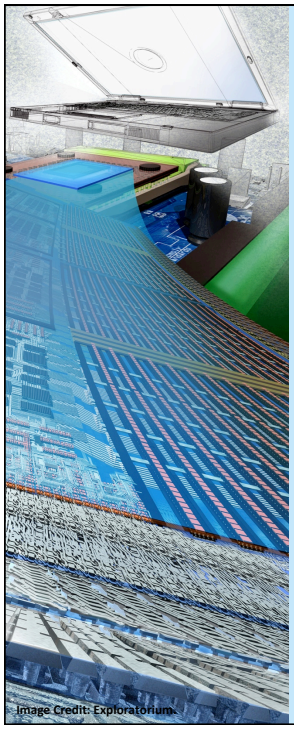


Research Challenges and Opportunities in a Mobility-centric World

Jim Kurose

Computer & Information Science & Engineering
National Science Foundation

College of Information and Computer Sciences
University of Massachusetts Amherst

Overview (a top down approach)

- introduction
- NSF: Computer & Information Science and Engineering (CISE) directorate
- NSF Computer and Network Systems (CNS)
  - overview
  - experimental systems and testbeds
  - smart and connected communities
  - MobilityFirst (FIA) modeling
- looking forward

It's a *great* time to be working in mobility

- MIMO, backscatter, mmWave
- 5G
- femto-cell networks
- SDR, SDN, NFV
- virtualization

technology push

application pull

- IoT, IoE
- smart and connected communities
- monitoring (health, community)
- mobile video
- vehicular nets
- data science

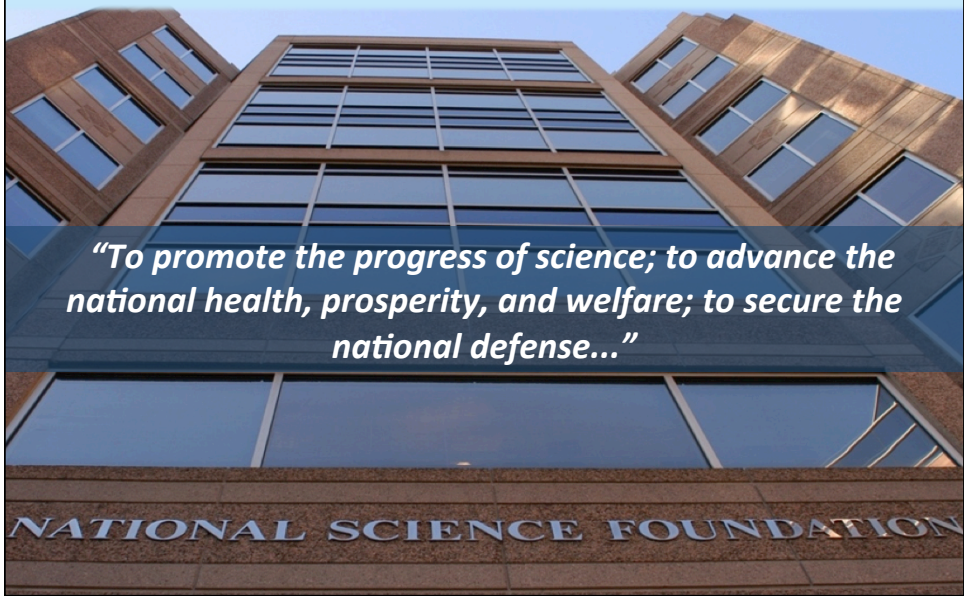
mobility is pervasive

- more wireless than wired Internet devices (~2014)
- 88% mobile traffic is "smart" (3G+)
- 10X increase in traffic predicted over 5 years

research

- research opportunities abound!

