Cyber-Physical Systems Research Challenges

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National Workshop on High-Confidence Automotive Cyber-Physical Systems
Troy, MI
3 April 2008

Cars Drive Themselves

Credit: PaulStamatiou.com

Cars are Networks of Computers

A BMW is "now actually a network of computers"
- [R. Achatz, Seimens, Economist Oct 11, 2007]

Cars are Nodes in a Network

"As smart as in-car navigation devices are, they could be smarter. They could talk to each other via the Internet and share information on how fast traffic is moving on the roads they have just traveled. And they could also use the Internet to let you search for places of interest, get map updates, or even receive new destinations wirelessly."

Credit: Dash Navigation, Inc.

Wall Street Journal, March 27, 2008

Cars are Nodes in a Network

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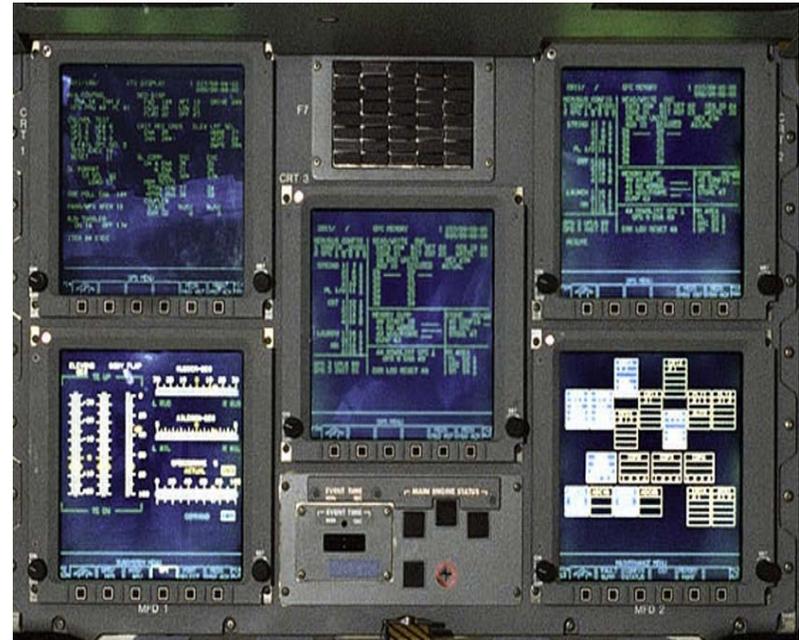
Credit: Dash Navigation, Inc.

Dash Express, $400.

Wall Street Journal, March 27, 2008

Cars Are Sensors and Actuators

- Anti-locking braking
- Adaptive cruise control
- Automatic airbags
- Automatic collision notification
- Blind spot reduction
- Collision sensing bumpers
- Headlight glare reduction
- Pedestrian sensors
- Rearward visibility enhancement
- …

Warning: Driver Attention

Zero Traffic Deaths

- Lampson's Grand Challenge:

    Reduce highway traffic deaths to zero.

    – Butler Lampson, Getting Computers to Understand, Microsoft, *J. ACM* 50, 1 (Jan. 2003), pp 70-72.
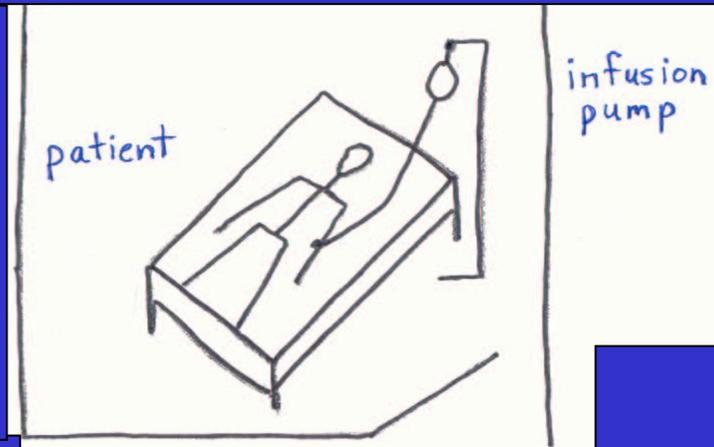
U.S Broader Research Agenda and Priorities

