Carnegie Mellon University
Silicon Valley

Electrical & Computer ENGINEERING

Timing API for Dynamically Federated Cyber-Physical Systems

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Key Points

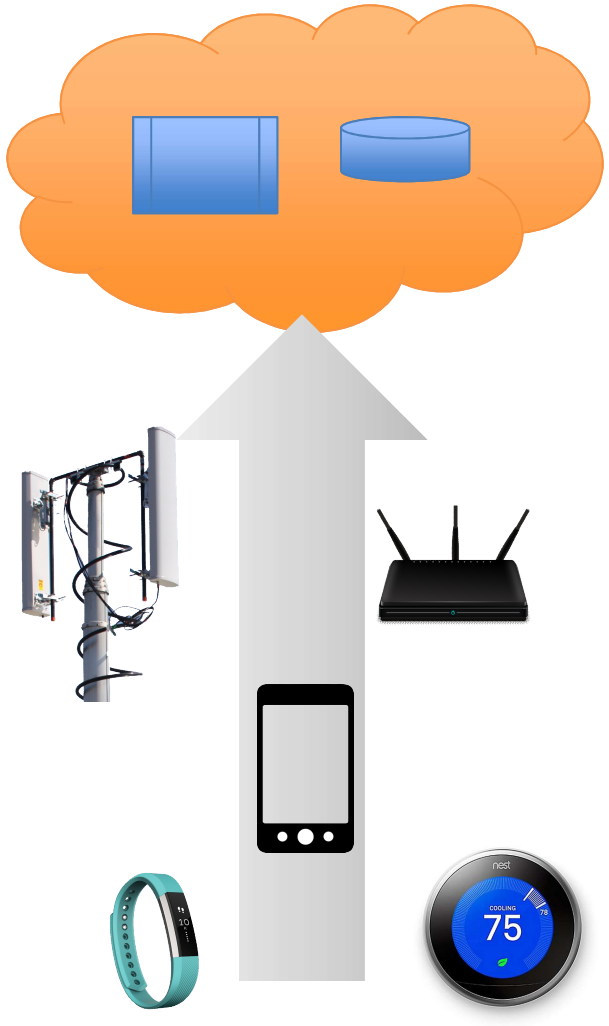
- The IoT is the Fifth platform
- It is inherently cyber-physical
- It will be distributed, federated, and energy-poor
- Time will be a first-order concept in programming it
- Traditional time-keeping approaches won't work
- Time islands may offer a workable abstraction

What is the IoT?

- internet of **THINGS**
  - WiFi/Bluetooth gadgets
  - Cloud-connected stuff
  - Phone-as-mediator
  - Fitbit, Nest, …
  - No significant network effect
- **INTERNET** of things
  - Cities, communities
  - Sharing
  - Openness
  - Programmability
  - Significant network effect
  - Cyber-physical

These differing views lead to wildly different thoughts abo

IoT Programing Today



Cloud programming
- Aggregation
- Machine learning
- Visualization

Effectively closed

Embedded programming
- Fixed functionality
- Focused on low-power operati
- Local power OR recharged rec

Sensors in the Real World: the Out-of-Building Experience

- An inside the box (building) IoT is easy but limiting
  - Power, cable plant, WiFi, tame physical conditions
- Outside the box
  - Offers none of these
  - But is essential for logistics, power systems, fleets, smart campuses, smart cities
- Cost of deployment and maintenance
  - Self-sufficient devices
  - 5-10 year lifetime
  - “OHIO”

BI1

An Hour in the Life of an OHIO Device: Energy is at a Premium

State	Seconds per hour
Sensing & processing	10
Receiving	10
Transmitting	5
Shut off	3575

- "Perfect" 1000 mAh battery with no energy harvesting
- LP-WAN radio
- Five year lifetime

Slide 6

BI1 Compute average current, "few mA for GPS", also show current from CSAC, show cost.
Bob Iannucci, 11/2/2016

But is the Ultimate Value in Devices?

