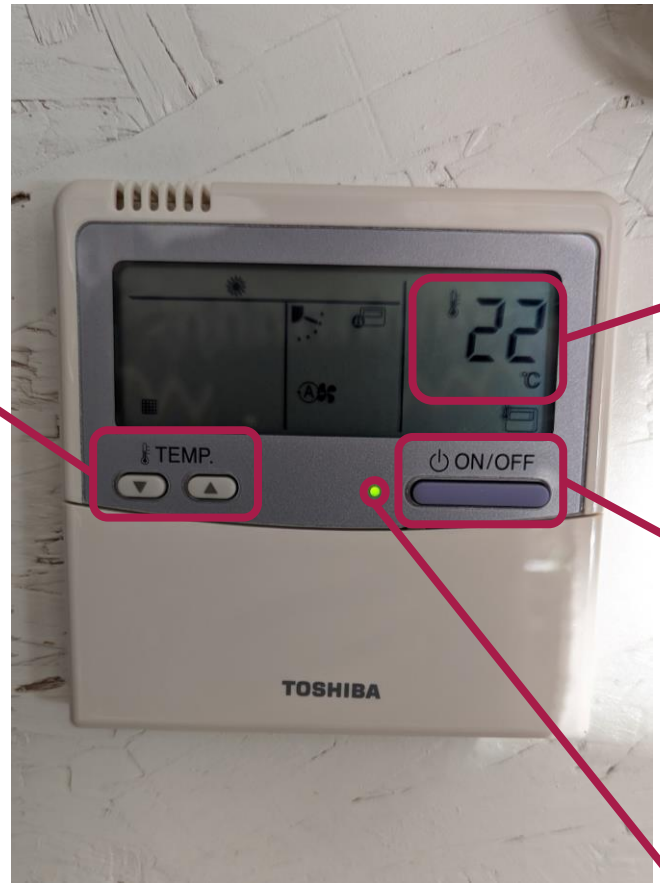
- Preconditions: Test subject is a motivated computer scientist or developer, **not a domain expert**.
- Method: **Autoethnography** of the process (self, supervised, and online-sourced)
- Limitations: the challenges are only the ones **we identified** for the target demographic (there may be many more)

Case Study I: Physical IoT Retrofitting

- Physical user interface components:
  - Buttons, levers, knobs and gears
- Target: Heating control panel
- Motivation: Conserve energy (fix inefficient programming)

Case Study I: Physical IoT Retrofitting

- Steps:
  1. Analyze the interface ←
  2. Identify necessary elements
  3. Find compatible hardware
  4. Build custom solution (HW and SW)



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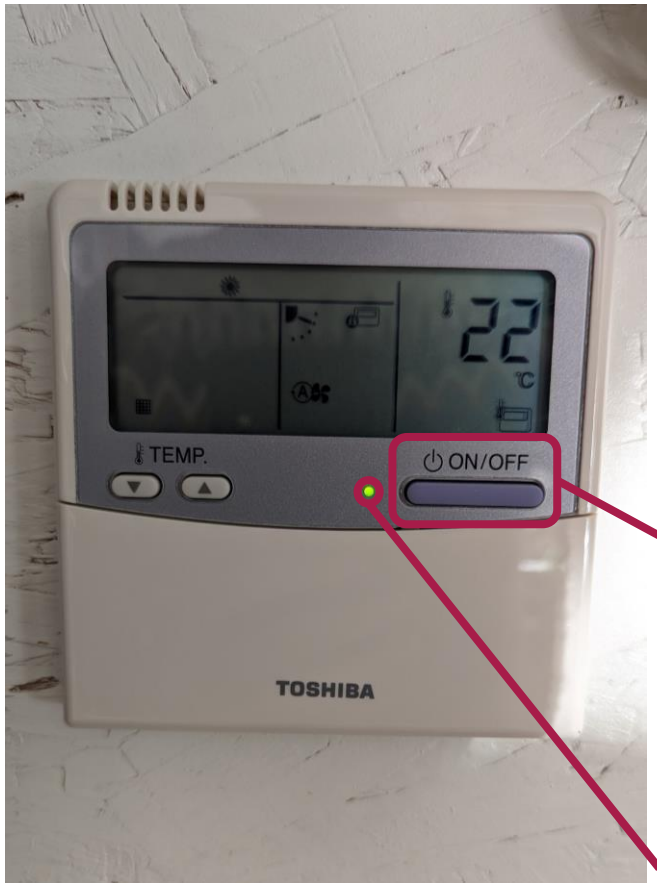

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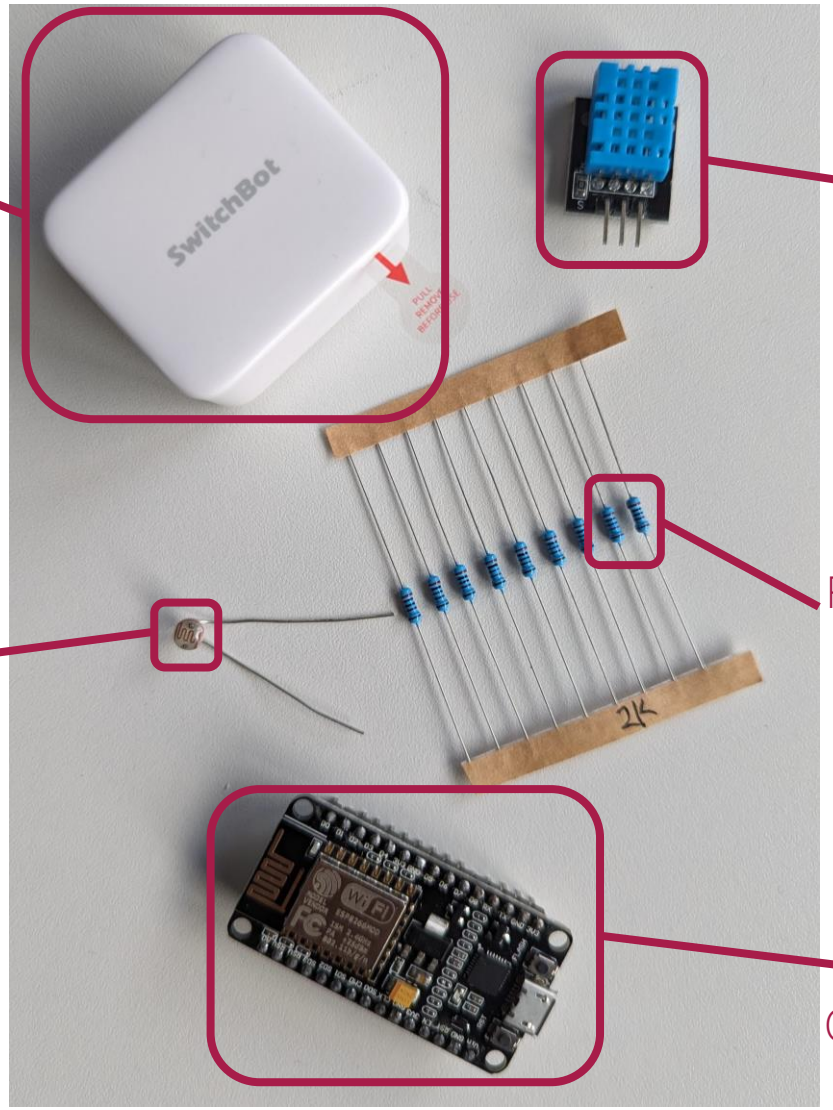

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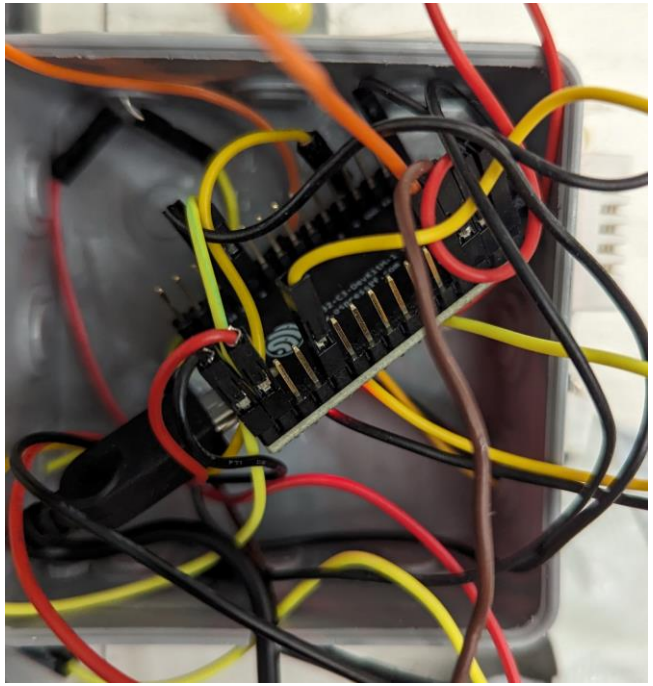

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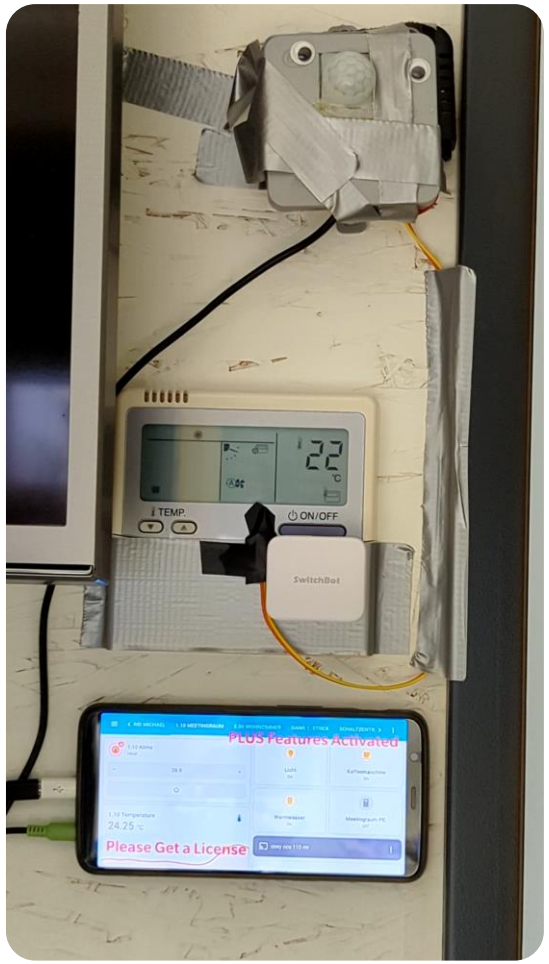

- Steps:
  1. Analyze the interface
  2. Identify necessary elements
  3. Find compatible hardware
  4. Build custom solution (HW and SW)
- Result:
  - A complex prototype consisting of multiple interlinked HW components

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Case Study I: Domain Specific Challenges

- Complexity
  - Requires creative cross-domain approach
  - Requires multiple different HW and SW components
- Functional impact
  - Solution may obstruct original UI
- Aesthetic impact
  - Solution impairs appearance of appliance
- Specific solution
  - Solution has to be custom fitted to appliance
  - Solution is not functionally generic

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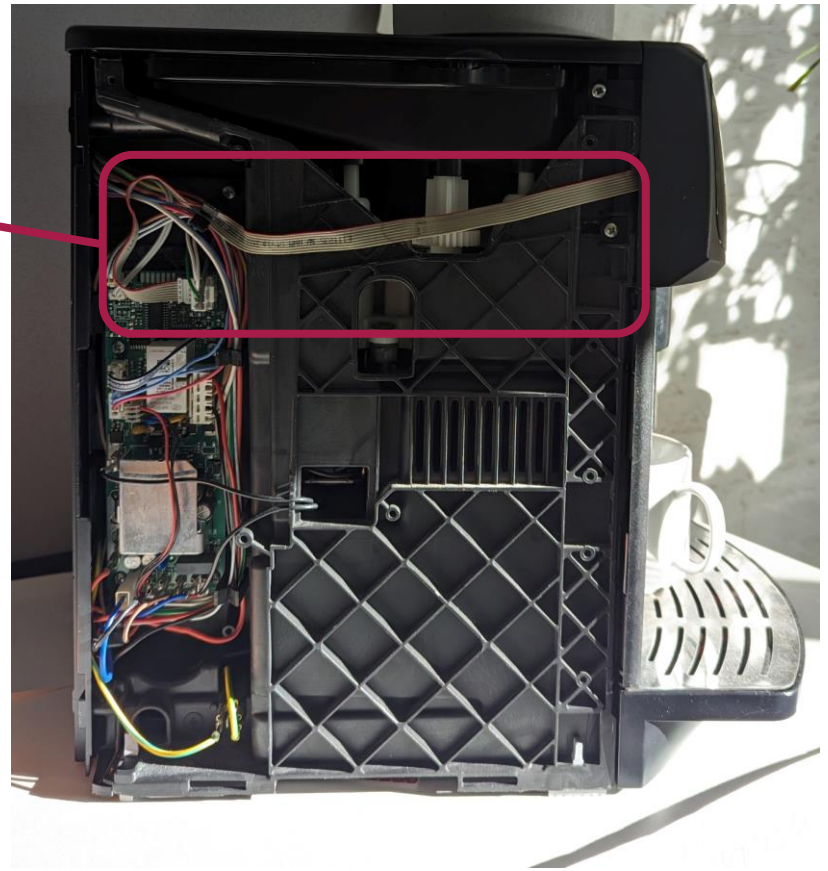
Case Study II: Electronic IoT Retrofitting

- Electronic interfaces:
  - Electrical contacts, interception of voltages
- Target: Espresso maker
- Motivation: Extend feature set, delay obsolescence

⚠⚠ Don‘t try this at home! ⚠⚠

Case Study II: Electronic IoT Retrofitting

- Steps:
  1. Find suitable entry point ←
  2. Measure and document electronic signals
  3. Reverse engineer meaning of electronic signals
  4. Reproduce electronic signals
  5. Build custom SW solution



