HIVEMIND: A HARDWARE-SOFTWARE SYSTEM STACK FOR SERVERLESS EDGE SWARMS

Liam Patterson, David Pigorovsky, Brian Dempsey,
Nikita Lazarev, Aditya Shah, Clara Steinhoff,
Ariana Bruno, Justin Hu, and Christina Delimitrou

Cornell University

sail.ece.cornell.edu

ISCA'22 – June 22nd 2022

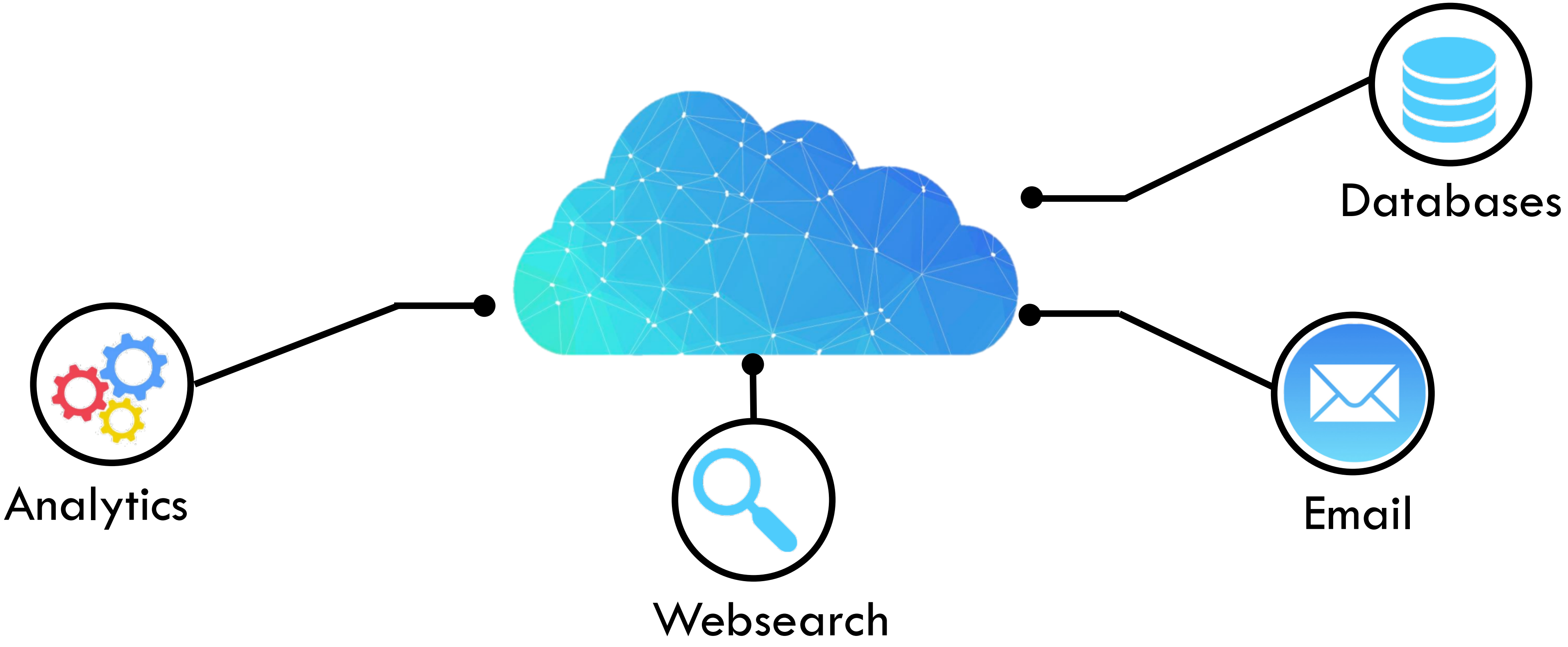
Executive Summary

- Edge swarms increasing in size & complexity:
  - Enable new IoT applications
  - Require rethinking the cloud-edge system stack

- Challenges:
  - Programming interface → abstract away system/app complexity
  - Execution environment → fine-grained, event-driven tasks
  - Hardware design → network communication, computation, etc.

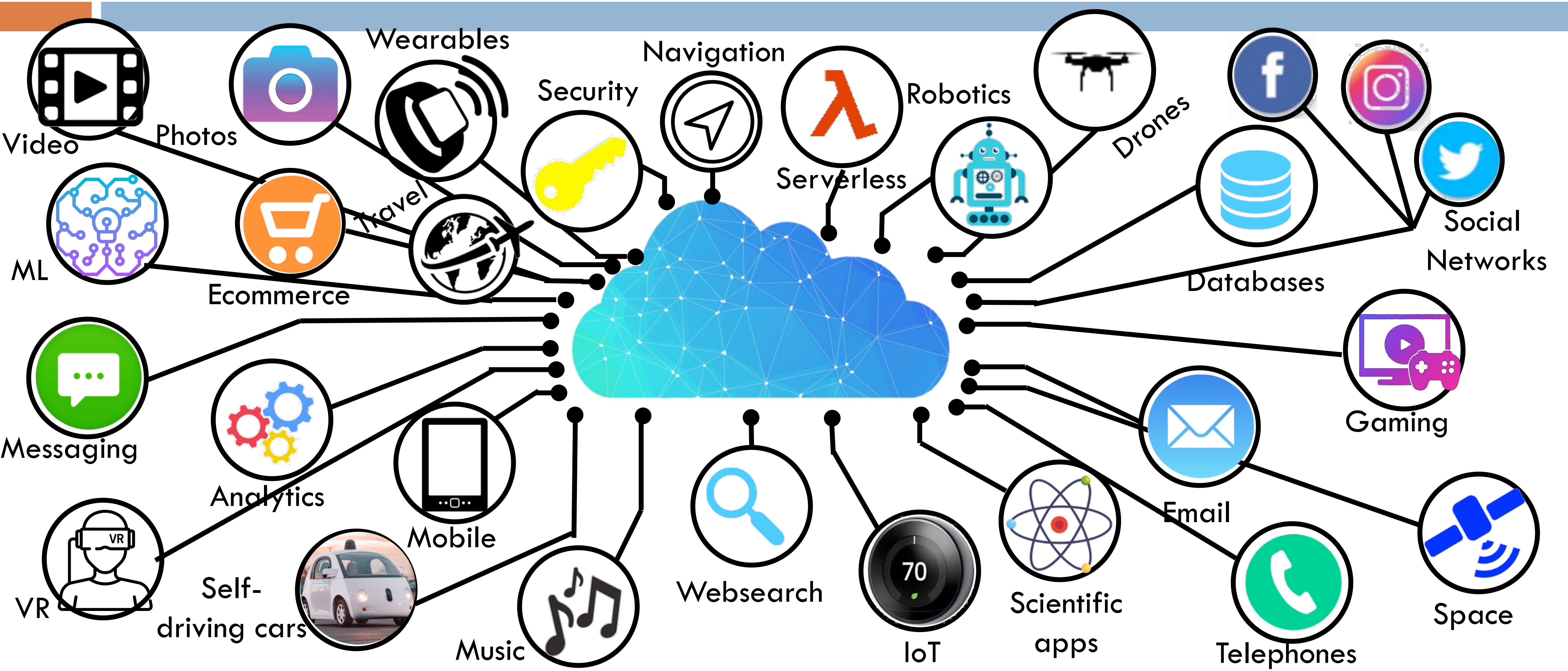
- HiveMind: end-to-end hardware-software stack for cloud-edge systems
  - Declarative programming interface, automated task/data placement
  - Serverless execution environment, reconfigurable hardware acceleration
  - Significant performance, efficiency, programmability gains vs. centralized and decentralized platforms

