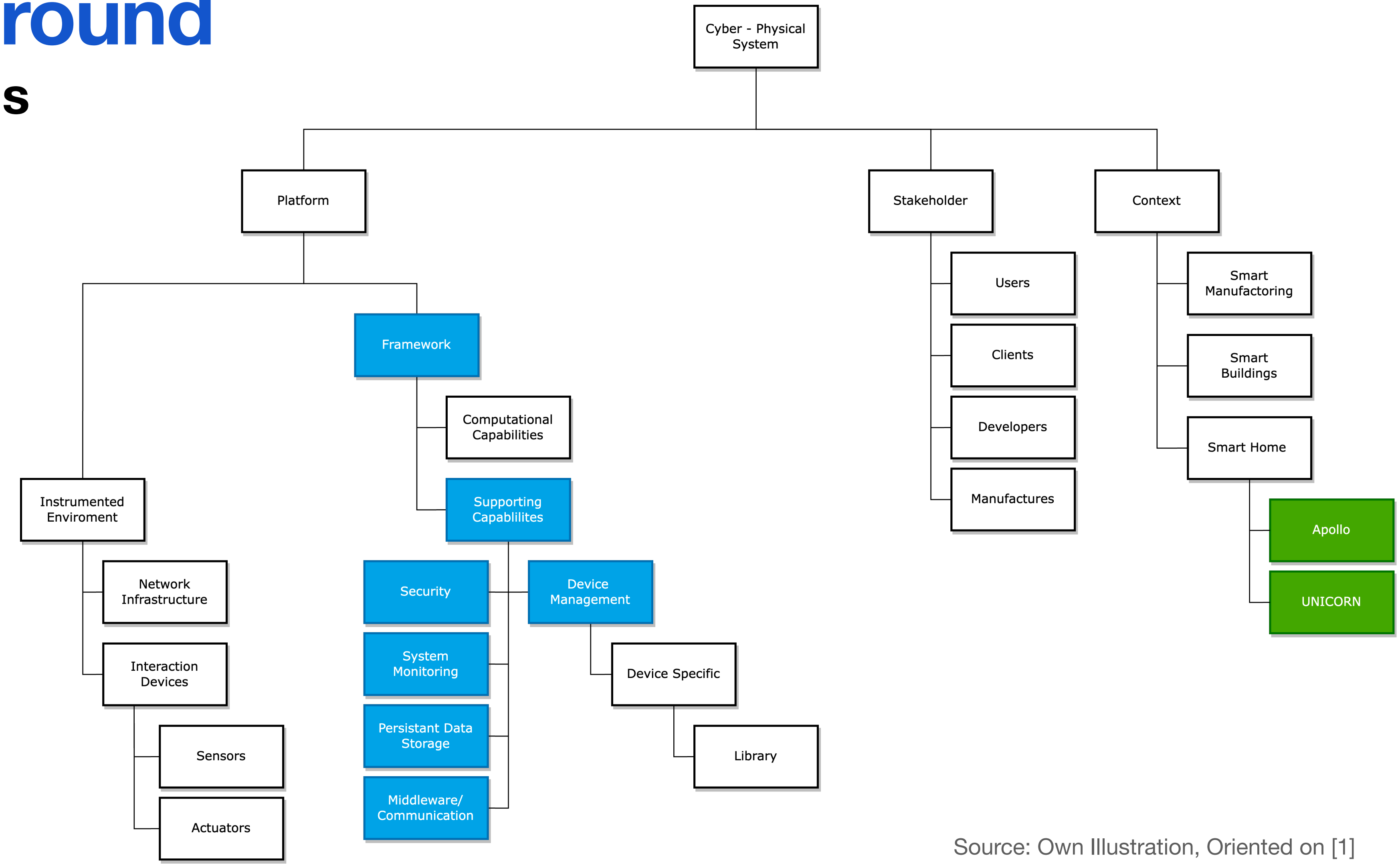
Bachelor Thesis

Framework for Performant, Modular and Reliable Smart Home Applications

Pascal Weißleder
Advisor: Prof. Dr. Bernd Brügge
Chair of Computer Systems
https://dse.in.tum.de/

15.11.2023 - 15.05.2024

Background
Definitions



Source: Own Illustration, Oriented on [1]

Background

Definitions

Cyber Physical Systems

Cyber Physical Systems (CPS) are integrated networks of computational and physical processes, facilitated by embedded systems, and communication technology. These systems are distinguished by their scalability, robustness, and capabilities for interaction with the physical environment and human operators [2, 3, 4].

Smart Devices

A device or object is smart if it is able to observe or manipulate its environment and is interconnected[1].

Smart Home

One of the application areas of Cyber-Physical Systems is the Smart Home. A Smart Home is defined as a residence equipped with interconnected smart devices and software or services designed to control, monitor, and manage these devices. These SH applications or services often allow users to automate tasks and remotely control the devices. Smart homes aim to enhance convenience, security, and energy efficiency for the inhabitants [5, 6, 7].

Background

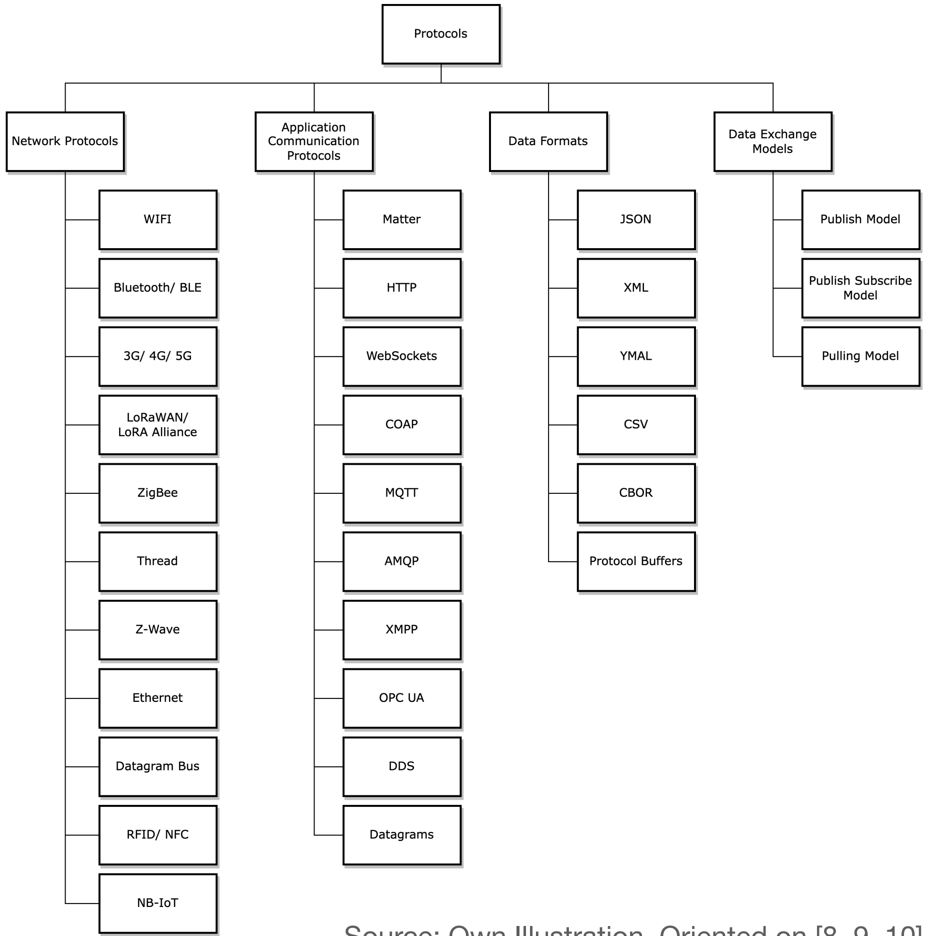
Protocols and Standards

MQTT [11]

- Message Queuing Telemetry Transport (MQTT)
- Lightweight, Publish-Subscribe Network Protocol

Matter [12]

- Open, based on the Application layer
- Supports Multiple Network Protocols
- IPv6 as Communication Protocol



Source: Own Illustration, Oriented on [8, 9, 10]

Motivation

Personal Motivation

- Work On Smart Home (SH) Applications
  - iPraktikum WS22/23
  - Work at Weptun GmBH

Experienced:

- Complexity of the Cyber Physical Systems (CPS) and Smart Home Domain
- Could Not Find Fitting Frameworks or Platforms
- Underutilized Potential for Use-Cases

Research

- Research Solution are Limited in Scope [8,10,13-15]
- Solutions for other Application Domains Exist[16]