Transducers	Bottom-of-Pyramid Devices	Middleware and Middle Devices	Aggregation	Federation	Analytics	Business Logic
1-10 trillion	100 billion	1 billion	10,000	10's	1000's	millions
Innovative manufacturing, longevity, electronic data sheets, reliability, repeatability, low power	Low power, low power, low power ("OHIO") Remote programmability, reliable wireless comms, ease of deployment, authentication	Programming tools for fleet deployment and management, version control, provenance management, generational control	Management of enormous volumes of mostly useless data (needle in a haystack), ability to summarize across time and space	Management of dissimilar standards, privacy, security "Marketplace"	Extraction of signals (useful data) from noise, hierarchical processing, real-time response	Traditional services business, tailored to the enterprise

An Uncomfortable Transition to the Future State

- Value is in aggregation of sensed information
- Sensing must be pervasive and flexible
- Pervasive sensing depends on ubiquitous coverage
- Creating coverage is a substantial investment
- Investment justified by a broad base of applications
- The first wave of IoT applications will be vertical
- The real value will come with the transition to horizontally-organized platform
- Similar to the platforms that preceded it

Platformization

*In each generation of computing, the emergence of a **standard platform** transforms the industry by shifting value from hardware to software and services.*

Computing Platforms: Past and Present

	Golden Age	Standard Platform	Compatibles	Value Shift to Software	Value Shift to Services
Mainframe	GE, NCR, CONTROL DATA, UNIVAC	IBM	amdahl, Magnuson Computer	CSC	IBM, Andersen Consulting, EDS
Mini	Prime, apollo, digital, Data General	digital	EMC², EMULEX	ORACLE, SAP	EDS
PC	ATARI, Commodore, Apple, sinclair	IBM Personal Computer	COMPAQ, DELL, hp	Microsoft	IBM, EDS
Mobile	BlackBerry, NOKIA, Google, SAMSUNG, Apple, htc	Mobile Apps plus cloud services			

What about the Platform for the Internet of Things?

IoT: the Fifth Platform (P5): What to Expect?

