A Smorgasbord of Embedded and Pervasive Computing Research

Kishore Ramachandran

(part of systems group which includes Ada Gavrilovska, Taesoo Kim, Ling Liu, Calton Pu, and Alexey Tumanov)

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- Current PhD inmates!

Enrique Saurez

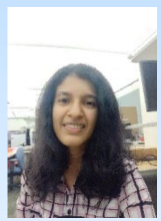
Harshit Gupta

Zhuangdi Xu

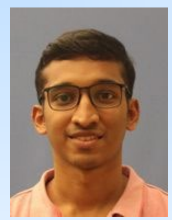
Adam Hall

Ashish Bijlani

Tyler Landle

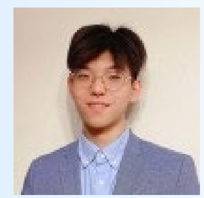


Manasvini Sethuraman



Anirudh Sarma

Alan Nussbaum



Difei Cao

Jinsun Yoo

- Recently escaped!
  - Hyojun Kim (IBM Almaden then Startup and now Google); Lateef Yusuf (Amazon then Google); Mungyung Ryu (Google); Kirak Hong (Google and now CTRL-labs); Dave Lillethun (Seattle U.); Dushmanta Mohapatra (Oracle); Wonhee Cho (Microsoft); Beate Ottenwalder (Bosch); Ruben Mayer (TU Munich), Ashish Bijlani (Startup)
- Plus a number of MS and UGs

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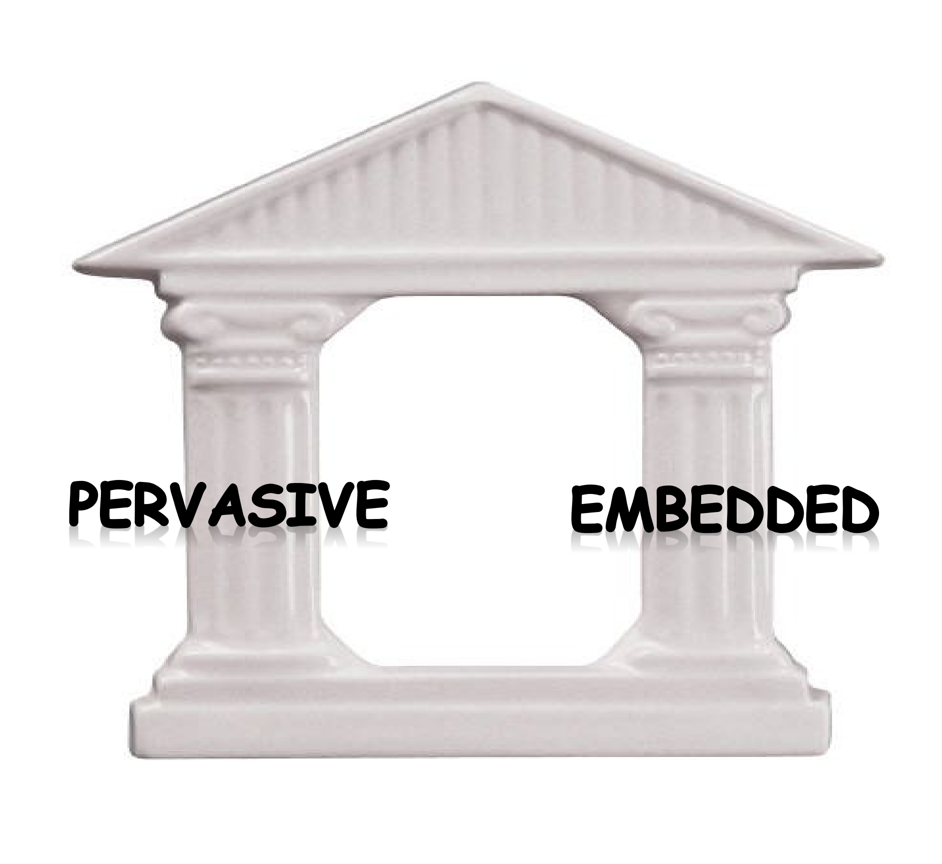
Embedded Pervasive Lab



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Pervasive side of the house

- Embedded devices treated as black boxes
- System Support for IoT
  - Fog/Edge computing

Current-Generation Applications

Cloud computing's utility model commoditized hardware…

Amazon
EC2

Microsoft
Azure

Google Cloud Platform

Enabling large-scale apps from centralized data centers…

facebook

NETFLIX

Next-Generation Applications

Future apps will be data-driven, model-driven, machine-in-the-loop, and far more demanding…

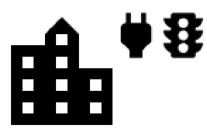
Autonomous Vehicles (AV)

Augmented / Virtual Reality (AR/VR)

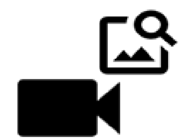
Latency <20 ms

Bandwidth >50 Mbps

Per device



Smart Cities



Smart Camera Networks

Next-Generation Applications

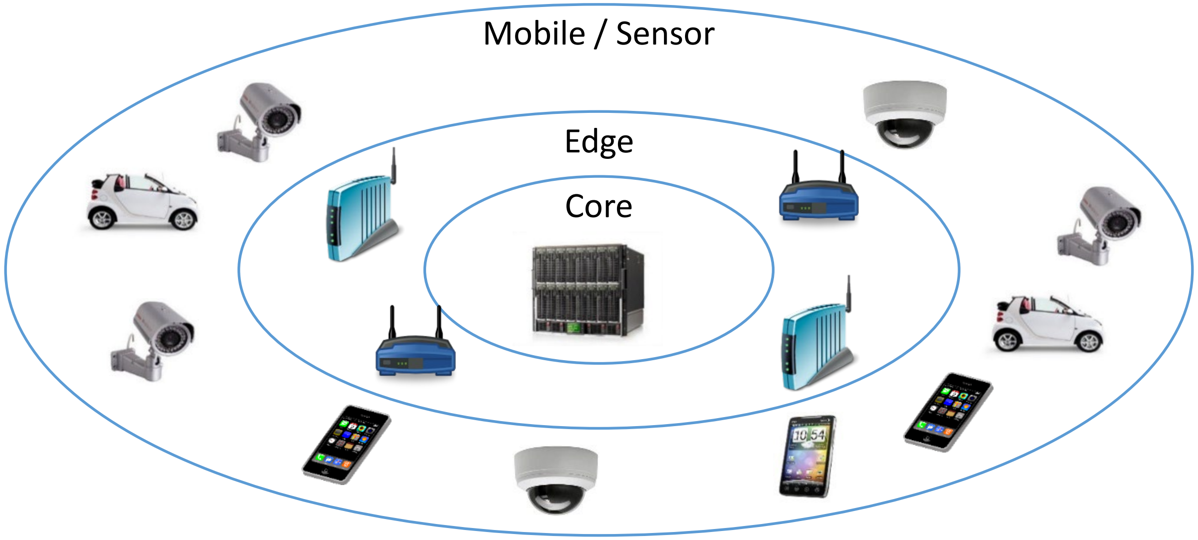
- Sense -> Process -> Actuate
- Common Characteristics
  - Dealing with real-world data streams
  - Real-time interaction among mobile devices
  - Wide-area analytics
- Requirements
  - Dynamic scalability
  - Low-latency communication
  - Efficient in-network processing

Cloud Computing

- Good for web apps at human perception speeds
  - Throughput oriented web apps with human in the loop
- Not good for many latency-sensitive IoT apps at computational perception speeds
  - sense -> process -> actuate
- Other considerations
  - Limited by backhaul bandwidth for transporting plethora of 24x7 sensor streams
  - Not all sensor streams meaningful
    => Quench the streams at the source
  - Privacy and regulatory requirements

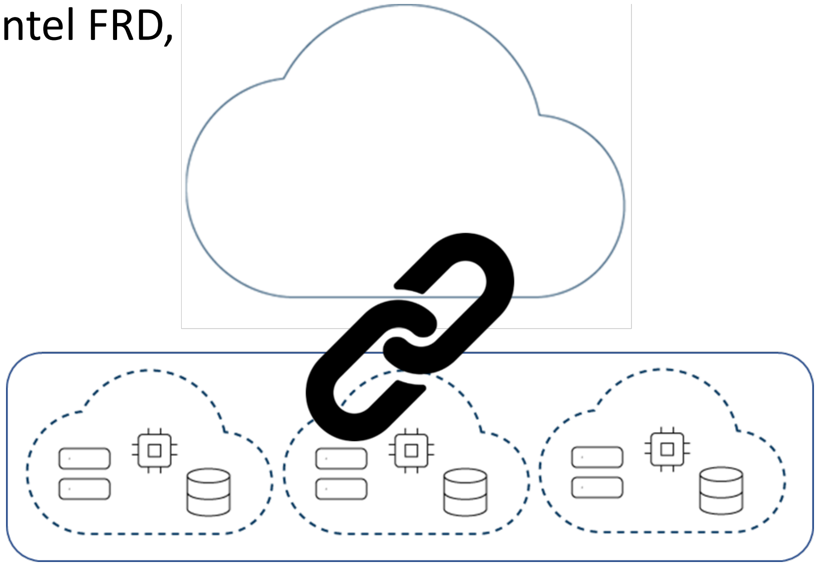
Fog/Edge Computing

- Extending the cloud utility computing to the edge
- Provide utility computing using resources that are
  - Hierarchical
  - Geo-distributed



