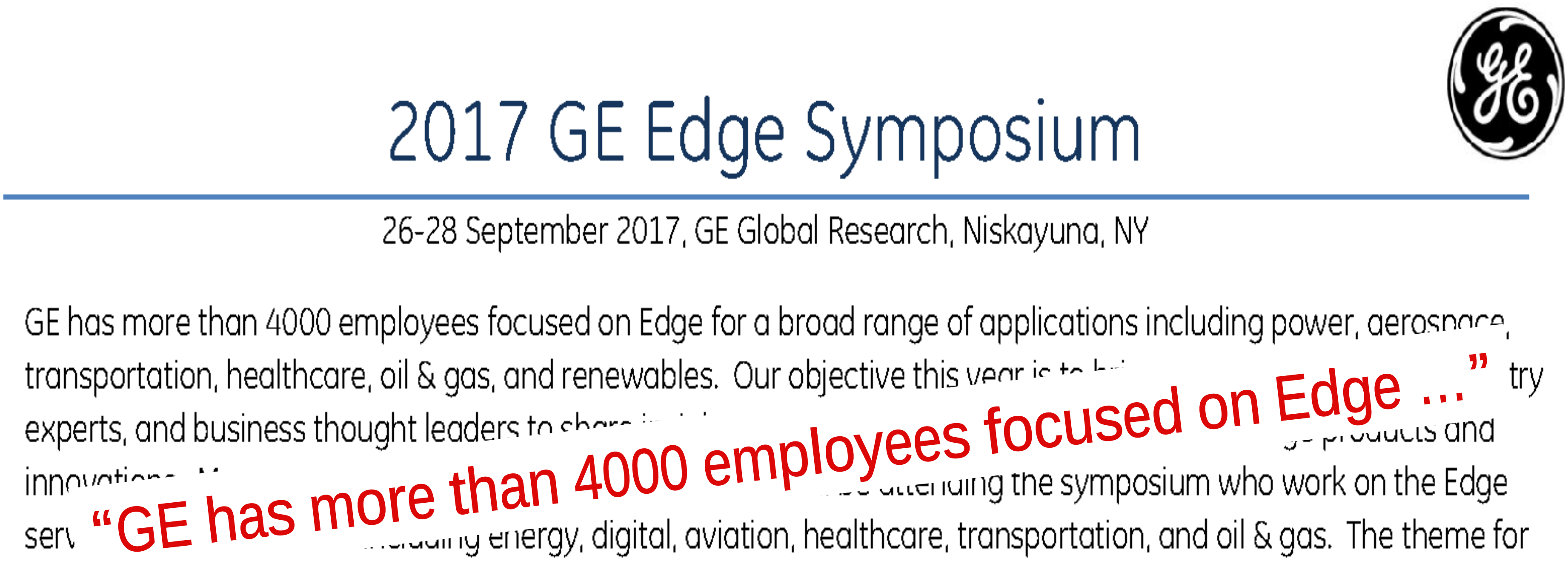
Edge Computing

A New Disruptive Force

Mahadev Satyanarayanan
School of Computer Science
Carnegie Mellon University

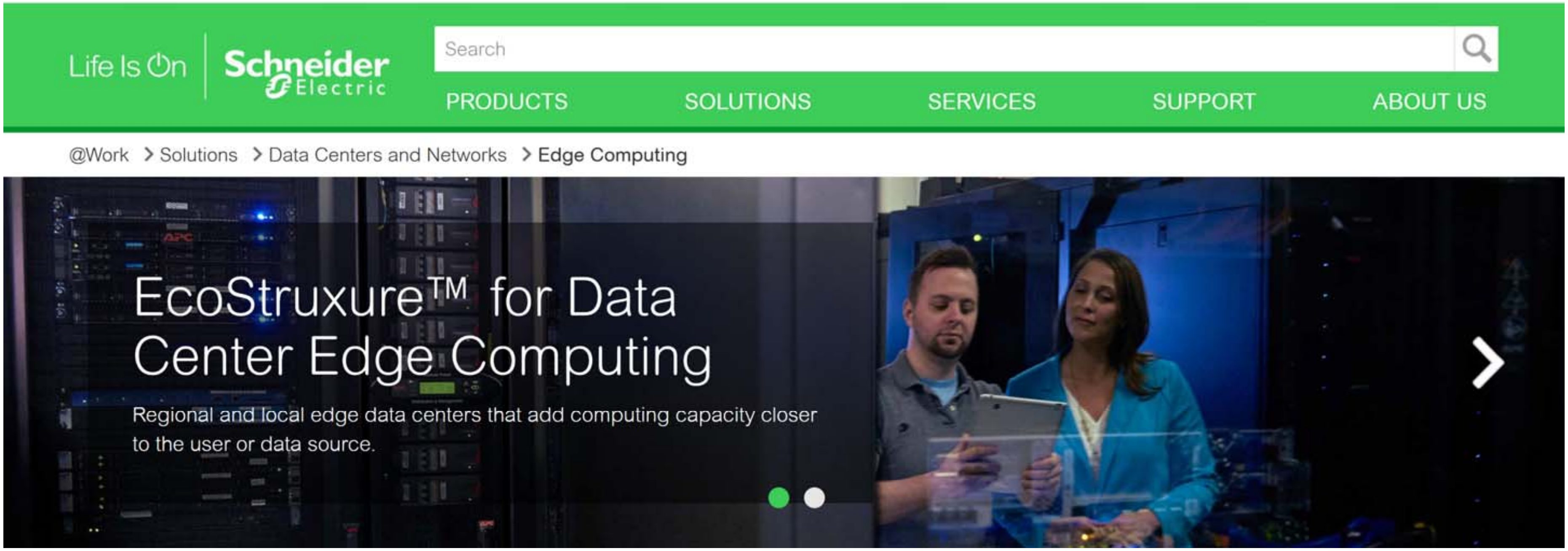


2017 GE Edge Symposium

26-28 September 2017, GE Global Research, Niskayuna, NY

GE has more than 4000 employees focused on Edge for a broad range of applications including power, aerospace, transportation, healthcare, oil & gas, and renewables. Our objective this year is to br try experts, and business thought leaders to share i products and innovation attending the symposium who work on the Edge serv including energy, digital, aviation, healthcare, transportation, and oil & gas. The theme for

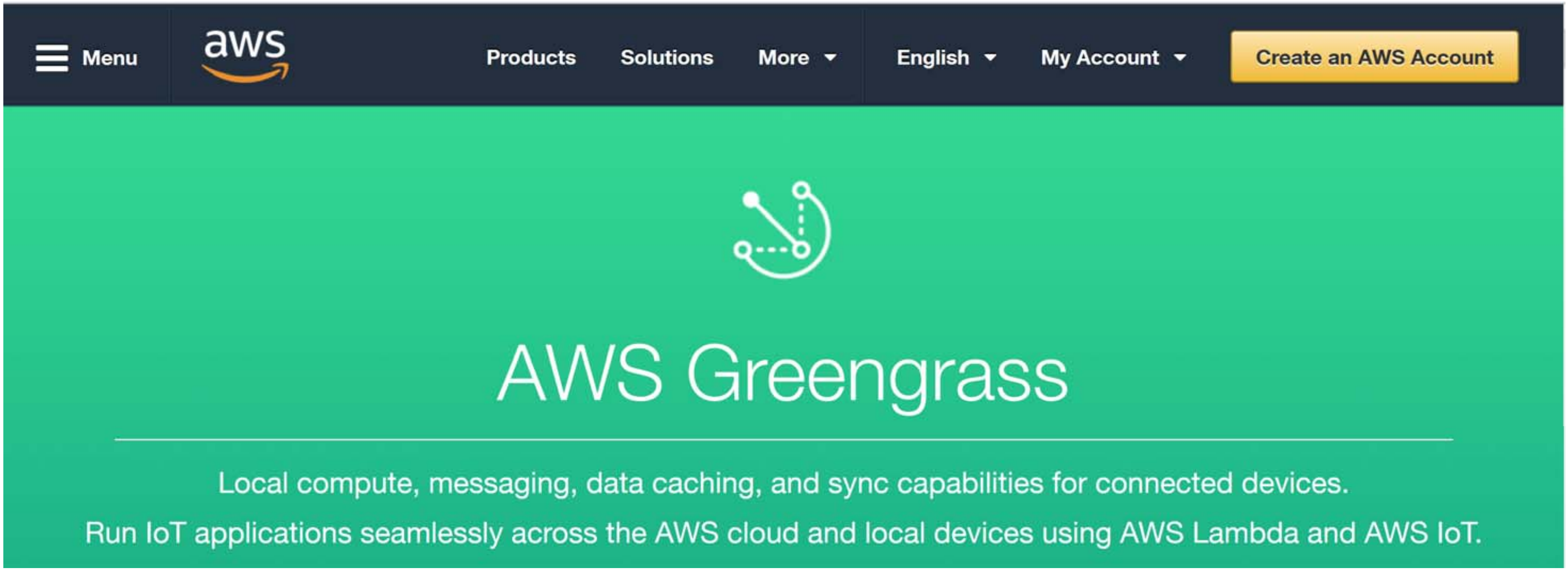
"GE has more than 4000 employees focused on Edge …"