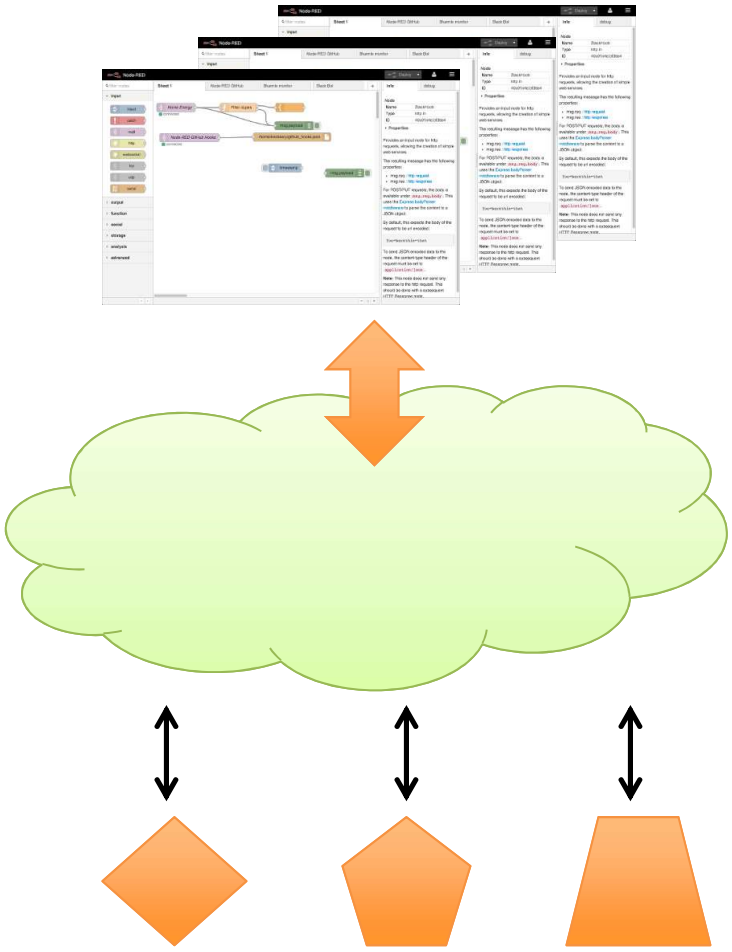
P5 will be a *combination* of

1. Flexible, powerful, programmable, open device families
2. Flexible, powerful, programmable, open networks

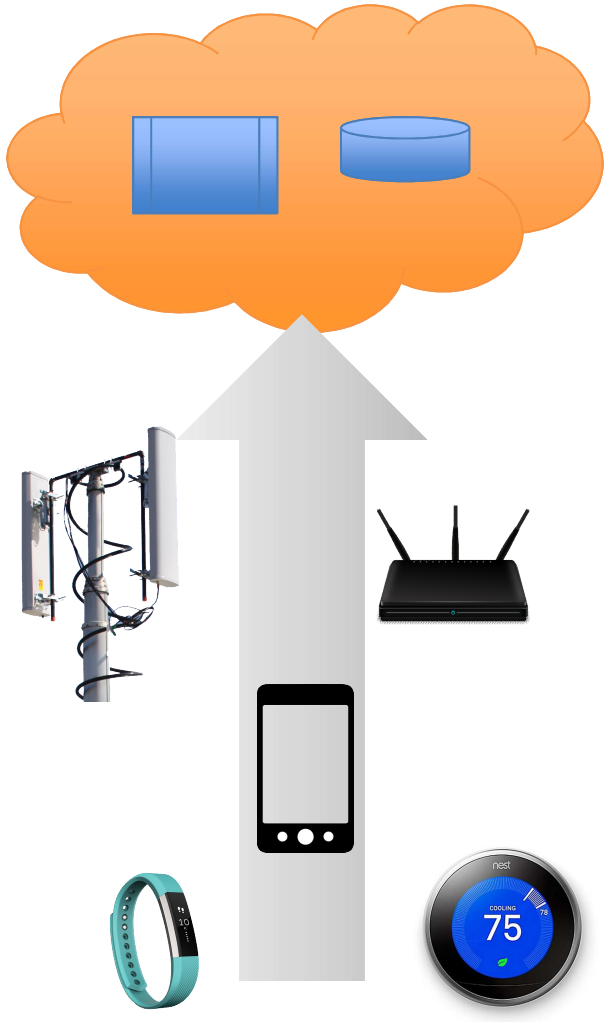
Observation: *#1 exists. #2 does not*

Challenges for P5

- Considerable early IoT research focused on creating connectivity
  - Mesh networking *vs*. device power
- LP-WANs shift away from meshes to stars
  - SigFox, LoRa, Ingenu RPMA
- Under-addressed: programming model
  - Device-centric? No, distributed.
  - Cloud-centric? No, too far away.
- Emerging: **enabling the network side of the IoT platform**
  - Computing moves to minimize latency
  - Better management of the Time Line



IoT Programing Future?




```
USING [ e23, e97 ]
DO [ b1 ]
SYNCHRONIZED TO c19 WITH TOLERANCE x
ONERROR [ b2 ]
```