Industry

- Platform Solutions for other IoT/ CPS Domains[17]
- Domestic-oriented Consumer Products and Open-Source Projects [18, 19]

Problem Statement

Problems

- Heterogeneous Environment [20, 21]
  - Device Manufacturers & Device Types
  - Standards & Protocols
- High Requirements for Quality Attributes [20, 21]
- High Development Efforts [22]
  - Quality Attributes & Integration Efforts of the Developed Application
  - Increased Cost

➡ Limit Adoption [23]

Goals & Objectives

Goals

- Provide Adaptability for Wide Ranging Use-Cases
- Reduce Development Efforts
- Increase Reliability and Performance

Objectives

1. Gain an Overview over IoT, CPS, Smart Home Domains
2. Identify Requirements posted to a Smart Home Application/ Framework
3. Design and Integrate a Smart Home Framework
4. Evaluate the Framework through Prototyping

Requirements

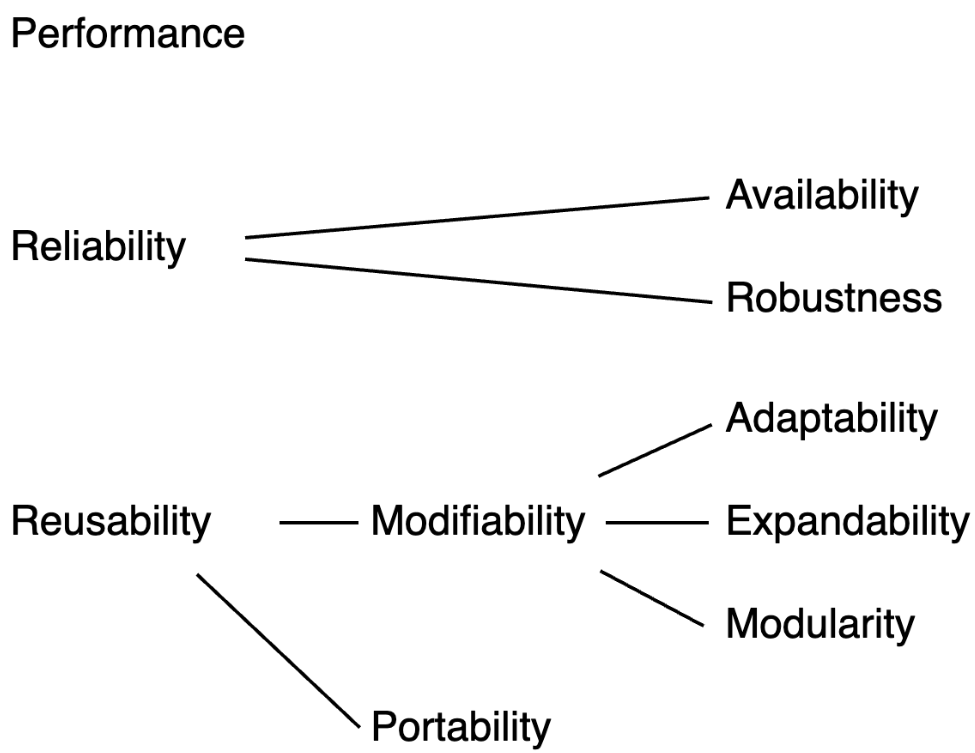
Functional Requirements

- Set of Functional Requirements to Ensure Typical Functionality of Smart Home Applications

Non-Functional Requirements

- Focus on NFR
- Framework Provides Underlying Capabilities

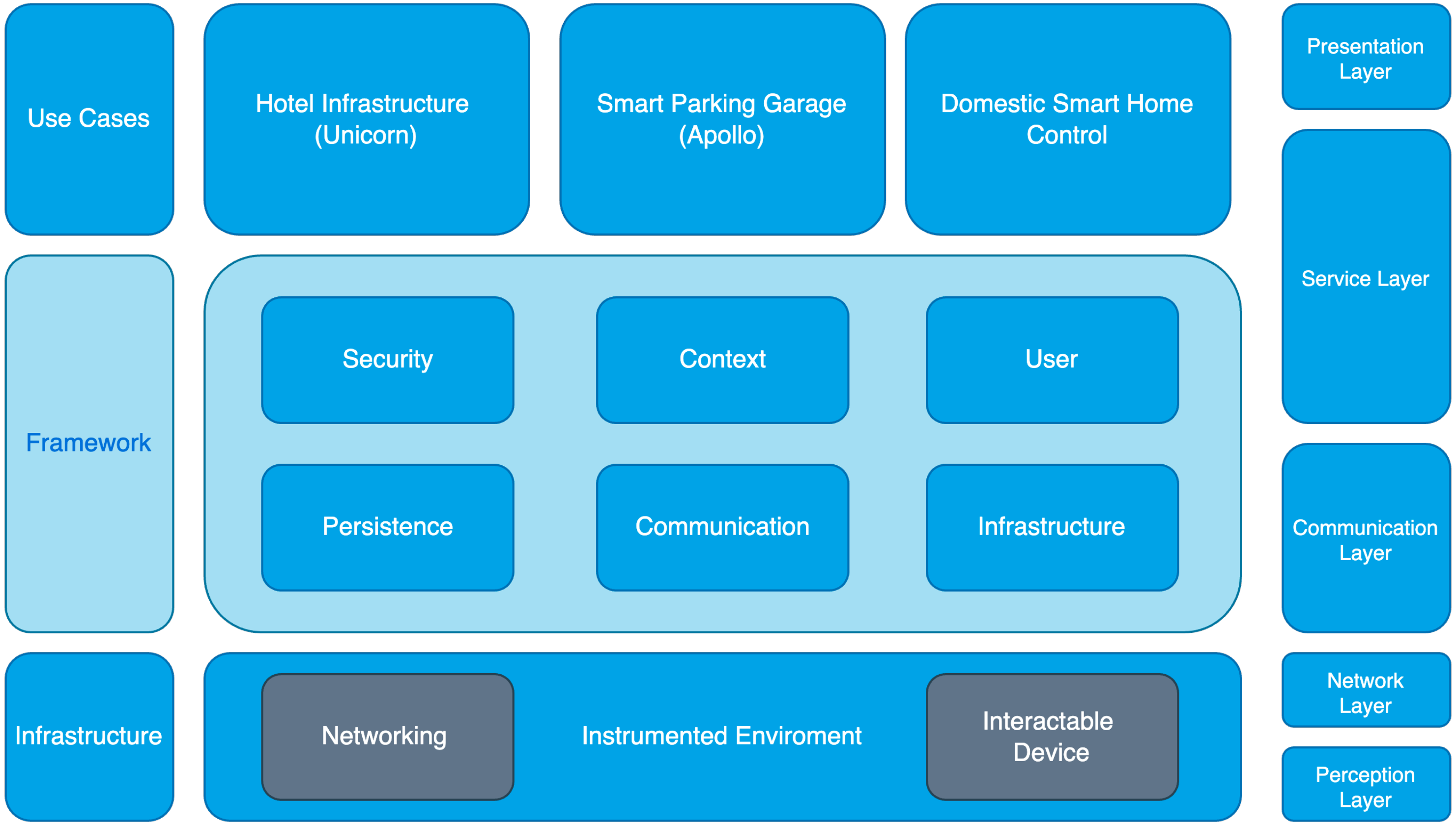
Identified NFR



Source: Own Illustration, Oriented on [23-27]

