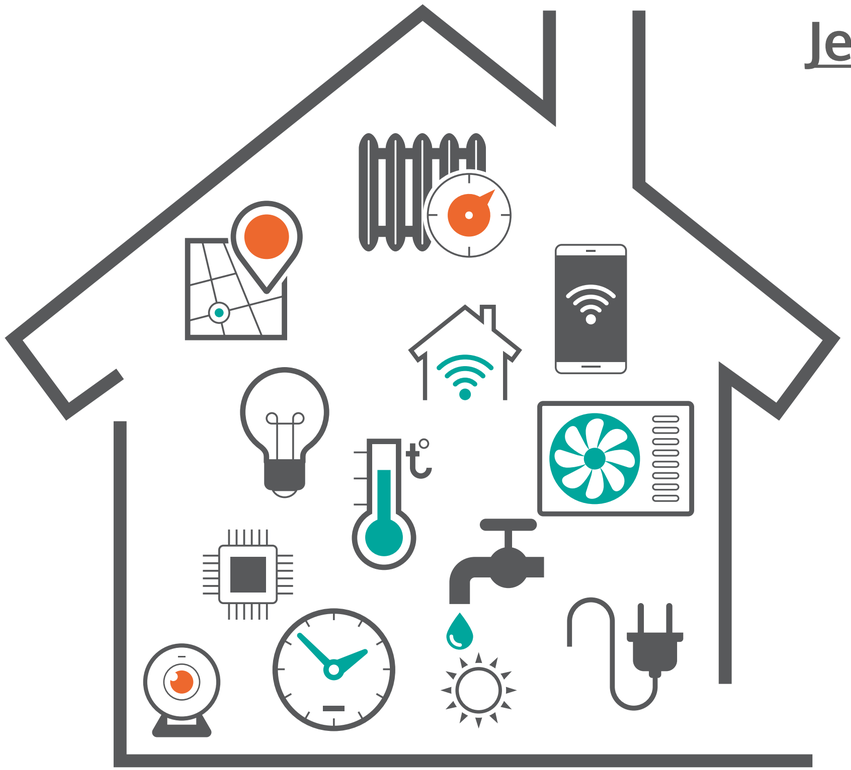
Lumos: Improving Smart Home IoT Visibility and Interoperability Through Analyzing Mobile Apps



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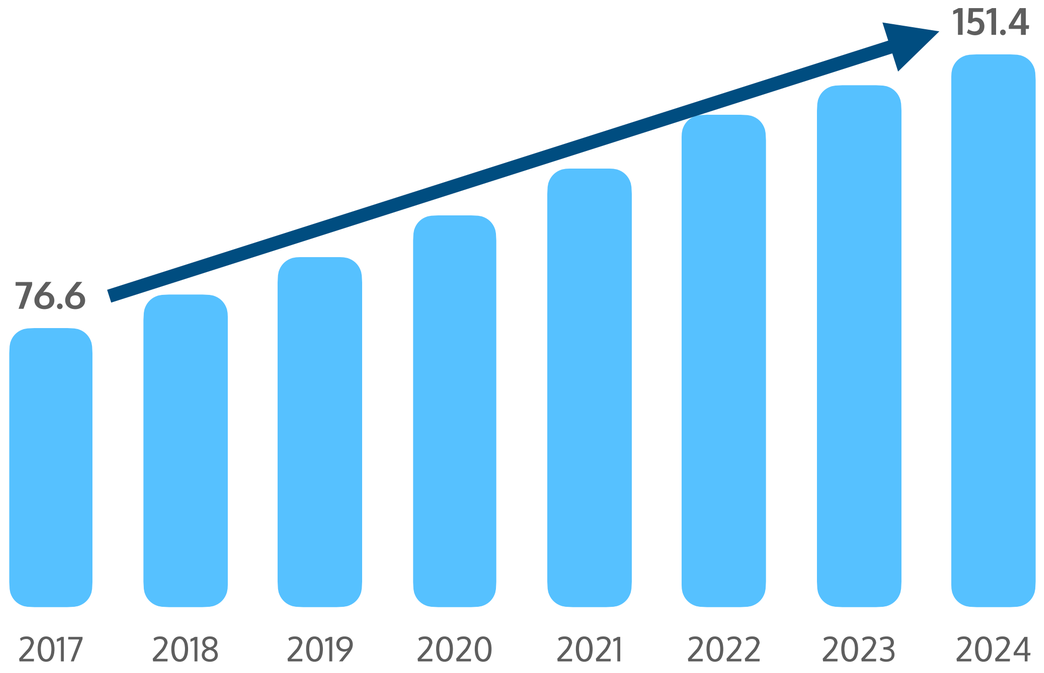
Smart Home (Internet-of-Things)

- Smart home (IoT) **integrates diverse "smart" devices** (sensors, actuators, and appliances)
- By 2024, the market value is expected to reach **$151.4 billion (CAGR 12.02%)**
- **Major players are struggling to increase their market share**
  - Market reports indicate the existence of **450 IoT platforms** world-wide as of 2017



Smart home market (USD billion)

Google

SAMSUNG

amazon.com

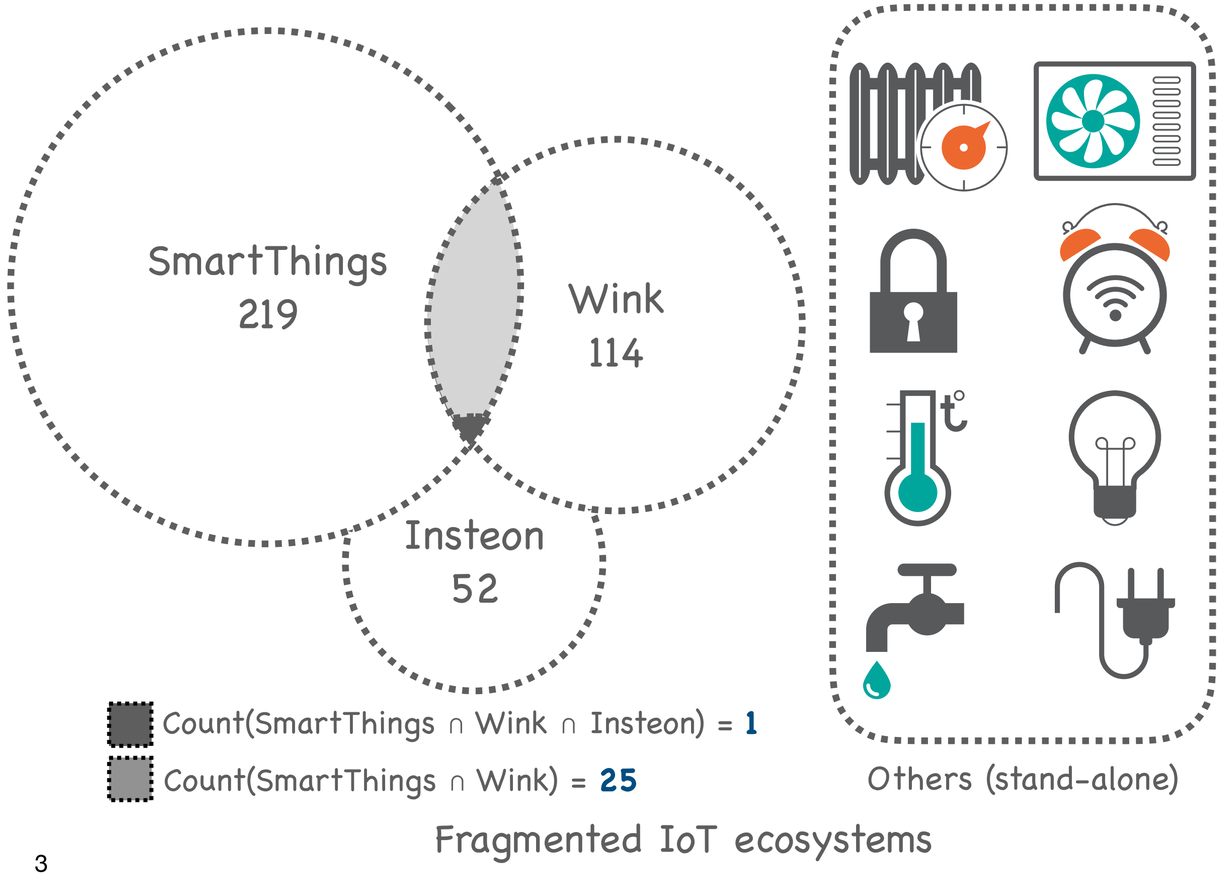
Honeywell

Major players in smart home market

IoT fragmentation is a significant barrier

Status quo of smart home ecosystems

- Three major smart home platforms and the number of devices they support
- Three observations
  - **Cross-platform interoperation is impossible**
  - Devices are **locked-in to a specific platform**
  - Many IoT devices are **still stand-alone**



Fragmented IoT ecosystems

Efforts to overcome the obstacle

Status quo of smart home ecosystems

Requirements

Related work

Research

2 3 6 14 31 57 68

Entirely changing current architecture

They are not widely deployed!!!!