@Work > Solutions > Data Centers and Networks > Edge Computing

EcoStruxure™ for Data Center Edge Computing

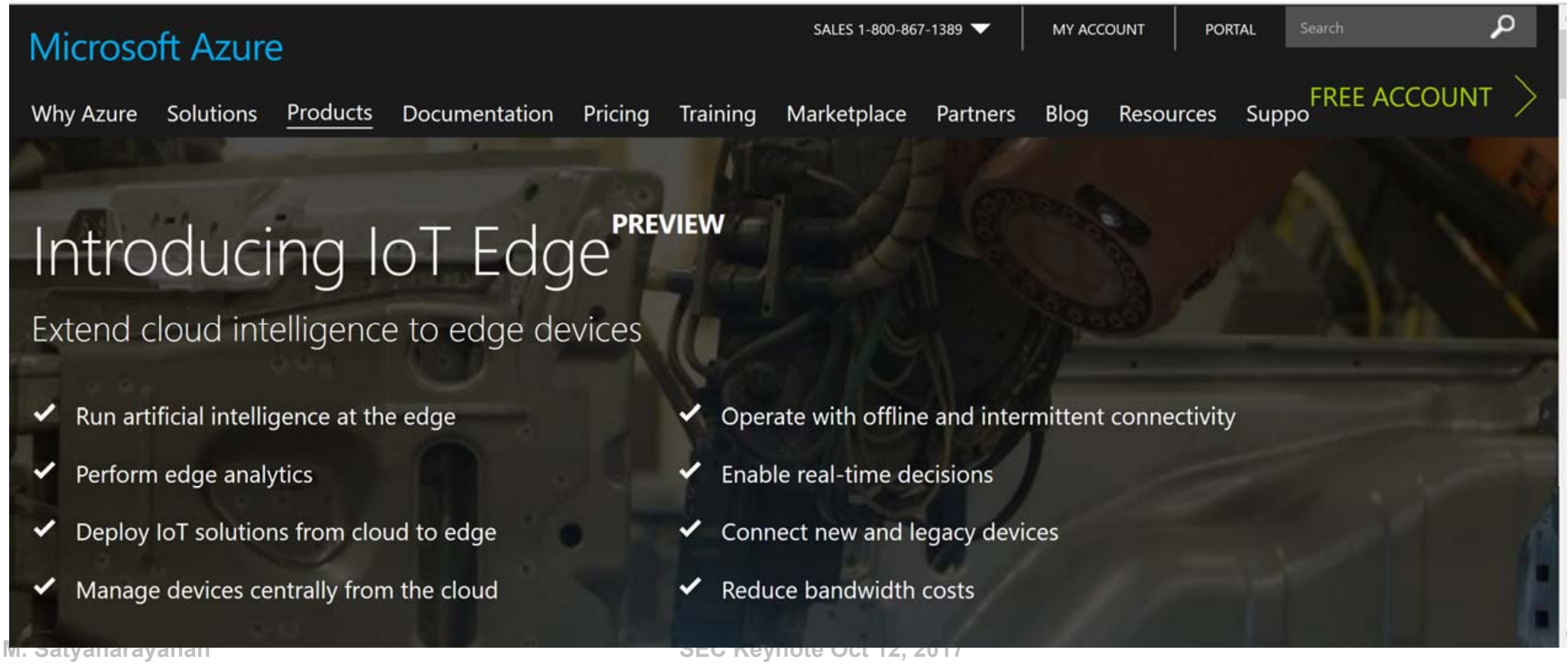
Regional and local edge data centers that add computing capacity closer to the user or data source.



AWS Greengrass

Local compute, messaging, data caching, and sync capabilities for connected devices.

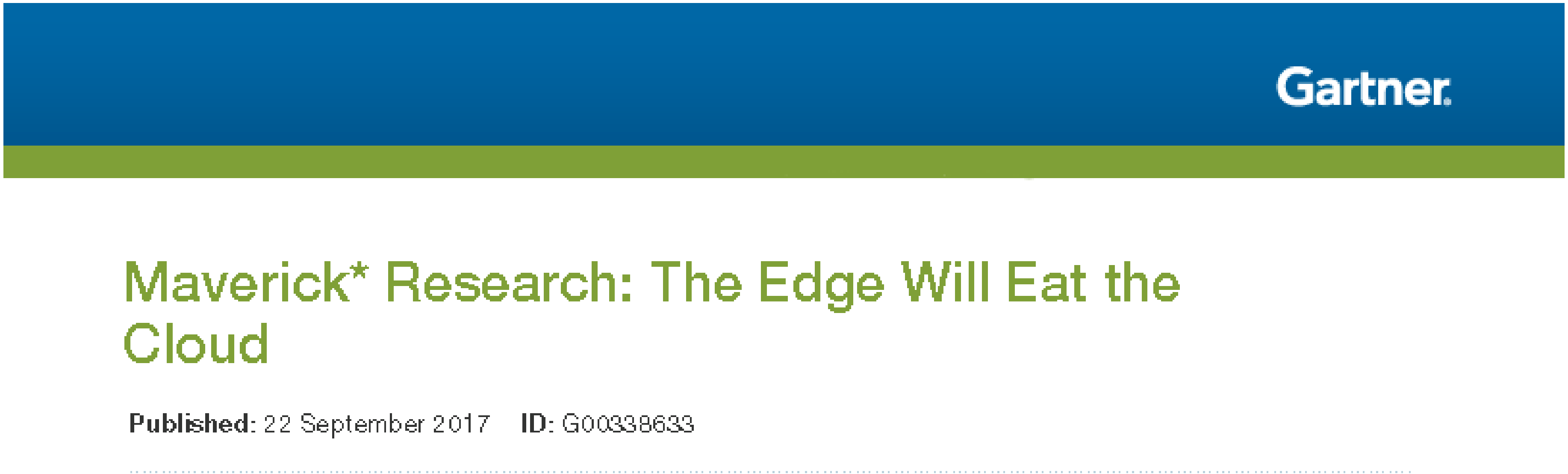
Run IoT applications seamlessly across the AWS cloud and local devices using AWS Lambda and AWS IoT.



Introducing IoT Edge PREVIEW

Extend cloud intelligence to edge devices

- ✓ Run artificial intelligence at the edge
- ✓ Perform edge analytics
- ✓ Deploy IoT solutions from cloud to edge
- ✓ Manage devices centrally from the cloud
- ✓ Operate with offline and intermittent connectivity
- ✓ Enable real-time decisions
- ✓ Connect new and legacy devices
- ✓ Reduce bandwidth costs



Gartner.

Maverick* Research: The Edge Will Eat the Cloud

Published: 22 September 2017 **ID:** G00338633

How Far We Have Come!

2009 NSF Panel Summary for my Expeditions Proposal

> *“Many panelists do not agree with the premise of the proposal in which distant cloud computing incurs too high latency to be acceptable by mobile applications. They question the validity of such assumption as the proposal provides no real data to justify it.”*

Needless to say, the proposal was rejected ☹

Time has proven the premise to be correct!

(NSF hosted workshop on “Research Challenges in Edge Computing” in 2016)

Why Is Edge Computing So Valuable?

1. Highly responsive cloud services *“New applications and microservices”*	**Latency** (mean and tail)
2. Edge analytics in IoT *“Scalable live video analytics”*	**Bandwidth** (peak and average)
3. Exposure firewall in the IoT *“Crossing the IoT Chasm”*	**Privacy**
4. Mask disruption of cloud services *“Disconnected operation for cloud services”*	**Availability**

“The Emergence of Edge Computing”
Satyanarayanan, M.
IEEE Computer, Vol. 50, No. 1, January 2017

What is a Cloudlet?

aka “micro data center”, “mobile edge cloud”, “fog node”

