# Mobile Phone Sensing is the Next **Big** Thing!

Andrew T. Campbell, Dartmouth College

ACM MobiOpp 2010 Keynote Address

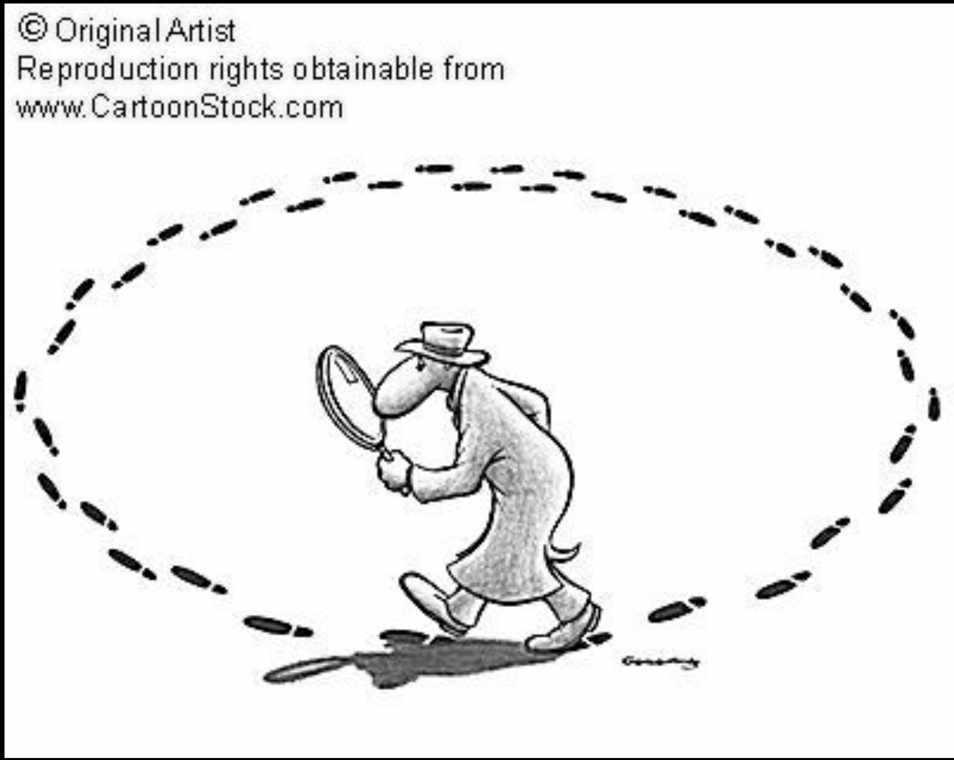
Wireless sensor networks have driven many great innovations over the last decade - represents a very active area of on-going research

# The mote have been a superb platform for research

## But, challenges remain

- Not ubiquitous
- Energy problem
- Scaling (cost and performance) problem
- Event unpredictability
- Don’t have economy of scale

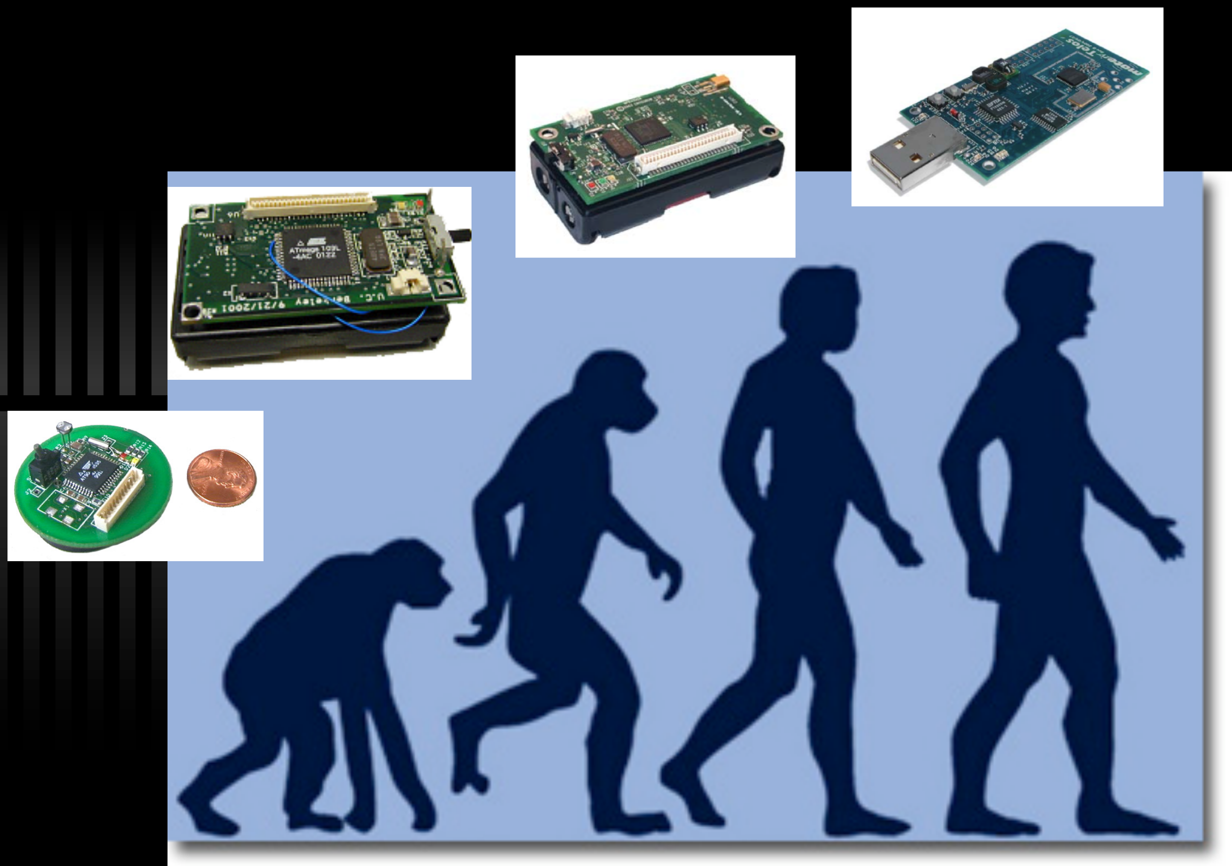
# Importantly, sensor networks don't impact our everyday lives. Why?




People are out of the loop

But that’s just changed

# There's revolution going on ..



# Meet the human "mote"

# We're awash with sensor-enabled phones

Embedded sensors:
- 3-axis accelerometer
- Digital compass
- Proximity sensor
- Microphone
- Camera
- GPS

They're ubiquitous, sort of solve the energy problem, have economy of scale, and scale in performance.

# Google Nexus one


Embedded sensors:

- 3-axis accelerometer
- Digital compass
- Proximity sensor
- Microphone
- Camera
- GPS
- Bluetooth

# Nokia 6210 Navigator


Embedded sensors:
- 3-axis accelerometer
- Digital compass
- Microphone
- Camera
- GPS
- Bluetooth

And, at some point in the future ..

# My fantasy phone: the cool green "emotional" phone

Embedded sensors:

- 3-axis accelerometer
- Proximity sensor
- Digital compass
- Pollution/air quality sensor
- GSR "emotion sensor"
- RFID/NFC
- Microphone
- Camera
- GPS
- Bluetooth

# Why is this moment great time for research?

- Availability of sensor-enabled phones
- “Openish” platforms (mostly Linux based) and good development tools
- App delivery system in place
- Large scale deployment and experimentation now possible
- Potential for huge rich data sets

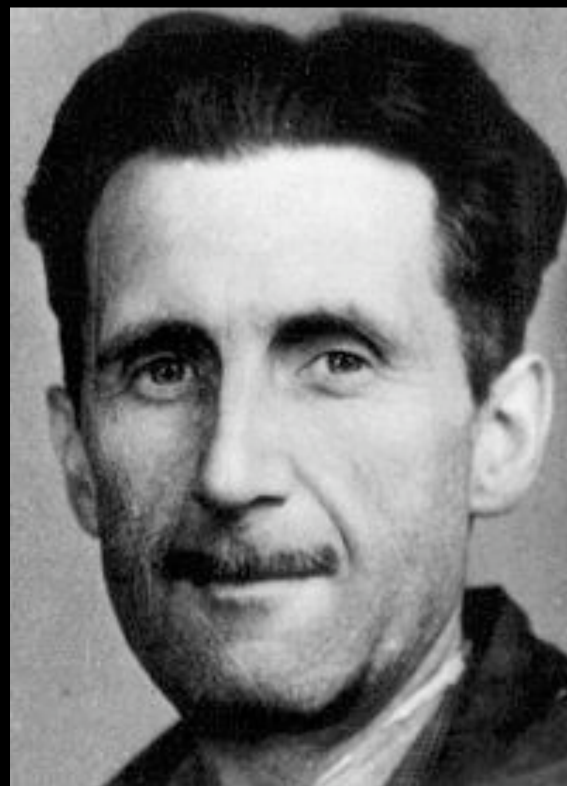
Your research can have significant impact.


You don’t need any infrastructure to do this –well, very little, mostly cloud stuff.

Your phone can learn your behavior and about your life

I know what you are thinking

# Sounds like an Orwellian nightmare!

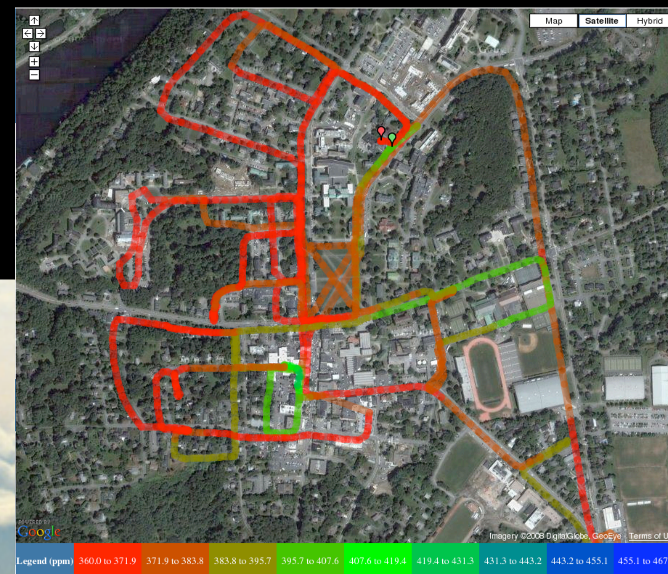


Critical challenges in trust, privacy,  security to be solved

# Why do this, really?

You’ll be able to answer lots of interesting questions and build new cool applications that could have significant societal impact or, just have fun.

# What is my personal air quality like today? Or, the air quality of my neighborhood, school, town, or city?



# How stressed is the city this morning?

You can learn quite a lot from the “continuous sensing” of a limited set of widely available sensors on the phone, e.g., accelerometer, microphone, GPS/WiFi/Bluetooth

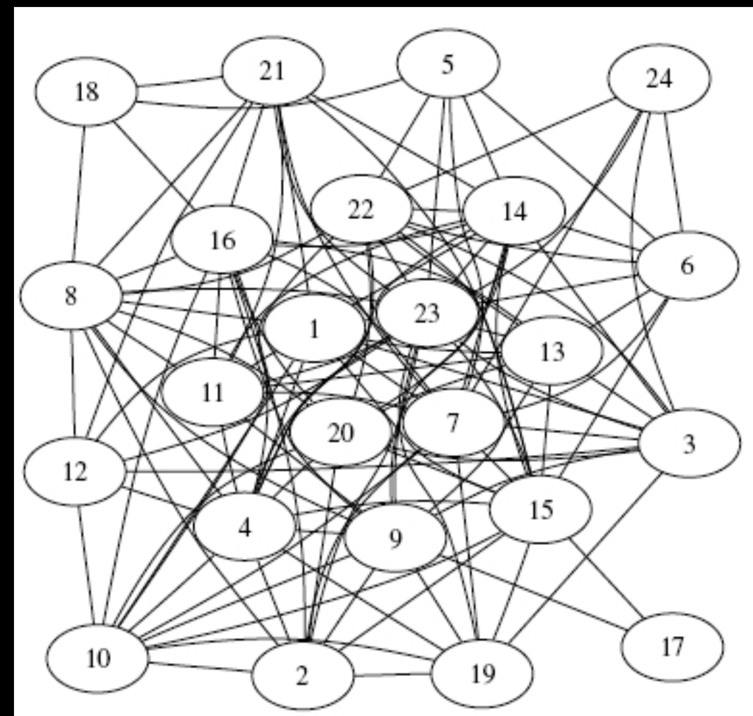
You can infer physical activity, social interaction, context and location.

In fact you should be able to infer a lot more about:

social networks, co-location, amount of time in conversation, intonation, isolation, emotion, loudness, modes of transportation, types of restaurants visited, cooking, eating, walking, cycling, watching TV, listening to music, in a meeting, jogging, using the ATM, at the gym, playing squash, depression, hypertension

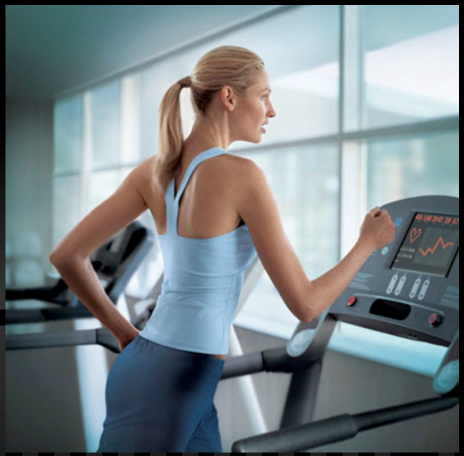
Many questions can be asked …

# How do social "conversation" networks evolve?




Work on audio networks by Tanzeem Choudhury (Dartmouth)

# How is my physical, emotional and cognitive health?



# Where are my friends and what are they doing right now?

# Now imagine 1 billion "sensor enabled mobile phones" scattered across the planet

people are in the loop

This will lead to …

# Societal scale sensing

## a global mobile sensor network

# Likely to be cross-cutting research

- Social networks
- Population well-being
- Transportation
- Green applications
- Recreation sports
- Virtual worlds
- Others.