Fog/edge computing today

- Edge is slave of the Cloud
  - Platforms: IoT Azure Edge, CISCO Iox, Intel FRD,
- Mobile apps beholden to the Cloud

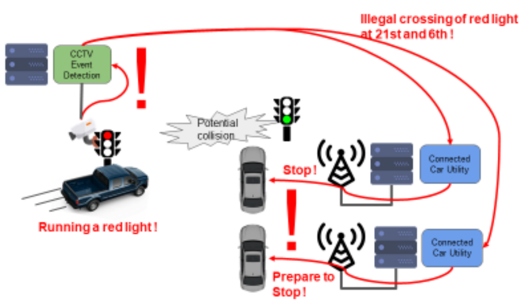


Vision for the future

- Elevate Edge to be a peer of the Cloud
  - Prior art: Cloudlets (CMU+Microsoft), MAUI (Microsoft)
- In the limit
  - Make the Edge autonomous even if disconnected from the Cloud

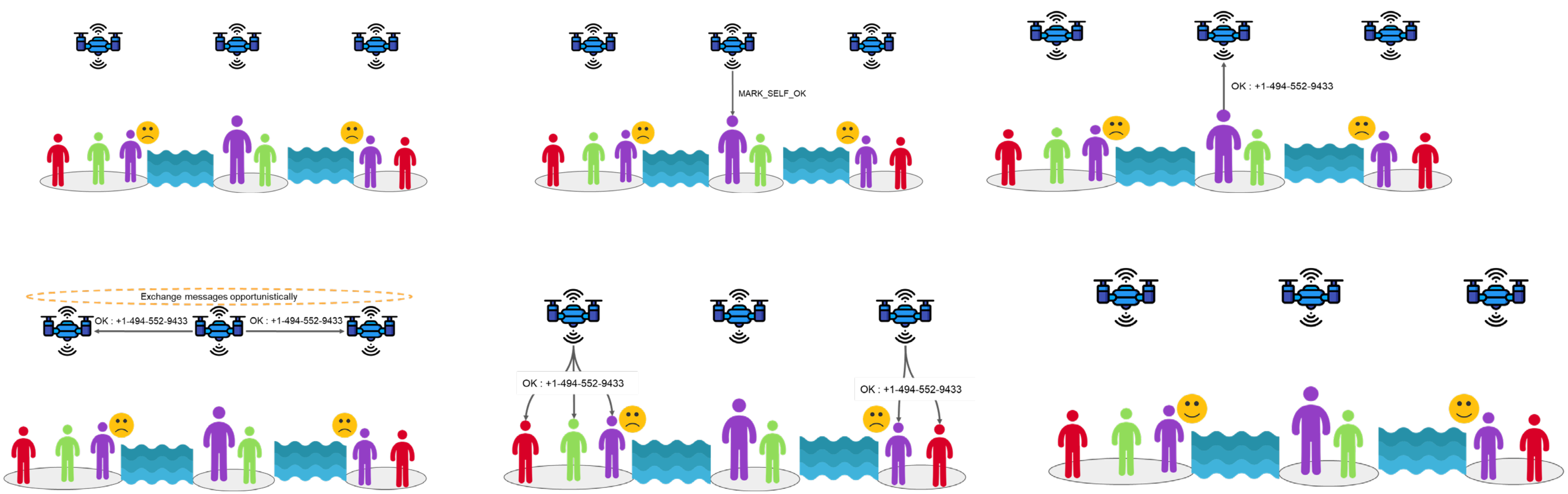
Why ?

- Interacting entities (e.g., connected vehicles) connected to different edge nodes
- Horizontal (p2p) interactions among edge nodes essential



Why ?

- Autonomy of edge (disaster recovery)



Challenges for making

- Need for powerful frameworks akin to the Cloud at the edge
  - Programming models, storage abstractions, pub/sub systems, …
- Geo-distributed data replication and consistency models
  - Heterogeneity of network resources
  - Resilience to coordinated power failures
- Rapid deployment of application components, multi-tenancy, and elasticity at the edge
  - Cognizant of limited computational, networking, and storage resources

Thoughts on Meeting the Challenges
(https://www.cc.gatech.edu/~rama/recent_pubs.html)

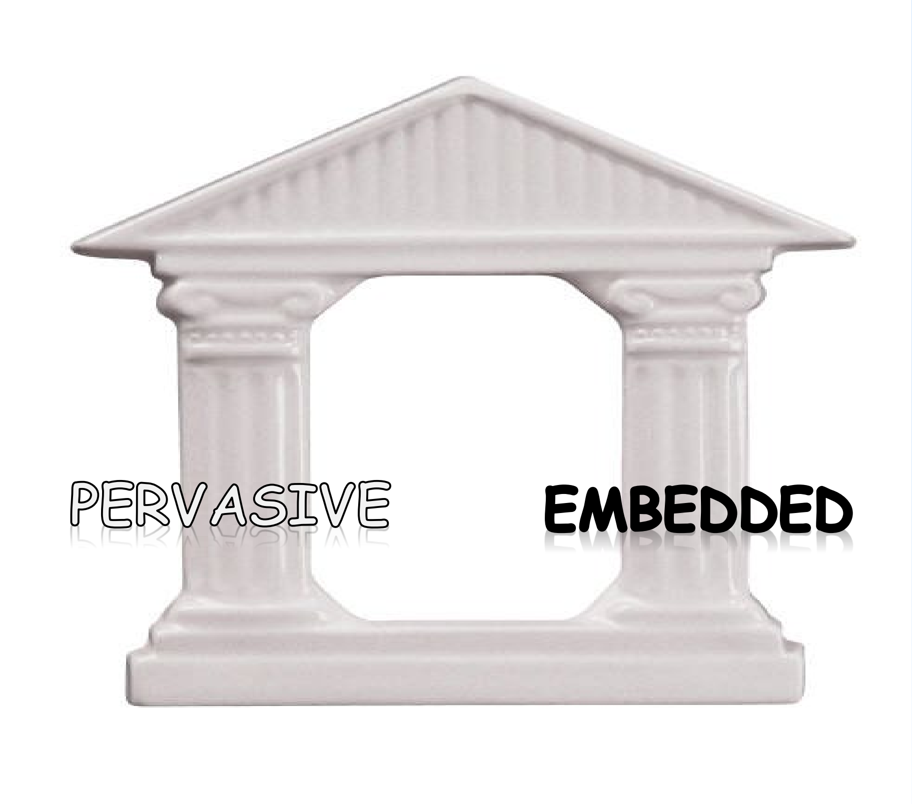
Theme: Elevating the Edge to be a peer of the Cloud

- Geo-distributed programming model for Edge/Cloud continuum
  - OneEdge (ACM SoCC 2021)
  - Foglets (ACM DEBS 2016)
- Geo-distributed data management – replica placement, migration and consistency
  - EPulsar (ACM SEC 2021)
  - FogStore (ACM DEBS 2018)
  - DataFog (HotEdge 2018)
- Efficient Edge runtimes
  - Serverless functions using WebAssembly (ACM IoTDI 2019)
- Applications using autonomous Edge
  - Social Sensing *sans* Cloud (SocialSens 2017)
  - STTR: Space Time Trajectory Registration (ACM DEBS 2018)
  - STVT: Space-Time Vehicle Tracking (HotVideoEdge 2019)
  - Coral-Pie: Space-Time Vehicle Tracking at the Edge (ACM Middleware 2020)
- Vision: “A case for elevating the edge to be a peer of the cloud”, GetMobile, 2020
- Vision: "eCloud: Vision for the Evolution of Edge-Cloud Continuum", IEEE Computer, 2021.

Ongoing Work

- eCloudSim (with **Daglis**, **Chatterjee**, **Dhekne**)
  - eCloud Simulation Infrastructure
- Prescient video prefetching at the edge for AV infotainment (With **Dhekne**)
  - Use route to JIT prefetching and caching for DASH player on vehicle
    - Foresight (ACM MMSys 2021)
  - Use mmWAVE (integrated with 5G LTE for edge node selection) to beam to passing vehicle
    - ClairvoyantEdge (in submission)
- Edge centric video data management systems for AV (With **Arulraj**)
  - Annotations with video for query processing, multi-tenancy, and sharing
    - EVA (To appear in ACM SIGMOD)
- Nimble execution environments for the Edge
  - Analyze cold start times in containers
  - Clean slate exec environment for FaaS
- NFSlicer: dataplane optimizations for processing network functions (With **Daglis**)
  - Selective data movement (e.g., header vs. payload) for NF chaining
    - NFSlicer (in submission)
- Performance isolation in the Edge (with **Sameh Elnikety** – Microsoft)
  - Harvest Container: Mixing latency-sensitive and throughput-oriented apps at the edge
- Hardware accelerators in micro-datacenters (with **Tushar Krishna**)
  - Efficiently using accelerators to improve efficiency in edge datacenters.

