Automatic Composition in IoT Systems

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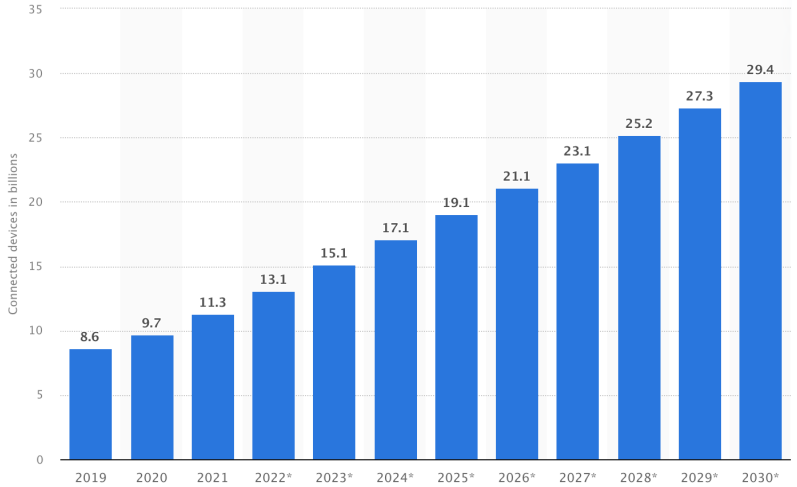
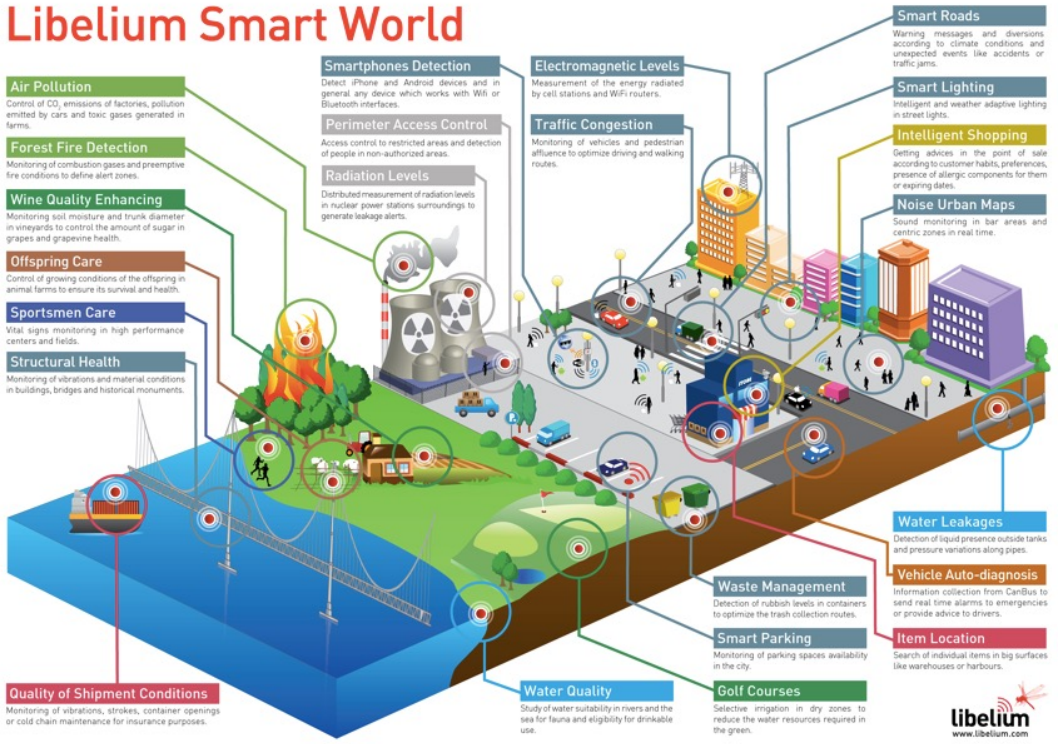
The Rise in IoT Uptake

- Technological advances
  - system-on-chip design and manufacturing
  - devices are highly available, affordable, small, power-efficient
  - network connectivity: LTE, 5G, WiFi, Zigbee, LoRaWAN
- Great progress in deploying applications over various fabrics
  - in situ sensing and actuating devices
- Lots of interesting verticals



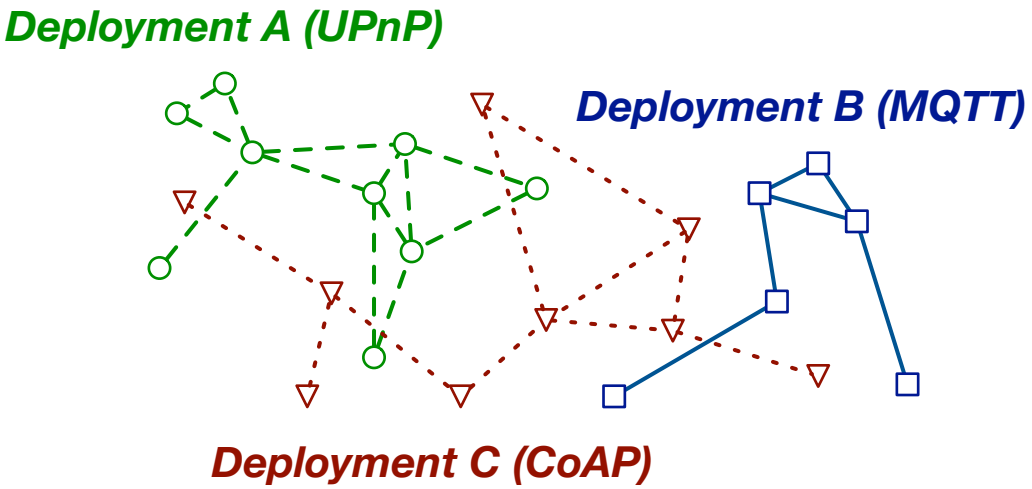
https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/



https://www.libelium.com/libeliumworld/top_50_iot_sensor_applications_ranking/

Problem Statement

- A variety of constituent systems
  - independently deployed
  - use proprietary APIs + data formats
  - co-exist in shared physical spaces
- Challenge:
  - heterogeneity makes it difficult to design, maintain and adapt *integrated systems*
  - system developers are overwhelmed with the amount of knowledge they need to acquire
  - difficult to future-proof applications for opportunistic interaction with other systems