Industry

IFTTT

Open Translators to Things

Industry projects

Vendors' participation

[2] : A LOI, et al., A mobile multi-technology gateway to enable IoT interoperability, IEEE IoTDI 2016.
[3] : A LOI, et al., Enabling IoT interoperability through opportunistic smartphone-based mobile gateways, Journal of Network and Computer Applications 81 2017
[6] : B LACKSTOCK, et al., IoT interoperability: A hub-based approach. In international conference on the internet of things, IEEE IOT 2014
[14]: D ESAI, et al., Semantic gateway as a service architecture for iot interoperability, IEEE MS 2015
[31]: K ILJANDER, et al., Semantic interoperability architecture for pervasive computing and internet of things, IEEE access 2 2014
[57]: SONG, et al., Semantic middleware for the internet of things, IEEE IOT 2010
[68]: Z ACHARIAH, et al., The internet of things has a gateway problem, ACM HotMobile 2015

Efforts to overcome the obstacle

Status quo of smart home ecosystems

Goal

Interacting IoT devices without vendor participation

Improving interoperability without architectural modifications

[2] : A LOI, et al., A mobile multi-technology gateway to enable IoT interoperability, IEEE IoTDI 2016.
[3] : A LOI, et al., Enabling IoT interoperability through opportunistic smartphone-based mobile gateways, Journal of Network and Computer Applications 81 2017
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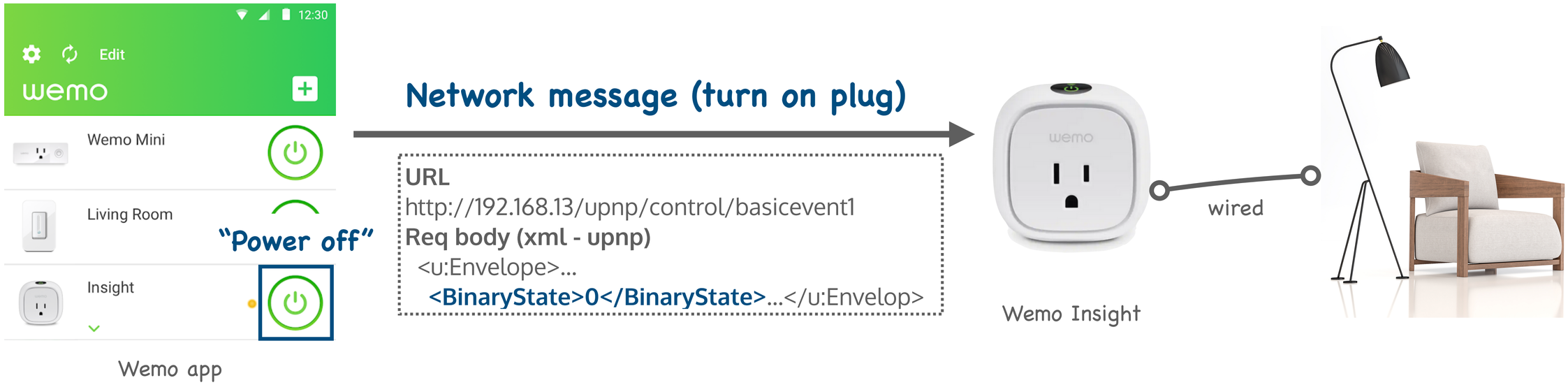
Mobile apps play a key role in interacting with IoT devices

Key insight

- **They contain valuable information for interoperability**
  - The ability to **monitor and control** IoT devices (**visibility and controllability**)
  - GUI of the apps includes **semantic information**

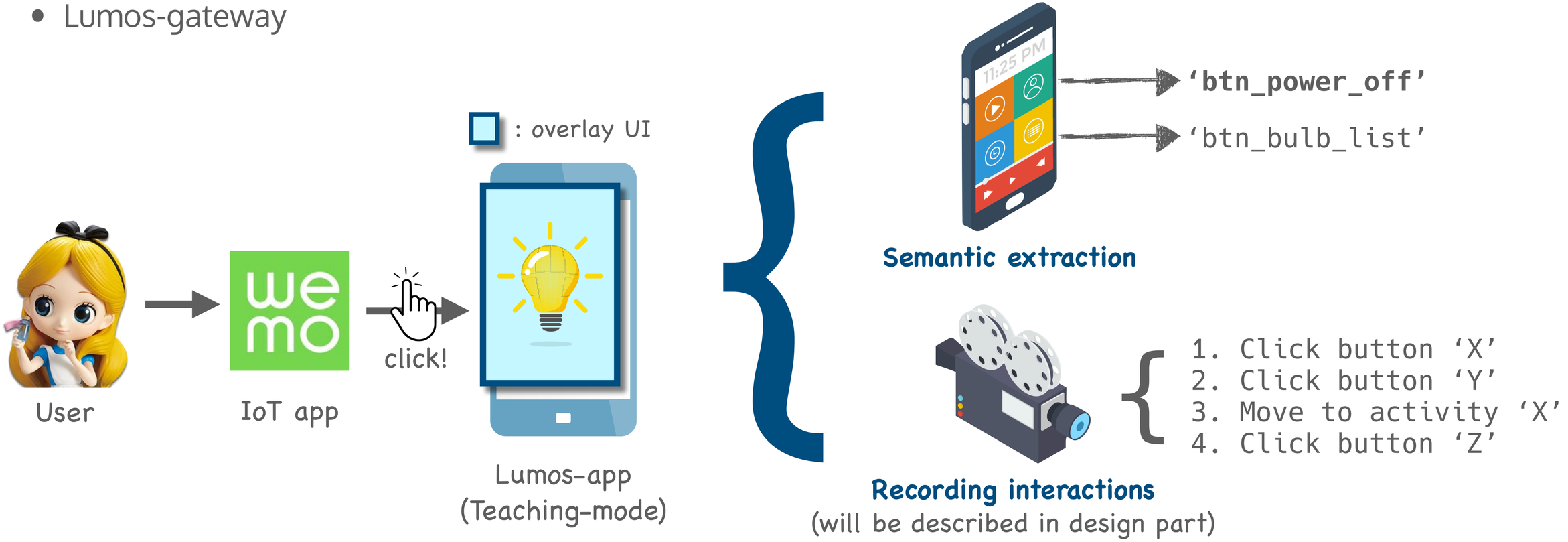



Interoperability and Visibility
Through Analyzing Mobile Apps

Power off a Wemo when watching a Netflix movie

Usage model: Lumos-app

- Our key insight reflects two software components of Lumos
  - **Lumos-app**
  - Lumos-gateway



Power off a Wemo when watching a Netflix movie

Usage model: Lumos-gateway

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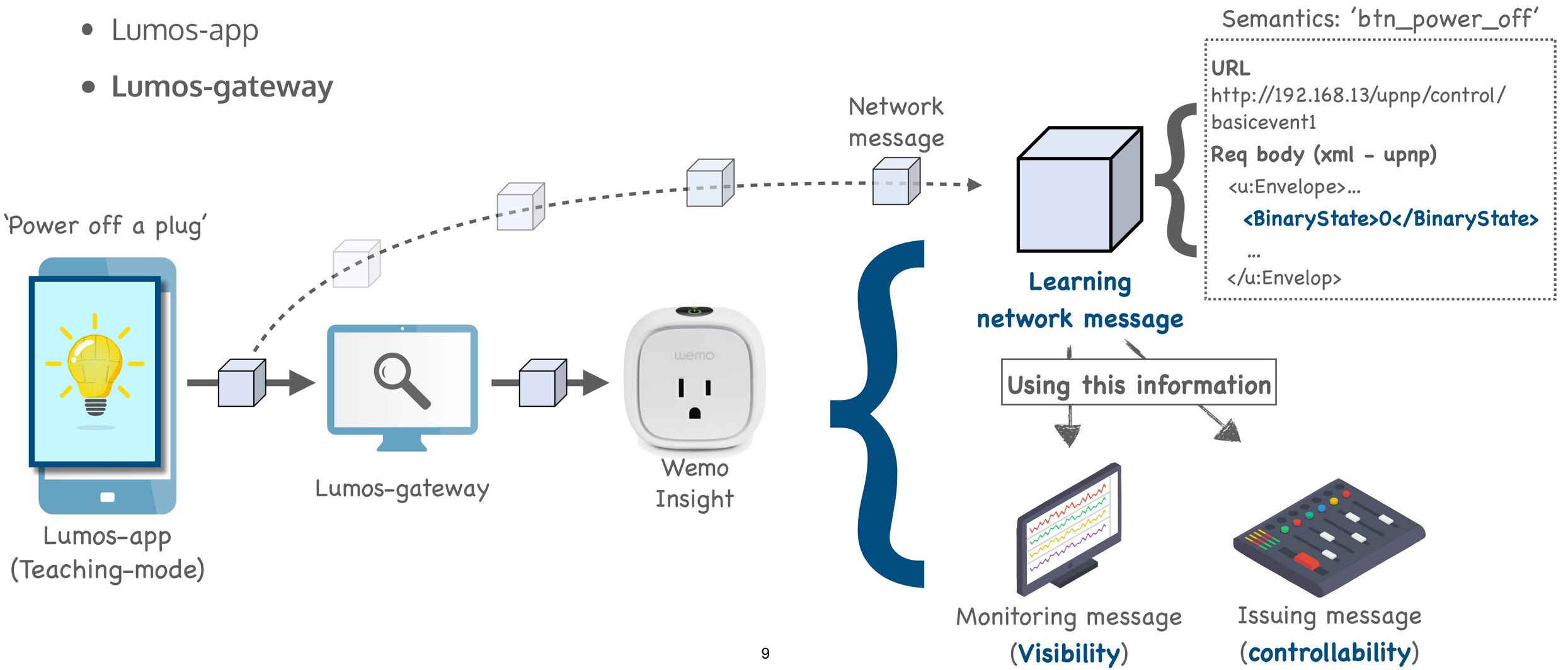
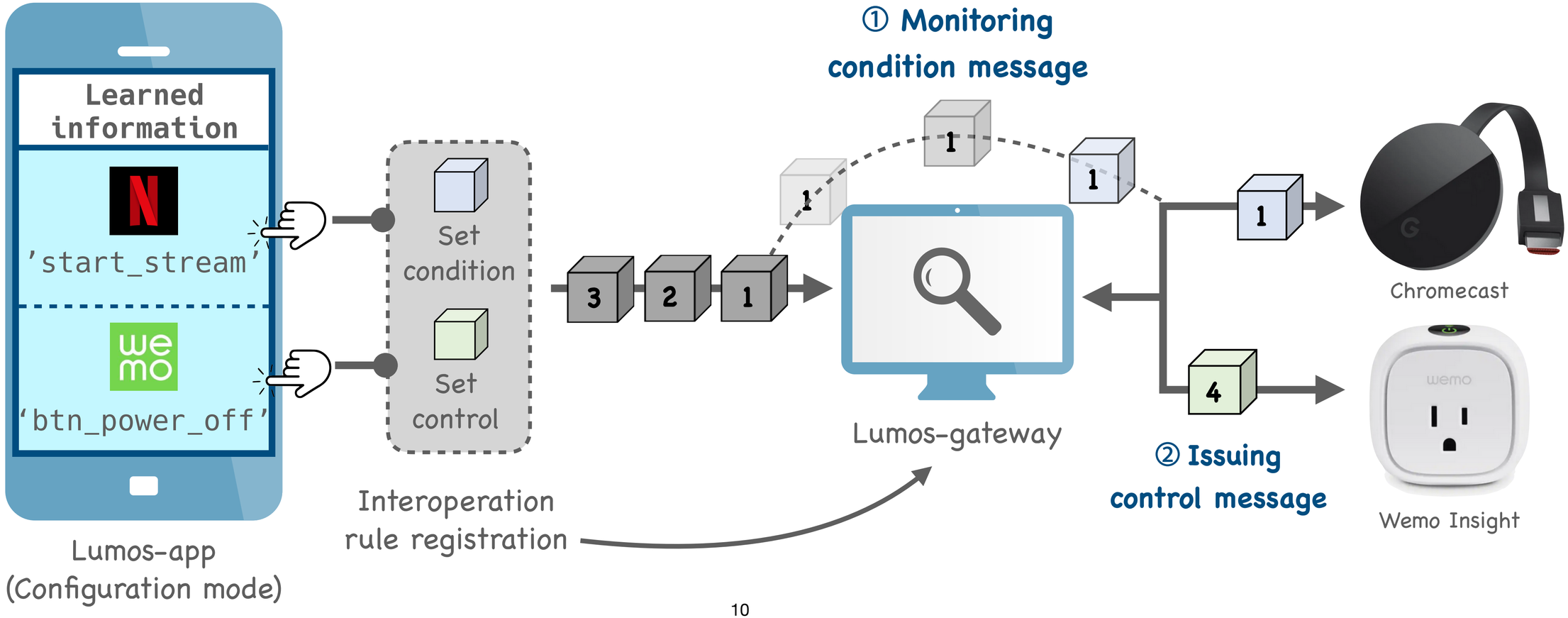
  - Lumos-app
  - **Lumos-gateway**