System Design

Framework

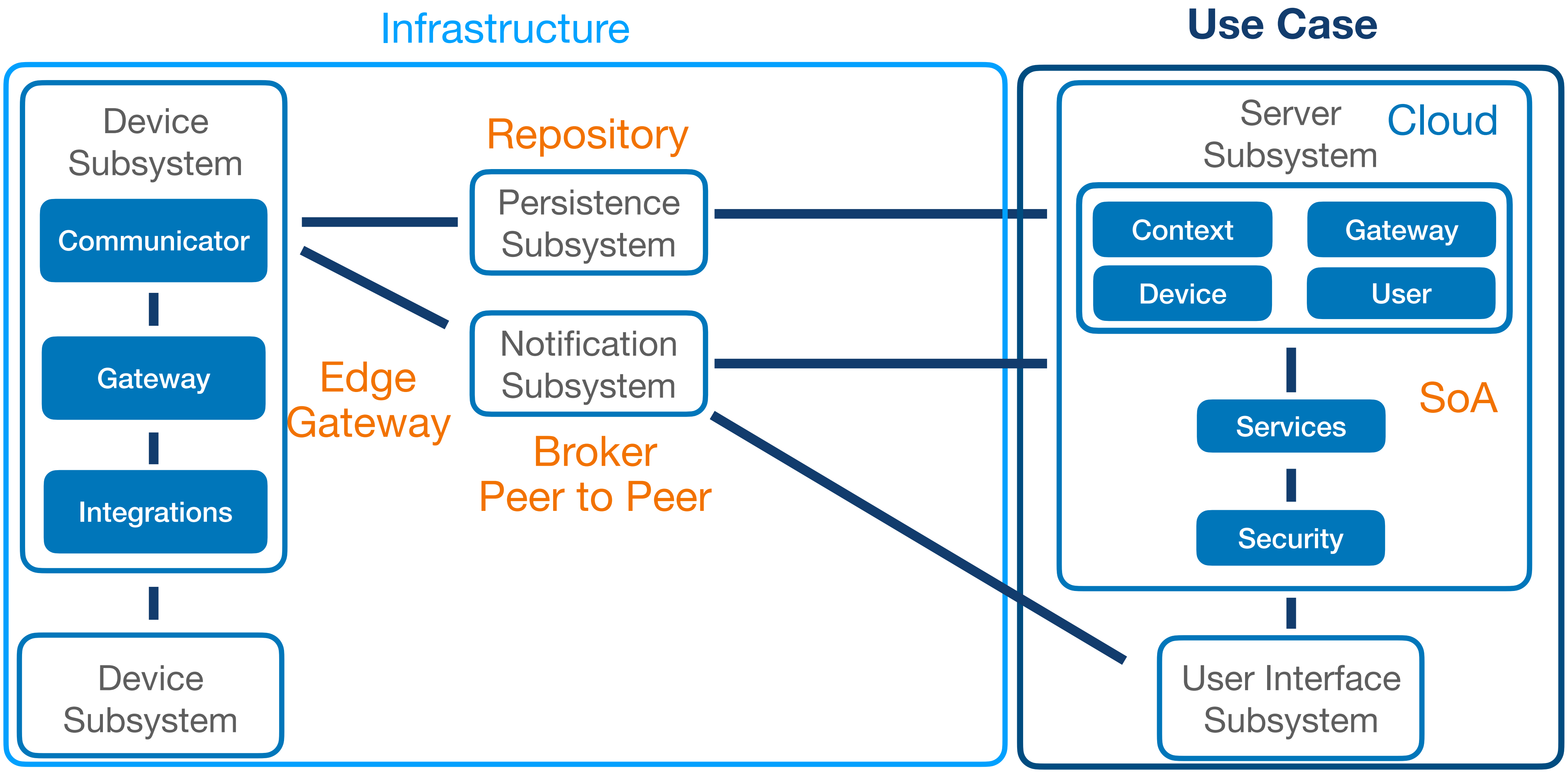


Source: Own Illustration

System Design

Architectural Styles

SoA: Service Oriented Architecture

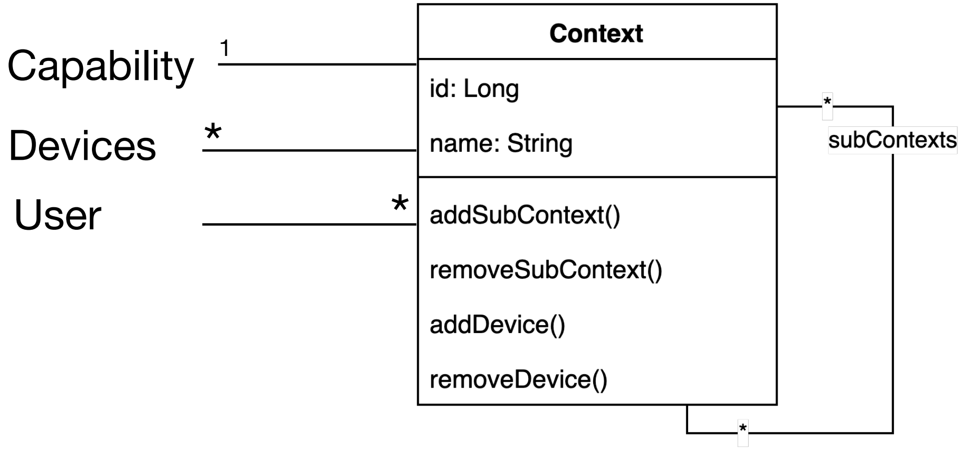


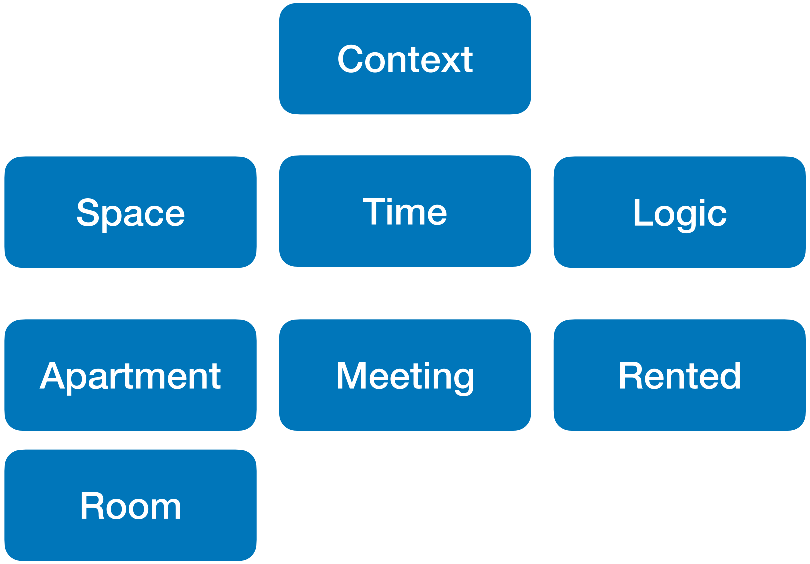
System Design

Object Model

Context

- Represent a Context-Specific Object
- Enable Diverse Set of Use-cases
- Nested Hierarchical Structure
- Acts as Capability for Access Control