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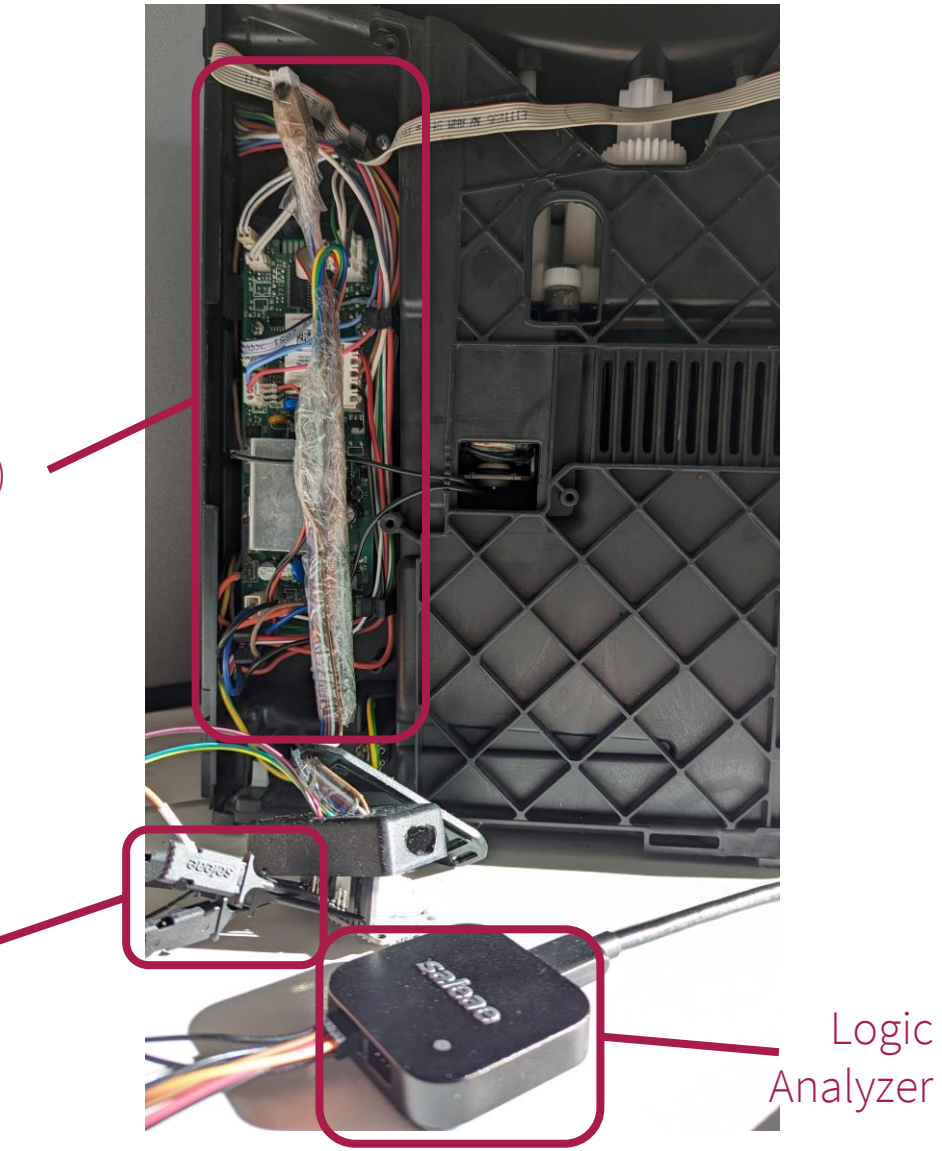

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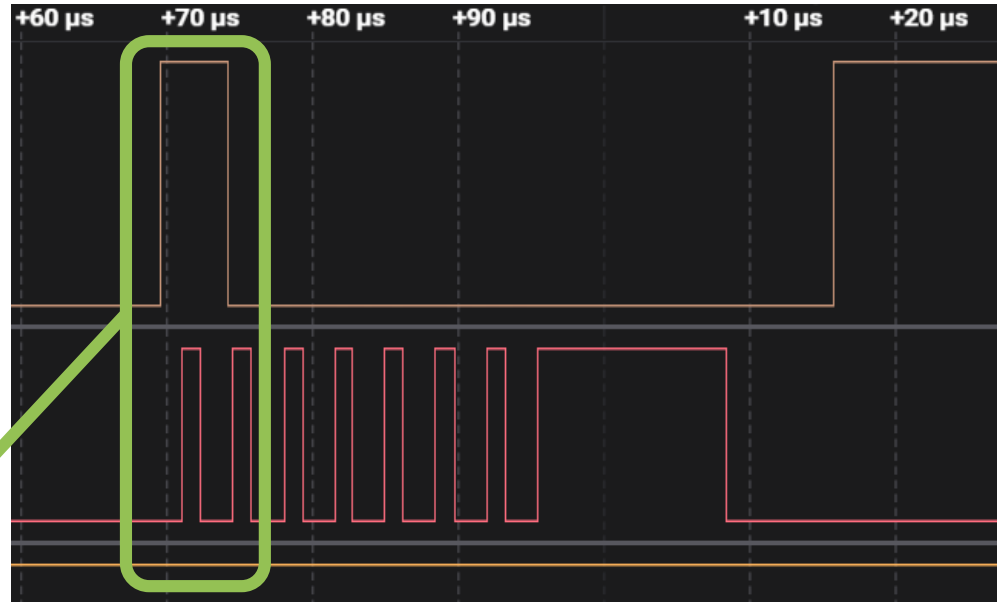

Single espresso button pressed

Case Study II: Electronic IoT Retrofitting

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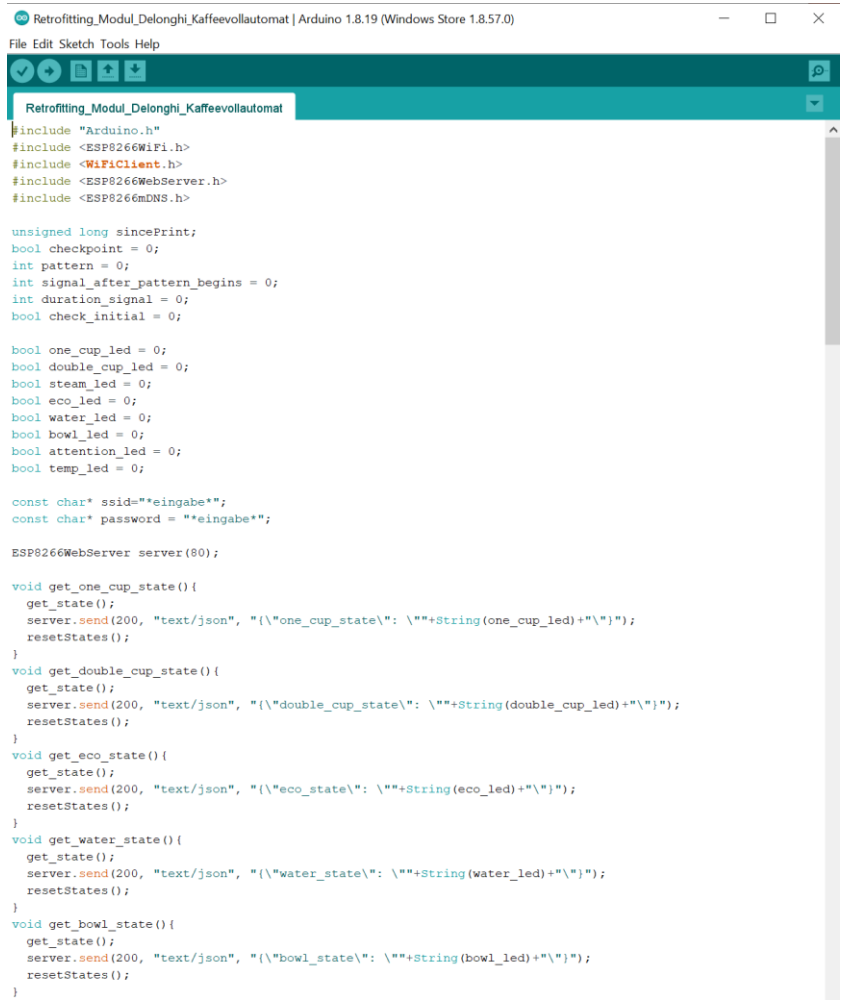

Case Study II: Electronic IoT Retrofitting

- Steps:
  1. Find suitable entry point
  2. Measure and document electronic signals
  3. Reverse engineer meaning of electronic signals
  4. Reproduce electronic signals
  5. Build custom SW solution
- Result:
  - A software prototype for ESP microcontrollers

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Case Study II: Domain Specific Challenges

- Measureability
  - Requires specialized hardware (oscilloscope/logic analyzer)
- Reverse engineering
  - Requires patience and precision
- Signal reproducability
  - Solution components have to be able to reproduce original signal (analog and digital)
- Specific solution
  - Software is specific to appliance (model)

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Case Study III: Digital IoT Retrofitting (Extending Work by Jirků*)

- Digital Interfaces: Serial ports, wireless ports, APIs
- Target: Soundbar speaker
- Motivation: Add Features, delay obsolescence

https://at.yamaha.com/de/products/audio_visual/sound_bar/yas-207/index.html

*see also https://wejn.org/tags/#yas_207

Case Study III: Digital IoT Retrofitting

- Steps:
  1. Identify interface ←
  2. Intercept communication
  3. Reverse engineer protocol
  4. Build custom SW solution

Bluetooth Classic ←→ BLE

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Case Study III: Digital IoT Retrofitting

- Steps:
  1. Identify interface
  2. Intercept communication ←
  3. Reverse engineer protocol
  4. Build custom SW solution

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Case Study III: Digital IoT Retrofitting

- Steps:
  1. Identify interface
  2. Intercept communication
  3. Reverse engineer protocol ←
  4. Build custom SW solution

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Case Study III: Digital IoT Retrofitting

- Steps:
  1. Identify interface
  2. Intercept communication
  3. Reverse engineer protocol
  4. Build custom SW solution ←

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Case Study III: Digital IoT Retrofitting

- Steps:
  1. Identify interface
  2. Intercept communication
  3. Reverse engineer protocol
  4. Build custom SW solution
- Result:
  - Software prototype for any platform depending on programming language

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Case Study III: Domain Specific Challenges

- Interception of communication
  - Requires product adherence to documented standards
  - Requires compatible hardware (easy to come by)
- Protocol reverse engineering
  - Requires specialized programming skills or example
  - Requires protocol to not be encrypted
- Genericity of Result
  - Solution not generic due to prioritization of own use case & lack of standardization (but appropriable)

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Takeaways:

- IoT retrofitting often **requires specialized hardware and skills**
- Different domains for retrofitting projects have different requirements
- **Physical**:
  - Cross-domain thinking
  - Different sensors/actuators
- **Electronic**:
  - Specialized hardware
  - Signal reproducability
- **Digital**:
  - Protocol readability
  - Standard adherence
- **Global challenge: Solutions lack genericity**

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We established: IoT retrofitting of legacy hardware is challenging. But what about current IoT devices?

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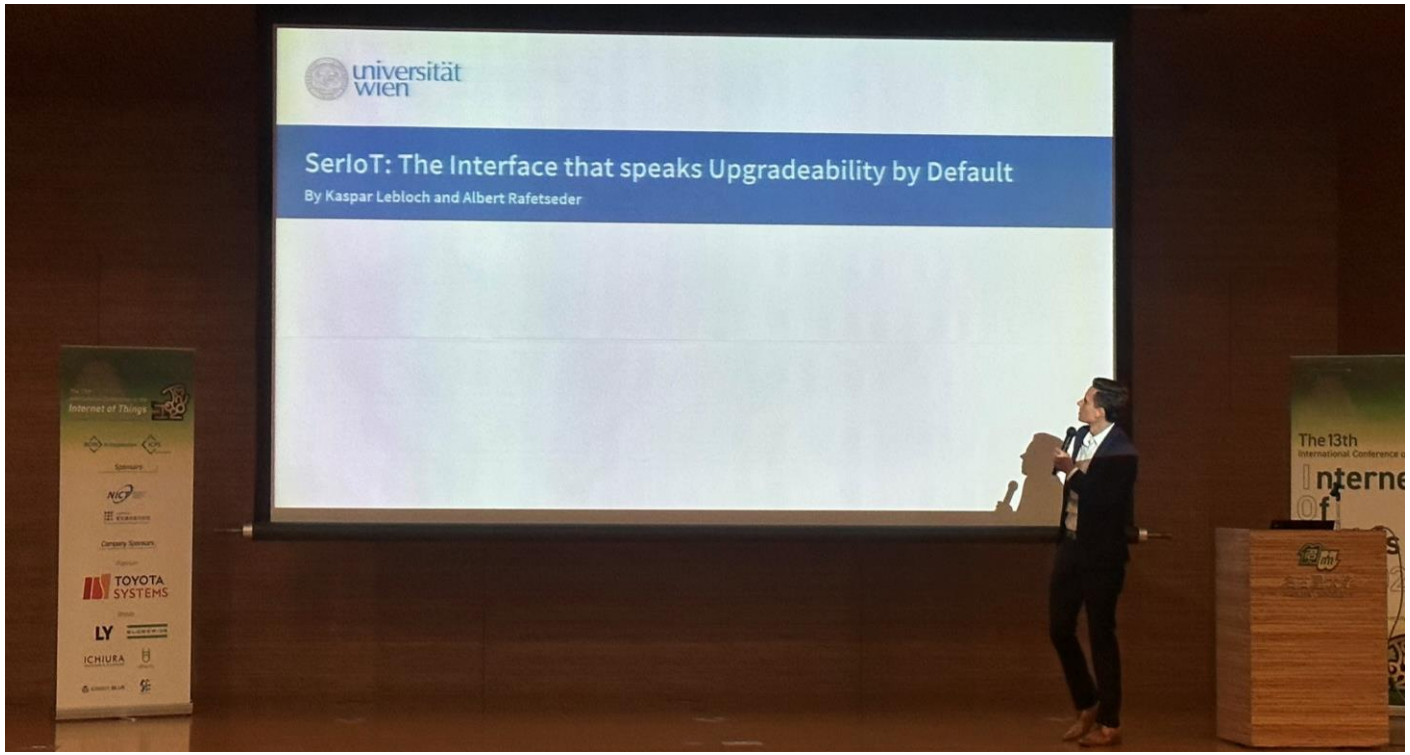
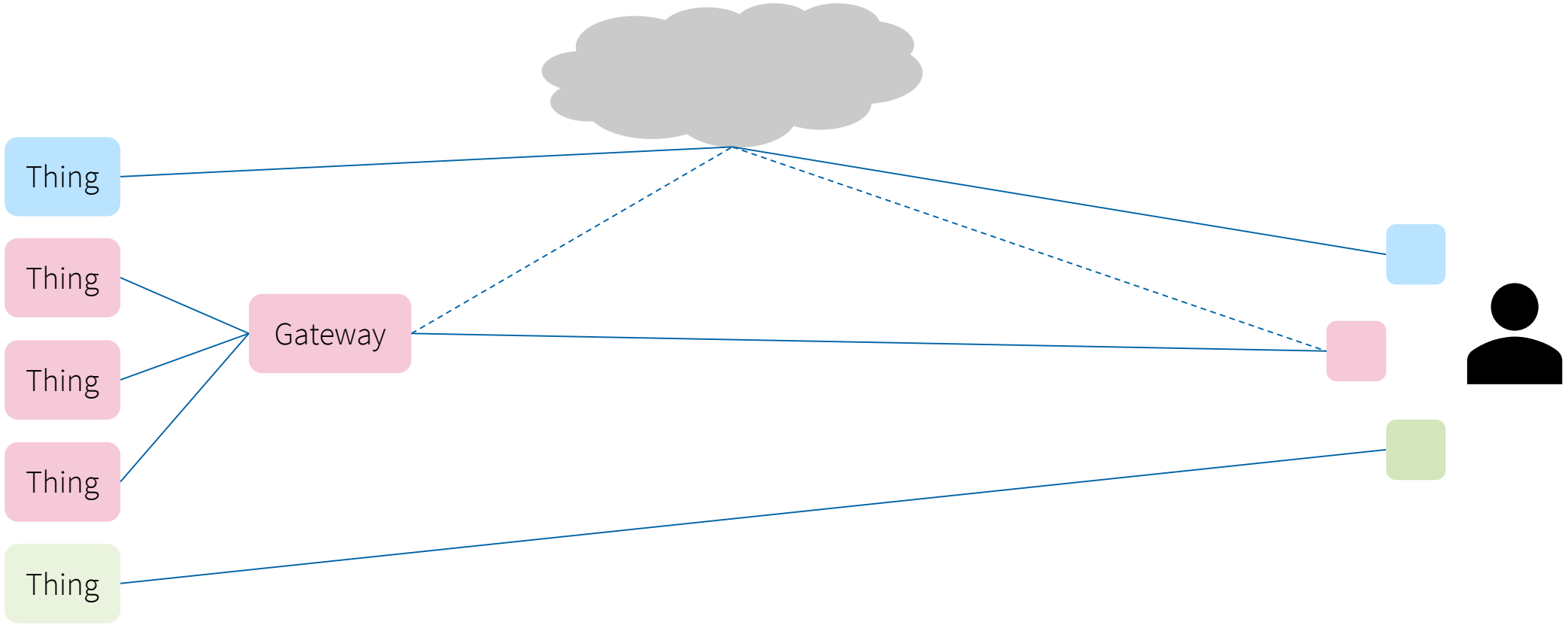
SerIoT: The Interface that speaks Ugradeability by Default