I know what you are thinking

You can’t cover a volcano with mobile phones!

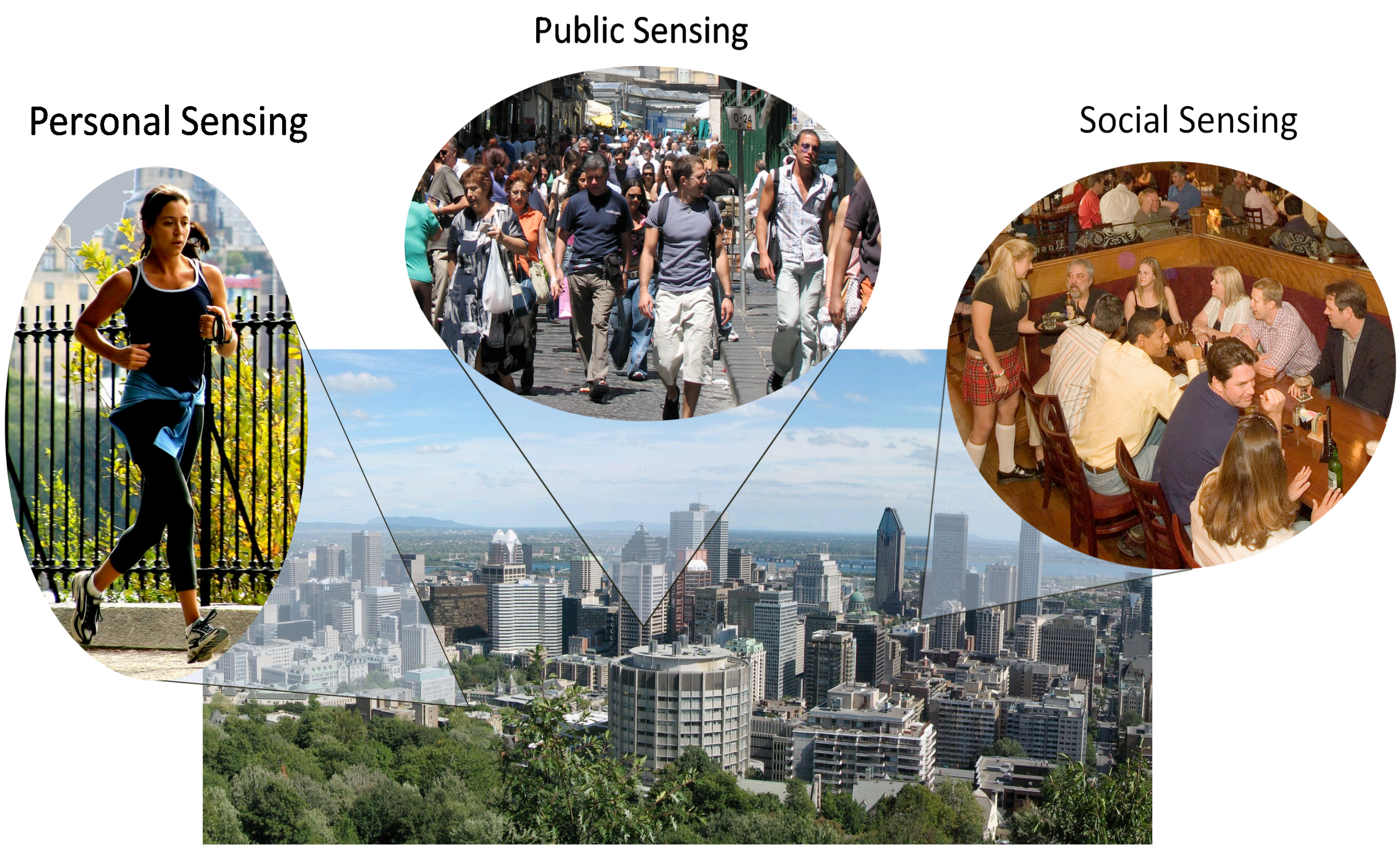
On second thoughts, phones are getting cheaper and we have a ready supply of adventurous grad students ;-)

Photograph by Carsten Peter

At an exciting point in the development of people-centric sensing applications

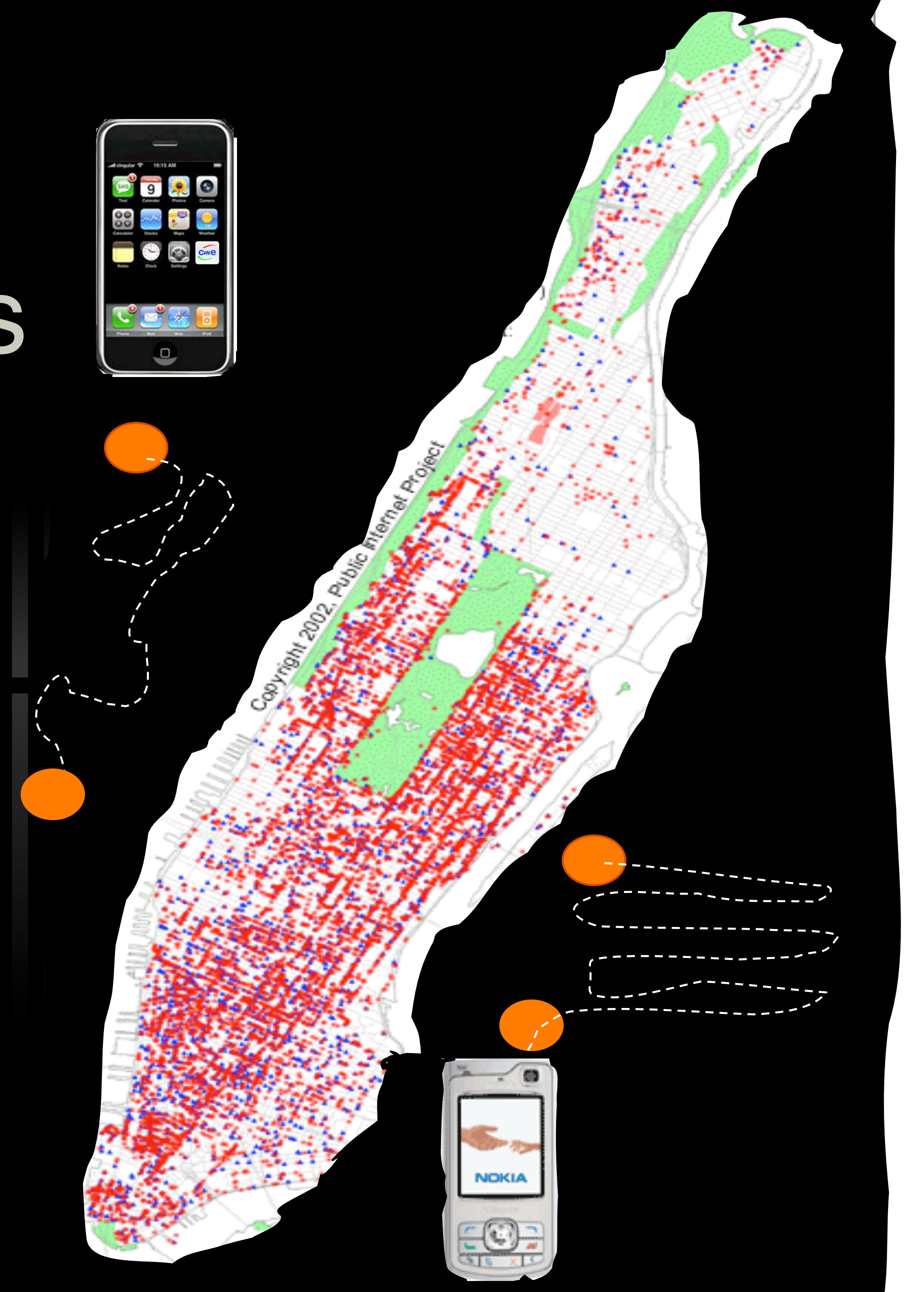
We started the metrosense project in 2006 to study people-centric sensing

# People-centric sensing application domains




*"The Rise of People-Centric Sensing", IEEE Internet Computing, July/August 2008*

Public sensing gains scalability and sensing coverage by using people opportunistically as mobile sensors



People-centric sensing is based on an "opportunistic sensing paradigm" and an "interaction model" that captures interaction between people, and, between people and their surroundings

# Emerging sensing paradigms

Participatory sensing (UCLA)

Hybrid approaches

Opportunistic sensing (Dartmouth)

I'll give an overview of the apps/systems we built and learnt from

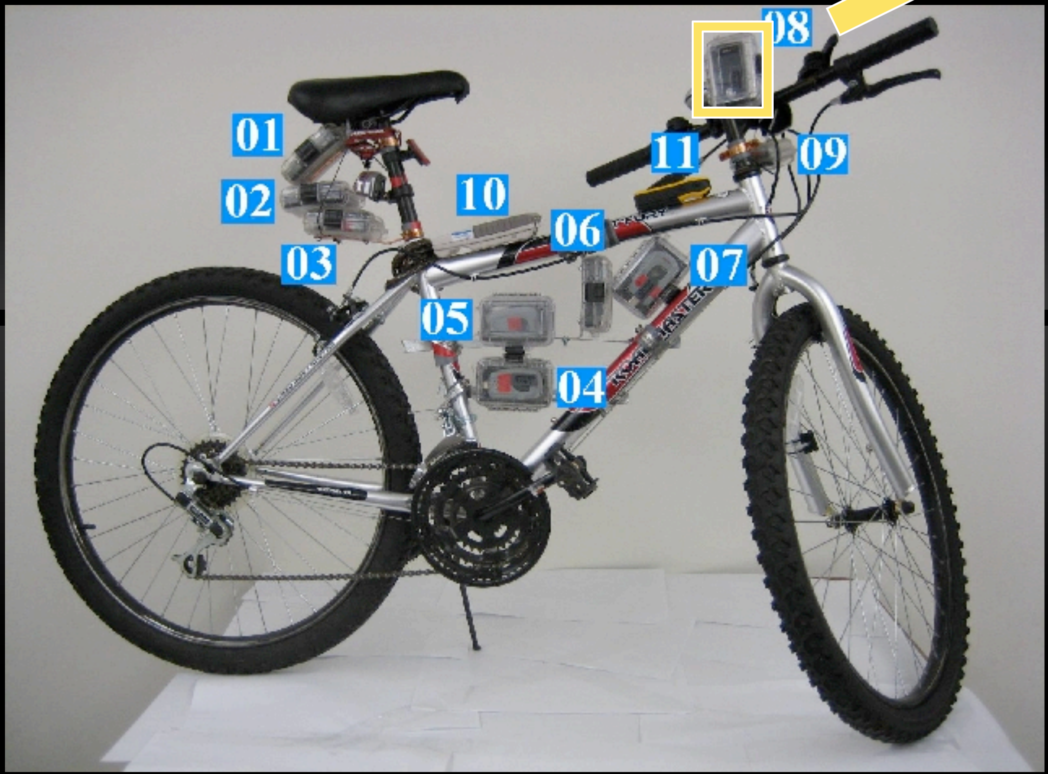
- BikeNet  (personal/public sensing)
- CenceMe (social sensing app)
- SoundSense (personal sensing app)

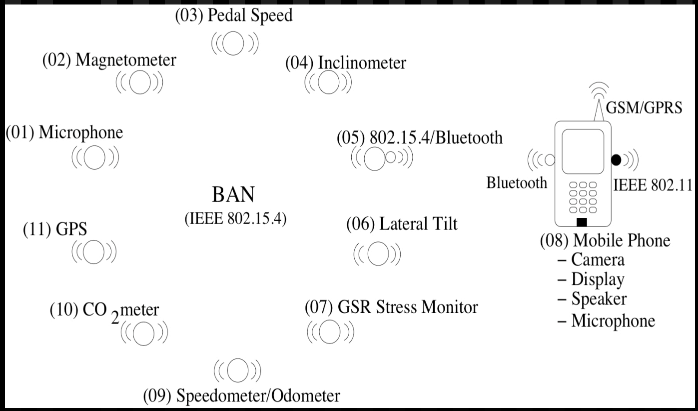
Then, I'll talk about the need for new research for mobile phone sensing:

- Sense-learn-persuasion model
- Software for the phone
- Killer app

# BikeNet - sensor bikes

N80 phone



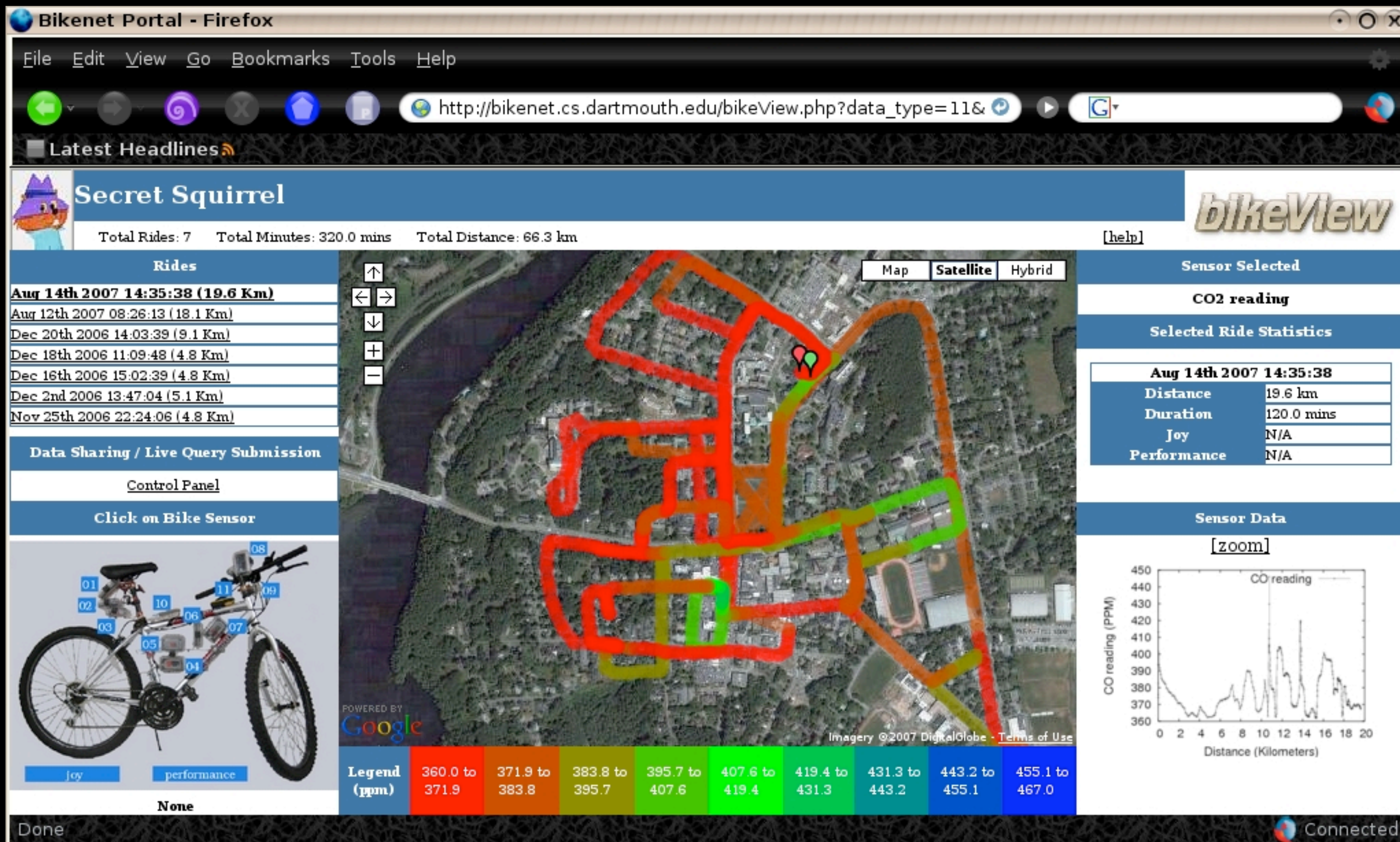

Phone controller for BAN

*"The BikeNet mobile sensing system for cyclist experience mapping", ACM SenSys '07*

# We can answer many questions from sensor data

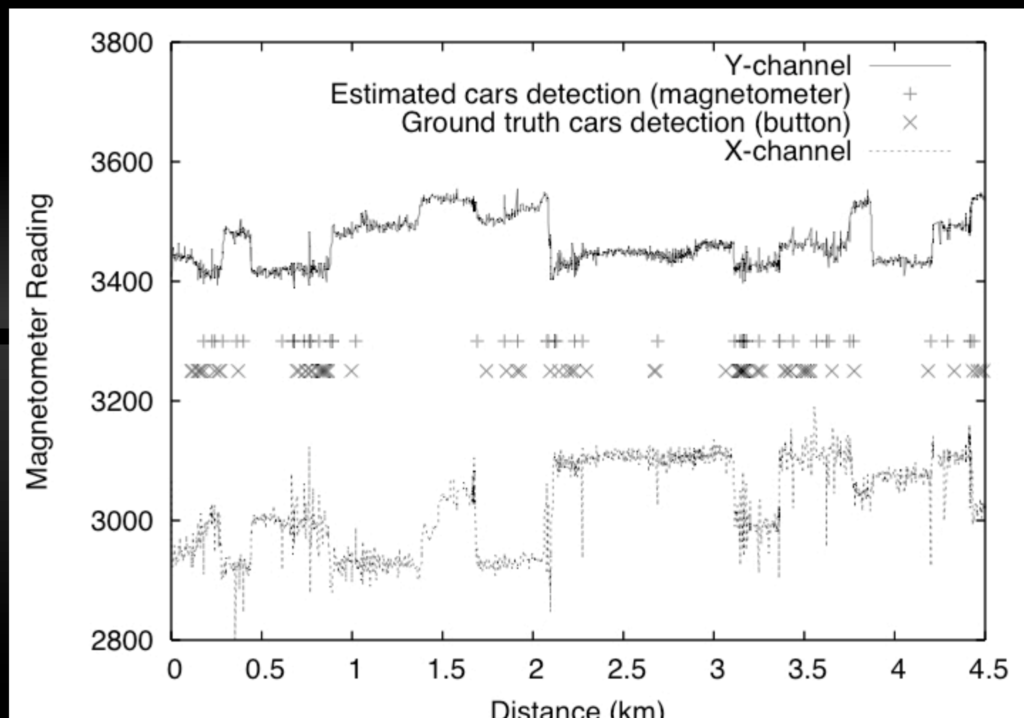
- How fit are you?
- Many cars along the route?
- What was the air quality and noise like?
- Lots of trivia: slopes, coasting, braking, working hard
- Overall health and performance along the route
- How did you compare to your buddies, community?
- Share information with your social network

# CO2 Map of Hanover




http://bikenet.cs.dartmouth.edu

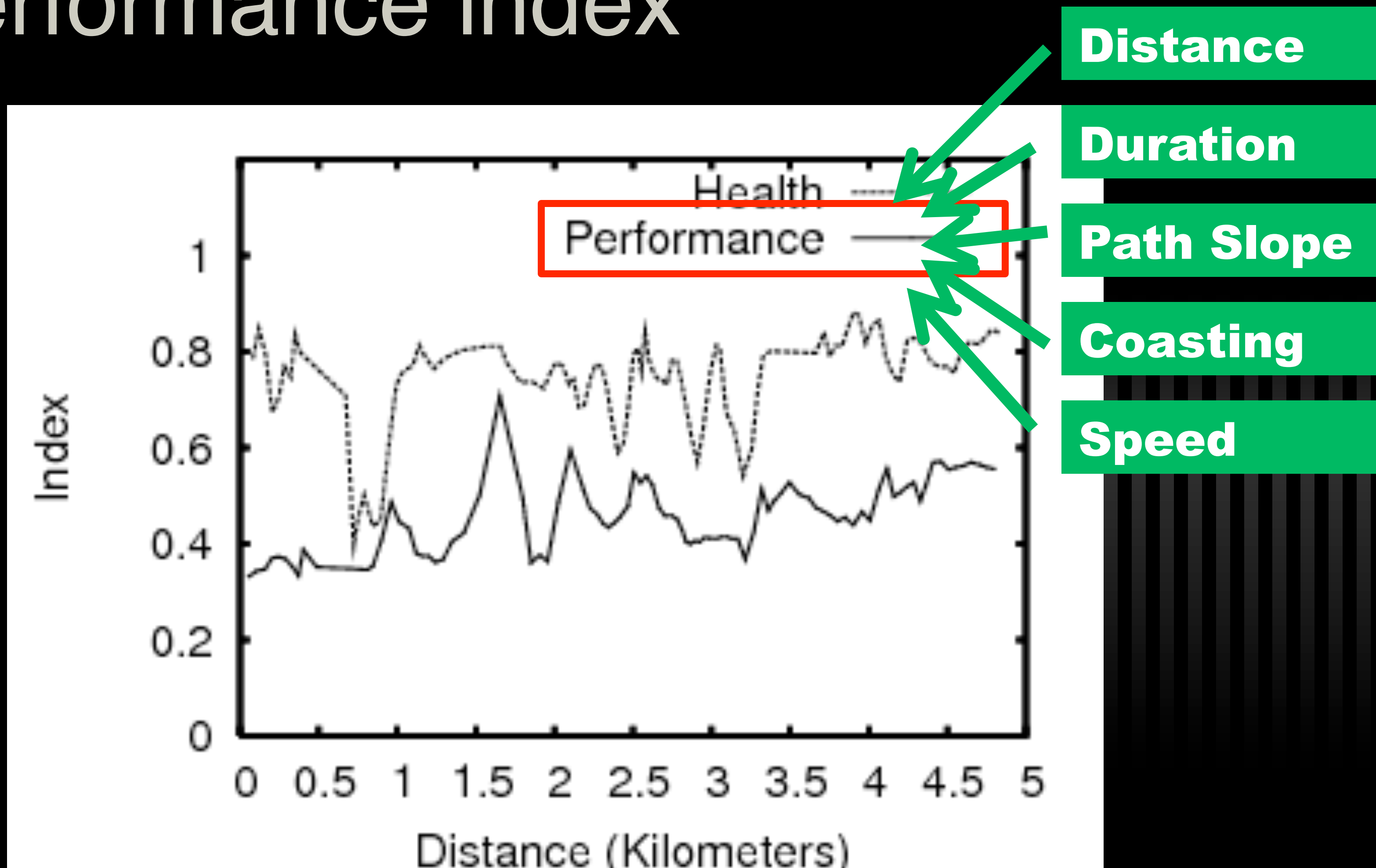
# Lots of cars on that route?



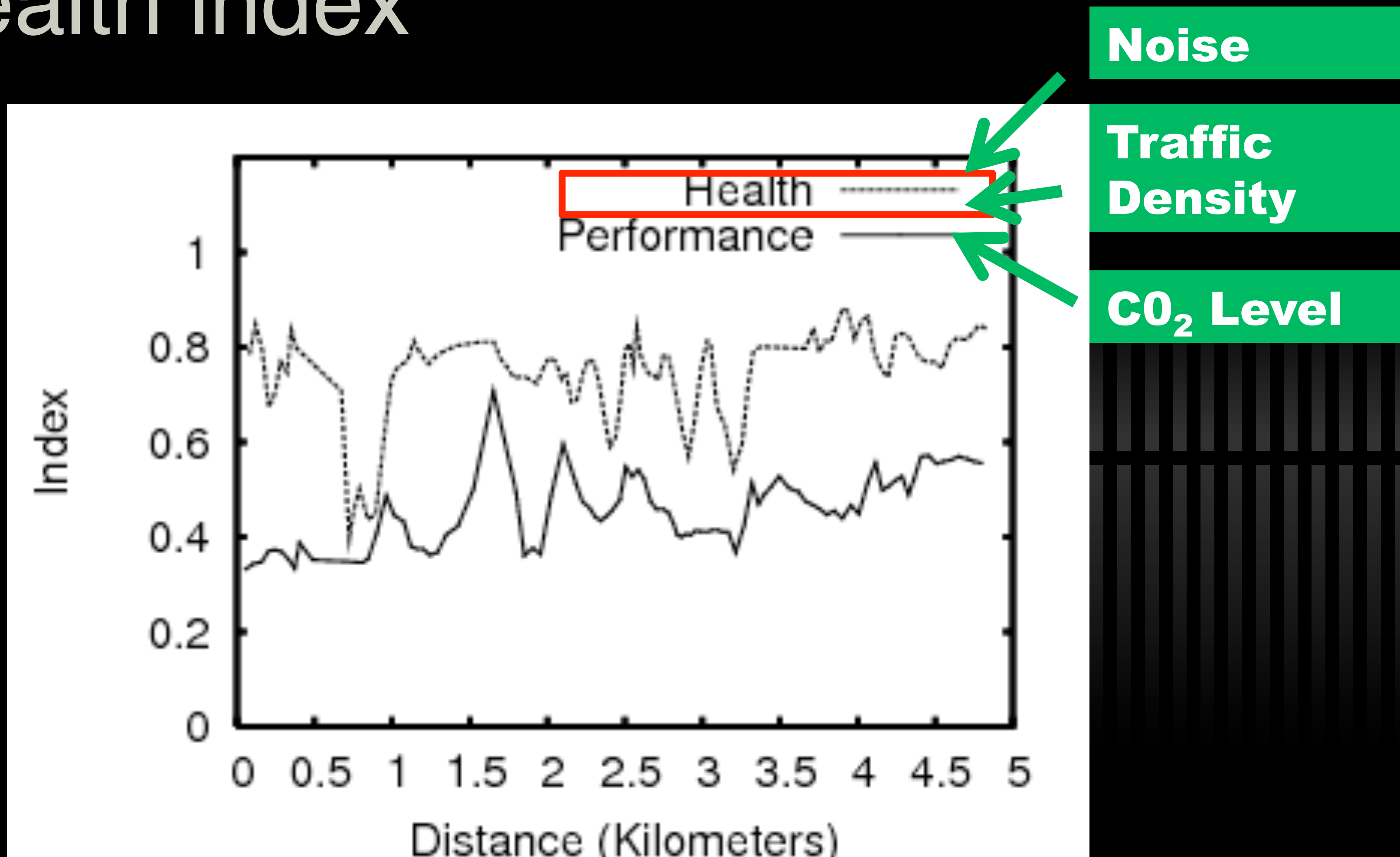
I know what you are thinking

# How do you do ground truth?

# Performance index



# Health index



# Many lessons learnt

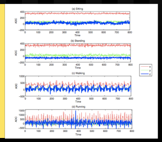

Debugging on the go is hard

# cenceme


*"Sensing Meets Mobile Social Networks: The Design, Implementation and Evaluation of the CenceMe Application", ACM SenSys 2008*