System Design

Object Model

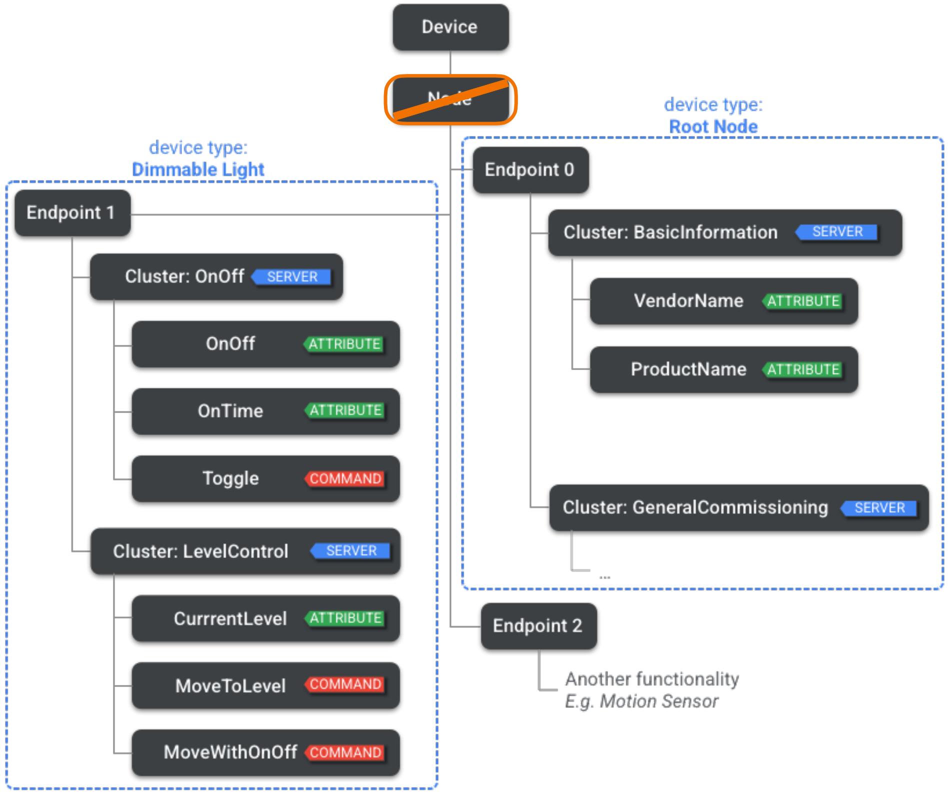
NodeID

Integration Identifier - Persistent Identifier

SHELLY-3CE90EC81142

Device Description

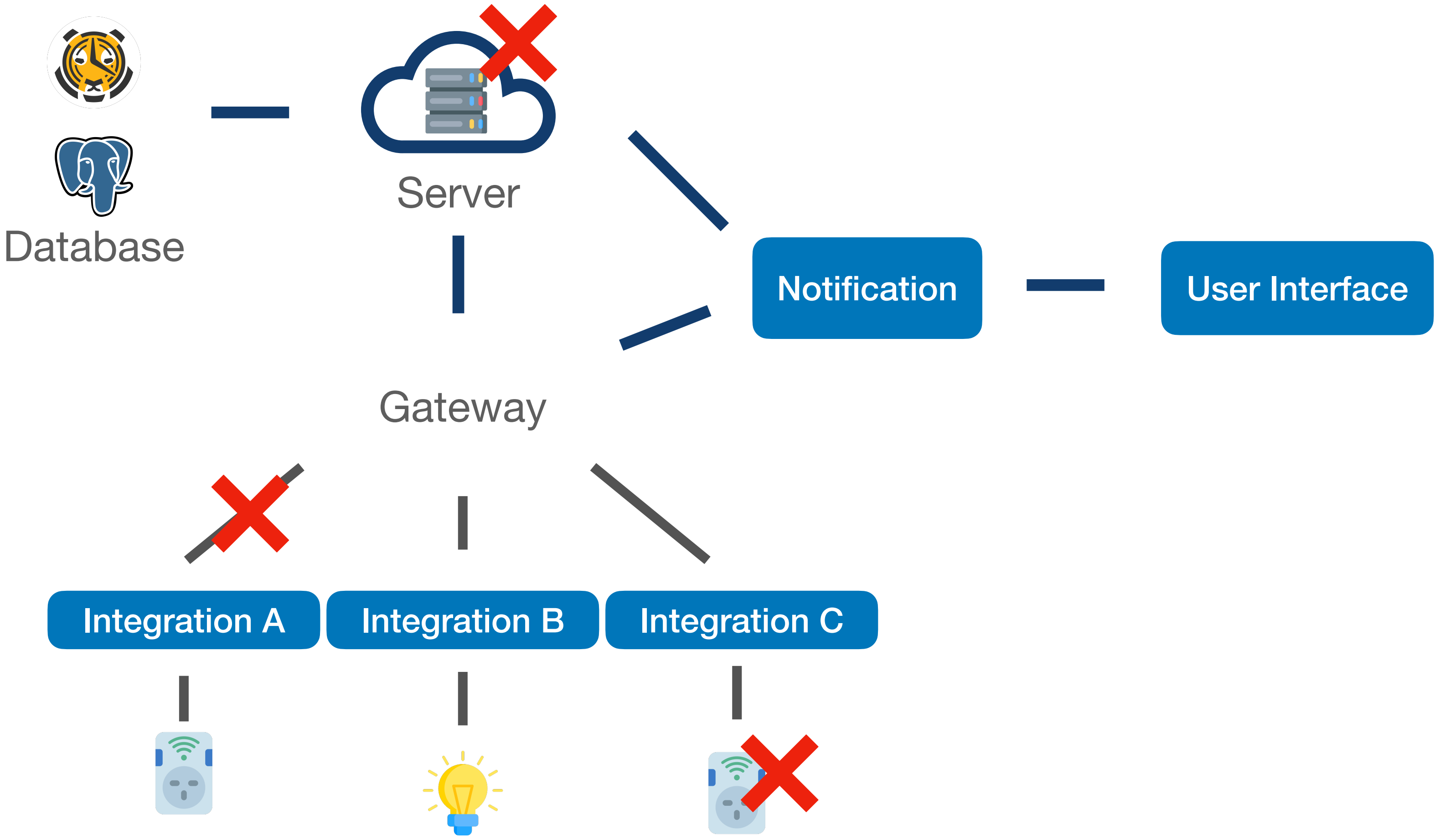
- Oriented on Matter Payload
  - Upcoming Industry Smart Home Standard
  - Extensible and Modular