National Science Foundation's Mission



CISE research: addressing n**ational priorities**

Data Science: From Data to Knowledge to Action

Manufacturing, Robotics, & Smart Systems

Understanding the Brain

National Strategic Computing Initiative

Secure Cyberspace

Computer and Network Systems

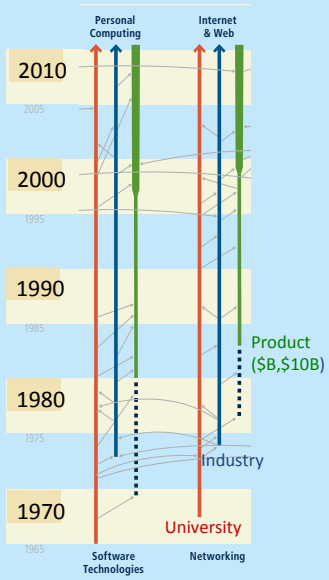
Education & Workforce Development

Augmenting Human Capabilities

From federally-funded research to $B industries

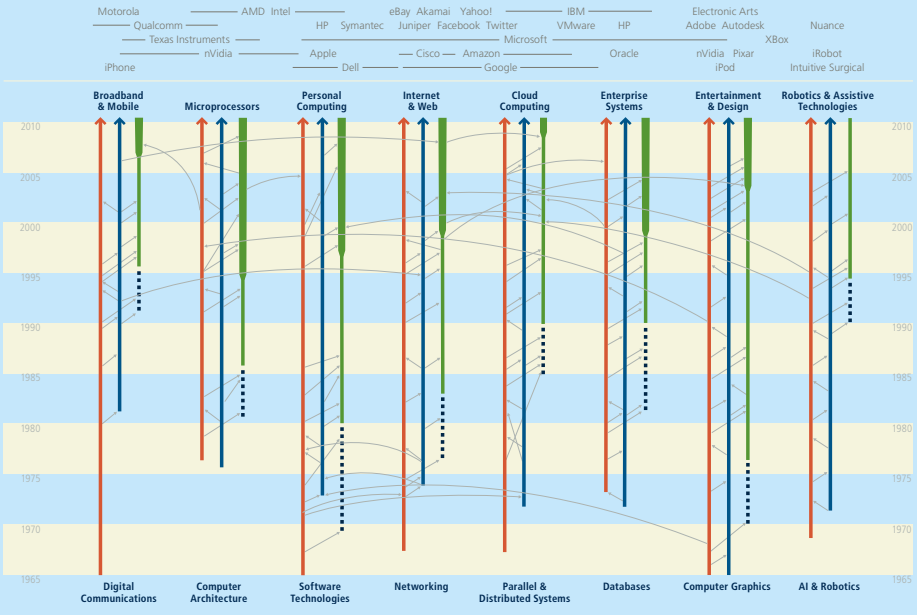
Advances in computing, communications, information technologies, cyberinfrastructure:

- drive U.S. competiveness, sustainable economic growth (IT: 25% of economic growth since 1995)
- underpin national security
- accelerate pace of discovery and innovation



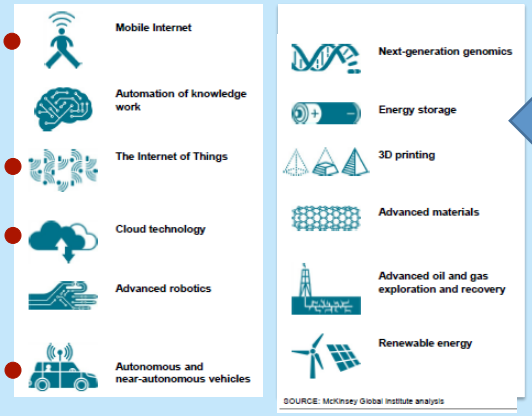
From *Continuing Innovation in Information Technology*, NRC, 2012.