Decomposition

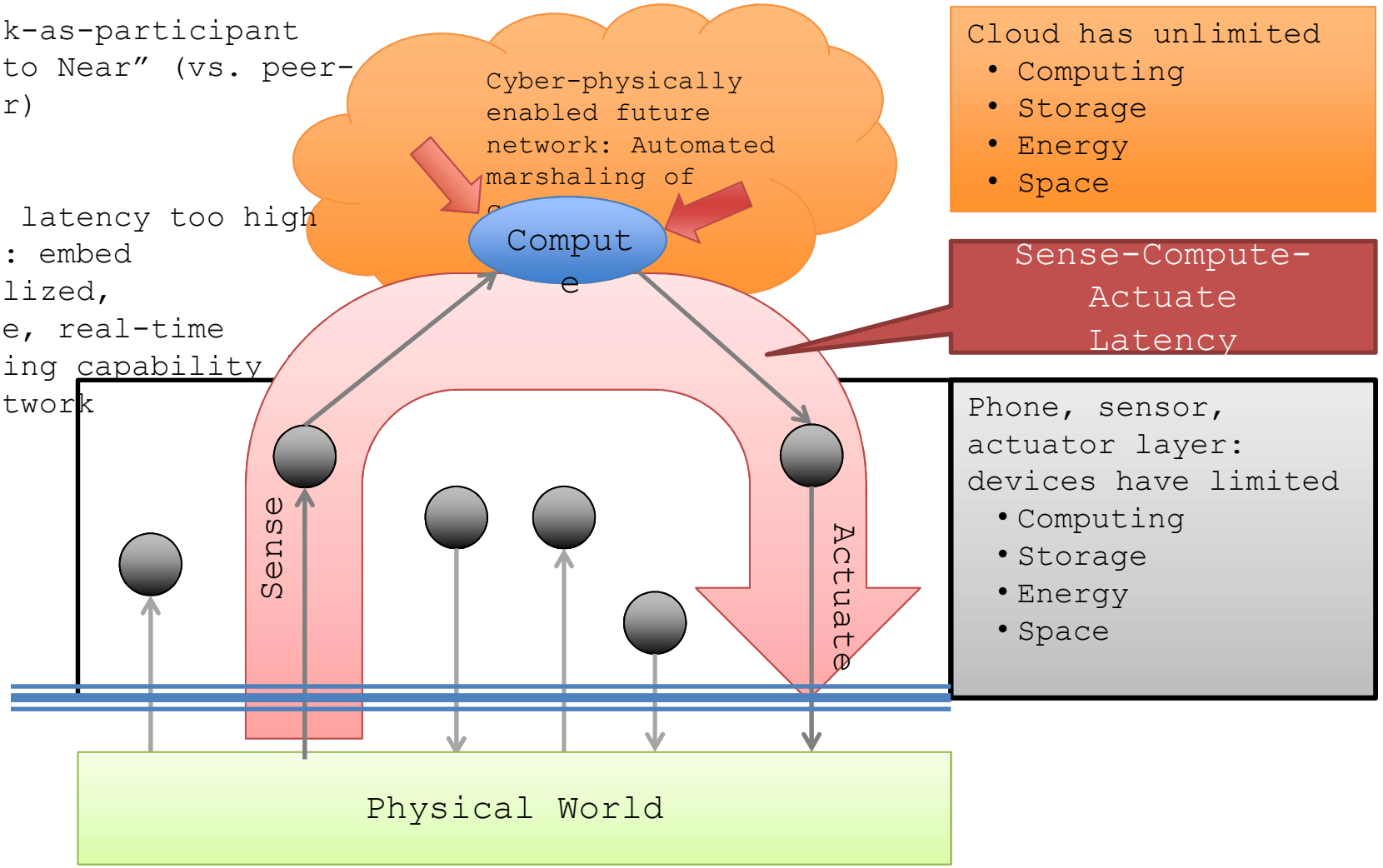
Implications

- One program on multiple c
- Multiple programs on one

The Cyber-Physical Network

Network-as-participant
"Near to Near" (vs. peer-to-peer)

Today: latency too high
Future: embed virtualized, movable, real-time computing capability the network