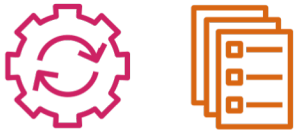


Approach Overview

- *Can we get IoT systems to talk to each other post-deployment?*
  - Yes, with a bit (lot!) of effort
- *How?*
  - Create a means to describe systems
  - Describe systems
  - Discover systems
  - Reason about composition
  - oh! and get users to write abstract workflows
  - … and sometimes we need to deploy mediators
- *Still more work to do?*
  - Always

High-level Vision

(4) System-of-system composition [SEAMS'20, FGCS'24]



(3) Workflow editing [IoT'22]

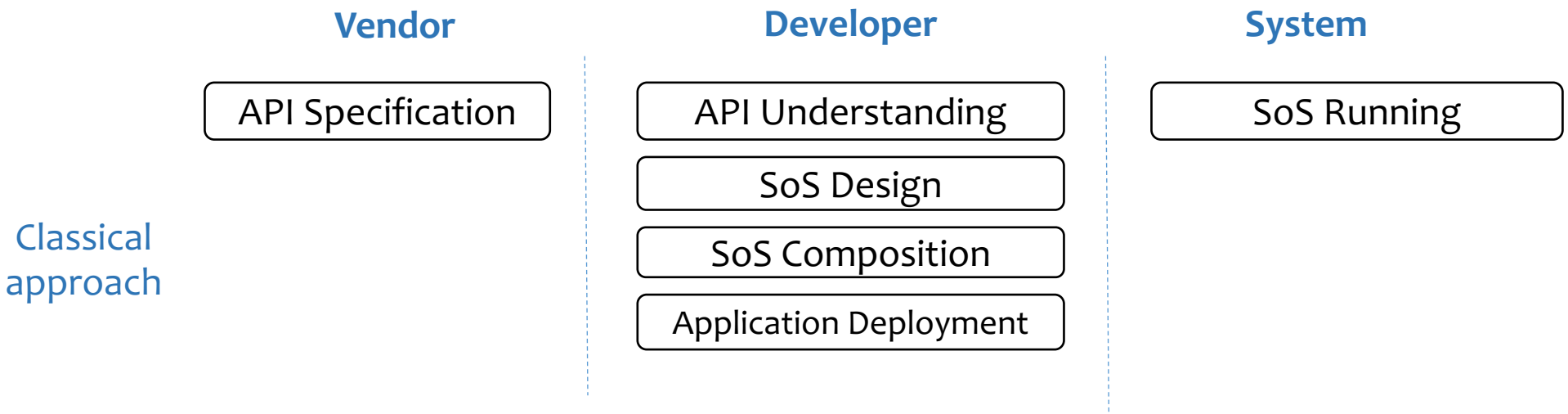
End User

(2) Holon description generation [FiCloud'22, ICWS'23]