…. across many industries

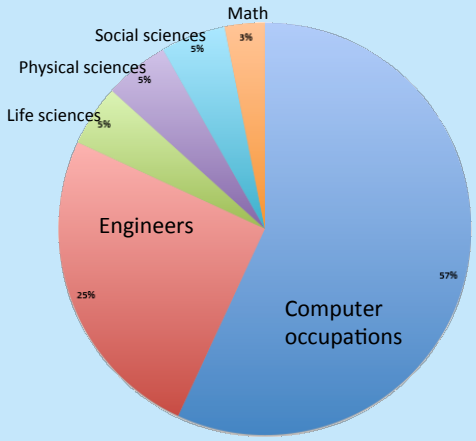


… and this impact will continue

Top twelve economically disruptive technologies (by 2025)



Many STEM jobs are in computing



Job Openings 2012 – 2022 (growth and replacement)

US Bureau of Labor Statistics

Data from the spreadsheet linked at http://www.bls.gov/emp/ep_table_102.htm

It is an
exciting, impactful and important time
to be in
computer and information science and engineering
(and in mobile and wireless systems)

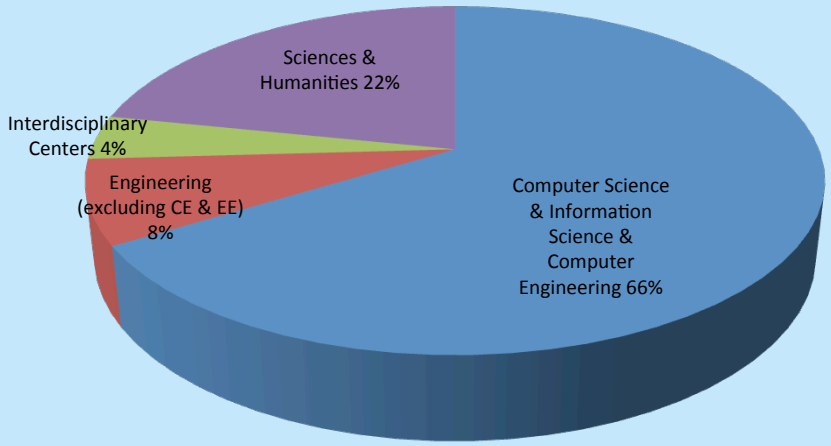
CISE Organization

CISE FY 2014 Activities … Reaching People

	CISE
Budget	$893M
Number of Proposals	7,436
Number of Awards	1,682
Success Rate	~23%
Average Annualized Award	$199K
Number of Panels Held	302
Number of People Supported	16,774

	CISE
Senior Researchers	6,663
Other Professionals	1,123
Postdoctoral Associates	491
Graduate Students	6,064
Undergraduate Students	2,433

CISE FY 2014 PI and Co-PI departments



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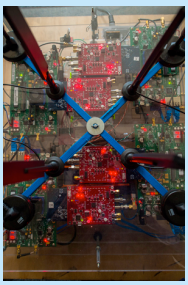
CISE: Computer and Network Systems

By the numbers

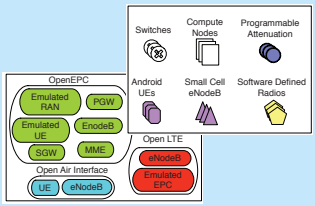
- ~550 active awards, half network, half wireless
- ~10 community workshops/ yr. Upcoming:
  - FIRE-GENI Workshop (GENI/EU SAVI meeting)
  - NSF/FCC QoE
  - EARS
  - Spectrum measurement
- international collaborations:
  - EU, WIFUS, PC3, JUNO, BDD, Brazil

Thyaga Nandagopal | Darleen Fisher | Wenjing Lou | Jack Brassil

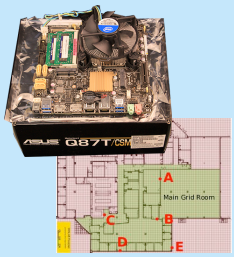
Recent CISE Awards: Wireless Testbeds



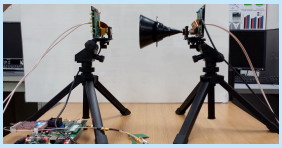
Reconfigurable Multi-Cell Research Platform for MIMO Networks (Rice)



PhantomNet: An End-to-End Mobile Network Testbed (Utah)



ORBIT Testbed with LTE and Cloud Radio Processing (Rutgers)



WiMi: A Reconfigurable Platform for mmWave Wireless Networking and Sensing (Wisconsin)

Community testbeds: much more than hardware (or software)