All Computing Involves the Cloud



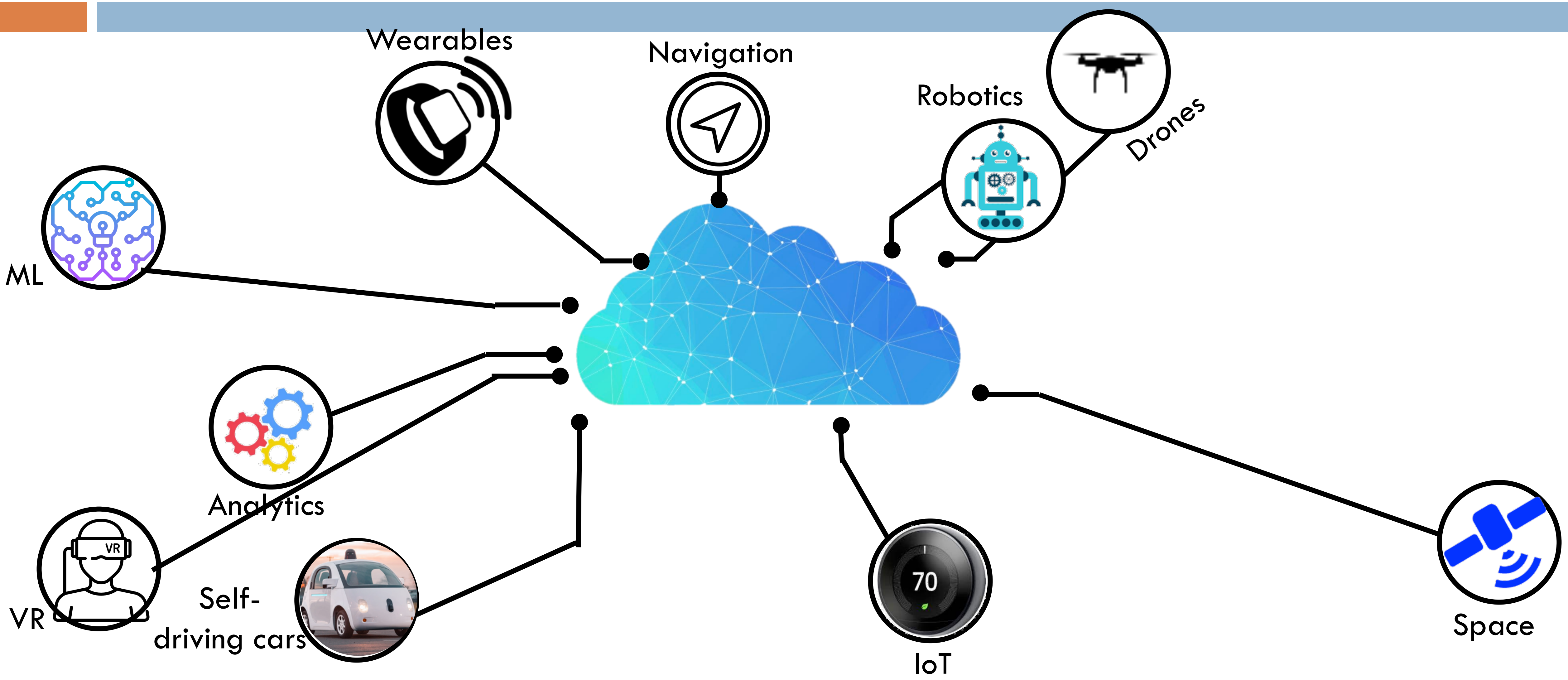
From few large applications…

All Computing Involves the Cloud

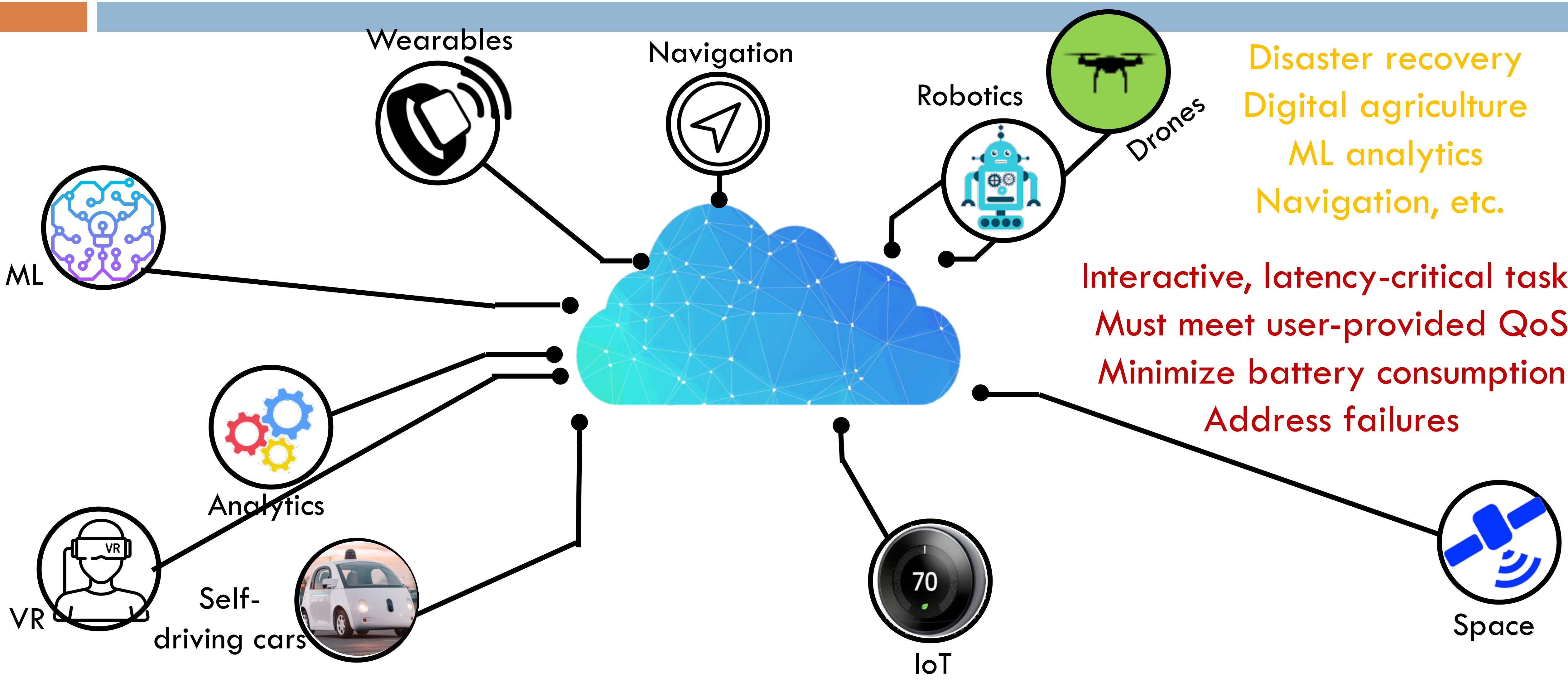


From few large applications to every service from every domain of human activity

Many Apps Running on Low-Power Edge Swarms



Many Apps Running on Low-Power Edge Swarms



Disaster recovery
Digital agriculture
ML analytics
Navigation, etc.

Interactive, latency-critical tasks
Must meet user-provided QoS
Minimize battery consumption
Address failures

Cloud-Edge System Stack Requirements

Programming framework → Abstract the complexity of managing a cloud-edge system from the end user

Cloud-Edge System Stack Requirements

Programming framework	Abstract the complexity of managing a cloud-edge system from the end user
Task & data placement	Automatically determine where computation & data should be placed to meet QoS, handle failures

Cloud-Edge System Stack Requirements

Programming framework	Abstract the complexity of managing a cloud-edge system from the end user
Task & data placement	Automatically determine where computation & data should be placed to meet QoS, handle failures
Execution environment	Match the fine-grained, event-driven and intermittent nature of IoT tasks

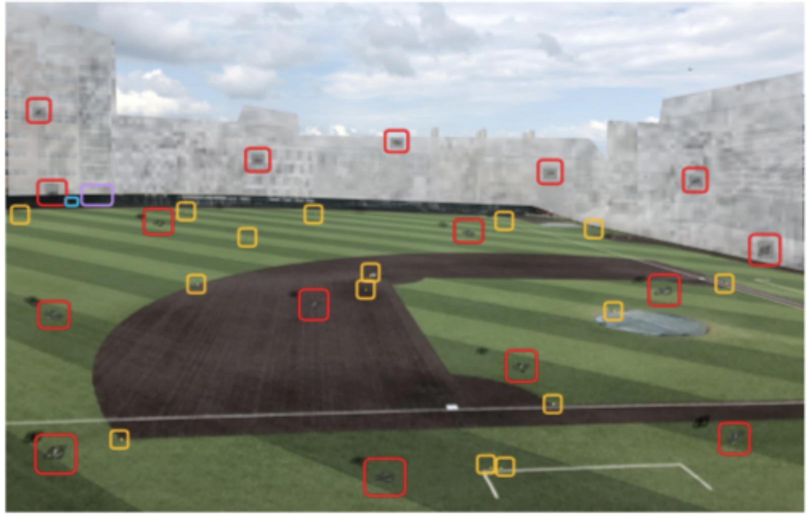
Cloud-Edge System Stack Requirements

Programming framework	Abstract the complexity of managing a cloud-edge system from the end user
Task & data placement	Automatically determine where computation & data should be placed to meet QoS, handle failures
Execution environment	Match the fine-grained, event-driven and intermittent nature of IoT tasks
Hardware design	Identify resource bottlenecks, enable reconfiguration to match IoT apps’ frequent updates