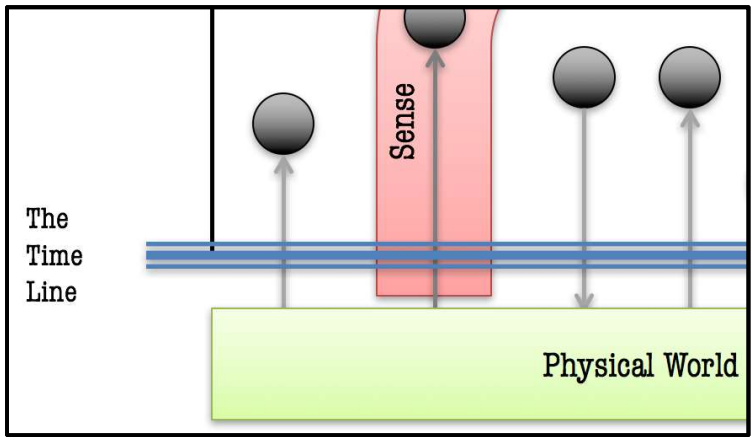
Cloud has unlimited
- Computing
- Storage
- Energy
- Space

Sense-Compute-Actuate Latency

Phone, sensor, actuator layer: devices have limited
- Computing
- Storage
- Energy
- Space

The Time Line

The Time Line



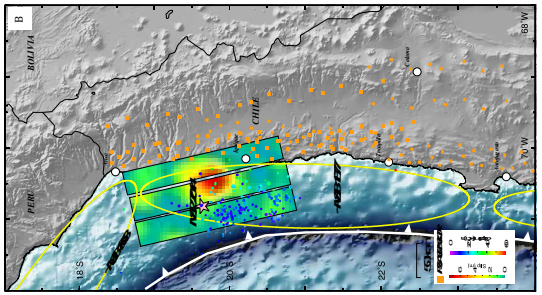
- Below the line: time is real
  - Concurrency, simultaneity, causality
- Above the line: time is meta-data
  - Programmer can manipulate the representation of time
- Crossing cyber to physical?
  - Translate programmer's intent to reality – not always possible
- Crossing physical to cyber?
  - In a distributed world, how do we time-label events in a way that is **correct enough** as to not give rise to subsequent errors?

Crossing the Line: Time Accuracy Requirements

- Crowdsourcing data from smartphones
  - Seconds → milliseconds
- Sensor fusion: situated and airborne sensors
  - Milliseconds → microseconds

Networked Situated Sensors

Networked UAV Sensors[1]



Crowdsourcing using Smartphones[2]

[1]Coverage: Teng, E., Falcao, J. D., Dominguez, C. R., Mokaya, F., Zhang, P., & Iannucci, B. ***Aerial Sensing and Characterization of Three-Dimensional RF Fields***. In Second International Workshop on Robotic Sensor Networks. Seattle, WA. 2015.

[2]Minson, S. E., Brooks, B. A., Glennie, C. L., Murray, J. R., Langbein, J. O., Owen, S. E., Heaton, T., Iannucci, R. A. and Hauser, D. L. ***Crowdsourced Earthquake Early Warning***. Science Advances, 1(3), 1–7. http://advances.sciencemag.org/content/1/3/e1500036

Sensor-Side Timekeeping is Costly

- Coin-cell-powered, OHIO, with 50¢ bill of materials
- GPS
  - Current tech @ 1 minute on/hour: >5 years → <2 years
- Cellular modem
  - Current tech: no (protocol overhead, power, cost)
  - NB-IOT: TBD
- CSAC
  - Current tech: 125 mW, $1k
  - Future: TBD
- TCXO
- Cost of timekeeping has to be sensor-appropriate
- Cost of timekeeping is application-dependent

TickTalk: Time-Oriented Meta-Language for P5

- **Concept**: time complexity of IoT programming must be reduced so that non-specialist programmers can create time-correct IoT programs including
  - Cloud elements
  - Network elements
  - Sensor / actuator elements
- One program per application instead of three
- Primitives for expressing syntonization, synchronization and simultaneity
- Bounded in time and space – **time islands**