Virtualized, "sliced" infrastructure

GLOBAL ENVIRONMENT FOR NETWORKING INNOVATIONS (GENI)

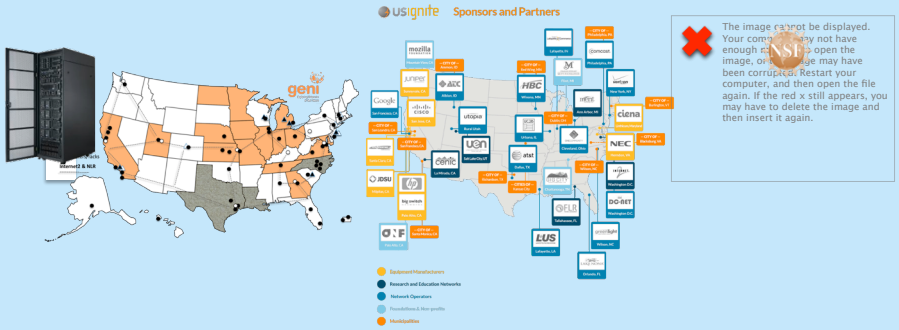
At-scale virtual laboratory enabling experimentation with deeply programmable slices of the network

US IGNITE

Stitching together islands of broadband and enabling development of gigabit applications with high-impact public benefit

NSFCLOUD

Extending virtualization beyond the network to resources in the "cloud"



CISE Research Infrastructure: Mid-Scale Infrastructure - NSFFutureCloud

Program foci:

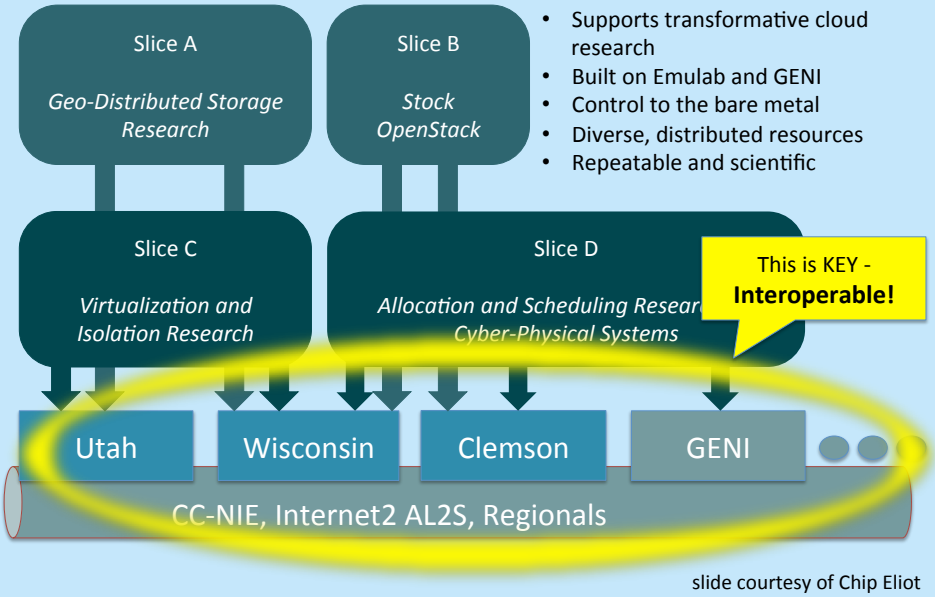
- Resource sharing in clustered computing
- Virtualization with software-defined networking technologies
- Interplay between applications and cloud computing architectures

CloudLab

Chameleon

Images: Logos from the NSF Cloud projects funded in FY2014

CloudLab



- Supports transformative cloud research
- Built on Emulab and GENI
- Control to the bare metal
- Diverse, distributed resources
- Repeatable and scientific

slide courtesy of Chip Eliot

CloudLab's Hardware

One facility, one account, three locations

- About 5,000 cores each (15,000 total)
- 8-16 cores per node
- Baseline: 4GB RAM / core
- Latest virtualization hardware
- TOR / Core switching design
- 10 Gb to nodes, SDN
- 100 Gb to Internet2 AL2S
- *Partnerships with multiple vendors*