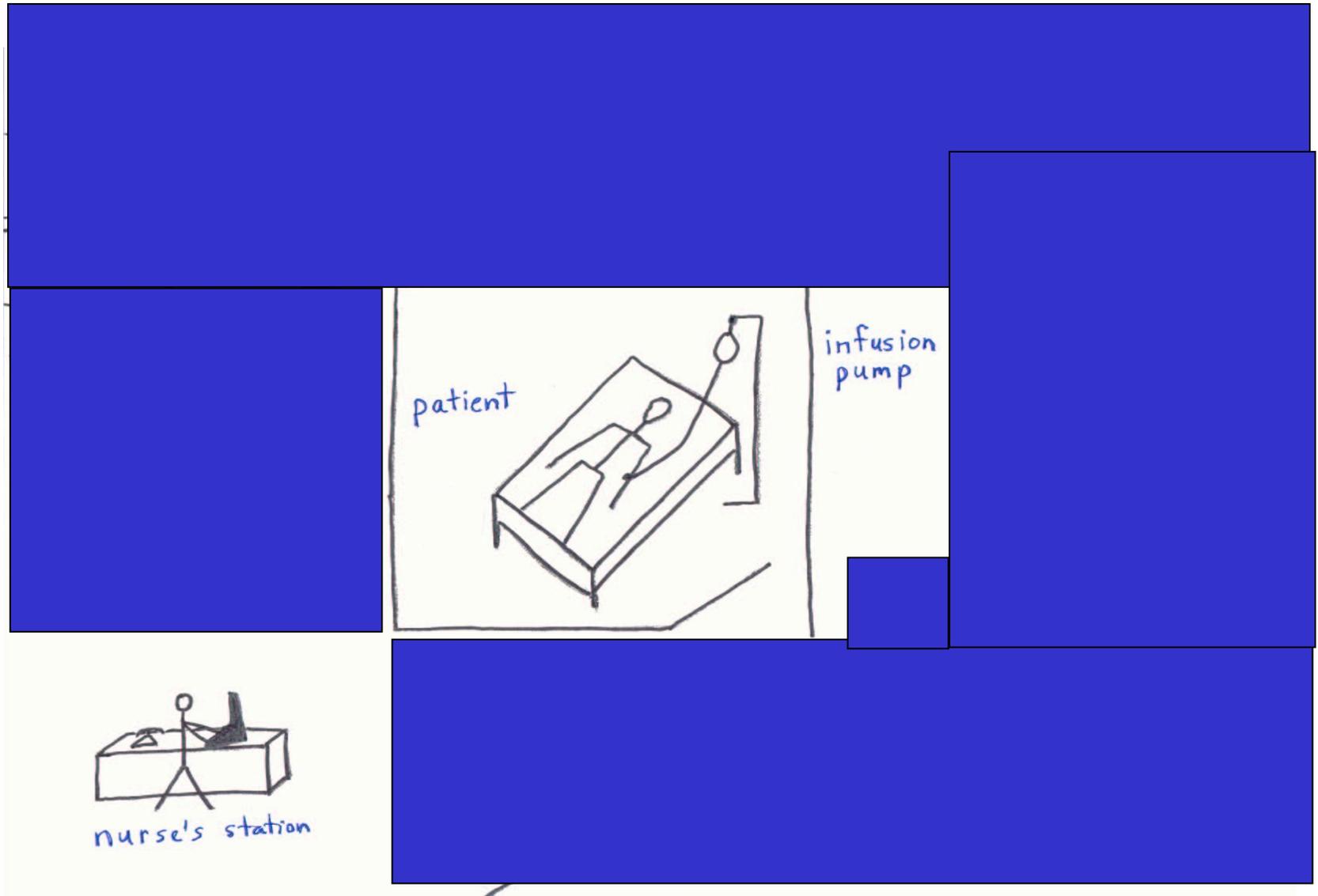President's Council of Advisors on Science and Technology

Networking and Information Technology Research and Development

- ## PCAST/NITRD report [August 2007]
  - – Dan Reed and George Scalise
  - – 8 priority areas listed, with the recommendation that the first 4 get disproportionately larger funding increases.

