A Recent History of Sensing
A Review

Tarek Abdelzaher

Dept. of Computer Science

University of Illinois at Urbana Champaign

Sensors

Compass technology (dates back to 200 BC)

Sun dials (clocks) date back to 3500 BC.

Canaries used hundreds of years ago in mine shafts to detect gas leakage:
Dead canary = leakage

Modern Networked Smart Sensors

Driver #1: Moore's Law

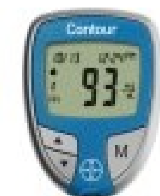
Data centers: Temperature measurement

Factory floor automation

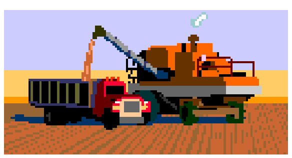
Cell-phones: GPS, accelerometers

Smart Home Appliances

Medical



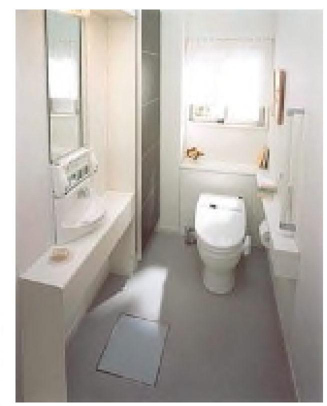
Glucose monitor



Agriculture: crop yield

Sportsware: Fitness monitoring

Cars: GPS, OBD-II interfaces



Smart spaces: Activities of daily living

Industrial

Games: Wii sensors

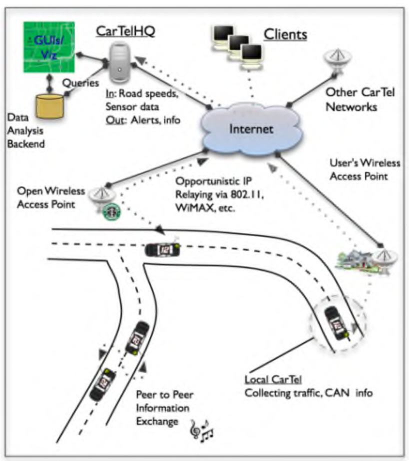
Social

Pulse oximeter

Heart rate monitor

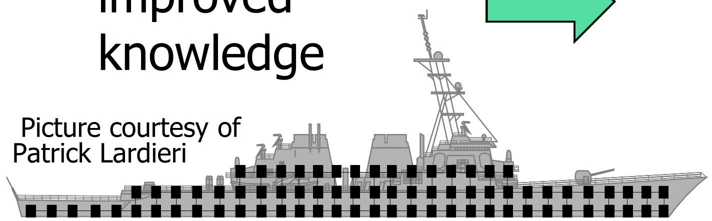
Modern Networked Smart Sensors
Driver #2: Networking Technology

Information integration → Global view, improved knowledge → Improved decision making, better resource use, …



World Wide Sensor Web
(Feng Zhao)

Picture courtesy of Patrick Lardieri



Total Ship Computing Environment (TSCE)

Global Information Grid

Future Combat System
(Rob Gold)

Global Domain Knowledge

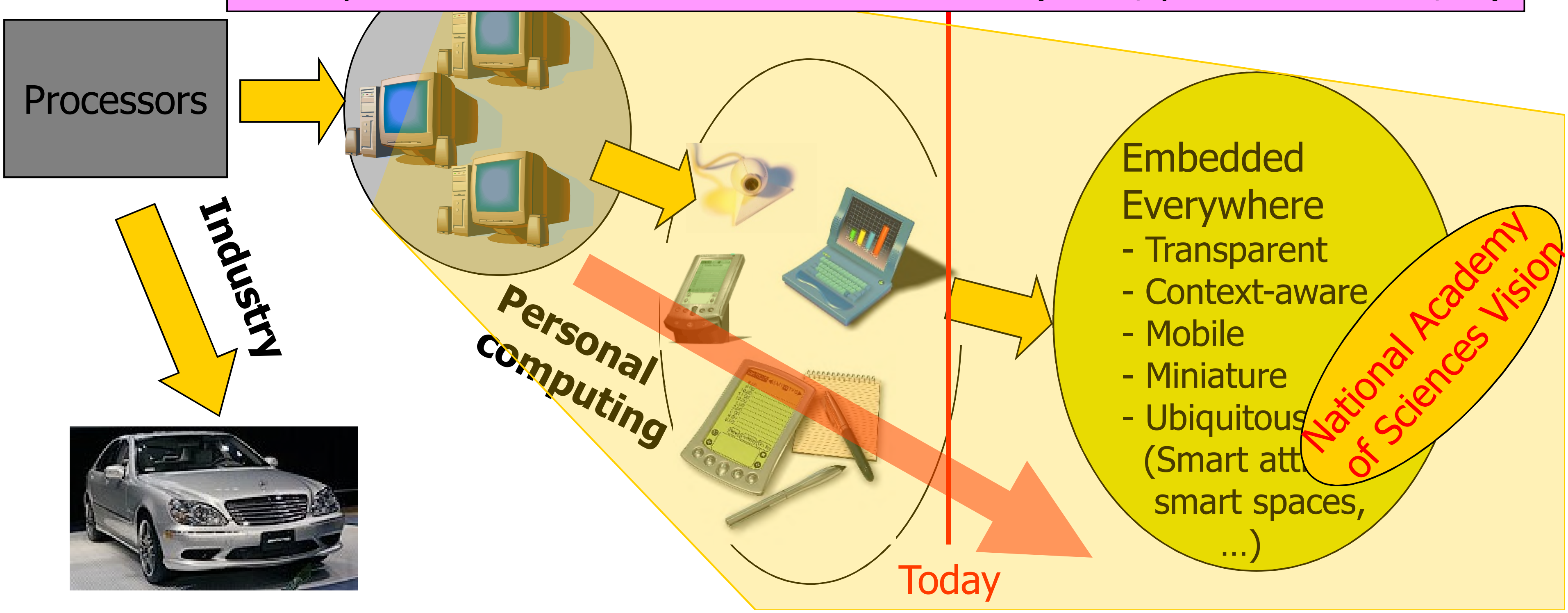
Low End ↔ High End

Embedded Everywhere (2001)

The "Modern Sensor Netwoks" Beginning

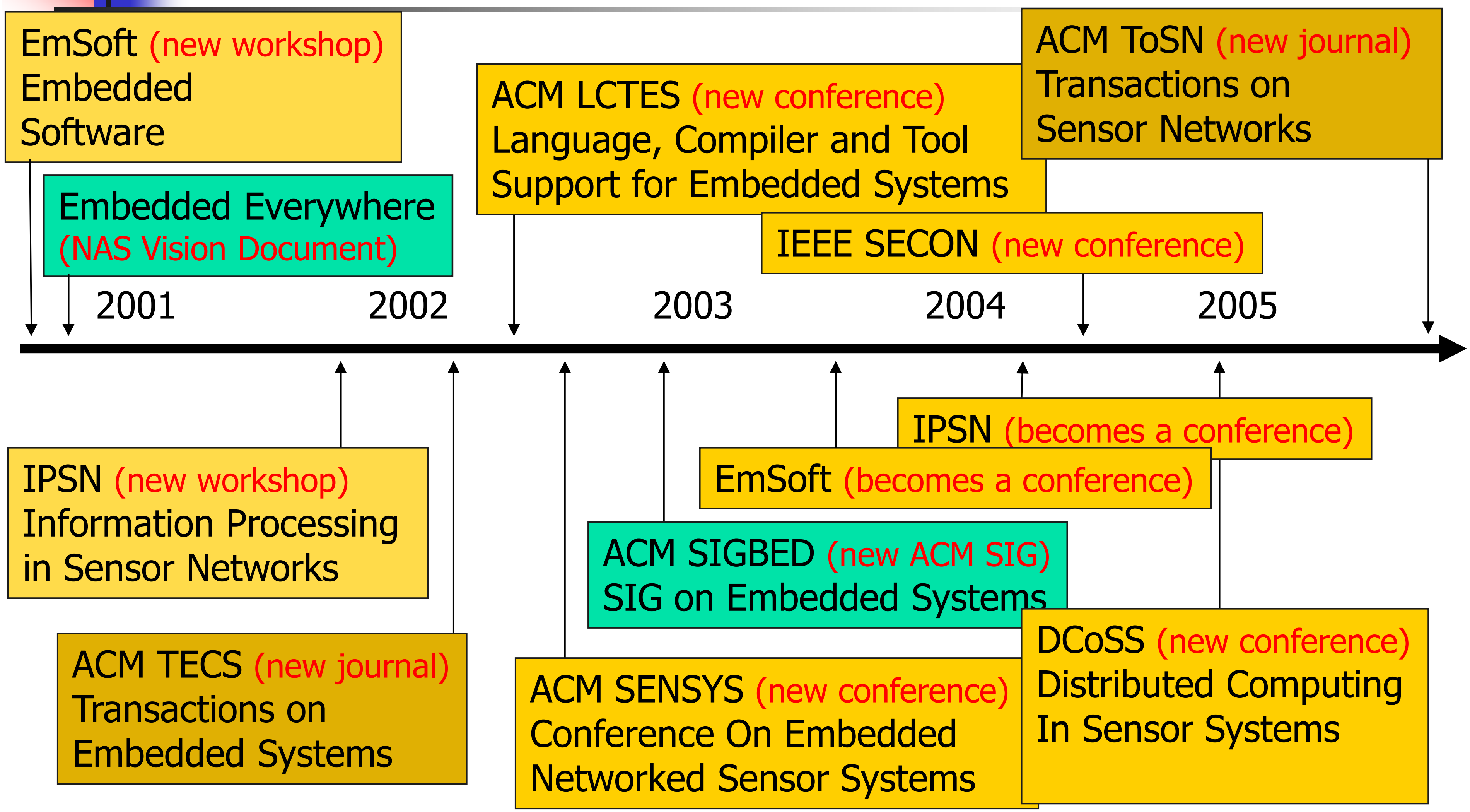
Trend:

- Invisible (embedded) computing, implicit interfaces
  (users need only 1 mobile device – rest should be non-intrusive)
- Context-aware computing (new sensors, new effectors)
- Ubiquitous – instrument what we use most (attire, personal effects, …)



Rise of Modern Networked Sensing

Early Days



Early Days of Sensor Networks

Early Assumptions

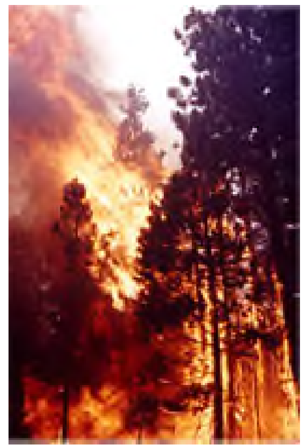
- Large scale multihop wireless networks
- Cheap miniature hardware
- Ad hoc sensor placement with some statistical distribution
- Homogeneous nodes with complex emerging behavior
- Highly redundant sensing (as opposed to centralized)

Early Days of Sensor Networks (1999-2004)

Habitat Monitoring

Precision Agriculture

Applications



Disaster Response

Features

- Ad hoc deployment
- Massive distribution
- Interaction with a physical environment
- Unattended operation

Target Tracking

Infrastructure Protection

Border Control

Popular (Early) Research Problems

- MAC-layer protocols
- Routing protocols (that are not ID-based)
- Energy-optimal data collection
- Optimal sensory coverage
- Optimal communication coverage
- Lightweight distributed target tracking
- Distributed localization (finding where you are)
- Clock synchronization

2003 2004 2005 2006 2007 2008 2009

Sensing Systems (in Sensys)

Surveillance (2003)

Binary tracking (2003)

Counter-sniper (2004)

Lightweight detection and classification (2005)

Binary tracking II (2006)

Habitat monitoring (2004)

Call & response (2004)

ZebraNet (2004)

Redwoods (2005)

Underwater networks (2005)

CenWits: Hiker monitoring (2005)

CarTel: Vehicular sensing (2006)

Luster (2007)

BeepBeep: Acoustic ranging with mobile phones (2007)

BikeNet: Bicycle track sensing (2007)

Flood detection (2008)

Water monitoring (2008)

Canopy closure (2009)

Soil monitoring (2009)

Wearable activity sensing (2009)

Nericell: Road traffic monitoring with smart phones (2008)

VTrack: Traffic delay estimation (2009)

CenceMe: Social sensing with mobile phones (2008)

PoolView: Participatory Sensing (2008)

Data center temperature monitoring (2009)

Structural monitoring (2004)