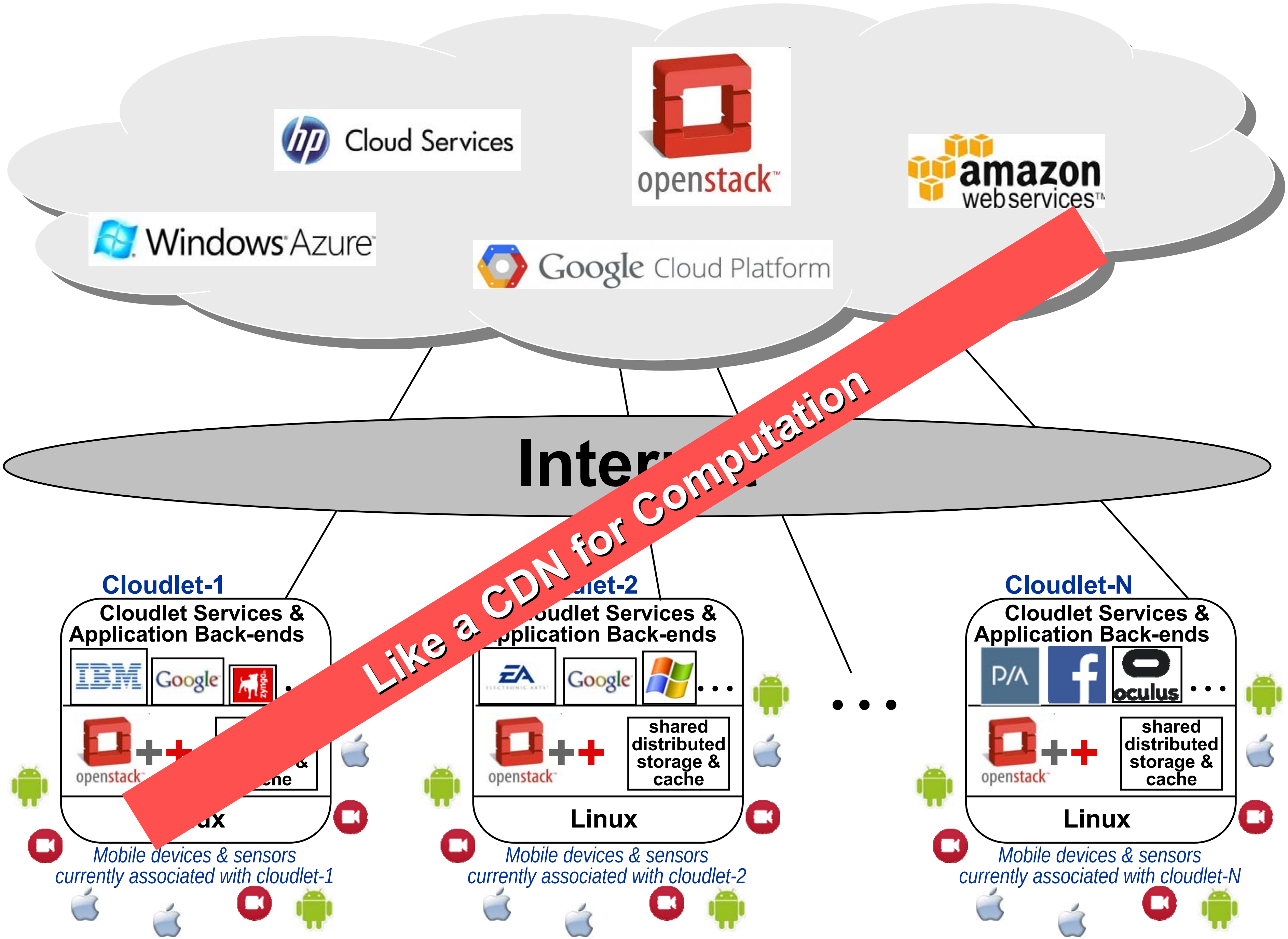
Small data center at the edge of the Internet (many sizes & forms)

- **one wireless hop (+fiber or LAN) to mobile devices**
  (Wi-Fi or 4G LTE or 5G)
- **multi-tenant, as in cloud**
- **good isolation and safety (VM-based guests)**
- **lighter-weight containers (e.g. Docker within VMs) also possible**

Non-constraints **(relative to mobile devices)**

- **energy**
- **weight/size/heat**

Catalyst for new mobile applications



Like a CDN for Computation

Cloudlet-1

Cloudlet Services & Application Back-ends

Linux

Mobile devices & sensors currently associated with cloudlet-1

Cloudlet-2

Cloudlet Services & Application Back-ends

shared distributed storage & cache

Linux

Mobile devices & sensors currently associated with cloudlet-2

Cloudlet-N

Cloudlet Services & Application Back-ends

shared distributed storage & cache

Linux

Mobile devices & sensors currently associated with cloudlet-N

LIVING EDGE LAB

An Open and Flexible Resource for Hands-on Experience with Edge Computing

Mission Statement

"We are building a real-world testbed for Edge Computing with leading edge applications and user acceptance testing."

LEL

Our Way Forward in 2017

Infrastructure, telco and research team up and **build testbeds**

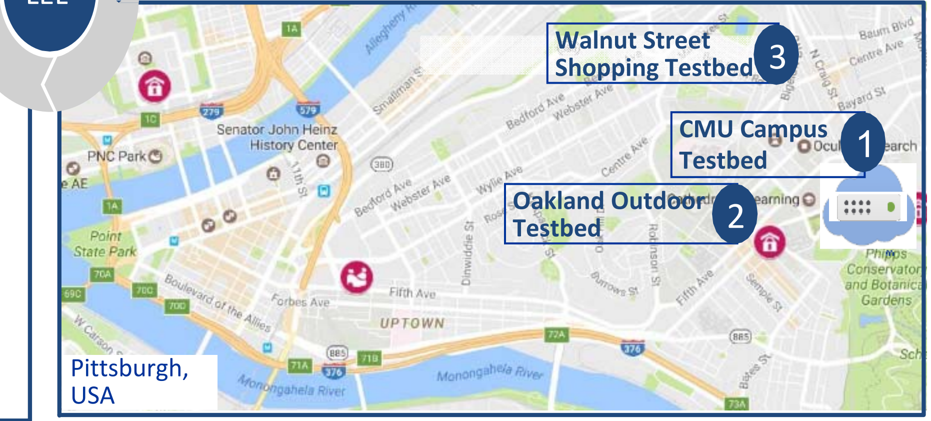
Application partners join the lab for dedicated test projects

Integration and testing of latest edge computing applications

Joint **evaluation and promotion** of results among partners

Key Elements

- **Partnership:** developers for apps, services and devices join forces with telco, infrastructure and research
- **Test Diversity:** various testbeds and latest technology available for a variety of use-case scenarios
- **Open Platform:** edge computing based on OpenStack



Walnut Street Shopping Testbed 3

CMU Campus Testbed 1

Oakland Outdoor Testbed 2

Pittsburgh, USA

Carnegie Mellon University · T · · CROWN CASTLE · intel · vodafone · NTT · NOKIA

Rest of This Talk

Does latency really matter?

Two “killer” use cases enabled by

- low end-to-end latency
- scalable bandwidth demand

Does Latency Really Matter?

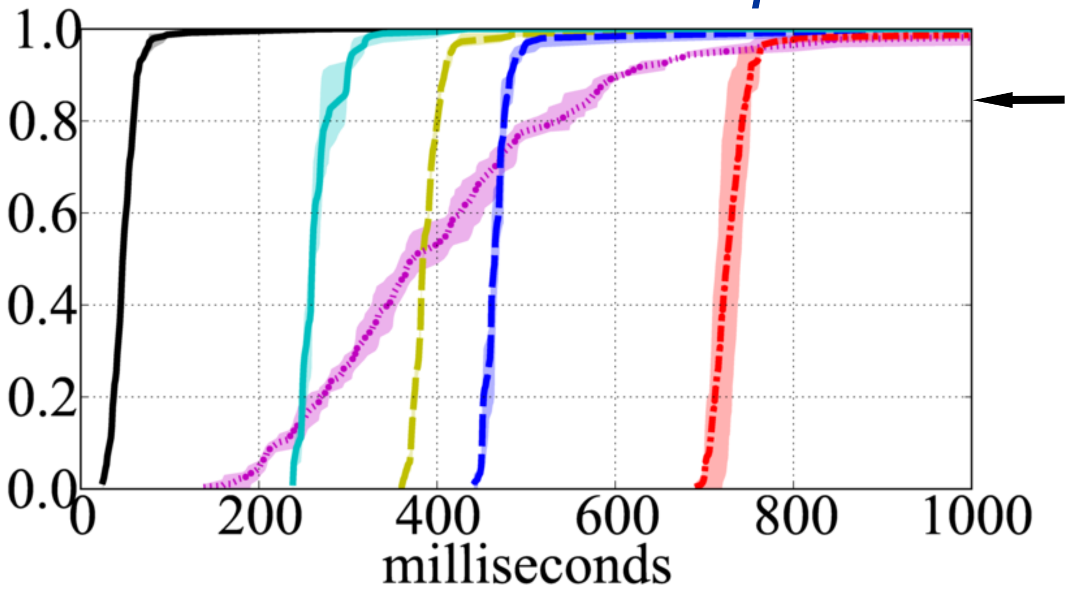
"The Impact of Mobile Multimedia Applications on Data Center Consolidation"
Ha, K., Pillai, P., Lewis, G., Simanta, S., Clinch, S., Davies, N., Satyanarayanan, M.
Proceedings of IEEE International Conference on Cloud Engineering (IC2E), San Francisco, CA, March 2013

"Quantifying the Impact of Edge Computing on Mobile Applications"
Hu, W., Gao, Y., Ha, K., Wang, J., Amos, B., Pillai, P., Satyanarayanan, M.
Proceedings of ACM APSys 2016, Hong Kong, China, August 2016