Wisconsin

- **Storage and net.**
- Per node:
  - 128 GB RAM
  - 2x1TB Disk
  - 400 GB SSD
- Clos topology
- *Cisco*

Clemson

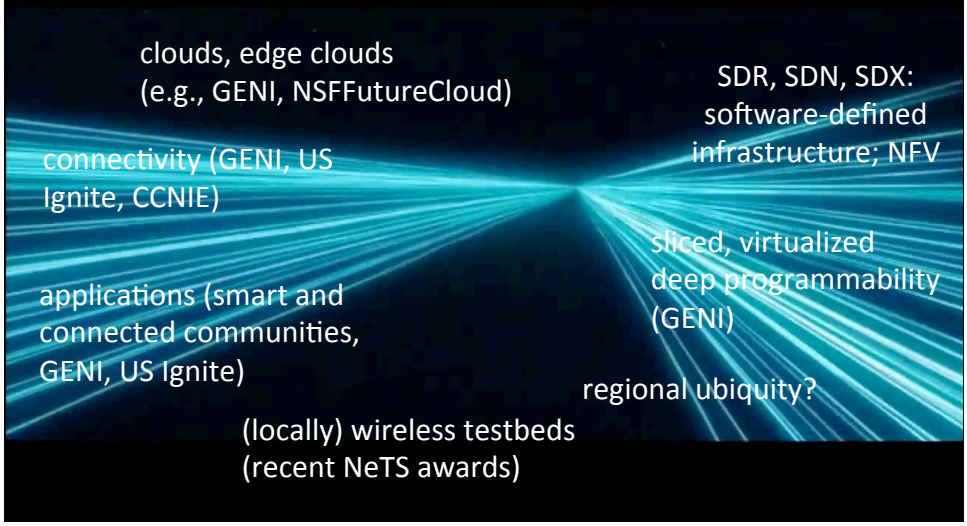
- **High-memory**
- 16 GB RAM / core
- 16 cores / node
- Bulk block store
- Net. up to 40Gb
- High capacity
- *Dell*

Utah

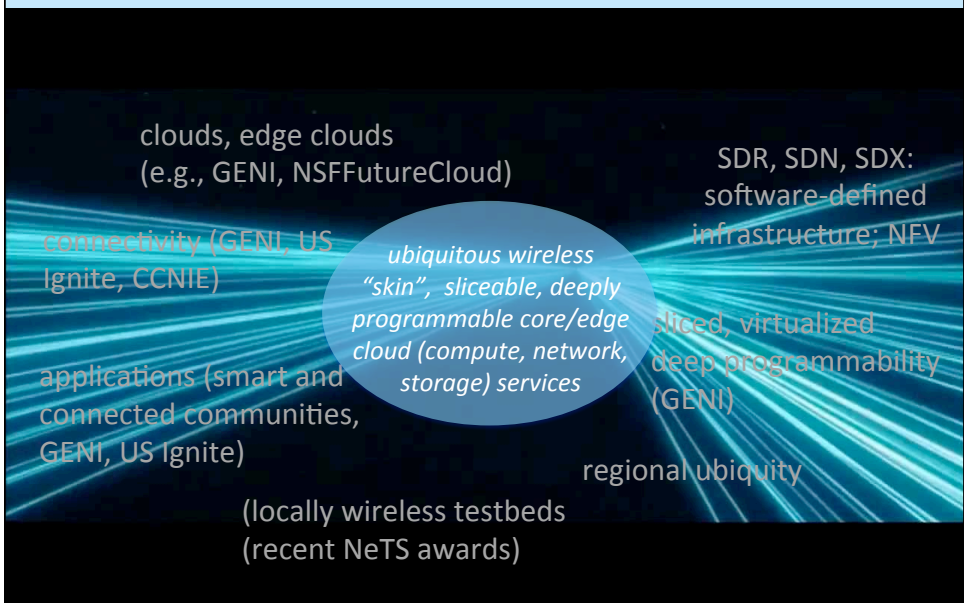
- **Power-efficient**
- ARM64 / x86
- Power monitors
- Flash on ARMs
- Disk on x86
- Very dense
- *HP*