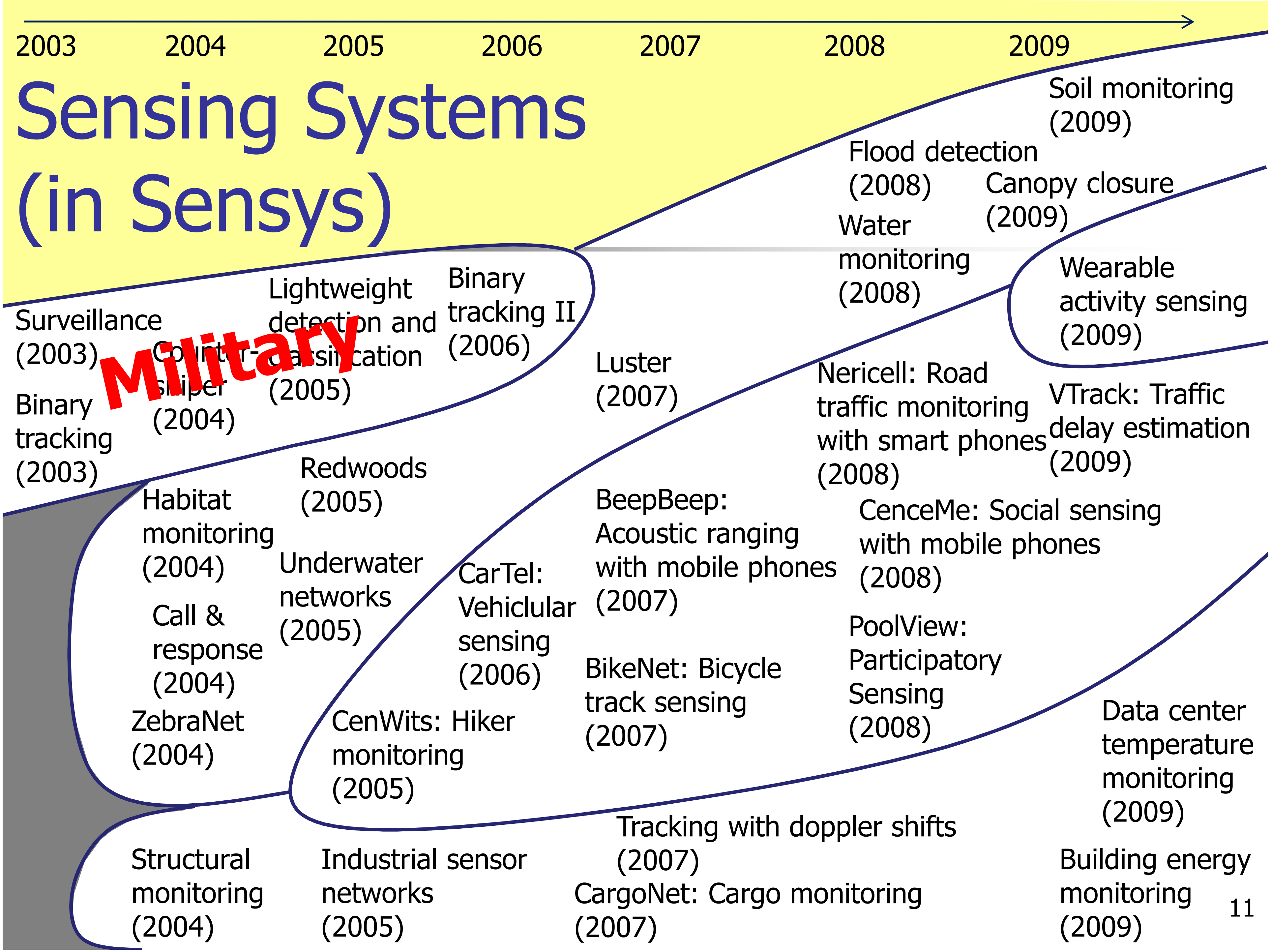
Industrial sensor networks (2005)

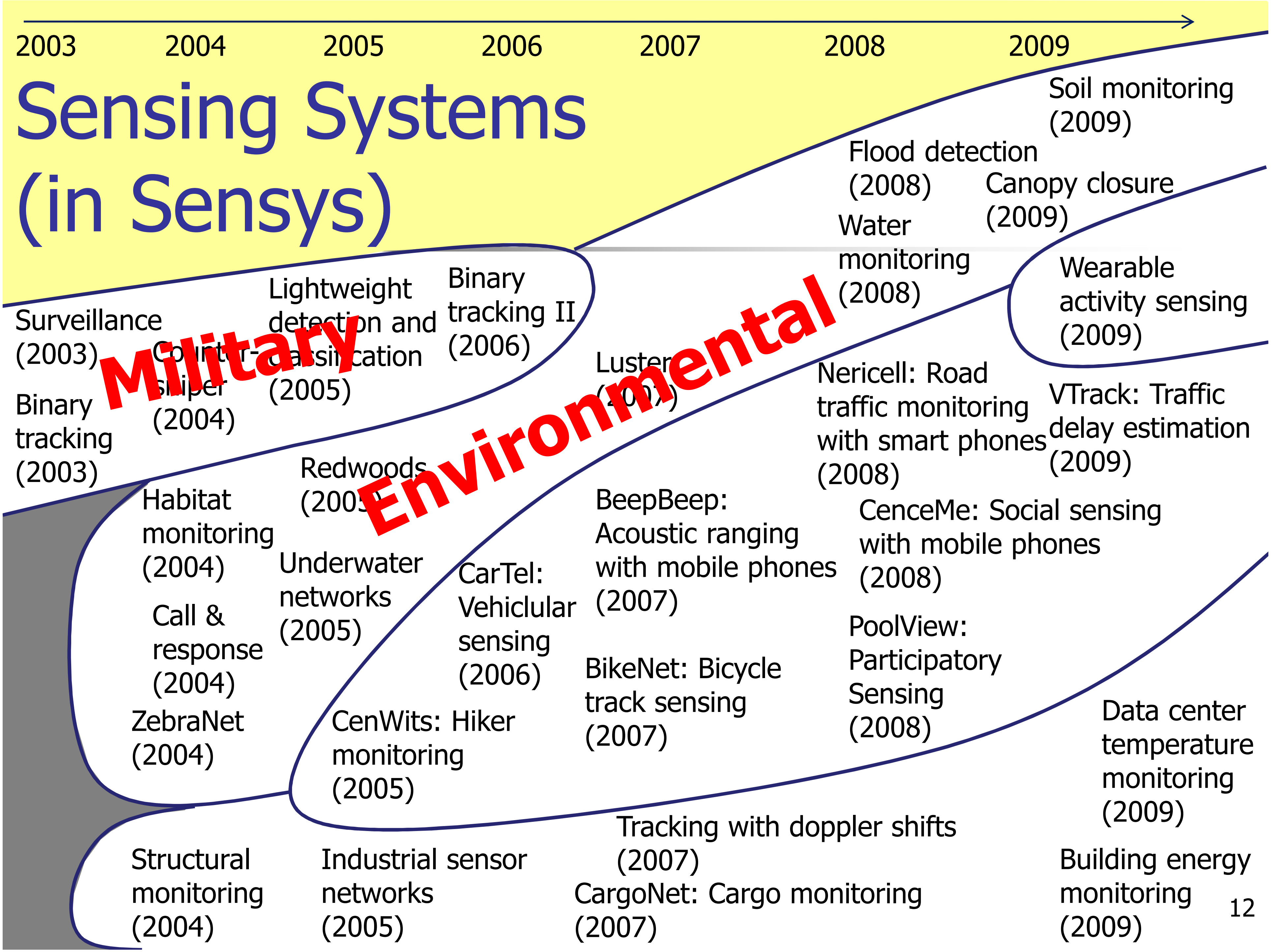
Tracking with doppler shifts (2007)

CargoNet: Cargo monitoring (2007)

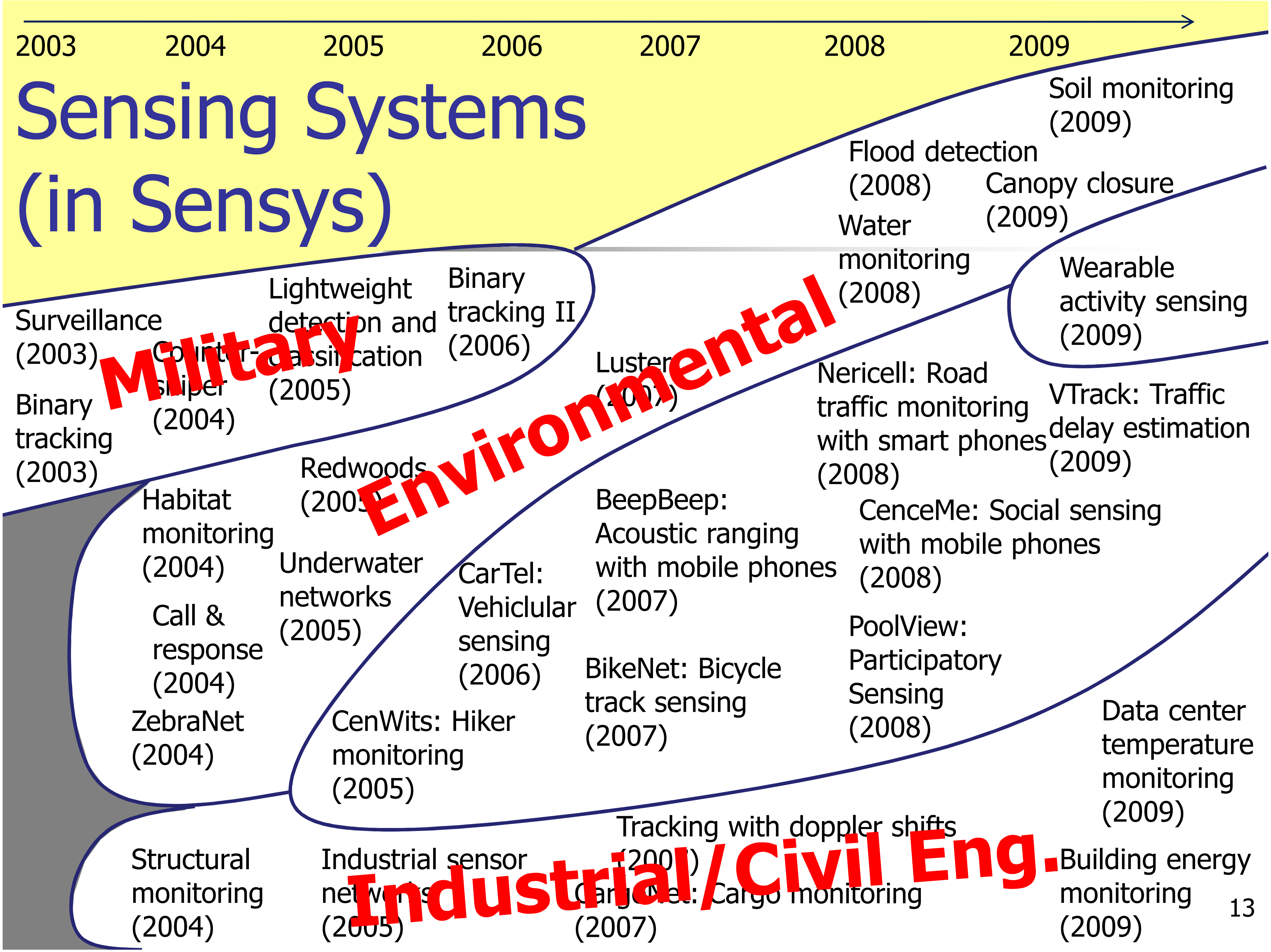
Building energy monitoring (2009)

Sensing Systems (in Sensys)