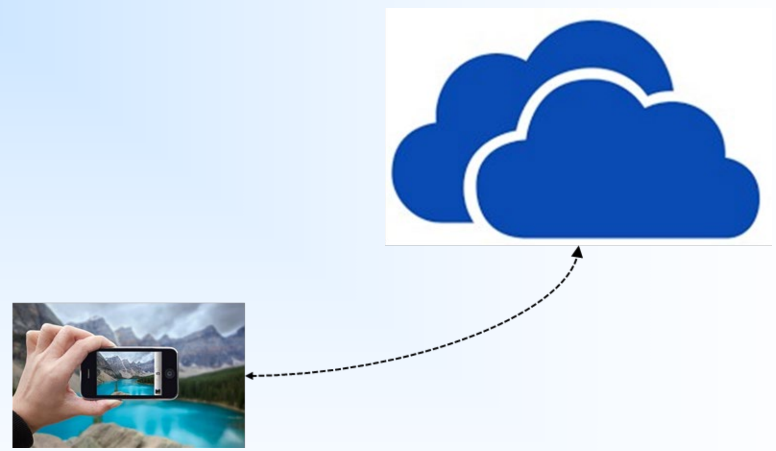
Embedded side of the house



- Infinite storage for mobile devices
- Optimizing Mobile Video Downloads

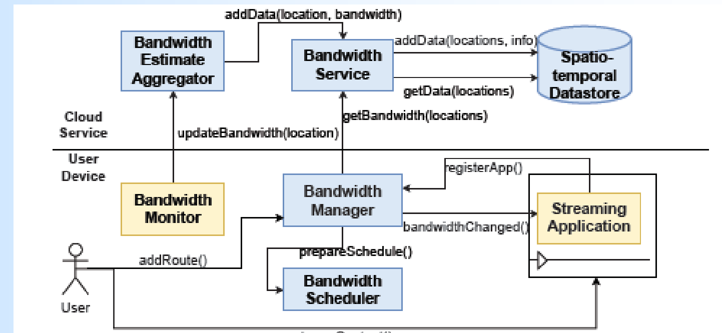
Infinite Storage for Mobile Devices

- Seamlessly extend the storage on mobile to the Cloud for any app
  - User space file system
    - APSys 2018, USENIX ATC 2019, Sigmetrics 2021
- Use machine learning to build user's everyday working set and (off)load (un)wanted data
- Issues
  - Latency
  - Energy consumption
  - Security and privacy

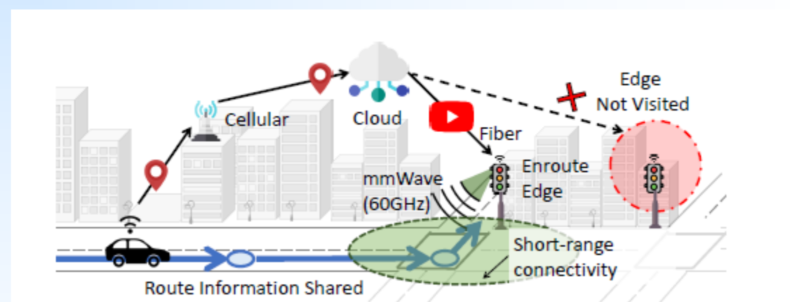


Optimizing Mobile Video Downloads

- Foresight (ACM MMSys 2021)
  - Bandwidth prediction across space and time for mobile users



- ClairvoyantEdge
  - Short range mmWave augmentation at Edge for high bandwidth video delivery



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Recap

- Infinite storage for mobile devices
- Optimizing Mobile Video Downloads
  - Foresight, ClairvoyantEdge

- Fog/Edge computing
  - eCloud
  - Foglets, OneEdge, thin virtualization for FaaS
  - Fogstore, DataFog, ePulsar, NFSlicer
  - STTR, Socialsens

Ongoing Projects

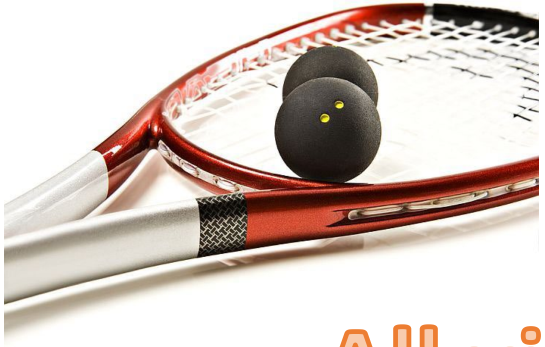
- **eCloud**: Device-Edge-Cloud continuum
- **OneEdge**: Device/Edge/Cloud control plane using AV as exemplar
  - Scheduling edge resources, monitoring, migration
- **Foresight** and **ClairvoyantEdge**: Prescient video prefetching at the edge for AV infotainment (With Prof. **Dhekne**)
  - Use route to JIT prefetching and caching for DASH player on vehicle
  - Use mmWAVE (integrated with 5G LTE for edge node selection) to beam to passing vehicle
- Edge centric video data management systems for AV (With Prof. **Arulraj**)
  - Annotations with video for query processing, multi-tenancy, and sharing
- Nimble execution environments for the Edge
  - Analyze cold start times in containers
  - Clean slate exec environment for FaaS
- **NFSlicer**: dataplane for processing network functions (With Prof. **Daglis**)
  - Selective data movement (e.g., header vs. payload) for NF chaining
- **MicroEdge**: Low-cost edge architecture for camera processing (With Prof. **Krishna**)
- Edge computing solution for underserved communities
  - Smart information services without WAN connectivity

Pubs:
http://www.cc.gatech.edu/~rama/recent_pubs.html

E-mail: rama@cc.gatech.edu

Lab:
http://wiki.cc.gatech.edu/epl

What does Kishore "really" do in his copious spare time when he is not teaching?



Squash anyone?

All virtual!

Soon real?

Table tennis anyone?

What you should take away?

- "Kishore" rhymes with "sea shore"
- Squash/Table-tennis
- EPL
- Fog/Edge computing
- Infinite storage on mobile/EdgeCaching

https://www.dreamstime.com/namaste-vector-hand-drawn-symbol-yoga-design-image112101574

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Extra slides on EPL projects underway

Kishore Ramachandran

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Two topics

Camera Processing @ Edge

Serverless @ Edge

Camera Network

Context

- Streaming 24 x 7
- Used by multiple applications
- Processing at ingestion time
- Processing at Edge

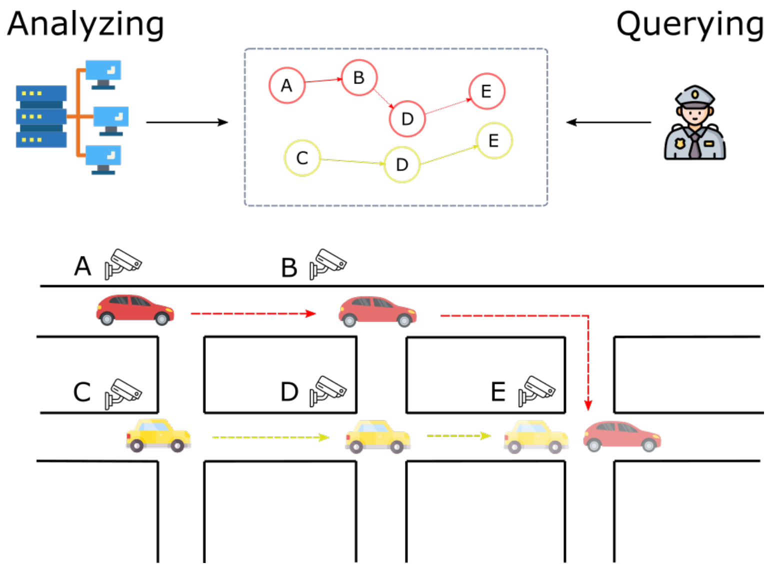
Applications

- Suspicious vehicle tracking
- Smart traffic light
- Camera-assisted navigation for the disability

Motivating Application

Space-Time Vehicle Tracking at video ingestion time

- Manual Checking
  - Labor-intensive
  - Error-prone due to lapses in attention
- Intelligent systems
  - Replace manual labor
  - Aid human decision-making