Source: https://developers.home.google.com/matter/primer/device-data-model

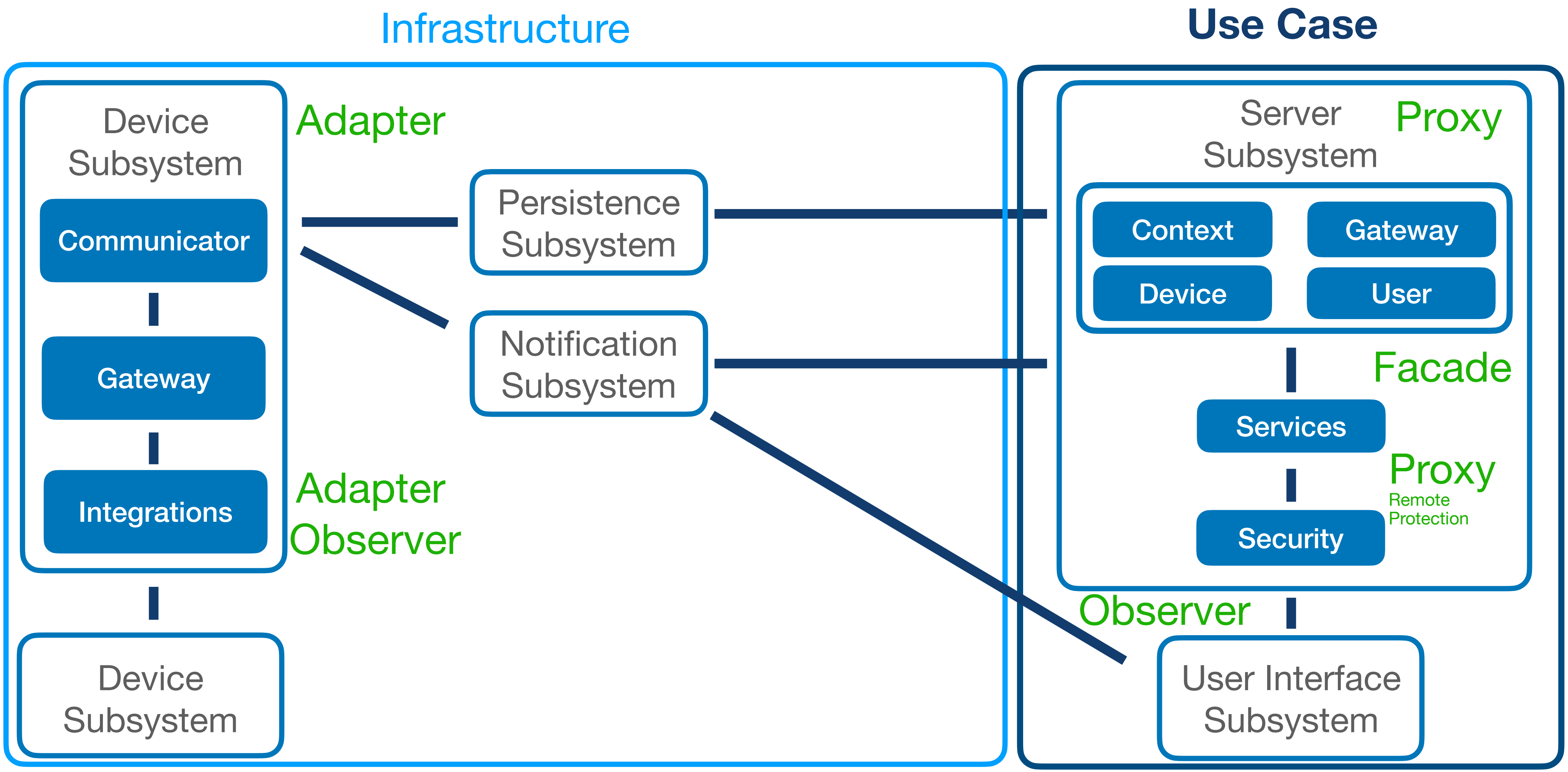
System Design

Boundary Conditions



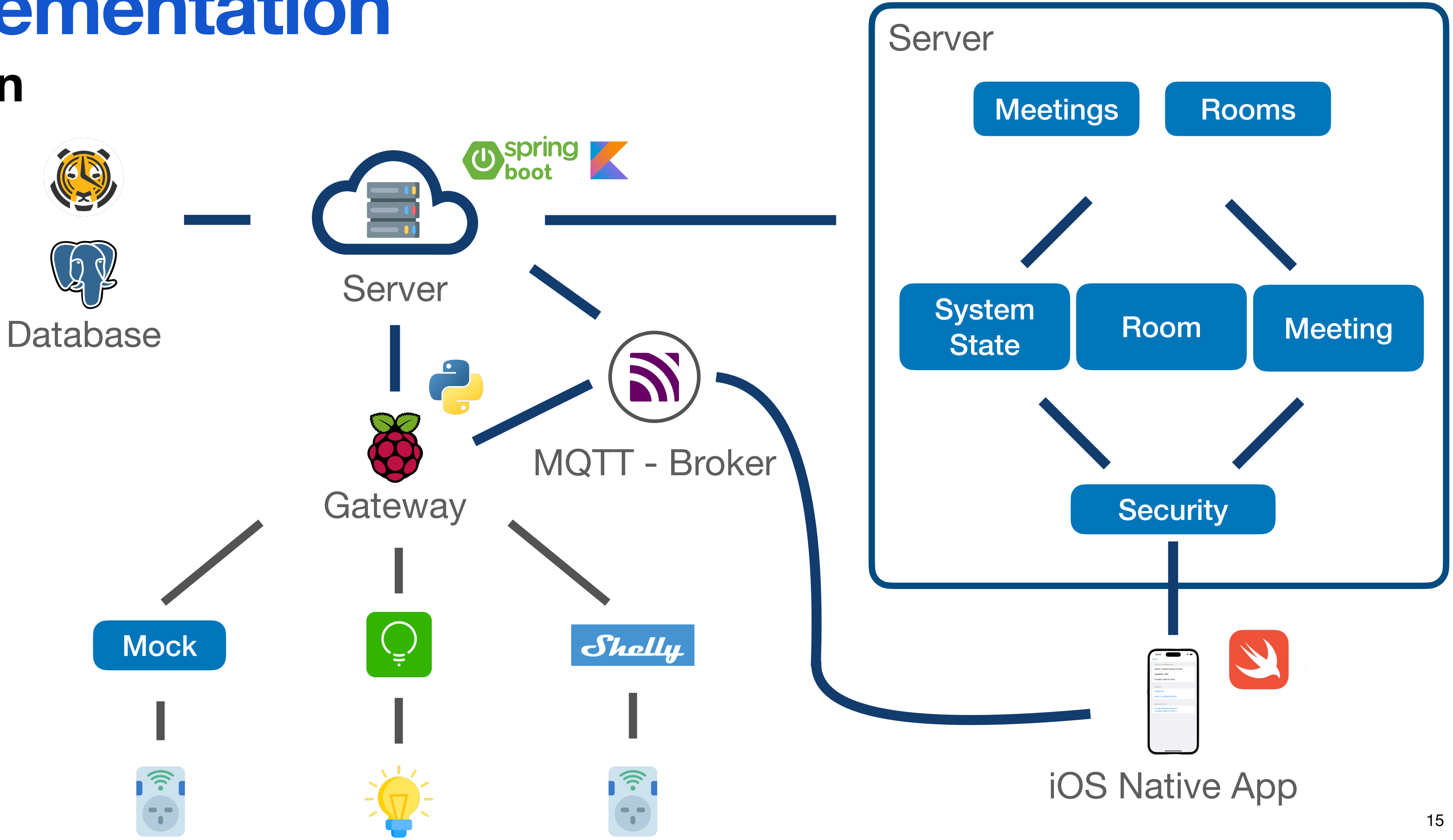
Software Patterns

System Design



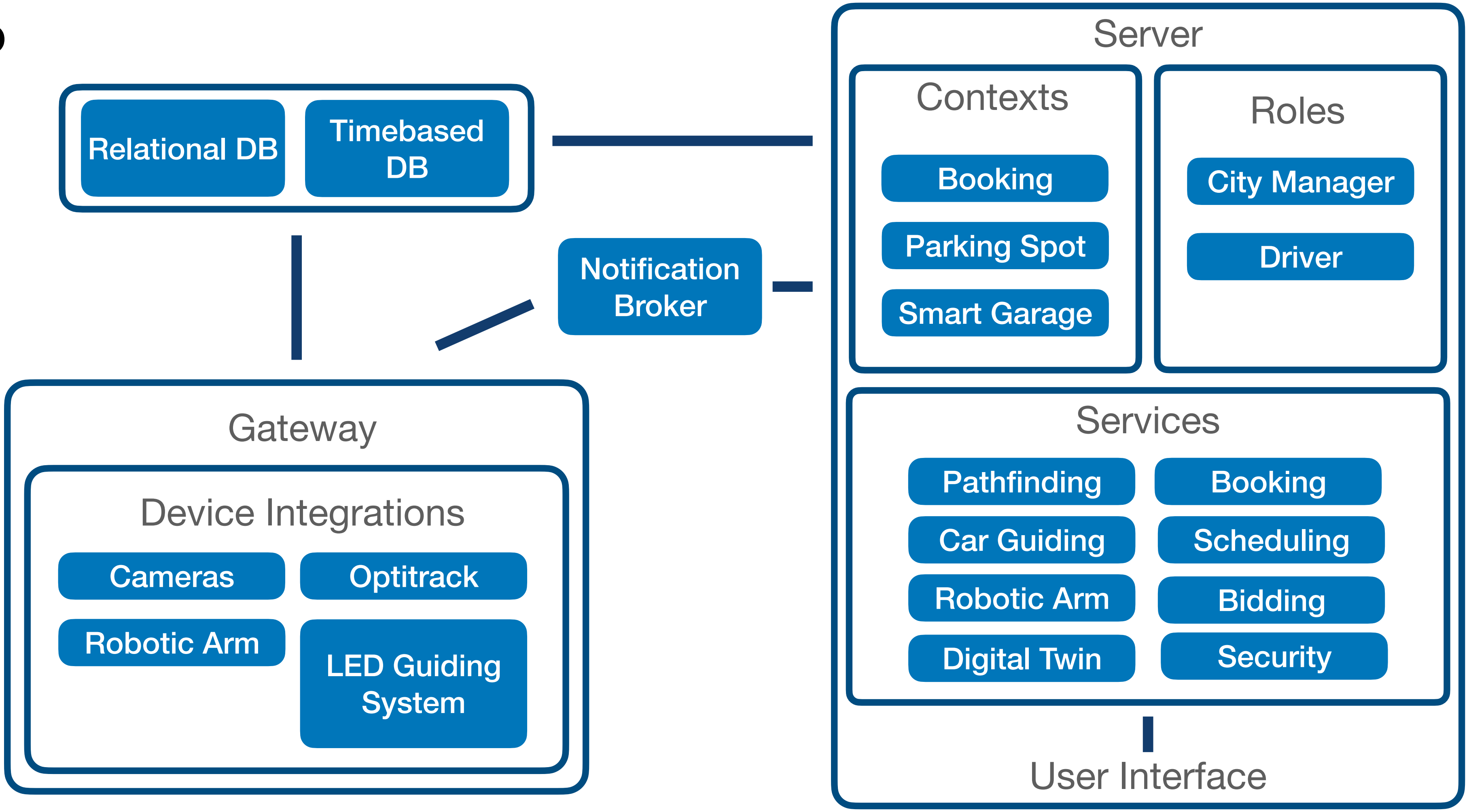
Implementation

Unicorn



Implementation

Apollo



Evaluation

Performance

- ✓ Command Invocation < 1 Sec
- ✗ State change representation time: ~ 5 Sec

Reliability

- ✓ Mean Gateway downtime: Around 10 Sec
- ✓ Mean Device downtime: Around 5 Sec

Reusability

- ✓ Portability
- ✓ Modifiability
  - ✓ Adaptability
  - ✓ Expandability
  - ✓ Modularity

✓ **Reduce Development Efforts**

Summary

- Provided Overview over CPS and SH Domain
- Identified Requirements Posted on a Smart Home Framework
- Designed and Implemented a Smart Home Framework

Showed with Design Research that

- Development Efforts indicate to be Reduce by Utilization of the Developed Framework
- The Developed Framework is Reusable
- Reliability is Provided for Most Common Failure Points

Future Work

Additional Features

- Group Functionality
- Enhanced Security Features
  - Encryption
  - Continuous Authorization on Notification Service

Scalability& Performance Improvements

- Improve the State Update Handling at the Gateway
- Load Balancer for Server Subsystem and Services