slide courtesy of Chip Eliot

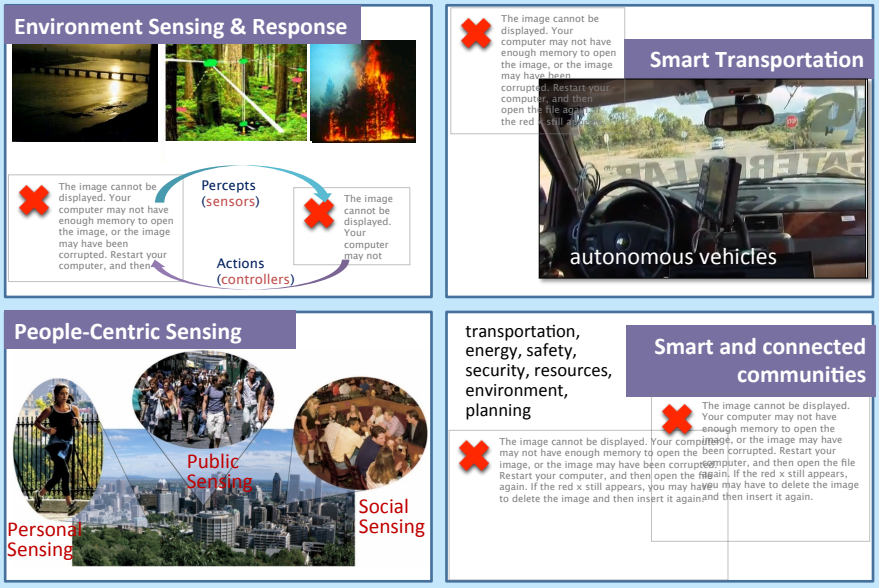
Testbeds: all the "pieces" in place?



Testbeds: all the "pieces" in place?



Smart Systems: Sensing, Reasoning, and Decision



Source: Sajal Das, Keith Marzullo

Images: *Courtesy of us-ignite.org*

NSF 15-541: Cyberphysical Systems

- **System Design:** safety, resilience, security, privacy
- **System Verification:** certification, safety
- **Real-time Control, Adaptation:** integrating big data in real-time control; achieving real-time in new cloud, network challenged spaces.
- **Smart Cities. Integrating** networked computing, devices, data, to impact QOL, effective management
- **Internet of Things.** Foundational research elements needed to harness the power of the IoT? From IoT to Internet of Dependable and Controllable Things

".. a mature science to support systems engineering of high-confidence CPS …"

"A new emphasis on CPS research toward "Smart Cities" has been added, along with discussion on the Internet of Things (IoT) and CPS"

NSF 15-541: Cyberphysical Systems

National Science Foundation

Directorate for Computer & Information Science & Engineering
Division of Computer and Network Systems
Division of Computing and Communication Foundations
Division of Information & Intelligent Systems
Division of Advanced Cyberinfrastructure

Directorate for Engineering
Division of Electrical, Communications and Cyber Systems
Division of Civil, Mechanical and Manufacturing Innovation
Division of Chemical, Bioengineering, Environmental, and Transport Systems

Department of Homeland Security, Science & Technology Directorate

U.S. Department of Transportation, Federal Highway Administration

National Aeronautics and Space Administration

National Institutes of Health

National Institute of Biomedical Imaging and Bioengineering

Office of Behavioral and Social Sciences Research

National Cancer Institute

National Center for Advancing Translational Sciences

Additionally:

Computer and Network Systems (CNS): Core Programs (15-572): specifically solicits proposals that bridge Computer Systems Research (CSR) and Networking Technology and Systems (NeTS)

CISE: Education, Workforce

- increasing number, diversity of K-14 students, teachers through alliances
- transforming computing education pre-college pipeline through CS10K
- increasing focus on undergraduate education: CS +X
- increasing system building/ experimentation skill via testbeds

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MobilityFirst: Project Background