# sensing with cenceme

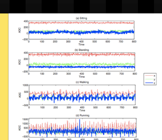
sensor data



inference

# cencing with cenceme

sensor data



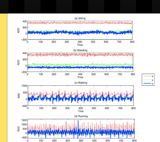
inference

inference

# cencing with cenceme

cenceme

sensor data



inference

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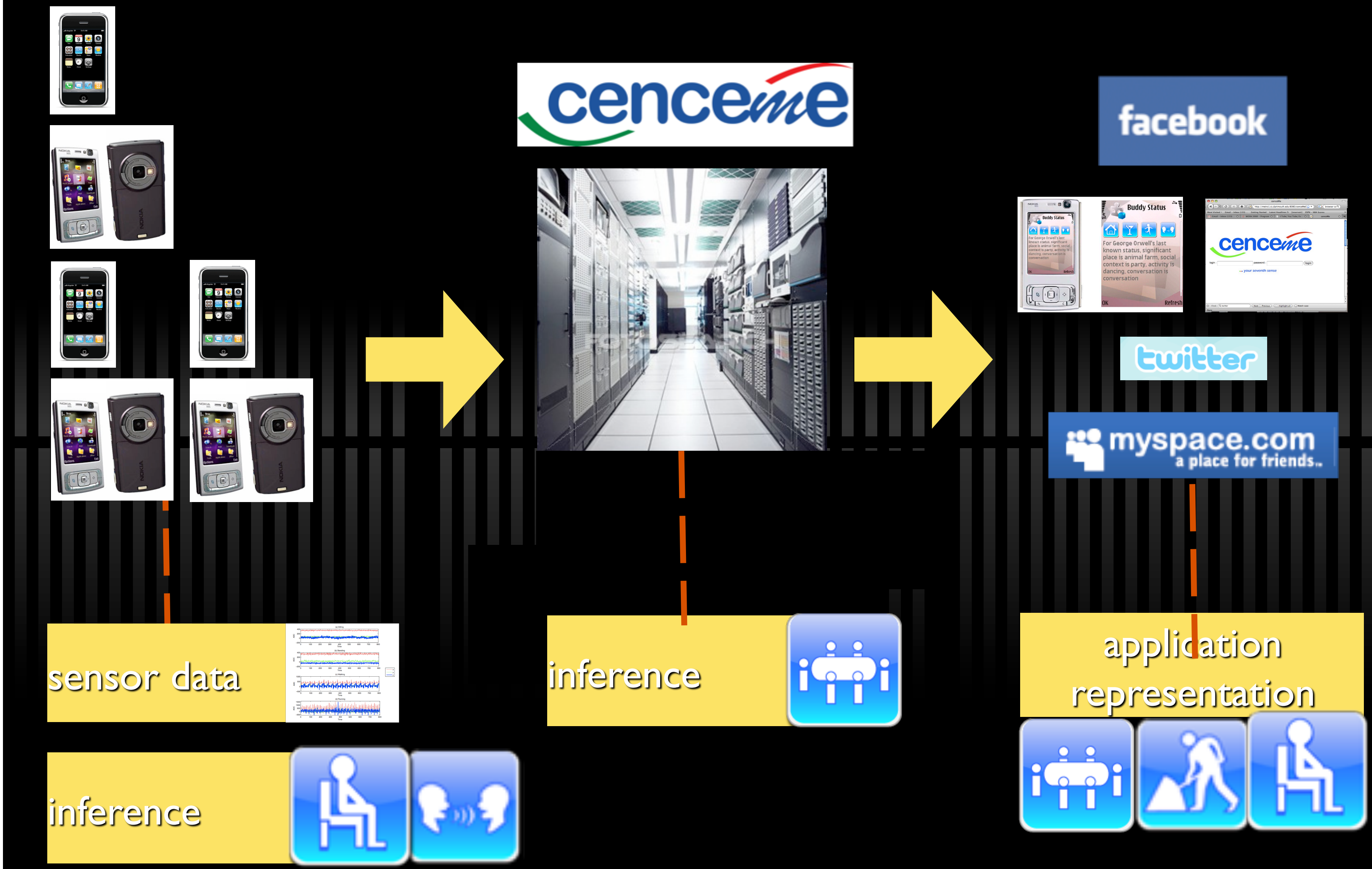