Outline

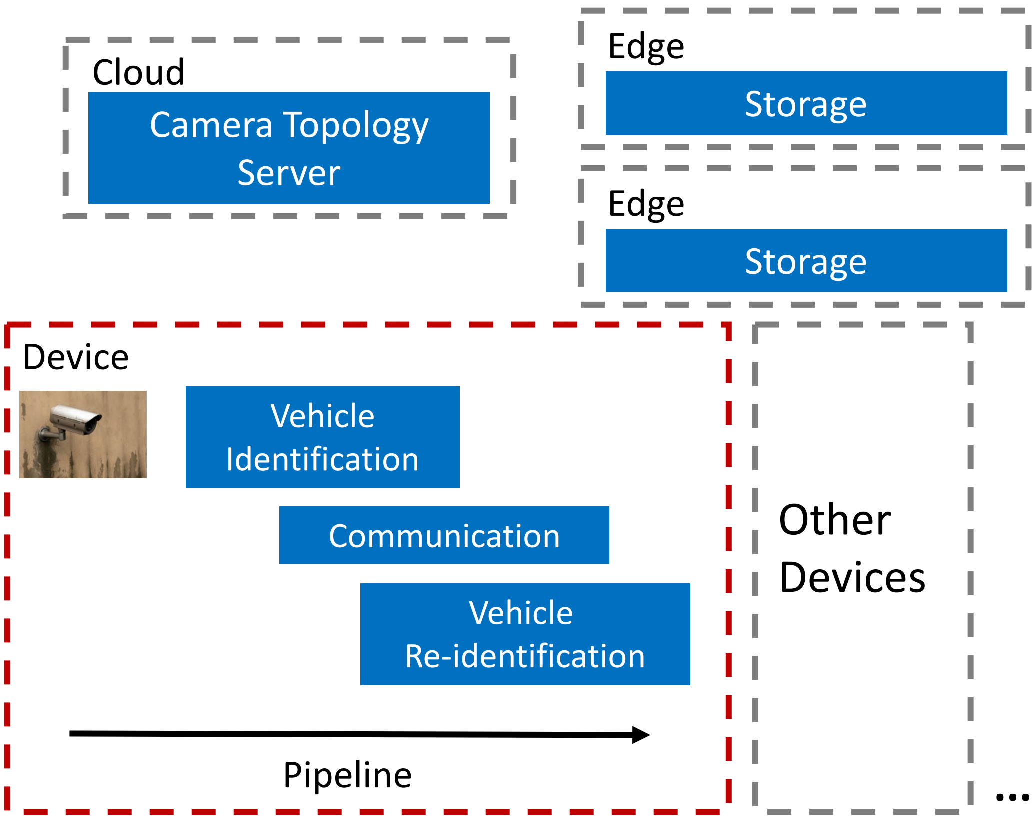
- Recent work on camera applications at Edge
  - Coral-Pie: Space-Time Vehicle Tracking at the Edge (**ACM Middleware 2020**)
- Proposed Work in a nutshell
  - Camera Networks at the Edge
    - MicroEdge: multi-tenancy edge system architecture
    - Accelerator orchestration in MicroEdge
  - Serverless at the Edge
    - Nimble orchestration for FaaS
    - Cross-site load balancing
    - Location-aware auto-scaling

Recent Work

Novel Principles

- "Scalable-by-design" camera processing at ingestion time
  - Per-camera latency-based subtask placement
  - Bounded network communication per camera
- Fault tolerance for geo-distributed camera network
  - Automatic camera topology management

Coral-Pie: Device-Edge-Cloud Continuum



Device:

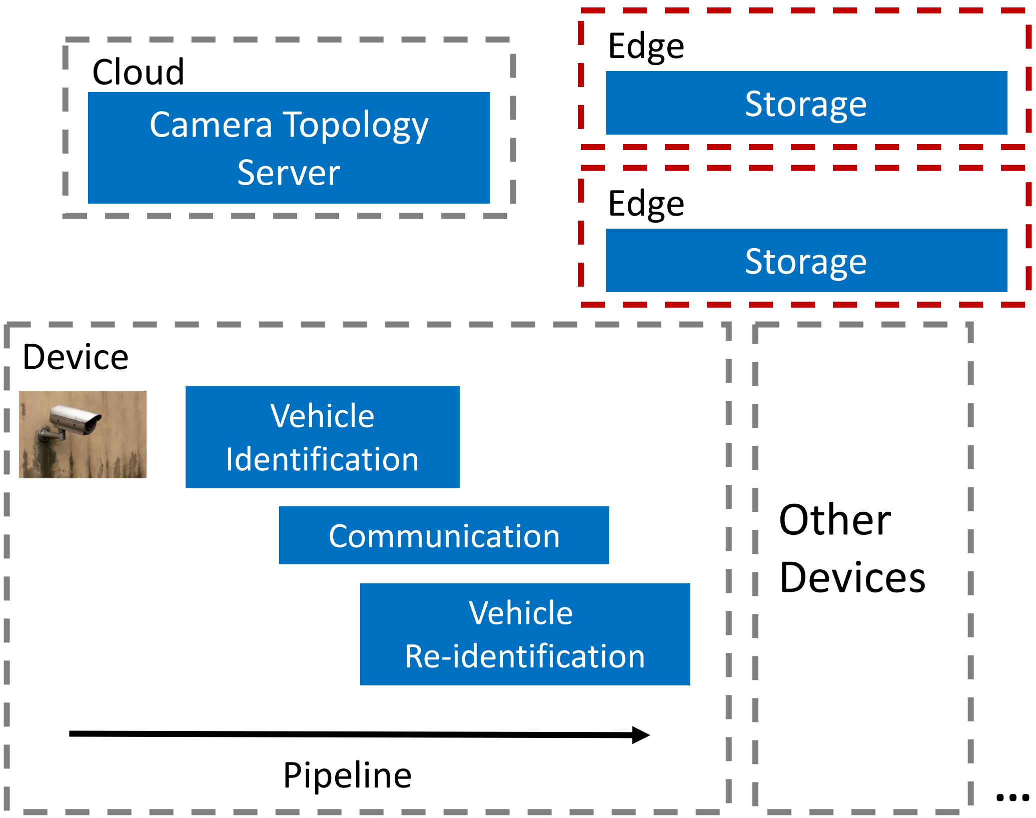
- Camera + 2 RPis + TPU

Heavy-lifting real-time camera processing

- **Deterministic latency bounds**
- **No pressure on the backhaul network bandwidth**

Pipelined processing to exploit parallelism

Coral-Pie: Device-Edge-Cloud Continuum



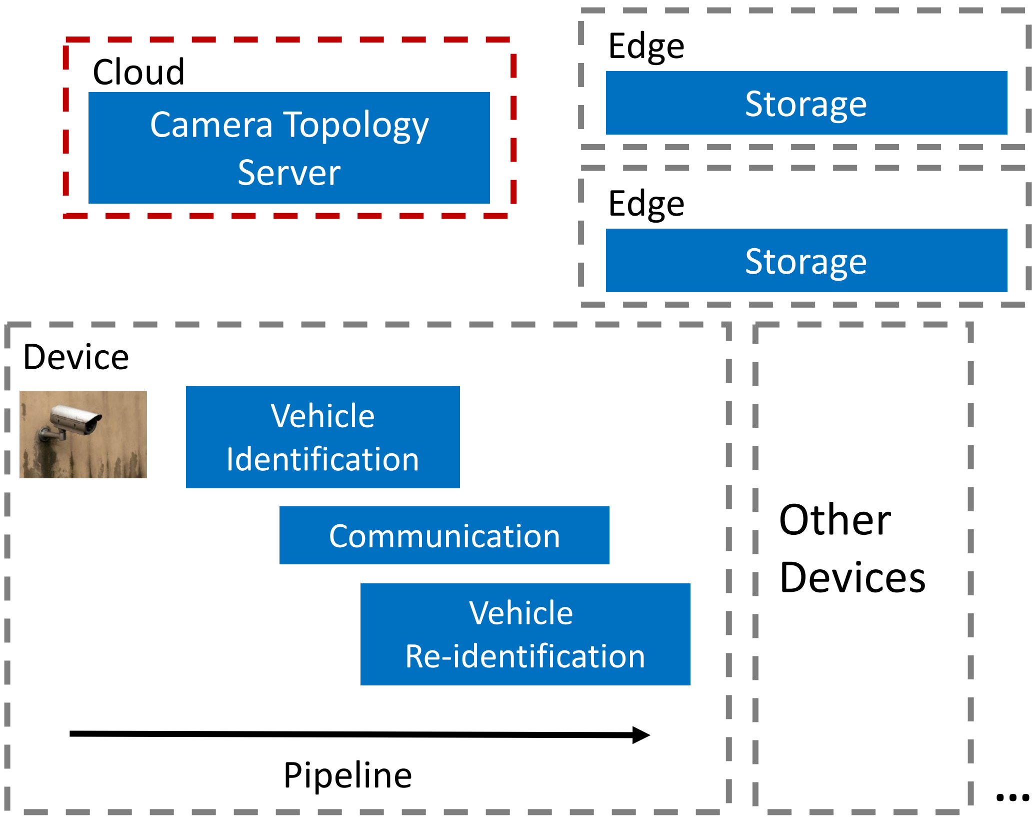
Edge:

- A multi-tenant micro-datacenter housed in a small footprint location
- **Few network hop(s)** away from Devices

Offloading storage

- ***Asynchronously***
- Helps balance the pipeline of tasks on the Devices
- Backhaul wide-area network (WAN) is not pressured

Coral-Pie: Device-Edge-Cloud Continuum



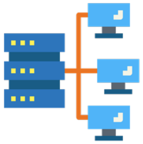
Cloud

- A centralized service provider that all devices can connect to
- **Global knowledge**

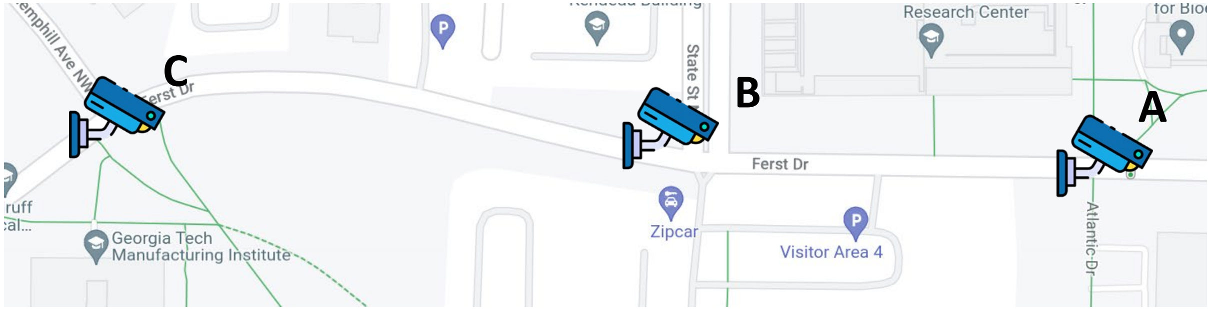
Maintains geographical relationship between the cameras

- Infrequently updated (i.e., a new camera is deployed or an old camera is removed)