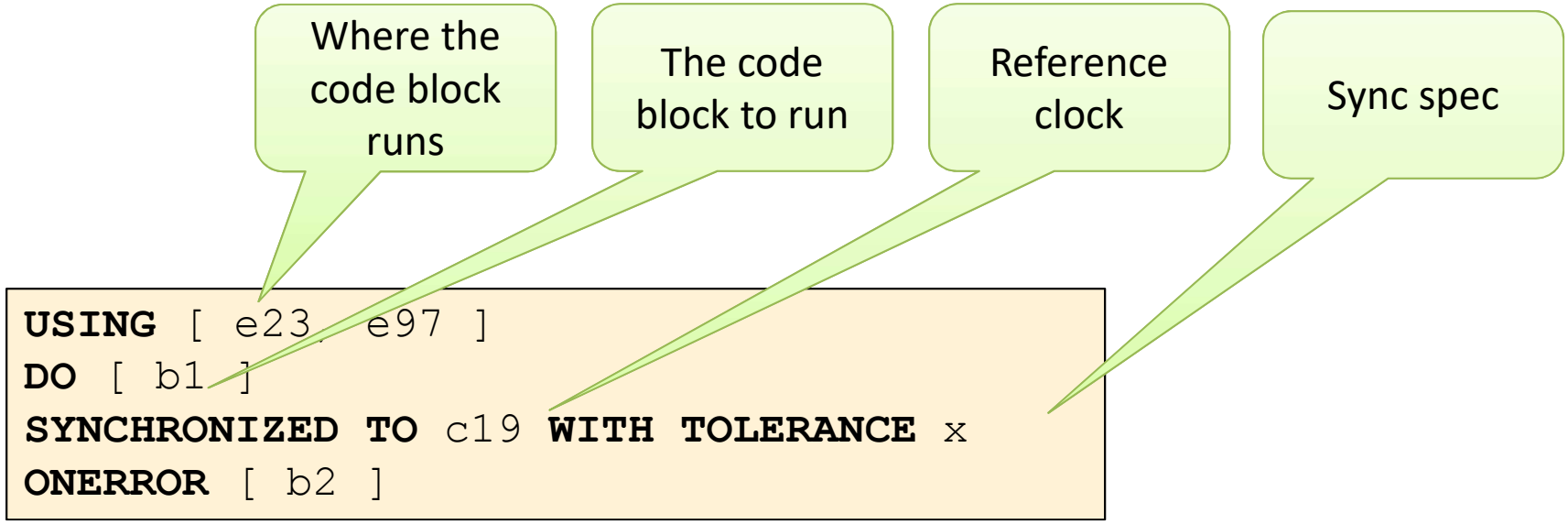
Joint work with Aviral Srivastava,

TickTalk: Core

- An easily-programmed Federation of Cyber-Physical Systems (FSCS)
- An FSCS is a tuple *(C, E, B):*
  - *C = { c1, c2, c3, … }* reference clocks
  - *E = { e1, e2, e3, ... }* computing / storage / communication ensembles. Each has at least one local clock capable of being synchronized to a reference clock. Each may have sensors or actuators.
  - *B = { b1, b2, b3, ... }* code blocks (program fragments) within which actions can be scheduled against an ensemble's local clock