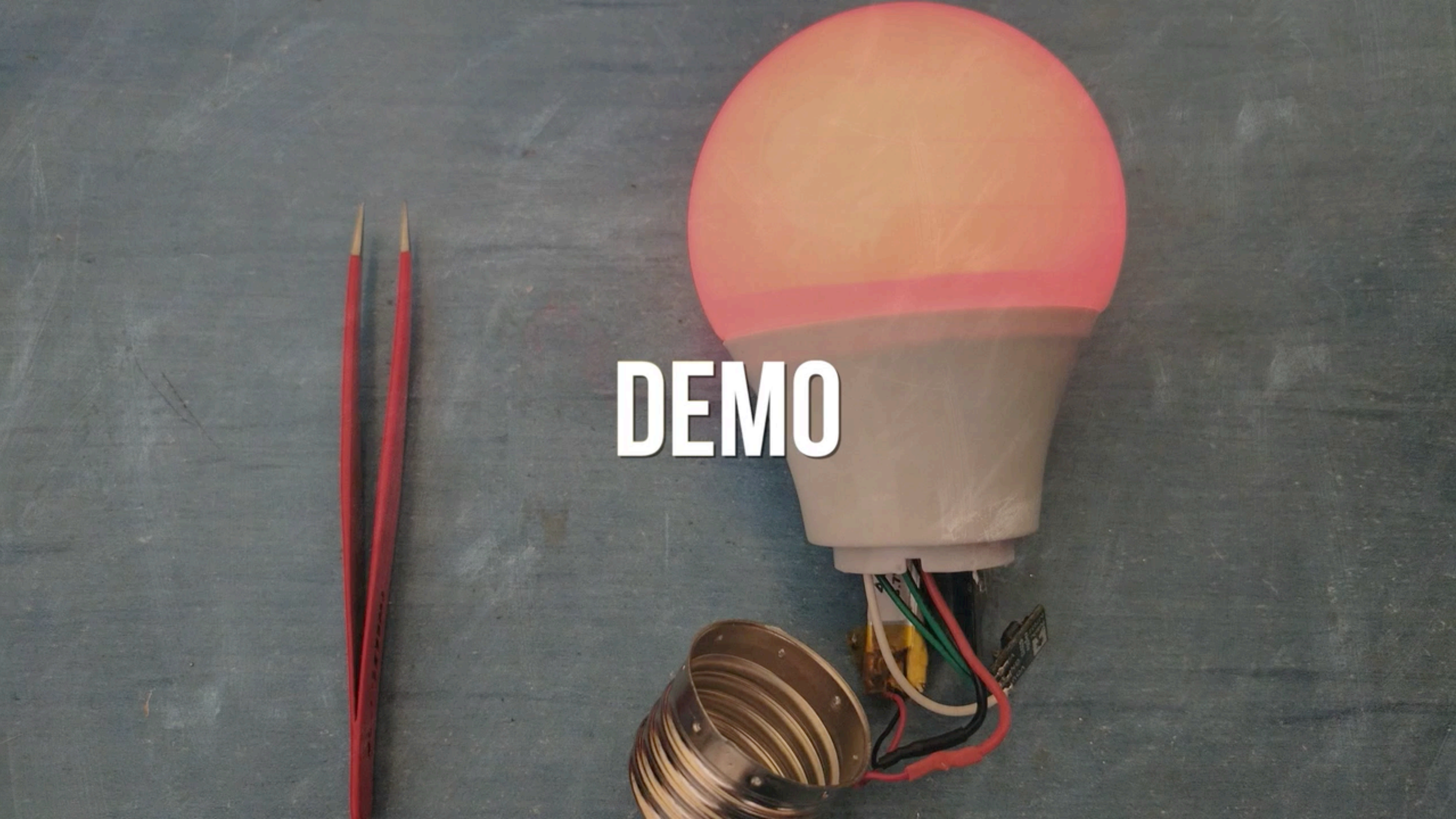


Power off a Wemo when watching a Netflix movie

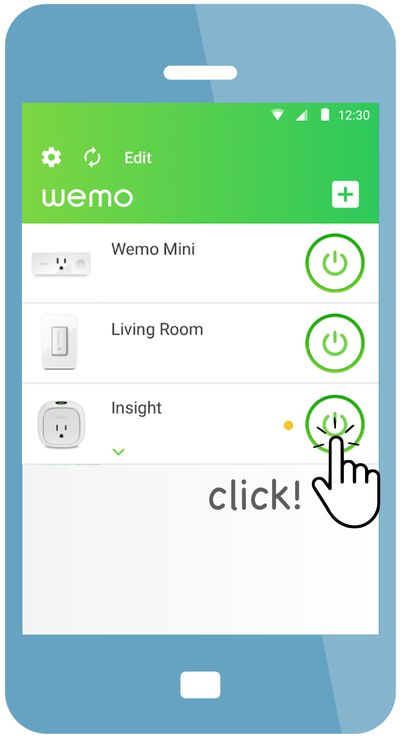
Usage model: configuring an interoperation rule

- After teaching phase, Alice **makes an configuration**
  - Rule consists of ‘condition’ and ‘control’