Augmented Reality

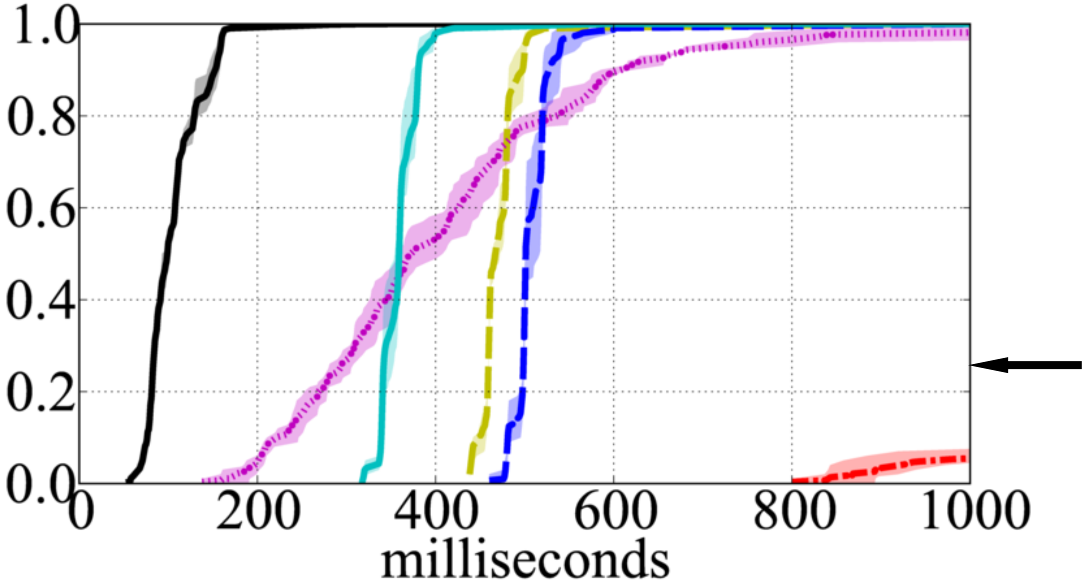
E2E Response Time CDF

1. Send JPG image from device to cloud/cloudlet
2. Recognize landmark buildings using computer vision
3. Send labels & coordinates back to device



Wi-Fi
802.11n

Mobile-only
Amazon East
Amazon West
Amazon EU
Amazon Asia
Cloudlet



4G LTE
T-Mobile for Cloud
In-lab Nokia eNodeB for Cloudlet

Per-Operation Energy Use by Device

Face Recognition			Augmented Reality
12.4 J	·······	Mobile-only	5.4 J
2.6 J	——	Cloudlet	0.6 J
4.4 J	——	Amazon East	3.0 J
6.1 J	– –	Amazon West	4.3 J
9.2 J	– –	Amazon EU	5.1 J
9.2 J	— ·	Amazon Asia	7.9 J

What is the Killer Use Case?

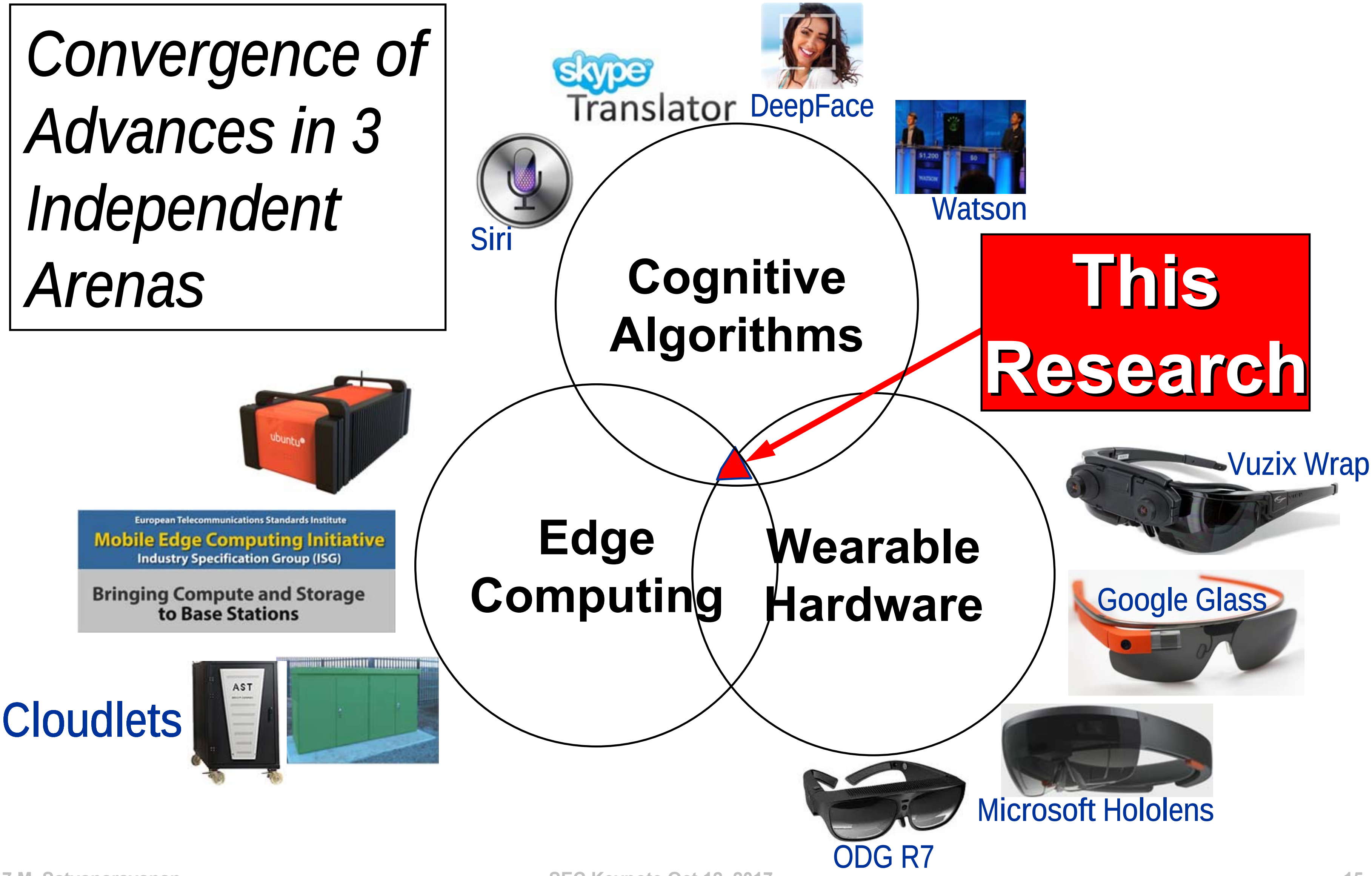
''Towards Wearable Cognitive Assistance''
Ha, K., Chen, Z., Hu, W., Richter, W., Pillai, P., Satyanarayanan, M.
Proceedings of the Twelfth International Conference on Mobile Systems, Applications, and Services (MobiSys 2014), Bretton Woods, NH, June 2014

"Early Implementation Experience with Wearable Cognitive Assistance Applications"
Chen, Z., Jiang, L., Hu, W., Ha, K., Amos, B., Pillai, P., Hauptmann, A., Satyanarayanan, M.
Proceedings of WearSys 2015, Florence, Italy, May 2015

"An Empirical Study of Latency in an Emerging Class of Edge Computing Applications for Wearable Cognitive Assistance"
Chen, Z., Hu, W., Wang, J., Zhao, S., Amos, B., Wu, G., Ha, K., Elgazzar, K., Pillai, P., Klatzky, R., Siewiorek, D., Satyanarayanan, M.
Proceedings of SEC 2017, San Jose, CA, October 2017

A Unique Moment in Time

Convergence of Advances in 3 Independent Arenas



Wearable Cognitive Assistance

A new modality of computing

Entirely new genre of applications

Wearable UI with wireless access to cloudlet

Real-time cognitive engines **on cloudlet**

- scene analysis
- object/person recognition
- speech recognition
- language translation
- planning, navigation
- question-answering technology
- voice synthesis
- real-time machine learning
- …

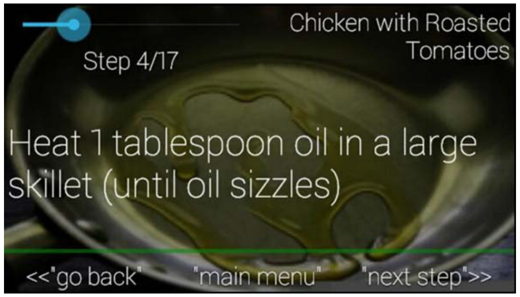
Low latency response is crucial

Seamlessly integrated into inner loop of human cognition

Task-specific Assistance

Example: cooking

passive recipe display


Chicken with Roasted Tomatoes

Step 4/17

Heat 1 tablespoon oil in a large skillet (until oil sizzles)

versus active guidance

“Wait, the oil is not hot enough”

