A Middleware for Automatic Composition and Mediation in IoT Systems

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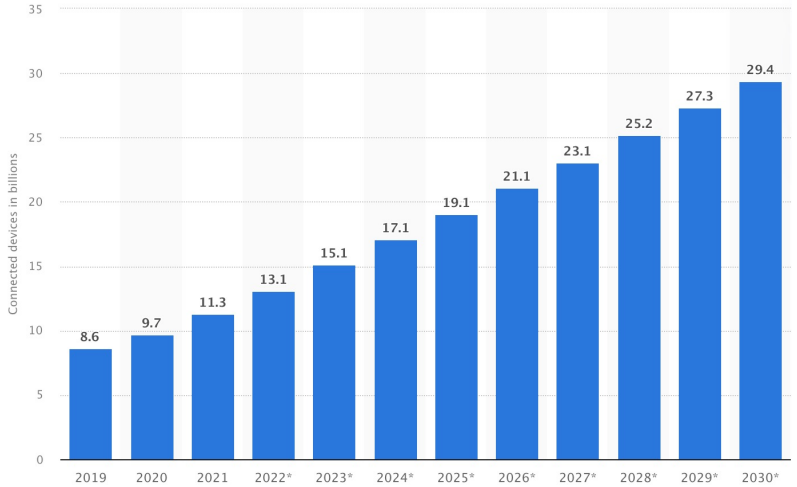
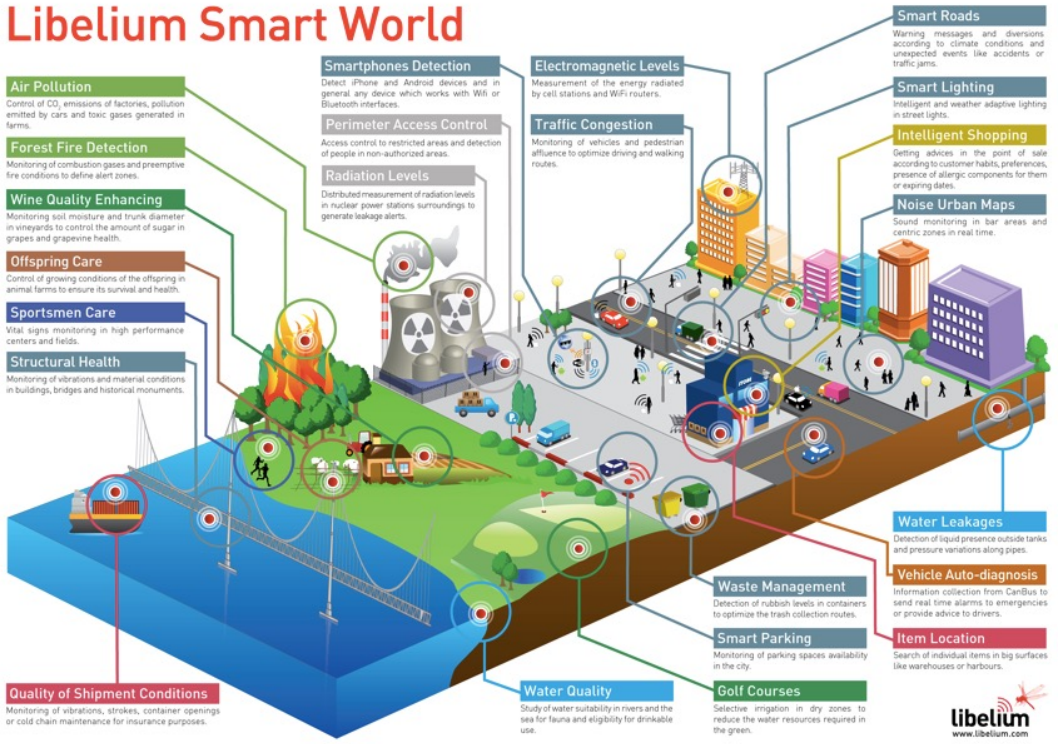
ABC
ADAPTIVE BROKERAGE FOR THE CLOUD

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



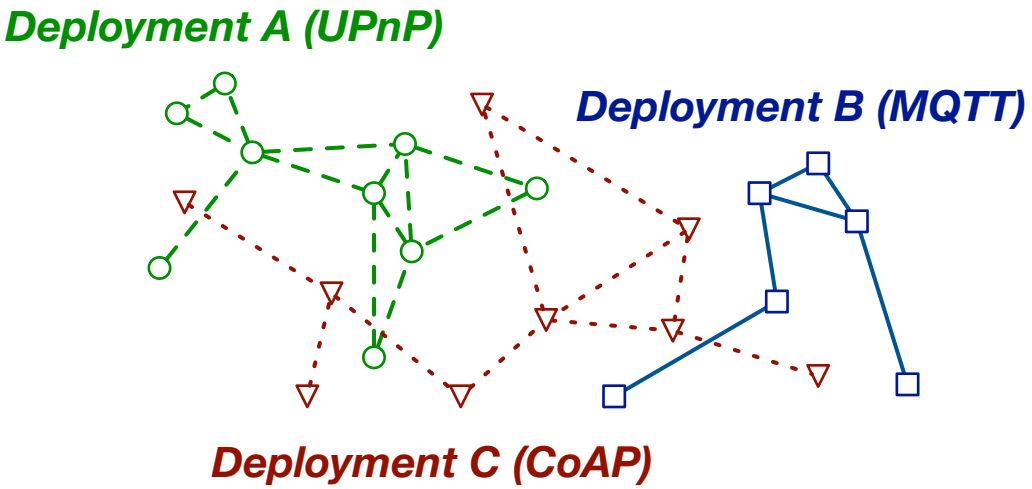
https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/