The corresponding paper will be available in the ACM-DL soon.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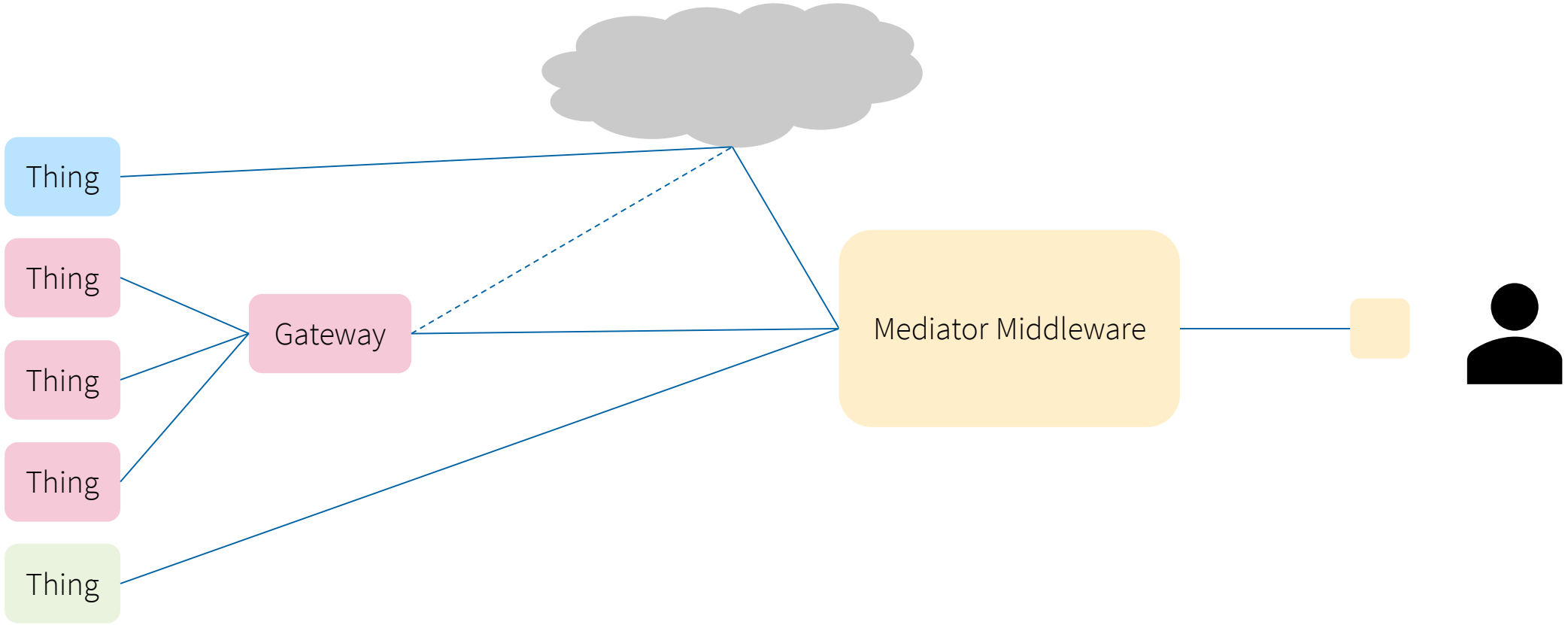
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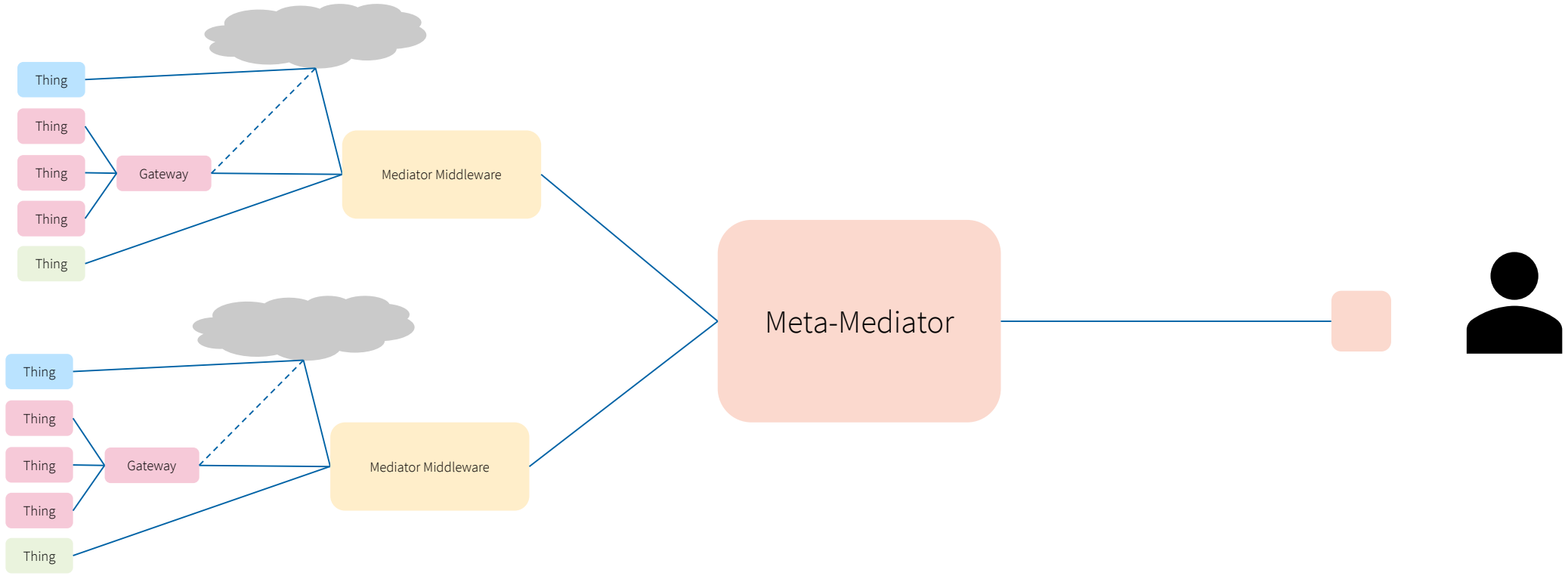
Mediator Middleware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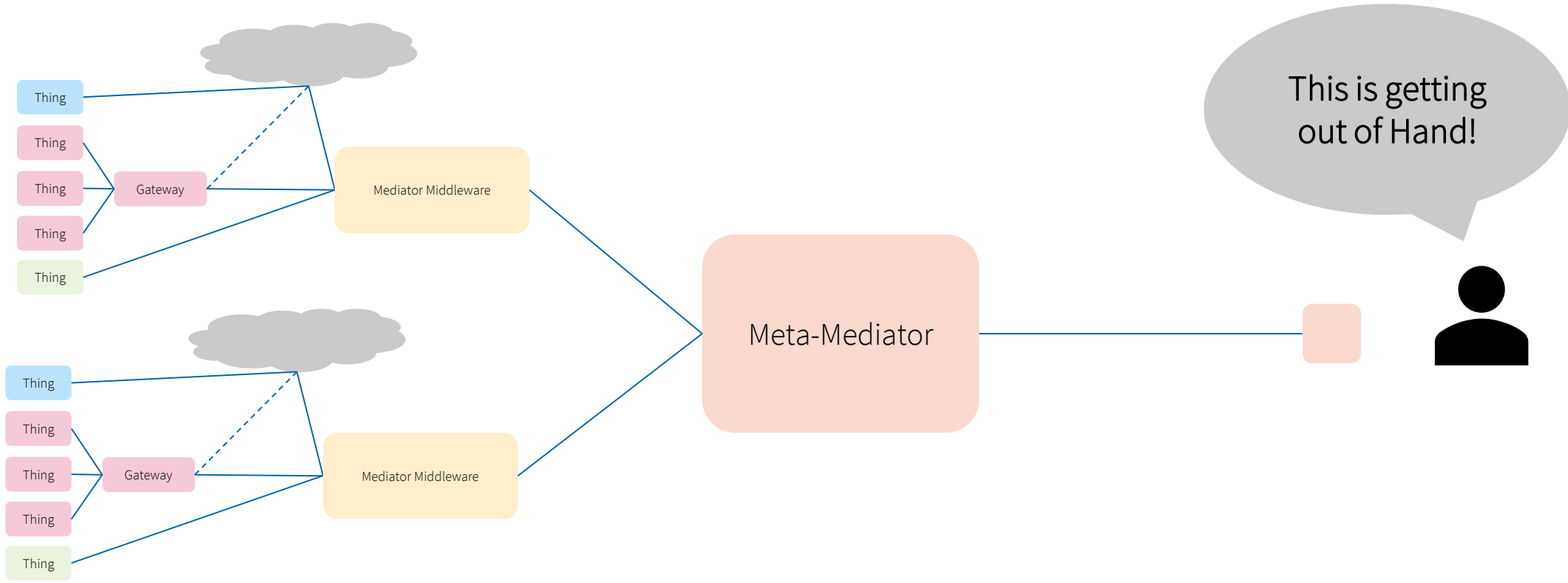
Mediator Middleware
Meta-Mediator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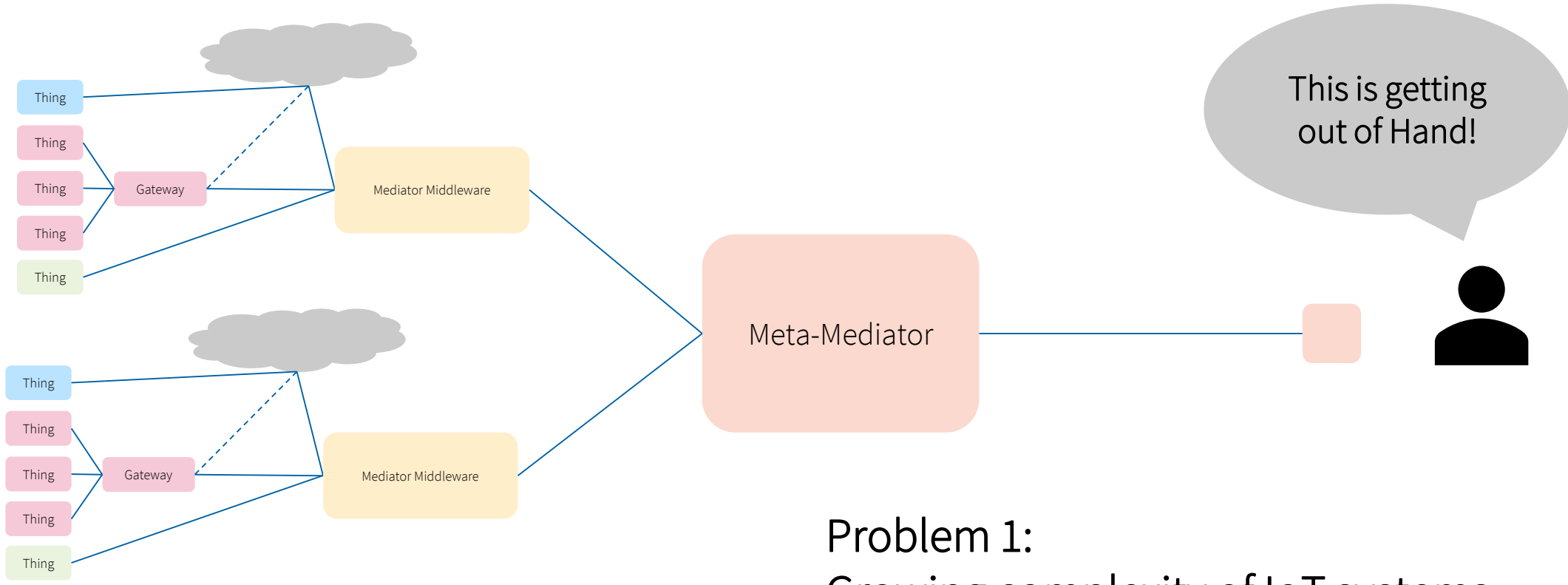
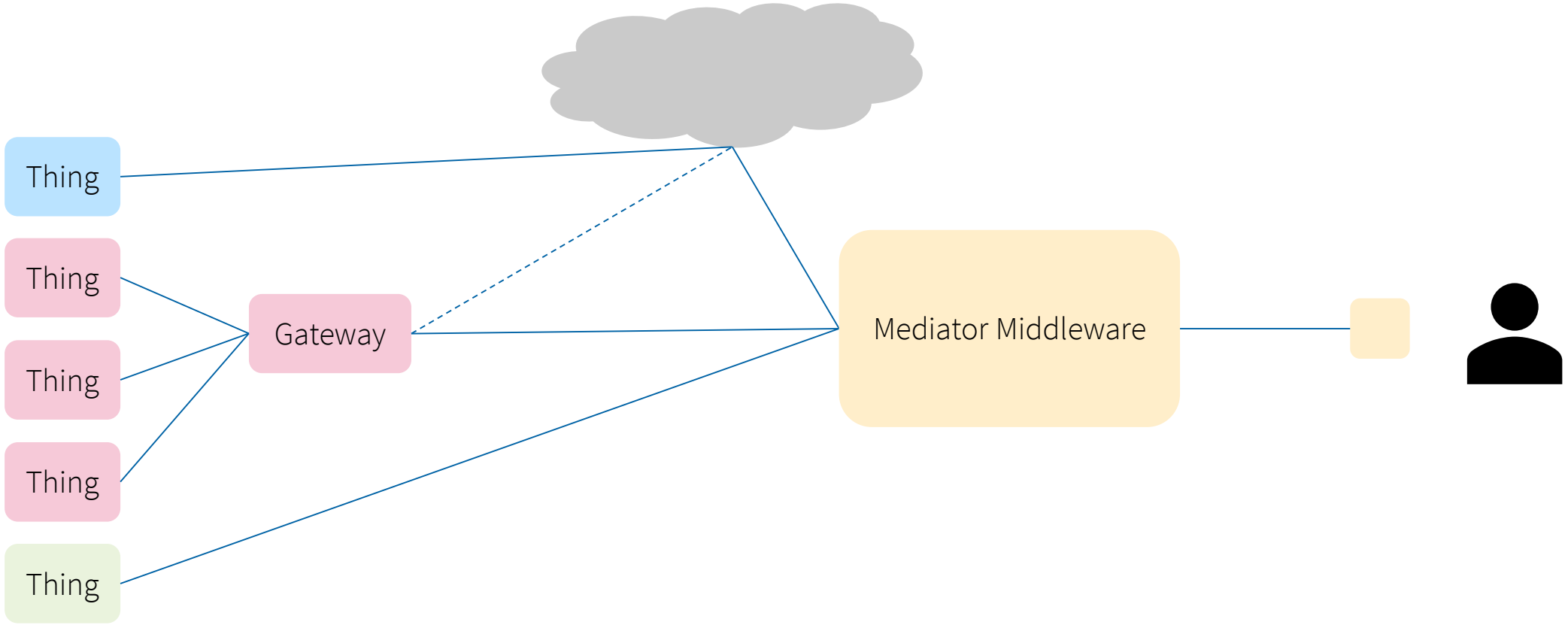
Meta-Mediator
This is getting out of Hand!