# supported inferences: sensing presence

activity

# supported inferences: sensing presence

activity

social context

# supported inferences: sensing presence

activity

social context

significant places

# supported inferences: sensing presence

activity

social context

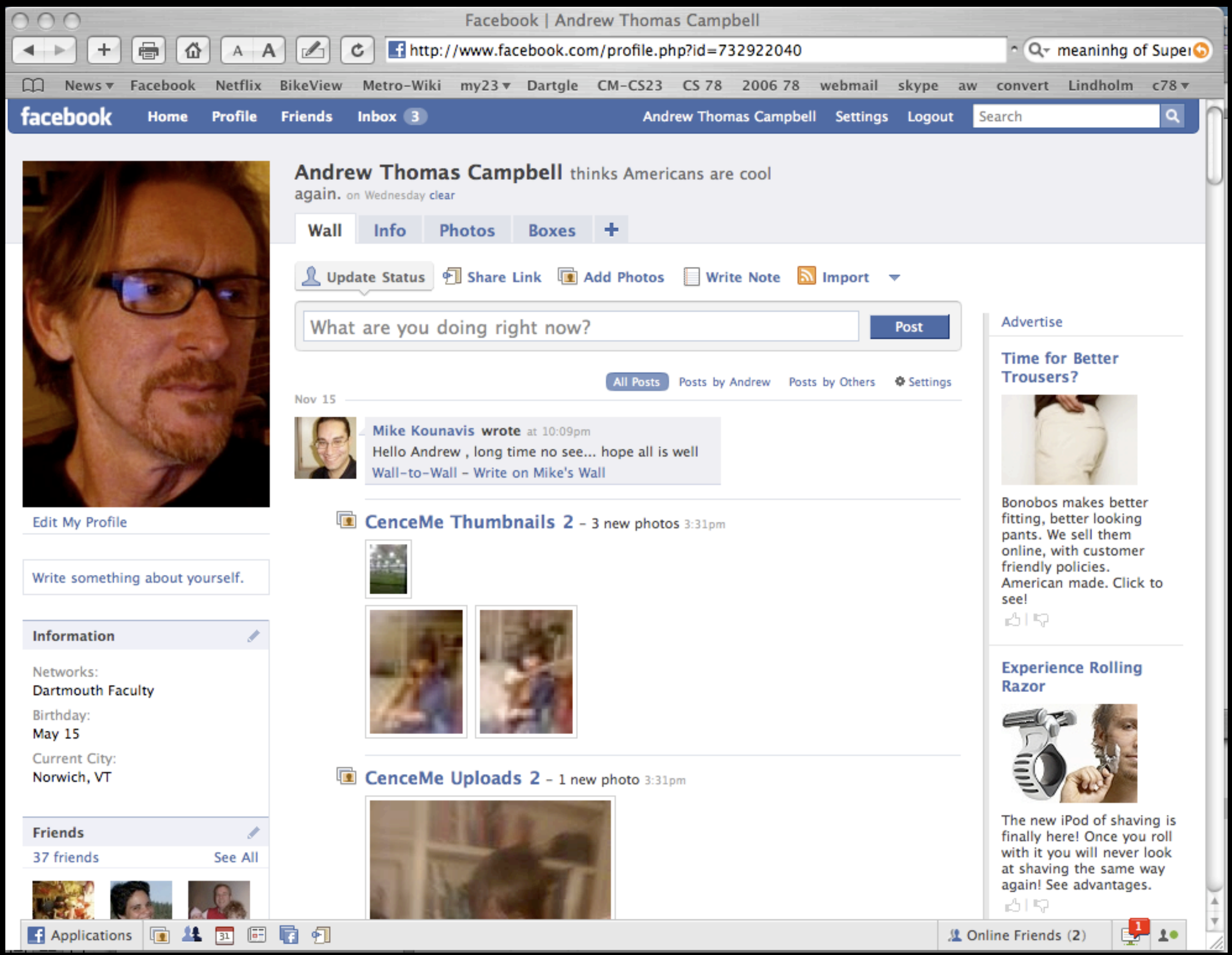
significant places

behaviour

greeny | nerdy | party animal | cultured | healthy

# CenceMe demo

# Sensor presence is published on Facebook, myspace, twitter



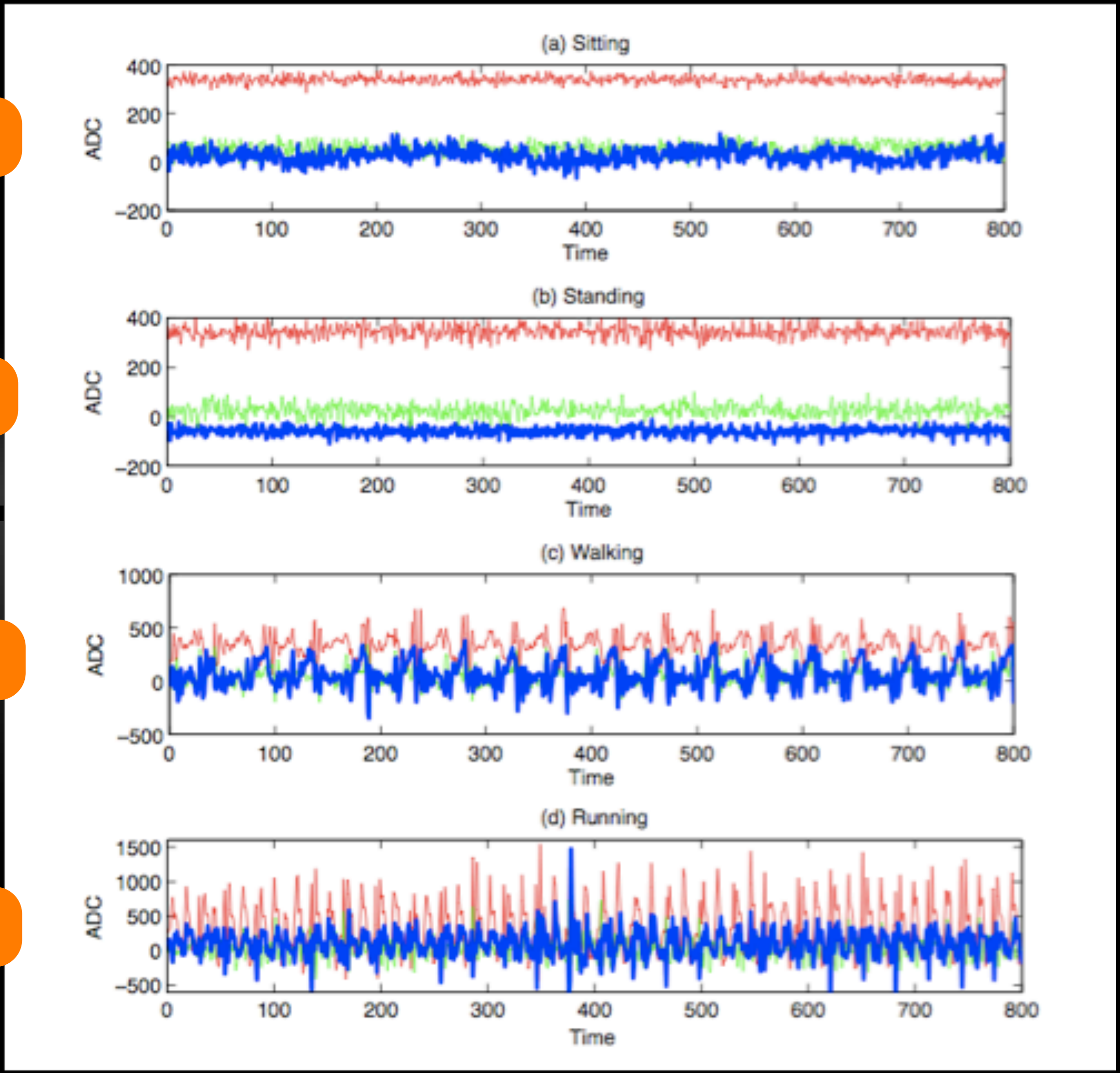
# Classifying activity on the Nokia N95

sitting

standing

walking

running



# Activity classifier confusion matrix on the Nokia N95

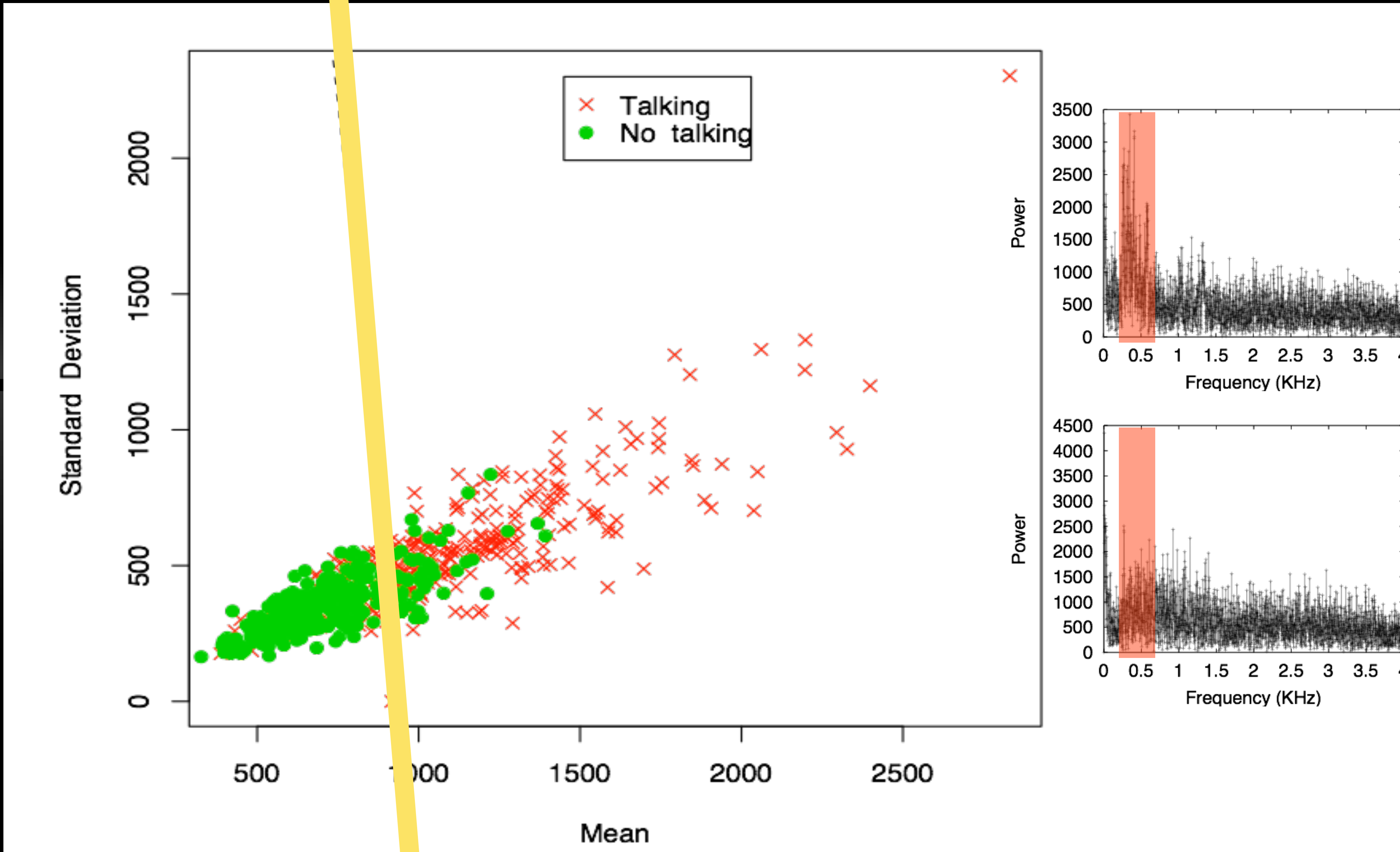
| | Sitting | Standing | Walking | Running |
|---|---|---|---|---|
| Sitting | 0.6818 | 0.2818 | 0.0364 | 0.0000 |
| Standing | 0.2096 | 0.7844 | 0.0060 | 0.0000 |
| Walking | 0.0025 | 0.0455 | 0.9444 | 0.0076 |
| Running | 0.0084 | 0.0700 | 0.1765 | 0.7451 |

Supervised learning approach

Differentiated between sitting and standing is hard

Custom sensing hardware (e.g., Intel's MSP)
can do better but these results are from the Nokia N95

# Classifying talking/ non-talking on the Nokia N95



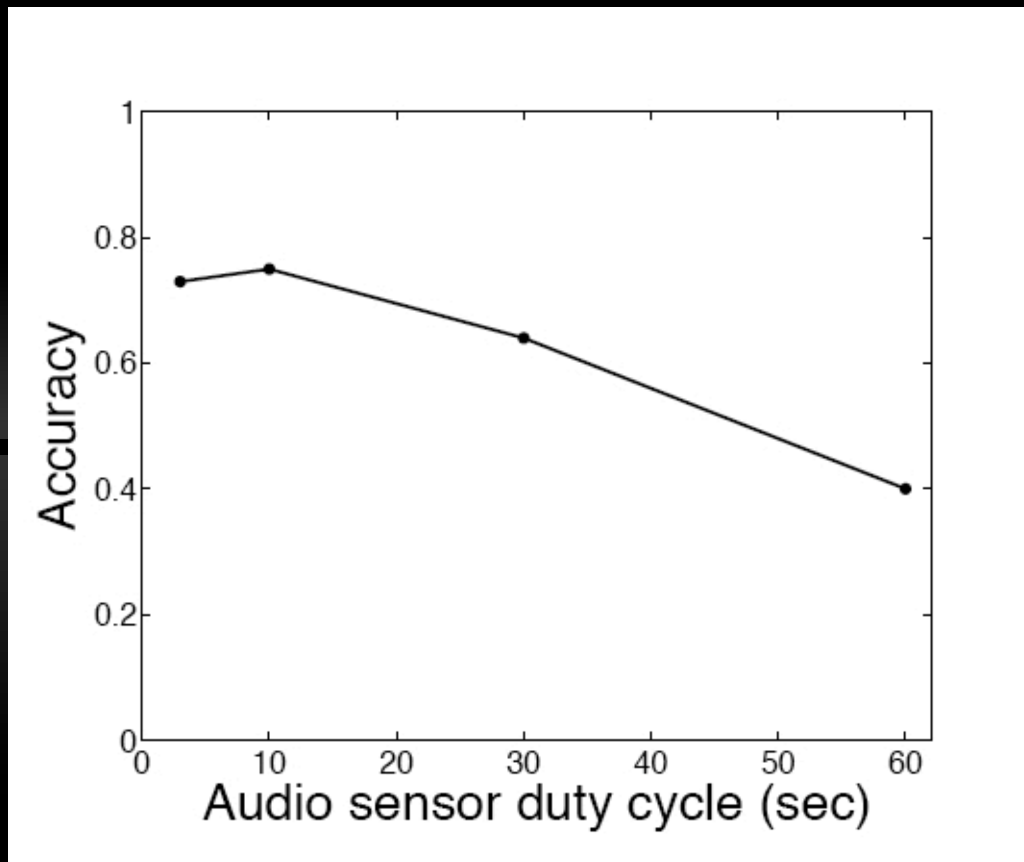
# Conservation classifier confusion matrix on the Nokia N95

| | Conversation | Non-Conversation |
|---|---|---|
| Conversation | 0.83.82 | 0.1618 |
| Non-Conversation | 0.3678 | 0.6322 |

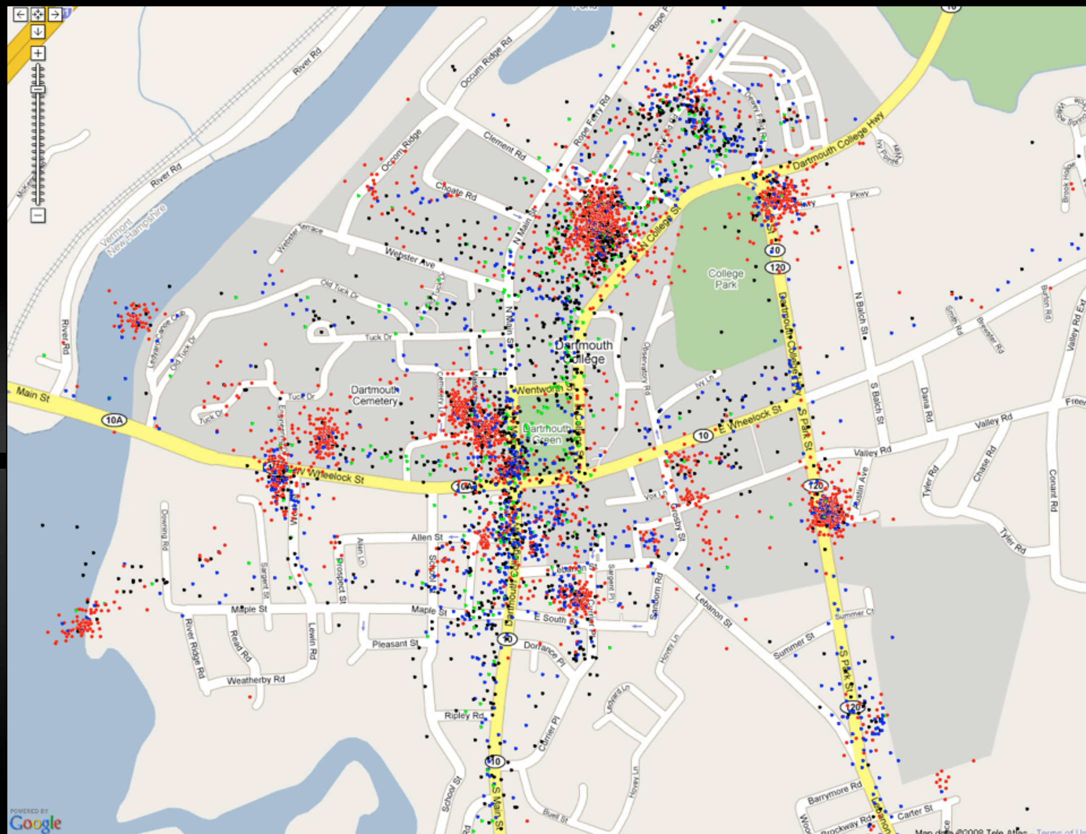
Design decision of 2/5 talk primitives to get into conversation and 4/5 to get out – more conservative

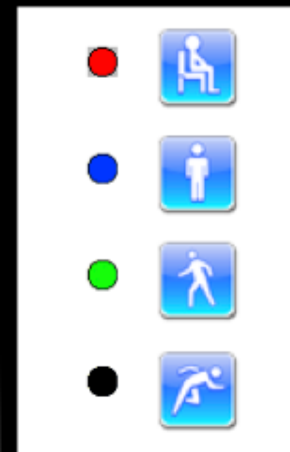
Poor performance for non conservation results because people aren't talking but others nearby are.

# Duty-cycling on the phone for continuous sensing is critical



# Results: Location and activity





*"Supporting energy-efficient uploading for continuous sensing us mobile phones", Pervasive 2010*

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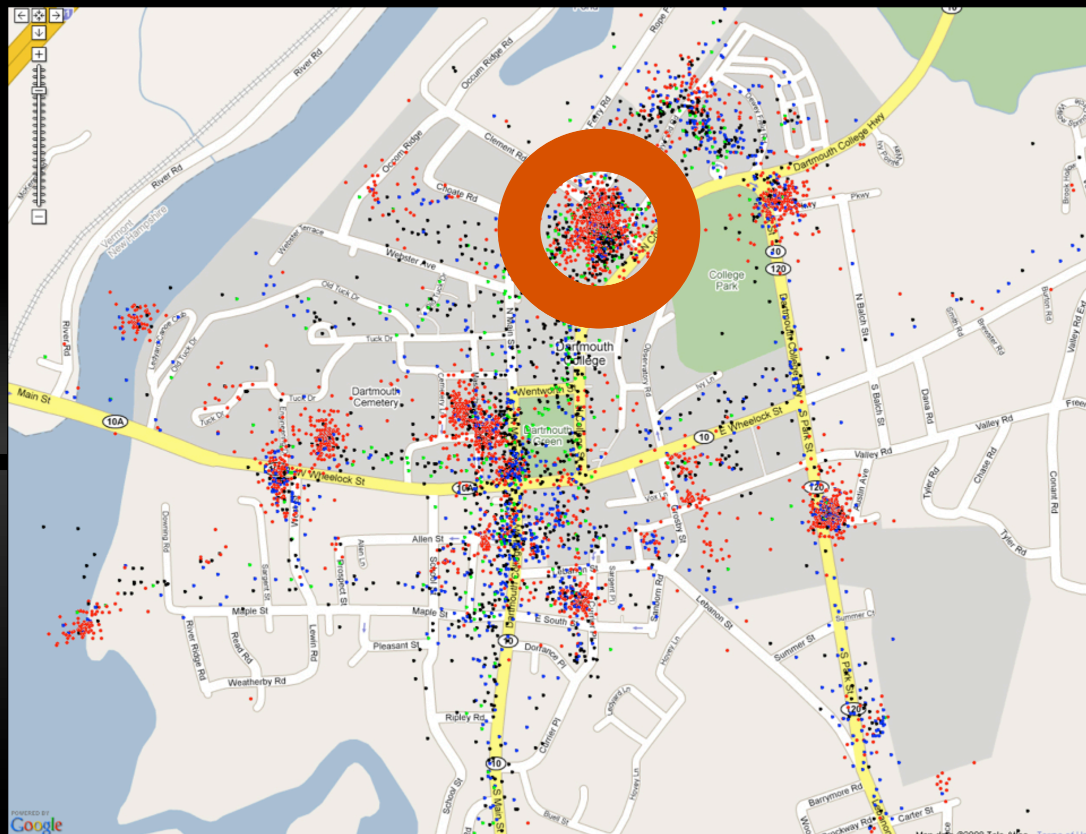


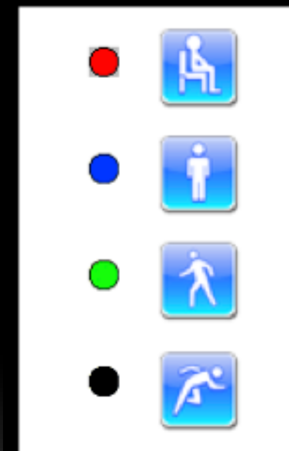

*"Supporting energy-efficient uploading for continuous sensing us mobile phones", Pervasive 2010*