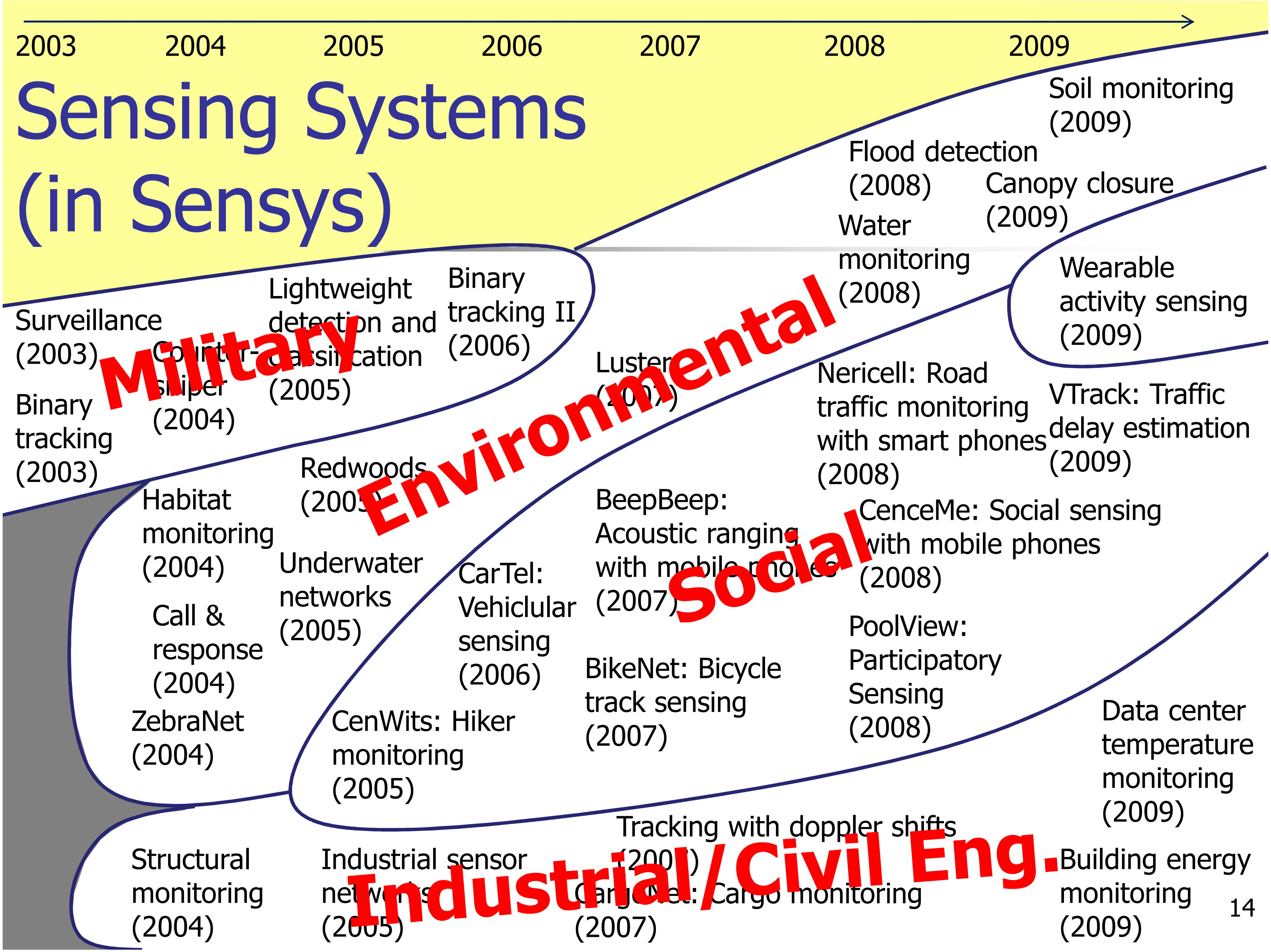


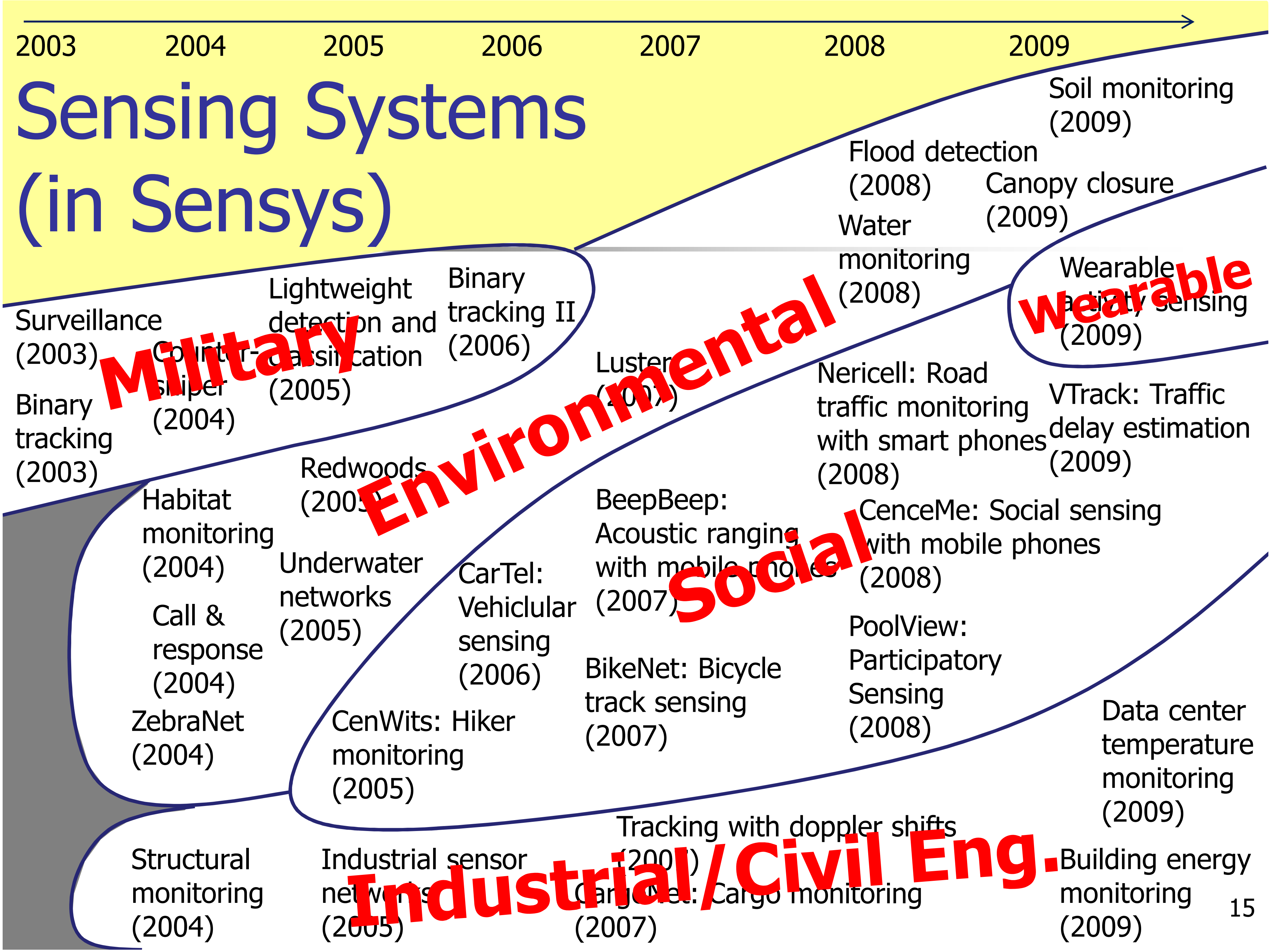

2003
2004
2005
2006
2007
2008
2009
Sensing Systems (in Sensys)
Military
Environmental
Surveillance (2003)
Binary tracking (2003)
Counter-sniper (2004)
Lightweight detection and classification (2005)
Binary tracking II (2006)
Habitat monitoring (2004)
Call & response (2004)
ZebraNet (2004)
Redwoods (2005)
Underwater networks (2005)
CarTel: Vehiclular sensing (2006)
CenWits: Hiker monitoring (2005)
Luster (2007)
BeepBeep: Acoustic ranging with mobile phones (2007)
BikeNet: Bicycle track sensing (2007)
Flood detection (2008)
Water monitoring (2008)
Soil monitoring (2009)
Canopy closure (2009)
Wearable activity sensing (2009)
Nericell: Road traffic monitoring with smart phones (2008)
VTrack: Traffic delay estimation (2009)
CenceMe: Social sensing with mobile phones (2008)
PoolView: Participatory Sensing (2008)
Data center temperature monitoring (2009)
Structural monitoring (2004)
Industrial sensor networks (2005)
Tracking with doppler shifts (2007)
CargoNet: Cargo monitoring (2007)
Building energy monitoring (2009)

Sensing Systems (in Sensys)



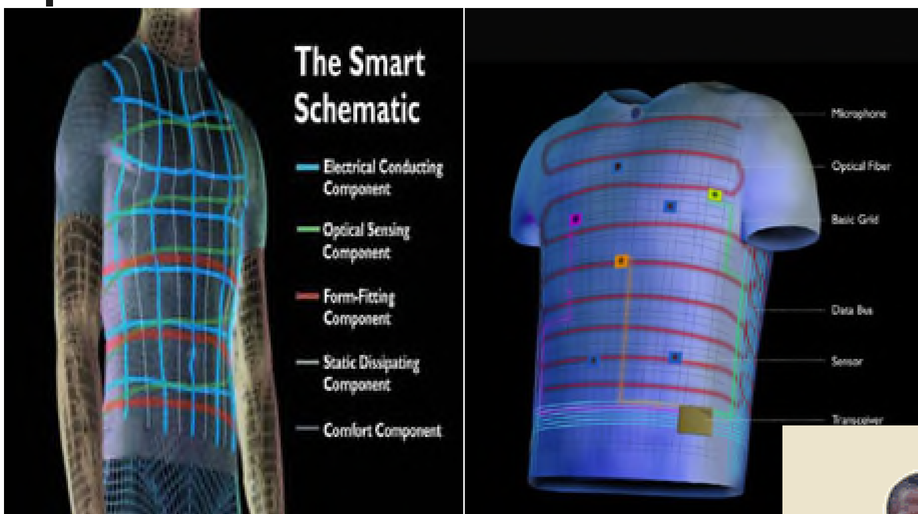
Sensing Systems (in Sensys)




2003
2004
2005
2006
2007
2008
2009
Sensing Systems (in Sensys)
Military
Environmental
Social
Wearable
Industrial/Civil Eng.
Surveillance (2003)
Counter-sniper (2004)
Lightweight detection and classification (2005)
Binary tracking II (2006)
Binary tracking (2003)
Luster (2007)
Soil monitoring (2009)
Flood detection (2008)
Canopy closure (2009)
Water monitoring (2008)
Wearable activity sensing (2009)
Nericell: Road traffic monitoring with smart phones (2008)
VTrack: Traffic delay estimation (2009)
Redwoods (2005)
Habitat monitoring (2004)
Underwater networks (2005)
Call & response (2004)
ZebraNet (2004)
BeepBeep: Acoustic ranging with mobile phones (2007)
CenceMe: Social sensing with mobile phones (2008)
CarTel: Vehiclular sensing (2006)
BikeNet: Bicycle track sensing (2007)
PoolView: Participatory Sensing (2008)
CenWits: Hiker monitoring (2005)
Data center temperature monitoring (2009)
Tracking with doppler shifts (2007)
Structural monitoring (2004)
Industrial sensor networks (2005)
CargoNet: Cargo monitoring (2007)
Building energy monitoring (2009)

Rise of Human-centric Sensing

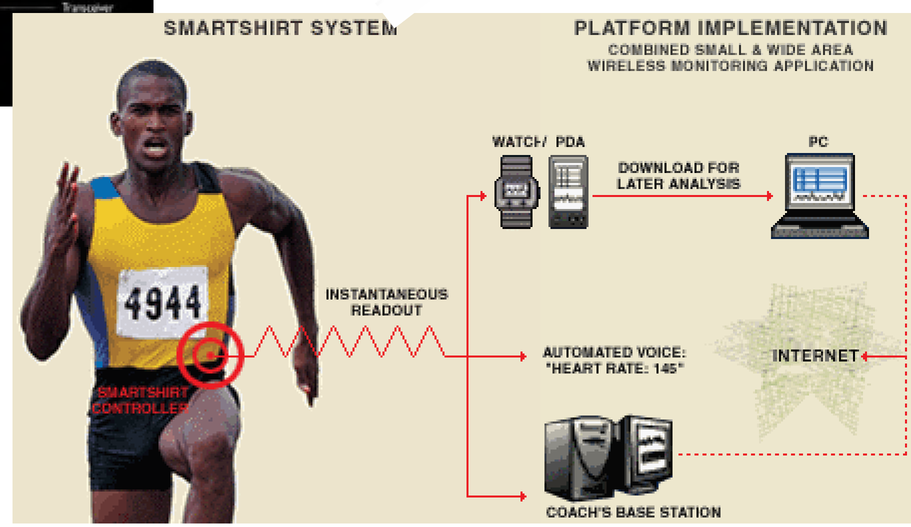
The Past Decade



http://www.sensatex.com

GPS

Nike -iPod



Spot

Wii

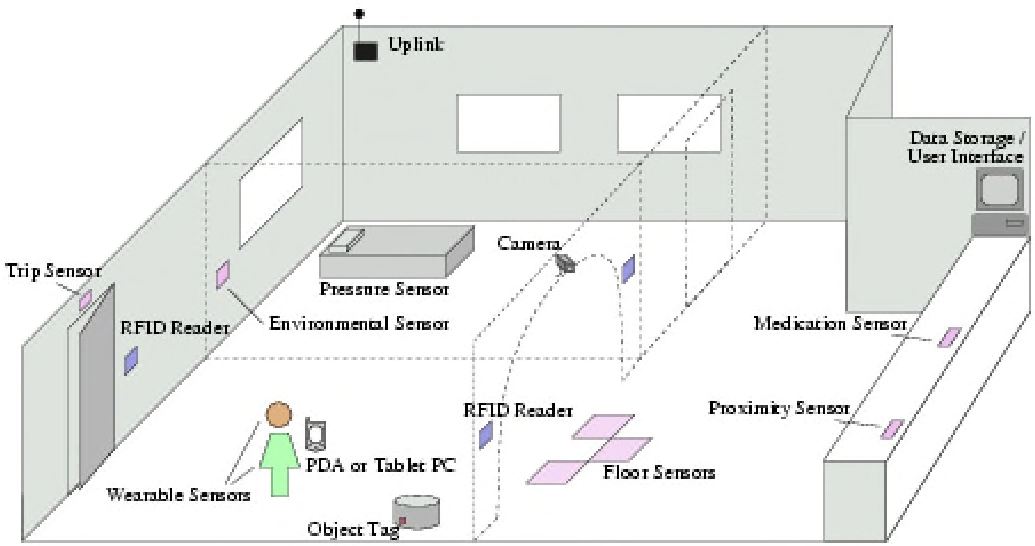
Example: "Smart Attire"