Joint work with Aviral Srivastava,

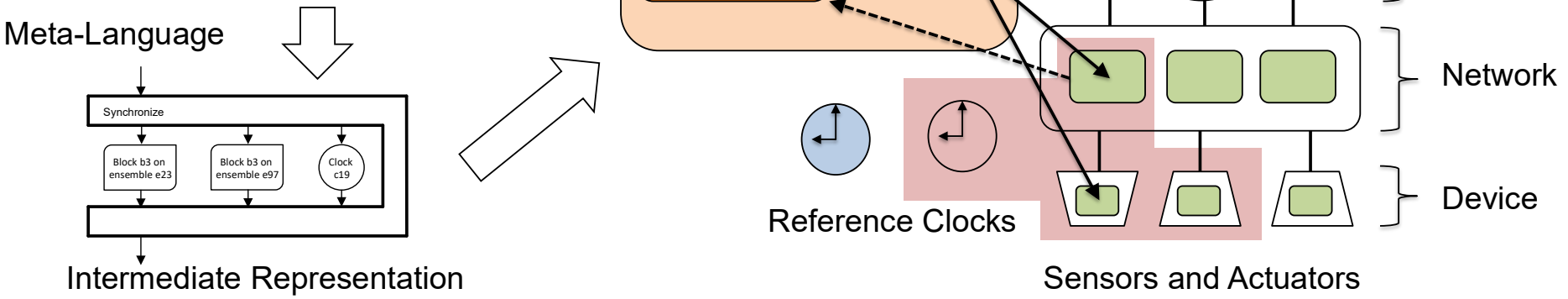
TickTalk: A Program Fragment



Joint work with Aviral Srivastava,

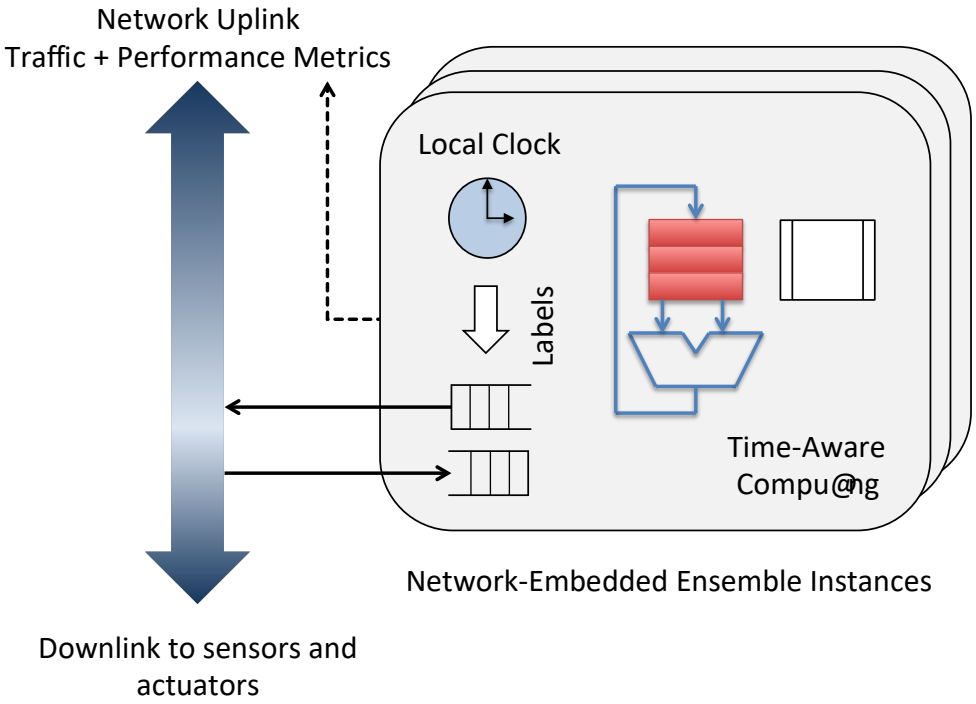
TickTalk: Runtime

```
USING [ e23, e97 ]!
DO [ b3;
    SIMULTANEOUSLY [ a1 ] WITH TOLERANCE y ONERROR [ b5 ];
    b4 ]
SYNCHRONIZED TO c19 WITH TOLERANCE x
ONERROR [ b2 ]
```



Joint work with Aviral Srivastava,

The TickTalk Network Ensemble



Joint work with Aviral Srivastava,

Summary

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Further Reading

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- Teng, E., Falcao, J. D., Dominguez, C. R., Mokaya, F., Zhang, P., and Iannucci, B. *Aerial Sensing and Characterization of Three-Dimensional RF Fields*. In *Second International Workshop on Robotic Sensor Networks*. Seattle, WA. 2015.
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Thank you!