- ## #1 Priority: Cyber-Physical Systems
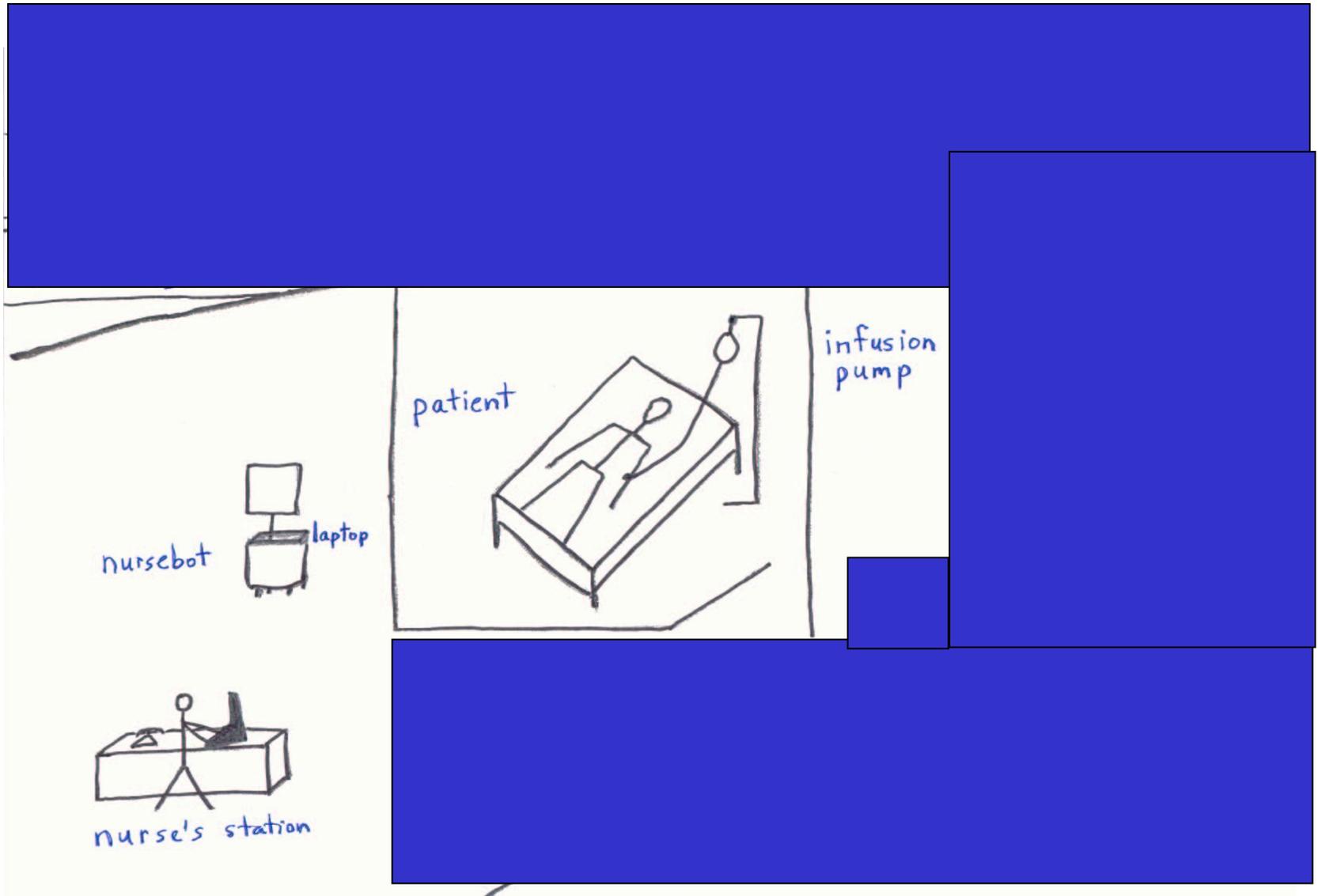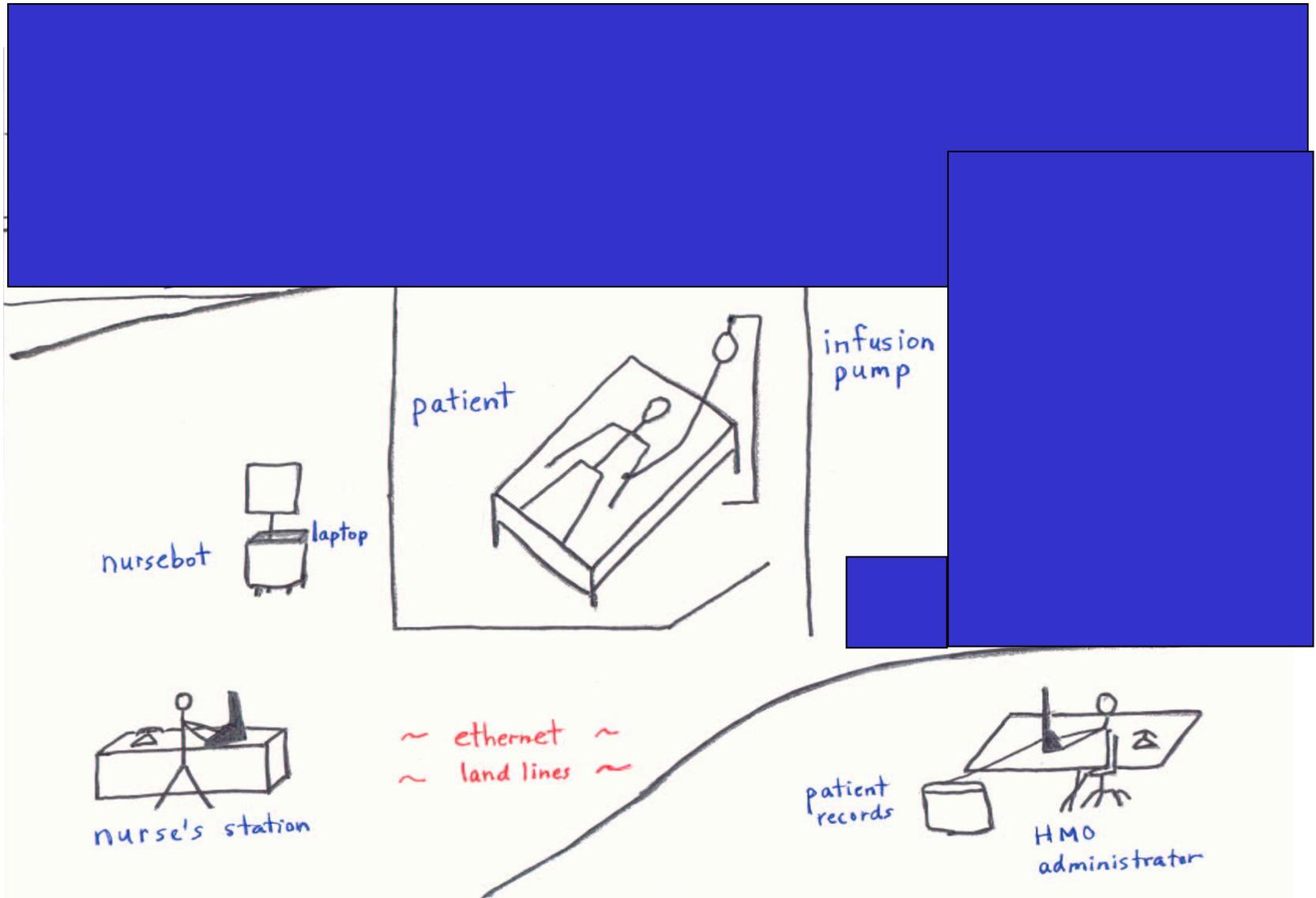 - – Our lives <u>depend</u> on them.