Human Activity Monitoring

Smart Jacket for Human Activity Monitoring

Example: Smart Spaces
Assisted Living

- Instrumented spaces for "aging in place"
  - Reduce cost of long-term care by facilitating independent living



AlarmNet testbed at the University of Virginia

Example: Health and Wellness
Microsoft HealthVault

- HealthVault (Microsoft): Fitness and biometric monitoring devices automatically upload data to a central repository for safekeeping and analysis
  - A significant number of medical device vendors announced devices compatible with healthVault

Precision weight scale

Glucose monitor

Blood pressure monitor

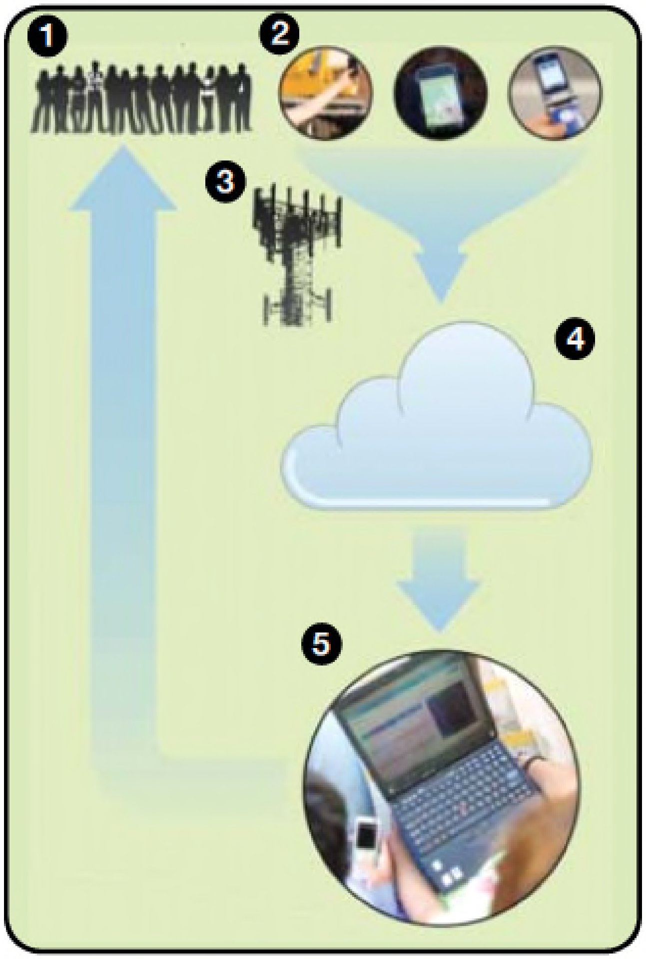
Pedometer

Pulse oximeter

Heart rate monitor

Community Sensing
Geo-tagging the World

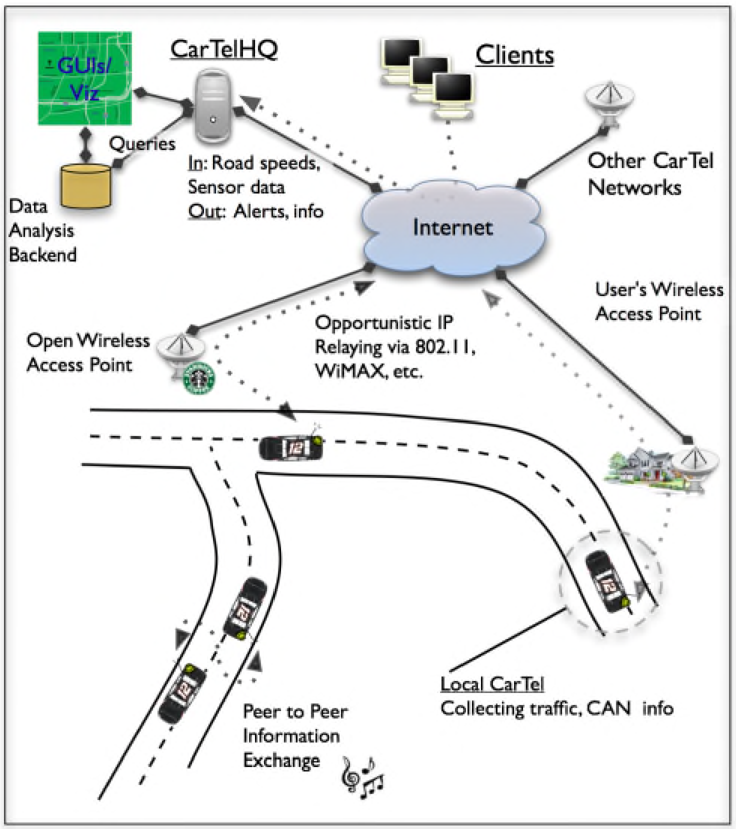
- Phone-based geo-tagging of events of interest (UCLA)
  - Crowds/pollution on beach
  - Invasive species (weeds)
  - Trucks in residential neighborhoods
  - Drinking fountains



Reprinted from UCLA/CENS

Community Sensing

Street Statistics: CarTel, BikeNet, …



Reprinted from http://cartel.csail.mit.edu/overview.html

- CarTel (MIT): An ad hoc network of vehicles with sensors
  - Measures road congestion
  - Generates annotated maps
- Bikenet (Dartmouth College): A self-selected community of biking enthusiasts
  - Shares bike route statistics

Challenges

Data →

Aggregation and Modeling

Challenges

1) Participants do not trust aggregator (do not want to reveal private data)

Data →

Aggregation
and
Modeling

→ A privacy-preserving collection service

Challenges

2) Aggregator does not trust participants (does not know how reliable sources and data are)

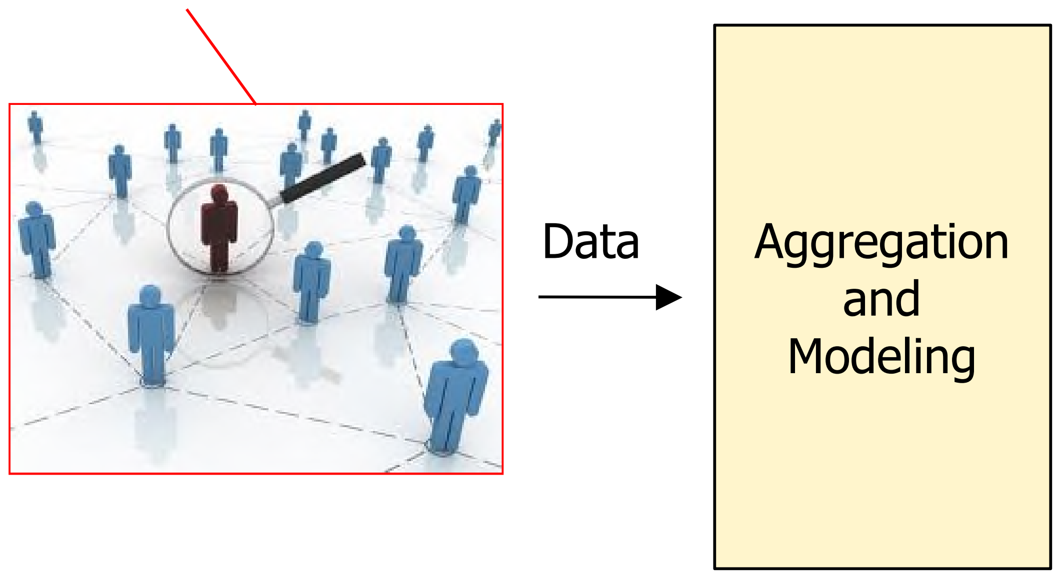
Data

Aggregation and Modeling

→ A fact-finding service

Challenges – Privacy

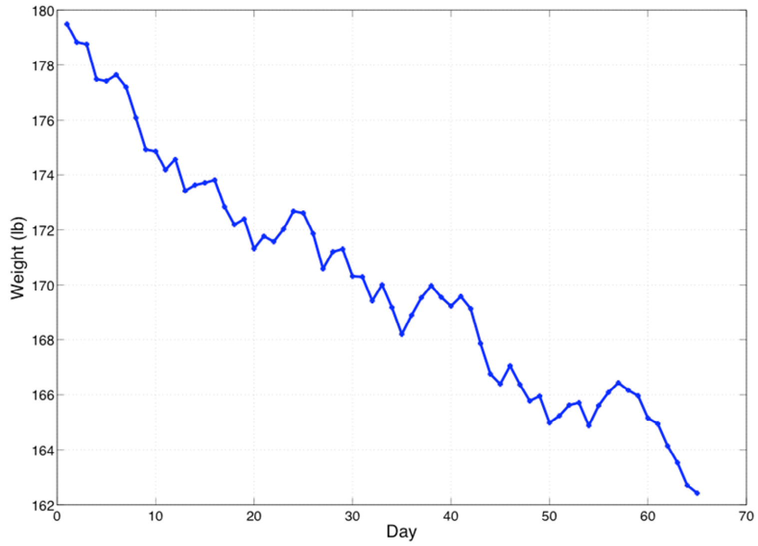
1) Participants do not trust aggregator (do not want to reveal private data)



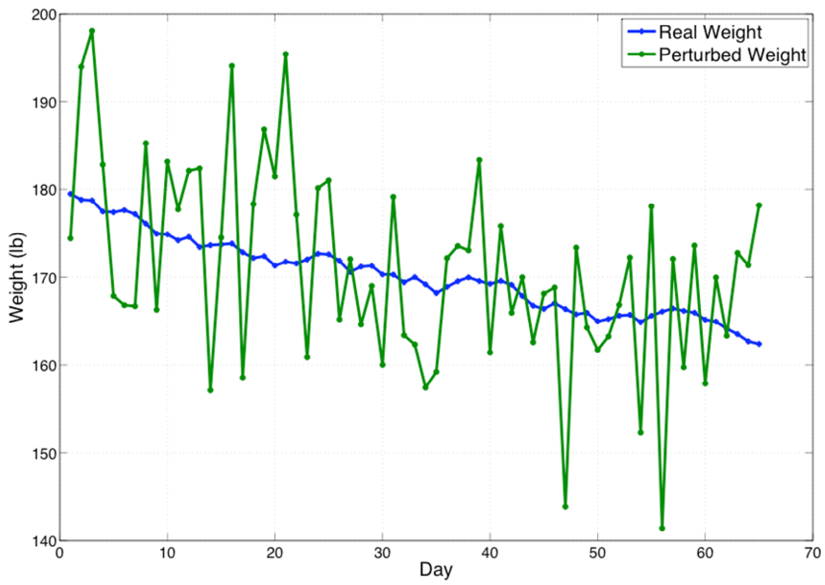
→ A privacy-preserving collection service

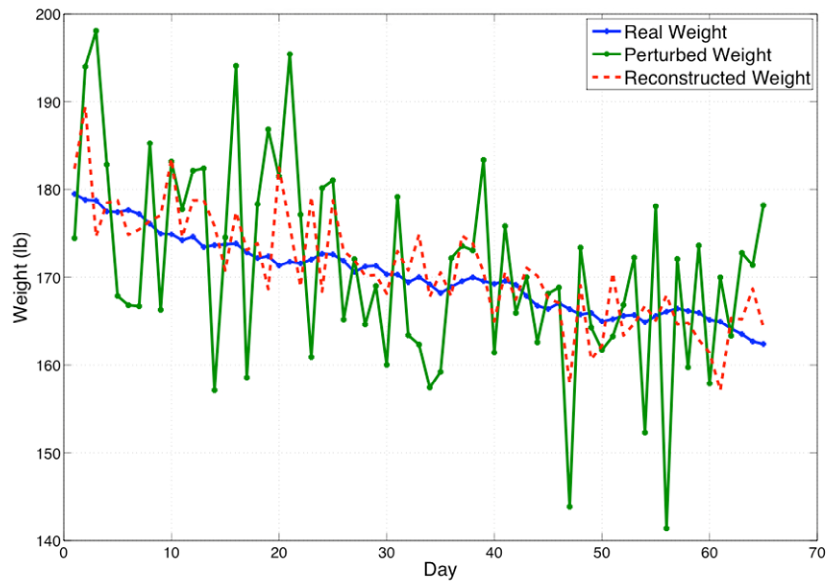
An Example

- Dieters want to share weight information to find efficacy of the given diet, without revealing their true weight, average, trend (loss or gain of weight), etc…



Perturb data? Add Noise?