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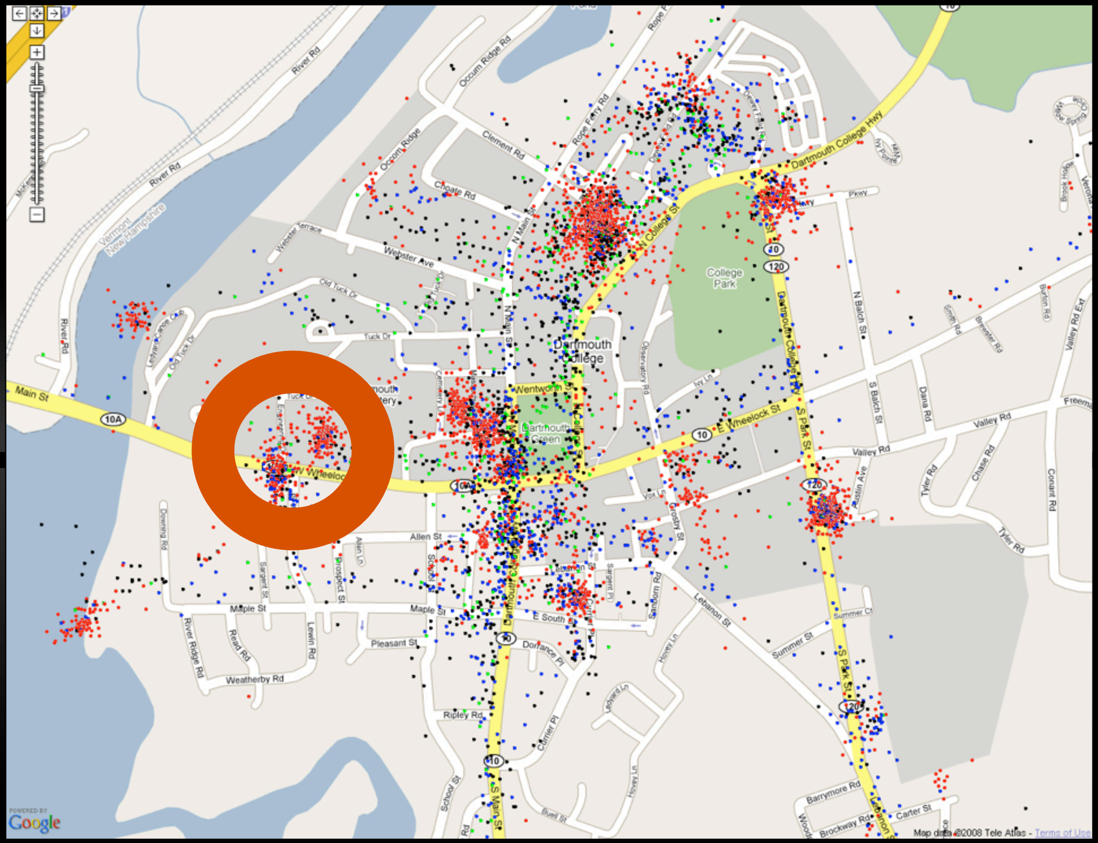


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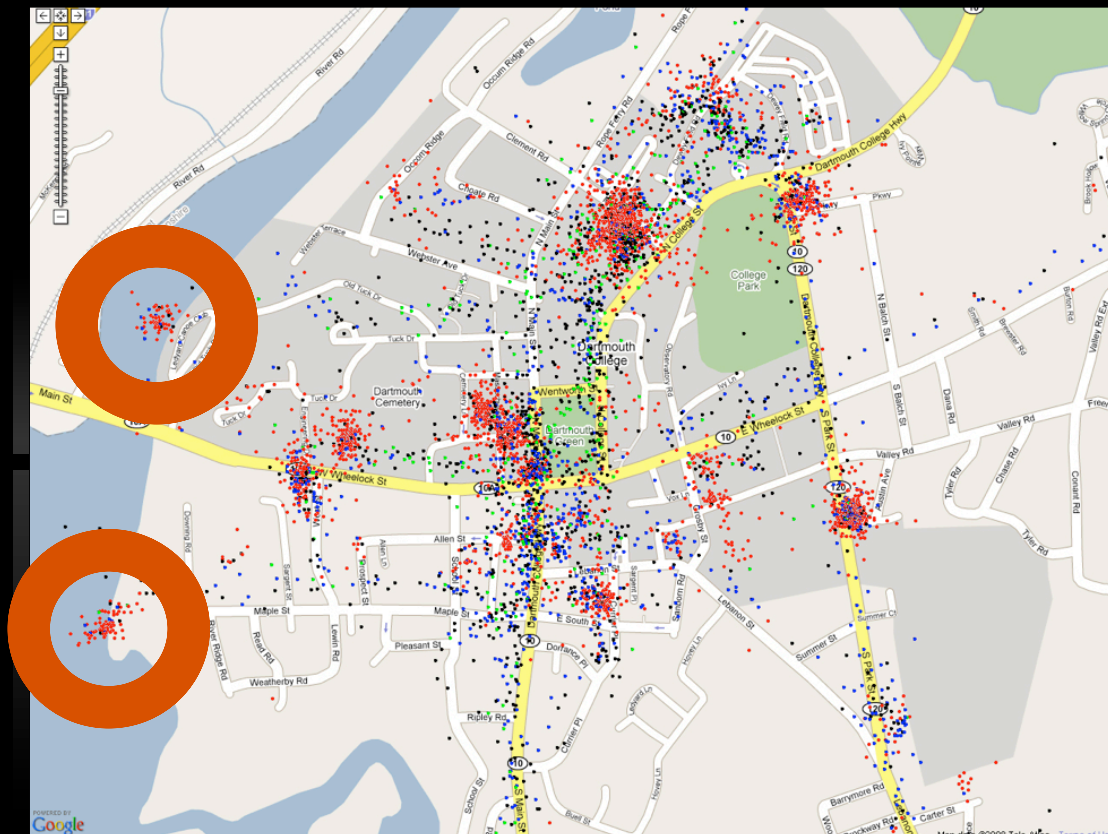
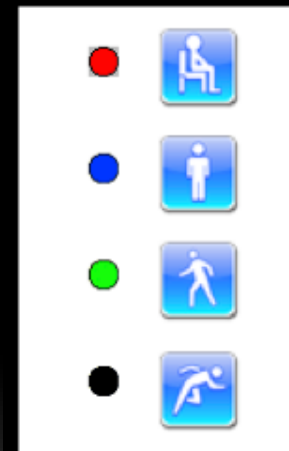
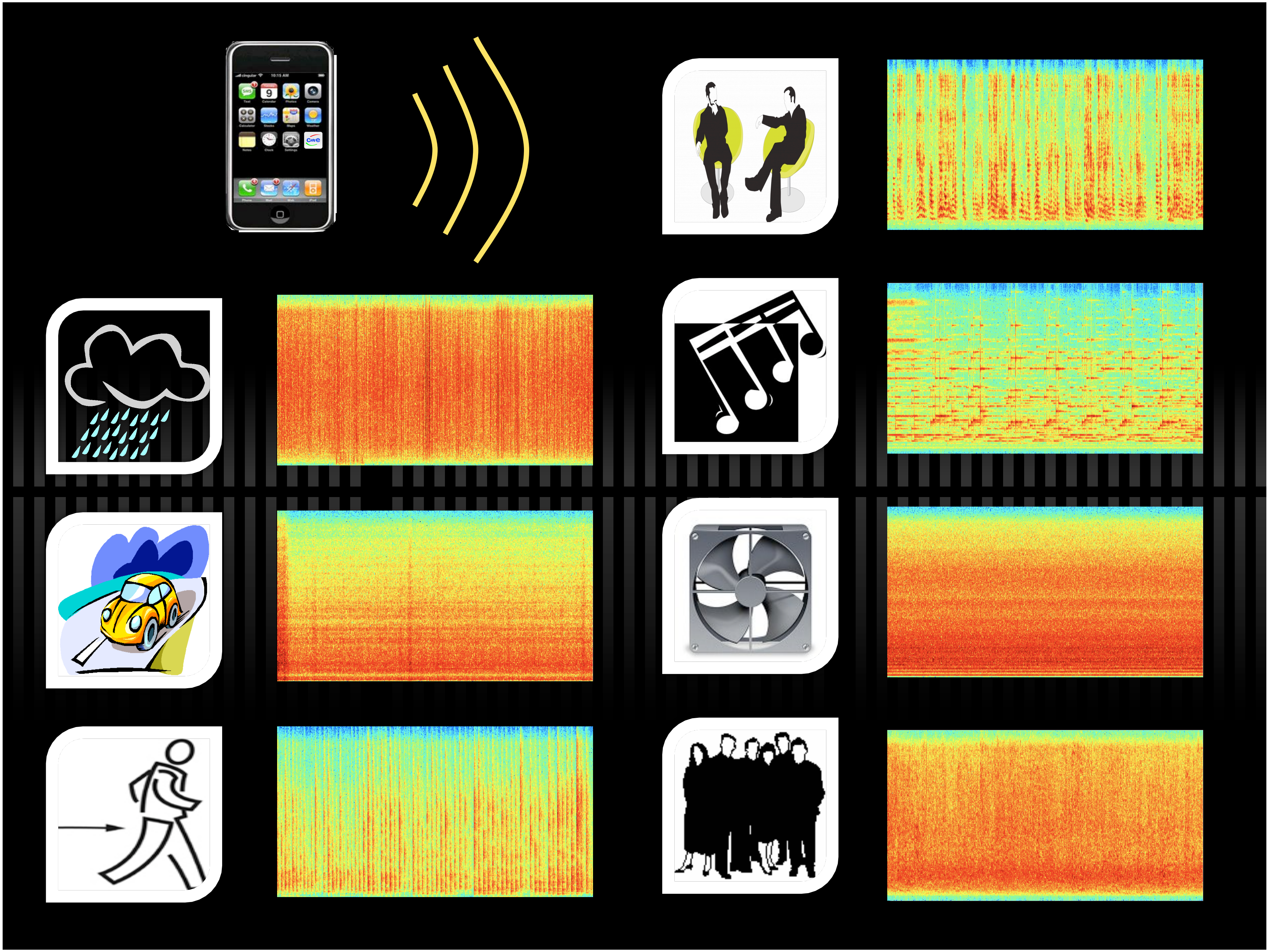


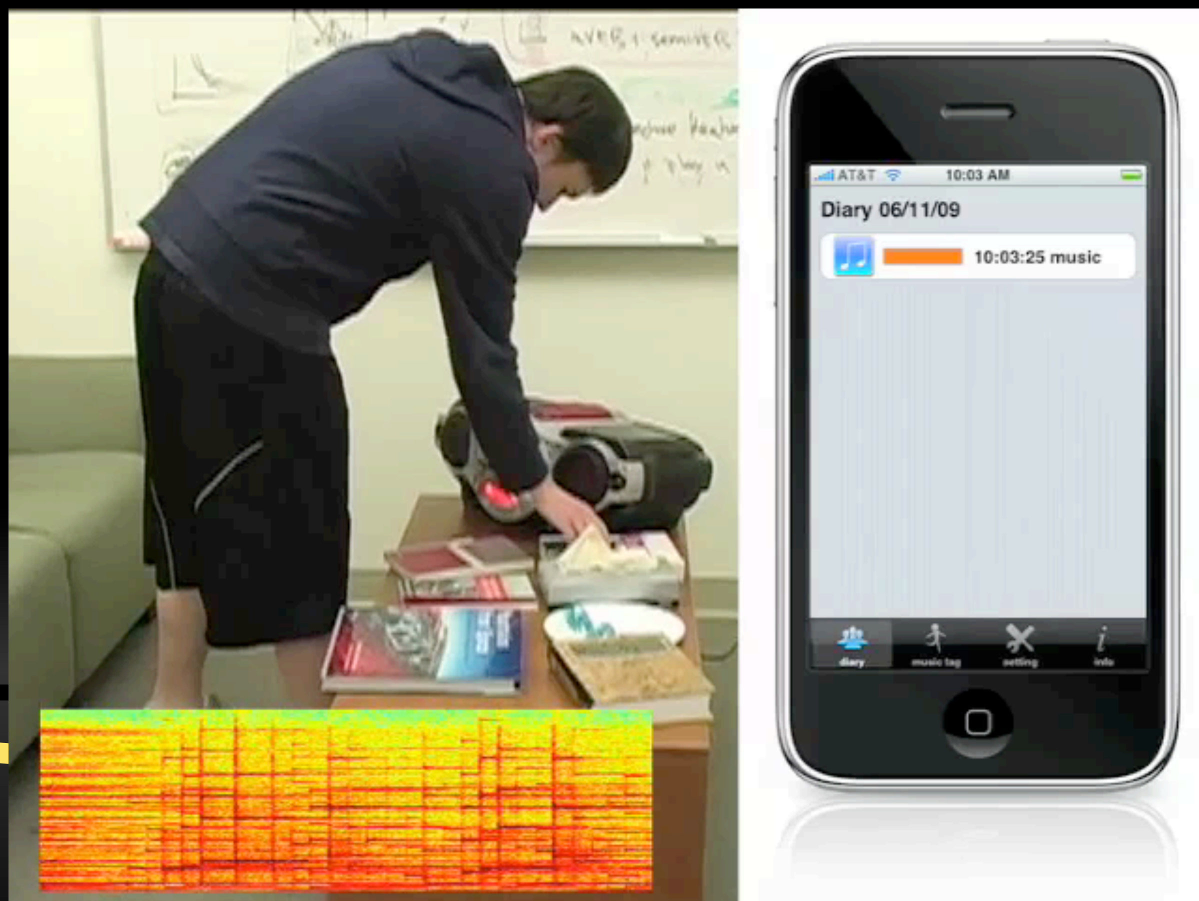
*"Supporting energy-efficient uploading for continuous sensing us mobile phones", Pervasive 2010*

# SoundSense

*"SoundSense: Scalable Sound Sensing for People-Centric Applications on Mobile Phones", ACM MobiSys 2009 (with Tanzeem Choudhury)*