Problem 1:
Growing complexity of IoT systems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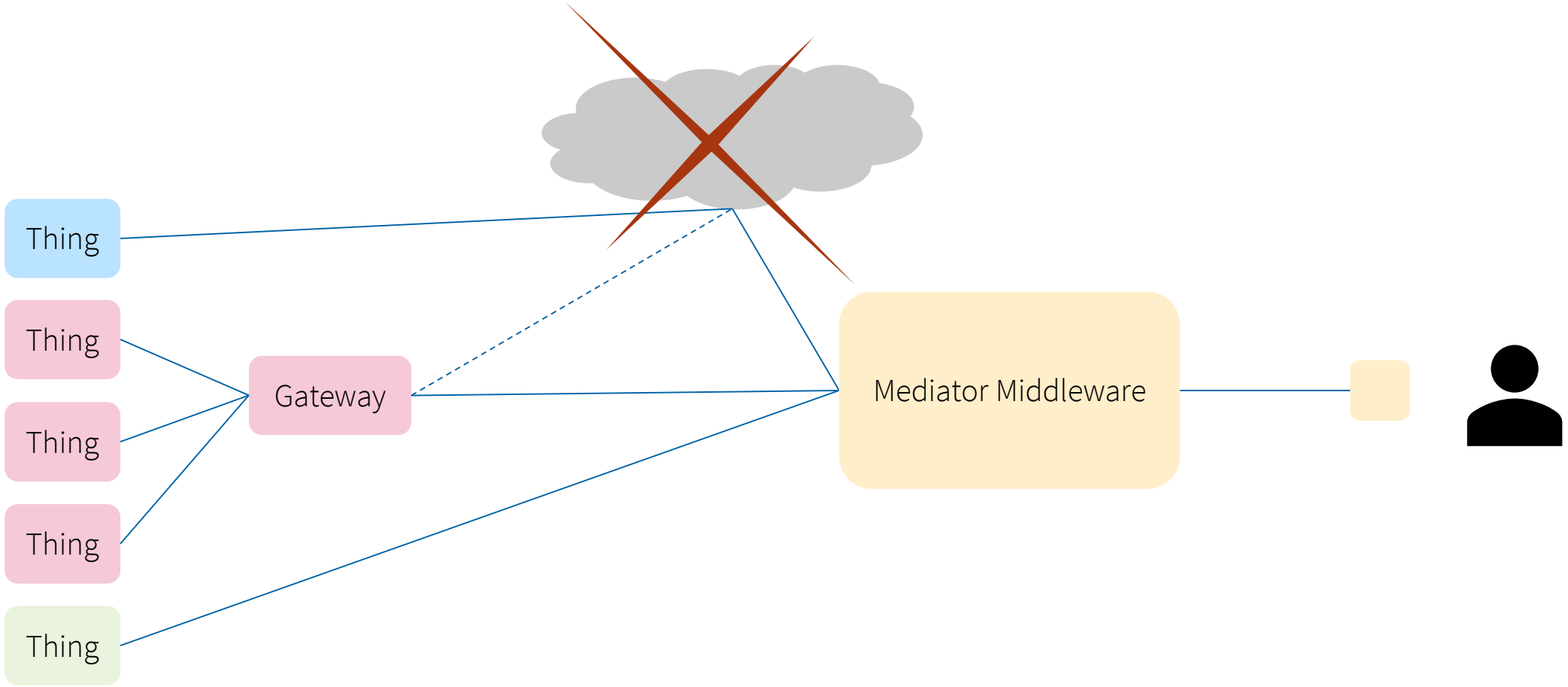
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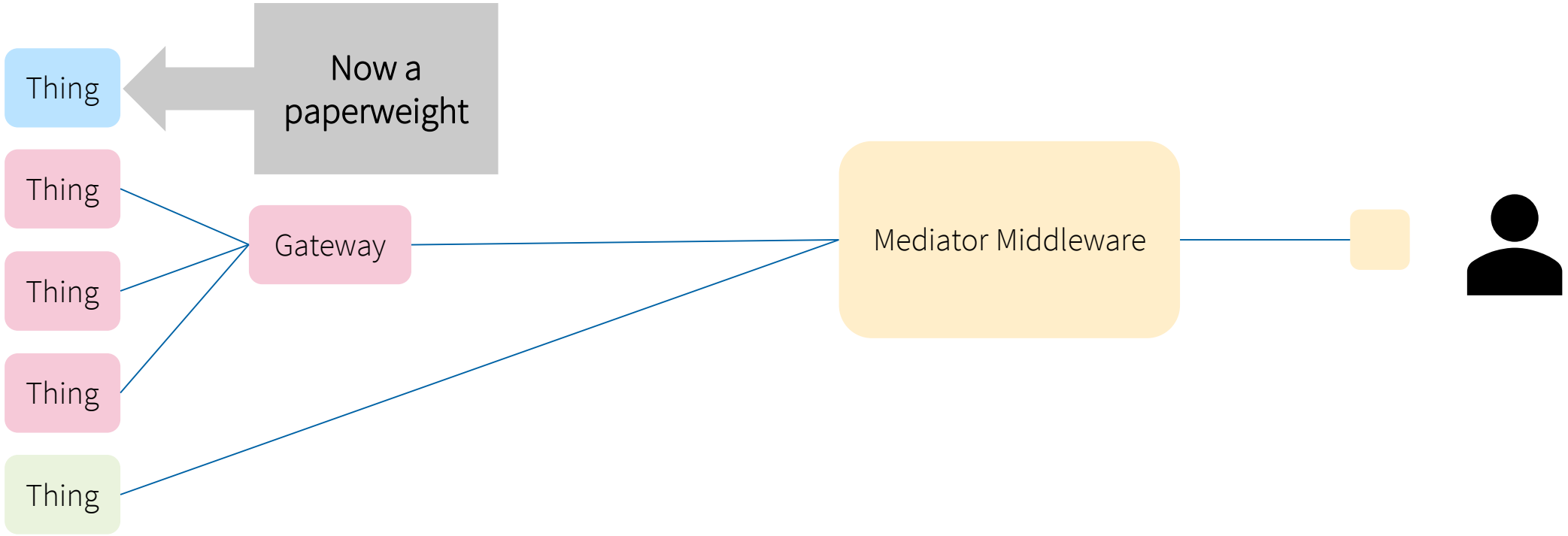
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Now a paperweight
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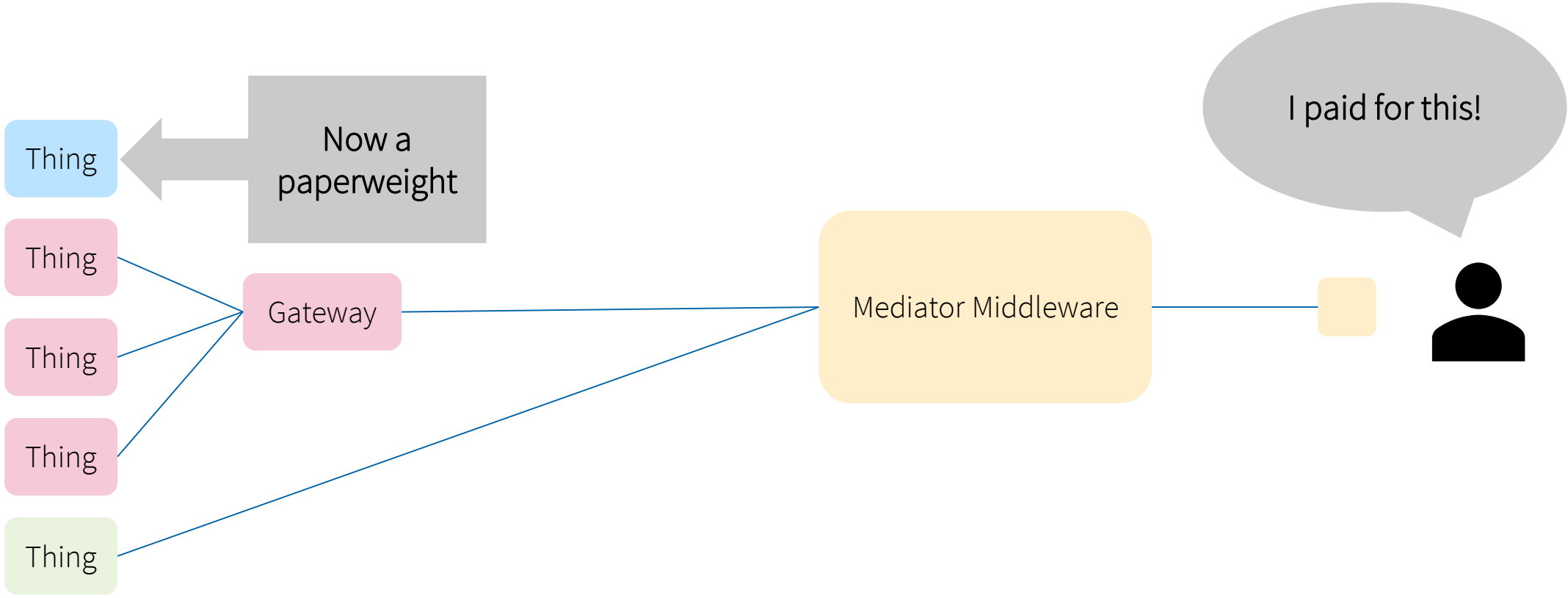
Gateway
Mediator Middleware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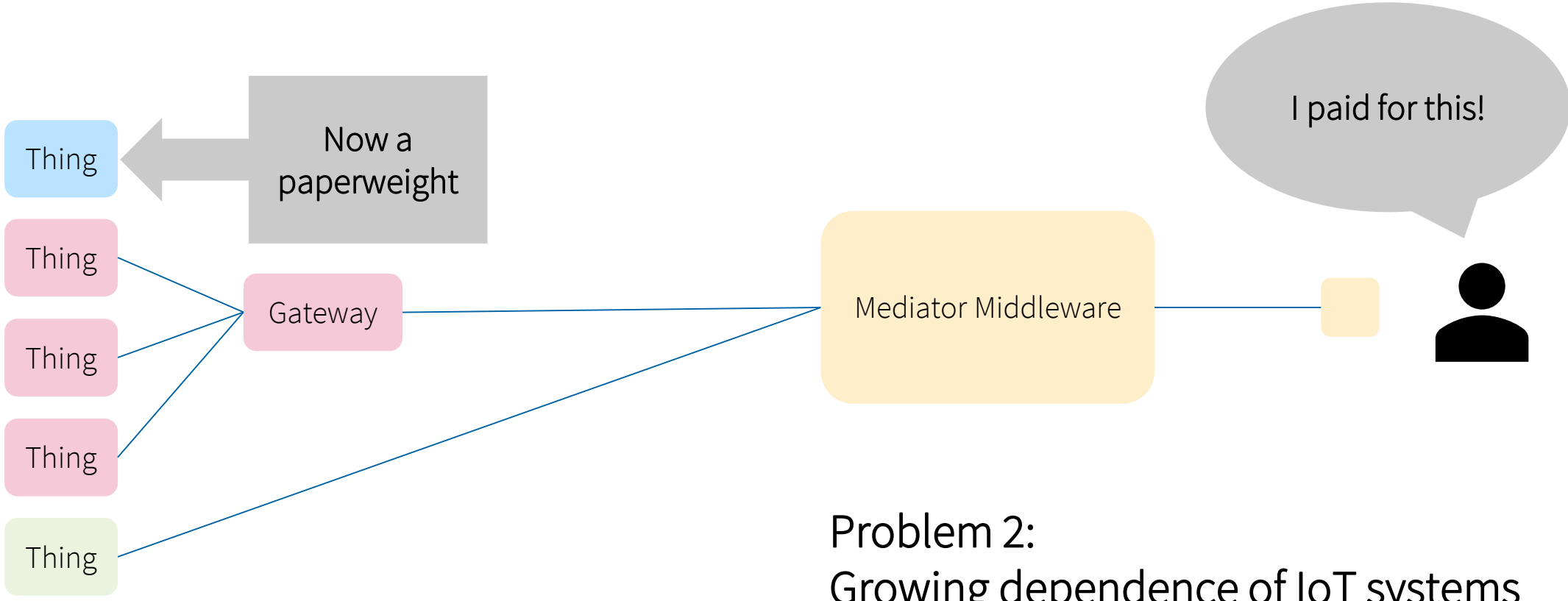
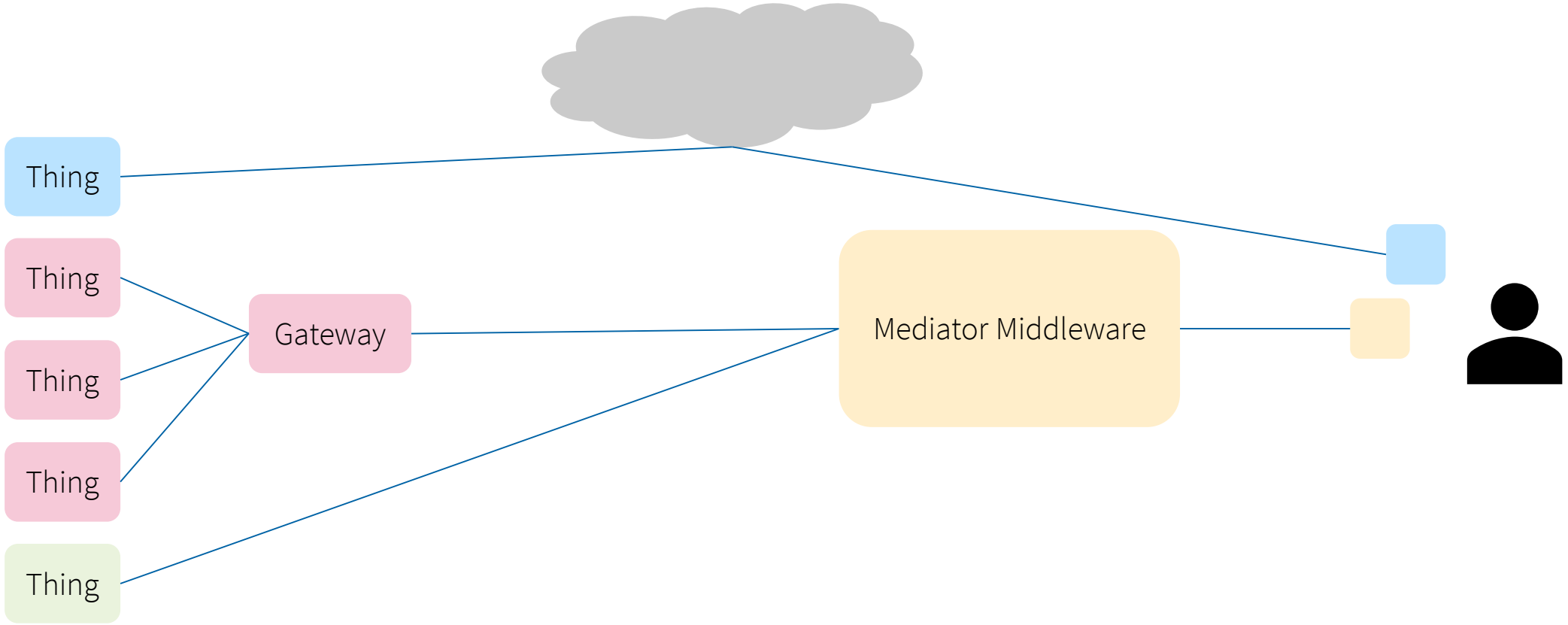
I paid for this!