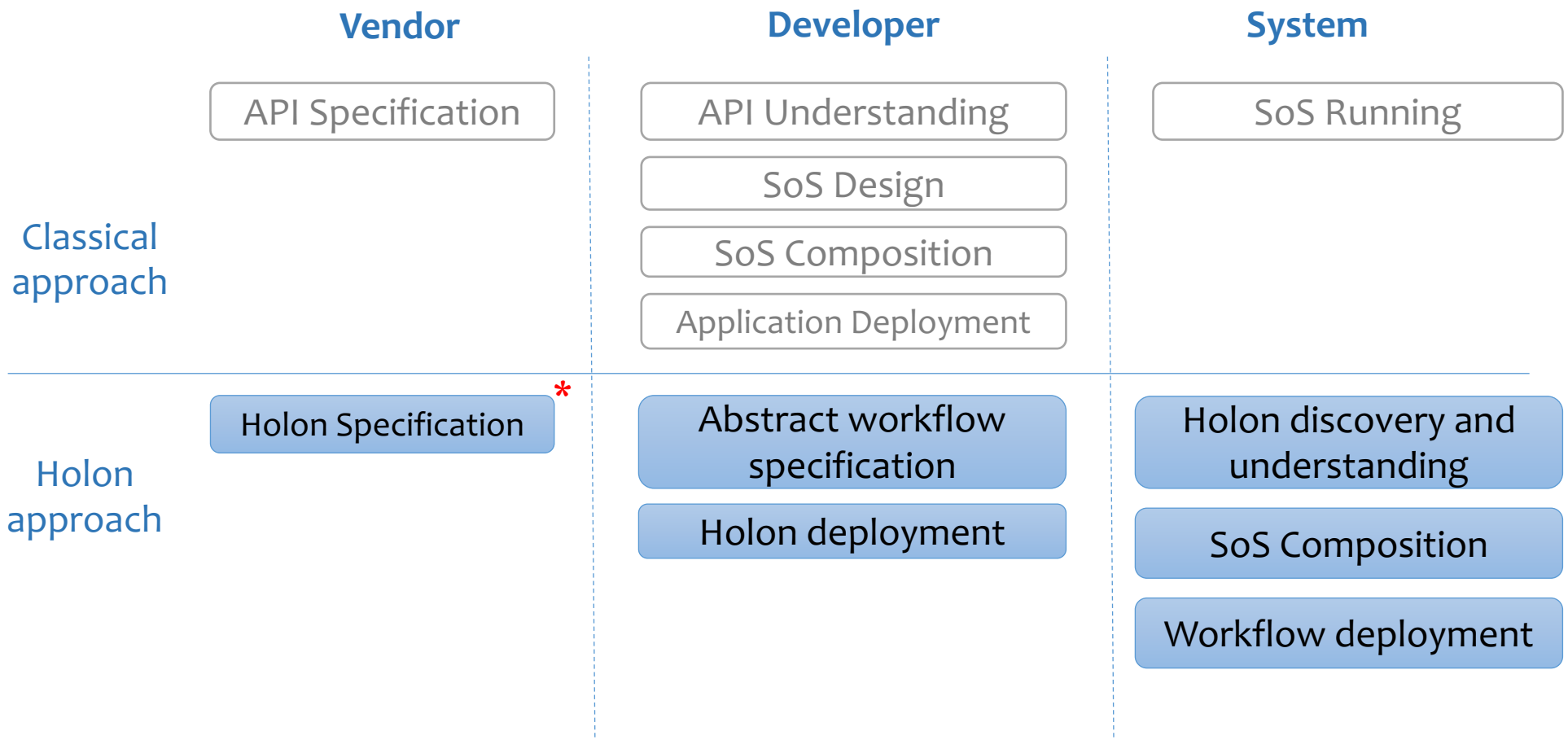
IoT Developer

(1) Device identification [ARM'15, ICIoT'20]

Problem and Solution



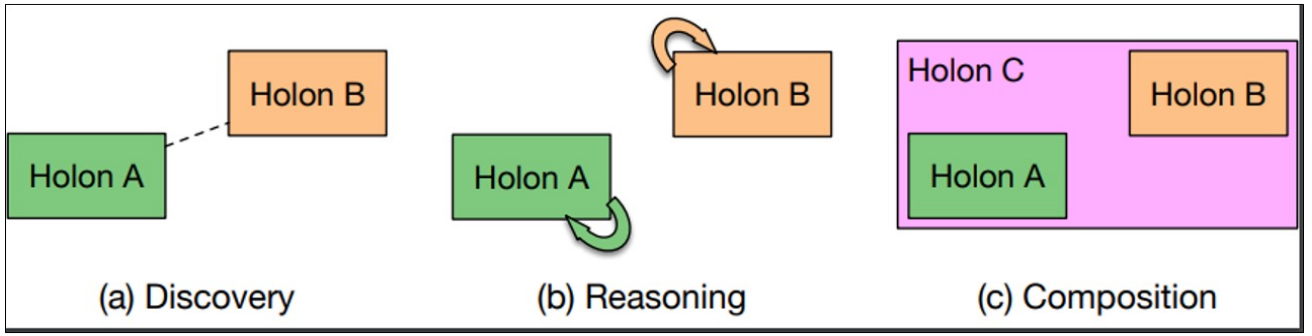
Problem and Solution



(1) Device identification

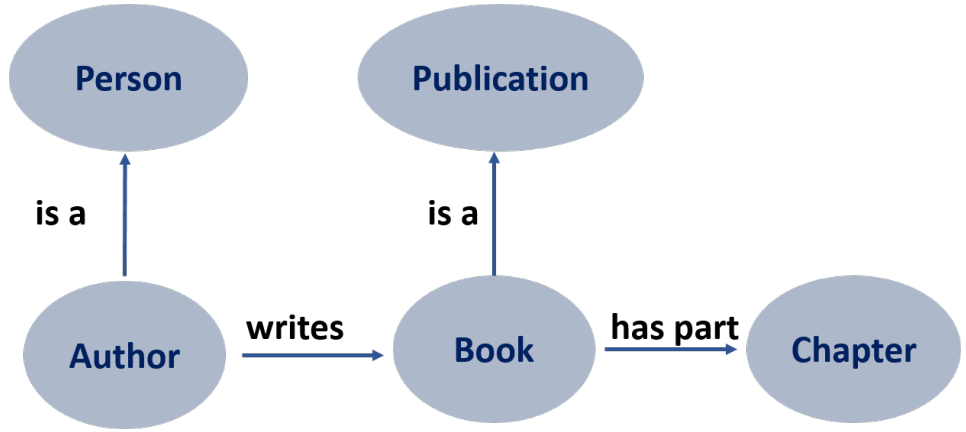
Holon?

- A *holon* is a self-describing system that appears as a whole when viewed from above whilst potentially comprising multiple subsystems when viewed from below
- A holon is described using an *ontology* that can be
  - advertised
  - discovered
  - used to reason about opportunistic composition

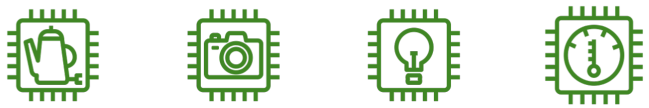


What is an ontology?