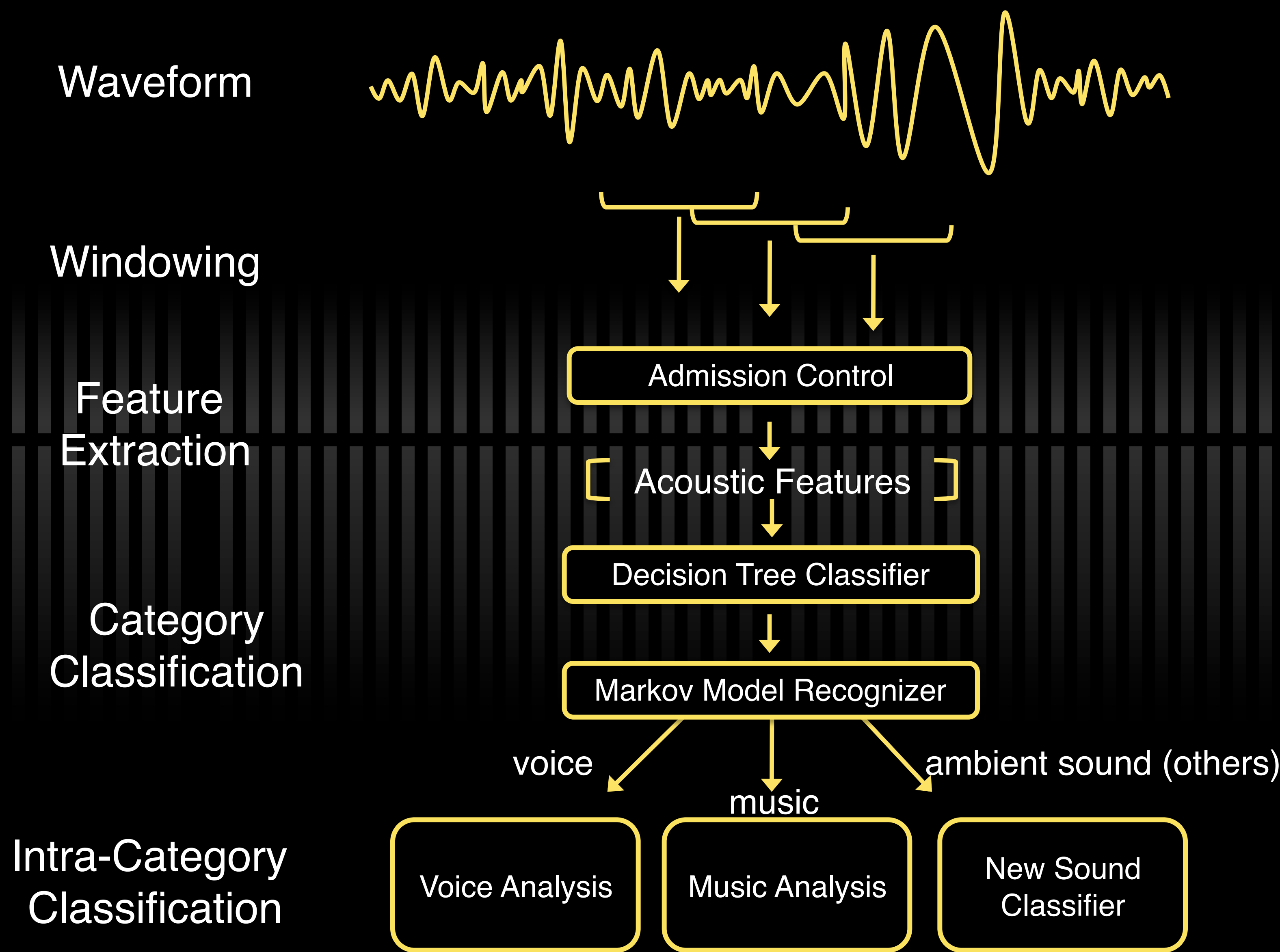


# SoundSense: Learn on the go




Detect Rank Learn

# SoundSense system



# Classification confusion matrix for iPhone

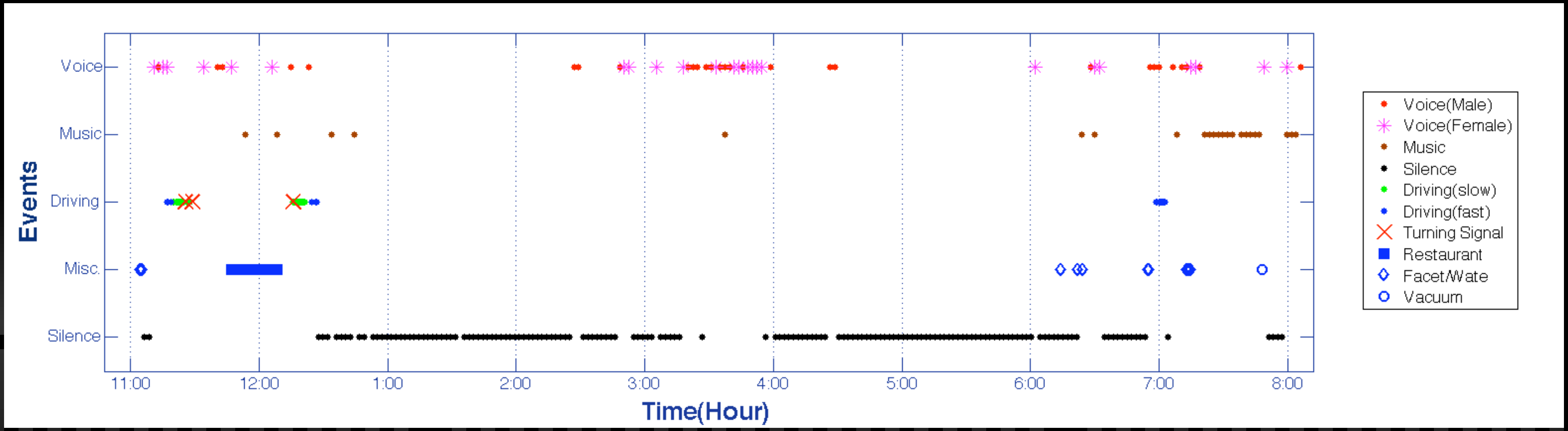
| | Ambient Noise | Music | Speech |
|---|---|---|---|
| Ambient Noise | 0.9159 | 0.0634 | 0.0207 |
| Music | 0.1359 | 0.8116 | 0.0525 |
| Speech | 0.0671 | 0.1444 | 0.7885 |

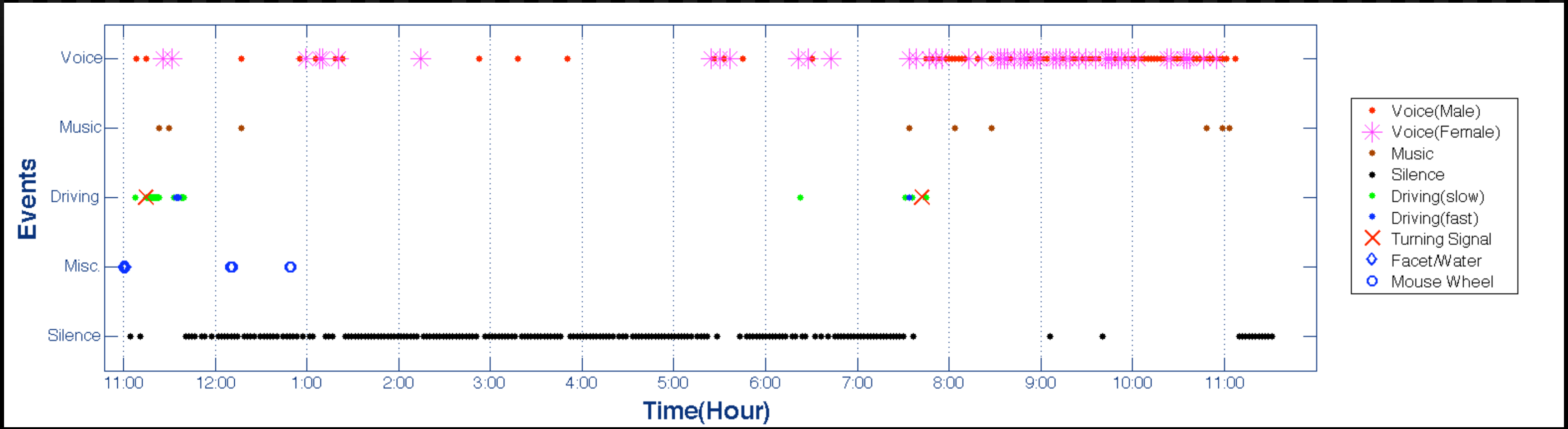
Accuracy of the decision tree classifier

| | Ambient Noise | Music | Speech |
|---|---|---|---|
| Ambient noise | 0.9494 | 0.0402 | 0.0104 |
| Music | 0.0379 | 0.9178 | 0.0444 |
| Speech | 0.0310 | 0.0657 | 0.9033 |

Accuracy of the markov model recognizer output

# Daily diary app



New research needed in mobile phone sensing to push the vision forward

How much intelligence can we push to the phone?

# Human behavior/context modeling

Label → Train → Classify

supervised learning

# User in the loop

Train → Label → Classify

supervised learning

# Current people-centric sensing model

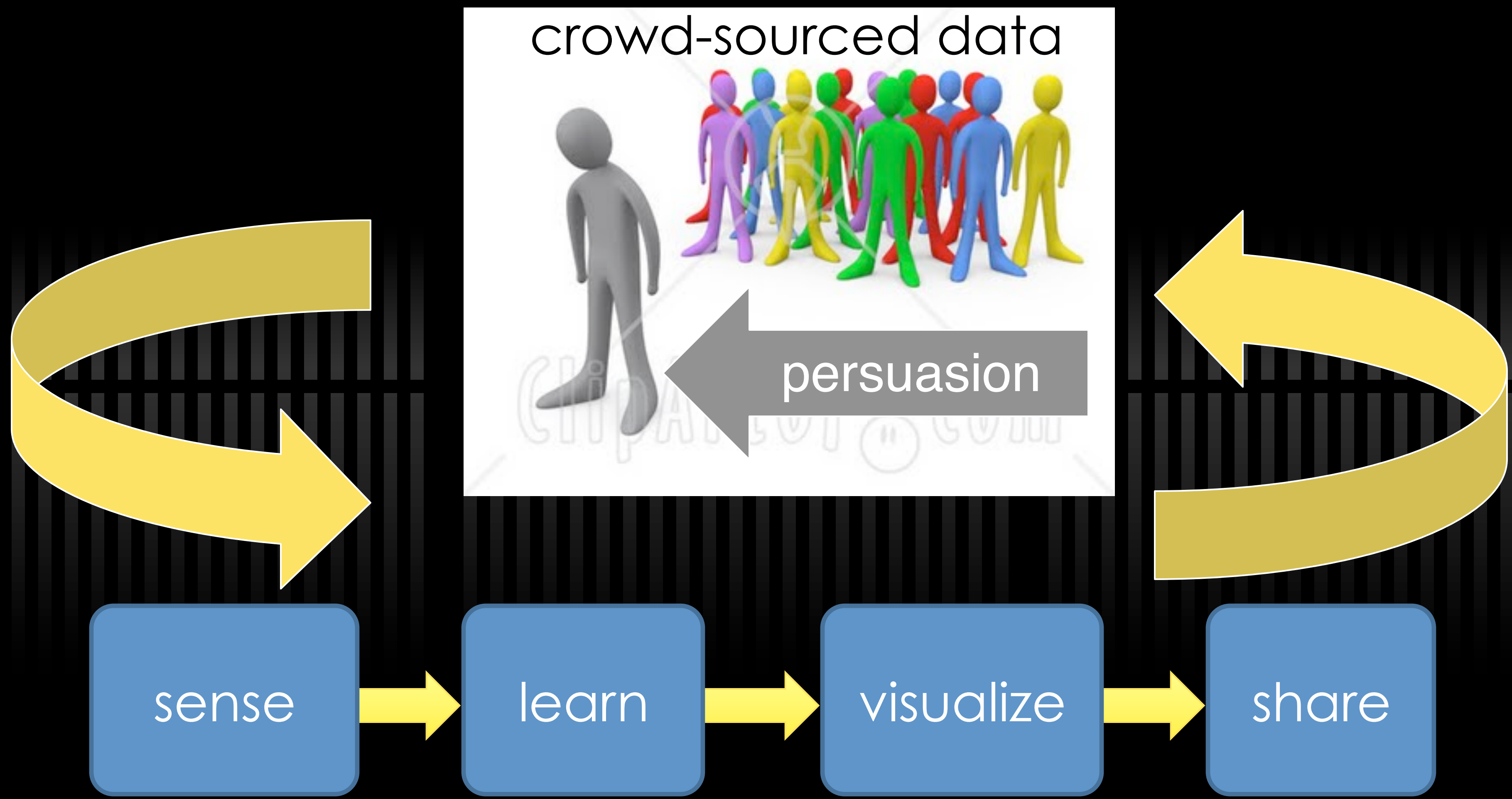
sense → learn → visualize → share

What else can we do with all that sensor data?

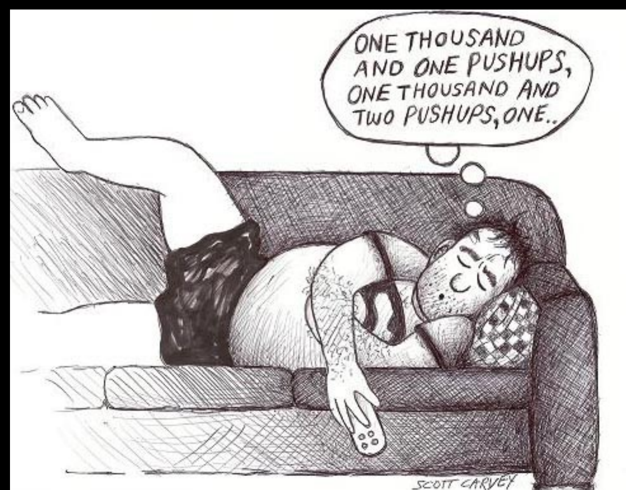
We can close the loop.

Be persuasive!