Reusability Improvements

- Dynamic Service and Device Integration at runtime

Citations

1. Constantin Scheuermann. "A Metamodel for Cyber-Physical Systems". en. PhD thesis. Technische Universität München, 2017, p. 163. url: https://mediatum.ub.tum.de/ 1366744
2. Kaiyu Wan, Ka Lok Man, and Danny Hughes. "Specification, Analyzing Challenges and Approaches for Cyber-Physical Systems (CPS)". In: 2010. url: https://api. semanticscholar.org/CorpusID:758875
3. Yang Liu, Yu Peng, Bailing Wang, Sirui Yao, and Zihe Liu. "Review on cyber-physical systems". In: *IEEE/CAA Journal of Automatica Sinica* 4.1 (2017), pp. 27–40. doi: 10.1109/ JAS.2017.7510349
4. Edward A. Lee. Computing Foundations and Practice for Cyber-Physical Systems: A Pre- liminary Report. Tech. rep. UCB/EECS-2007-72. May 2007. url: http://www2.eecs. berkeley.edu/Pubs/TechRpts/2007/EECS-2007-72.html.
5. Sumathi Balakrishnan, Hemalata Vasudavan, and Raja Kumar Murugesan. "Smart Home Technologies: A Preliminary Review". In: Proceedings of the 6th International Conference on Information Technology: IoT and Smart City. ICIT '18. Hong Kong, Hong Kong: Association for Computing Machinery, 2018, pp. 120–127. isbn: 9781450366298. doi: 10.1145/3301551.3301575.
6. Andres Bejarano, Alejandra Fernández, Miguel Jimeno, Augusto Salazar, and Pedro Wightman. "Towards the Evolution of Smart Home Environments: A Survey". In: International Journal of Automation and Smart Technology 6 (Sept. 2016), pp. 105–136. doi: 10.5875/ausmt.v6i3.1039
7. A. Chakraborty et al. "Smart Home System: A Comprehensive Review". In: Journal of Electrical & Computer Engineering (2023), pp. 1–30. doi: 10.1155/2023/7616683. url: https://research.ebsco.com/linkprocessor/plink?id=ca283a8f-c368-325d- aad1-c16e3dca5ee5.
8. Marco Lombardi, Francesco Pascale, and Domenico Santaniello. "Internet of Things: A General Overview between Architectures, Protocols and Applications". In: *Information* 12.2 (2021). issn: 2078-2489. doi: 10.3390/info12020087. url: https://www.mdpi. com/2078-2489/12/2/87.
9. Tomás Domínguez-Bolaño, Omar Campos, Valentín Barral, Carlos J. Escudero, and José A. García-Naya. "An overview of IoT architectures, technologies, and existing open-source projects". In: *Internet of Things* 20 (2022), p. 100626. issn: 2542-6605. doi: https://doi.org/10.1016/j.iot.2022.100626. url: https://www.sciencedirect. com/science/article/pii/S254266052200107X
10. Olutosin Taiwo, Lubna A. Gabralla, and Absalom E. Ezugwu. "Smart Home Automa- tion: Taxonomy, Composition, Challenges and Future Direction". In: *Computational Science and Its Applications – ICCSA 2020*. Ed. by Osvaldo Gervasi, Beniamino Murgante, Sanjay Misra, Chiara Garau, Ivan Blecˇic´, David Taniar, Bernady O. Apduhan, Ana Maria A. C. Rocha, Eufemia Tarantino, Carmelo Maria Torre, and Yeliz Karaca. Cham: Springer International Publishing, 2020, pp. 878–894. isbn: 978-3-030-58817-5.
11. Priyanka Thota and Yoohwan Kim. "Implementation and Comparison of M2M Proto- cols for Internet of Things". In: 2016 4th Intl Conf on Applied Computing and Information Technology/3rd Intl Conf on Computational Science/Intelligence and Applied Informatics/1st Intl Conf on Big Data, Cloud Computing, Data Science & Engineering (ACIT-CSII-BCD). 2016, pp. 43–48. doi: 10.1109/ACIT-CSII-BCD.2016.021
12. https://csa-iot.org/all-solutions/matter/
13. Muddasser Alam, Alper T. Alan, Alex Rogers, and Sarvapali D. Ramchurn. "Towards a Smart Home Framework". In: Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings. BuildSys '13. Roma, Italy: Association for Computing Machinery, 2013, pp. 1–2. isbn: 9781450324311. doi: 10.1145/2528282.2528317.
14. Marco Esposito, Alberto Belli, Lorenzo Palma, and Paola Pierleoni. "Design and Implementation of a Framework for Smart Home Automation Based on Cellular IoT, MQTT, and Serverless Functions". In: Sensors 23.9 (2023). issn: 1424-8220. doi: 10.3390/s23094459.
15. Bogdan-Cosmin Chifor, Stefan-Ciprian Arseni, Ioana Matei, and Ion Bica. "Security- Oriented Framework for Internet of Things Smart-Home Applications". In: 2019 22nd International Conference on Control Systems and Computer Science (CSCS). 2019, pp. 146– 153. doi: 10.1109/CSCS.2019.00033.
16. Malihe Asemani, Fatemeh Abdollahei, and Fatemeh Jabbari. "Understanding IoT Platforms : Towards a comprehensive definition and main characteristic description". In: *2019 5th International Conference on Web Research (ICWR)*. 2019, pp. 172–177. doi: 10.1109/ICWR.2019.8765259.
17. https://aws.amazon.com/de/iot/
18. https://www.home-assistant.io/
19. https://www.iobroker.net/#en/intro
20. Andres Bejarano, Alejandra Fernández, Miguel Jimeno, Augusto Salazar, and Pedro Wightman. "Towards the Evolution of Smart Home Environments: A Survey". In: International Journal of Automation and Smart Technology 6 (Sept. 2016), pp. 105–136. doi: 10.5875/ausmt.v6i3.1039.
21. A. Chakraborty et al. "Smart Home System: A Comprehensive Review". In: *Journal of Electrical & Computer Engineering* (2023), pp. 1–30. doi: 10.1155/2023/7616683.
22. Udoh, I.S. and Kotonya, G. (2018), Developing IoT applications: challenges and frameworks. IET Cyber-Physical Systems: Theory & Applications, 3: 65-72. https://doi.org/10.1049/iet-cps.2017.0068
23. Wenda Li, Tan Yigitcanlar, Isil Erol, Aaron Liu. "Motivations, barriers and risks of smart home adoption: From systematic literature review to conceptual framework". In: Energy Research & Social Science 80 (2021), p. 102211. issn: 2214-6296. doi: https://doi.org/10.1016/j.erss.2021.102211
24. Kevin MacG. Adams. *Non-Functional Requirements in Systems Analysis and Design*. ProQuest Ebook Central, accessed 2024-05-08. Springer International Publishing AG, 2015. url: http://ebookcentral.proquest.com/lib/munchentech/detail.action? docID=2096854.
25. Barry W. Boehm, John R. Brown, and Michael Lipow. "Quantitative evaluation of soft- ware quality". In: *Proceedings of the 2nd International Conference on Software Engineering*. Ed. by R. T. Yeh and C. V. Ramamoorthy. Los Alamitos, CA: IEEE Computer Society Press, 1976, pp. 592–605
26. James A. McCall and Mike T. Matsumoto. *Software Quality Measurement Manual*. *Volume 2*. Final technical report ADA086986. Accession Number: ADA086986. Sunnyvale, CA: General Electric Co Sunnyvale CA, Apr. 1980, p. 71
27. Rick Kazman, S. Jeromy Carrière, and Steven G. Woods. "Toward a discipline of scenario-based architectural engineering". In: *Annals of Software Engineering* 9.1 (2000), pp. 5–33. issn: 1573-7489. doi: 10.1023/A:1018964405965. url: https://doi.org/10. 1023/A:1018964405965