HiveMind Design

- Hardware-software system stack for cloud-edge systems
  - Focus on low-power edge devices
  - Focus on multi-phase computation that requires data transfer across phases

Parrot A.R. Drone 2.0



- Methodology:
  - Focus on programmable drones:
    - ARM core on-board, 4GB of memory + 24GB of SSD
    - Generalizes to other swarms
  - 20-server backend cloud with 2-socket Intel servers
  - Applications:
    - Single-tier tasks (face recognition, weather analytics, SLAM, obstacle avoidance, etc.)
    - Multi-tier scenarios (treasure hunt, people search)

HiveMind Programming Model

Declarative Programming Interface (HiveMind DSL)

User expresses {task graph, i/o, task logic} in Python

End-to-end source, and inter-task APIs synthetized automatically

Task graph

```
TaskGraph(list=['createRoute','collectImage',
'obstacleAvoid','faceRecognition',
'deduplication'],constraint=[execTime='10s'])
```

HiveMind Programming Model

Declarative Programming Interface (HiveMind DSL)

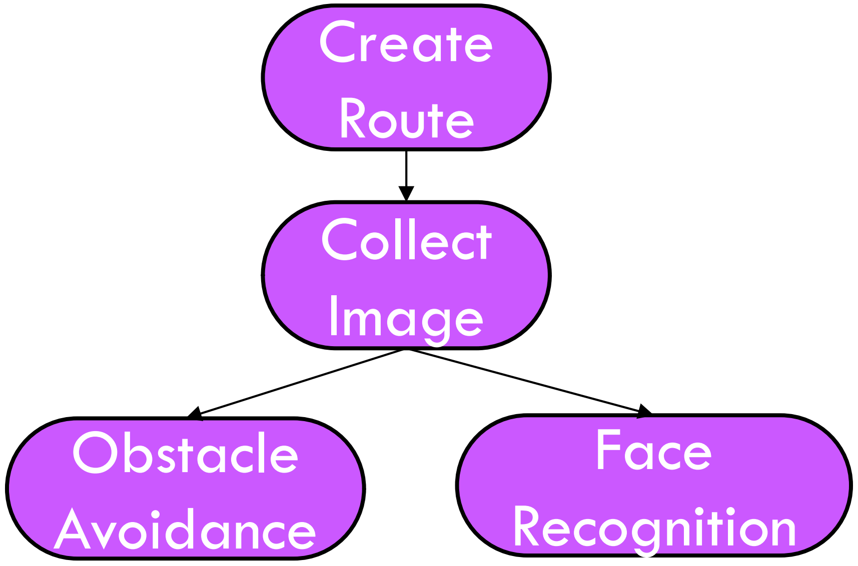
User expresses {task graph, i/o, task logic} in Python

End-to-end source, and inter-task APIs synthetized automatically

Task graph

Task description

```
Task(collectImage,None,sensorData,
'filepath/to/task/code',
speed='4',resolution='1024p',
colorFormat='color',
parentTask=['createRoute'],childTask=
['obstacleAvoidance','faceRecognition'])
```



HiveMind Programming Model

Declarative Programming Interface (HiveMind DSL)

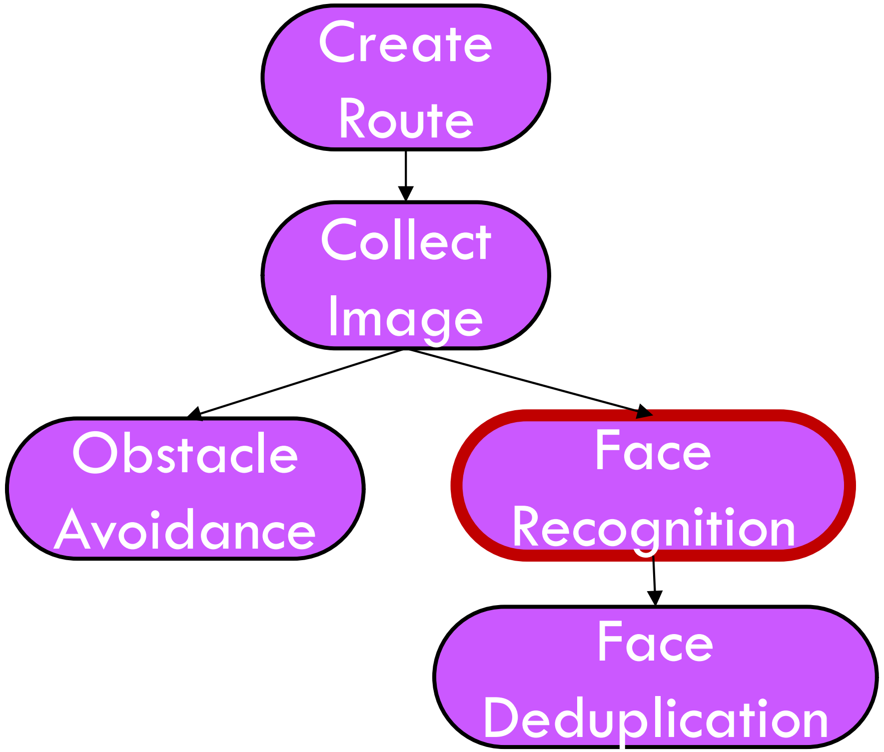
User expresses {task graph, i/o, task logic} in Python

End-to-end source, and inter-task APIs synthetized automatically

Task graph

Task description

```
Task(faceRecognition,sensorData,recognitionStats,
'filepath/to/task/code',
trainingData='zoo',
algorithm='tensorflow_zoo',
parentTask=['collectImage']],
childTask=['deduplication'])
```



HiveMind Programming Model

Declarative Programming Interface (HiveMind DSL)

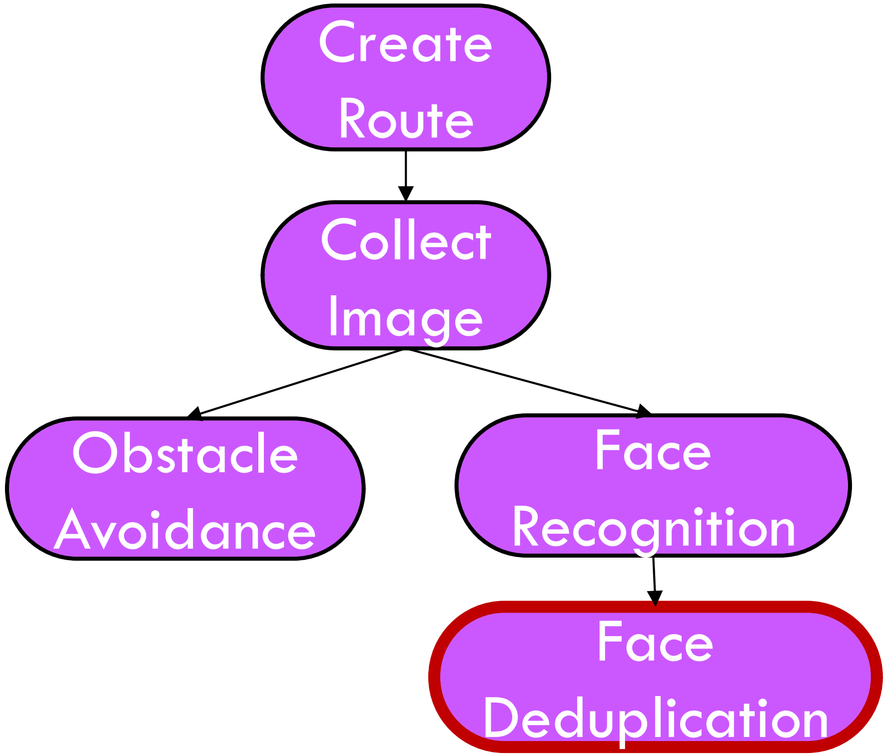
User expresses {task graph, i/o, task logic} in Python