This is Not Science Fiction

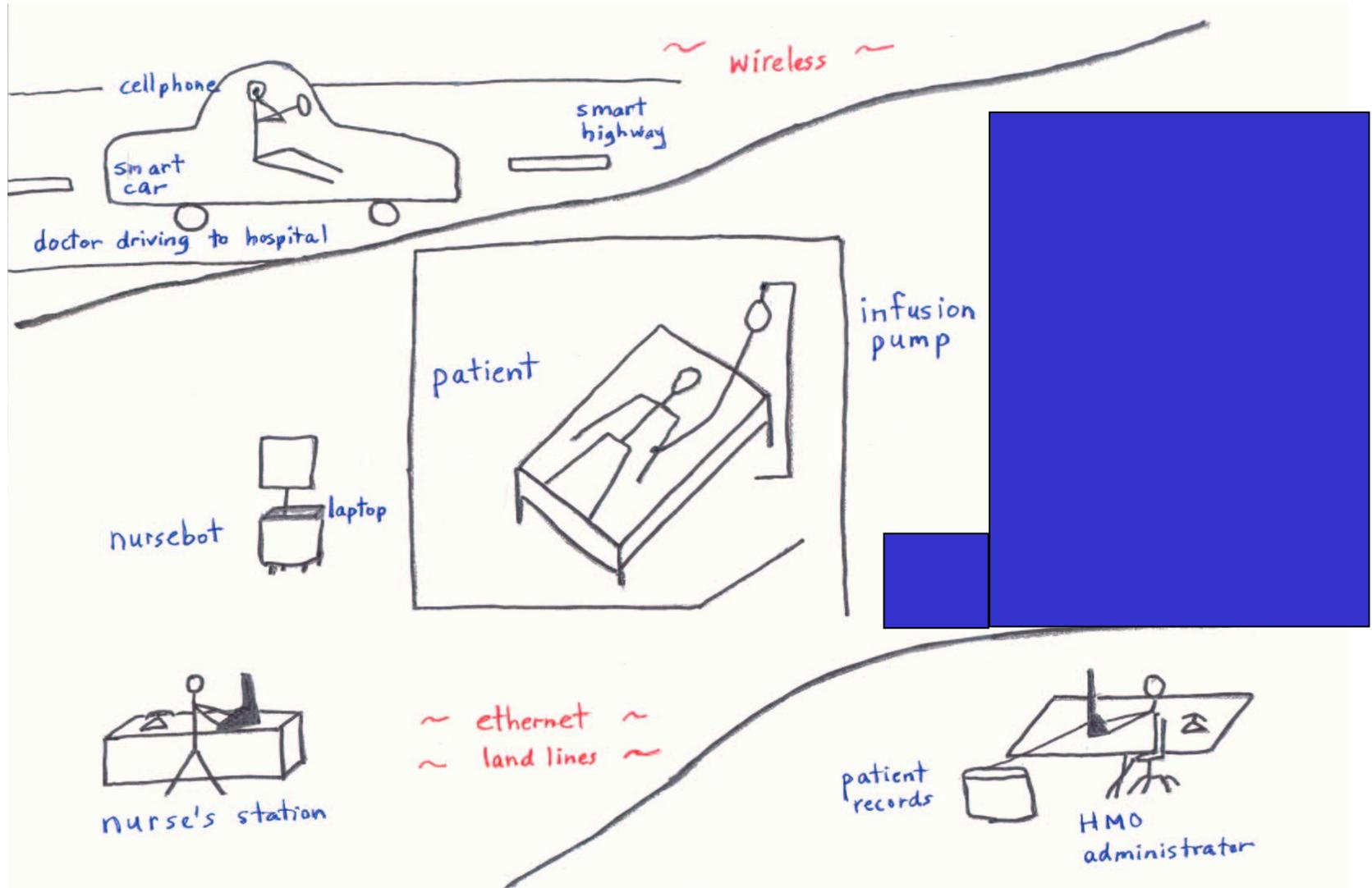# This is Not Science Fiction

patient

infusion pump

nurse's station

This is Not Science Fiction

infusion pump

patient
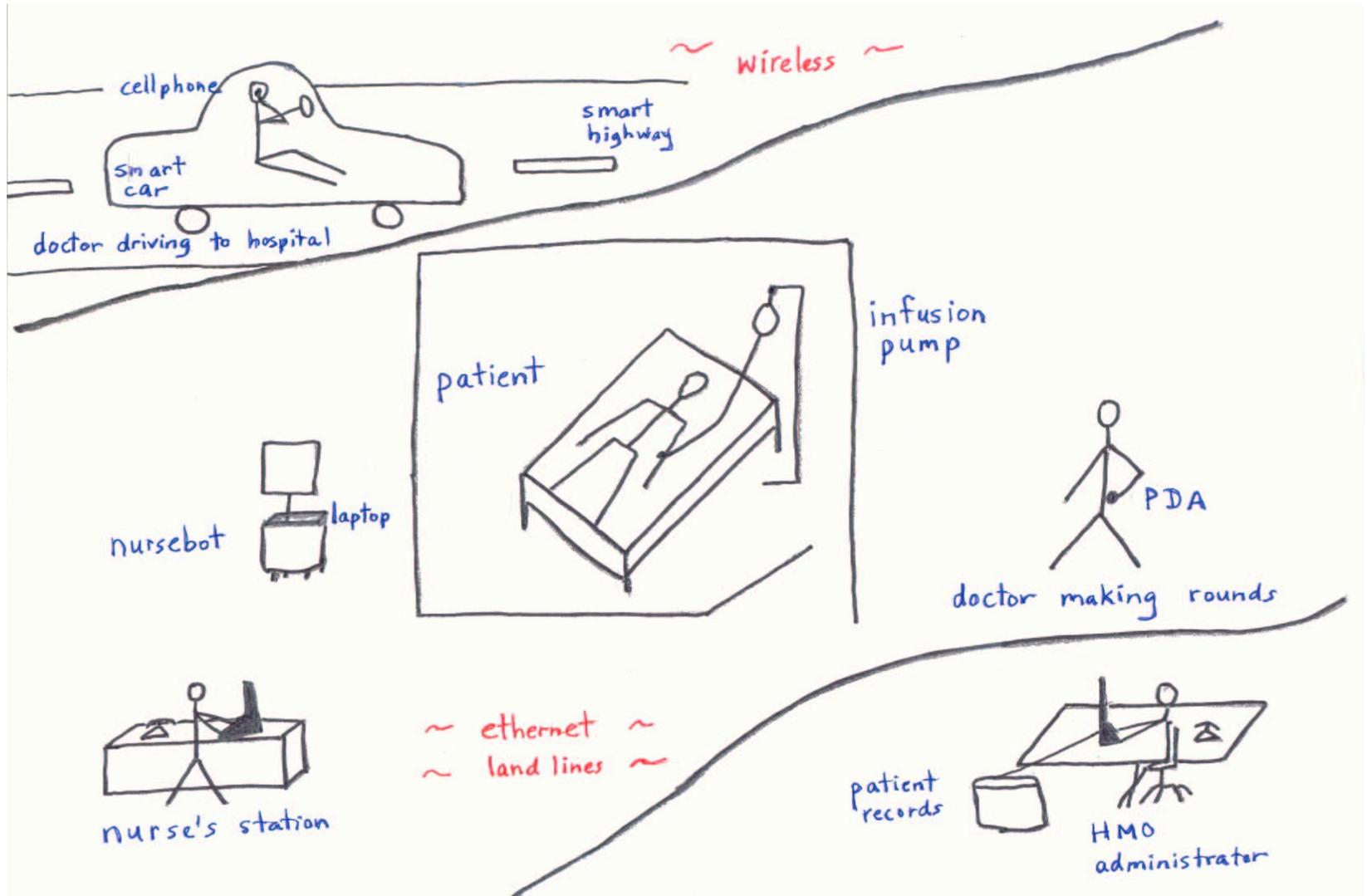
nursebot

laptop

nurse's station

This is Not Science Fiction

This is Not Science Fiction

This is Not Science Fiction

This is Not Science Fiction

soldier in smart tank

battlefield with hidden mines

GIG

Wireless

cellphone

smart highway

smart car

doctor driving to hospital

medic in MASH unit