Icons

https://www.flaticon.com/free-icon/plug_6629353

https://www.google.com/url?sa=i&url=https://iconscout.com/free-icon/timescaledb-1958407&psig=AOvVaw3yFGxvoAhr088pkjsuoByI&ust=1717265599623000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCIicpYK_uIYDFQAAAAAdAAAAABAE

https://www.google.com/url?sa=i&url=https://en.m.wikipedia.org/wiki/File:Postgresql_elephant.svg&psig=AOvVaw1ew-IuZ3w9OS0kP1yPMJy5&ust=1717265626951000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCJiuko-_uIYDFQAAAAAdAAAAABAE

https://www.google.com/url?sa=i&url=https://dev.to/zaiddoussama/a-deep-dive-into-spring-boot-3k62&psig=AOvVaw1_EPN0SnaKCp97Y9-zlD5D&ust=1717265668543000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCNDF0KS_uIYDFQAAAAAdAAAAABAE

https://www.google.com/url?sa=i&url=https://www.logo.wine/logo/Kotlin_%28programming_language%29&psig=AOvVaw0jSQxN2UuwTPpqsqGZsI5M&ust=1717265723919000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCPiEsr2_uIYDFQAAAAAdAAAAABAE

https://www.google.com/url?sa=i&url=https://iconscout.com/free-icon/swift-2038869&psig=AOvVaw1Cy4gqhIfD19bveHaGkRPX&ust=1717265765706000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCPDHoNO_uIYDFQAAAAAdAAAAABAE

https://www.google.com/url?sa=i&url=https://www.hooc.ch/&psig=AOvVaw0gYl2UUE9dLdrdLMI8ONY0&ust=1717265794407000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCIiHjOC_uIYDFQAAAAAdAAAAABAR

https://www.google.com/url?sa=i&url=https://www.cleanpng.com/png-python-computer-icons-programming-language-executa-7247110/&psig=AOvVaw1vlO852E-DMuPSTCgqDkN_&ust=1717265969687000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCMDs87LAuIYDFQAAAAAdAAAAABAE

https://www.google.com/url?sa=i&url=https://mystrom.com/de/support/mystrom-app/&psig=AOvVaw17XpbiAcsskO-vlOmIGYMc&ust=1717266000081000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCPjAicHAuIYDFQAAAAAdAAAAABAI

https://www.google.com/url?sa=i&url=https://de.wikipedia.org/wiki/Datei:Raspberry_Pi_Logo.svg&psig=AOvVaw0TELhteoao2coIree2XZ1A&ust=1717266034288000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCKC6xtHAuIYDFQAAAAAdAAAAABAJ

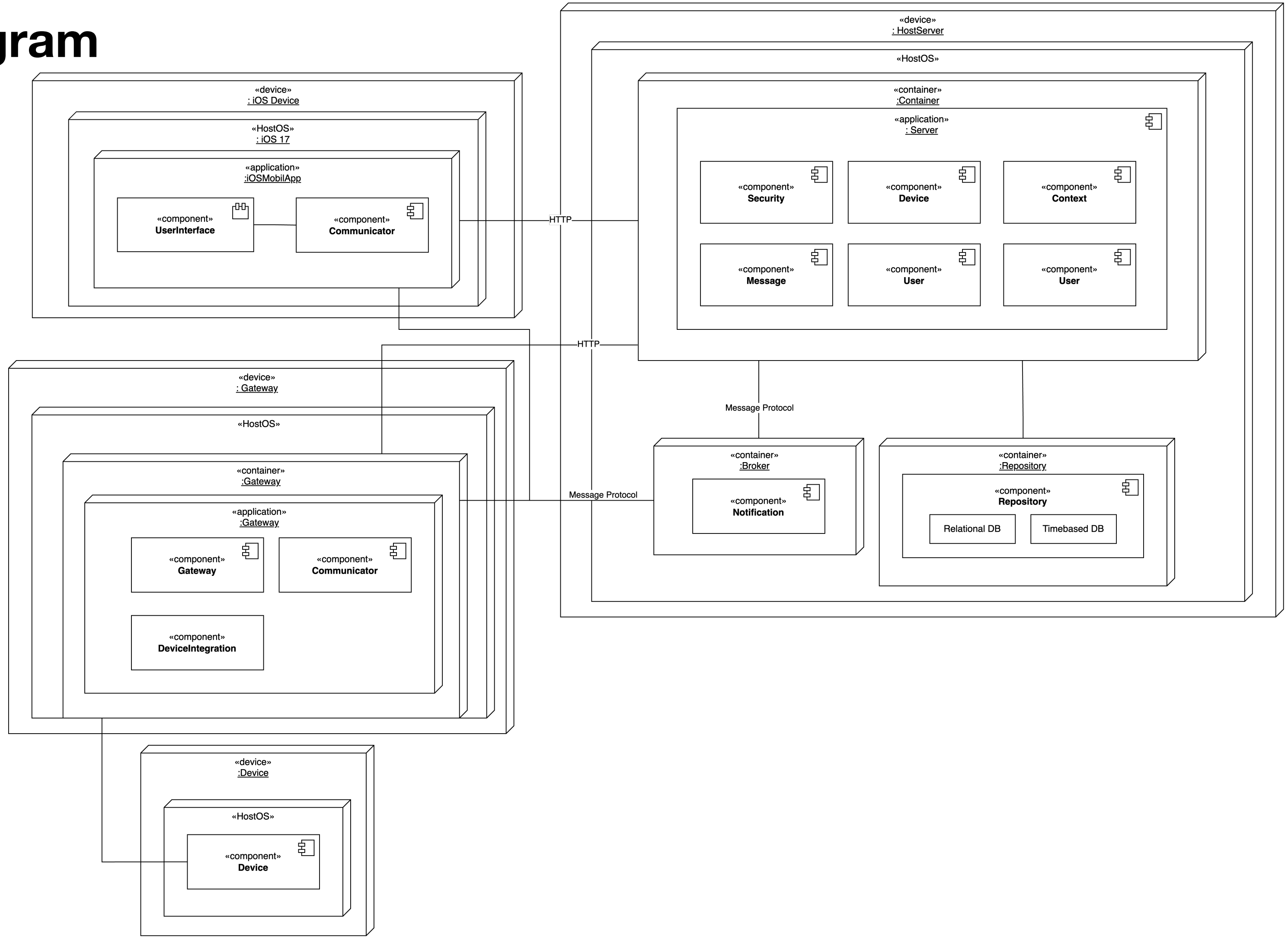
https://www.google.com/url?sa=i&url=https://www.lykalyte.co.nz/collections/shelly-relays&psig=AOvVaw2uF-GpdPhgxbYG5ecbgobj&ust=1717266059141000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCKDRxN3AuIYDFQAAAAAdAAAAABAE

https://www.flaticon.com/de/kostenloses-icon/server_3208726

https://www.flaticon.com/free-icon/bulb_16118860?term=light+bulb&page=1&position=84&origin=search&related_id=16118860