Problem 2:
Growing dependence of IoT systems on manufacturer cloud services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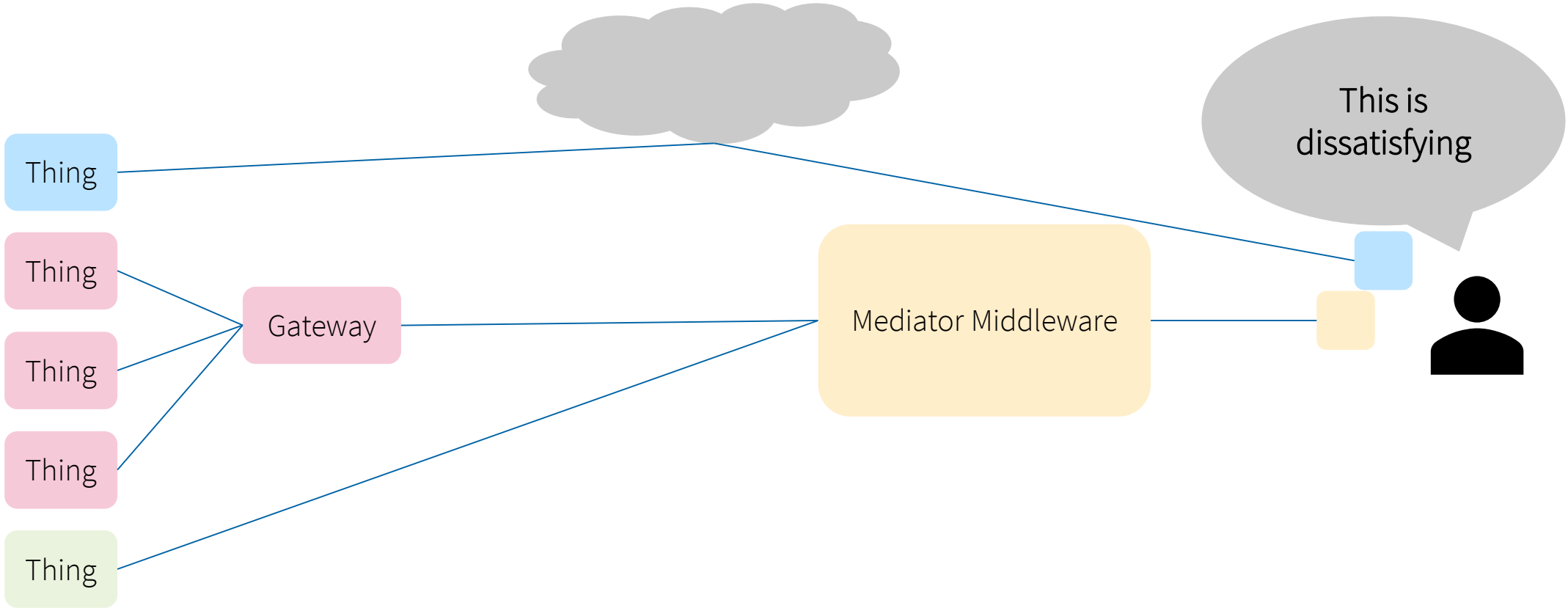
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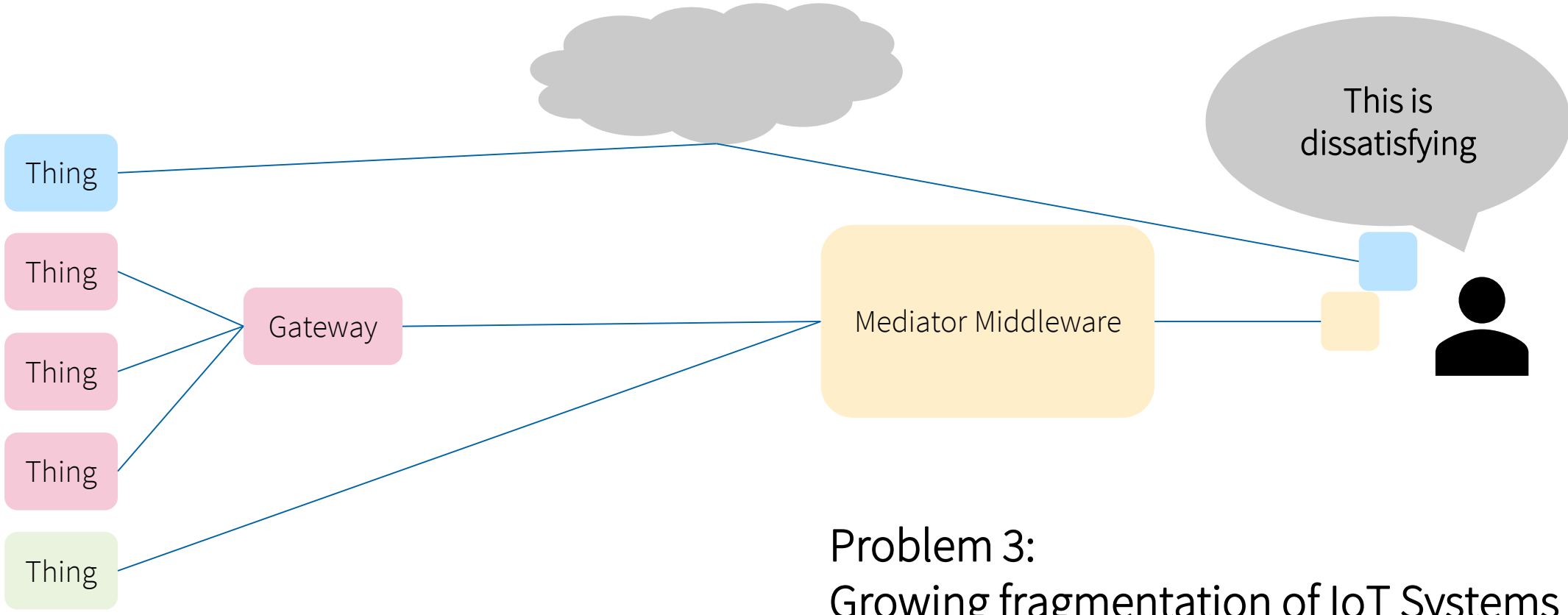
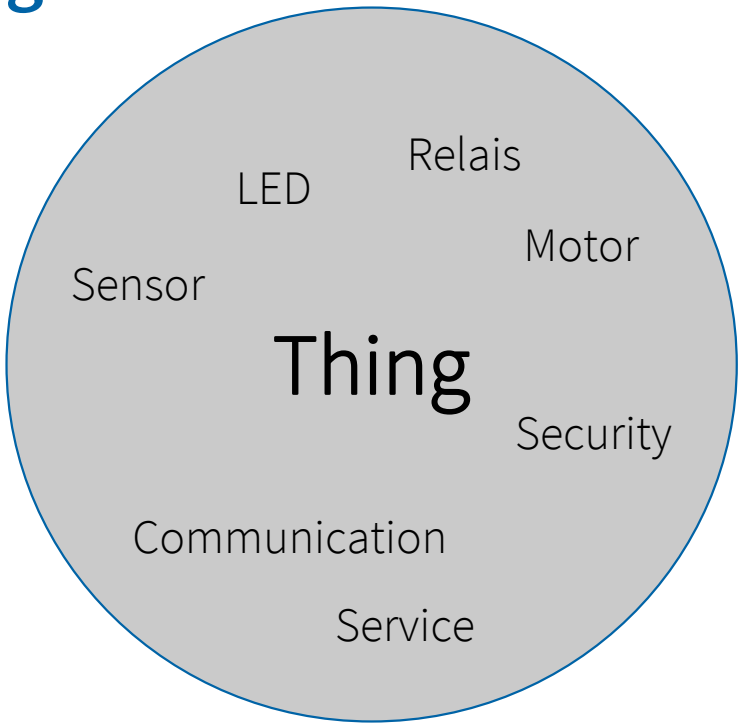
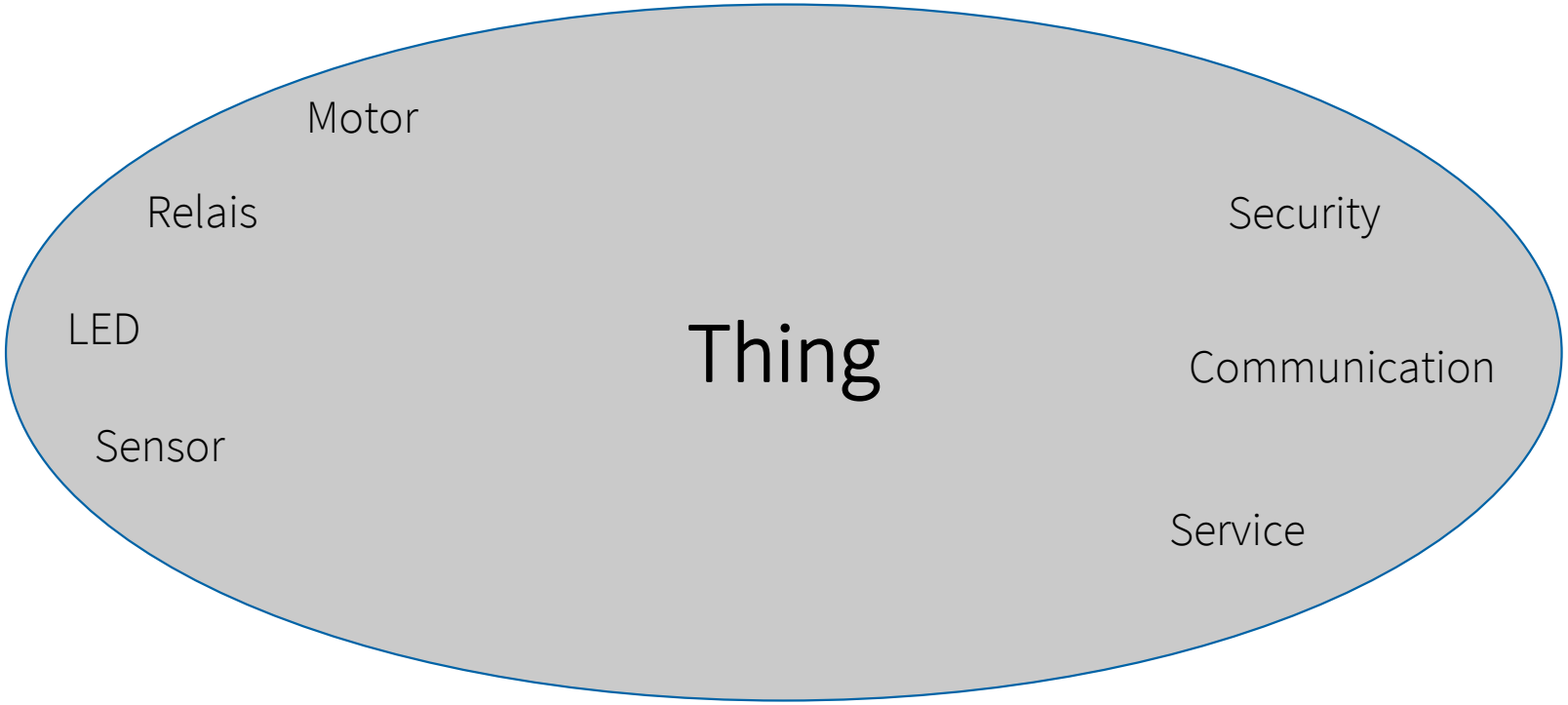