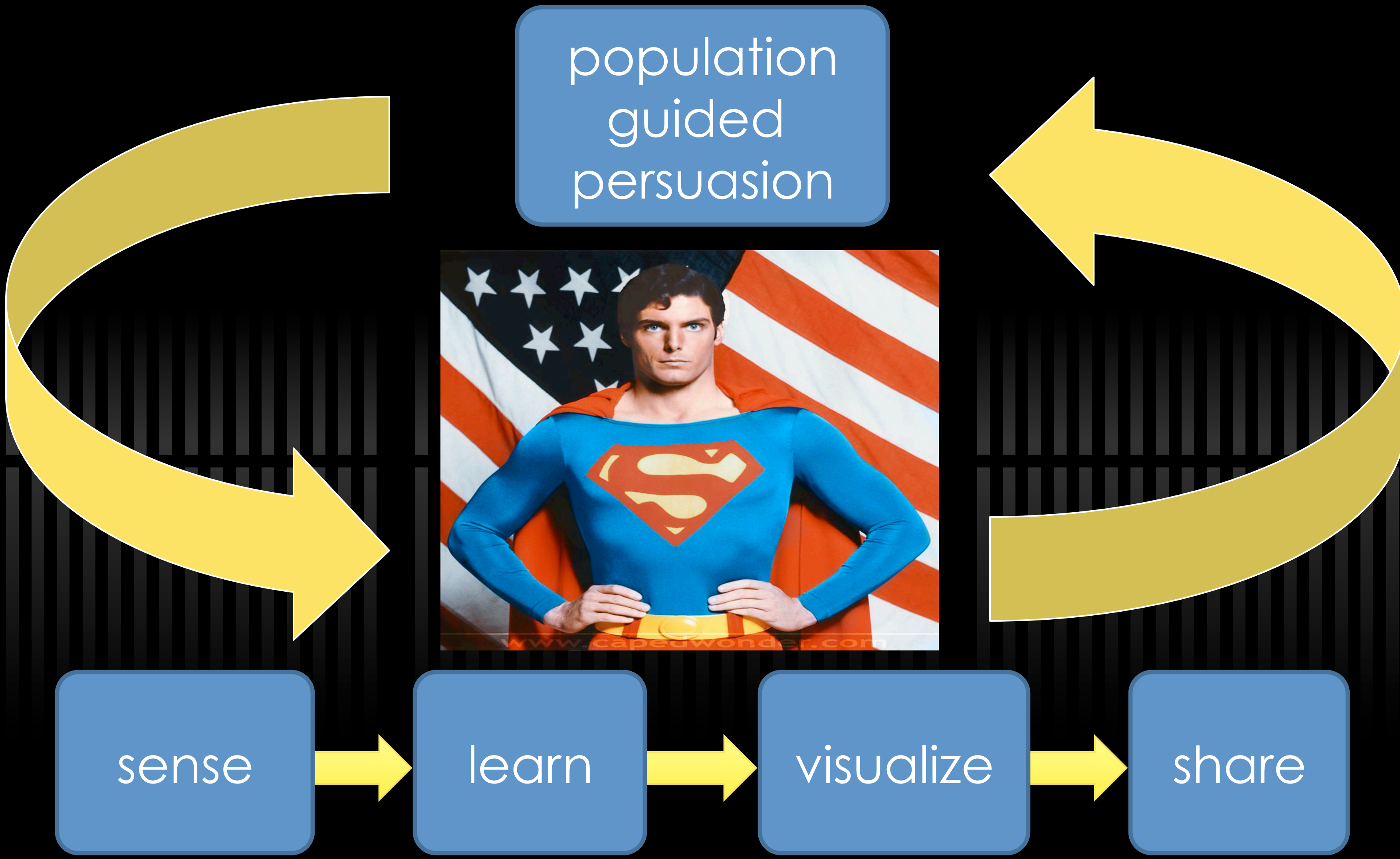
# Persuasion model



population guided persuasion




sense → learn → visualize → share




Sense-Learn-Persuasion Model

# Killer app for Sense-Learn-Persuasion Model

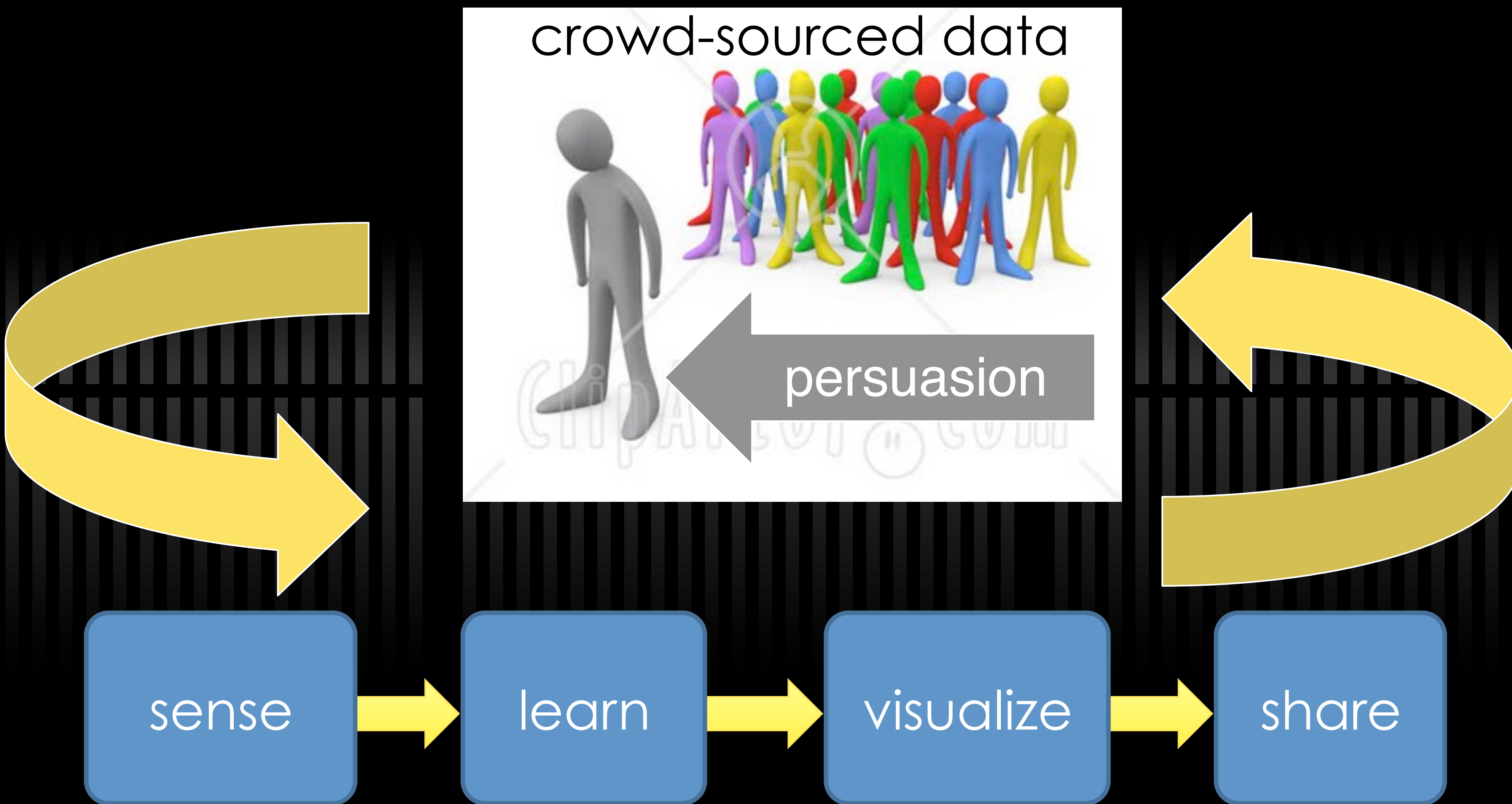
# A microscope for personal, community and population-scale well-being

Well-being in health encompasses an overall state of wellness, not just the absence of disease.

# Possible health related outcomes

Obesity, anxiety, depression, dementia, aging in place, metabolic syndrome (diabetes, elevated lipids, blood pressure), disease prevention (activity, food choices)

# Well-being networks: the killer app?



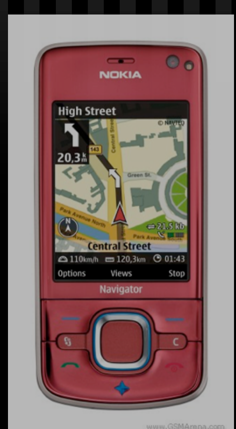

With Ethen Berke, John Canny, Tanzeem Chodury, James Landay

# Need for enabling software technology for mobile phone sensing

# Phone SensorWare

Supporting continuous sensing significant challenge

Many open challenges




Priv.-aware sub/pub

Inferencing

Sensor sharing

Duty cycling

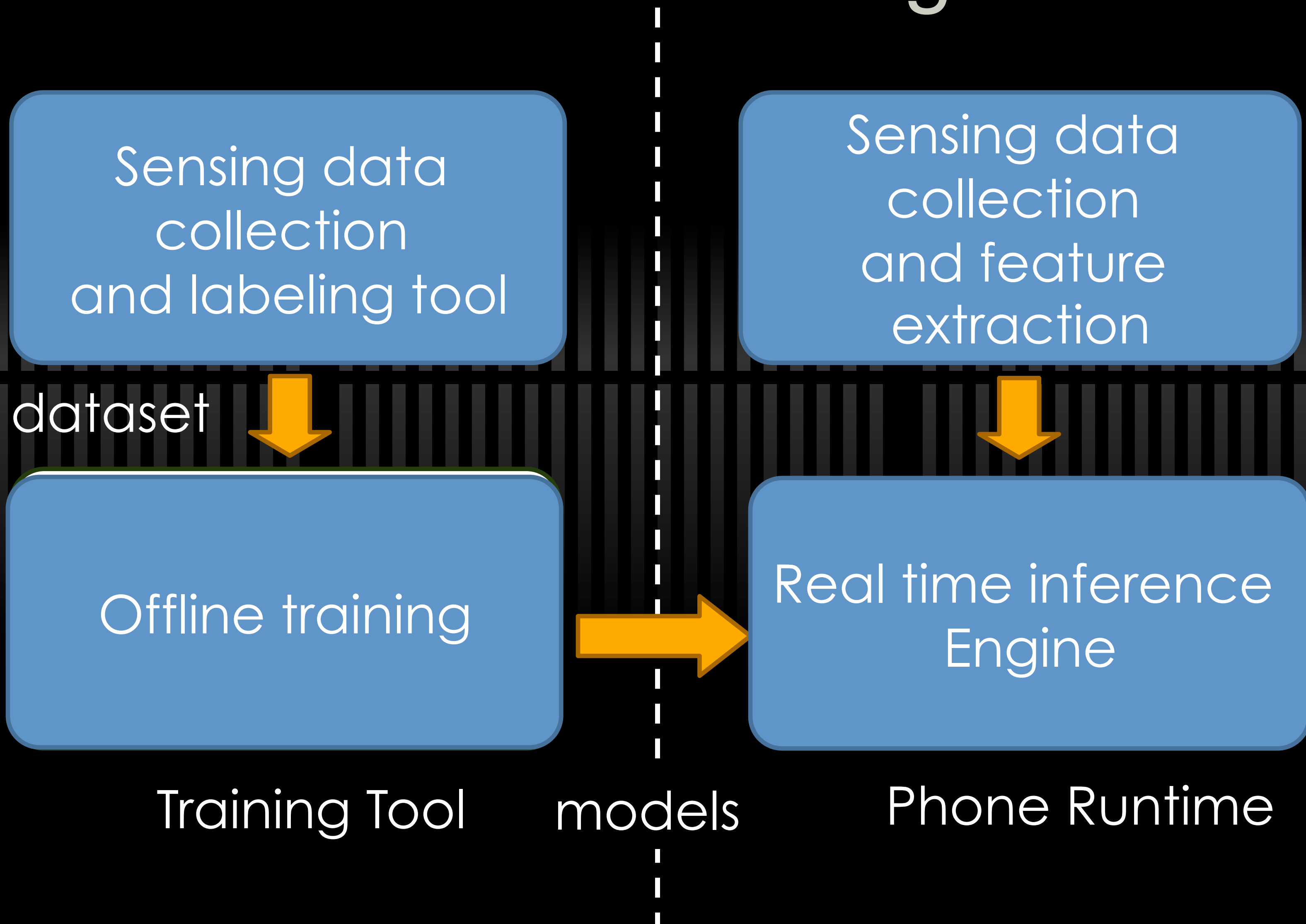
Calibration

Context

RF | Sensing

Andriod, iPhoneOS, Nokia

# Phone Machine Learning Toolkit



Many open technical challenges, such as:
continuous sensing, duty cycling, comms, privacy, robust features, scaling, exploiting crowd-sourced data, light-weight classifiers, sharing, etc.

In summary, ….

# Growing interest in sensing on mobile phones

- Applications
  - WatchMe, iCAMS, PEIR, Nericell
- Sensing with mobile phones
  - UCLA, UIUC, Intel, Nokia, Microsoft, Motorola, UW, Duke, start ups: e.g., Sense Networks
- Human activity inferencing
  - MIT, Intel, UW
- Workshops
  - UrbanSense 08, MODUS 08

The mobile phone will serve as the main platform for sensing innovation over the next decade.

Your mobile phone will sense your surroundings, learn your behavior (what you do, where you go and how you interact with people and your environment), and help you navigate your day and improve quality of life.

Collectively, mobile phones will form societal scale sensor networks in support of community, urban, and global sensing applications and problem solving.

# Thanks for listening!

- Project page, papers, etc:

http://metrosense.cs.dartmouth.edu

- Thanks to many people's contributions

http://metrosense.cs.dartmouth.edu/metro-people.html

- Sponsors