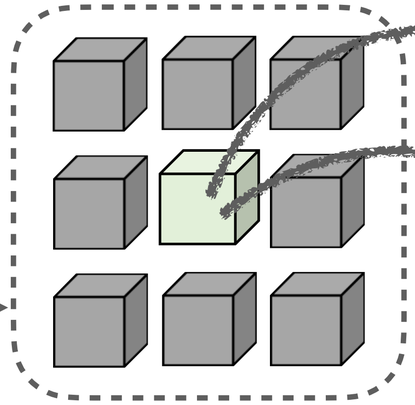



DEMO

Challenges



IoT app



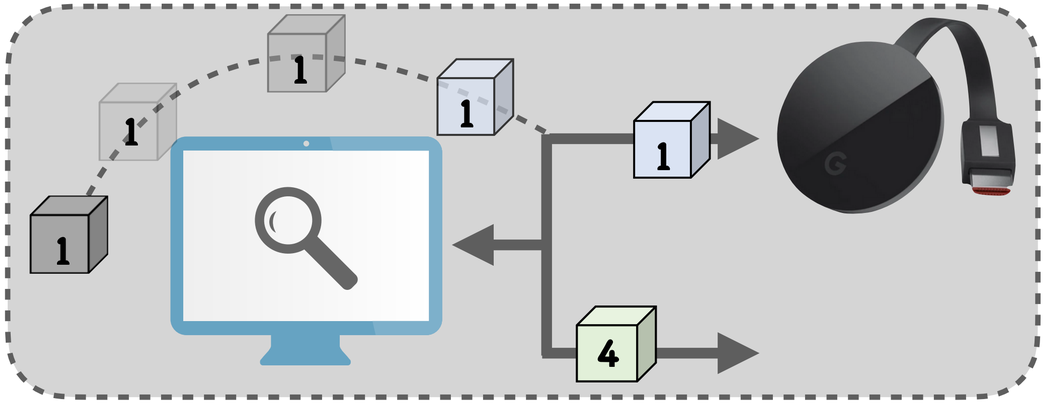
Unrelated traffic
in background

C1: identifying a specific message

C2: learning semantic of a specific message

C3: supporting interoperation

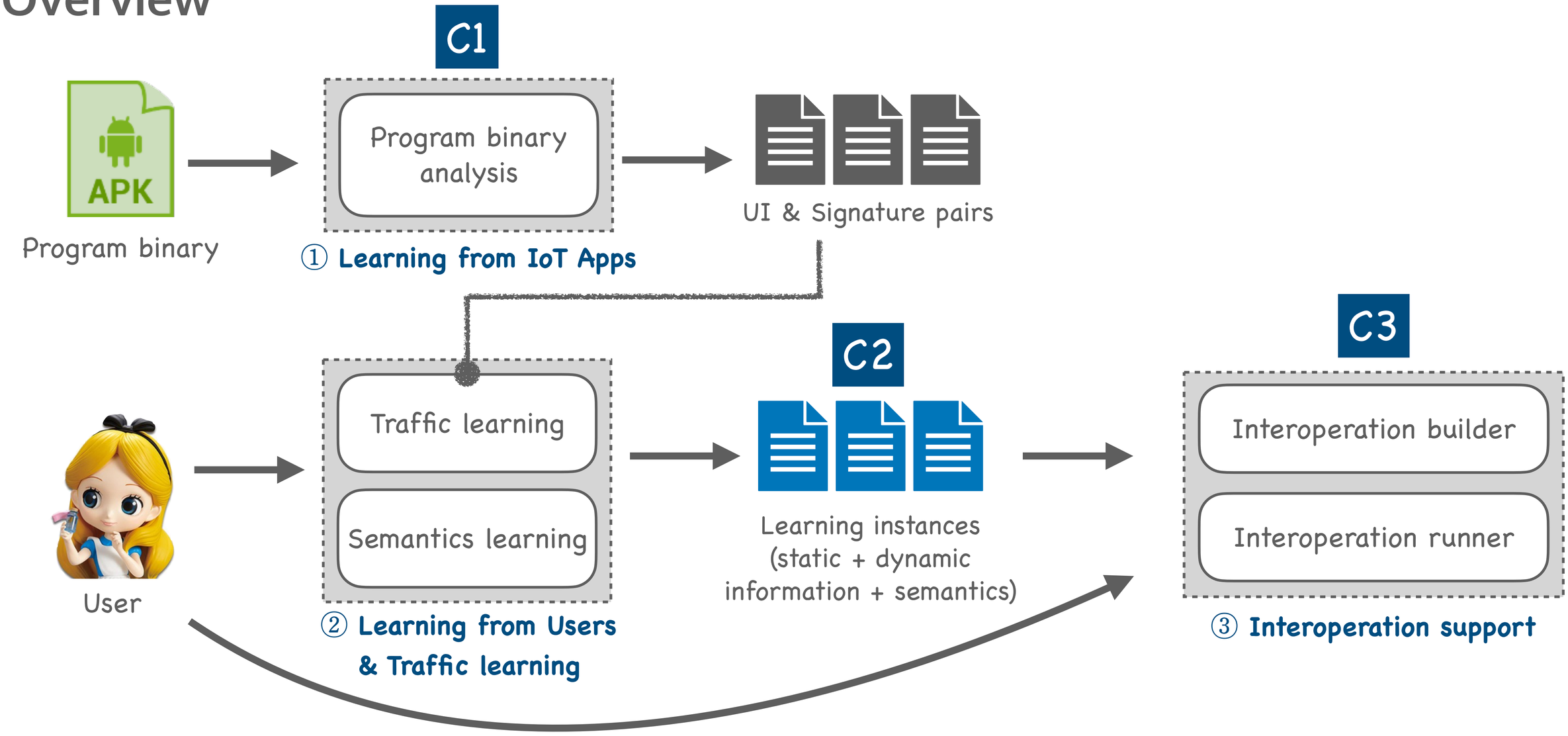
Monitoring condition message



Issuing control message

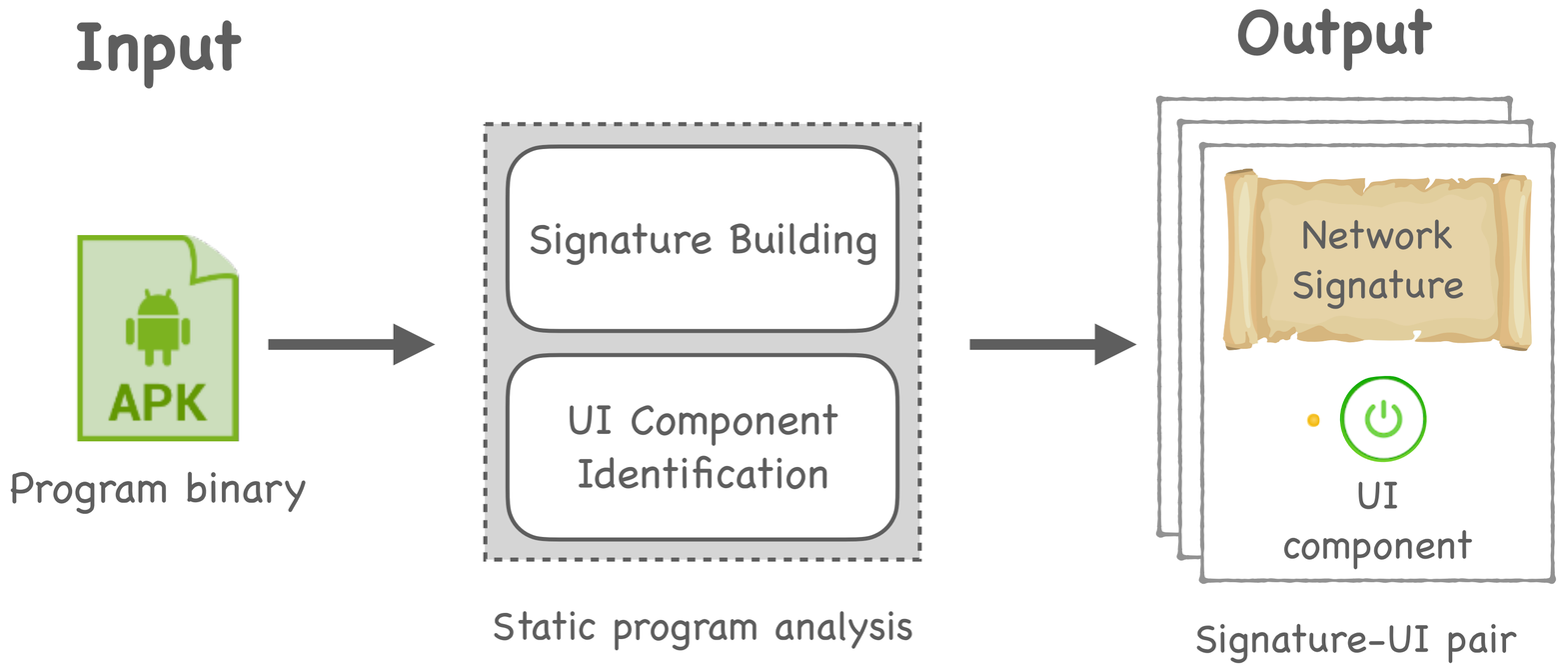
System design

Overview



System design

C1 Learning from program binary (APK)

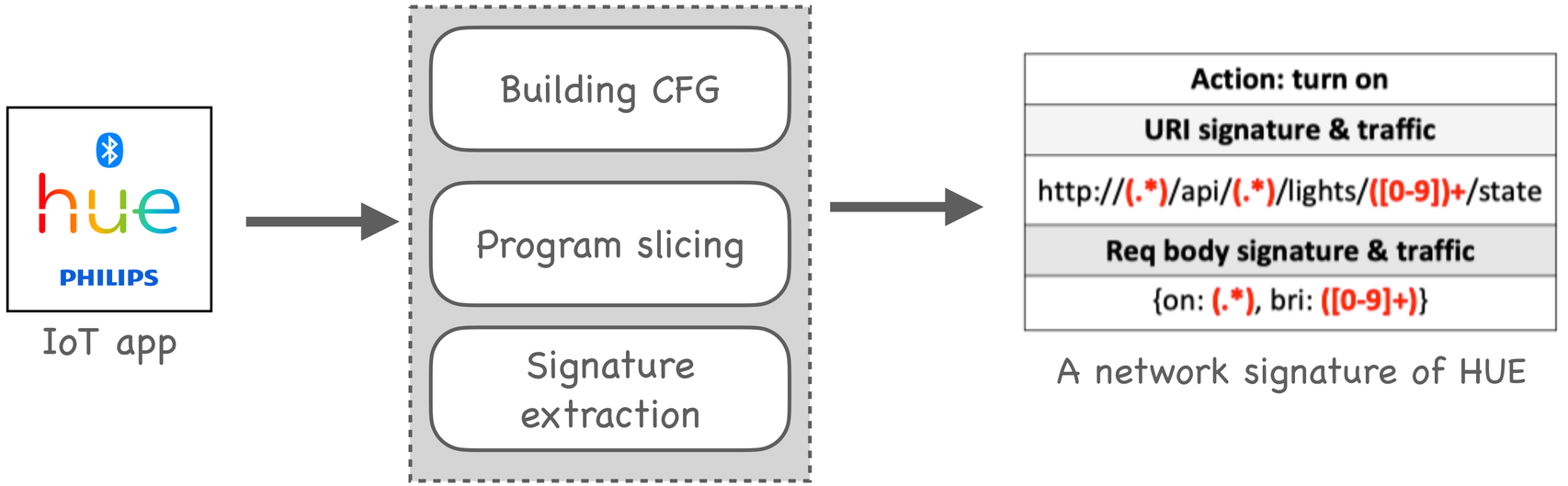


Objective: **pairs a UI component with the regex signatures of control/status messages**

System design

C1 Learning from program binary (APK)

- **Signature building [Extractocol CoNEXT'16]**
  - It conducts a static taint analysis to extract network message signatures
  - It also provides a call graph of an app that is used in the UI component identification



System design

C1 Learning from program binary (APK)

- **UI control Identification**
  - Identifying all event listeners that eventually generate network messages
  - Performing a backward call graph analysis for each event listener
  - Identifying the resource ID for an event listener through a taint analysis

```
class: BrightnessSeekBarView
public BrightnessSeekBarView(Context arg7, AttributeSet arg8, int arg9) {
 …
 this.a = this.findViewById(0x7F0D009C)
 this.a.setOnSeekBarChangeListener(((SeekBar$OnSeekBarChangeListener)this));
 …
}
```