soldier on smart stretcher with smart dogtag

patient

infusion pump

medicbot

nursebot

laptop

PDA

doctor making rounds

IPv6

ethernet

land lines

emergency supplies station

nurse's station

patient records

HMO

military records administration
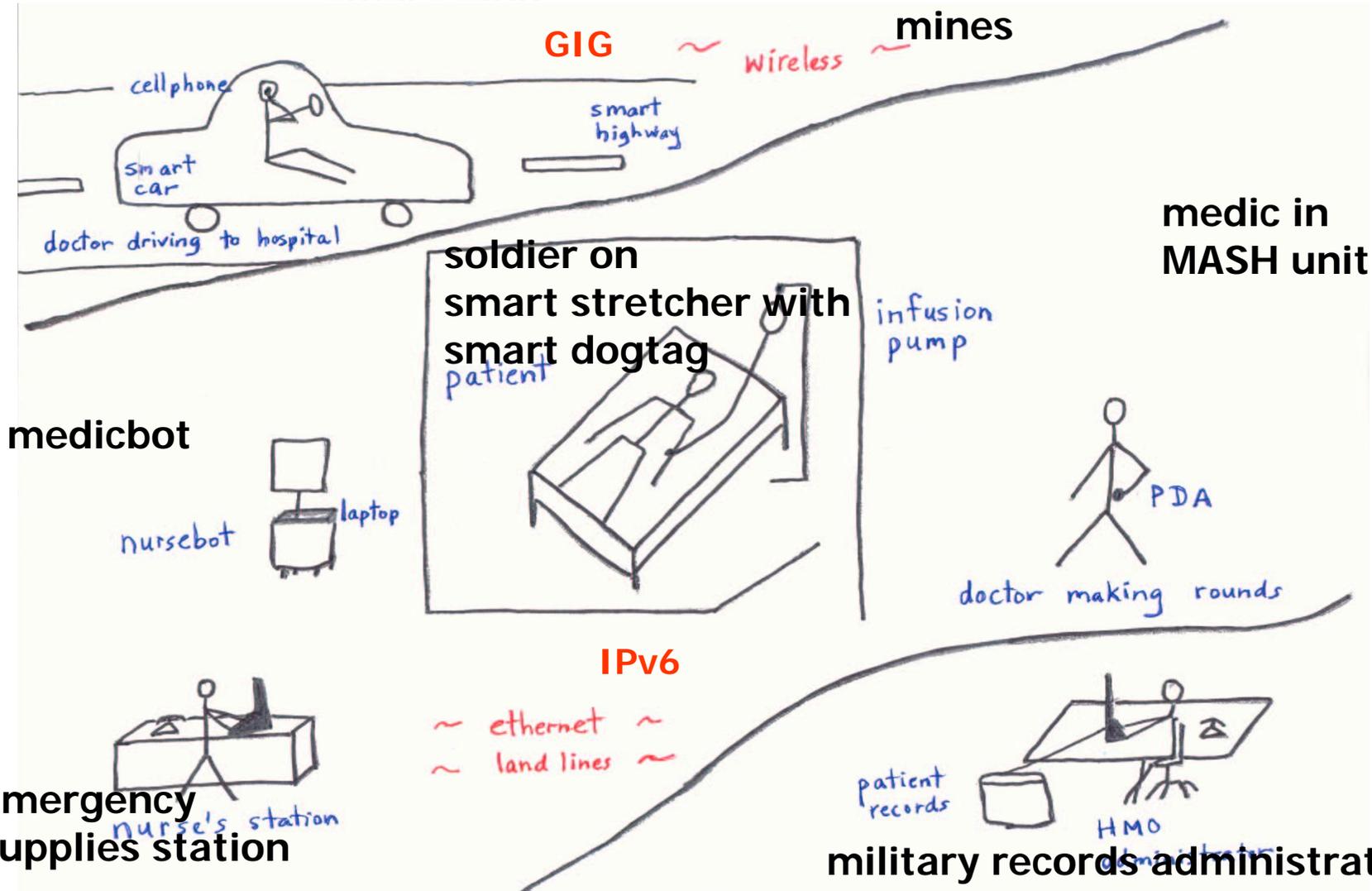
Research Challenges

Drivers of Computing

Society

Science ⟷ Technology
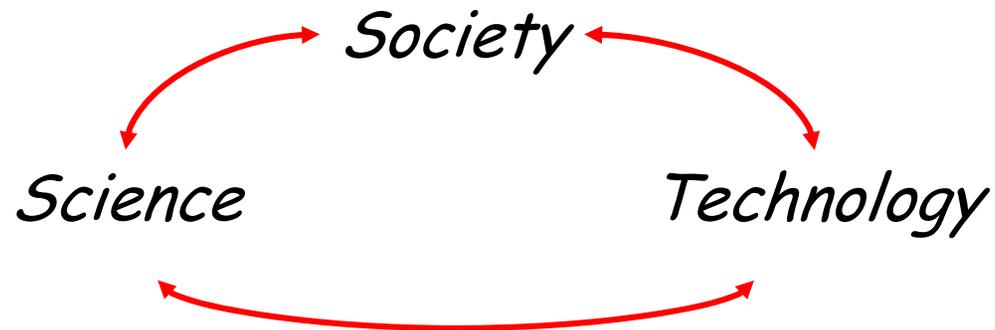
Users and Society

- <u>Expectations:</u> 24/7 availability, 100% reliability, 100% connectivity, instantaneous response, store anything and everything forever, ...