Inspiration: GPS Navigation Systems

Turn by turn guidance

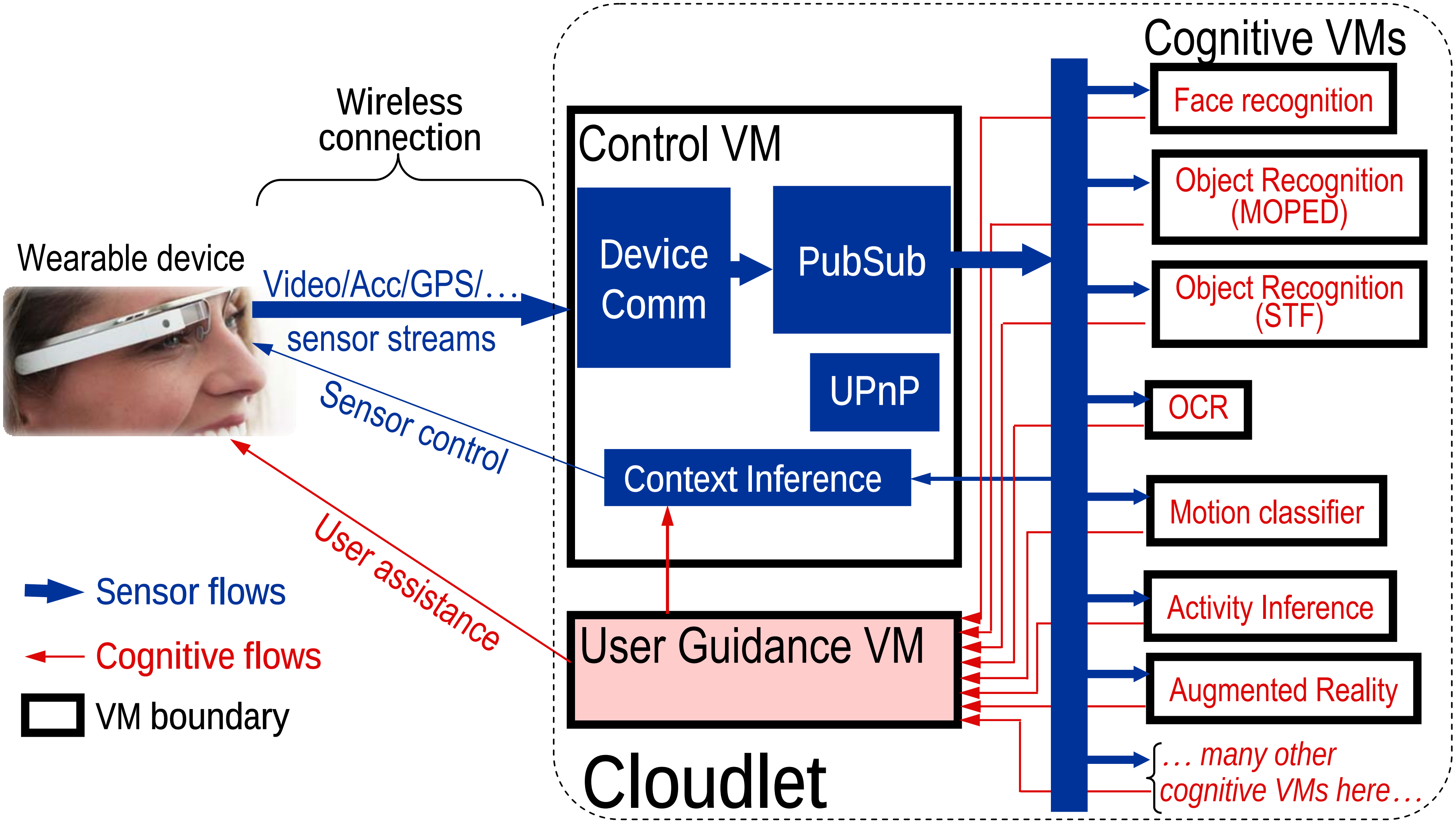
- Ability to detect and recover
- Minimally distracting to user

Uses only one type of sensor: location from GPS

Can we generalize this metaphor?

Gabriel Architecture

(PaaS for Wearable Cognitive Assistance)



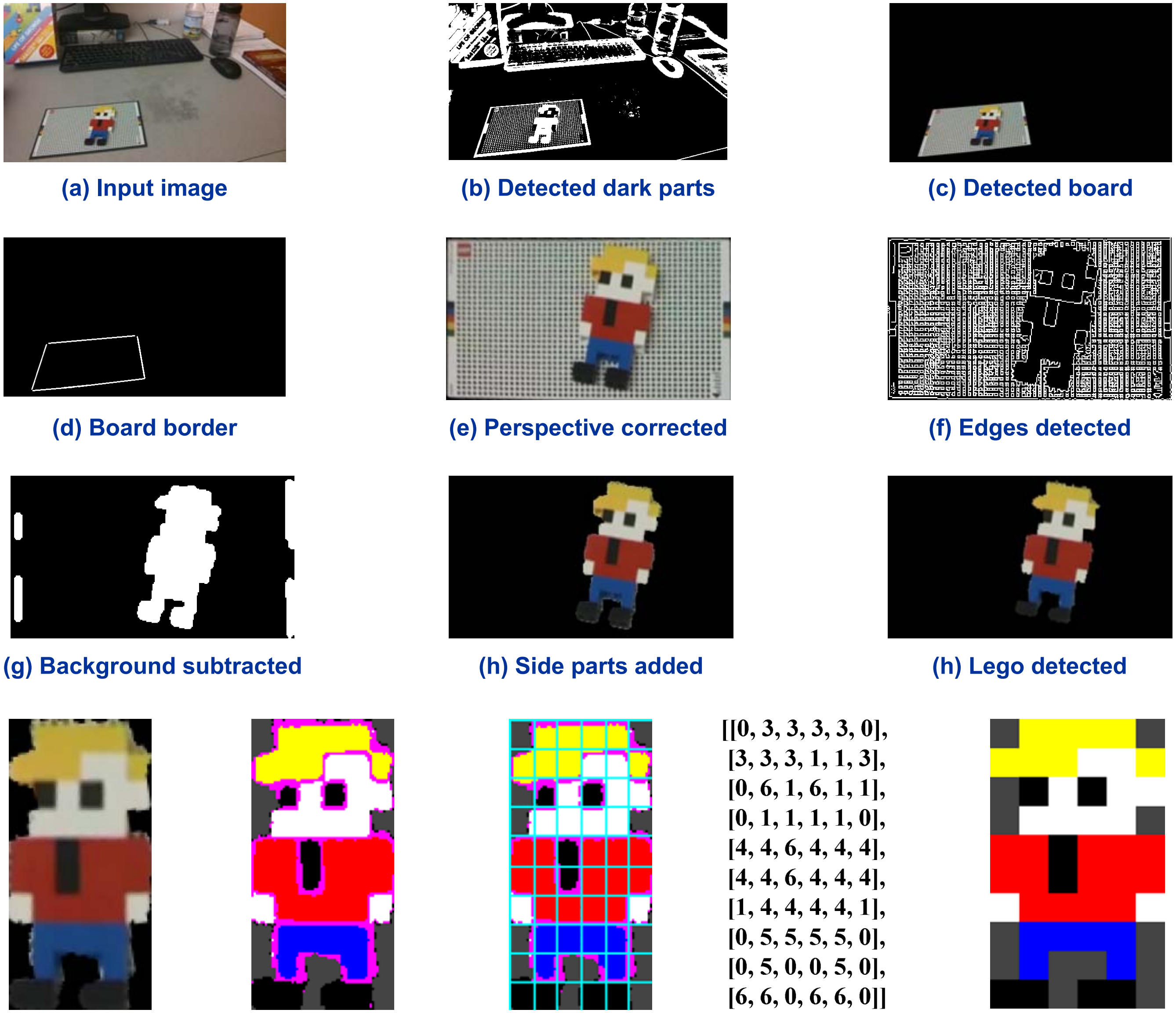
Baby Steps: 2D Lego Assembly

Very first proof-of-concept (September 2014)

Deliberately simplified task to keep computer vision tractable

2D Lego Assembly (YouTube video at http://youtu.be/uy17Hz5xvmY)

On Each Video Frame



(a) Input image

(b) Detected dark parts

(c) Detected board

(d) Board border

(e) Perspective corrected

(f) Edges detected

(g) Background subtracted

(h) Side parts added

(h) Lego detected

(i) Unrotated

(i) Color quantized

(j) Partitioned

```
[[0, 3, 3, 3, 3, 0],
 [3, 3, 3, 1, 1, 3],
 [0, 6, 1, 6, 1, 1],
 [0, 1, 1, 1, 1, 0],
 [4, 4, 6, 4, 4, 4],
 [4, 4, 6, 4, 4, 4],
 [1, 4, 4, 4, 4, 1],
 [0, 5, 5, 5, 5, 0],
 [0, 5, 0, 0, 5, 0],
 [6, 6, 0, 6, 6, 0]]
```

(j) Matrix

(k) Synthesized

When Milliseconds Matter

Ping-pong assistant

(https://www.youtube.com/watch?v=_Ip32sowyUA)

Assembling an IKEA Kit

IKEA kit assistant

(https://www.youtube.com/watch?v=qDPuvBWNIUs&index=5&list=PLmrZVvFtthdP3fwHPy_4d61oDvQY_RBgS**)**