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 IoT 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

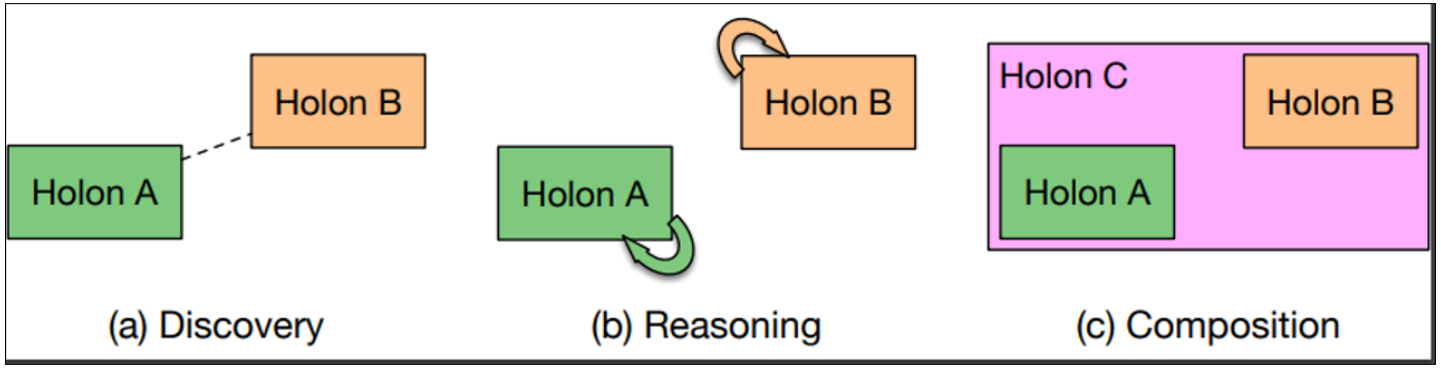


Research Focus

- Aim:
  - allow IoT development at a high-level as an *abstract workflow*
  - enable automated opportunistic construction and mediation in IoT contexts
- Objectives:
  - design development tools for high-level application logic
  - identify independent systems with their unique characteristics
  - recognize the need to compose with other systems
  - detect the need for mediation logistics
  - set in action any support roles needed to actuate mediation

Holon?

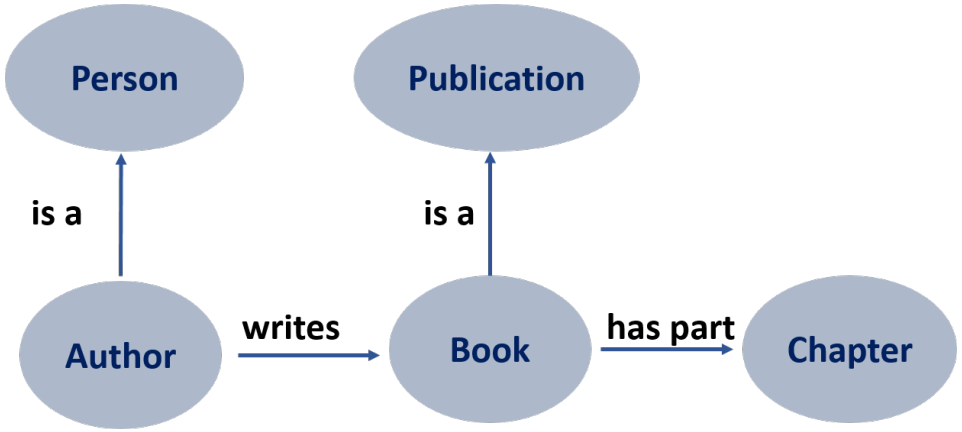
- A *holon* is a self-describing system that appears as a whole when viewed from above whilst potentially comprising multiple subsystems when viewed from below
- A holon is described using an ontology that can be
  - advertised
  - discovered
  - used to reason about opportunistic composition



Gordon Blair, Yérom-David Bromberg, Geoff Coulson, Yehia Elkhatib, Laurent Réveillère, Heverson B. Ribeiro, Etienne Rivière, and François Taïani, “Holons: Towards a Systematic Approach to Composing Systems of Systems”, Workshop on Adaptive and Reflective Middleware, 2015.