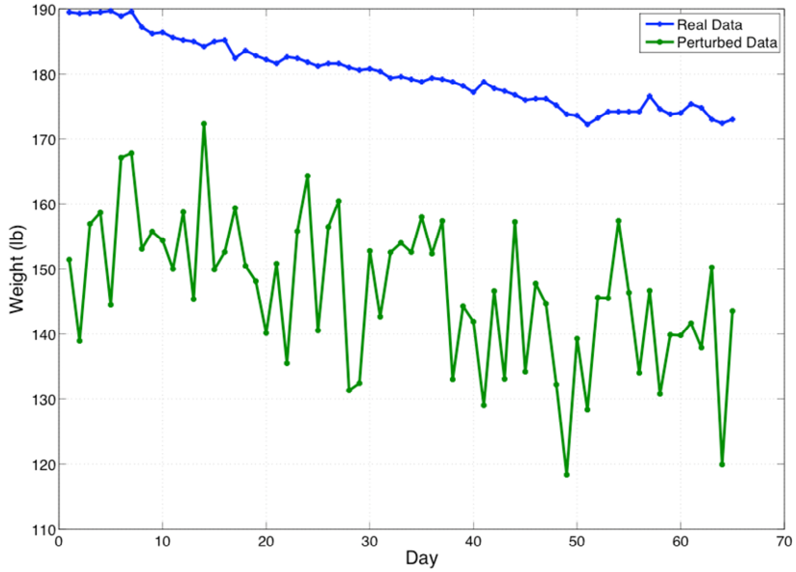


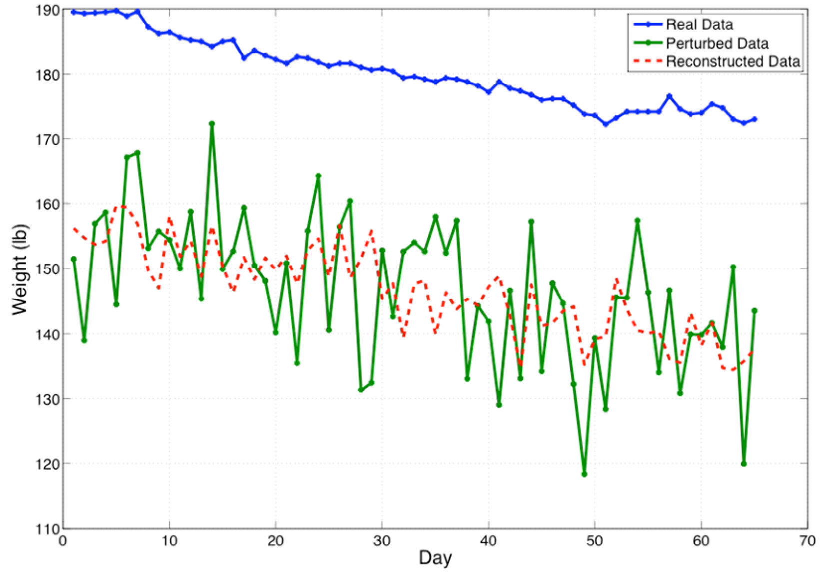


Weight curve perturbed by adding independent random noise (Gaussian in this case)

Estimation using a filter can breach privacy of user

Add Noise and Random Offset?





Weight curve perturbed by adding independent random Gaussian noise and a random offset

Estimation can still observe trend

Challenge

- Develop perturbation that preserves privacy of individuals
  - Cannot infer individuals' data (values and trends) without large error
  - Reconstruction of community distribution can be achieved within proven accuracy bounds

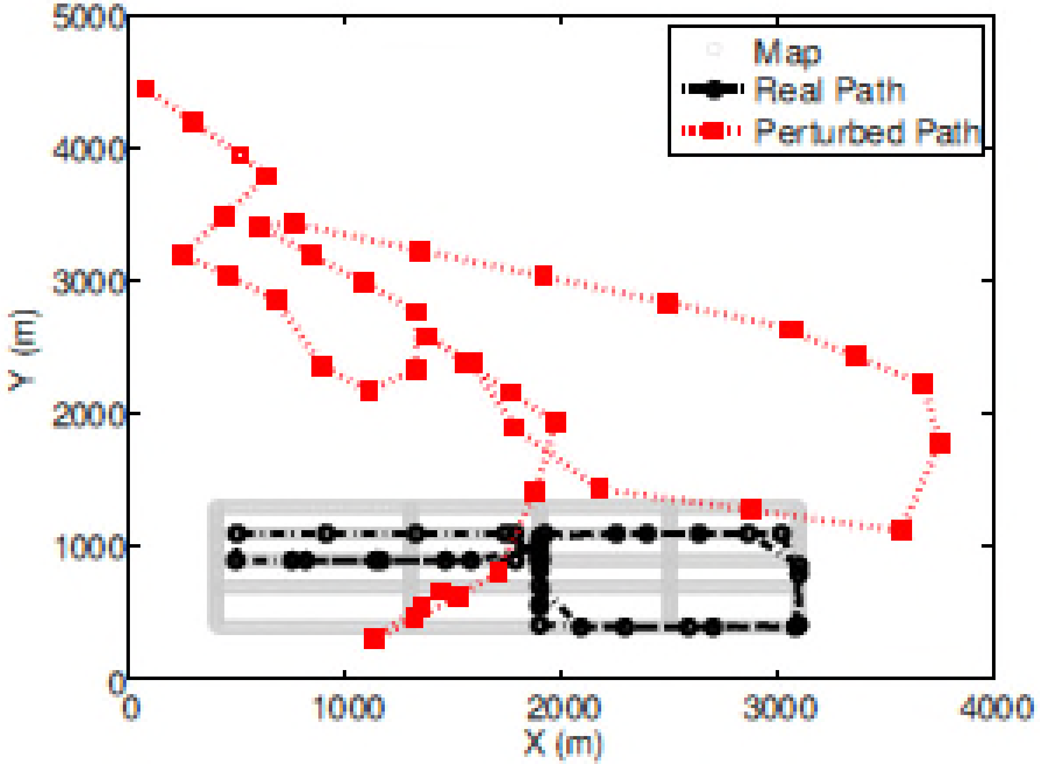
Initial Thoughts

- Add noise that itself is a time-series that "significantly overlaps" in the frequency domain with the data signal
  - Filtering cannot separate data from noise
- Aggregate perturbed signals from multiple sources
- Use de-convolution to recover the distribution of the original data signal from that of the perturbed signal and that of noise

* Raghu Ganti, Nam Pham, Yu-En Tsai, Tarek Abdelzaher "PoolView: Stream Privacy for Grassroots Participatory Sensing," *Sensys*, Raleigh, NC, November 2008.

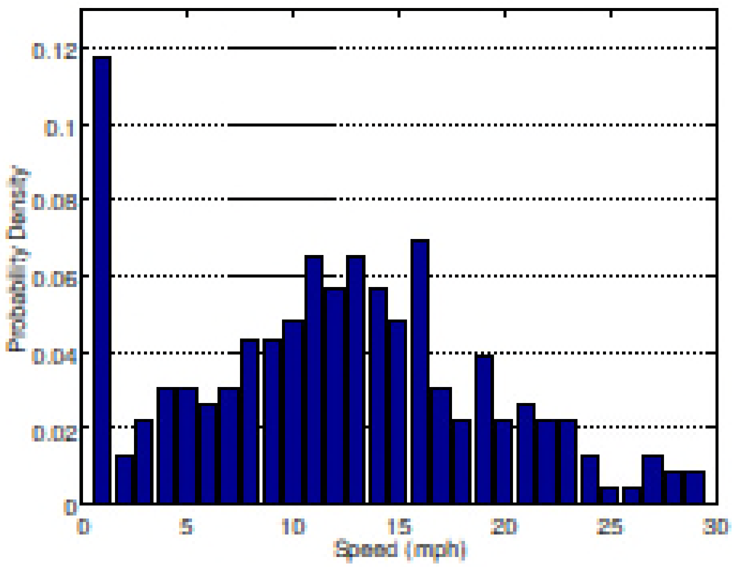
Example: Perturbing Speed and Location

- Clients lie about both location and speed
- Server reconstructs actual speed at real location

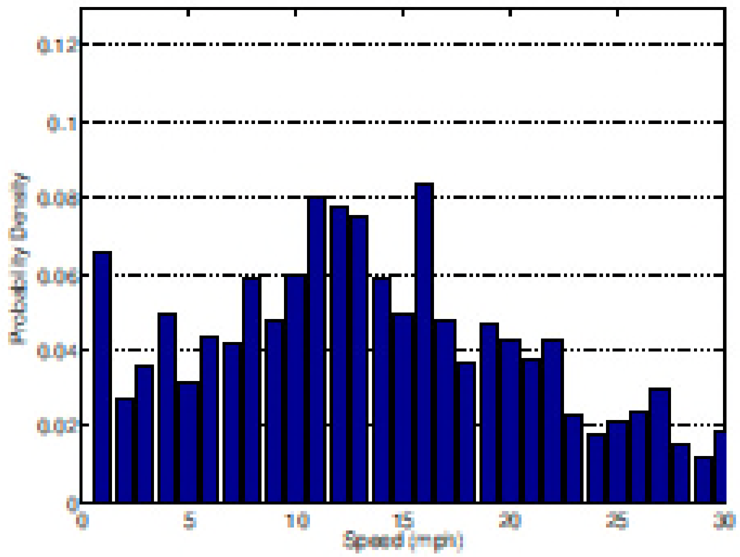


Reconstruction Accuracy

Real versus reconstructed speed of cars on UIUC campus



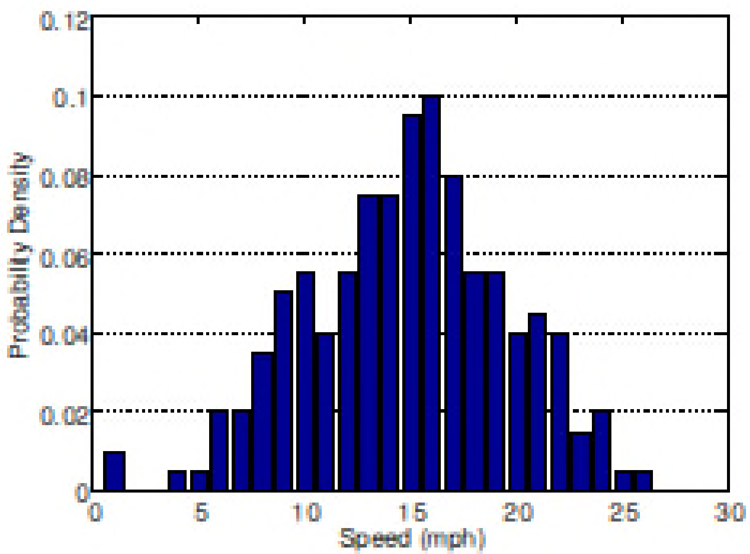
Real community distribution of speed



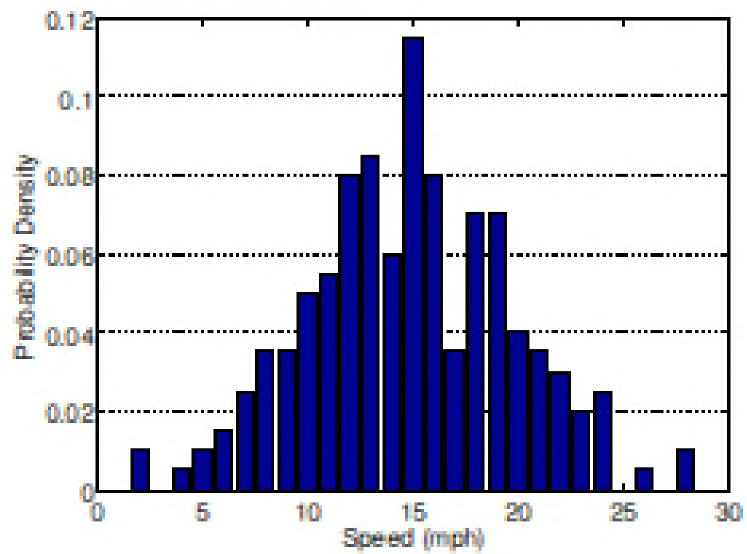
Reconstructed community distribution of speed

More on Reconstruction Accuracy

Real versus reconstructed speed on Washington St., Champaign



Real community distribution of speed



Reconstructed community distribution of speed

How Many Cars are Speeding on UIUC Campus?