- An ontology is an abstract model of the world, or some domain
- An ontology introduces a vocabulary that is relevant to the domain
  - Explicitly defines concepts, properties, relations, and constraints

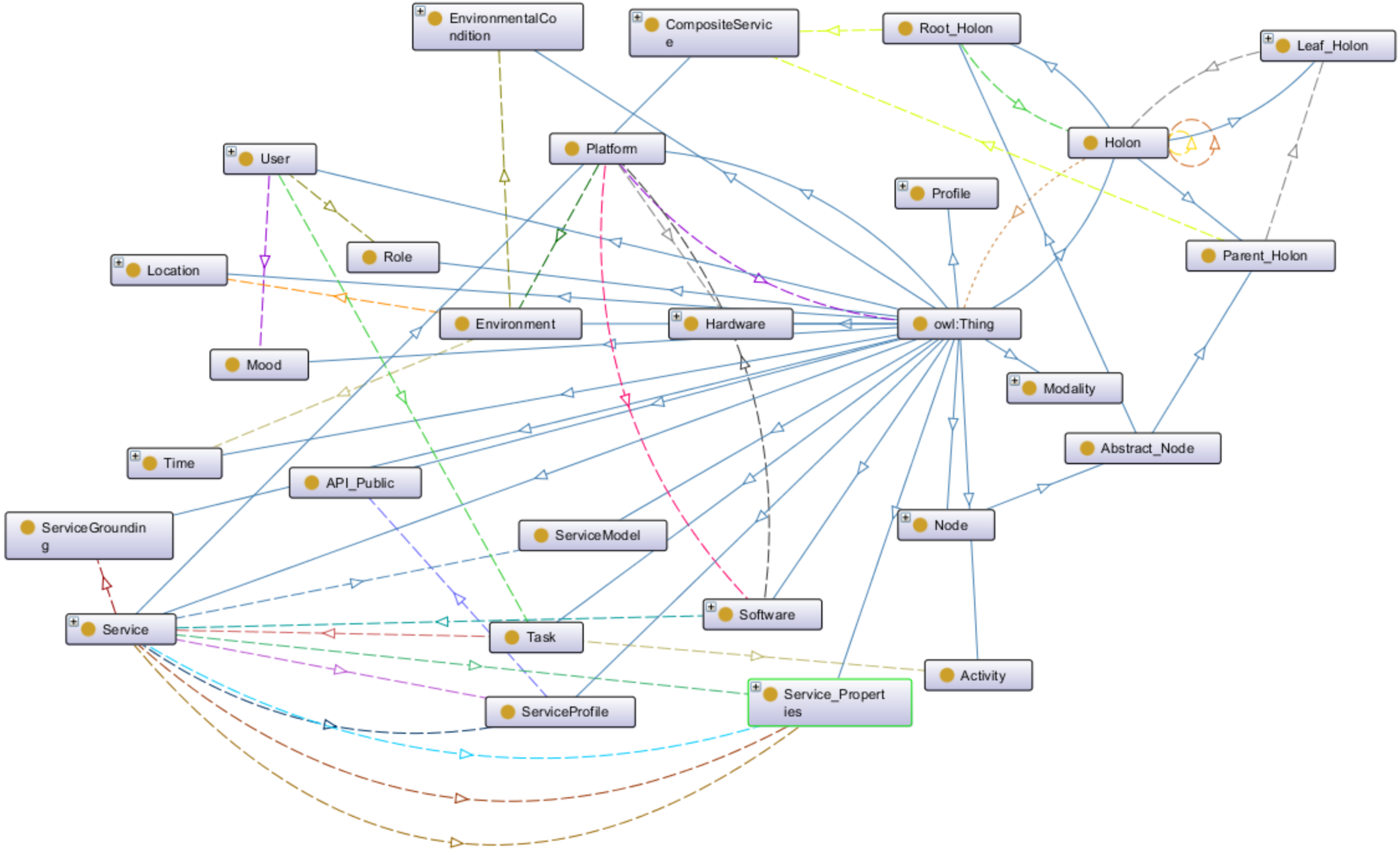


(1) Device identification

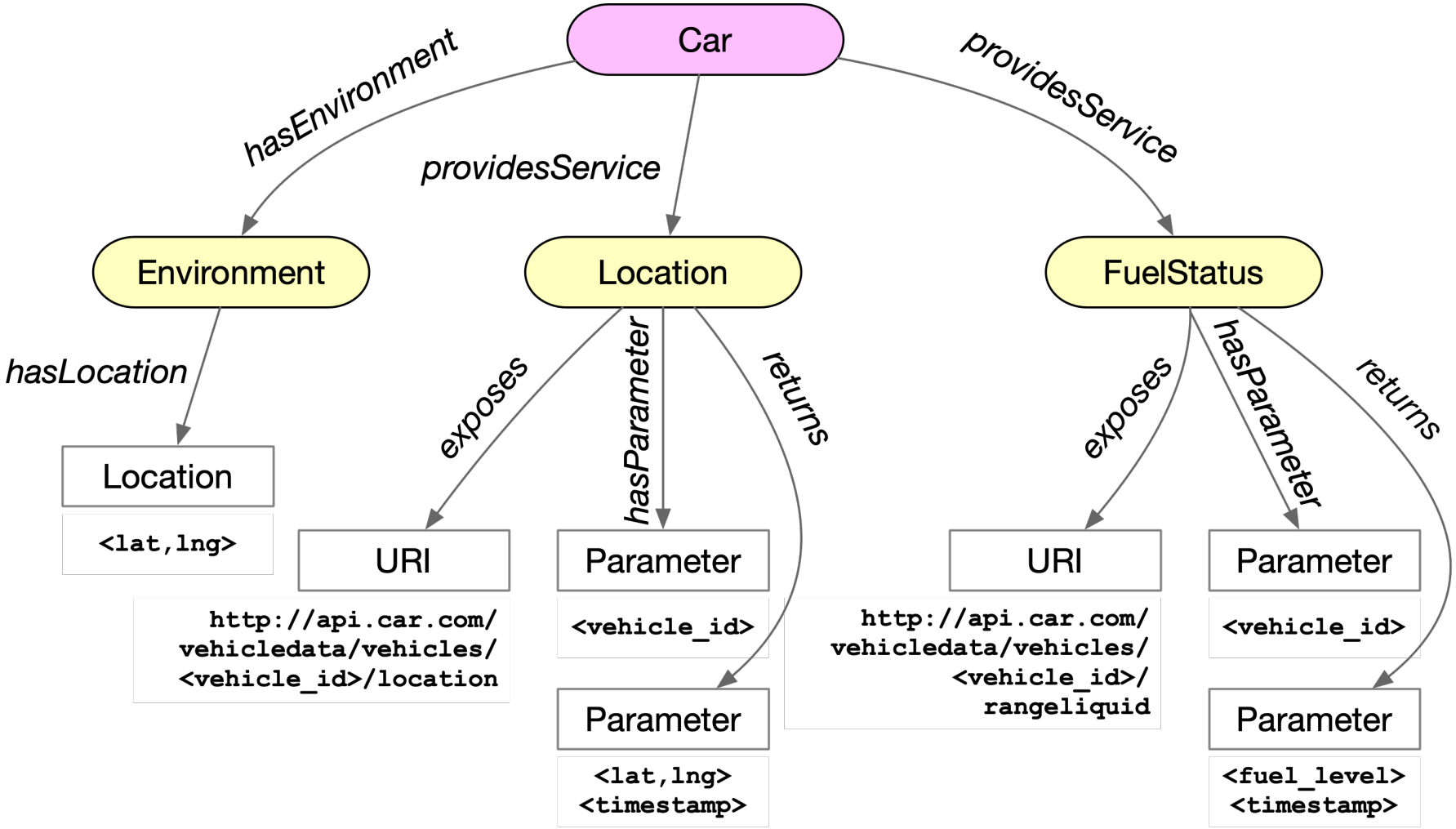


Specifying a Holon

- HOLON:
  - has parent (**holon**); has children (**holons**); supports **services**
  - Membership **properties**: has Children, is Member
  - Physical **properties**: power level; location; mobile; firmware; …
- SERVICE:
  - requires properties; desires properties; guarantees properties; may provide properties; exposes API
- PROPERTY: *(domain-specific)*
  - e.g. smart home: sensing temperature, humidity, motion; data storage; controlling climate, doors, windows, curtains; …

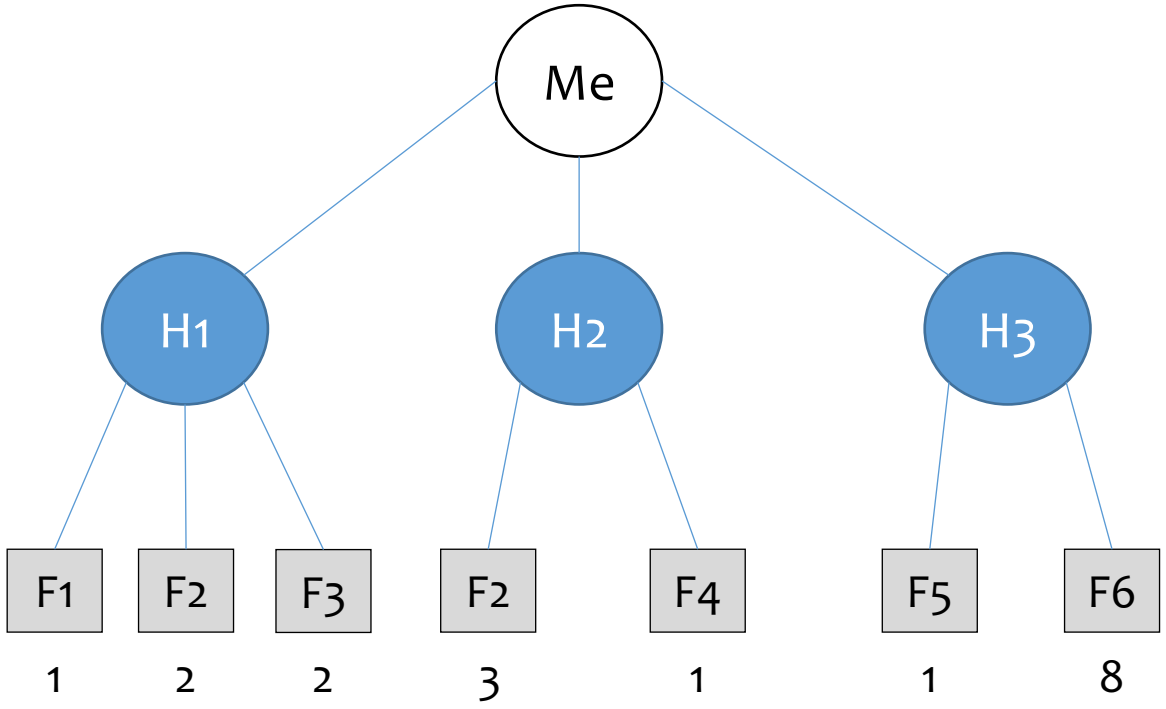

EnvironmentalCondition
CompositeService
Root_Holon
Leaf_Holon
Holon
Platform
User
Profile
Parent_Holon
Location
Role
Environment
Hardware
owl:Thing
Mood
Modality
Time
Abstract_Node
API_Public
ServiceGrounding
ServiceModel
Node
Software
Service
Task
Activity
Service_Properties
ServiceProfile