Resource ID

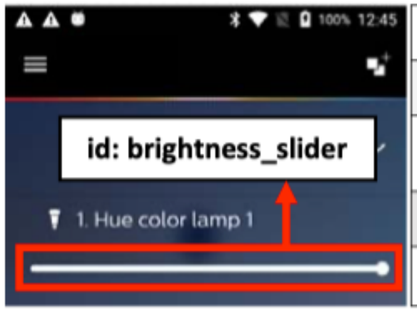
③ set a taint seed

② Identify Set eventListener

```
class: AbstractBrightnessSeebar implements SeekBar&OnSeekBarChangeListener
public void onProgressChanged(SeekBar arg4, int arg5, boolean arg6) {
 this.c = arg6;
 this.d.Turn_on_a_bulb_method(((c)this), this.c, arg6, false);
}
```

① Backward call-flow traversal

HUE app UI finding example

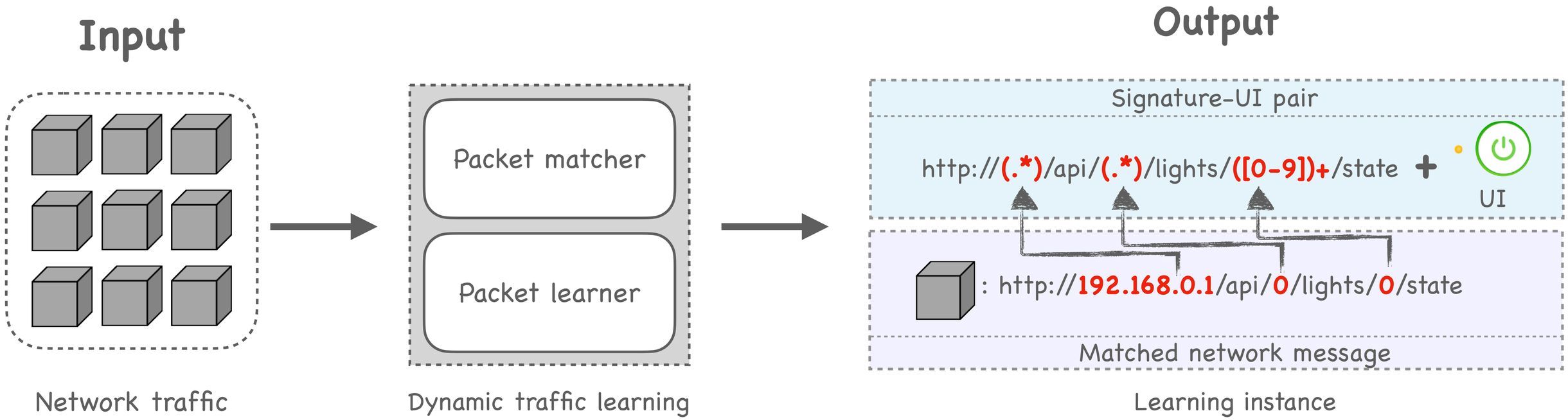


Action: turn on
URI signature & traffic
http://(.*)/api/(.*)/lights/([0-9])+/state
Req body signature & traffic
{on: (.*), bri: ([0-9]+)}

A pair of signature and UI component of HUE

System design

C1 Dynamic traffic learning

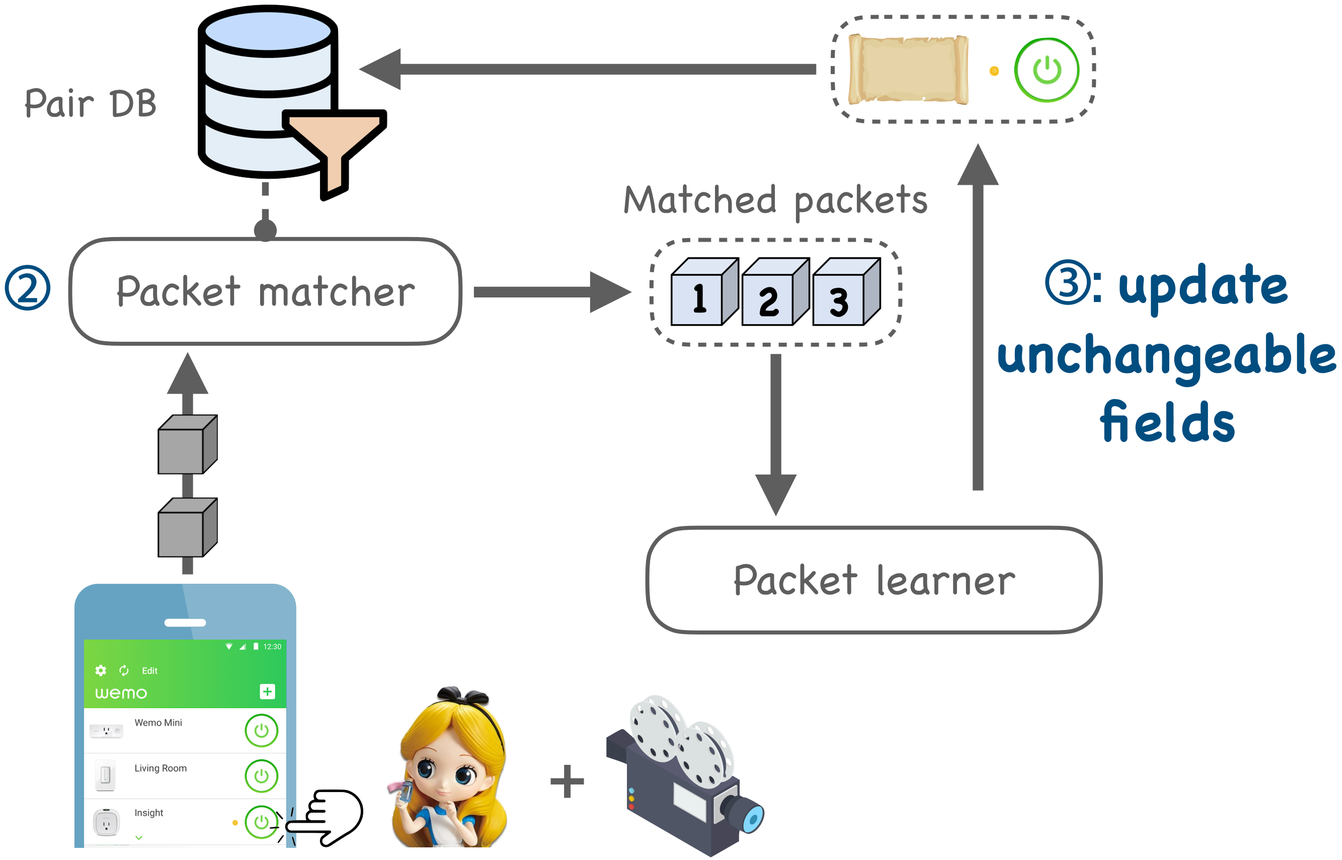


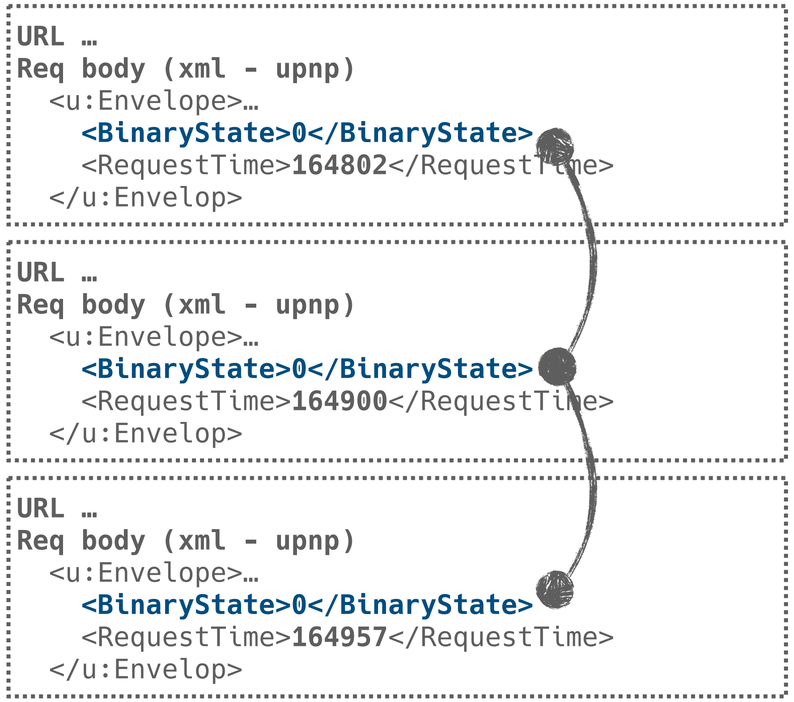
Objective: learns values that are determined at runtime