End-to-end source, and inter-task APIs synthetized automatically

Task graph

Task description

```
Task(deduplication,recognitionStats,dedupList,
'filepath/to/task/code',
sync='all',
parentTask=['faceRecognition']],
childTask=[])
```



HiveMind Programming Model

Declarative Programming Interface (HiveMind DSL)

User expresses {task graph, i/o, task logic} in Python

End-to-end source, and inter-task APIs synthetized automatically

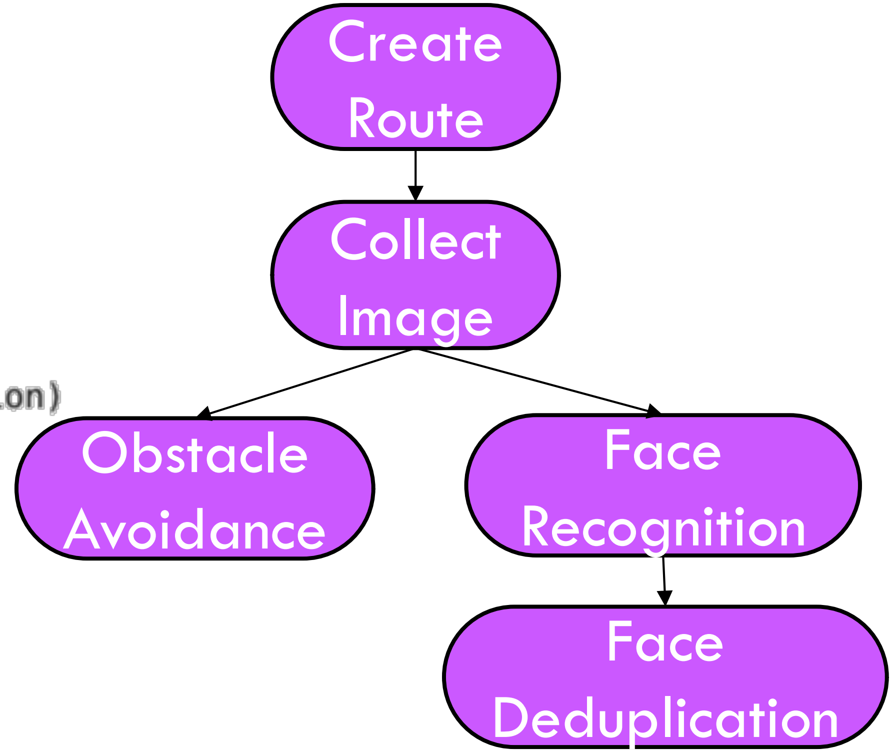
Task graph

Task description

Properties & constraints

```
Parallel(obstacleAvoidance,faceRecognition)
Serial(faceRecognition,deduplication)
Learn(faceRecognition,'Global')

Place(obstacleAvoidance,'Edge:all')
Persist(faceRecognition)
Persist(deduplication)
```



HiveMind Programming Model

Declarative Programming Interface (HiveMind DSL)

User expresses {task graph, i/o, task logic} in Python

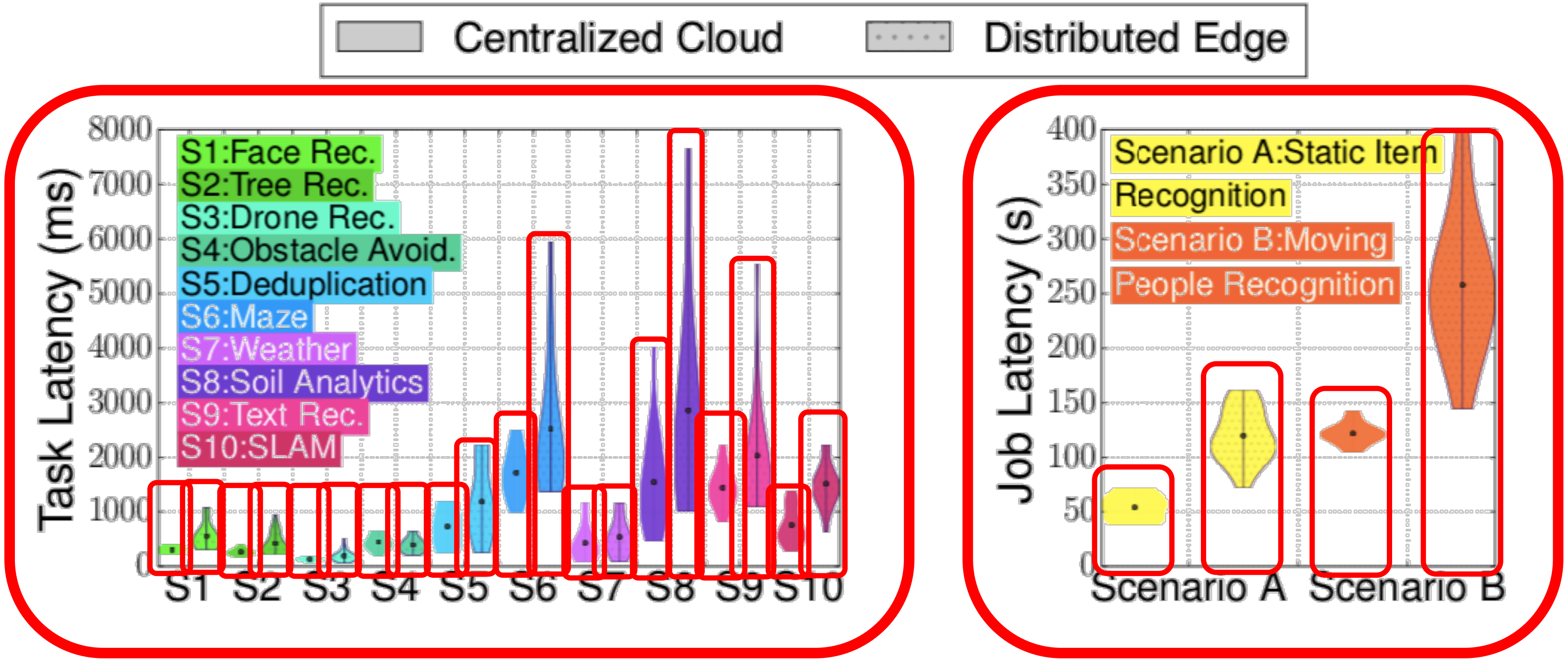
End-to-end source, and inter-task APIs synthetized automatically

Output

end-to-end application code base, and inter-task APIs for different placement options (cloud, edge, hybrid)

HiveMind Scheduler

Automated Task & Data Placement



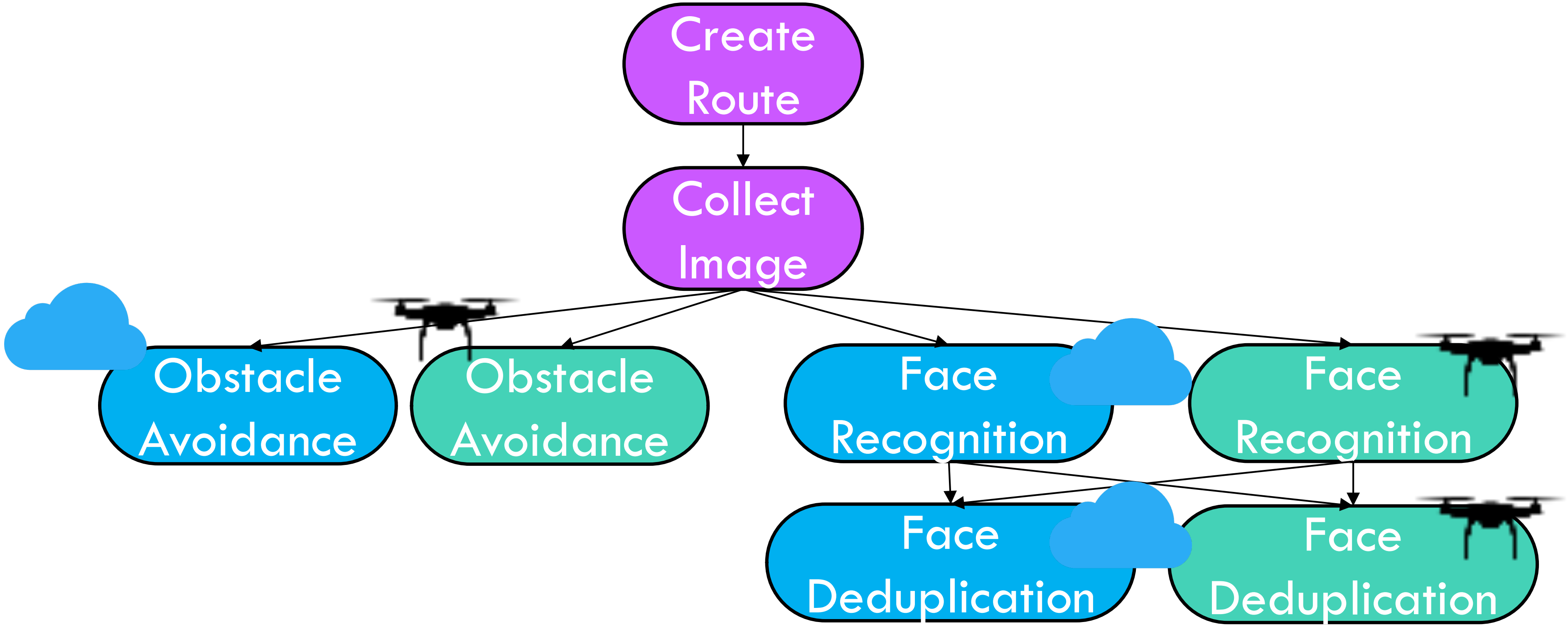
Cloud execution is usually faster, not always
Performance variability is higher at the edge