Real versus estimated percentage of speeding vehicles on different streets (from data of users who “lie” about both speed and location)

Street	Real % Speeding	Estimated % Speeding
University Ave	15.6%	17.8%
Neil Street	21.4%	23.7%
Washington Street	0.5%	0.15%
Elm Street	6.9%	8.6%

Sensing in Social Spaces

The Current Decade

http://courses.engr.illinois.edu/cs598tar/

Tarek Abdelzaher

Dept. of Computer Science

University of Illinois at Urbana Champaign

Sensing in Social Spaces

Information Services for a Smarter World

People

Sensors

Analytics

Data

Future Applications

Social Sensing (Crowd-sensing) Humans + Cyber + Physical

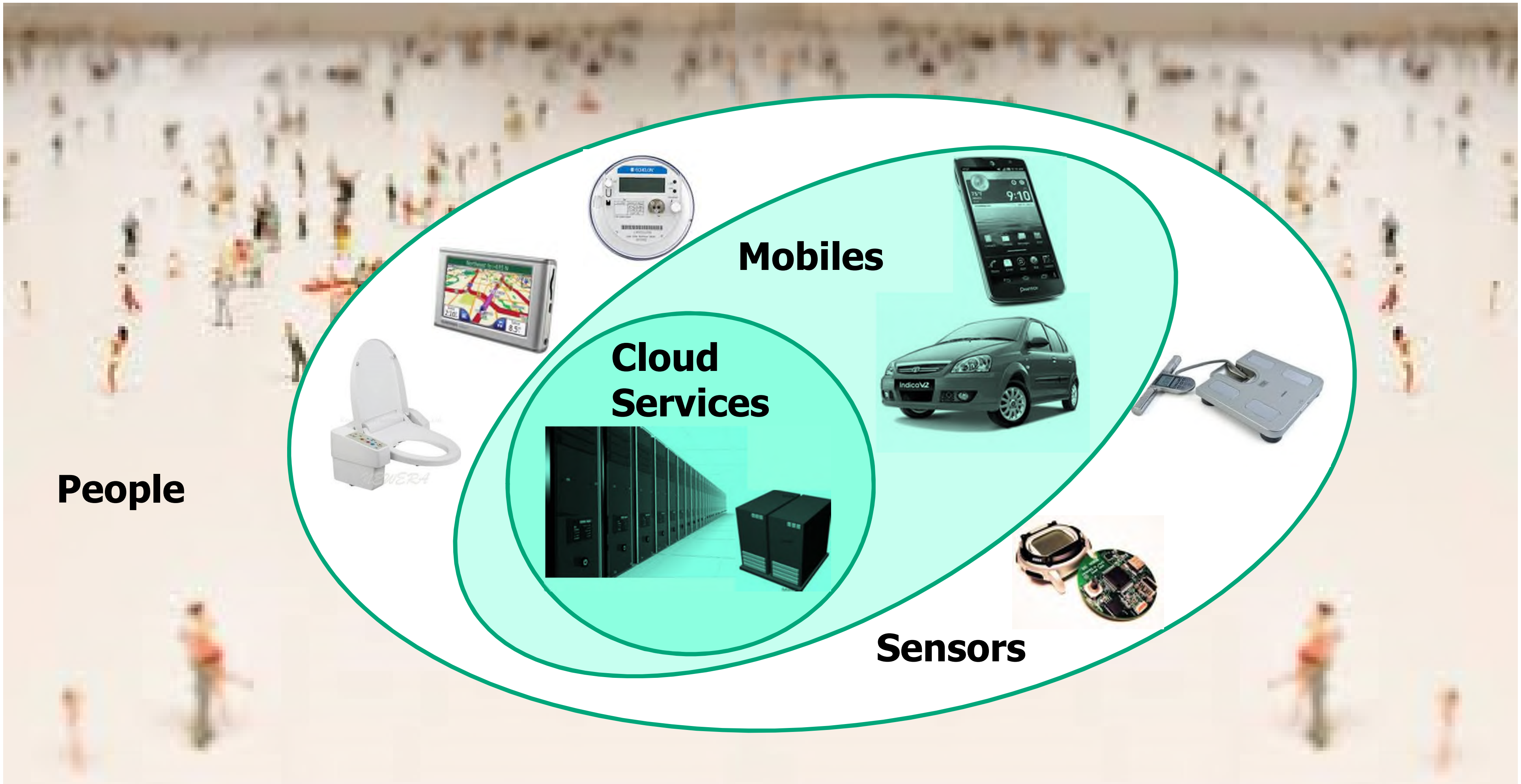
http://www.golem.de/news/crowd-management-smartphone-soll-massenpanik-verhindern-1209-94331.html

http://vimeo.com/album/2020385

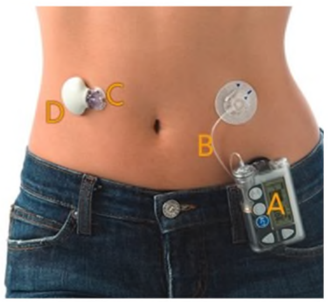
Ensuring safety of pilgrims during Hajj
http://www.crowdsensing.net/crowdsensing/

http://asmarterplanet.com/studentsfor/blog/category/transportation-systems

Internet of Things
Cloud + Mobiles + Sensors + People

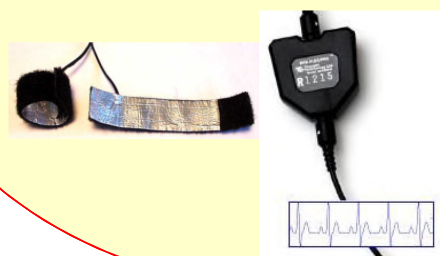


Applications: Personal (e.g., Medical/Tele-health)



Medical
Insulin pumps, pacemakers, glucose monitors, …

Bio-feedback Sensors



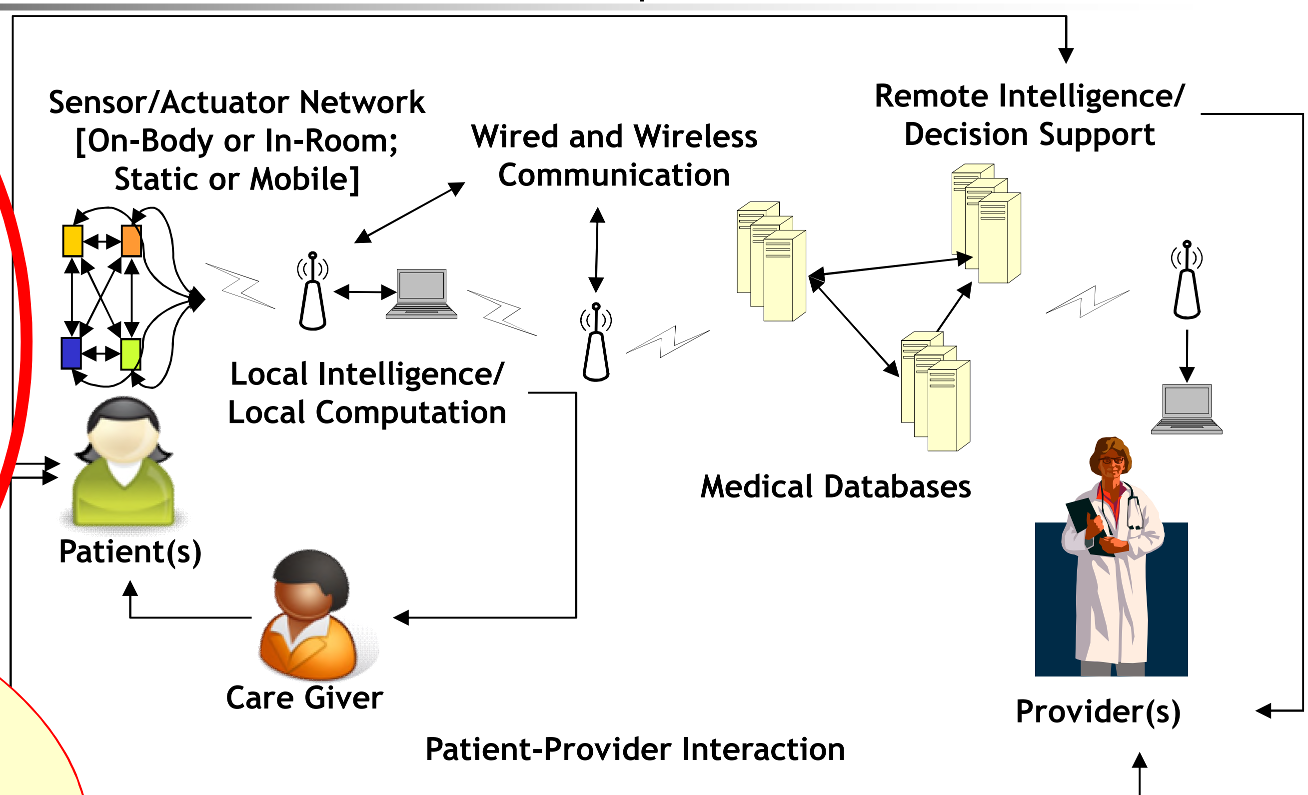
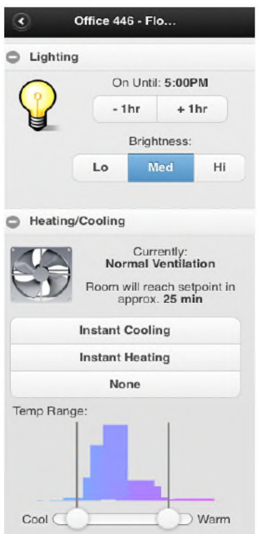
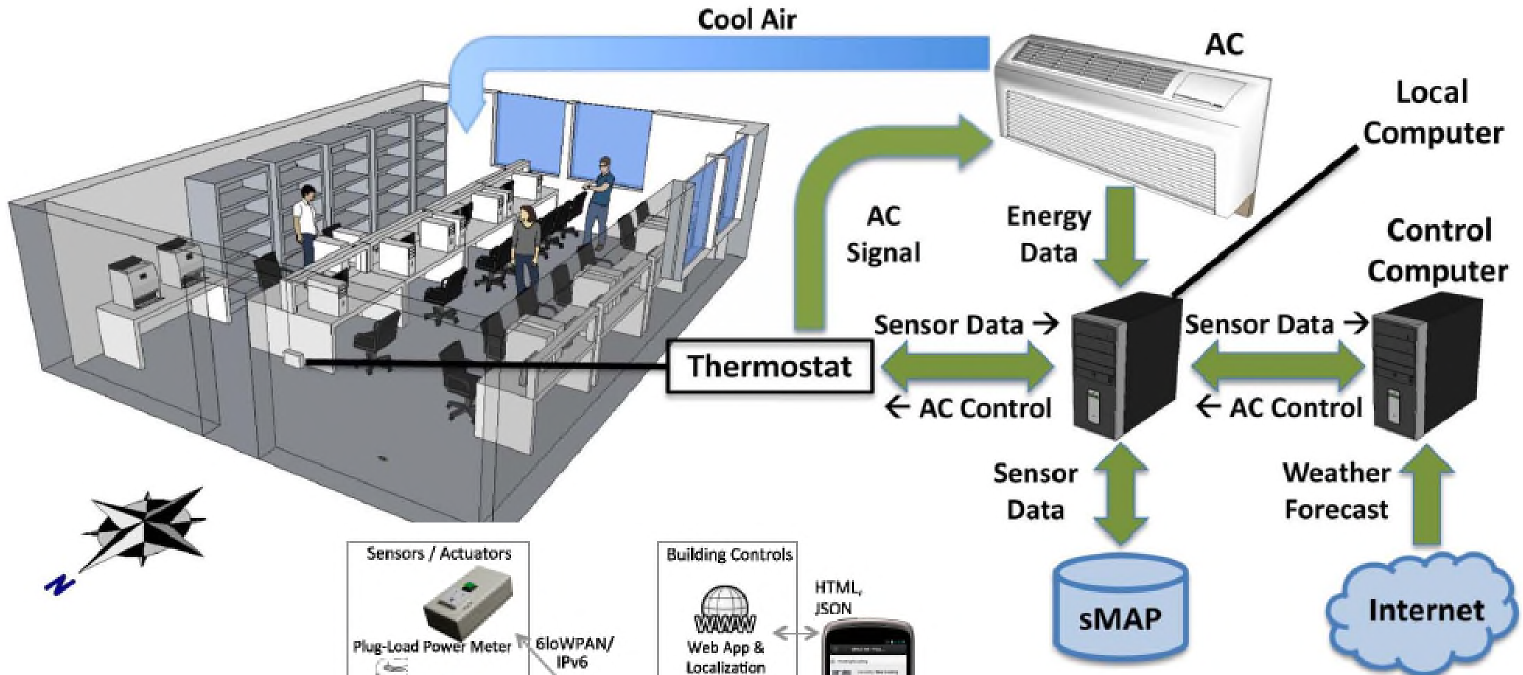