Many Monetizable Use Cases …

Assembly instructions

Industrial troubleshooting

Medical training

Correct Self-Instrumentation

Strengthening willpower

AR Meets AI

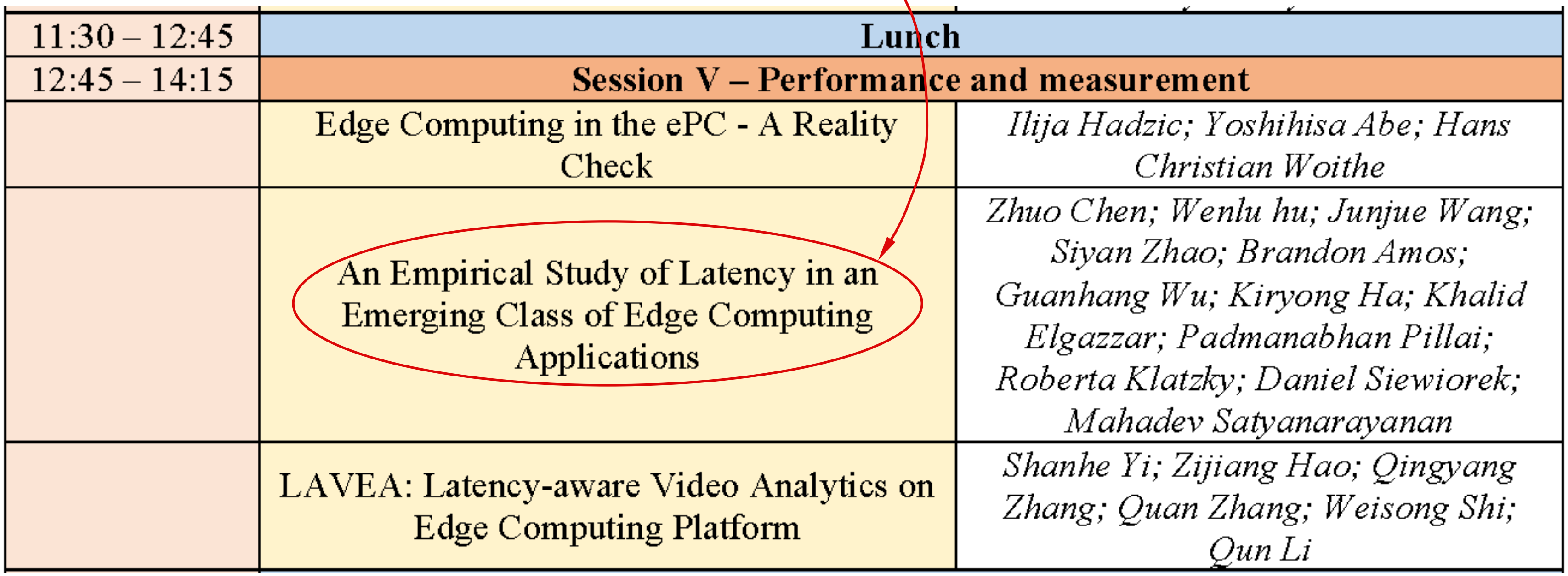
Latency intolerance of Augmented Reality + Compute intensity of AI

October 9, 2016: CBS “60 Minutes” special on AI

- Short (90 seconds) video clip on Gabriel
- YouTube video at https://youtu.be/dNH_HF-C5KY
- Full 60 Minutes special (~30 minutes) at CBS web site: http://www.cbsnews.com/videos/artificial-intelligence

Where Does the Time Go?

Attend Zhuo Chen's talk tomorrow:



11:30 – 12:45	Lunch	
12:45 – 14:15	Session V – Performance and measurement	
	Edge Computing in the ePC - A Reality Check	*Ilija Hadzic; Yoshihisa Abe; Hans Christian Woithe*
	An Empirical Study of Latency in an Emerging Class of Edge Computing Applications	*Zhuo Chen; Wenlu hu; Junjue Wang; Siyan Zhao; Brandon Amos; Guanhang Wu; Kiryong Ha; Khalid Elgazzar; Padmanabhan Pillai; Roberta Klatzky; Daniel Siewiorek; Mahadev Satyanarayanan*
	LAVEA: Latency-aware Video Analytics on Edge Computing Platform	*Shanhe Yi; Zijiang Hao; Qingyang Zhang; Quan Zhang; Weisong Shi; Qun Li*

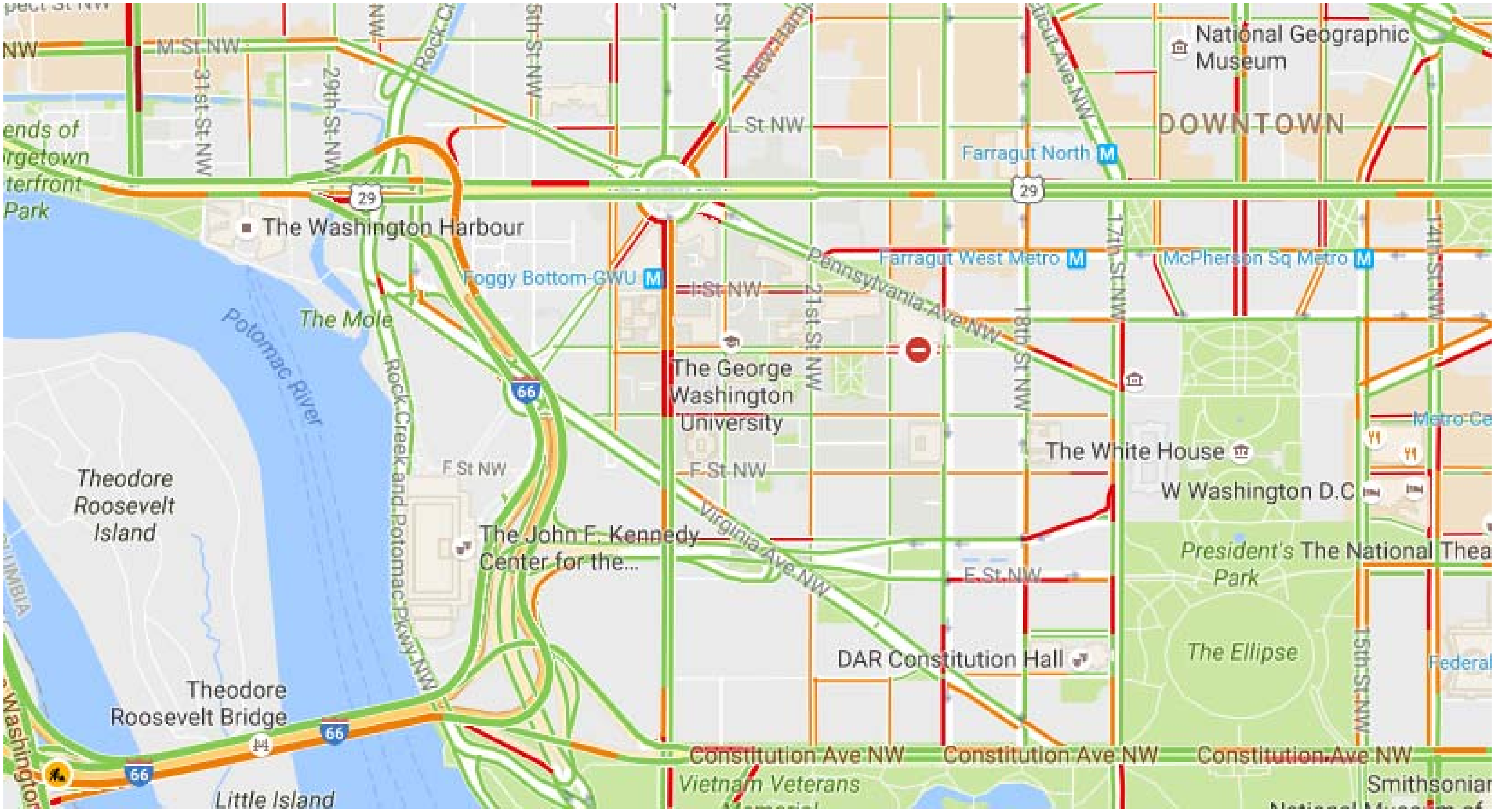
Edge Computing for Situational Awareness

‘‘Edge Computing for Situational Awareness’’
Satyanarayanan, M.
Proceedings of the 23rd IEEE International Symposium on Local and Metropolitan Area Networks (LANMAN 2017), Osaka, Japan, June 2017

“Live Synthesis of Vehicle-Sourced Data Over 4G LTE”
Hu, W., Feng, Z., Chen, Z., Harkes, J., Pillai, P., Satyanarayanan, M.
Proceedings of MSWiM '17 (20th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems), Miami, FL, November 2017