System design

C1 Dynamic traffic learning

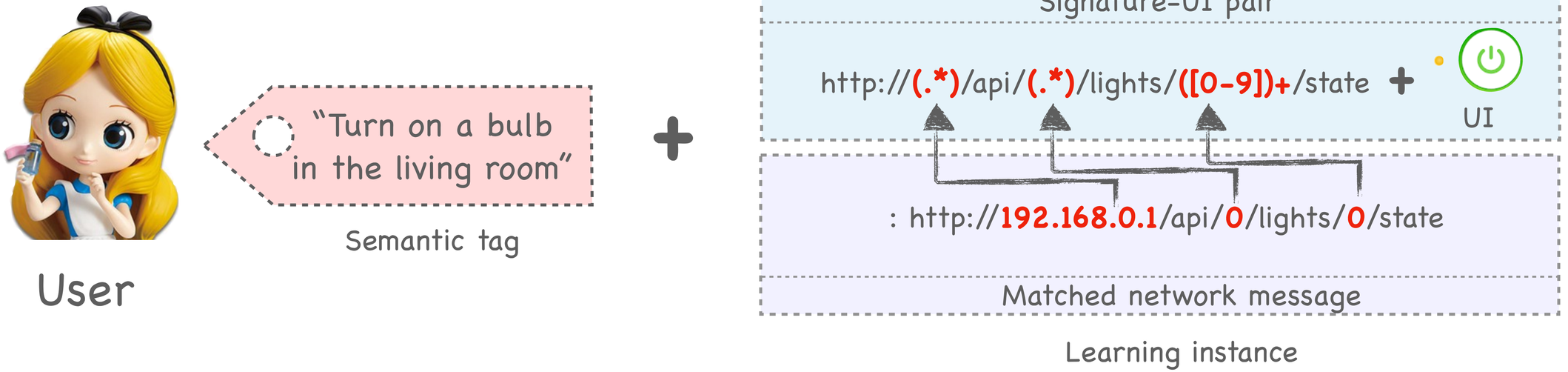
- Lumos-gateway detects and captures the network messages that match the network signatures
- It also filters some of the attribute values not-change over time by automatically message generating





System design

C2 Semantic learning from User

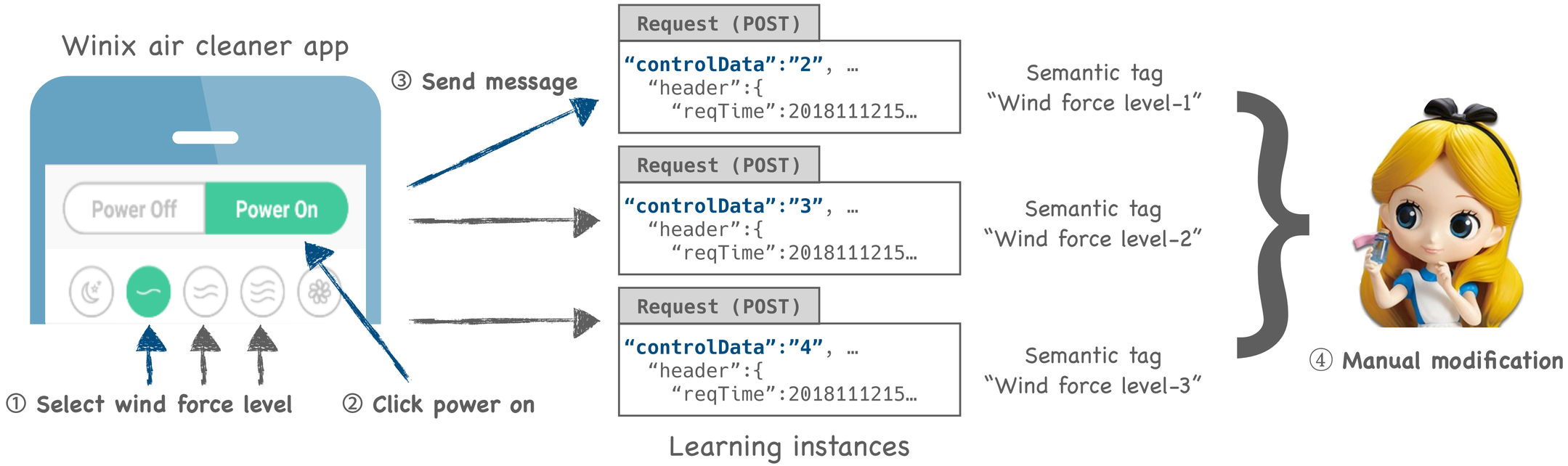


Objective: **learns semantic of a specific network message**

System design

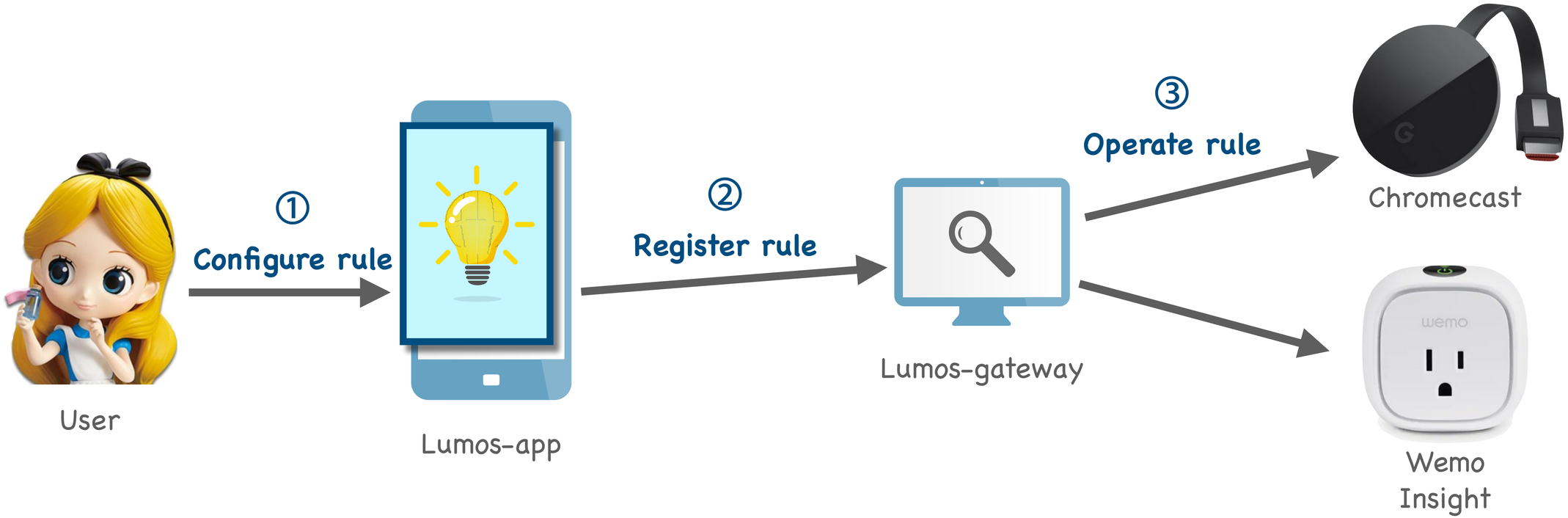
C2 Semantic learning from User

- **However, it might be insufficient**
  - Case 1: some UI label IDs do not contain any semantic information (e.g., button1)
  - **Case 2**: a single button may even trigger a different action depending on the context



System design

C3 Supporting interoperation

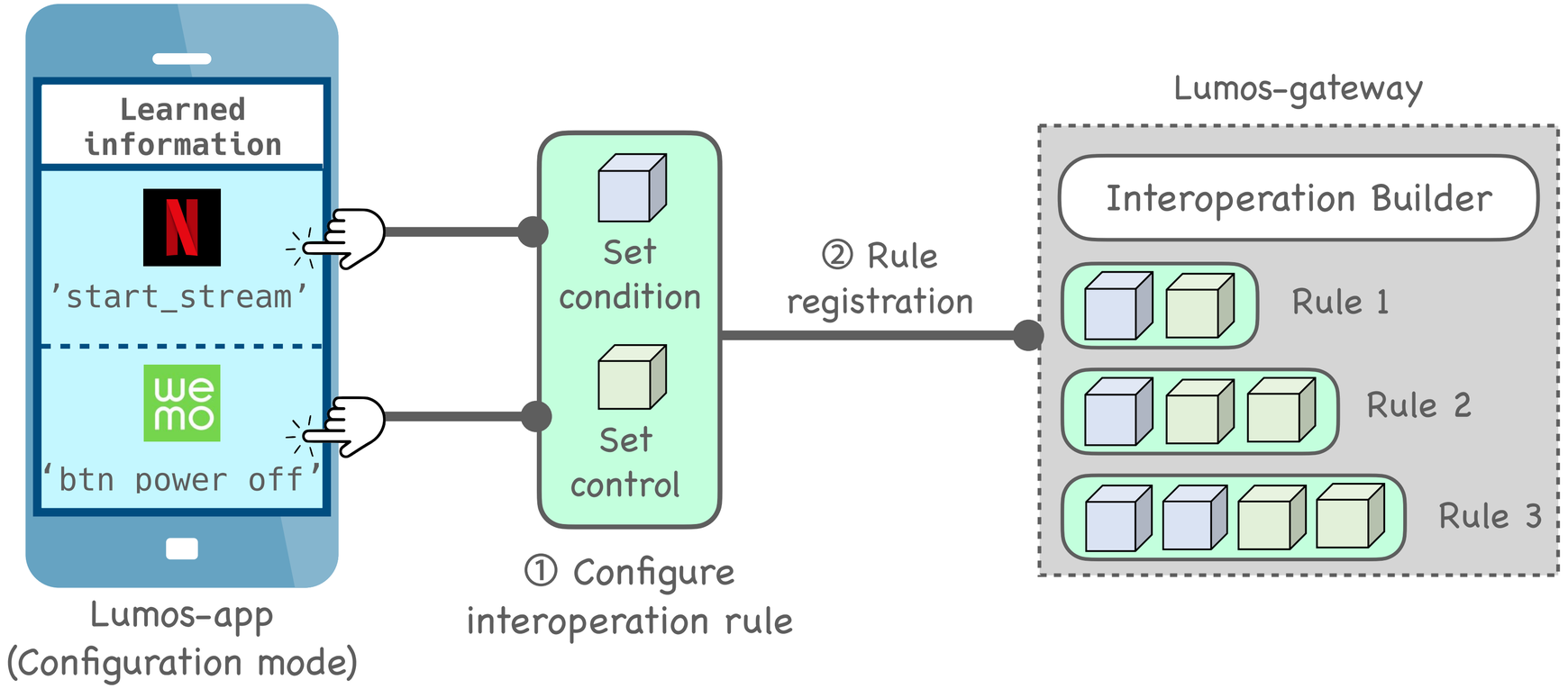


Objective: **supports interoperation without any changes to current architecture**