Cloud offloading quickly
saturates network link

HiveMind Scheduler

Automated Task & Data Placement

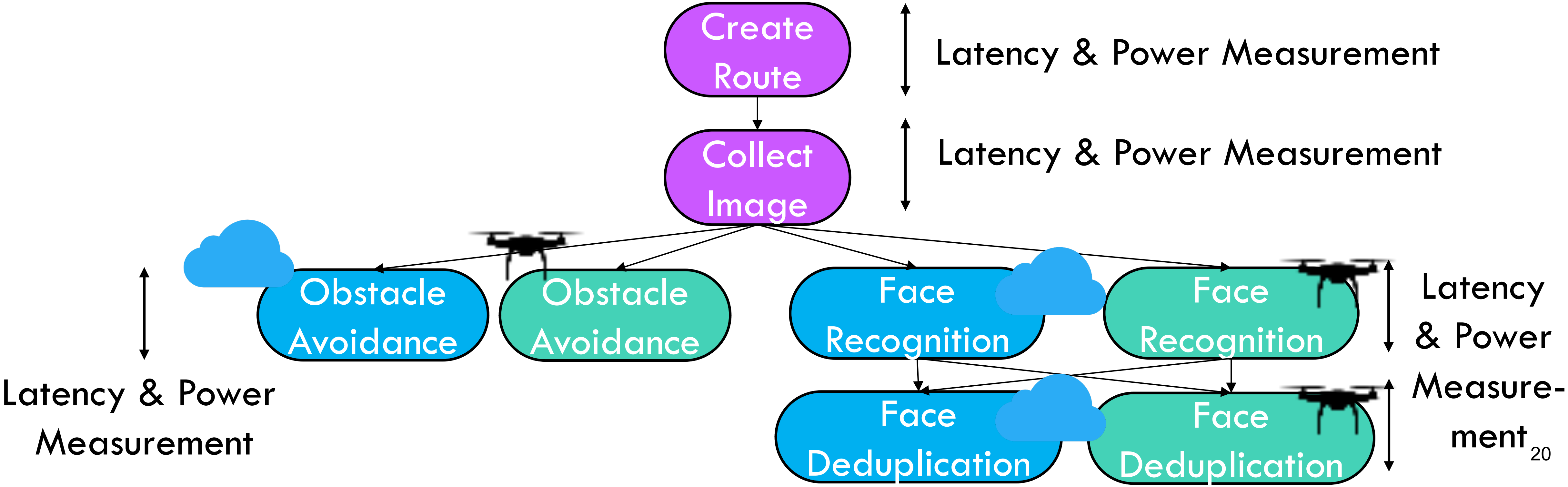
Explores division of tasks across cloud and edge resources to meet end-to-end QoS (performance and/or power) constraints



HiveMind Scheduler

Automated Task & Data Placement

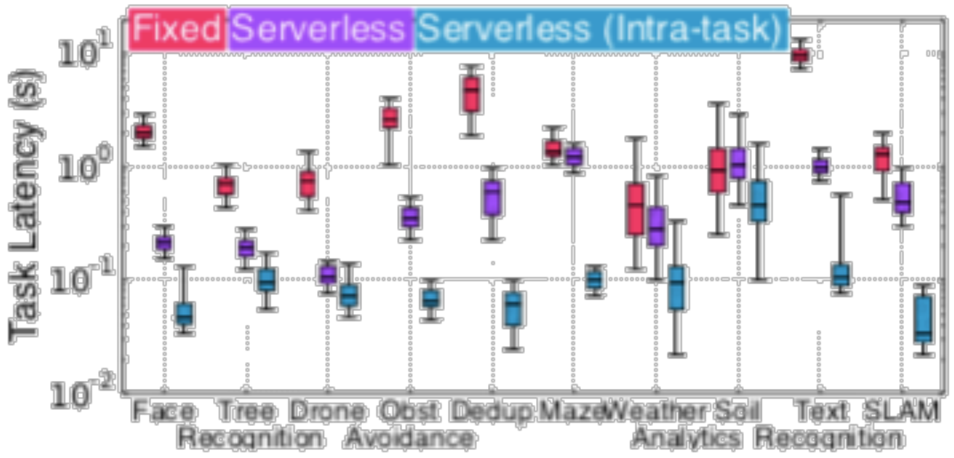
Explores division of tasks across cloud and edge resources to meet end-to-end QoS (performance and/or power) constraints



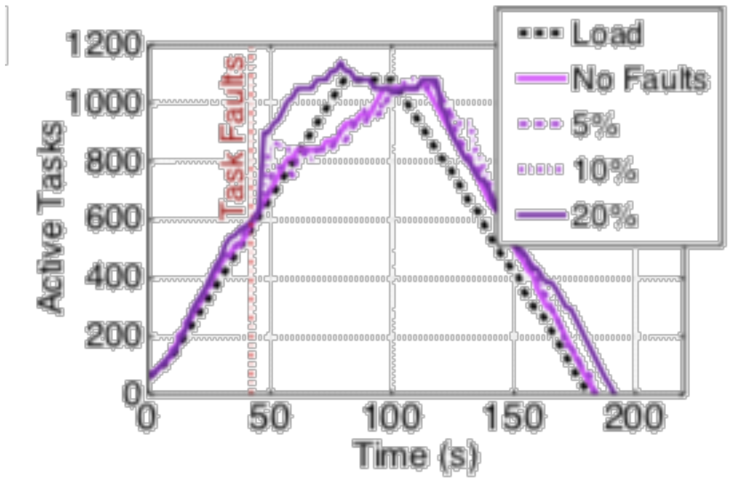
HiveMind FaaS Environment

Serverless Execution Environment

Leverages FaaS to offload computation to the cloud



Much lower latency compared to cost-equivalent reserved resources



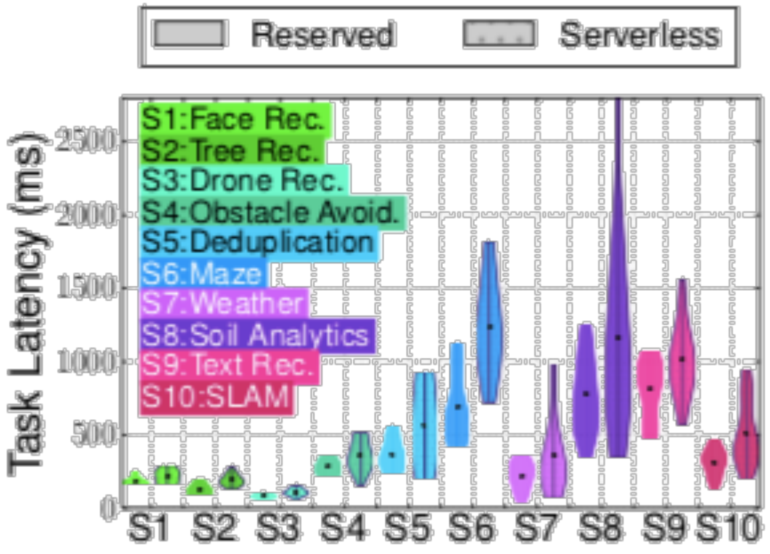
Adjusts much better to load fluctuations