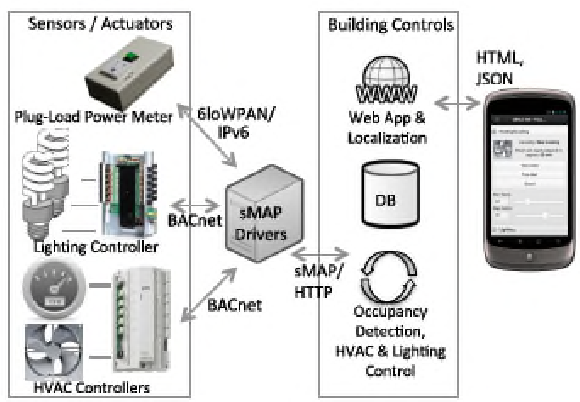
Figure courtesy of Mark Spong and Bill Sanders

Medical

Applications: Group-oriented (e.g., Building Management)





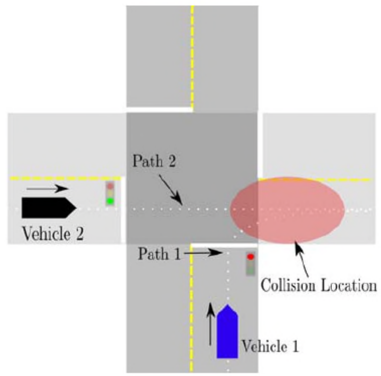


Figures courtesy of Berkeley BRITE Lab

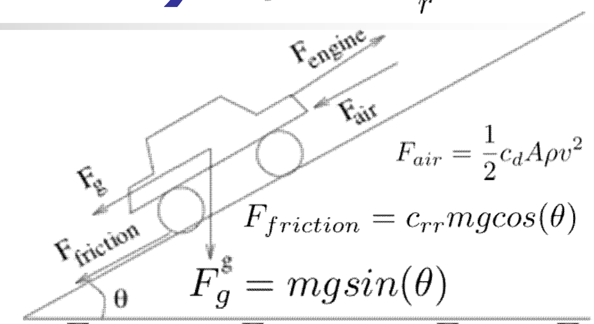
Zero-energy Building: Science House at the Science Museum of Minnesota

Residential Energy

Applications: Urban Efficiency (e.g., Transportation)



$$F_{engine} = \frac{\Gamma(\omega) G g_k}{r}$$

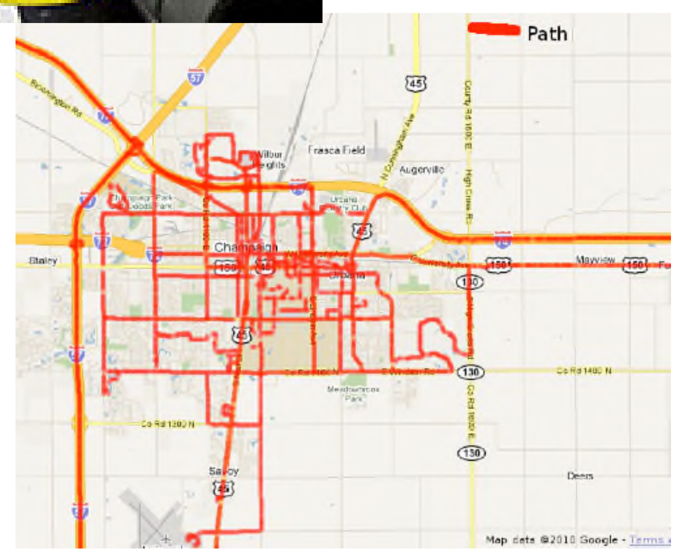


$$F_{air} = \frac{1}{2} c_d A \rho v^2$$

$$F_{friction} = c_{rr} m g cos(\theta)$$

$$F_g^g = m g sin(\theta)$$

$$F_{car} = F_{engine} - F_{friction} - F_{air} - F_g$$



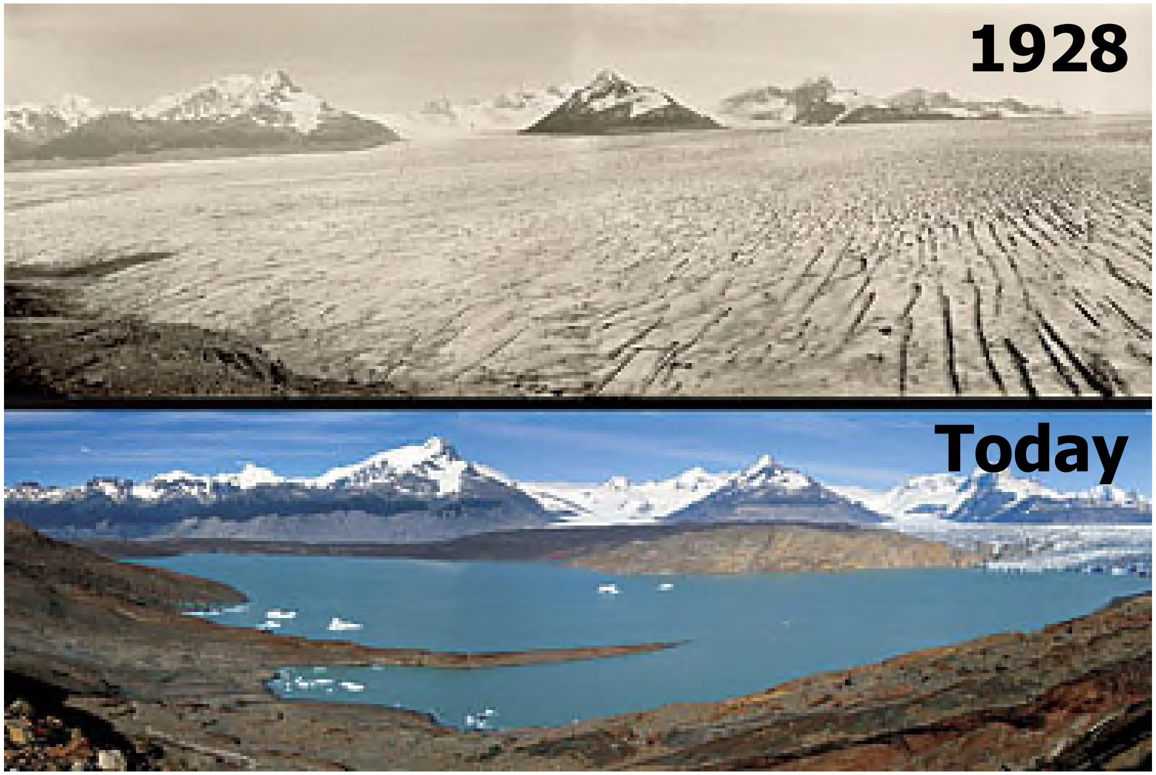
Transportation

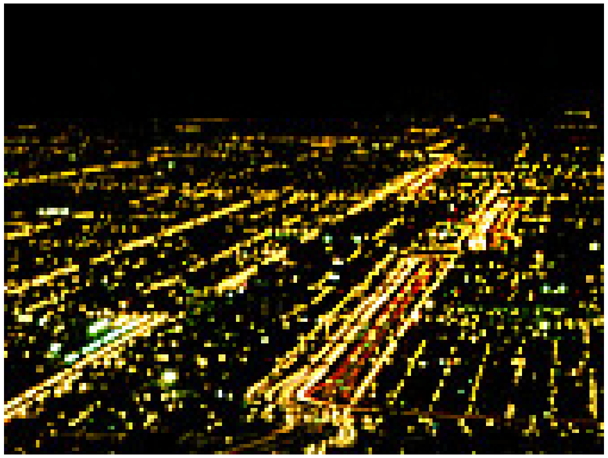
Applications: Urban Efficiency (e.g., Disaster Response)

Japan’s Tsunami and Nuclear Event, 2011

Applications: Urban Sustainability

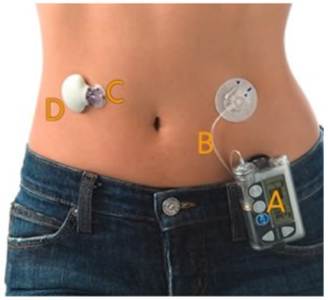
Uppsala Glacier (Time Magazine, Special Issue on Global Warming, March 26, 2006)





Sustainability

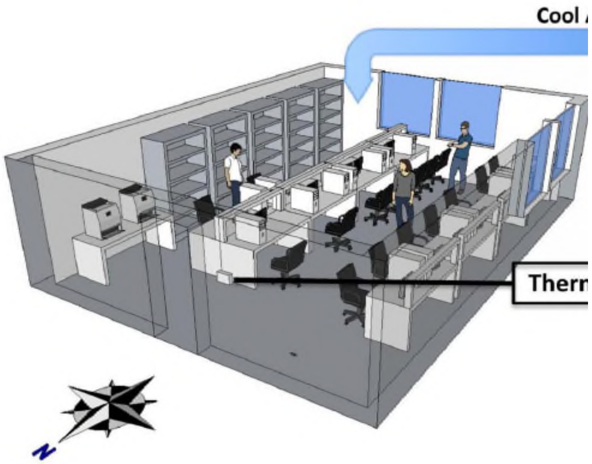
Sensing Applications



Medical
Insulin pumps, pacemakers, glucose monitors, …

Disaster Recovery

What is in common?



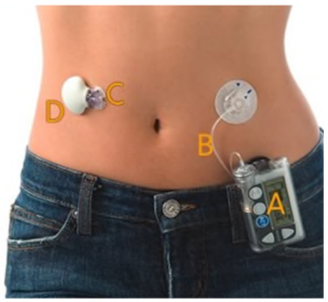
Energy

Transportation

Sustainability

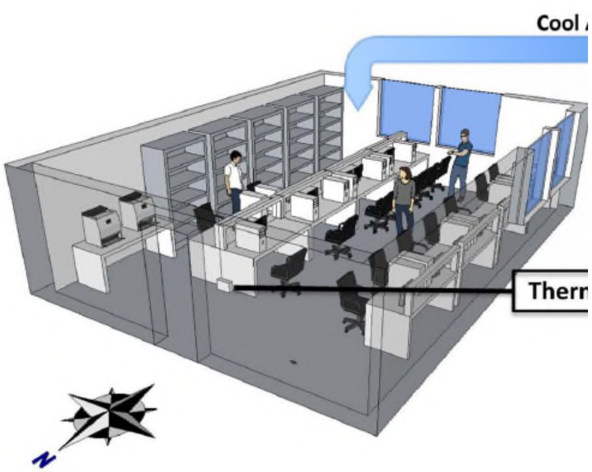
Sensing Applications

Lots of Data from People!



Medical
Insulin pumps, pacemakers, glucose monitors, …

Disaster Recovery



Energy

Transportation

Sustainability

Leverage the Most Versatile Sensing "Platform"