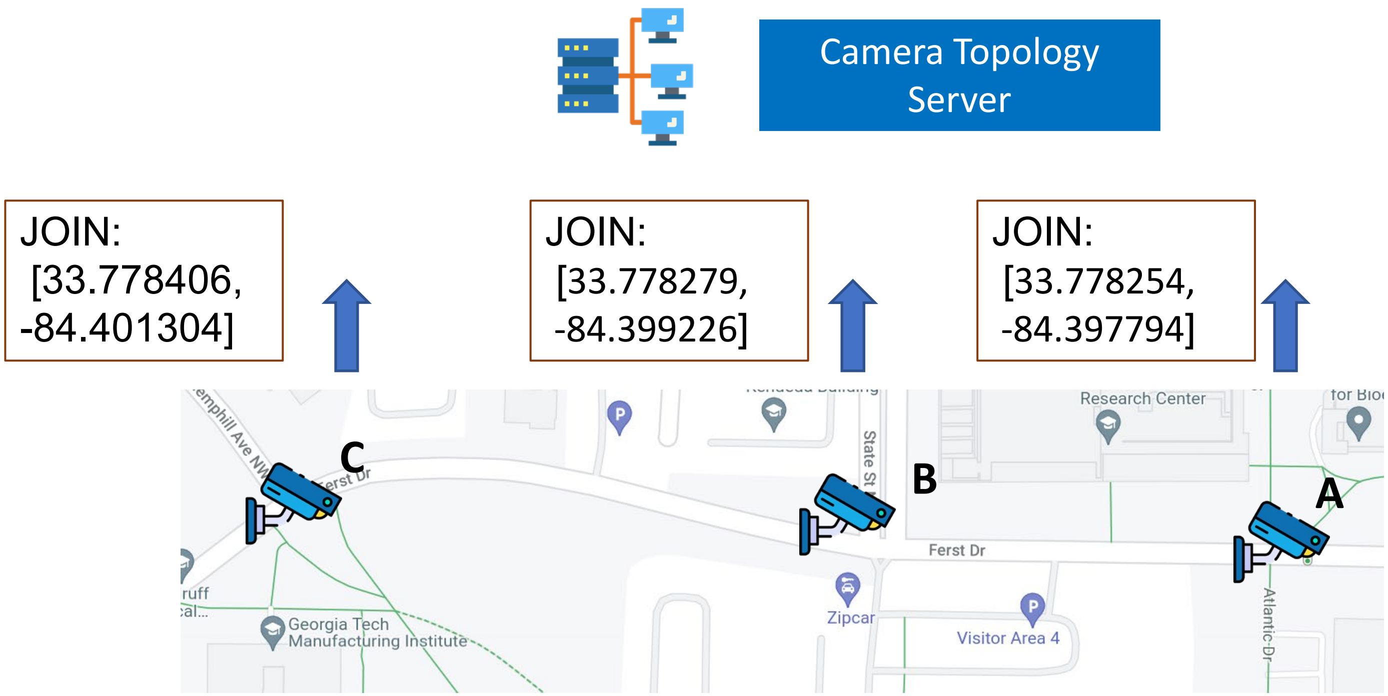
Coral-Pie in Action



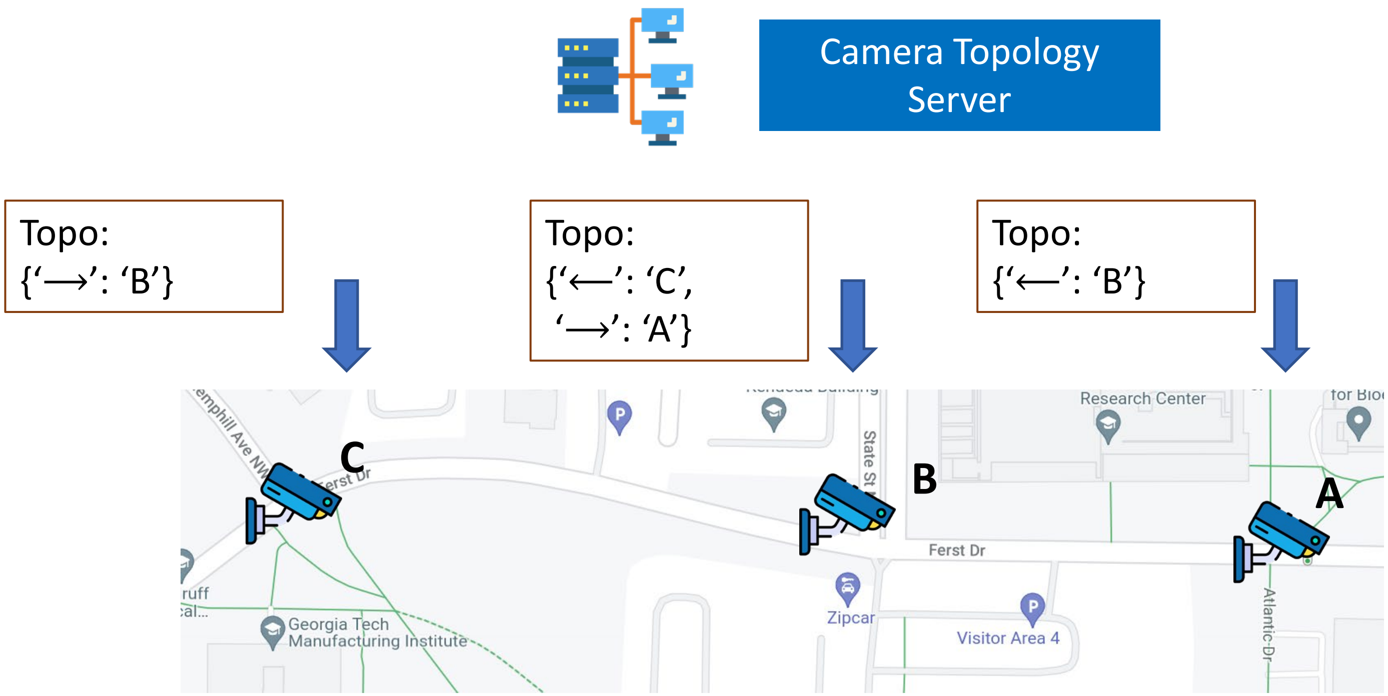
Camera Topology Server



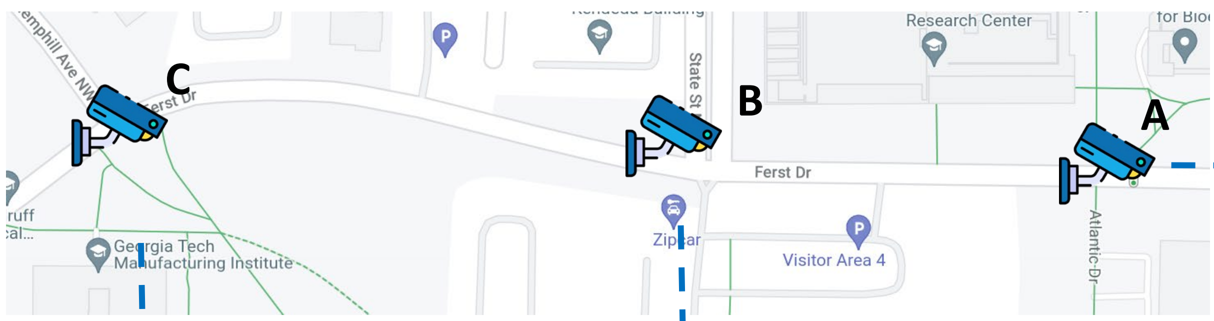
Cloud: Management of Camera Topology



Cloud: Management of Camera Topology

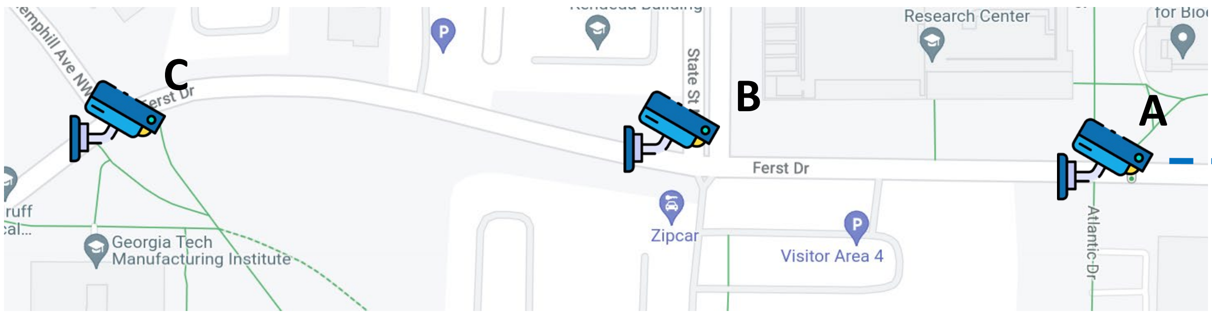


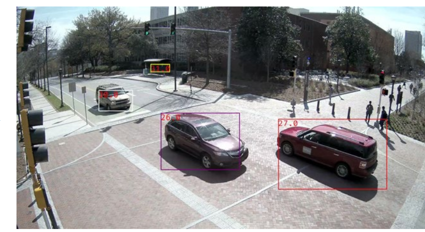
Device: Vehicle Identification



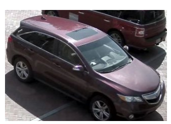
```
DetectionEvent_A_0:
{
    camera: A,
    timestamp: 18:19-07/10/2019,
    tracklet: [(bbox, frameId),...],
    features: {
        moving_direction: 270 (⟵),
        histogram: np.array([...])
    }
}
```

Device: Communication



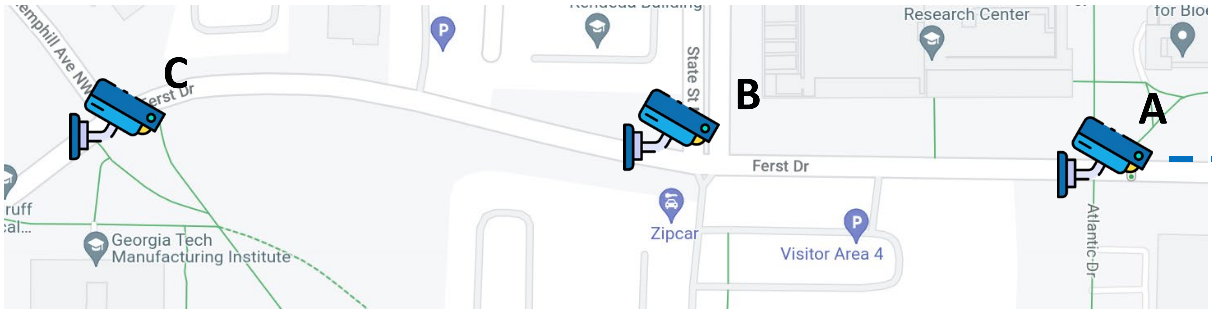


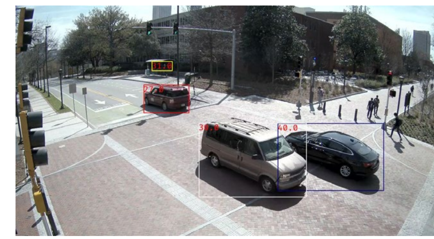
Camera B's Candidate Pool:

DetectionEvent_A_0: 

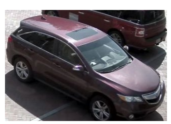
DetectionEvent_A_0:
{
    camera: A,
    timestamp: 18:19-07/10/2019,
    tracklet: [(bbox, frameId),...],
    features: {
        moving_direction: 270 (⟵),
        histogram: np.array([...])
    }
}

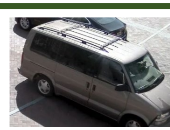
Device: Communication





Camera B's Candidate Pool:

DetectionEvent_A_0: 

DetectionEvent_A_2: 

DetectionEvent_A_2:
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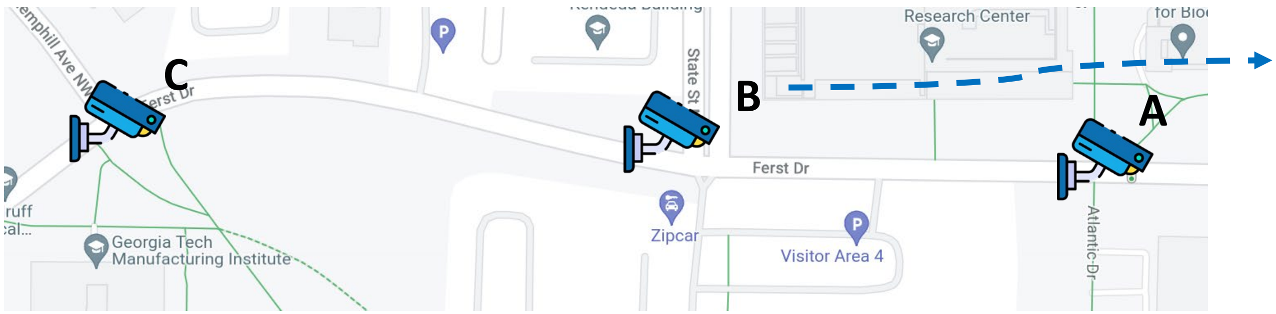
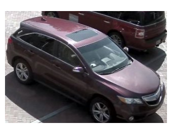
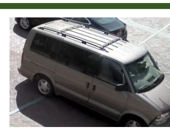
camera: A,
timestamp: 18:19:09-07/10/2019,
tracklet: [(bbox, frameId),...],
features: {
moving_direction: 270 (⟵),
histogram: np.array([...])
}
}

Device: Vehicle Re-Identification at Camera B



Camera B’s Candidate Pool:

DetectionEvent_A_0: 

DetectionEvent_A_2: 

Matching!

```
DetectionEvent_B_7:
{
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   timestamp: 18:19:26-07/10/2019,
   tracklet: [(bbox, frameId),...],
   features: {
      moving_direction: 270 (⟵),
      histogram: np.array([...])
   }
}
```
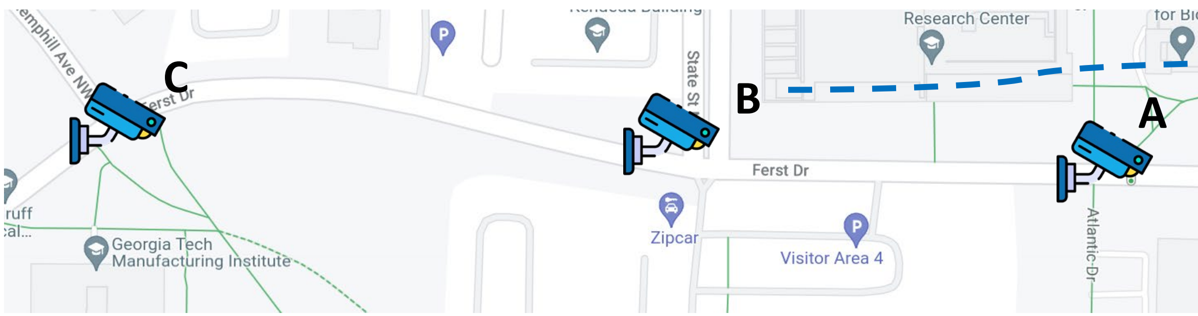
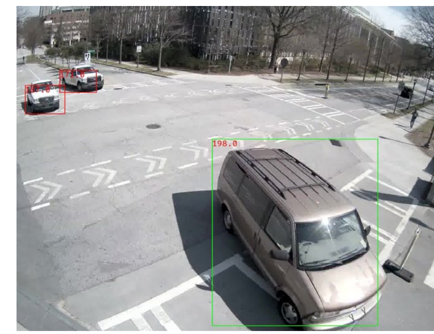
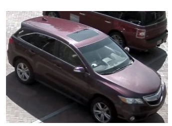