Handles failures more smoothly

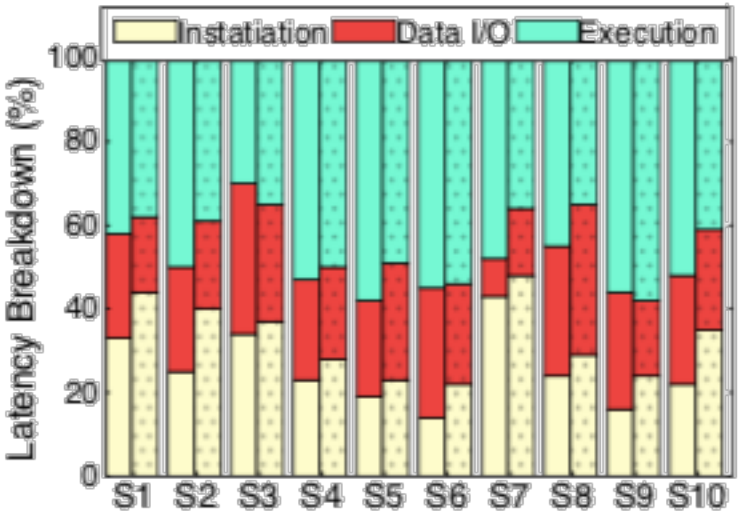
HiveMind FaaS Environment

Serverless Execution Environment

Leverages FaaS to offload computation to the cloud



Higher latency variability



High instantiation &
control plane overheads
High data transfer overheads

HiveMind FaaS Environment

Serverless Execution Environment

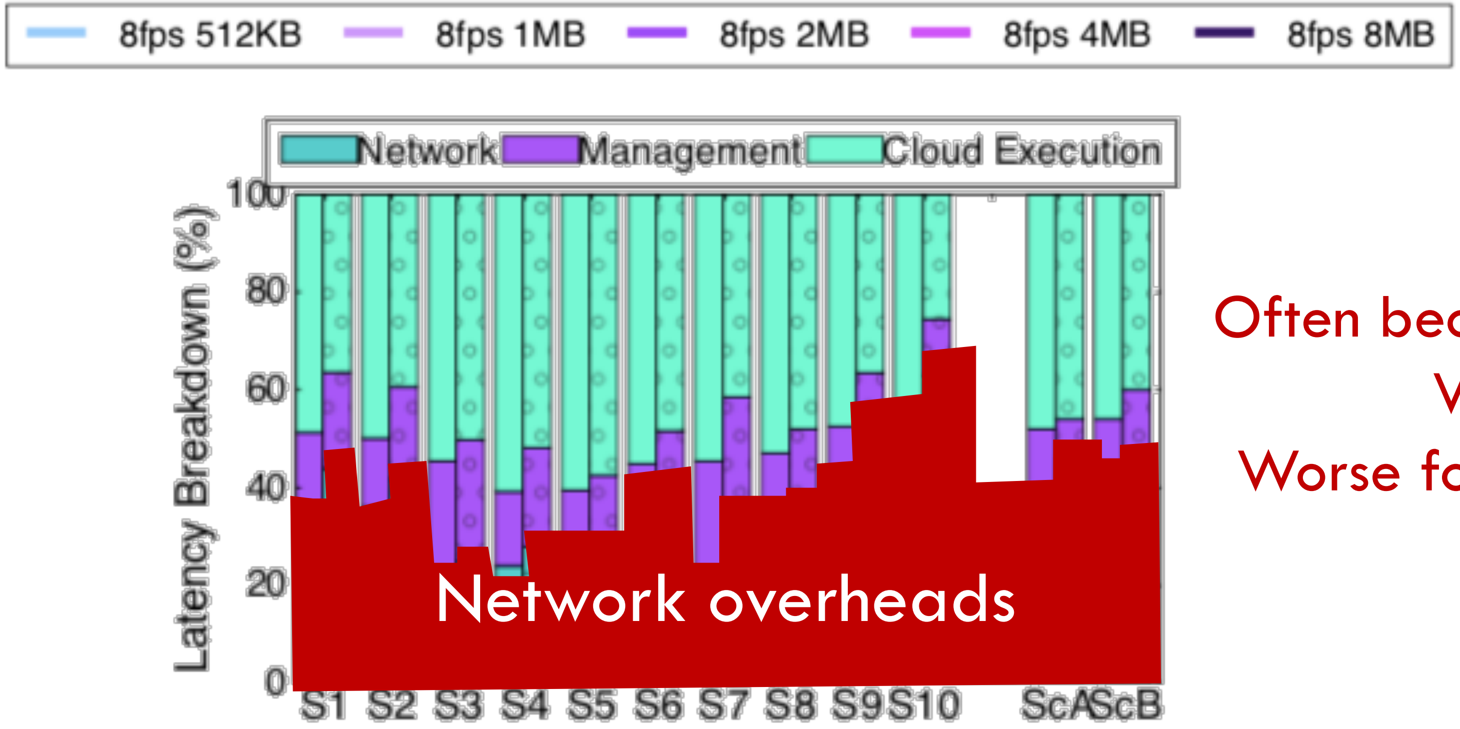
Leverages FaaS to offload computation to the cloud

- Centralized cloud controller implemented in OpenWhisk:
  - Global visibility into cloud and edge resources
  - Pre-warms containers and caches images with high reuse probability
  - Places dependent functions physically close (same container or same node)
  - Motivates need for hardware support for remote memory access

HiveMind Hardware Design

Hardware design

Accelerates communication between cloud-edge and within cloud tasks



Often becomes the performance bottleneck

Worse for ML-heavy tasks

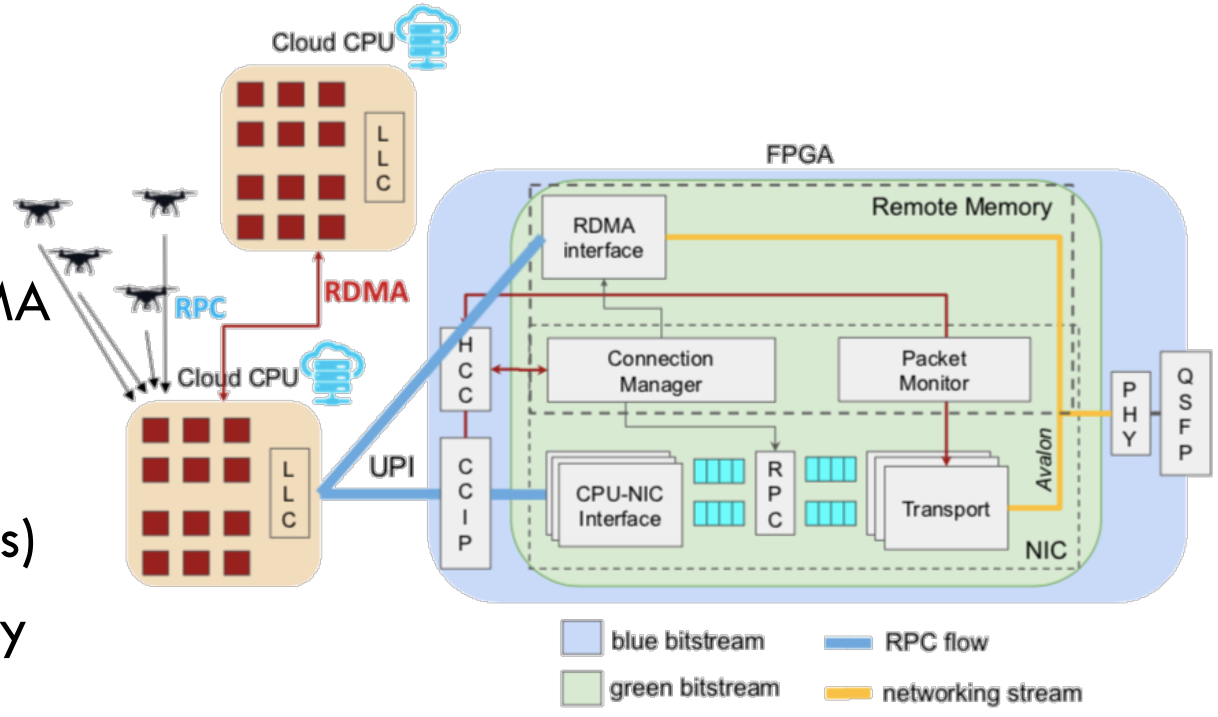
Worse for unreliable network connectivity