- <u>Classes:</u> young to old, able and disabled, rich and poor, literate and illiterate, ...

- <u>Numbers:</u> individual $\rightarrow$ cliques $\rightarrow$ acquaintances $\rightarrow$ social networks $\rightarrow$ cultures $\rightarrow$ populations

  <u>Cyber-Physical Systems will be everywhere, used by everyone, for everything</u>

Societal Challenge

- How can we provide people and society with cyber-physical systems they can <u>bet their lives on</u>?
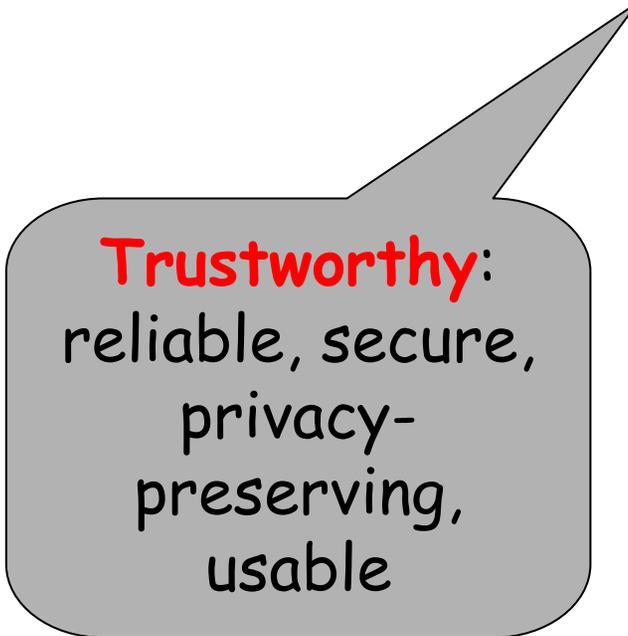
Trustworthy: reliable, secure, privacy-preserving, usable

Important Trends in Systems

Credit: Wikimedia

- Nature of tomorrow's systems
  - Dynamic, ever-changing, 24/7 reliability
  - Self-* (aware, diagnosing, healing, repairing, managing)

  - Two important classes converging
    - Embedded and real-time
      - Networked architecture, e.g., sensor nets (see below)
      - Safety-critical apps, e.g., medical, automotive, aero&astro
    - Pervasive and mobile

      - Focus on sensors and actuators, not just the devices and communication links
      - Prevalence of cell phones, iPods, RFIDs, …

Credit: Apple

Credit: Missouri Department of Transportation

# Technical Challenge

- (How) can we build systems that interface between the cyber world and the physical world? Ideally, with predictable, if not adaptable behavior.

- Why this is hard:
  - We cannot easily draw the boundaries.
  - Boundaries are always changing.
  - There are limits to digitizing the continuous world by abstractions.
  - Complex systems are unpredictable.

Characteristics of System Complexity

Tipping points
- Stampeding in a moving crowd
- Collapse of economic markets
- "Mac for the Masses" – P. Nixon
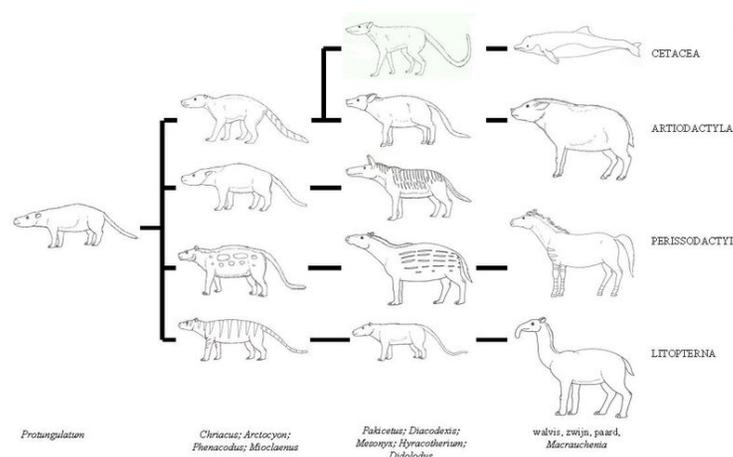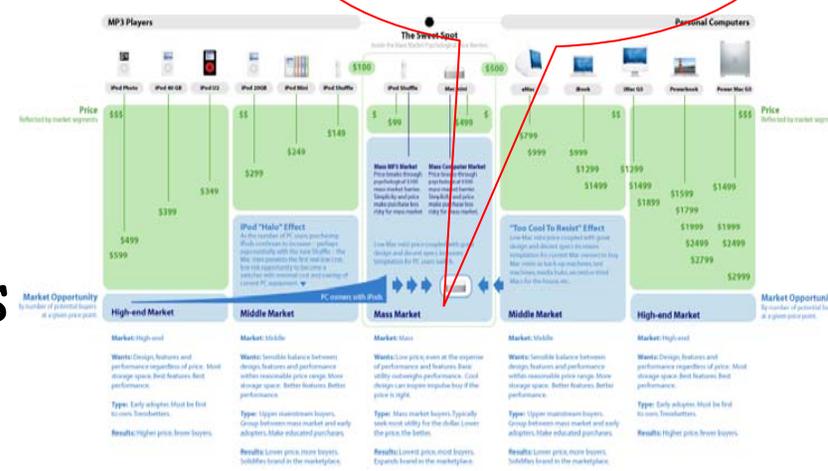
Emergent phenomena
- Evolution of new traits
- Development of cognition, e.g., language, vision, music
- "Aha" moments in cognition

Predictable Behavior

- *Predictable* is ideal

A <u>complicated</u> system is a system with lots of parts and whose behavior as a whole can be entirely understood by reducing it to its parts.