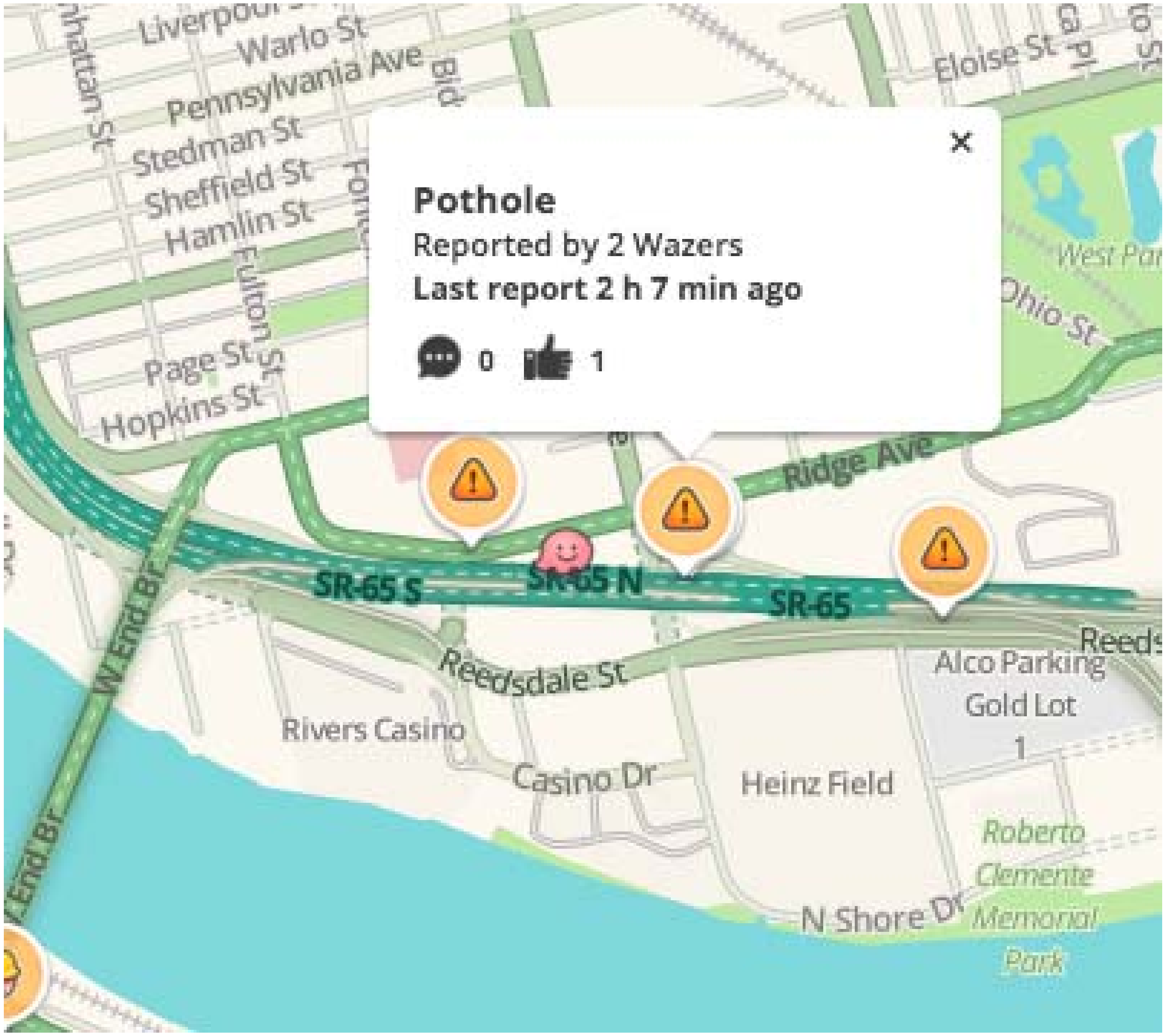
Real-Time Data Overlaid on Maps

(periodic GPS location reports from participating vehicles)



Waze: Crowd-Sourced Human Annotations

(purchased by Google for ~$1B in 2013)



Pothole

Reported by 2 Wazers

Last report 2 h 7 min ago

💬 0 👍 1

Best of Both Worlds?

Detailed, Automated and Distraction-free

Computer vision instead of just using GPS measurements

- 1+ video cameras on every vehicle
- video analytics to extract high-level information
- both driverless and drivered vehicles can contribute data

Rich overlay of detailed information on map

- **road hazards** (potholes, dead animals, rocks, stalled cars, lane closures …)
- **road conditions** (fog, icy patches, deep snow, flooding, …)
- **"street view" updates** (new store, old building torn down, …)
- … any other useful information that can be visually sensed/inferred

Improve Situational Awareness

Situational Awareness

“up-to-the-minute cognizance or awareness required to move about, operate equipment, or maintain a system”

highly mission-specific *(broad interpretation of “mission”)*

what matters is highly context-sensitive

Who Cares?

1. Local government
   - police chief, fire chief, road crews, …
   - where to direct scarce resources (salt trucks, fire trucks, patrol cars, …)
   - make better real-time decisions

2. Individual drivers
   - better anticipation of road conditions
   - better planning of travel
   - seamless integration with auto GPS

3. Driverless vehicles
   - acute need for up-to-date detailed map information
   - expensive to collect manually, why not crowd-source?
   - accurate maps allow proactive actions (rather than reactive)

4. Long-term planners
   - accurate and detailed information as free by-product
   - avoids expensive special-purpose data collection

Inspiration From the Past

(RAF Uxbridge, circa September 1940)

"Sensors" were radar stations with edge processing (human processors and communicators)

"Visualization" required you to sit at this vantage point in the room

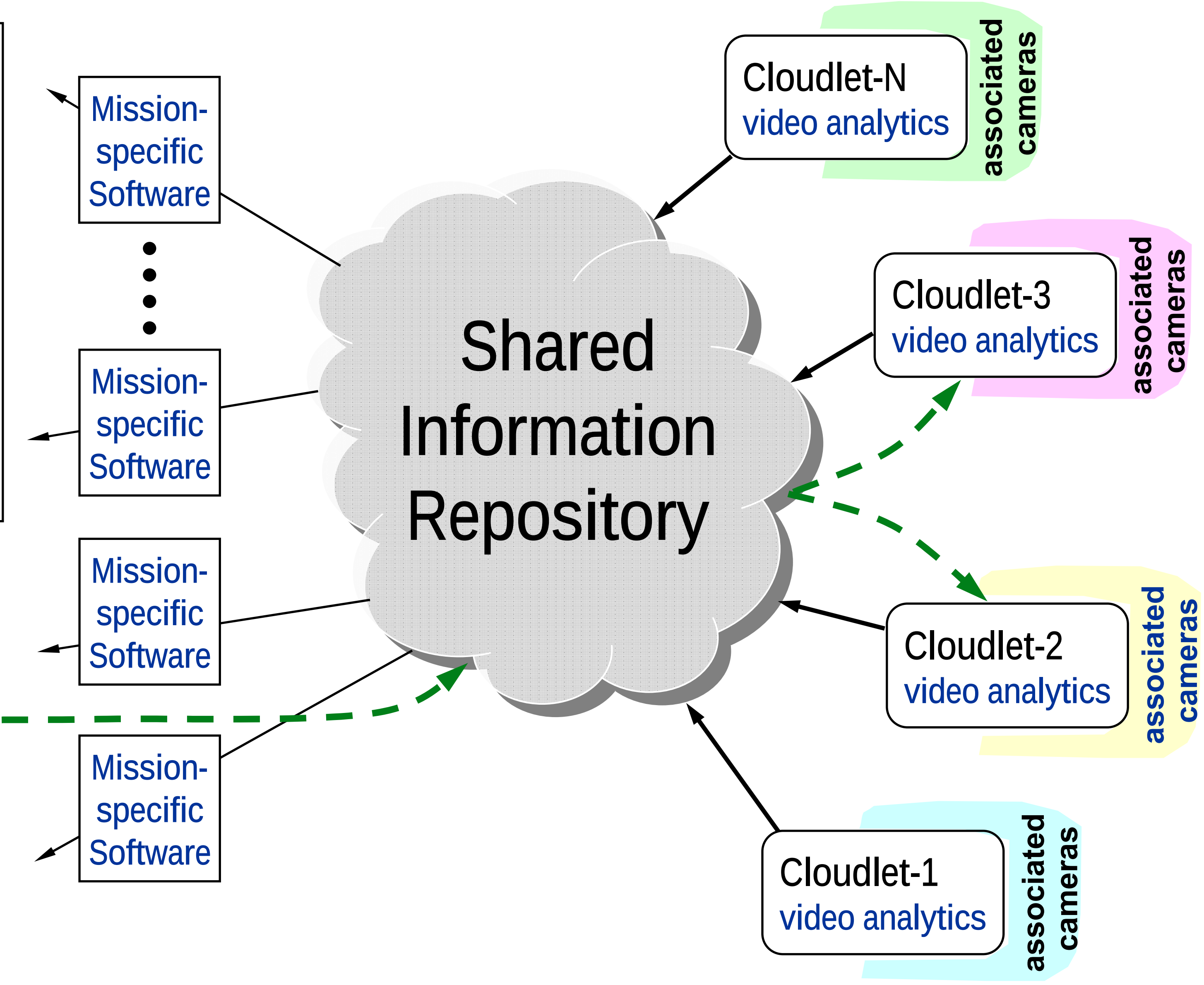
Priceless in allocating scarce resources for survival (aircraft & pilots, just in time)

Fast Forward to 2017

End Users

- wide range of visualization devices
- handheld displays (tablets, smartphones)
- in-vehicle displays
- wall-sized displays

…



Mission-specific Software

Mission-specific Software

Mission-specific Software

Mission-specific Software

Shared Information Repository

Cloudlet-N
video analytics

associated cameras

Cloudlet-3
video analytics

associated cameras

Cloudlet-2
video analytics

associated cameras

Cloudlet-1
video analytics

associated cameras

Customizability

ability to download under tight access control mission-specific algorithms (e.g., object recognition)

Many Questions

1. Do we really need cloudlets?
2. Is computer vision up to the task?
3. How large a coverage area can we target?
4. How can we achieve scalability?