(1) Device identification



Composition

- The composition model is represented as a weighted tree of depth three



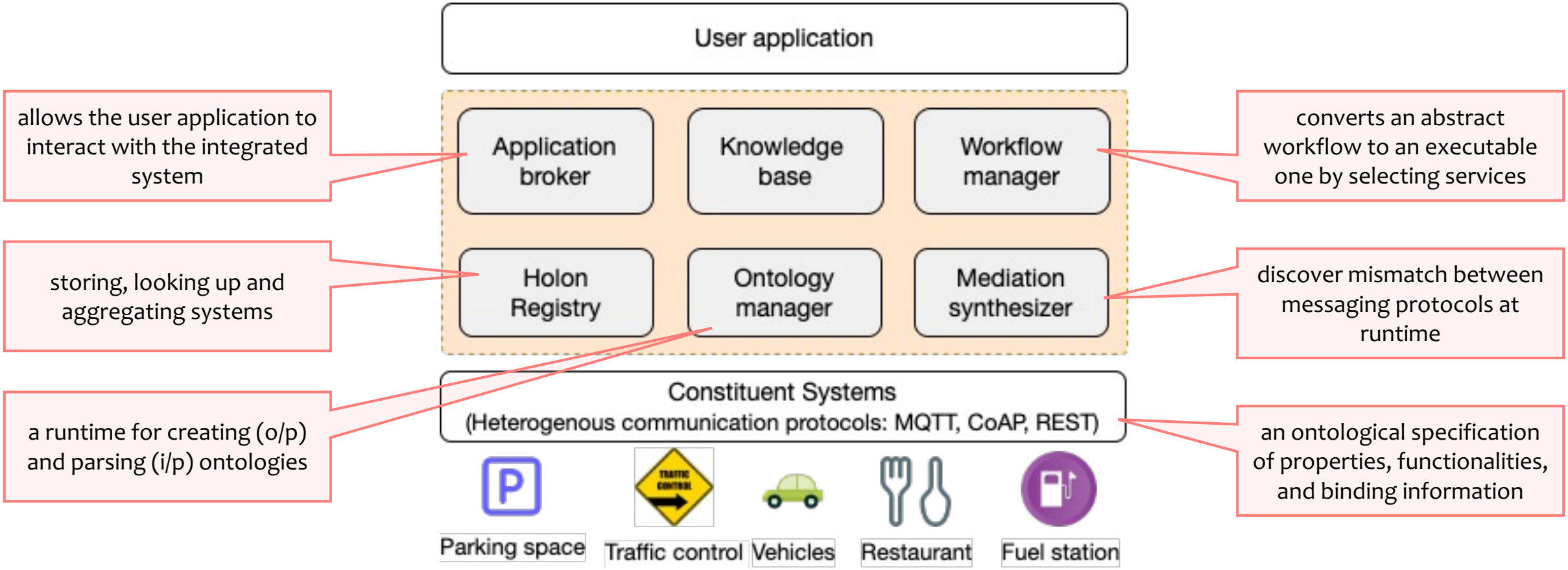
Level 1: The holon itself

Level 2: Holons that are directly reachable by the root holon

Level 3: Detected functionalities

Cost of accessing the functionality

Hetero-Genius Architecture

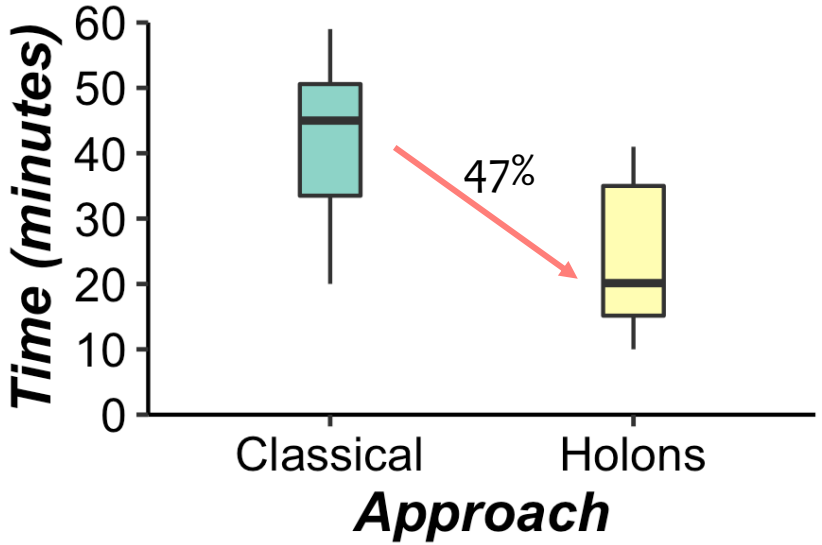


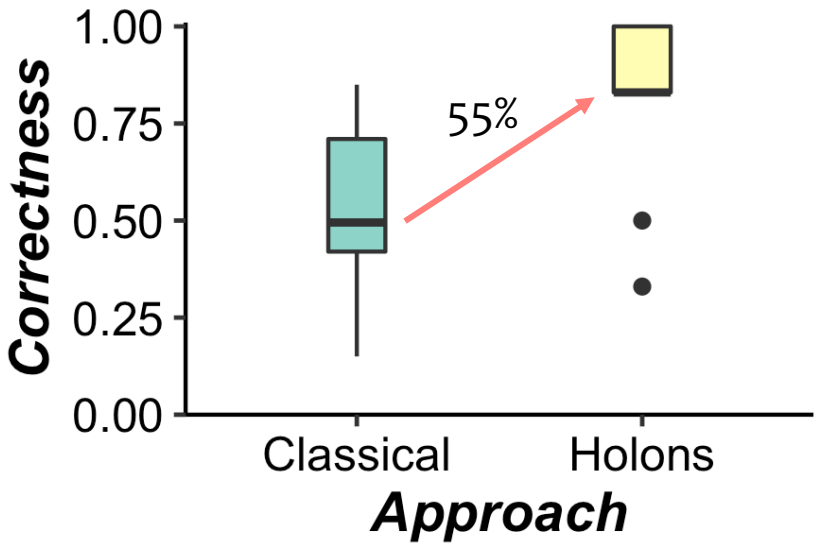
Sample Response – Classical

```
String vehicleId = "123";
int fuelThreshold = 111;
Location locationToNavigate; //assume Location data format exists
String token = ""; //authentication todo
String resultFuel = call("https://api.mercedes-benz.com/vehicledata/v2/vehicles/vehicleId/resources/rangeliquid", token);
int factFuel = JsonParser.parse(resultFuel).get("rangeLiquid").get("value");
if (factFuel <= fuelThreshold) {
    String location = "" //find location todo
    String resultStations = call("https://api/alt-fuel-stations/v1/nearest.format?parameters", location);
    double factLatitude = JsonParser.parse(resultStations).get("latitude");
    double factLongitude = JsonParser.parse(resultStations).get("longitude");
    locationToNavigate = find(factLatitude, factLongitude); //assume find function exists
}
String resultRestaurants = call("https://foodbukka.herokuapp.com/api/v1/restaurant");
String[] factResuatrants = JsonParser.parse(resultrestaurants).get("businessName");
String selectedRestaurant;
if (selectedResuarant.equals("Foodfusion") {
    String FoodfusionToken = "";
    String restaurant = "Foodfusion";
    int noOfPersons = 1;