Problem 3:
Growing fragmentation of IoT Systems

The Conventional „Thing“



tight integration


Motor
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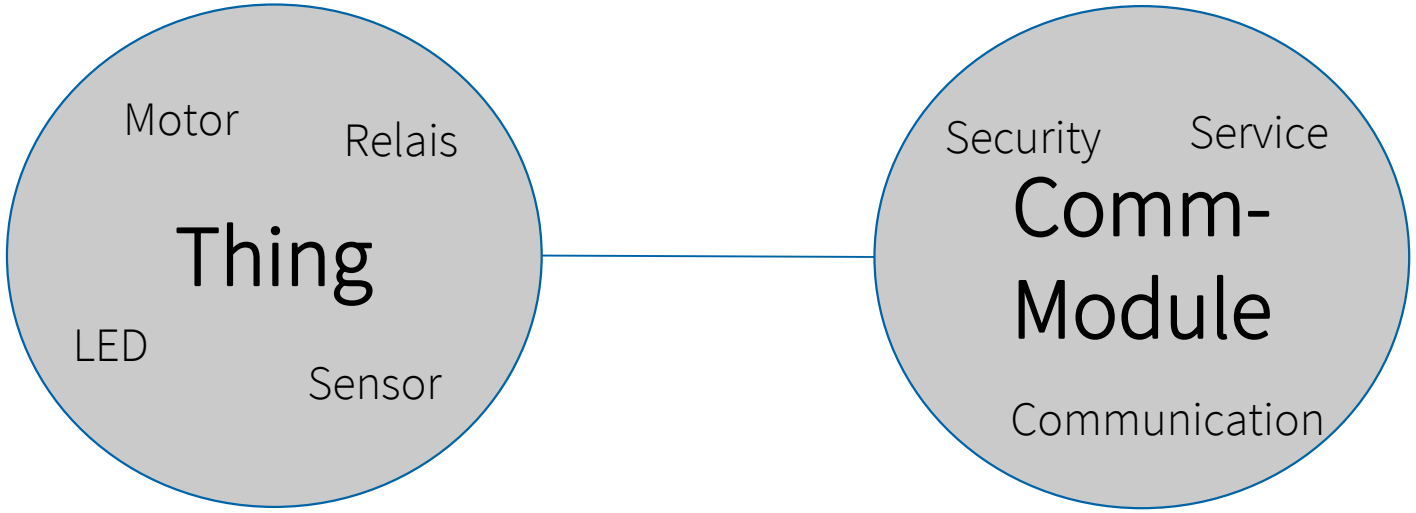
Security
Communication
Service

We Propose:
A Separation of Concerns



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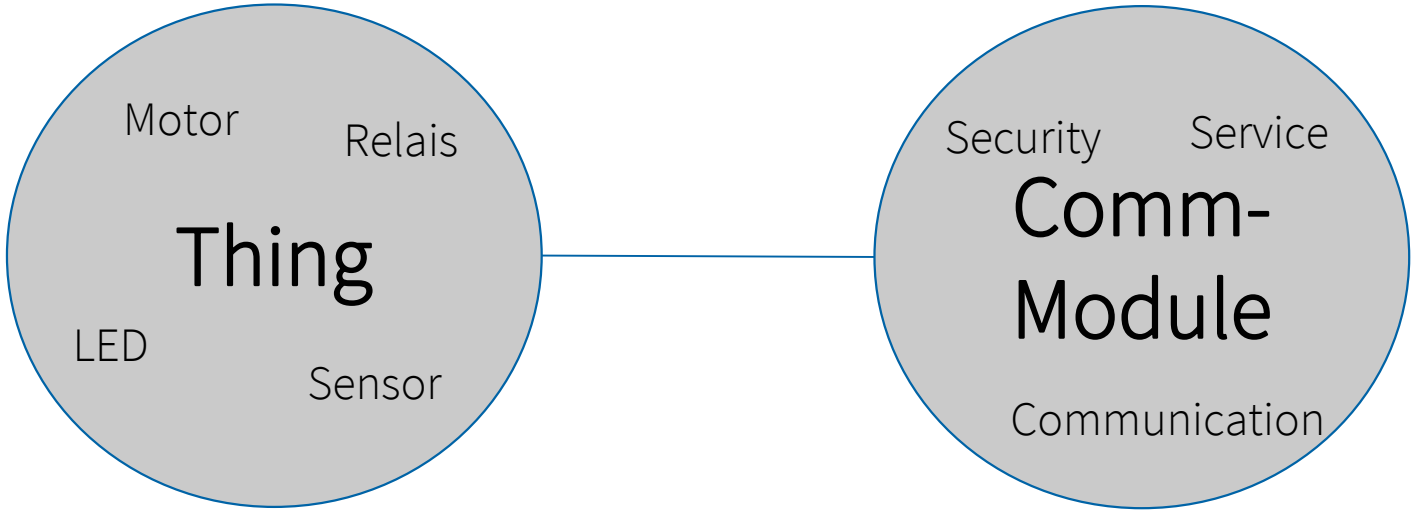

PHYSICAL and DIGITAL

Capabilities

We Propose:
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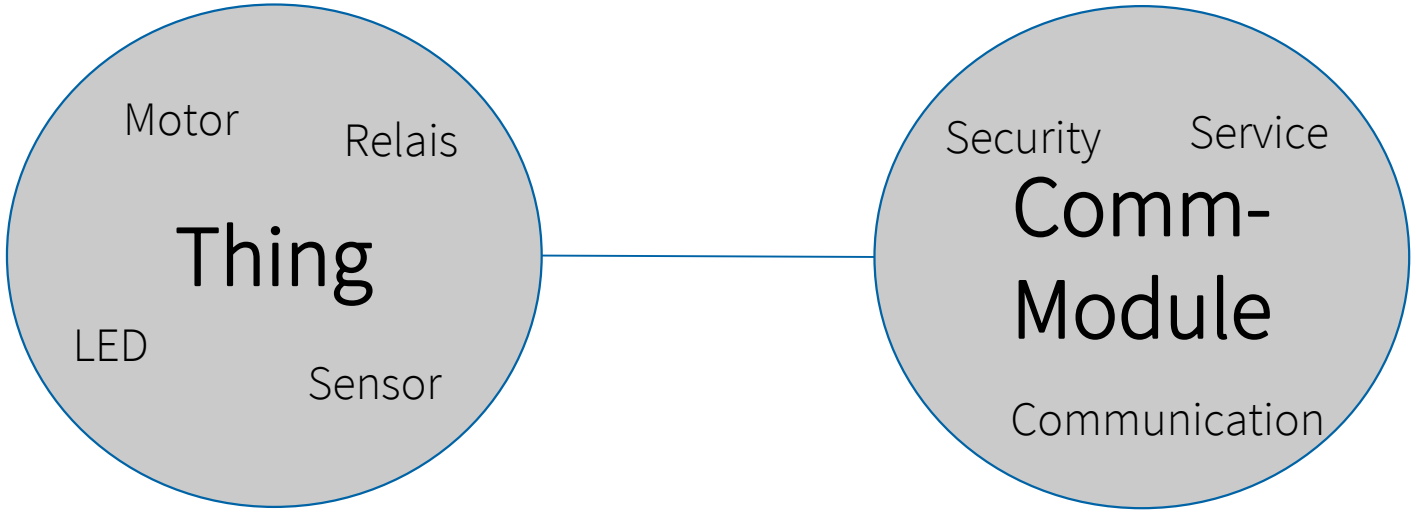

IMMUTABLE and DYNAMIC

Properties

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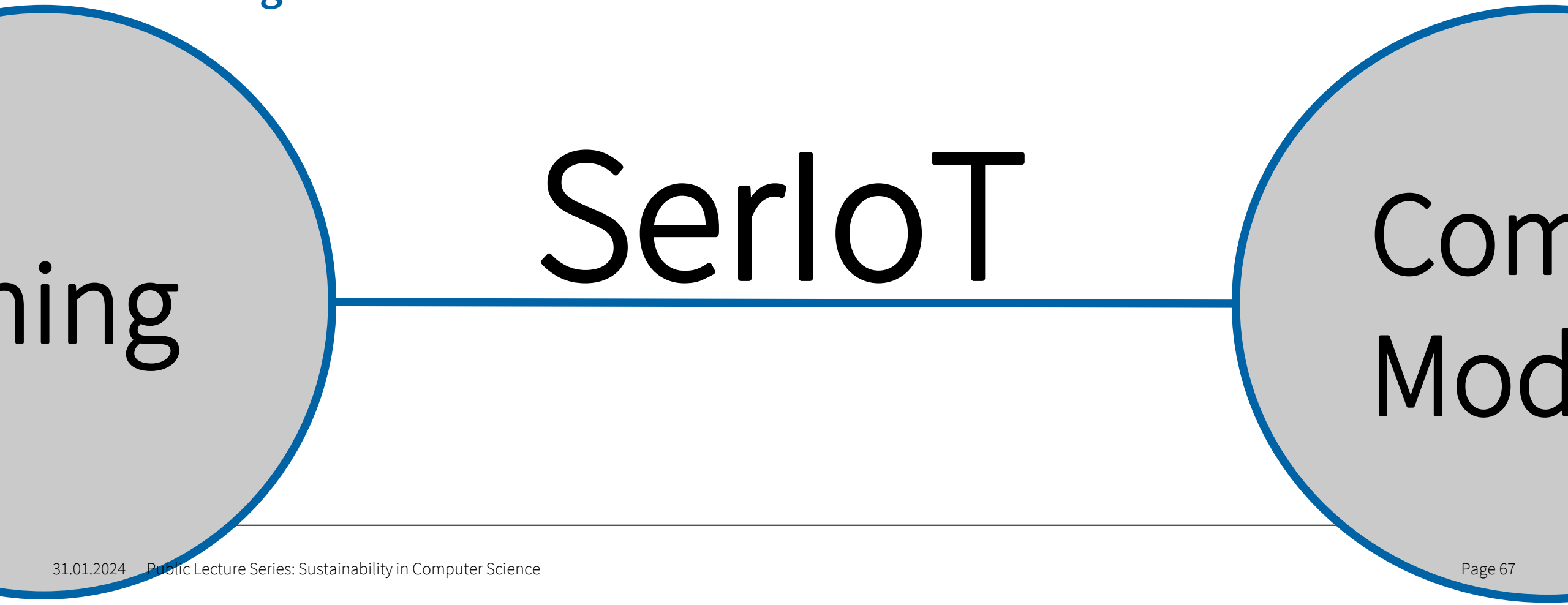
Introducing



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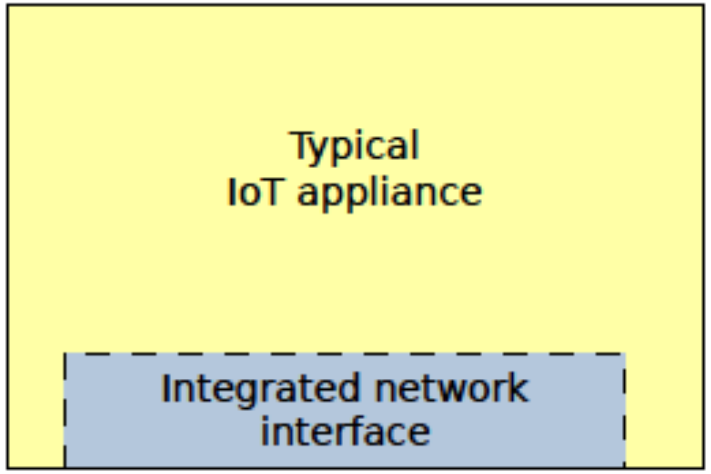
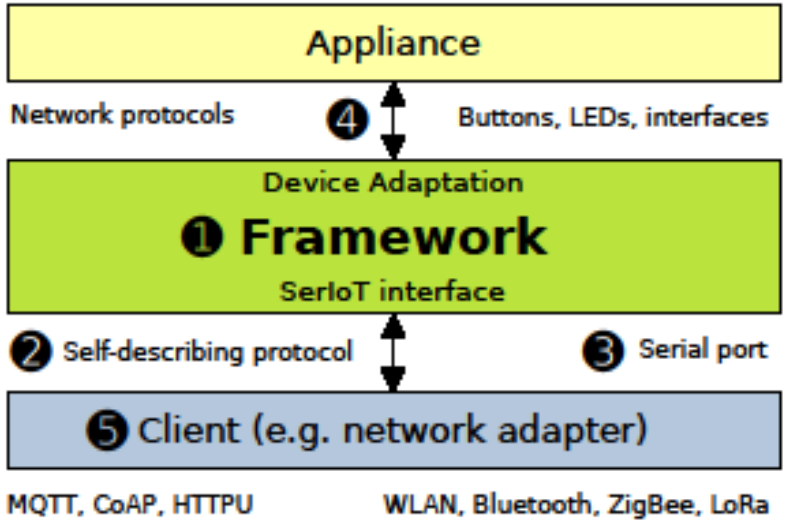
Overview