- MobilityFirst project started in 2010 under NSF FIA, continuing under FIA-NP
- Project team: Rutgers, UMass, Michigan, Wisconsin, Duke, MIT, Nebraska
- Clean-slate architecture motivated by fundamental shift of Internet services to mobile platforms → ~10B in 2020!
- Use cases:

Mobile Data
("5G", WiFi First, …)

Vehicular Networks

Emergency Networks

Content Delivery

Internet-of-Things

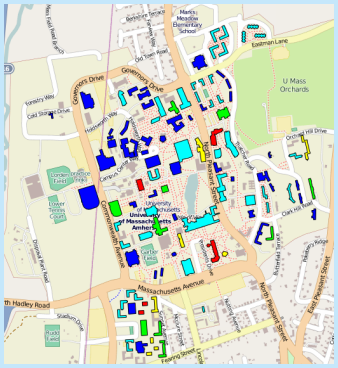
Cloud Services

Characterizing user mobility

- "your father's mobility": physical mobility among access points
  - device mobility in a network (cellular BSs, WiFi APs)
- "*not* your father's mobility:" characterize mobility *among* networks
  - distinctly different from physical mobility, models
  - physically mobile users may be stationary (from network transition POV); stationary users may move among networks (multi-homing, multiple devices)
  - both users and content may be mobile
- use: workload models for mobile architecture, protocol evaluation

Measuring/modeling campus user mobility

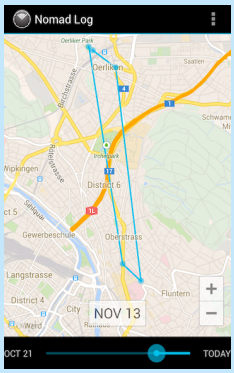
- UMass campus network: 4.5K APs, 25K users
- syslog event -> user trajectories
- Markov chain model of canonical individual moving among APs
  - probabilistic mobility
- conjecture: single user model not sufficient
  - clustering users few "classes," each governed by own MC



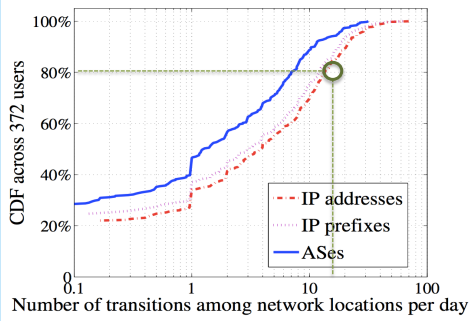
J. Steshenko, V. Chaganti, J. Kurose. "Demo: Mobility in a large-scale WiFi network - From syslog events to mobile user sessions," 17th ACM Int. Conf. Modeling, Analysis and Simulation of Wireless and Mobile Systems, Sept. 2014.

Client-measured mobility

- Nomadlog app
- 350+ users, 12 months



- mobility *among* networks the norm: 20% of users > 10 addresses per day

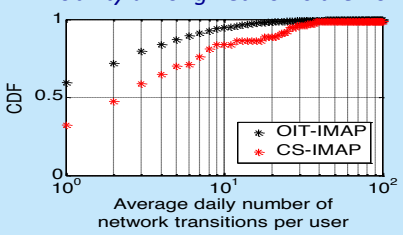


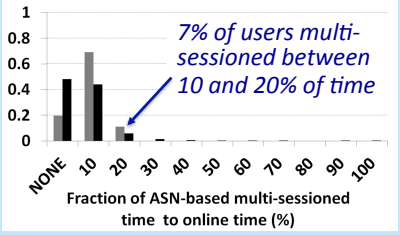
Z. Gao, A. Venkataramani, J. Kurose, S. Heimlicher, Towards a Quantitative Comparison of Location-Independent Network Architectures, *ACM Sigcomm 2014*

Server-inferred mobility

- infer mobility via IMAP logs: users periodically "push" or intentionally check e-mail
  - kurose@cs.umass.edu generated 7,482 IMAP entries in 8 weeks
  - track network of IMAP access
- 7.1K users, 4/14/13 – 5/14/14

mobility among networks the norm





S. Yang, S. Heimlicher, J. Kurose, A. Venkataramani. "User Transitioning Among Networks - a Measurement and Modeling Study," *2015 IEEE Infocom*.