A Car and Driver

A Car

A <u>complex</u> system is a system with lots of parts that when put together has *emergent* behavior.

Systems Research Challenges

- We need systems that are <u>compositional</u>, <u>scalable</u>, and <u>evolvable</u>.
  - Big and small components
  - One component to billions of components
  - New and old technology co-exist, e.g., from standard cars to autonomous cars, all on smarter and smarter highways

- We need ways to <u>measure</u> <u>and</u> <u>certify</u> the "performance" of CPS.
  - Time and space, but multiple degrees of resolution
  - New metrics, e.g., energy usage
  - New properties, e.g., security, privacy-preserving

- We need new <u>engineering</u> <u>processes</u> for developing, maintaining, and monitoring CPS.
  - Traditional ones won't work.

Software, the Great Enabler

- Good: You can do anything in software!
- Bad: You can do anything in software!

▶ It's the software that effects system complexity.

Software Research Challenges

- We need new notions of "<u>correctness</u>".
  - Factor in context of use, unpredictable environment, emergent properties, dynamism
  - What are the desired <u>properties</u> of and <u>metrics</u> for both software (e.g., weak compositionality) and systems (e.g., power)?

- We need new <u>formal</u> <u>models</u> and <u>logics</u> for reasoning about cyber-physical systems.
  - E.g., hybrid automata, probabilistic real-time temporal logic
  - For verification, simulation, prediction

- We need new <u>verification</u> <u>tools</u> usable by domain engineers.
  - Push-button, lightweight
  - Integrated with rest of system development process
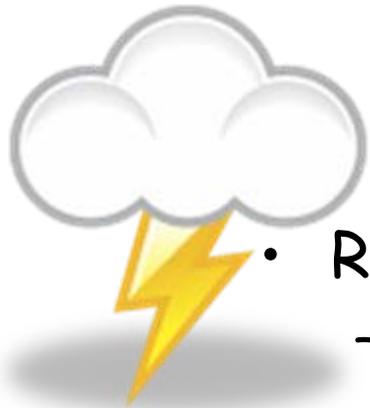
Research Vision

- To provide automotive engineers with lightweight "push-button" tools, each checking a specific application-specific property.
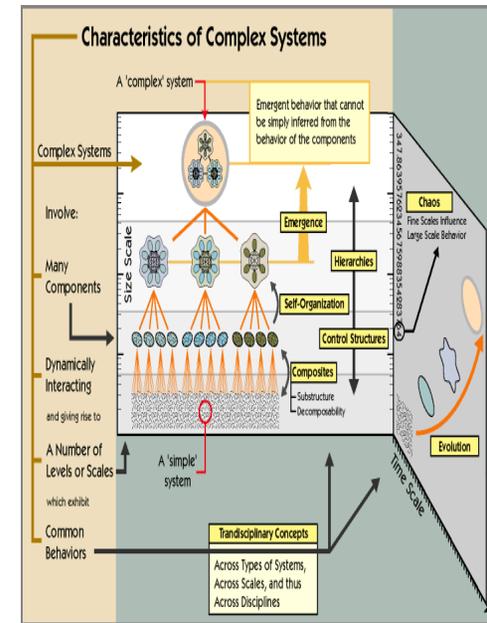

Check Restart

Check Deadlock

Check Race

Check Power usage

Check Fuel usage
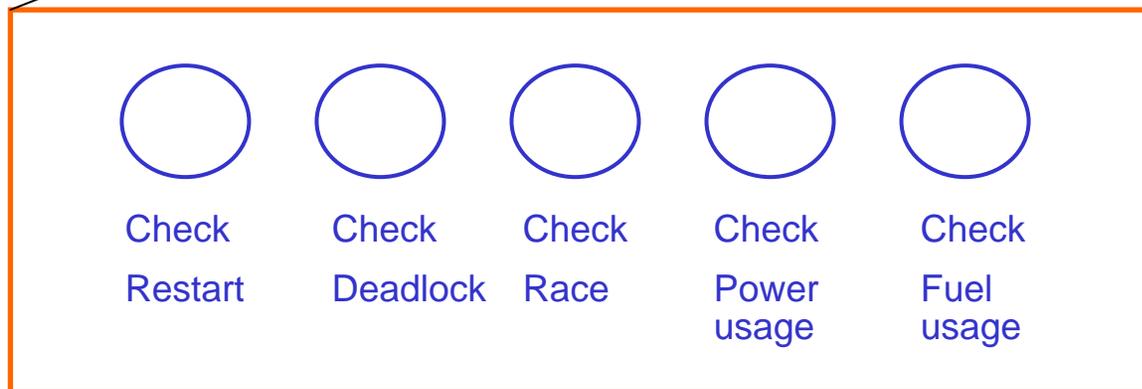
Fundamental Scientific Challenges

- ## Co-existence of Booleans and Reals
  - Discrete systems in a continuous world

- ## Reasoning about uncertainty
  - Human, Mother Nature, the Adversary

- ## Understanding complex systems
  - Emergent behavior, tipping points, …
  - Chaos theory, randomness, …

Communities Needed to Meet These Challenges

Disciplines and Sectors

- Academic Disciplines
  - Civil engineering
  - Control systems
  - Electrical engineering
  - Embedded systems
  - Formal methods
  - Human-computer interaction
  - Hybrid systems
  - Mathematics
  - Mechanical engineering
  - Probability and statistics
  - Real-time systems
  - Robotics
  - Security and privacy
  - Software engineering
  - Systems engineering
  - Usability
  - …