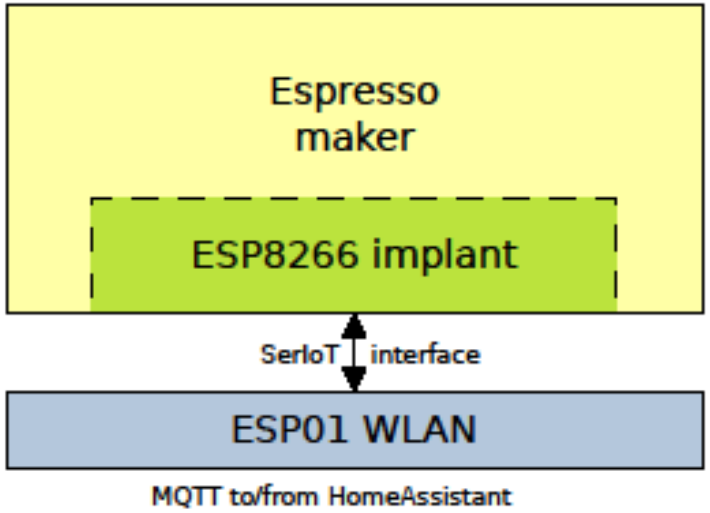
STATE OF THE ART



DESIGN



IMPLEMENTATION



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Physical Protocol

- Simple low-voltage serial port
- Based on Universal Asynchronous Receiver-Transmitter (UART)
- Supported by many microcontrollers and other hardware
- Can be interfaced from PC with simple adapter
- Connector would need to be standardized in the future

- → High compatibility and readily available hardware

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Logical Protocol

- ASCII-based
- Human readable
- JSON
- „start“-command to request device description
- Around 128 bytes per interaction affordance

- → Anything needed to operate the interface is provided by the interface itself
- → Client devices can always be developed anew


```
{
  "id": 1,
  "name": "Espresso Maker",
  "model": "Caffe Cortina",
  "manufacturer": "DeLonghi",
  "description": "Automatic Espresso maker with steam wand",
  "properties": [
    {
      "title": "eco_state",
      "description": "The Machine is in Eco State",
      "type": "bool"
    },
    {
      "title": "attention_state",
      "description": "There is a problem, check the Machine",
      "type": "bool"
    }, ...
  ],
  "actions": [
    {
      "title": "turn_on",
      "description": "Turn on the Espresso Maker"
    },
    {
      "title": "single_espresso",
      "description": "Make a single Espresso"
    },  ...
  ]
}
```

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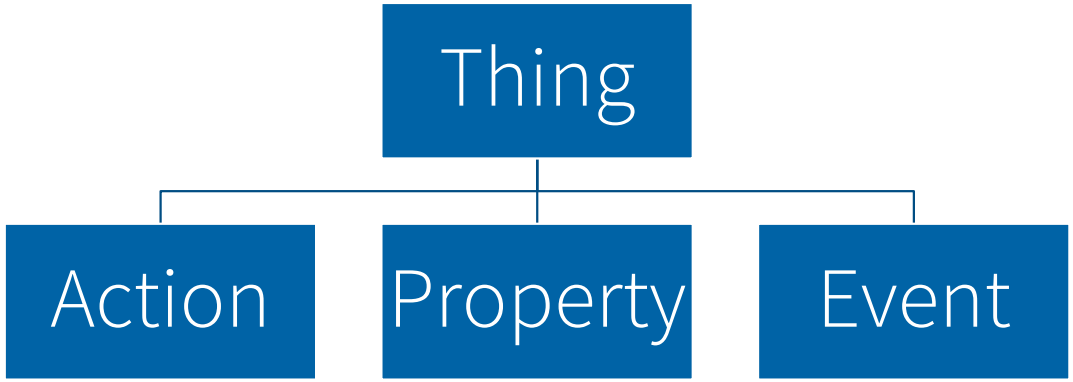
Data Model

- Based on the **Web of Things**‘ Things Description
  - Actions
  - Properties
  - Events



→Simple and comprehensible

→ Potential for Integration with WoT Technologies

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Device Adaptation Layer

- SerIoT needs Device Adaptation Layer (DAL) code to access actual device functions
- Callable functions are required for the interaction affordances within the DAL
- Mapped to the framework and SerIoT with glue code

→ The DAL-Code is interchangeable and any Arduino-compatible retrofitting project can be integrated with SerIoT

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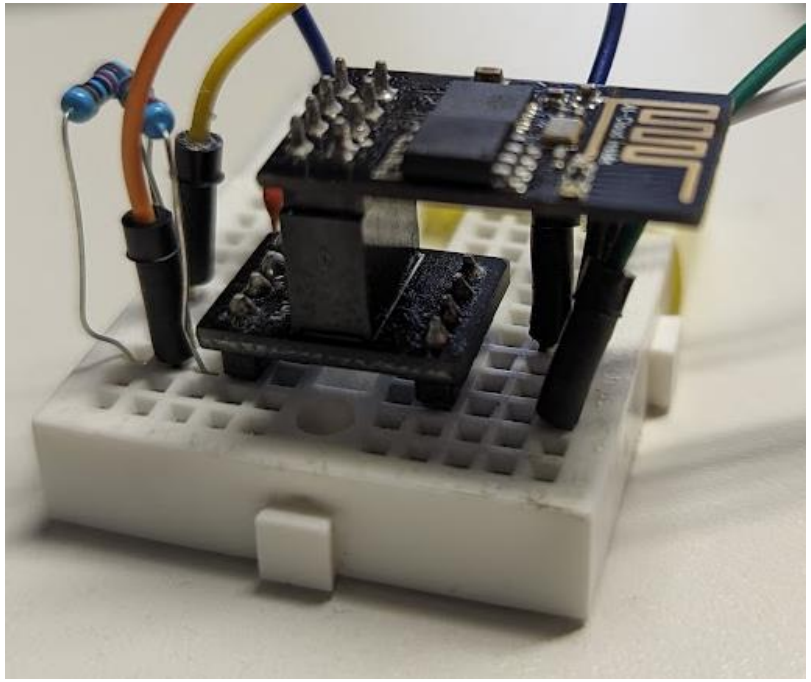
Client

- Connects to the SerIoT interface
- Can be anything
  - Alternative physical user interface (e.g. for Accessibility)
  - Use any communication standard (e.g. LoRa, ZigBee, Ethernet)
- Needs to map SerIoT device description to own communication-oriented data model



→ Consumers can select service providers and communication technologies

→ Manufacturer bankruptcy scenario sidestepped

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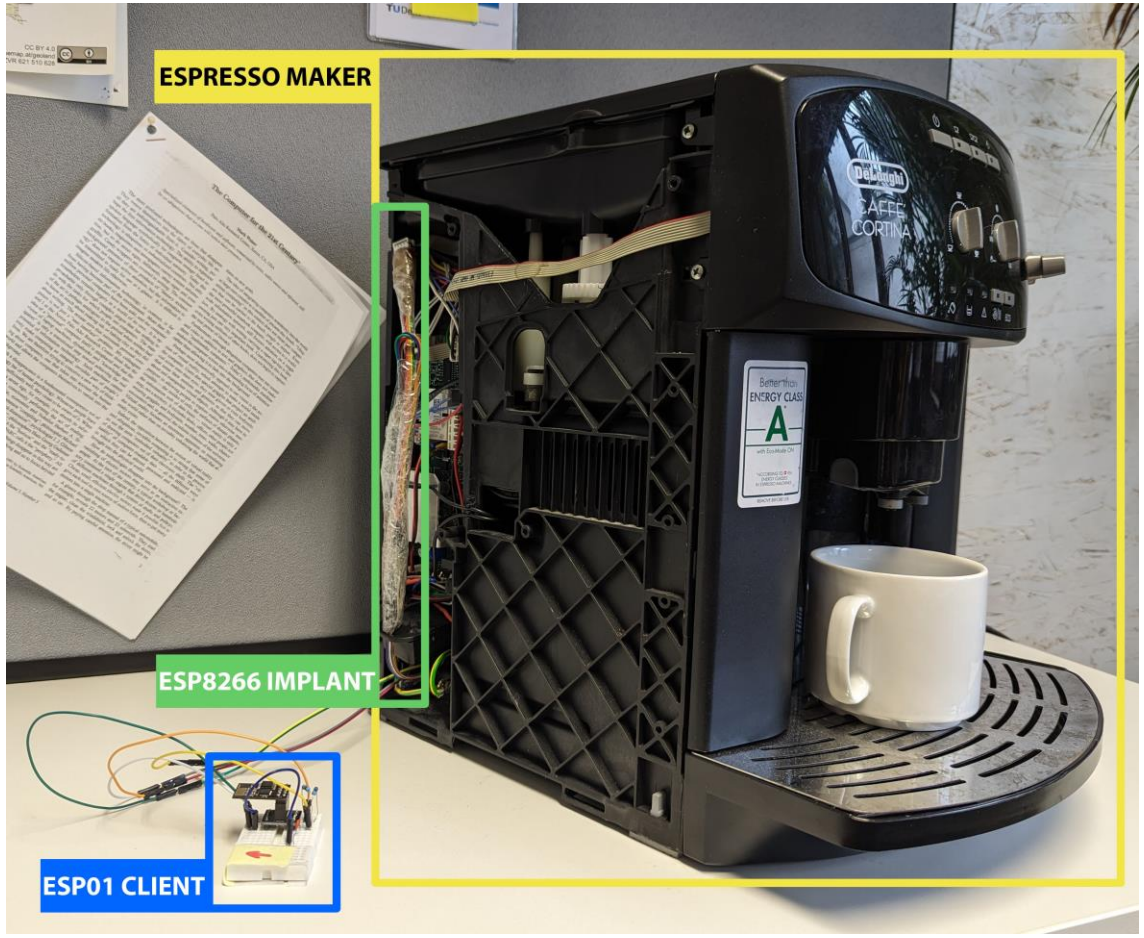
Implementation: The Big Picture

- Implant for espresso maker
  - Framework in Arduino C++
  - Glue code
  - Pre-existing device specific DAL code
- Client device with WiFi
  - Configurable via WiFi hotspot
  - MQTT as transport protocol
  - Supports Home Assistant MQTT autodiscovery
  - Generic: would work on any SerIoT interface



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Evaluation

- Proof of concept

→ Successful establishment of communication between Home Assistant and DAL

Part	SLOCs	RAM	Flash
Model only	222	-	-
Model + SerIoT	261	28.1KB	265KB
Glue code	15	-	-
DAL	408	28.0KB	260KB
Full implementation	**684**	**29.5KB**	**280KB**
Original retrofit	343	29.2KB	302KB

Table 1: Source code, memory, and storage consumption of our Framework, compared to original retrofit

- Evaluation of resource consumption on microcontroller
  - RAM
  - Flash

→ Minimum overhead compared to DAL only

→ Negative overhead compared to original DAL with webserver on Microcontroller

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Takeaways:

- SerIoT provides Upgradeability by Default
  - Human readability & self description
  - Basic protocols
  - Basic data model
  - Accessible interface
- SerIoT is retrofit-friendly
  - Framework is open source
  - Framework is designed to incorporate foreign code
- SerIoT enables competition for IoT services
  - Open local interface allows for developing new adapters and services

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Going Forward?

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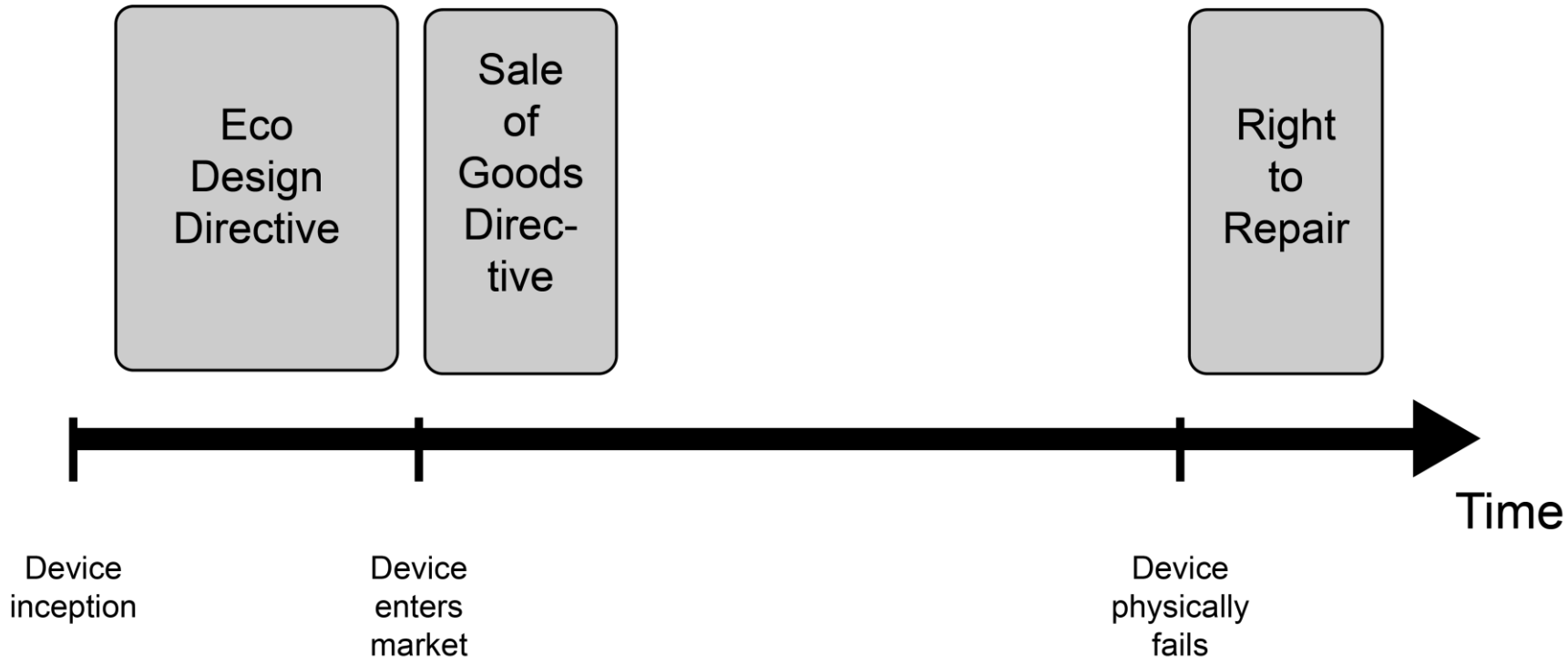
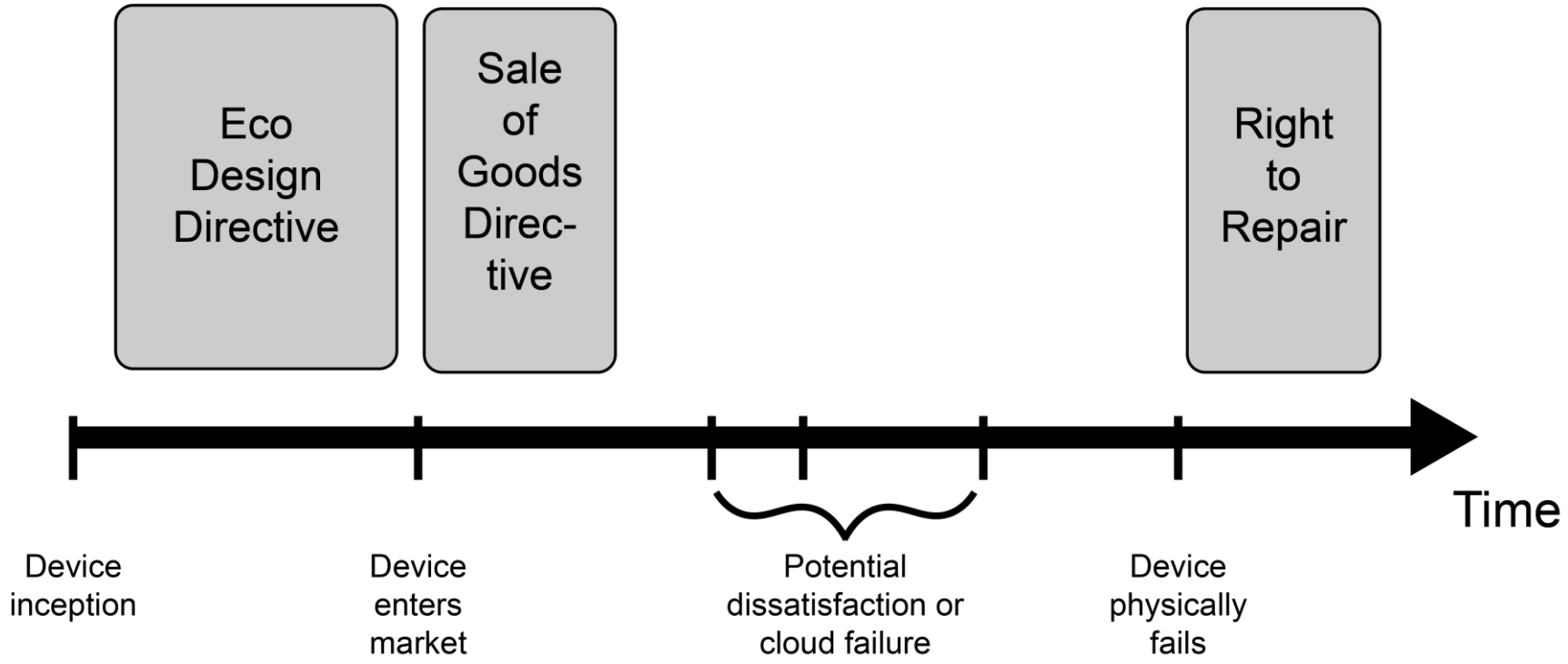
1. UN SDG 12: Responsible Production and Consumption
2. Product Obsolescence and the legal Framework in the EU
3. Domain Specific Challenges of IoT Retrofitting
4. SerIoT: An Interface for Upgradeability-by-Default
5. Towards a Right to Improve