Do We Need On-board Cloudlets?

Scarce wireless bandwidth

- for the foreseeable future, vehicle connectivity will be 4G LTE
- already under severe pressure from customer demand
- limited and expensive spectrum, falling profit margins
- only small fraction can be spared for public service/safety

Non-solution

- rich highway infrastructure (e.g. roadside Wi-Fi)
- politically infeasible in the US
- may be feasible in other countries (e.g., Germany, Japan (?))

Consider small cell in Manhattan (2 block x 2 block)

- **roughly 400 vehicles under rush hour conditions**
  non-urban settings have lower vehicle density, but larger cells (evens out)
- **Netflix estimates 3 Mbps per SD video stream → 1.2 Gbps uplink demand**
  HD video is even worse (6.8 Mbps per video stream) → 2.7 Gbps uplink demand
  4K and future higher resolutions will be much worse
  higher resolution → improved accuracy, smaller features detectable
- **4G LTE uplink capacity is only ~500 Mbps**
- **5G will improve matters, but many other demands on wireless bandwidth**

Shipping all video to cloud not scalable

- **3-4 orders of magnitude lower demand with edge analytics in vehicle**
- **still true even if brief video clips or images accompany each report**
- **on-board cloudlet is crucial**

Is Computer Vision Up to the Task?

Accuracy: challenging on diverse recognition tasks

- **just within reach with deep neural networks**
- **very compute-intensive**
  (need GPU or other specialized hardware)

Lot more work ahead in terms of speed, accuracy, versatility, and reporting format

Basic premise ok

Speed is important

- **continuous processing of video for timeliness of reporting**
- ***but less stringent than for V2V use cases*** (e.g., convoying, collision avoidance, …)
- **recognition ≈ a few seconds at highway speeds** (before object disappears)

Two examples

- ***deer detection*** (https://www.youtube.com/watch?v=_GrP42359z8)
- ***pothole detection*** (https://www.youtube.com/watch?v=U7_QAVbiF8U)
- **only modest accuracy on classic metrics** (e.g. ROC curve or precision/recall)
- **acceptable accuracy for "detect before object disappears"**
  "few seconds" ⟶ many hundreds of video frames, accuracy improves as object gets closer
- **acceptable speed** (7 FPS with high-end GPU on 3.4 GHz i7 using Faster R-CNN)

How Large a Coverage Area?

Ideal: entire planet

At least two reasons why this is unlikely

1. ***end-to-end latency for near-real-time tracking of the real world***
   both mean and variance matter: each network hop hurts
2. ***national security, anti-terrorism, etc.***
   nation-states unwilling to export fine-grain real-time street-level knowledge
   static Street View of Google Maps is already causing angst

#2 is a showstopper

some deliberate degradation in timeliness or spatial resolution or both likely

More likely: *federation of autonomous zones*

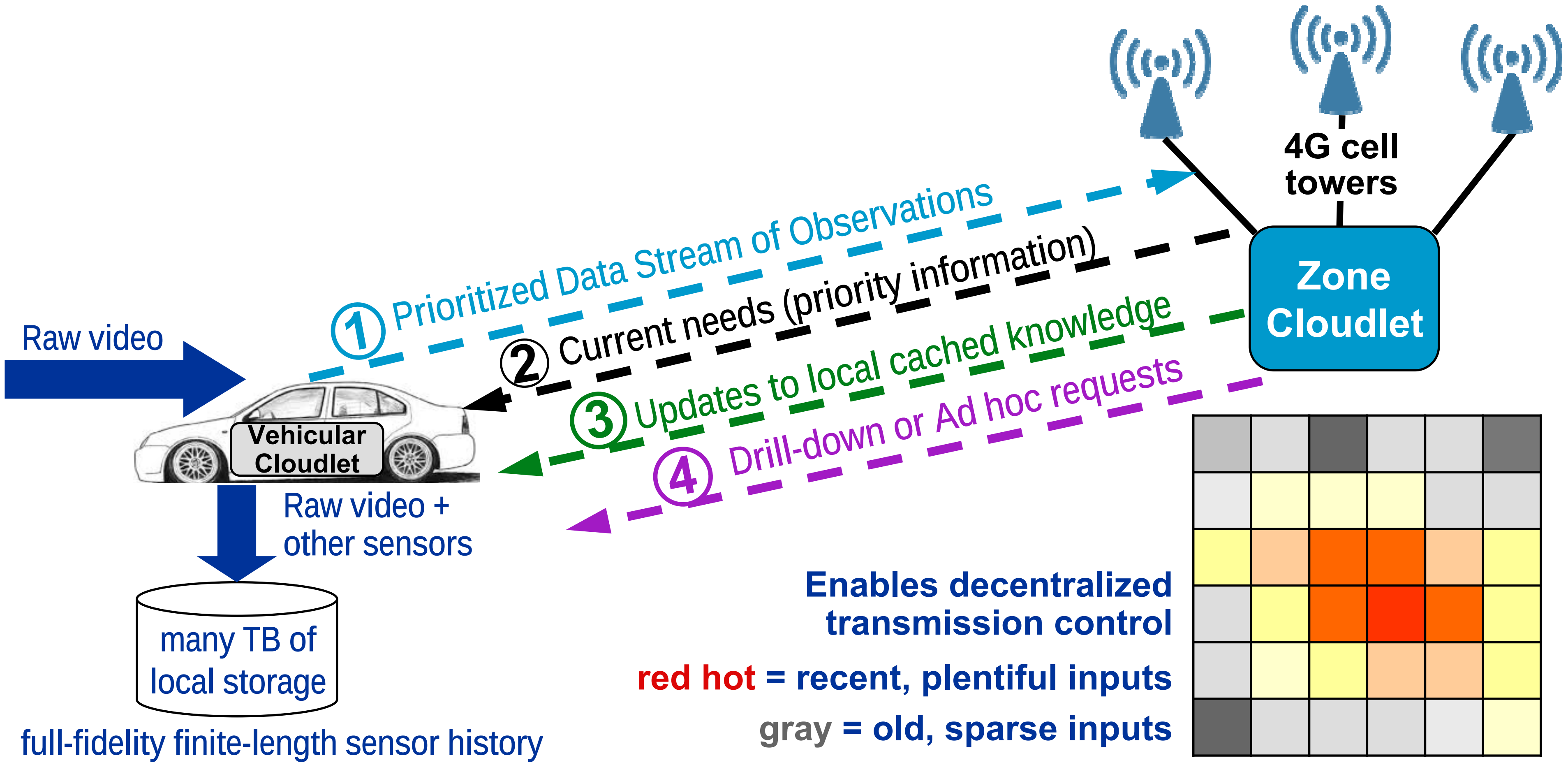
- **each zone retains full control over authentication and access control**
- **controlled cross-zone sharing possible**

Zone size: city or county in US (~500 square miles) most likely

coincides with local government boundary for organization control

Vehicle to Zone Cloudlet Interactions

Known Unknowns & Unknown Unknowns



Raw video
Vehicular Cloudlet
Raw video +
other sensors
many TB of local storage
1 Prioritized Data Stream of Observations
2 Current needs (priority information)
3 Updates to local cached knowledge
4 Drill-down or Ad hoc requests
4G cell towers
Zone Cloudlet

full-fidelity finite-length sensor history

Enables decentralized transmission control

red hot = recent, plentiful inputs

gray = old, sparse inputs

Heat Map Data Structure

cached everywhere
master copy at
zone cloudlet

Video Retention

- 3 GB per hour of HD video per camera
- single 4 TB disk → ~50 days of retention
- storage is cheap (~$100 for 4 TB disk)

Scalability Results

"Live Synthesis of Vehicle-Sourced Data Over 4G LTE"

Hu, W., Feng, Z., Chen, Z., Harkes, J., Pillai, P., Satyanarayanan, M.

Proceedings of MSWIM 2017 (The 20th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems), Miami, FL, November 2017 (to appear)

Closing Thoughts

Navigating Edge Computing

1. “Let a thousand flowers boom”

Cloudlets will appear in many form factors and connectivities, with diverse levels of scale, management quality, and business models.

2. “One application, many cloudlets”

In spite of cloudlet diversity, an end-user application should see a single programming interface. Ideally, the same as in the cloud.

3. “The value chain begins with the end-user”

Without new applications that delight users and deliver long-term value to them, the business impact of cloudlets will be zero-sum.

4. “The edge is real, the cloud is abstract”

The new breed of latency-sensitive and bandwidth-hungry applications involve real-time processing of rich multi-sensor input streams using deep neural networks. These strongly suggest the need for application-specific hardware accelerators in cloudlets.

In Closing

Edge Computing is transformative

It enables new applications

It is truly disruptive

It is here!