System design

C3 Supporting interoperation

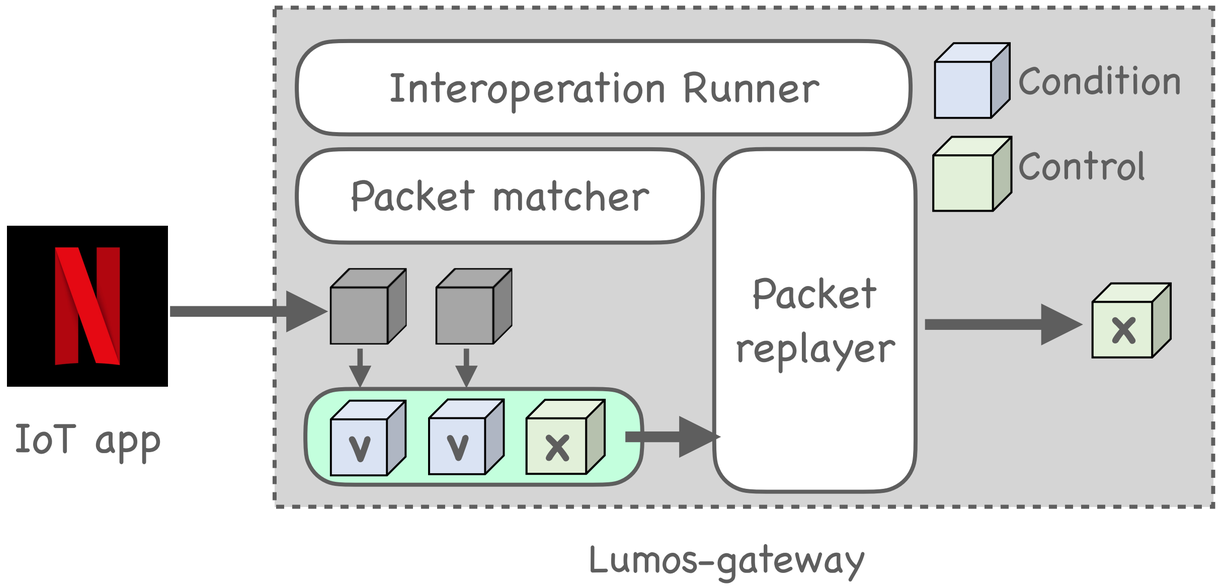
- **Rule builder** allows users to compose interoperation rules with **conditions** and **control** actions
  - **Interoperation rule consists of multiple conditions and control actions**
  - “passive” condition vs “active” condition

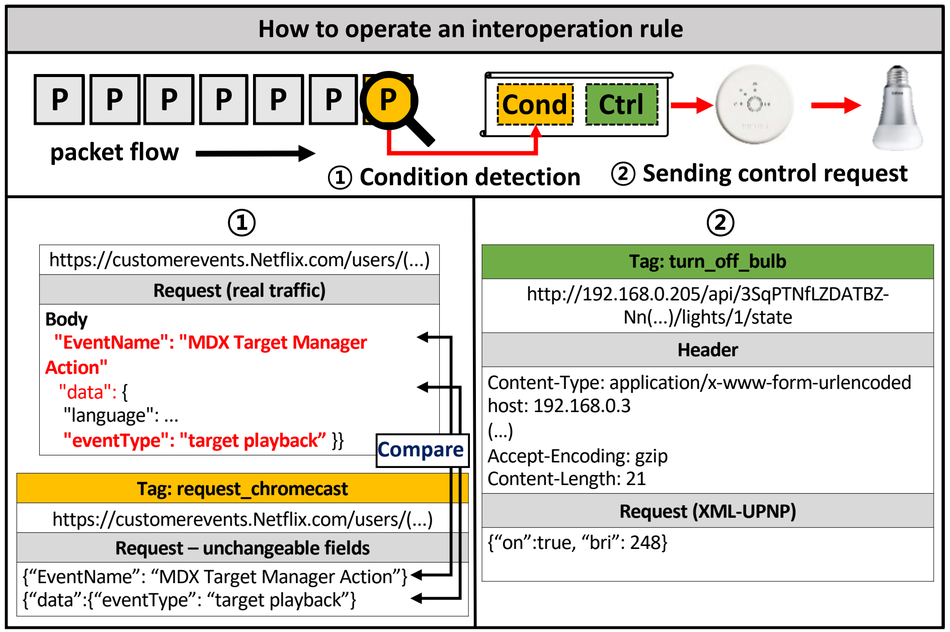


System design

C3 Supporting interoperation

- **Interoperation runner**
  - Lumos-gateway monitors network traffic to check for the condition of the rule
  - When it matches, Lumos-gateway generates an HTTP request for desired action and issue it





Evaluation

Three key questions

- Q1: **Does Lumos enable interoperation** across diverse IoT devices and platforms?
- Q2: Is Lumos-gateway capable of **emulating key functionalities of the IoT apps**?
- Q3: **How easy is it for a user to configure interoperation rules** using Lumos?

Evaluation

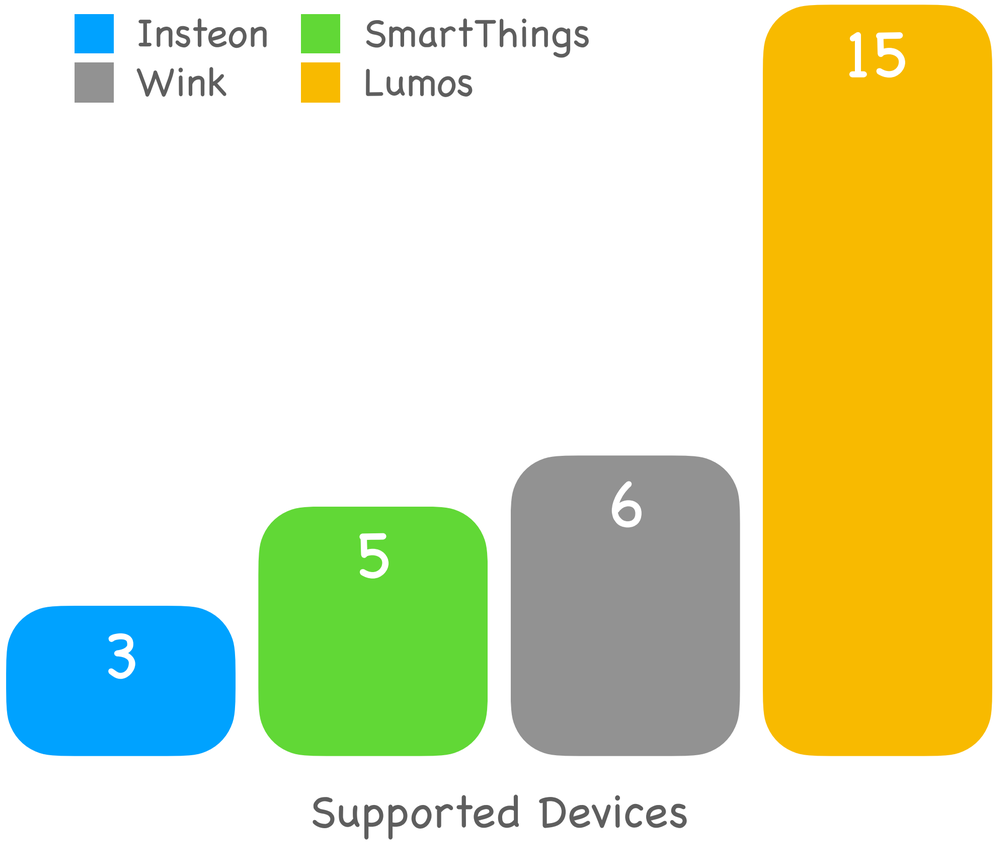
- We evaluate Lumos using **three popular platforms and 15 IoT devices with nine app**
  - **Three popular smart home platforms**
    - SmartThings, wink, INSTEON
  - **5 stand alone**
    - August smart lock, Chromecast, HUE bulb, Nest Protect and Wemo Insight
  - **10 devices belongs to one of the three platforms**
    - Nine sensors (motion, multi-purpose, and water leak)
    - One chime

Does Lumos enable interoperation across diverse IoT devices and platforms?

Evaluation

- IoT applications and devices with types that we used

Application	Device	Type
August	Smart lock pro	Door lock
Netflix	Chromecast	Streaming-dongle
Philipse HUE	HUE	Bulb
Insteon	Insteon doorsensor Insteon plug Insteonwater leak sensor	Door sensor Smart plug Water leak sensor
Nest	Nest Protect	CO&smoke detector
SmartThings	SmartThings plug SmartThings motion sensor SmartThings door sensor	Smart plug Motion sensor Door sensor
Wemo	Wemo Insight plug	Smart plug
Wink	Wink chime Wink door sensor Wink motion sensor	Siren&chime Door sensor Motion sensor
Winix	Winix air cleaner	Air cleaner