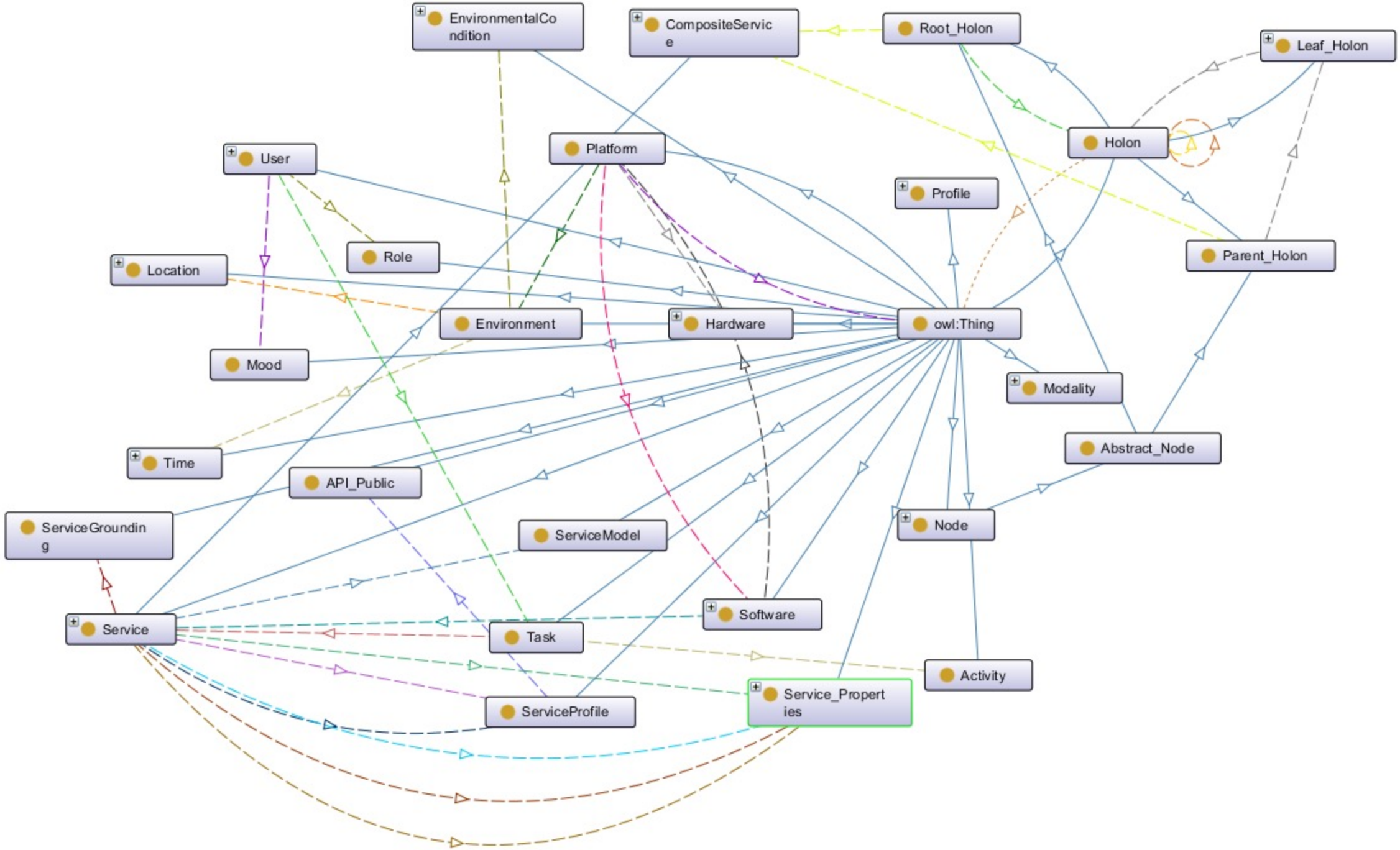
What is an ontology?

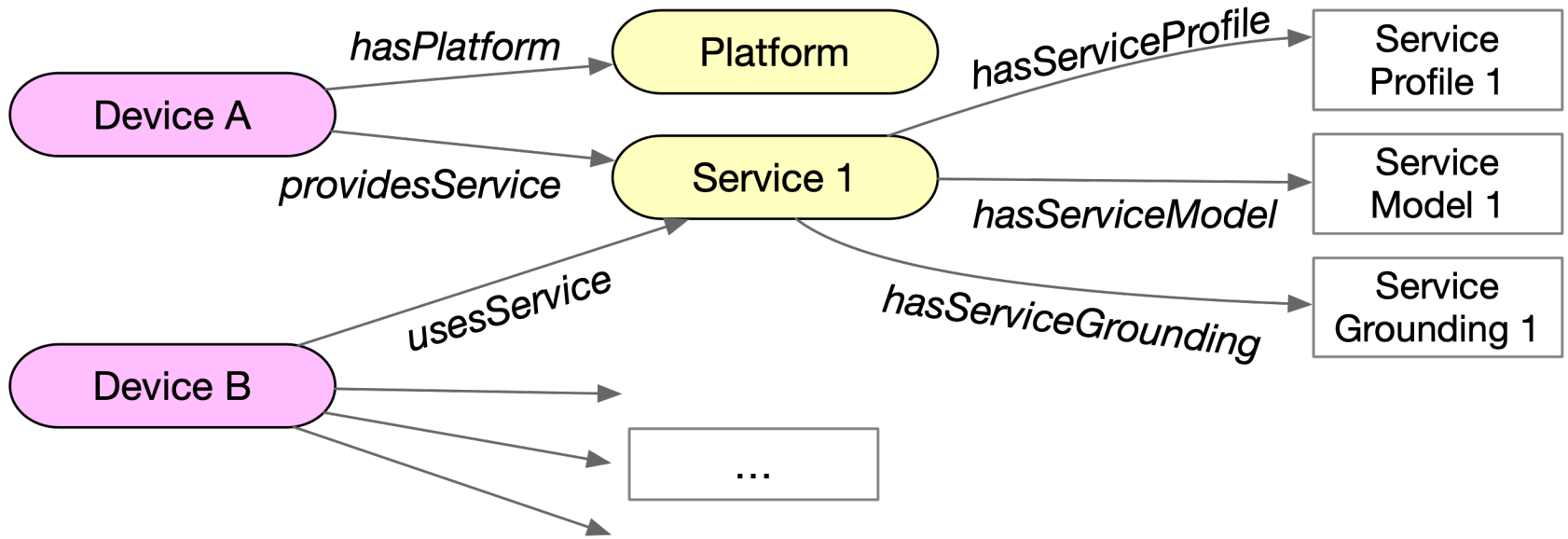
- An ontology is an abstract model of the world, or some domain
- An ontology introduces a vocabulary that is relevant to the domain
  - Explicitly defines concepts, properties, relations, and constraints found in the domain