HiveMind Hardware Design

Hardware design

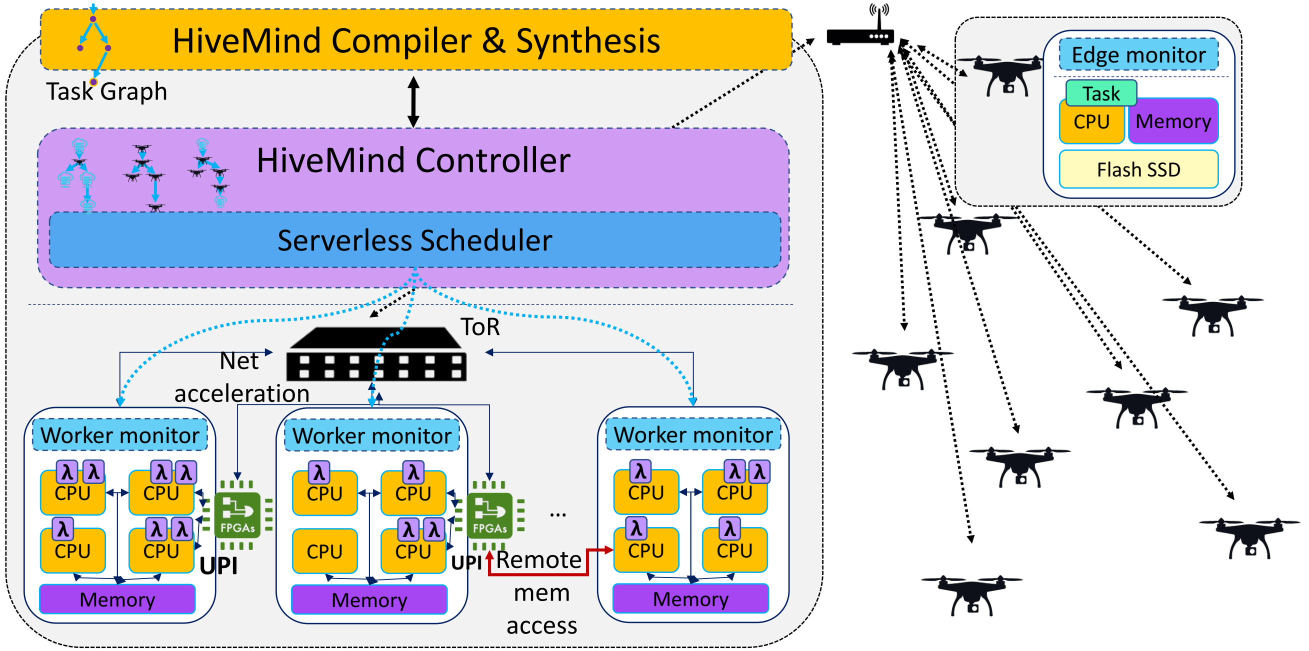
Accelerates communication between cloud-edge and within cloud tasks

- Two reconfigurable acceleration fabrics:
  - Cloud-edge communication → RPC acceleration
  - Cloud-cloud function communication → RDMA acceleration
  - Implemented in a tightly-coupled cache coherent FPGA (NUMA interconnect, UPI bus)
  - Spatially partitioned, supports multi-tenancy and resource isolation



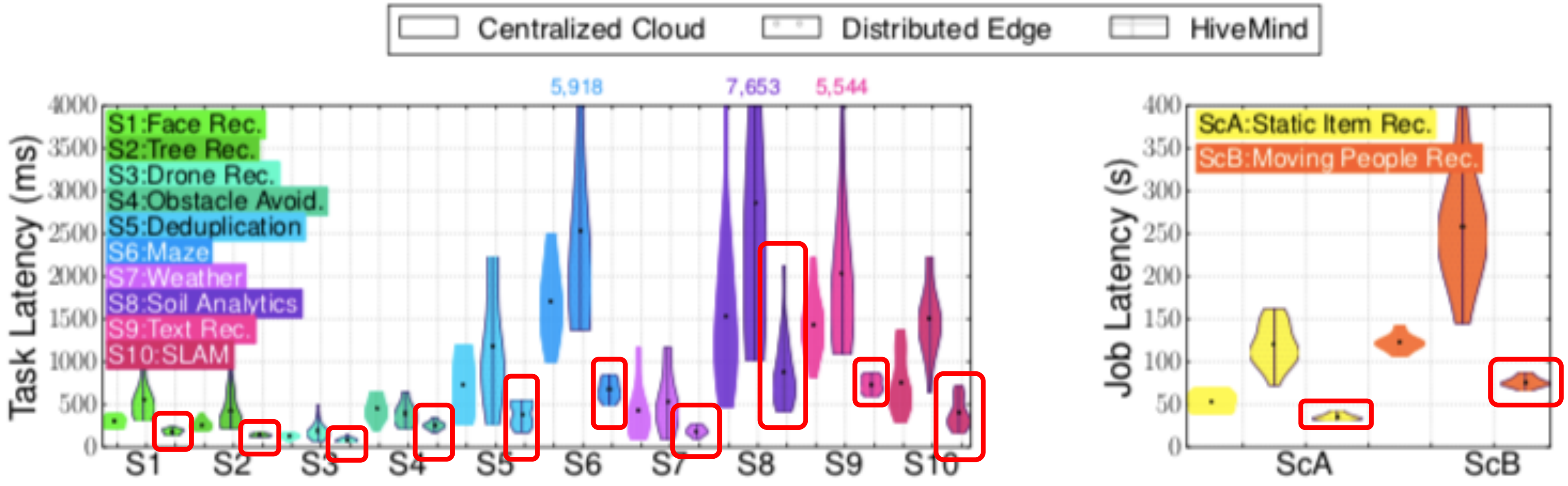
HiveMind System Stack

- **Implementation:**
  - ~28,000 LoC (C++, Python, node.js, Verilog, VivadoHLS)
  - Centralized controller
    - Hot stand-by copies
  - End-to-end monitoring system (minimal perf overhead)



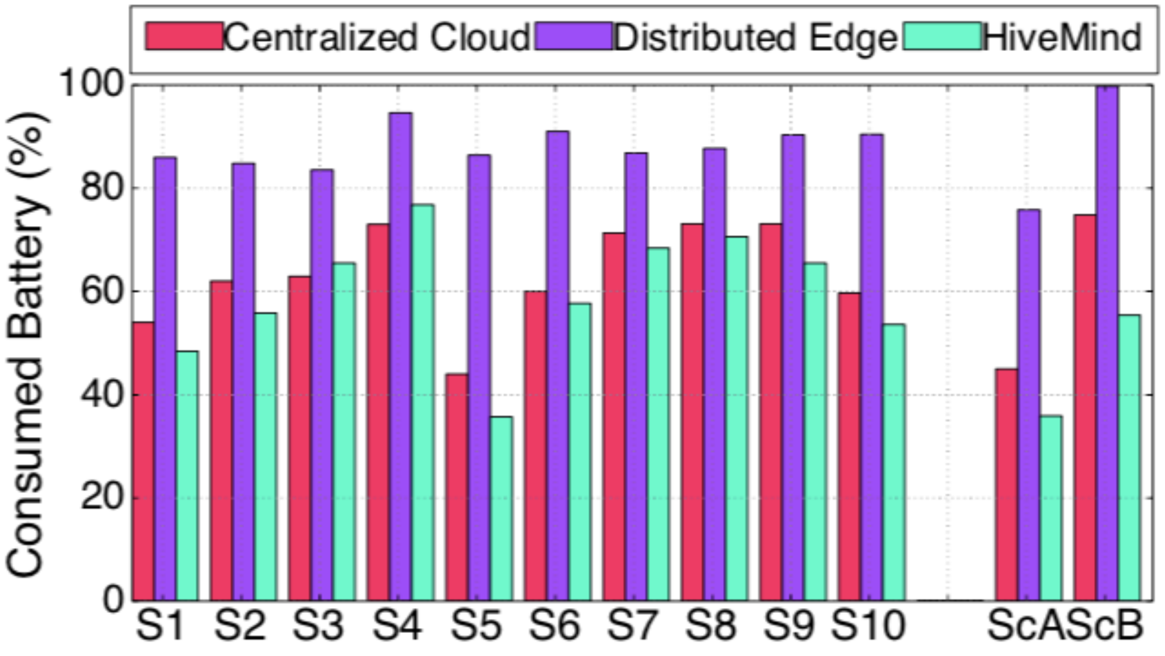
- **Other features:**
  - Fault tolerance → load rebalancing
  - Straggler detection
  - Online learning → per-device, swarm-wide
- **Comparisons:**
  - Fully centralized system
  - Fully decentralized system
  - With and without serverless