Device: Vehicle Re-Identification at Camera B



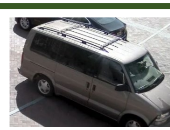


Camera B's Candidate Pool:

DetectionEvent_A_0:



DetectionEvent_A_2:



Matching!

```
DetectionEvent_B_9:
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   timestamp: 18:19:29-07/10/2019,
   tracklet: [(bbox, frameId),...],
   features: {
      moving_direction: 180(↓),
      histogram: np.array([...])
   }
}
```
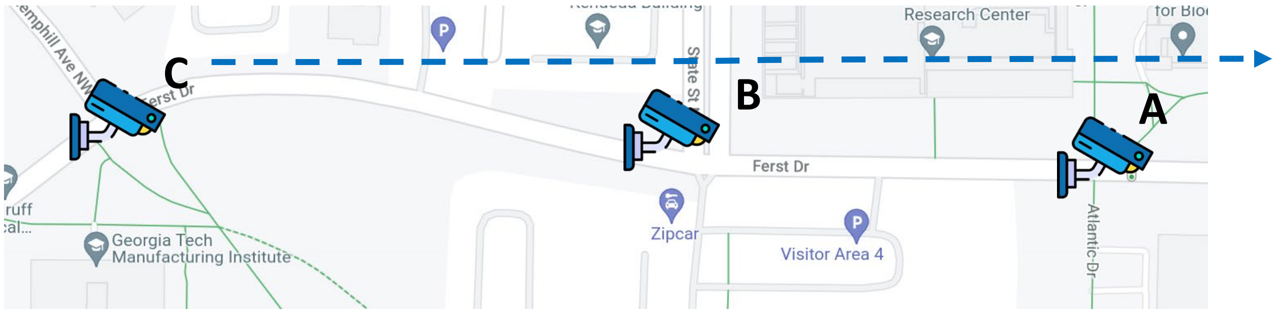

Device: Vehicle Re-Identification at Camera C



Camera B's Candidate Pool:

DetectionEvent_B_7: 

Matching!

```
DetectionEvent_C_12:
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   timestamp: 18:19:46-07/10/2019,
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   features: {
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      histogram: np.array([...])
   }
}
```
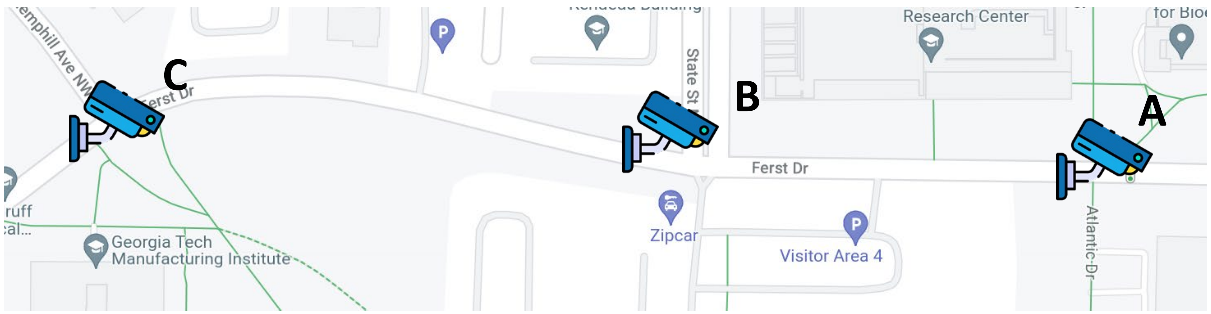
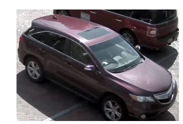

Edge: Storage



- Trajectory Storage as Graph
- Frame Storage - traceability

DetectionEvent_C_12 ← DetectionEvent_B_7 ← DetectionEvent_A_0



DetectionEvent_B_9 ← DetectionEvent_A_2

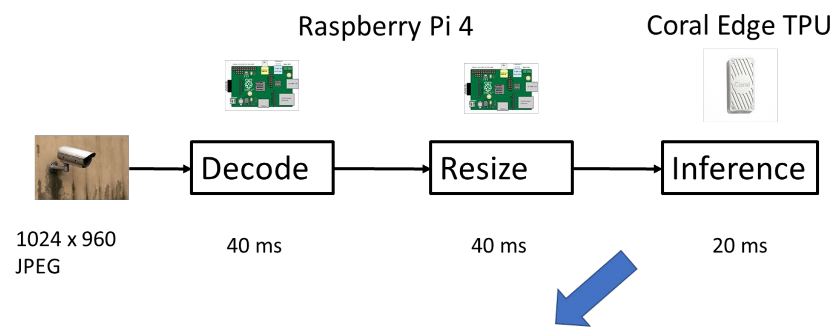
From Coral-Pie to MicroEdge

Limitations of Coral-Pie

- Dedicated hardware resources for each camera processing pipeline
  - ➢ Each pipeline may not use the resources all the time
- Camera network intended for multiple applications

Opportunity

- Share TPU, CPU, and memory resources within and across applications



- 50% TPU utilization with 25 FPS stream
- 20% TPU utilization with 10 FPS stream

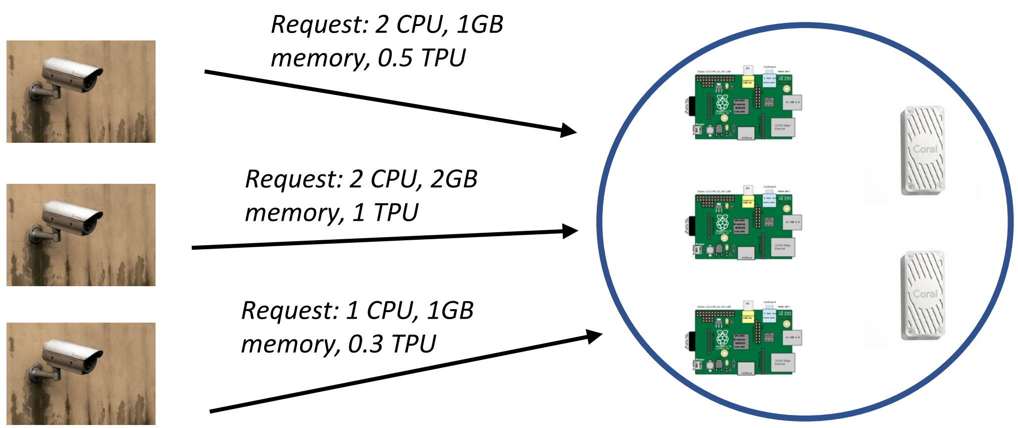
Limitations of the State-of-the-art

- Prior art focus on GPU management in resource-rich clusters
  - NVIDIA Docker and NVIDIA MPS
  - Clockwork[1], Heimdall[2], Infaas[3], and Clipper[4]
- Lack of support for multiplexing TPU resources across containers
- Missed opportunity in container-orchestration systems (e.g., Kubernetes, K3s)
  - Under-utilization of TPU resources

[1] Gujarati, Arpan et al. "Serving DNNs like Clockwork: Performance Predictability from the Bottom Up." OSDI (2020).
[2] Yi, Juheon and Youngki Lee. "Heimdall: mobile GPU coordination platform for augmented reality applications." Proceedings of the 26th Annual International Conference on Mobile Computing and Networking (2020).
[3] Romero, Francisco et al. "INFaaS: Automated Model-less Inference Serving." USENIX Annual Technical Conference (2021).
[4] Crankshaw, Daniel et al. "Clipper: A Low-Latency Online Prediction Serving System." NSDI (2017).

MicroEdge Vision

- A low-cost edge cluster serves computational resources for a set of geo-local cameras.
- A performant **multi-tenancy** architecture.