Remember The Legal Framework in the EU?



The Legal Framework in the EU misses the IoT



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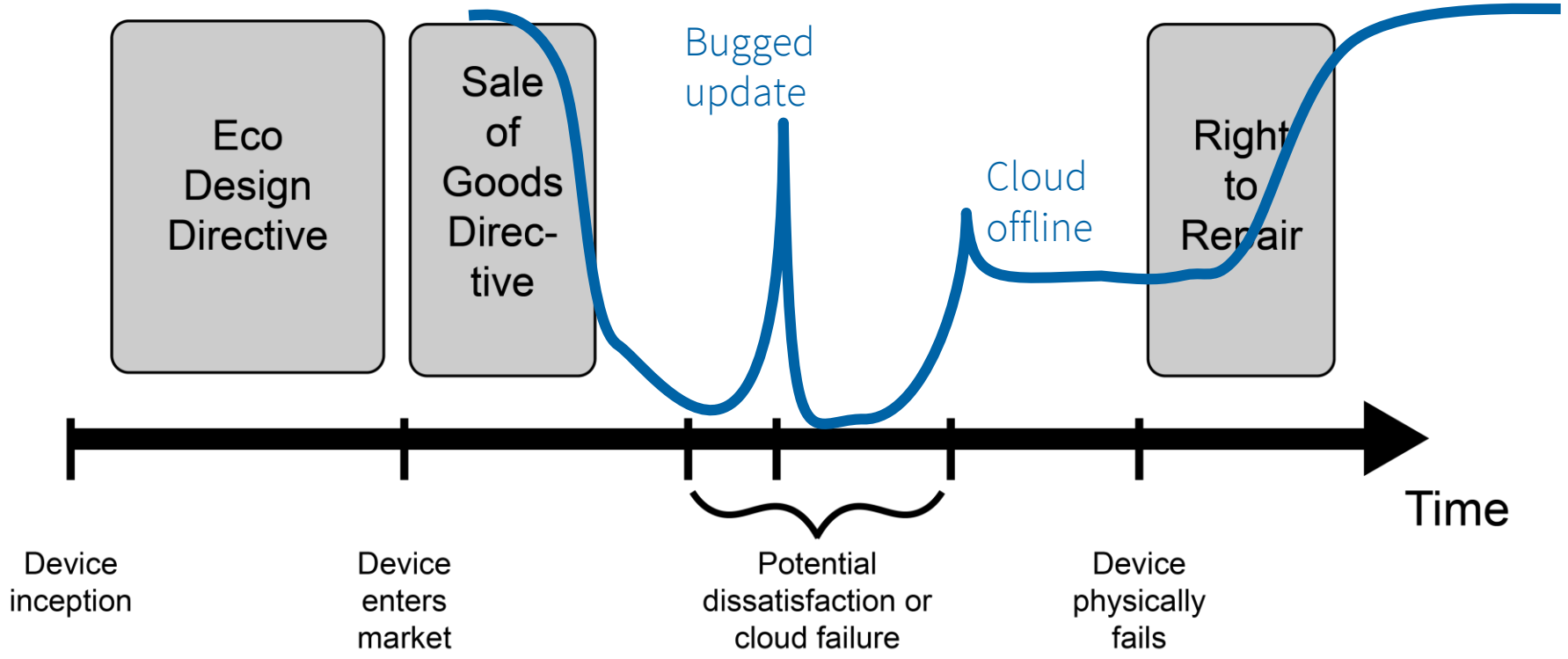
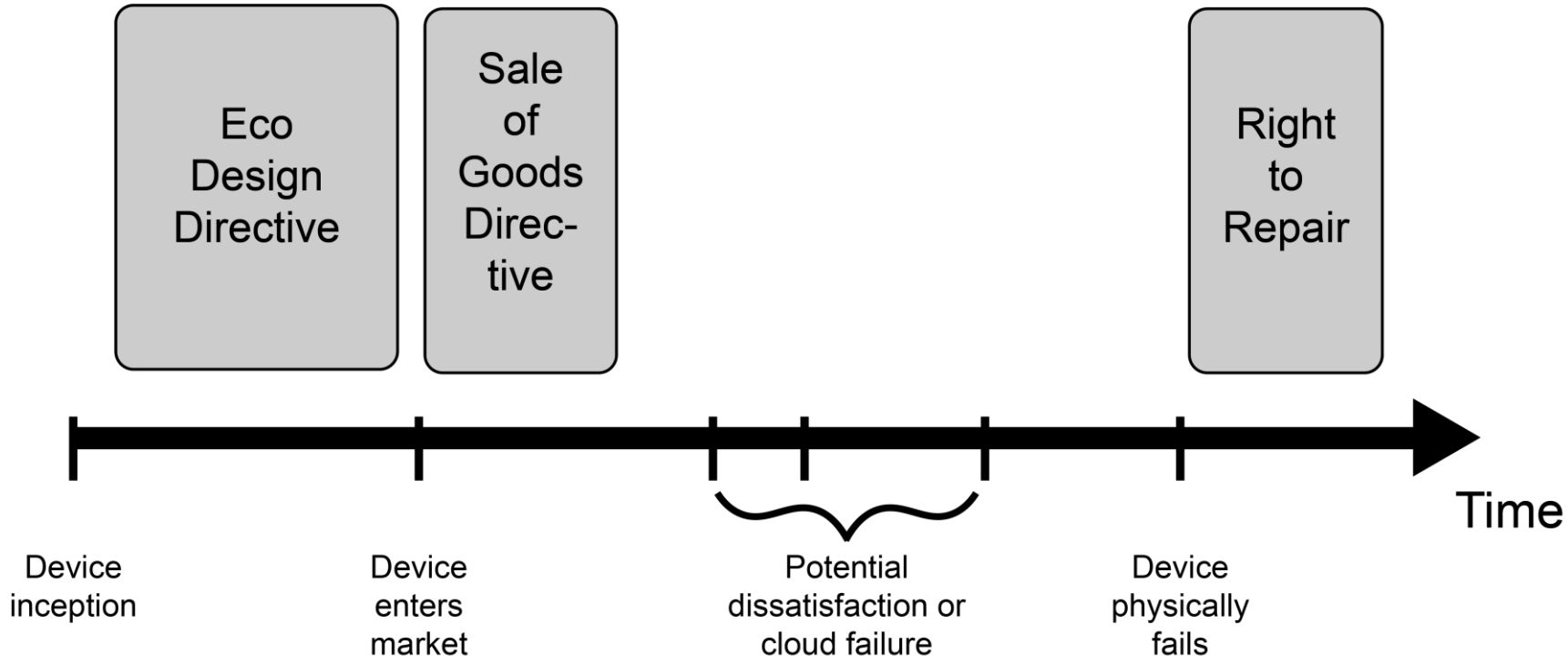
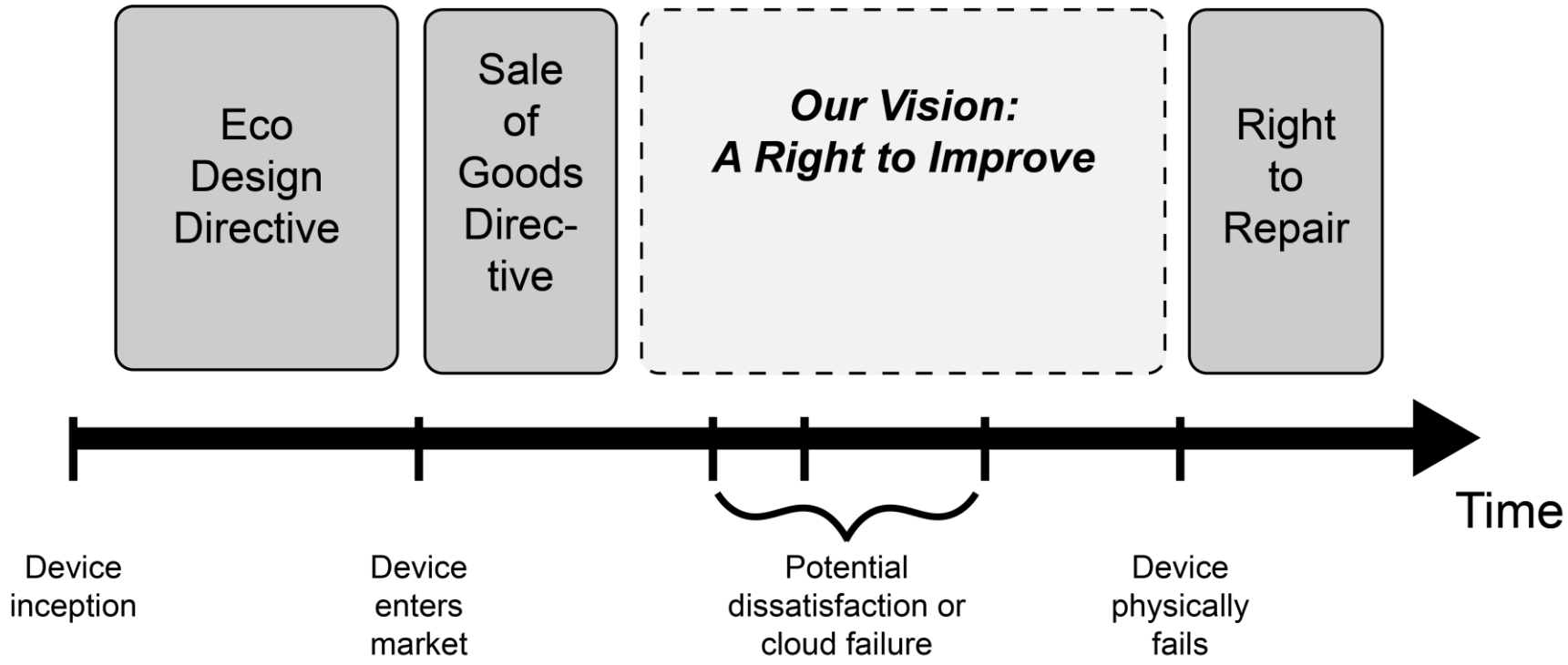


The Legal Framework in the EU misses the IoT



A Right to Improve



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Towards a Right to Improve

- Systematic review of academic literature
- Screened over 400 Sources in
  - ACM-DL
  - IEEEXplore
- Analyzed over 80 Sources in-depth
  - For arguments supporting a Right to Improve

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Evidence supporting a Right to Improve

- Techical feasibility
  - Case studies & SerIoT above
  - (Industrial) IoT retrofitting in literature

- User desires in literature
  - Desire of users to „compose“ smart home devices
  - Failure of current smart home systems to support specific use cases

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How could a Right to Improve look like?

Manufacturer Obligation

- Analogous to the Ecodesign Directive
- Mandate of Interface
- Interface specifications
- See also: USB-C charging interface for mobile phones

Consumer Right

- Analogous to the Right to Repair
- Consumer entitlement to accessible interface
- More freedom in design
- Abstraction leaves Scope open

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Conclusion! Today, you‘ve heard about:

- The SDG #12 and some aspects of how the EU hopes to further it
  - But we can act beyond that!
- Product obsolescence and the „Bathtub curve“
  - No „Thing“ lasts forever
- Retrofitting IoT capabilities to household appliances
  - Adding features is already possible, but challenging
- SerIoT, an interface for retrofitting and upgradeability for IoT devices
  - An alternative technological path
- Our vision for a Right to Improve
  - A Vision, founded in a systematic review of academic literature*

*and to appear in Frontiers in the Internet of Things (currently under review)

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Special Thanks to:

- Albert Rafetseder
- Raphael Ornetsmüller
- Harry Fesenmayr

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The SerIoT Framework is available as Open Source Software on Github →

https://github.com/harryf98/Device-Framework

Thank you for your attention!

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Discussion