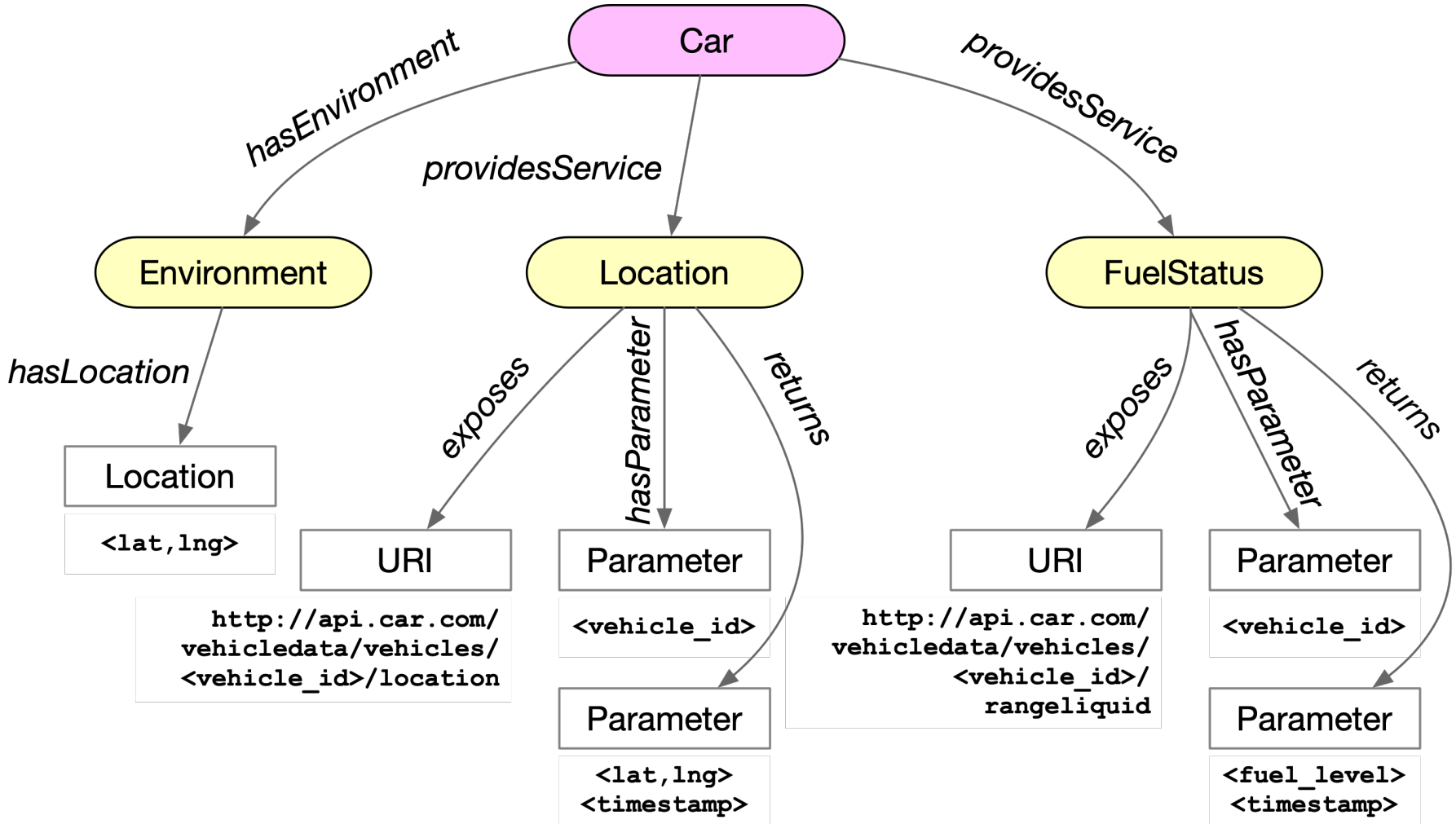


Specifying a Holon – Upper classes

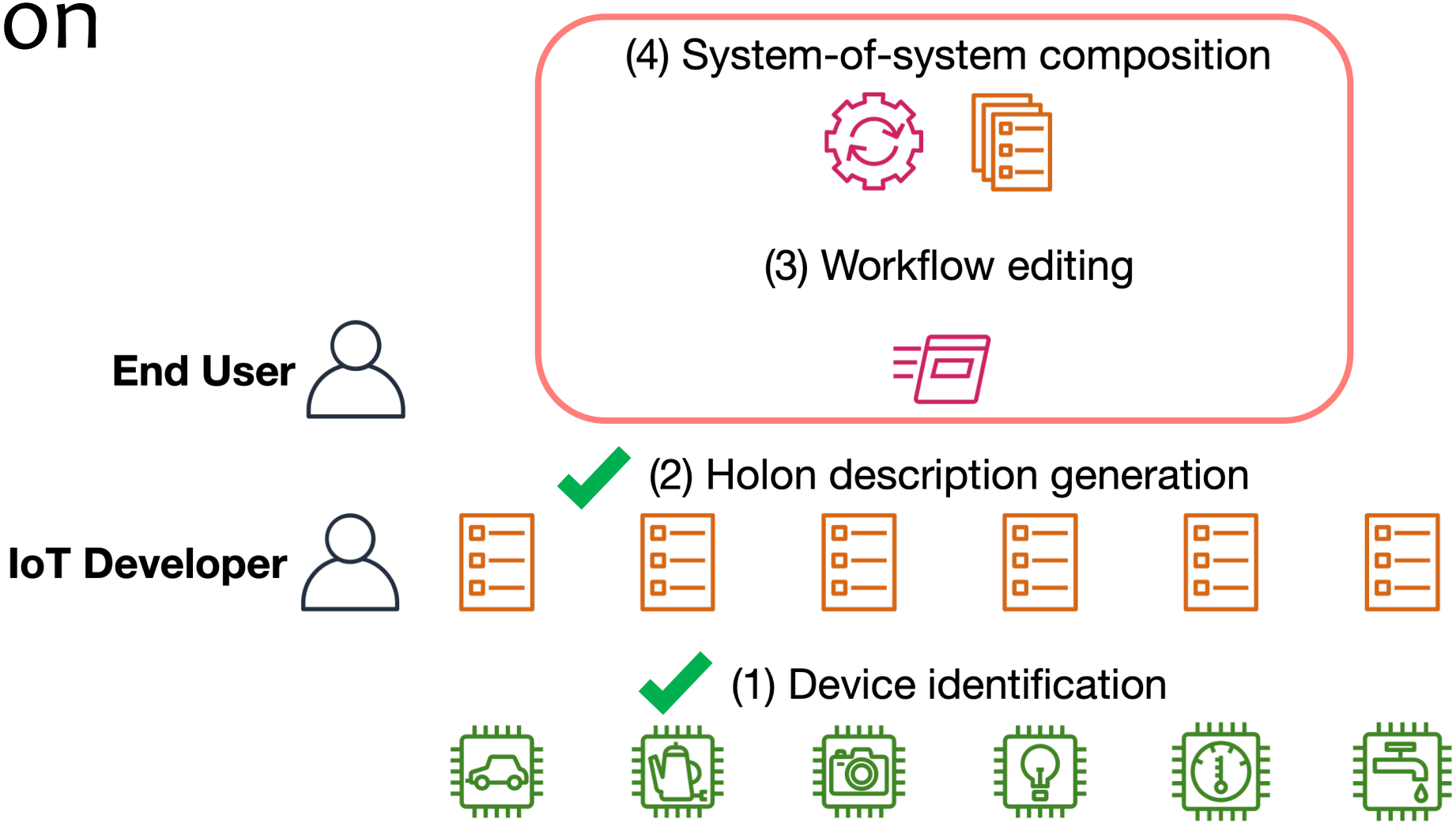
- HOLON:
  - has parent (**holon**); has children (**holons**); supports **services**
  - Membership **properties**: has Children, is Member
  - Physical Properties: power level; location; mobile; firmware; …
- SERVICE:
  - requires properties; desires properties; guarantees properties; may provide properties; 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


Device A
Device B
hasPlatform
providesService
usesService
Platform
Service 1
...
hasServiceProfile
hasServiceModel
hasServiceGrounding
Service Profile 1
Service Model 1
Service Grounding 1


Car
hasEnvironment
providesService
providesService
Environment
Location
FuelStatus
hasLocation
exposes
hasParameter
returns
exposes
hasParameter
returns
Location
<lat,lng>
URI
http://api.car.com/
vehicledata/vehicles/
<vehicle_id>/location
Parameter
<vehicle_id>
Parameter
<lat,lng>
<timestamp>
URI
http://api.car.com/
vehicledata/vehicles/
<vehicle_id>/
rangeliquid
Parameter
<vehicle_id>
Parameter
<fuel_level>
<timestamp>