Objectives of MicroEdge System Architecture

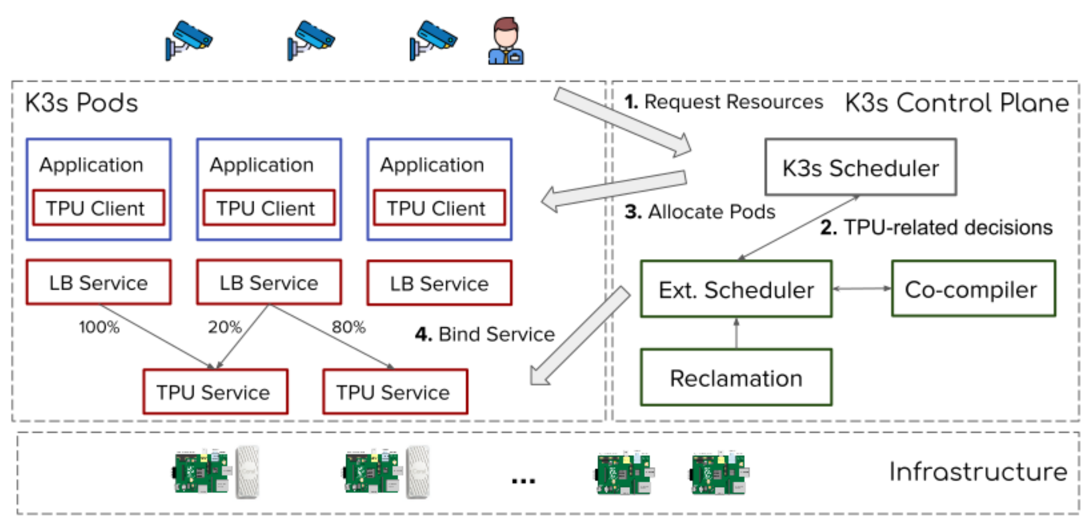
- Share TPU resources across independent application pipelines
- Performance isolation across independent application pipelines
- Load-balance incoming inference requests across TPU resources
- Co-compile different models on TPUs to reduce model swapping overhead

MicroEdge System Architecture

Research Questions
- **How do we extend the state of the art?**

Extensions to K3s's control plane
- Orchestrate TPU resources on creation and destruction of application pods
  - ➢ Admission Control
- Key components:
  - ➢ Extended scheduler, TPU co-complier, Resource reclamation

Extensions to K3s's data plane
- Mechanisms to multiplex TPU resources across applications
  - ➢ Monitoring TPU usage
- Key components:
  - ➢ TPU service, TPU service client library, Load balancing service



Evaluation Plan

Application Study

- Space-time vehicle tracking
- Can MicroEdge improve the resource utilization while meeting the SLA of application?

Trace-based Study

- Azure Function Traces [1]
- Map to ephemeral application pipelines
- Can MicroEdge effectively allocate and reclaim TPU resources?

[1] Shahrad, Mohammad, et al. "Serverless in the wild: Characterizing and optimizing the serverless workload at a large cloud provider." 2020 USENIX Annual Technical Conference (USENIX ATC 20). 2020.

Serverless at the Edge for camera networks

- Motivation: Workload at the edge is highly variable with time
  - Dedicating resources leads to overprovisioning
  - Scarce resources at the Edge
- Original vision for Coral-Pie was to create space-time track for all vehicles all the time
  - But most of the time, we are interested only in "suspicious" vehicles
  - Increases the chance for resource multiplexing
  - Number of interesting objects detected is sporadic

=> Move toward Serverless at the Edge

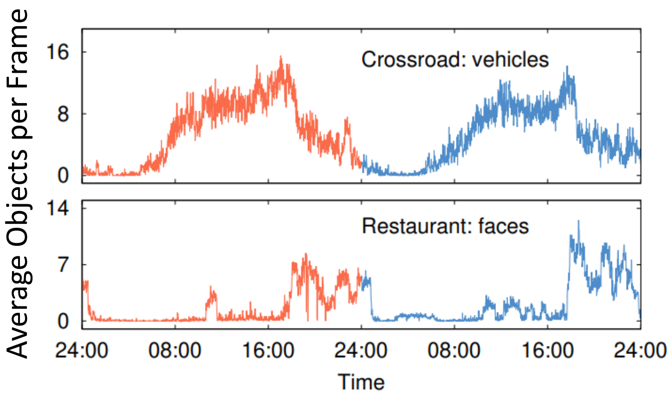
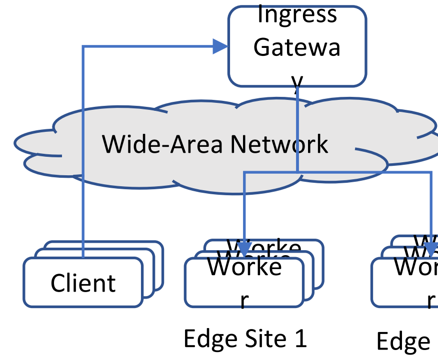
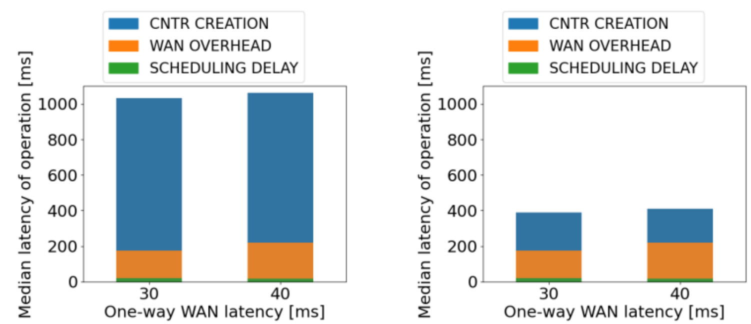


Image source: Zhang, Miao, et al. "Towards cloud-edge collaborative online video analytics with fine-grained serverless pipelines." *Proceedings of the 12th ACM Multimedia Systems Conference*. 2021.

Limitations of State-of-the-Art

- Cloud-based FaaS platforms
  - OpenFaaS, KNative (backed by K8s)
  - High Latency for OpenFaaS in MicroEdge
    ==> High container creation overhead
  - Multiple WAN traversals
    ==> High WAN overhead
  - Location-agnostic scheduling





(b) Latency breakdown with container cold start.

(c) Latency breakdown with pre-warmed containers.

Figure 2: Experimental results with Kubernetes.

WAN latency = 80 ms RTT

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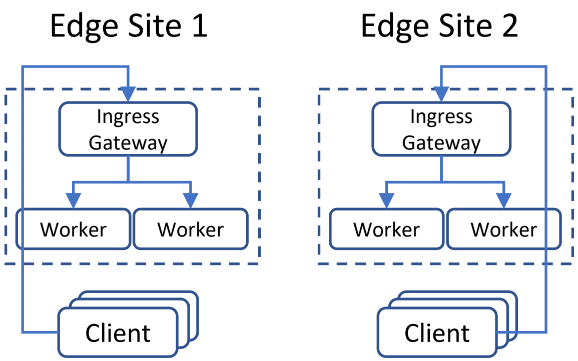
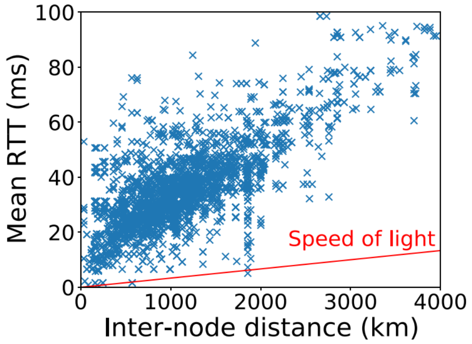
- Edge-specific FaaS platforms
  - Mu (SoCC'21)
    - Fine-grained queue-size based load-balancing to meet latency requirement
  - CEVAS (MMSys'21)
    - Optimal partitioning of serverless video processing between edge and cloud
  - Both platforms focus only on resources of 1 edge site
  - Load-balancing and Scaling policies are unaware of load on other sites



Objectives for Serverless @ Edge

- Cross-site load-balancing of function invocation requests
- Location-aware auto-scaling
- Nimble edge execution environment
- Handle heterogeneous network latencies between edge sites



Inter-edge-site latencies

Image source: Xu, Mengwei, et al. "From cloud to edge: a first look at public edge platforms." Proceedings of the 21st ACM Internet Measurement Conference. 2021.

Initial set of Research Questions

- Cross-site load balancing policy
  - Whether and to which site to offload?
- Global autoscaling policy
  - How to predict spatio-temporal distribution of client requests?
  - Where to provision function containers to minimize resource wastage and meet application requirement?
- Monitoring
  - What metrics are needed to enable above policies?
  - How to efficiently and scalably propagate per-site system state to other sites?
- Agility-oriented optimizations in Kubernetes to reduce cold start overhead
- Network proximity monitoring
  - How to do so accurately, efficiently, and at scale? (Network coordinates?)

Evaluation Plan

- Load balancing policy
  - Proposed network proximity and load-aware approach
  - Compare with
    - Coarse-grained monitoring (e.g., uniform load distribution *a la* OpenFaaS)
    - Fine-grained monitoring (e.g., fine-grained queue-sizes *a la* Mu)
- Autoscaling policy
  - Proposed spatio-temporal demand distribution based approach
  - Compare with
    - Techniques based on CPU utilization/request rate (*a la* OpenFaaS) and latency-aware (*a la* Mu)
- Network proximity
  - Is the use of network coordinates accurate, efficient, and scalable ?

Expected Contributions of the Proposed Research

MicroEdge

- Control and data-plane mechanisms for orchestrating accelerator resources
- Policies for efficient allocation of accelerator resources
- Admission Control and Monitoring policies

Serverless @ Edge

- Cross-site load and latency aware load-balancing policy
- Spatio-temporal demand based cross-site autoscaling policy
- Integrating network coordinates for network proximity monitoring

END