The Most Versatile Sensing Platform

twitter

flickr

YouTube

Instagram

facebook

foursquare

Social Sensing:
Using the Most Versatile Sensing Platform

500 million tweets daily

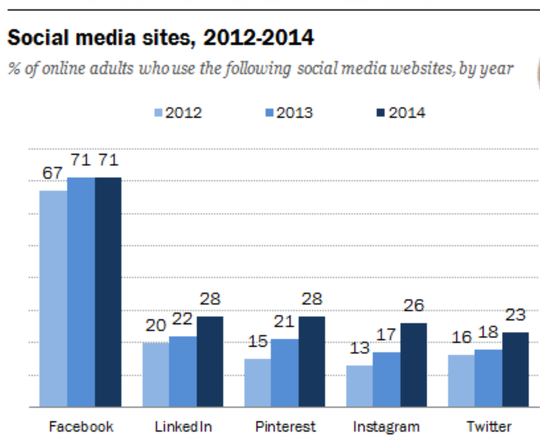
2 million special-interest groups

80 million pictures daily

300 hours of video every minute

1.44 billion active users

60 million venues



Social Sensing:
Using the Most Versatile Sensing Platform

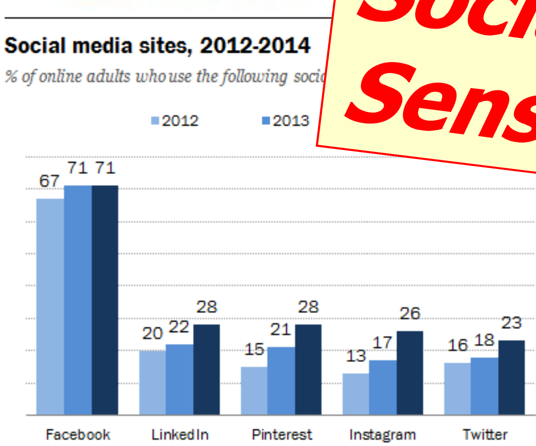
500 million tweets daily

2 million special-interest groups

80 million pictures daily

300 hours of video every minute

1.44 billion active users

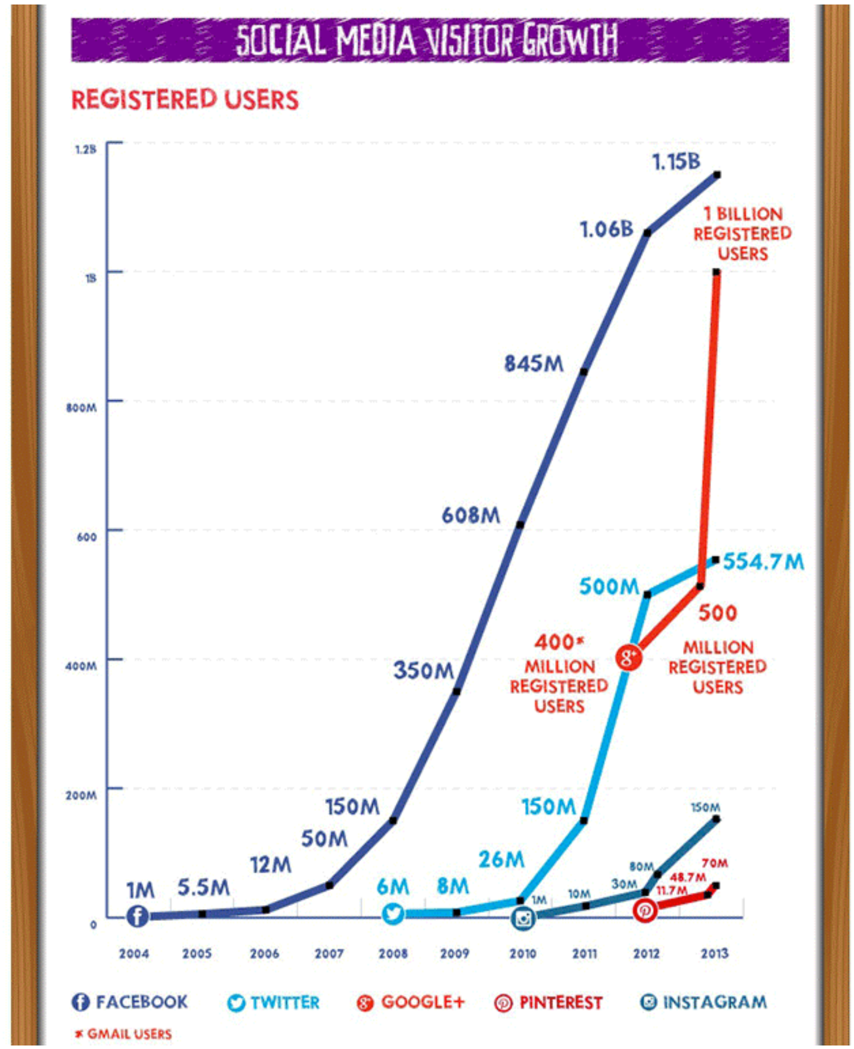


Social Networks as Sensor Networks?

60 million venues

The Growth of Social Media

- Situation awareness
- Anomaly explanation
- Surrogate sensing
- Social optimization



http://www.sociallystacked.com/2014/01/the-growth-of-social-media-in-2014-40-surprising-stats-infographic/

An Internet Minute

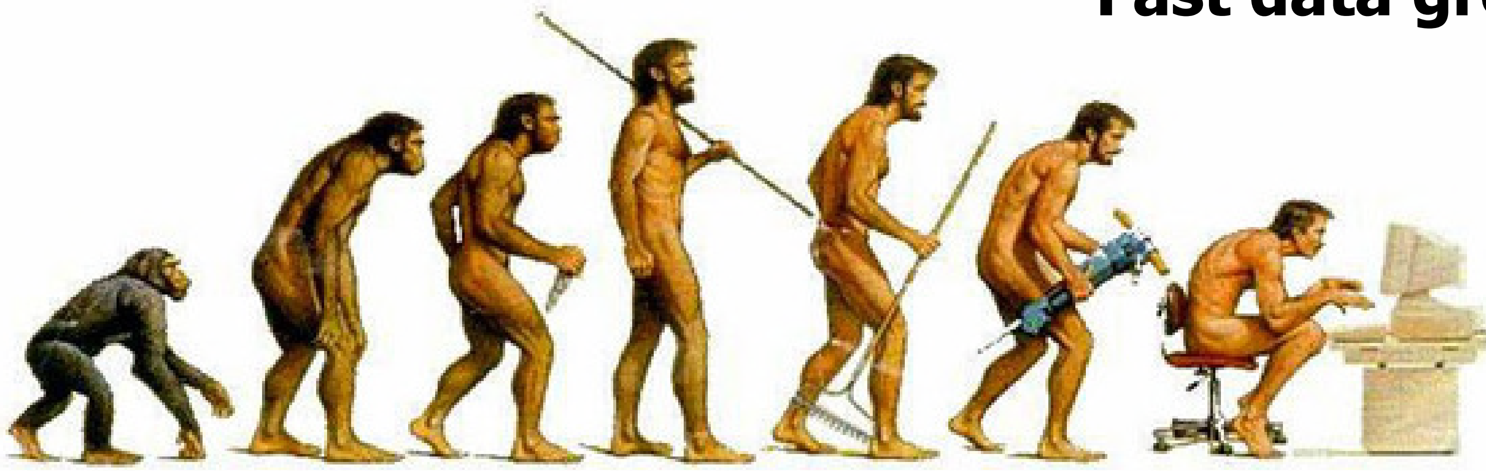
Today: Growing Social Network *Data* Size!
→ Novel Social Data Management Services!

60 seconds on the Internet

A Deluge of Information!!!

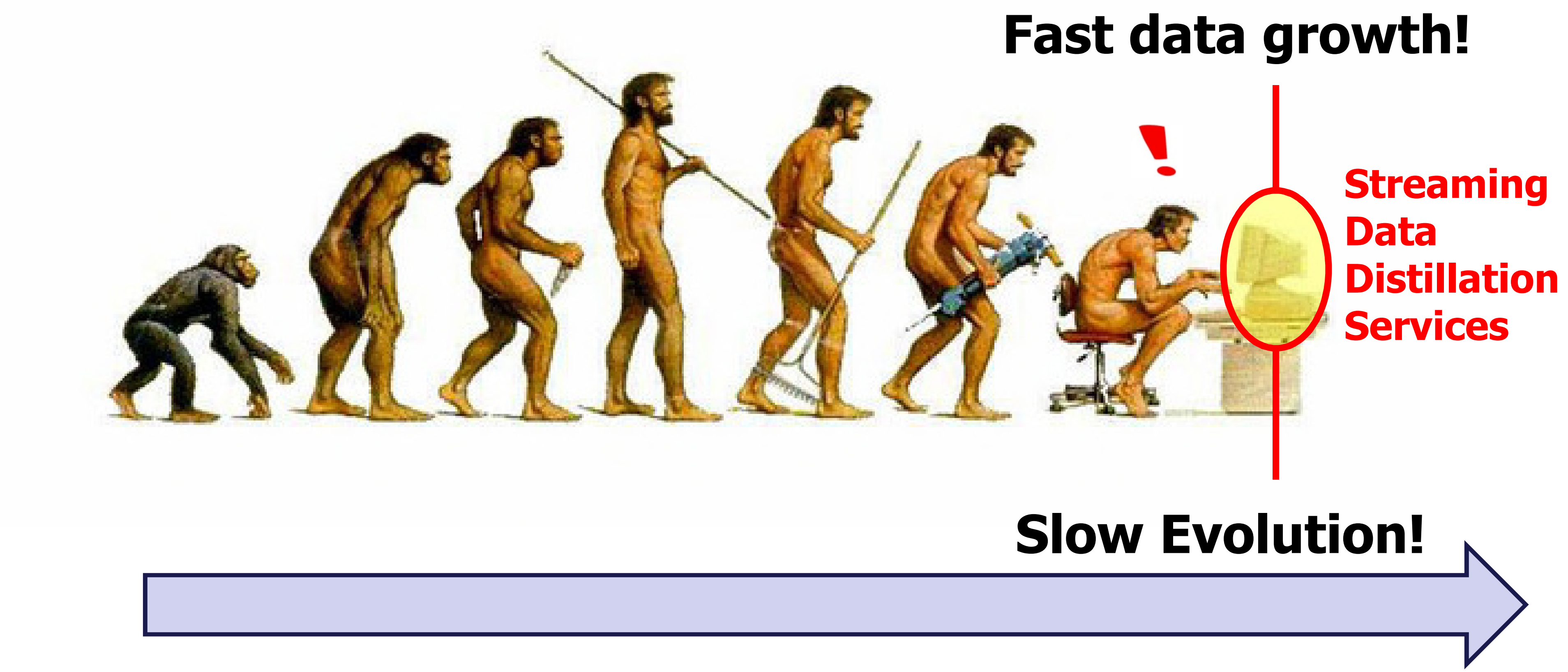
Real-time data grows much faster than our cognitive ability to consume it

Fast data growth!



Slow Evolution!

Real-time data grows much faster than our cognitive ability to consume it



Emergence of Social Sensing
Information Services for a Smarter World

People

Sensors

Analytics

Data

Future Applications

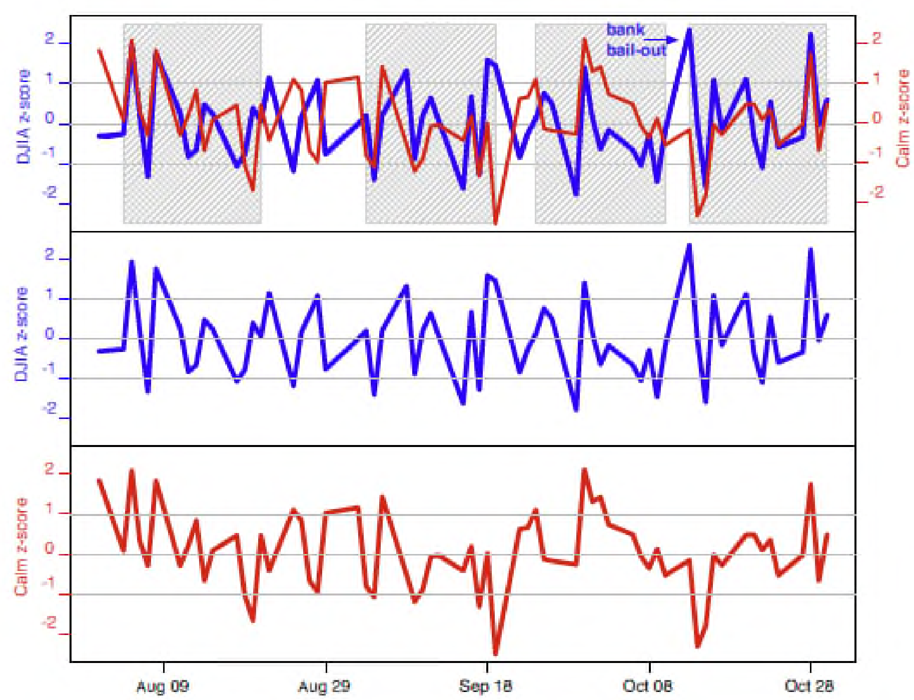
Examples of Real-time Content Analytics

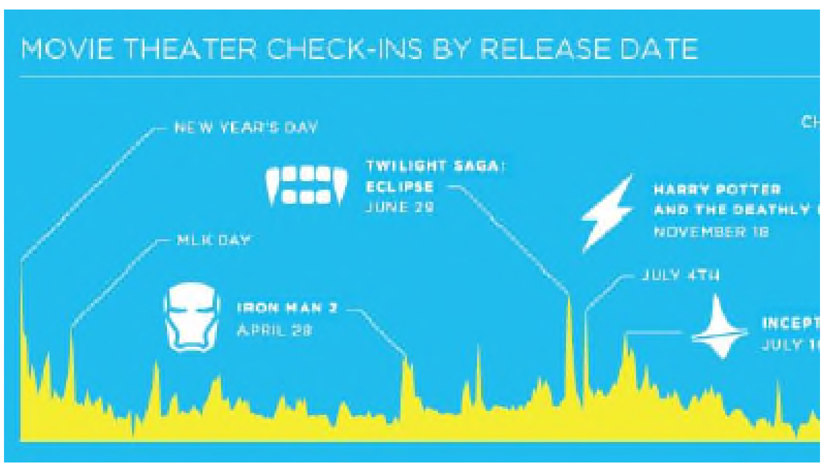
Dataminr

Uses Twitter to analyze and predict global events

Twitter mood predicts stock market trends

J. Bollen et al. / Journal of Computational Science 2 (2011) 1–8





FourSquare: Keeps track of human spatio-temporal data

Towards Information Distillation Services

- Much like Google organizes (relatively static) world content, we need an engine for organizing real-time/streaming data feeds and:

Reconstructing the "State of the World", Physical and Social!

A firehose of text, images, video, sound, and time-series data

Information distillation

Clean structured representation, high quality of information

Conclusions

- The world's streaming content is growing
- Sensor devices are increasingly available to the common user
- An opportunity to enhance real-time situation understanding from streaming human and sensor data
- An opportunity to better interpret context of sensor observations
- Analytic foundations and tools are being developed for data cleaning, disambiguation, and search