    Date bookingFrom = Date.now;
    String resultFoodfusion = call("https://foodfusion/booking", FoodfusionToken, restaurant, noOfPersons, bookingFrom);
    String factFoodfusion = JsonParser.parse(resultFoodfusion).get("statusCode");
    if (!"OK".equals(factFoodfusion)) {
        //repeat booking
    } else {
        //locationToNavigate = this restaurant
    }
} else if (selectedResuarant.equals("Hathaway") {
    String name = "John";
    String number = 1;
    String email = "john@gmail.com";
    Date date = Date.now;
    String resultHathaway = call("https://api.hathawayfood.com/booktable", name, number, email, date);
    String factHathaway = JsonParser.parse(resultHathaway).get("statusCode");
    if (!"OK".equals(factHathaway)) {
        //repeat booking
    } else {
        //locationToNavigate = this restaurant
    }
}
//navigate to locationToNavigate
```

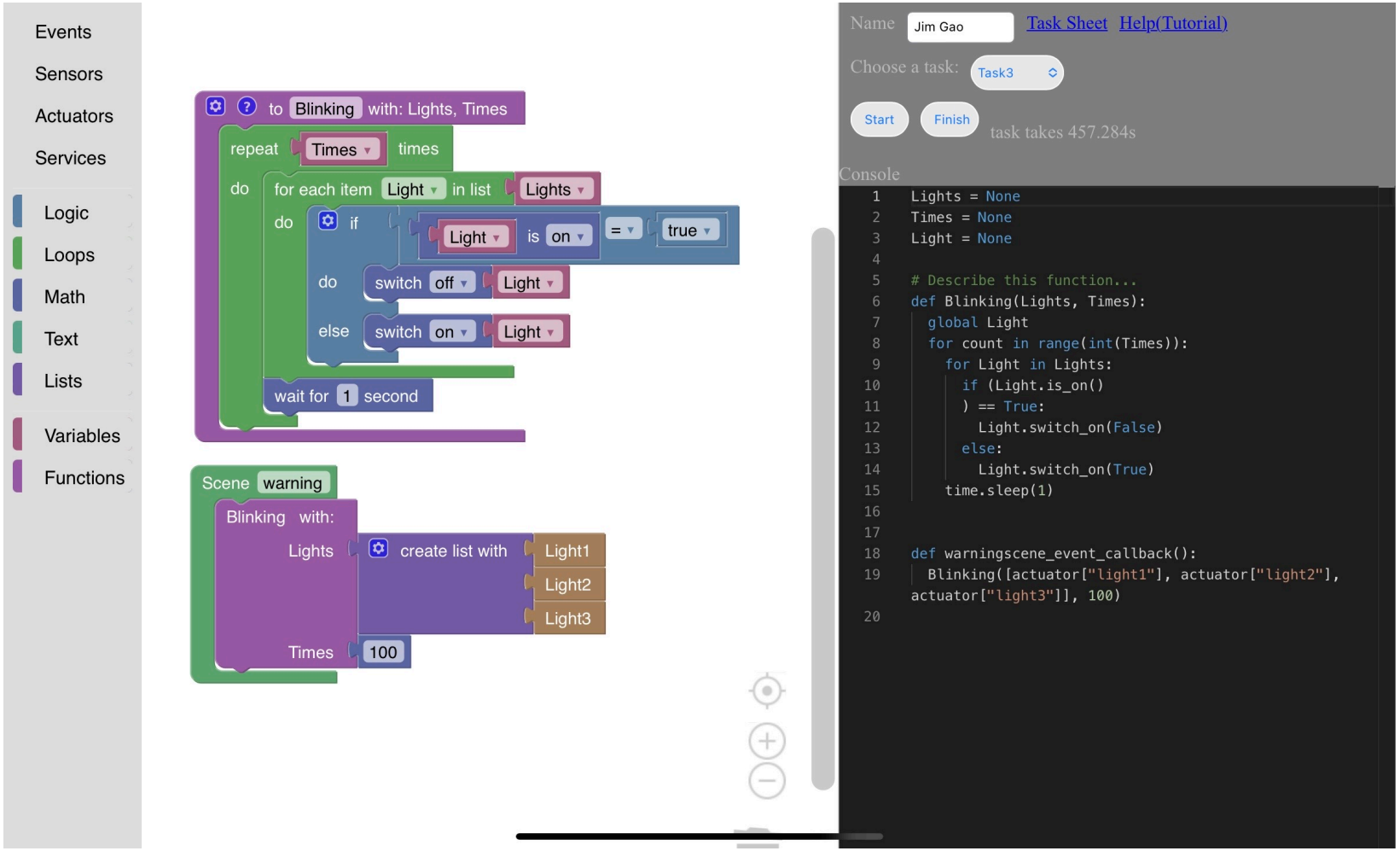
Sample Response – Holon DSL

```
String vehicleResult = call("http://holons/registry/getHolon?holonID");
vehicle= Holon.parse(vehicleResult);
connection = vehicle.call(AUTHENTICATE);
fuel= vehicle.call(CAR_RANGE);
threshold = 5;

if(fuel < threshold ) {
    String stationResult= call("http://holons/registry/getHolon?type=station&longitude=longitudeValue&latitude=latitudeValue)";
    fuelStation= Holon.parse(stationResult);
    echo "Fuel Station";
}

String restaurantResult= call("http://holons/registry/getHolon?type=restaurant&longitude=longitudeValue&latitude=latitudeValue");
restaurant= Holon.parse(restaurantResult);

restaurant.call(BOOK_TABLE);
```