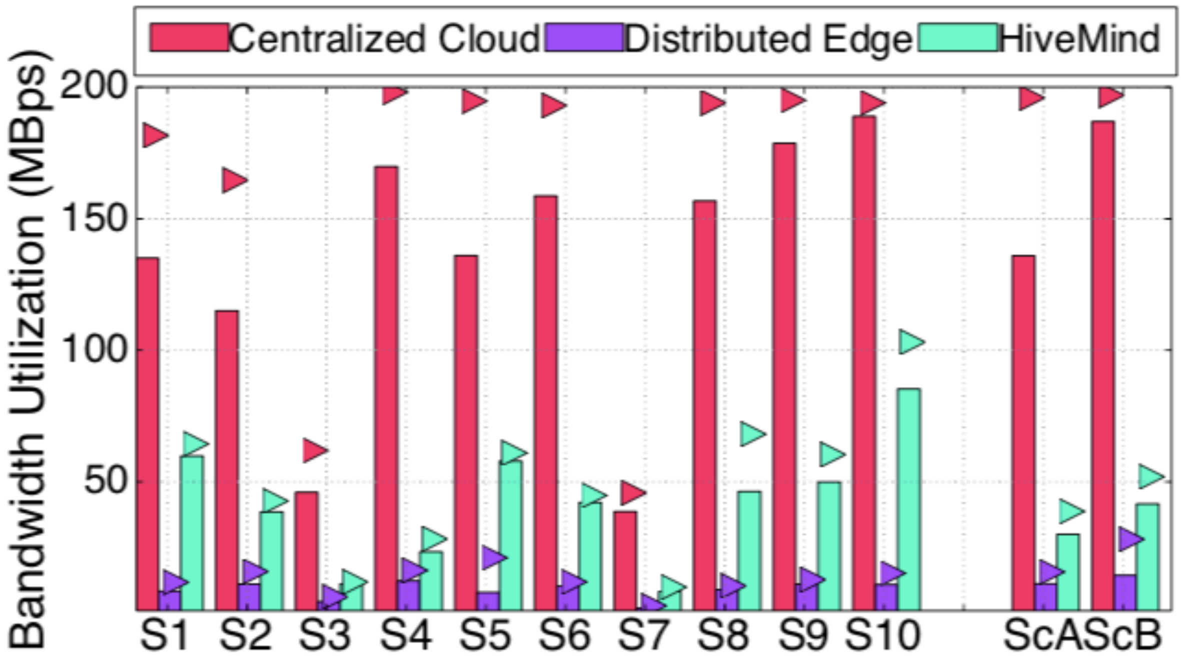
Evaluation: Performance



- Task/Job latency:
  - Lower than both centralized and distributed
  - More predictable (less variability)
  - Mostly benefits multi-tier compute-/data-intensive jobs

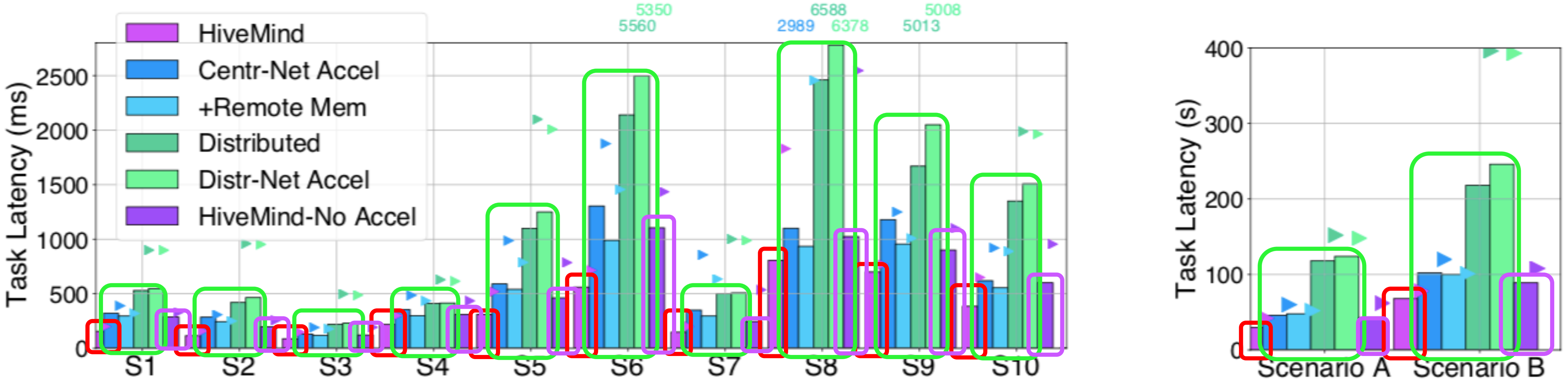
Evaluation: Power Consumption & Net Bandwidth





- Power consumption:
  - 73% lower power consumption than distributed
  - 18% lower power consumption than centralized
- Network bandwidth:
  - 78% lower bandwidth utilization than centr.
  - ~3x higher bandwidth utilization than distributed

Evaluation: Modularity

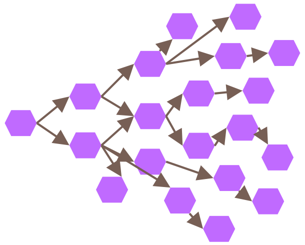


- Task/Job latency:
  - Modular design → performance & efficiency can benefit from subset of techniques
  - But all techniques are needed to achieve best performance and efficiency

Other Experiments (in the paper)

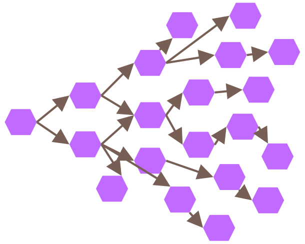
- Latency breakdown
- Fault tolerance
- Scalability with swarm size, resource requirements
- Portability to other swarms (robotic cars)
- Online learning
- Etc.

Conclusions

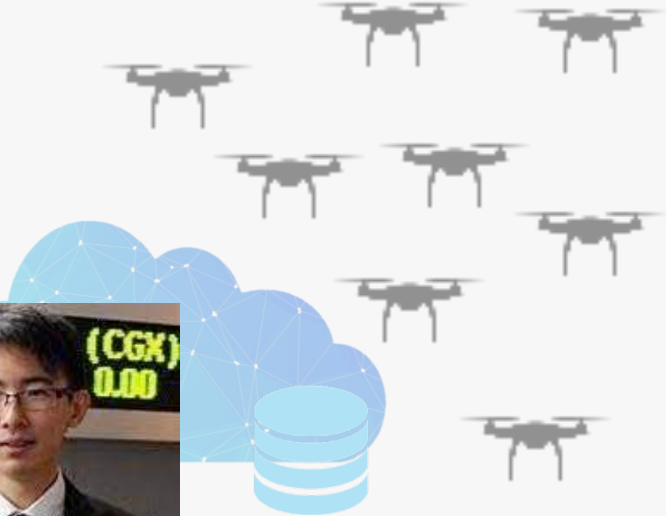


- Edge swarms increasing in size & complexity:
  - Enable new IoT applications
  - Require rethinking the cloud-edge system stack
- Challenges:
  - Programming interface → abstract away system/app complexity
  - Execution environment → fine-grained, event-driven tasks
  - Hardware acceleration → network communication, computation, etc.
- HiveMind: end-to-end hardware-software stack for cloud-edge systems
  - Enables programmable cloud-edge platforms
  - Automates task and data placement
  - Leverages serverless compute and reconfigurable hardware acceleration
  - Offers significant performance and efficiency gains vs. centralized and decentralized platforms

Questions?



- Edge swarm ... n size & ... :
  - Enable new ... ns
  - Require ret ... d-edge ...



- Chall...
  - Pr ... face → ... y syste ... xity
  - Exe ... ent → ... event-...
  - Ha ... ation → ... munica ... n, etc.

- HiveMind: end-to-end hardware-software stack for cloud-edge systems
  - Enables programmable cloud-edge platforms
  - Automates task and data placement
  - Leverages serverless compute and reconfigurable hardware acceleration
  - Offers significant performance and efficiency gains vs. centralized and decentralized platforms