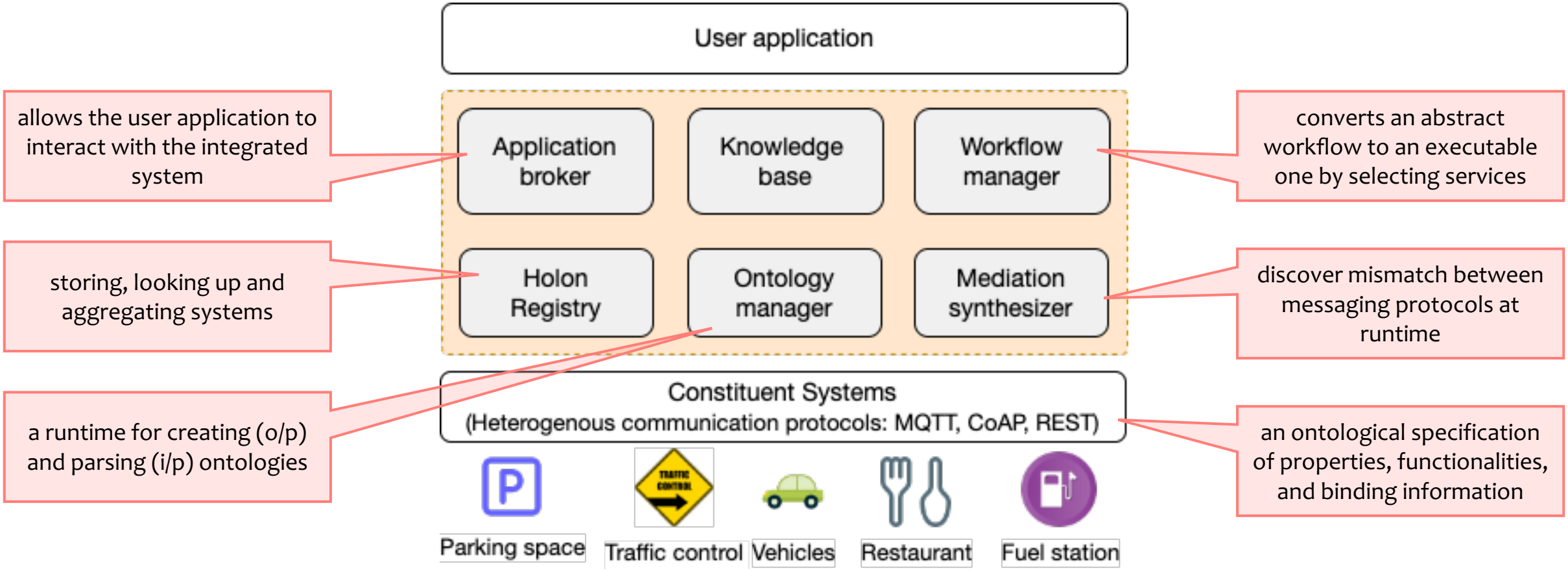
Vision


(4) System-of-system composition
(3) Workflow editing
End User
(2) Holon description generation
IoT Developer
(1) Device identification

Approach

- Apply the concept of ***holons*** to represent systems recursively
- Build an architecture for automated composition of holons
  - discover other systems and their services
  - opportunistically integrate with them to satisfy a user request
  - detect the need for mediation
  - create mediators at runtime for direct interaction with other systems
- Evaluate using a real-world Internet of Vehicles (IoV) scenario
  - productivity of and value added to developers through a user study

Hetero-Genius Architecture

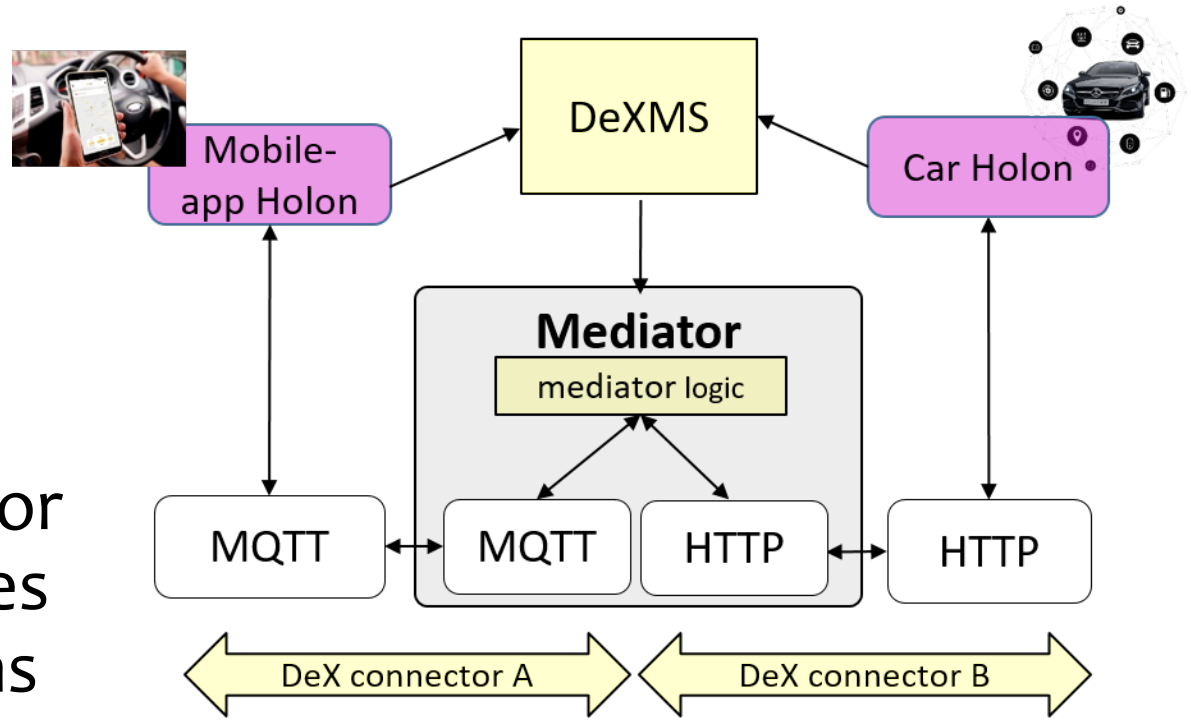


Concertizing an Abstract Workflow

- Find physical systems that provide the required services
- AB queries the HR for descriptions of suitable systems
- AB verifies the response to match:
  - the annotations of the required services (specified in the workflow), with
  - the annotations of the provided services (specified in the system's holon)
- Return the binding information of each service to the user application, along with messaging info (API, protocol)