BACKUP

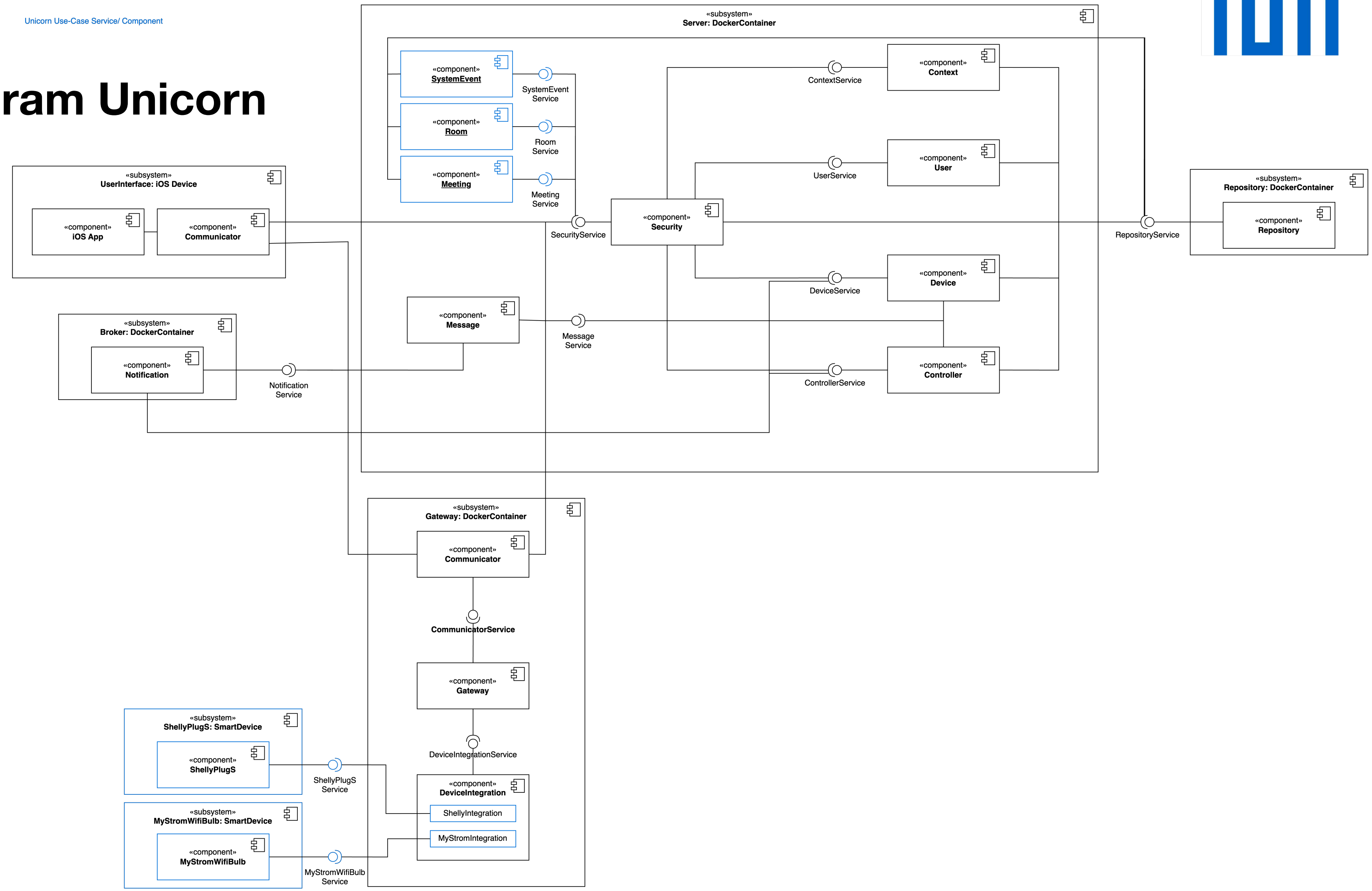
Deployment Diagram Framework



BACKUP

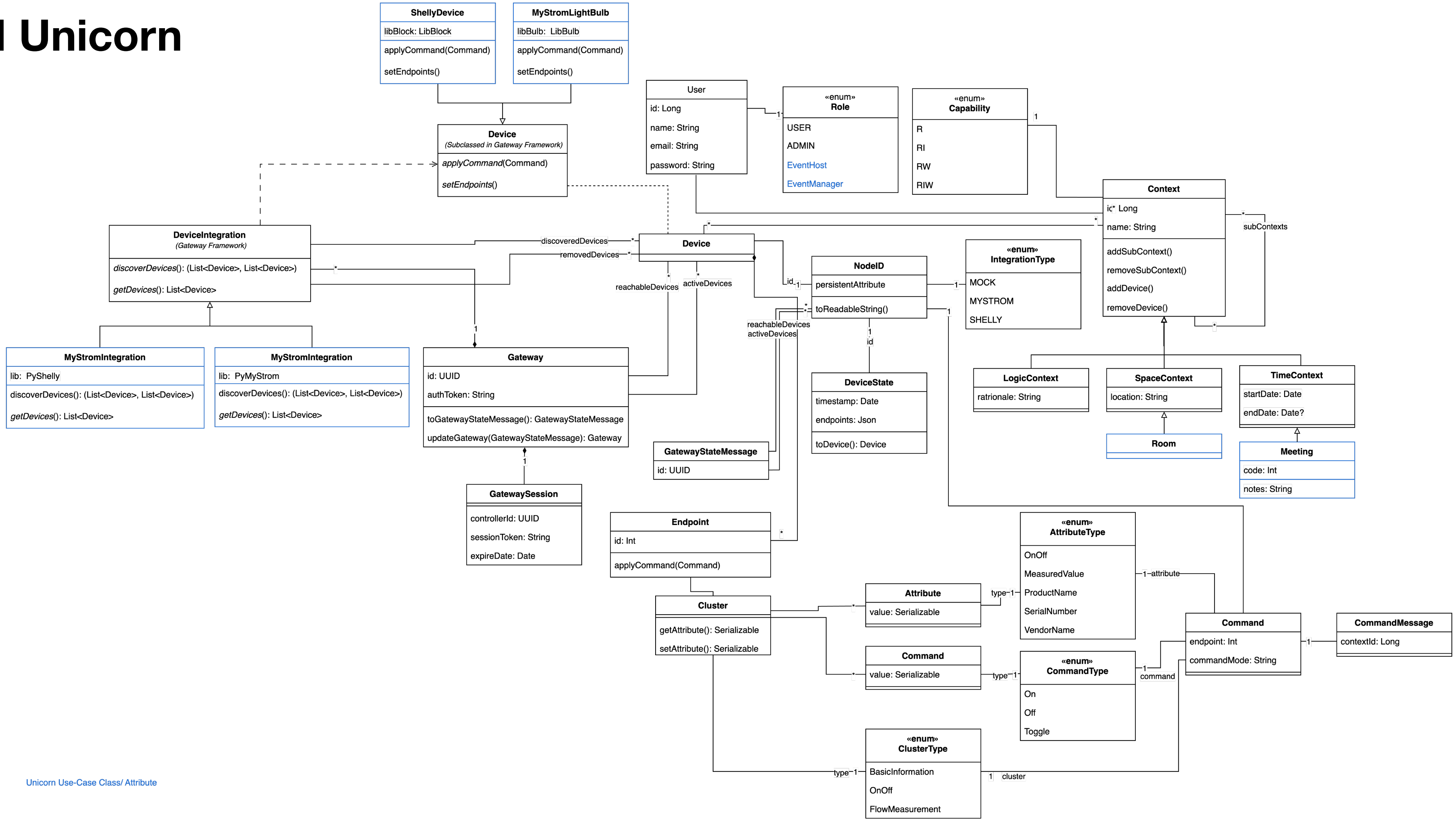
Component Diagram Unicorn

Unicorn Use-Case Service/ Component



BACKUP

AOM Unicorn



Unicorn Use-Case Class/ Attribute

BACKUP

	Research Methodology		Development Methodology		Results		
	Design Research		Object-Oriented Software Engineering after Brügge and Dutoit		Thesis		
	Design Stages	Purpose	Design Stages	Activities	Resulting Artifacts	Context	Chapter
1	Problem Identification	Understand Context			Constructs(Domain Knowledge & Definitions), Models	CPS, IOT, SH	3,4
		Gather Requiements	Requiements Elicitation and Analysis	Understand Problem Enviroment an Identify & Analyse Requirements	Constructs(Set of Scenarios, Requirements), Models	Framework Requirements	5
3	Artifact Design	Design and Develop a Potential Solution	System Design	Conceptualization of Solution	Constructs, Models, Methods	Conceptualization of Framework	6
			Object Design	Development within the Solution Domain	Models, Methods, Instanciations (General Implementation)	Implementation of Framework	7
4	Artifact Implementation	Integrate the Potential Soution within the Defined Context	Object Design	Development within the Solution Domain	Models, Methods, Instanciations (Context Implementation)	Usage of Framework for Prototype Implementation	8
5	Evaluation	Evaluation of the Implemantaion within the Defined Context	Testing	Test the Developed Solution		Evaluation of Framework and Prototype Implementation	9

BACKUP

AUC3: Reusablility

Source: Developer

Stimulus: Development of an new SH-application

Artifact: Framework, user interface, device integrations, SH-server

Environment: Design and development

Response: The developer utilizes the framework to develop an application for a specific use-case

Response Measure:

- Development effort
- New defects introduced
- Interference with existing functionality

BACKUP

5.3.2. Functional Requirements

FR1 Device Integration: The system is capable of integrating a new device.

FR2 Device Controlling: The system can display the current status of a device, including any state changes initiated on the device itself or externally. Additionally, it is capable of controlling the individual functionalities of the device.

FR3 System Monitoring: The system can determine if a device is reachable and reactive. All significant system actions are logged by the framework

FR4 Computational Services: The System is able to accommodate and execute computational services, such as device automations.

FR5 Persistent Storage: The System can save current and historical device data (dynamic states/ static information) persistently, depending on the configuration.

FR6 Authentication and Authorization: The system is able to identify a certain user and limit resource access.

BACKUP

5.3.3. Non Functional Requirements

NFR1 Performance: The system should provide low latency and fast response times, especially related to device state updates and the invocation of device functionalities.

NFR2 Reliability: The system should ensure high availability of its functionalities and be able to handle and/or recover from a number of common failure patterns in the SH domain.

NFR3 Reusability: The system should support the adaptation to a variety of Smart Home related use-cases and allow the extension of services and supported devices in a modular fashion. The system should also be deployable in various execution environments.

NFR4 Security: The system should be resistant to external malicious activities and uphold the CIA metrics.

NFR5 Scalability: The system should be able to accommodate an increasing number of integrated devices.

The NFRs for maintainability and efficiency were also identified as relevant requirements, were assigned a lower priority and consequently not the focus of this thesis due to its limited scope.

BACKUP

RQ1: Does the developed framework and subsequently the implemented prototype satisfy the functional requirements?

RQ2: Does the developed prototype implementation satisfy the non-functional requirements performance **NFR1** and reliability **NFR2**?

RQ3: Does the developed framework satisfy the **NFR3** reusability?

RQ4: Does the usage of the framework enable the reduction or re-focus of development efforts?