Data: the need and a challenge

- "real world" mobility traces (trajectories) needed to design, evaluate mobile network protocols
  - handoff, routing, BS association, caching, management …
  - non-networking analyses: co-traveller analysis, recently-visited locations (competitors, feeder locations)
  - human trajectories just one type of digital "trajectory" (e.g., sequence of web sites visited)

The "problem"
- companies (e.g., X, Y, Z) treat mobility data as competitive advantage
- public institutions, people concerned about privacy

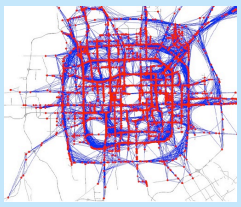
→

The "result"

"no data"
(or toy data, or old data)

A technical challenge

real-world mobility trajectories (private)



→

published mobility trajectories
(noisy but with privacy guarantees)

↕

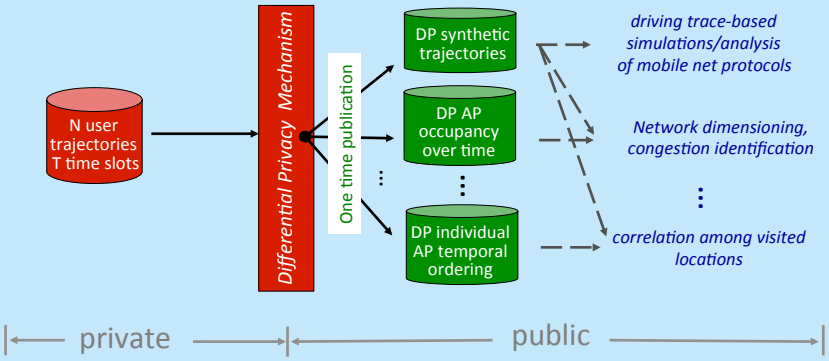
analyst

↓

accurate, fit-for-use predictions

Differential privacy: *non-interactive*

- publish "noisy" data, analysts perform *any* task (*any* number of times) on published data



How *useful* is noisy DP trace?

- added noise may render noisy DP trace useless (or not) for a given purpose
- tradeoff between privacy (ε) and usefulness-for-purpose

$$\text{context-specific utility} = \frac{\text{Analysis Task Performance (noisy\_db)} - \text{Analysis Task Performance (original db)}}{\text{Analysis Task Performance (original\_db)}}$$

- many possible analysis uses:
  - analyzing new routing, handoff protocols in mobile nets
  - system occupancy / dimensioning
  - co-traveller analysis

… on-going research

Data: the even bigger picture(s)

- as our (systems) CS research becomes more human-centered, IRBs become mandatory
- data (and software) critical for robust and reliable science
- Feb. 2013 OSTP memo: US Federal agencies to develop plans to make publicly available to the "greatest extent and with the fewest constraints possible and consistent with law" the "direct results of federally funded scientific research
  - NSF'S PUBLIC ACCESS PLAN: Today's Data, Tomorrow's Discoveries, NSF 15-52, March 2015.

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- conclusions, looking forward

CISE Research and Education

- CISE: **rich intellectual agenda** – highly creative, highly interactive, with enormous possibilities for changing the world!
- Thriving basic research community foundational for long-term **discovery** & **innovation**, **economic prosperity**, **national security**
- Growing investment in **cyberinfrastructure** is crucial to accelerating scientific discovery and engineering innovation across all disciplines
- Investments in **research, education, and infrastructure** have returned exceptional dividends to our Nation

Mobility & Wireless

- vision: ubiquitous wireless access, backed by sliceable, deeply programmable core/edge cloud (computer, network, storage)
- smart and connected communities: rich set of applications
  - IoT, CPS, smart-and-connected-*
- reliability, robustness, security, privacy critical (for at least some services)
- integrated architecture avoids stovepipes
  - leverage network-effect among services

It is an
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computer and information science and engineering
(and in mobile and wireless systems)