Addressing Interoperability

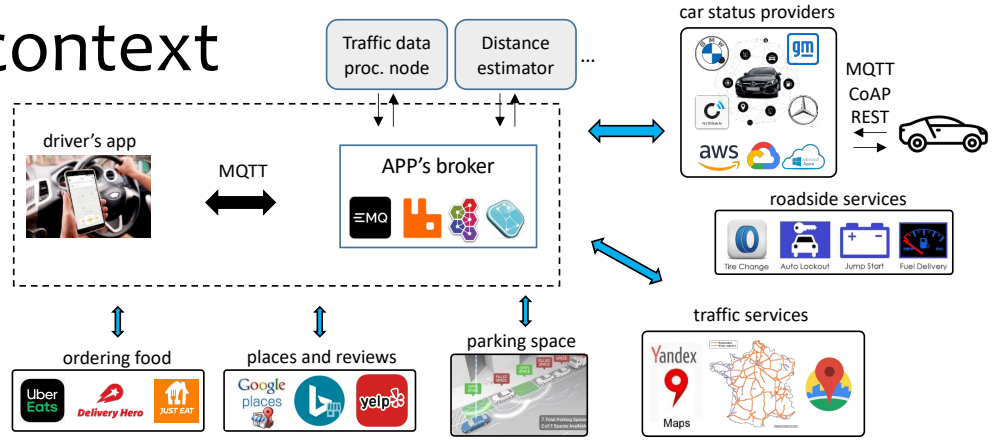
- Systems have different protocols, data-serialization formats, and interaction paradigms
- AB can detect this from holon descriptions
- We use the Data eXchange Mediator Synthesizer (DeXMS), which creates bridges between divergent systems



Georgios Bouloukakis, Nikolaos Georgantas, Patient Ntumba, and Valérie Issarny, “Automated Synthesis of Mediators for Middleware-layer Protocol Inter- operability in the IoT”, Future Generation Computer Systems 101 (2019), 1271 – 1294, 2019.

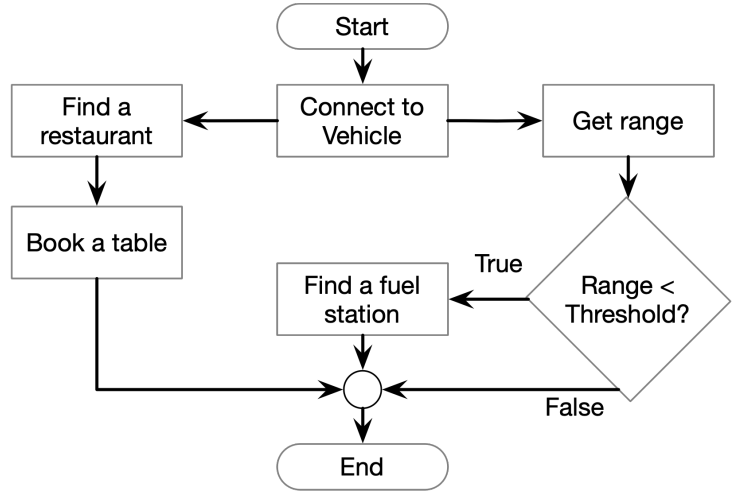
Evaluation – Overview

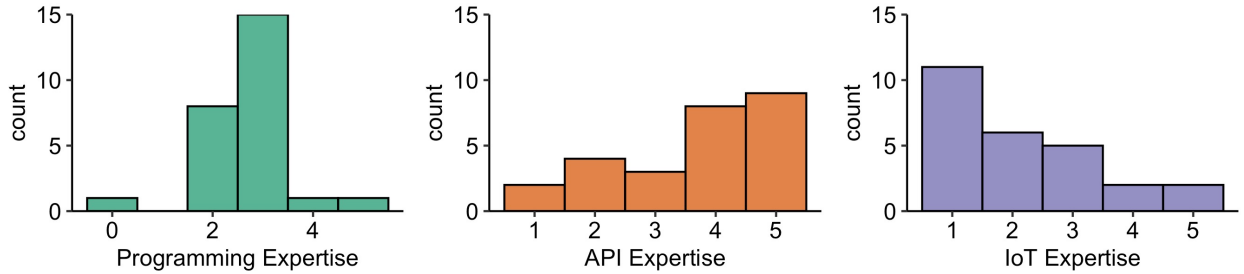
- Aim to measure:
  - Productivity – time required to develop application logic
  - Correctness – adherence to usage of correct APIs
- Strategy: user experiments from an IoV context
  - stop for food (and fuel?) on a car journey
- 4 systems:
  - car – provides **`fuelStatus`**, **`location`**
  - fuel station – provides **`location`**
  - restaurant – provides **`menu`**, **`details`** (location, contact details, etc)
  - traffic control unit (TCU) – provides **`trafficStatus`**



Evaluation – Procedure

- Simple workflow (round robin allocation)
  - classic – use native APIs to implement functionality
  - using holons – learn annotations and implement
- Duration: up to 1 hour (+5 minutes intro)
- Reward: £15 Amazon voucher
- Recruitment: 26 participants
  - researchers, students, developers at campuses, local startups, incubators
- Self-reported expertise levels:





Sample Response – Classical

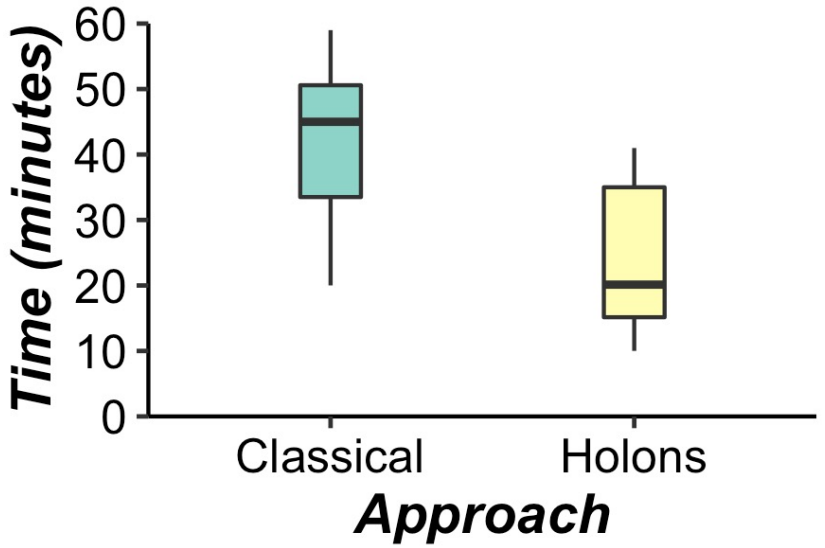
```
String vehicleId = "123";
int fuelThreshold = 111;
Location locationToNavigate; //assume Location data format exists
String token = ""; //authentication todo
String resultFuel = call("https://api.mercedes-benz.com/vehicledata/v2/vehicles/vehicleId/resources/rangeliquid", token);
int factFuel = JsonParser.parse(resultFuel).get("rangeLiquid").get("value");
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

```
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);
```

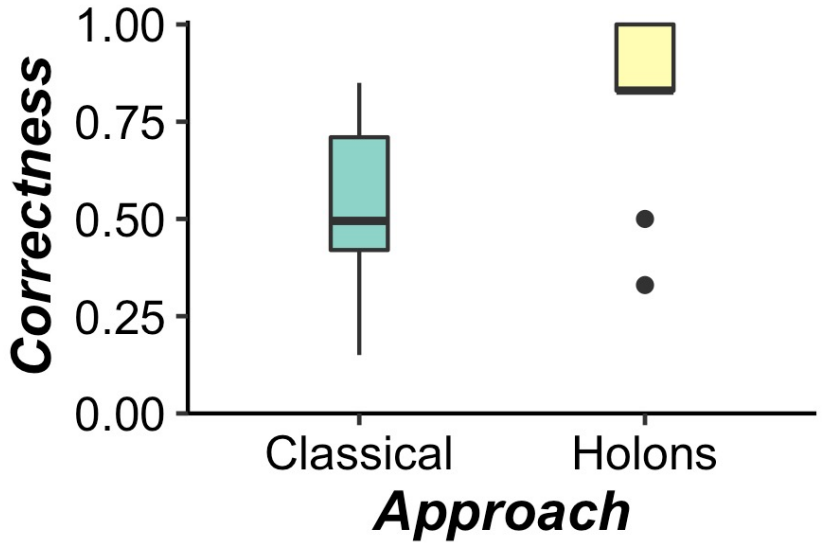
Results – Productivity

- Average / median time to complete task
  - classic – 43.82 / 45.30
  - holons – 23.25 / 20.13
- Level of improvement varies according to the level of programming expertise
- Overall, we improve productivity by 47%



Results – Correctness

- We manually inspect participant code for
  - correct usage of the required APIs
  - adherence to realizing the given workflow
- Calculate percentage score
  - one point for each correct API
  - one point per milestone code statement
- Average / median % correctness score
  - classic – 54.25 / 49.50
  - holons – 84.35 / 83.00
- Overall, we improve correctness by 55%



FAQ/Cs

- You can't have "one ontology to rule them all"
  - just one means, with a tradeoff between generality and usefulness
  - overhead is not insurmountable as evidenced by our experiments
  - we do not expect manufacturers to change anything
- Developer overhead still too high, e.g. end users
  - developed an approach using graphical programming techniques

    Zhuo Wang, Yehia Elkhatib, and Abdessalam Elhabbash, "HolonCraft – An Architecture for Dynamic Construction of Smart Home Workflows", Conf on Future Internet of Things and Cloud (FiCloud), IEEE, August 2022.
  - developed NLP method to automatically generate Holon descriptions

    Ziyu Zhang, Yehia Elkhatib, Abdessalam Elhabbash, "An NLP Method for Automated Generation of Smart Home Ontological System Description for Reasoning and Composition", *(in progress)*

Conclusion and Next Steps

- Ontology-based architecture for composition, reasoning, mediation
- Evaluated efficacy in a IoV user study
- Next:
  - Quantitative evaluation to investigate effectiveness (latency) and computational overhead (CPU, memory, messages) at different scales
  - Tools for generalising to other IoT ecosystems
    - wildfire detection, disaster rescue, dynamic cluster management

Thanks for your attention!

https://yelkhatib.github.io/


Abdessalam


Yehia


Georgios


Maria