- Industrial Sectors
  - Aeronautics
  - Automotive
  - Buildings
  - Consumer/Home
  - Energy
  - Finance
  - Medical
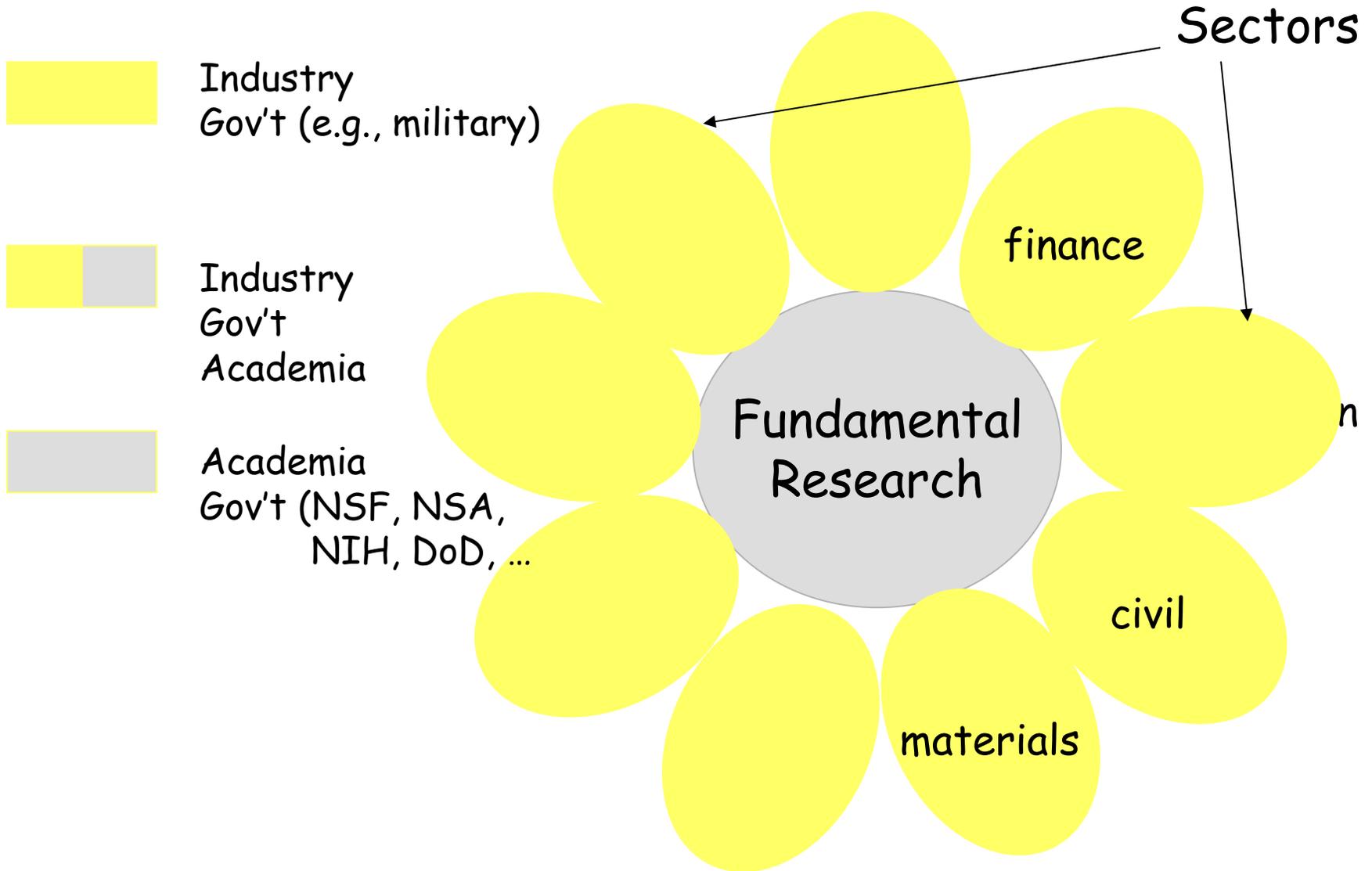 - Telecommunications
  - …

Broader Implications

- ## Nature of research
  - Interdisciplinary
  - Collaborative across disciplines, between industry and academia

- ## Education: Workforce and training
  - Discrete and continuous mathematics
  - Software, hardware, device and systems engineering
  - Need major improvements in Science, Technology, Engineering and Mathematics (STEM) education in K-12

Partnerships

- Theoreticians, experimentalists, domain experts

- Computer scientists, electrical and mechanical engineers

- Industry, Academia, Government
  - domain experts, domain problems
  - general solutions that work for specific problems

A Model for Expediting Progress

Industry
Gov't (e.g., military)

Industry
Gov't
Academia

Academia
Gov't (NSF, NSA,
    NIH, DoD, …)

Sectors

finance

Fundamental
Research

n

civil

materials

New Models for Academia-Industry-Government Partnership

- For example: Google+IBM and NSF
  - Google+IBM providing software and services on large data cluster to academic community reached by NSF. Why?
    - NSF's broad reach: all US academic institutions, all sciences and engineering
    - NSF's merit review process and infrastructure

- Other companies welcome!
- Other models of engagement welcome!

NSF's Interests in CPS

- Two directorates, CISE and ENG, working together

- Within CISE, across all three divisions
  - Foundations (CCF), systems (CNS), AI/appl'ns (IIS)

- Plans for a new FY09 initiative.
  - Please be on the lookout for our solicitation!

- Related foundation-wide initiative: Cyber-Enabled Discovery and Innovation (CDI)
  - Understanding Complex Systems

Thank you!

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