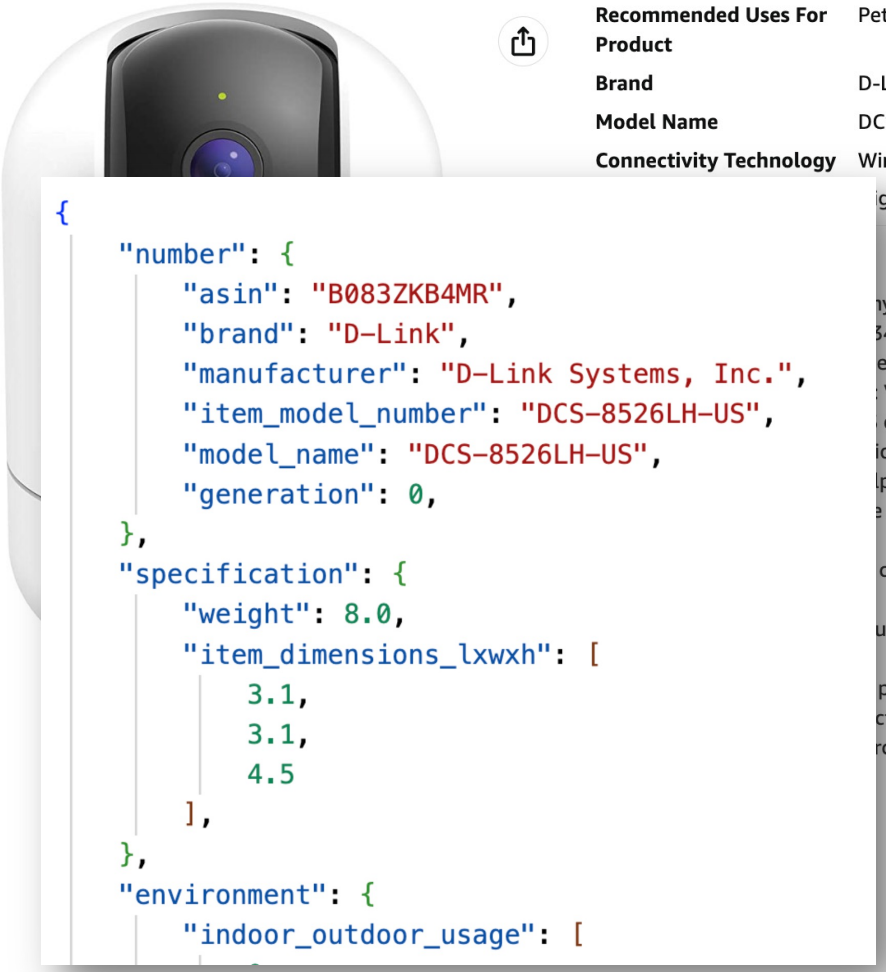


Graphical Workflow – HolonCraft



Knowledge Extraction

(2) Holon description generation



Parameters

Key-value pairs that include parameters and device properties

Functional Description

Several paragraphs of unstructured text, describing the functions of the device

(2) Holon description generation

Knowledge Extraction

- Robustly optimized BERT approach (RoBERTa), a model using the Stanford Question Answering Dataset (SQuAD.0)
- Experiment on 140 devices
  - Learning rate: 5e-5
  - Batch size 32, Epoch 20

	Precision	Recall	F1
Parameter	98.17%	94.81%	96.11%
Function description	94.64%	78.00%	84.19%
Overall Holon description	96.72%	87.53%	91.90%

#	Device Category	Number of Devices
1	Smart camera	28
2	Speaker	17
3	Smart plug	16
4	Smart bulb	15
5	TV	15
6	Sensor	11
7	Smart coffee maker	8
8	Smart cooker	8
9	Smart washer	7
10	Smart refrigerator	5
11	Smart vacuum cleaner	5
12	Smart toilet	5

References

https://yelkhatib.github.io/

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Challenges

- IoT-motivated ontology
  - Evaluated in contexts like smart home, IoV, etc.
  - Cross ecosystem boundaries
- Discovery through announcement
  - Architecture relies on systems advertising themselves
  - Passive discovery still possible, but more challenging
- Trust
  - Assume that it is safe to compose
  - Assume that we are not compromising inherent system

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