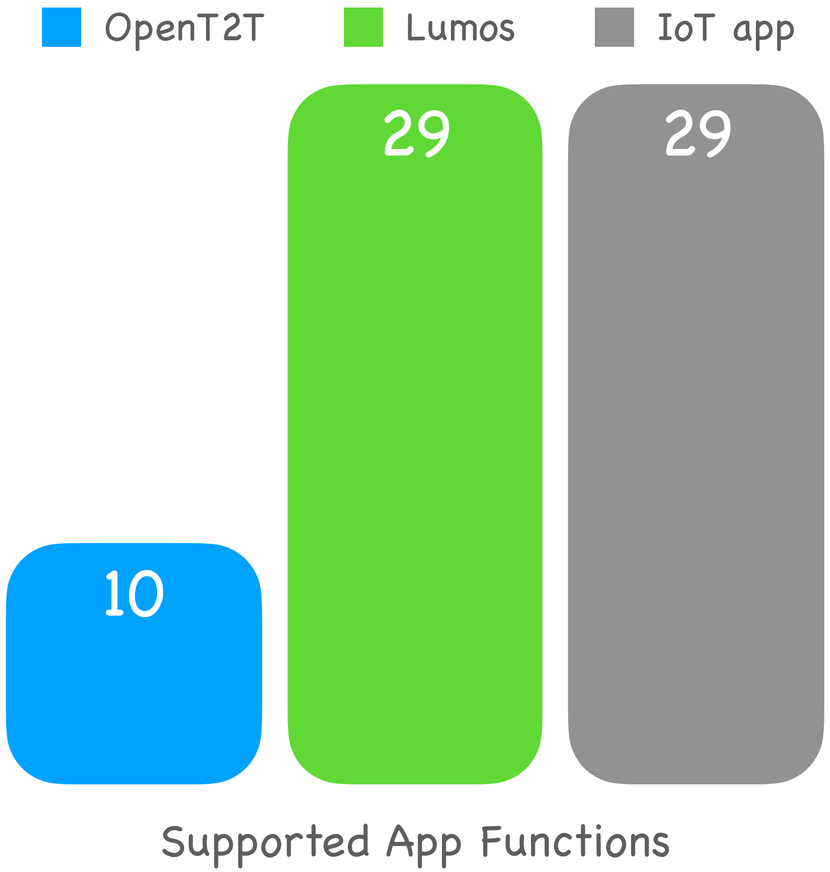


Is Lumos-gateway capable of emulating key functionalities of the IoT apps?

Evaluation

- Devices with functionalities that IoT app support

Device	App function	Device	App function
August	Lock/unlock Get status history	SmartThings motion sensor	Active or not Get status history
Netflix	Request Chromecast	SmartThings door sensor	Open or not Get status history
Philipse HUE	Turn on/off Change brightness Change color Get status	Wemo Insight Plug	Power on/off Get current voltage
Insteon door sensor	Open/close status	Wink chime	Play bell
Insteon plug	Power on/off	Wink door sensor	Open or not Get status histroy
Insteon water leak sensor	Get leak status	Wink motion sensor	Active or not Get status history
Nest Protect	Get CO status Get smoke status Get battery	Winix air cleaner	Turn on/off Change wind force Get current status
SmartThings plug	Power on/off Get status history		



How easy is it for a user to configure interoperation rules using Lumos?

Evaluation

- We also conducted a user study in which we asked our participants to use Lumos
  - **Participants and environment**
    - ✓ 24 participants in university
    - ✓ IoT experience on a three point scale
    - ✓ The experiment was conducted in a test room with IoT devices/platforms
    - ✓ We also installed Lumos-app and Lumos-gateway

I've never used any IoT devices

9 Beginners

I've used some standalone IoT devices

8 Intermediates

I've configured some automation among IoT devices using IoT platforms

7 Experts

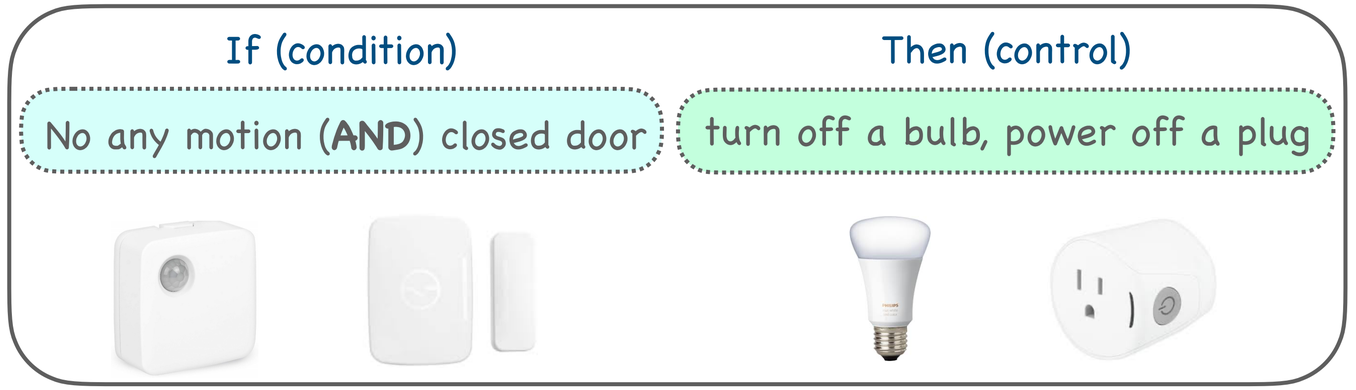
How easy is it for a user to configure interoperation rules using Lumos?

Evaluation

- **Missions**
  - **Five missions** that are based on common interoperation scenarios
  - Participants are assigned four missions **in random order**
- **Procedure**
  - The experiment took about one hour per participants
  - They learned how to use platform-native apps and Lumos during tutorial session
  - We **measured the number of clicks and time for mission**

Mission	# devices	Condition
Tutorial	2	-
Insteon	2	-
Stand-alone	3	-
SmartThings	4	AND
Wink	3	OR

Mission overview

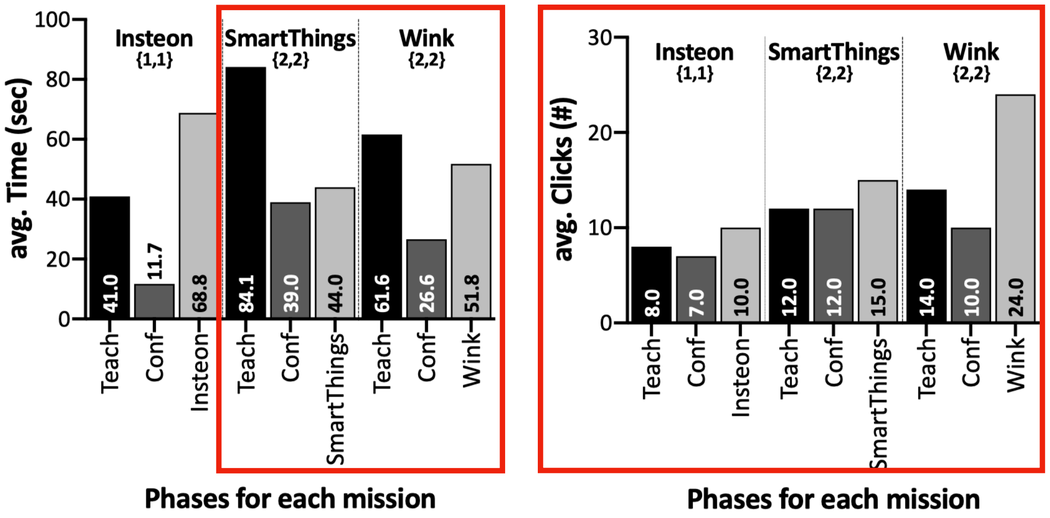


SmartThings mission

How easy is it for a user to configure interoperation rules using Lumos?

Evaluation

- **Overall results**
  - 23 out of the 24 (95.8%) participants succeeded in all four missions
  - One succeeded in three missions
- **Analysis**
  - Platform-native apps vs Lumos-app for Insteon, SmartThings, and Wink
  - In general, using Lumos-app for all missions except **Insteon tooks more time, and an equal or more number of clicks**
  - **Note that, the teaching results are reusable**
  - **Also, teaching phase can even be omitted using information sharing and automated re-learning**



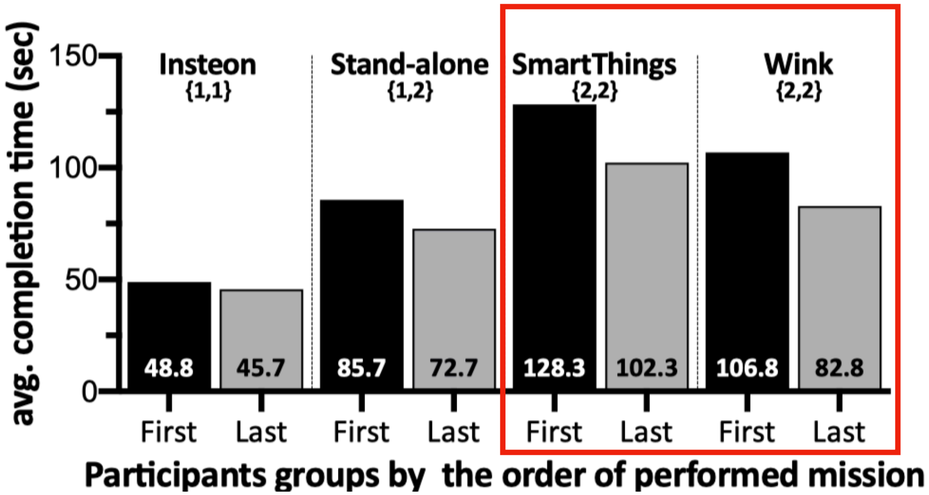
(a) The avg. completion time (b) The avg. completion click

The comparison of three platform-native apps and Lumos-app

How easy is it for a user to configure interoperation rules using Lumos?

Evaluation

- We look at whether the time to complete missions decreased as users gained more experience
  - Figure shows the average time required to complete each mission by two groups (“First” and “Last”)
  - “First” stands for a group that conducted a specific mission first
  - “Last” stands for a group that conducted a specific mission last
- **The average time of “Last” is smaller than “First”, which means that participants tend to obtain a better understanding with the last mission**
- **Note that the difference in average time between both is more noticeable for more complex missions (Wink and SmartThings)**



The average completion time (sec) grouped by the order that they conducted

Conclusion

- We posit that efforts that rely on vendor support or architectural changes face a fundamental challenge in deployment
- Lumos takes **a best-effort** approach that leverages information embedded in IoT apps and combines it with semantic information from users
  - **High coverage** in terms of controllability and visibility for IoT devices
  - **Reasonable effort** compared to popular IoT platforms