MOBILE COMPUTING

CSE 40814/60814

Spring 2021

Mobile Sensing

- Smartphones (and tablets, etc.) not only serve as a key computing and communication device, but also come with a rich set of **embedded sensors**
- Which enables **new applications** across a wide variety of domains, such as transportation, social networks, environmental monitoring, healthcare, etc.
- Giving rise to new research areas such as mobile sensing, crowdsensing, mobile data mining, etc.
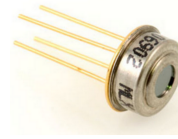
Sensors & Sensing

- **Transducer:** a device which converts one form of energy to another
- **Sensor:** transducer that measures a physical quantity and converts it into a signal which can be read by an instrument (physical phenomenon -> electric signal)
- **Actuator:** a transducer that converts an electric signal to a physical phenomenon
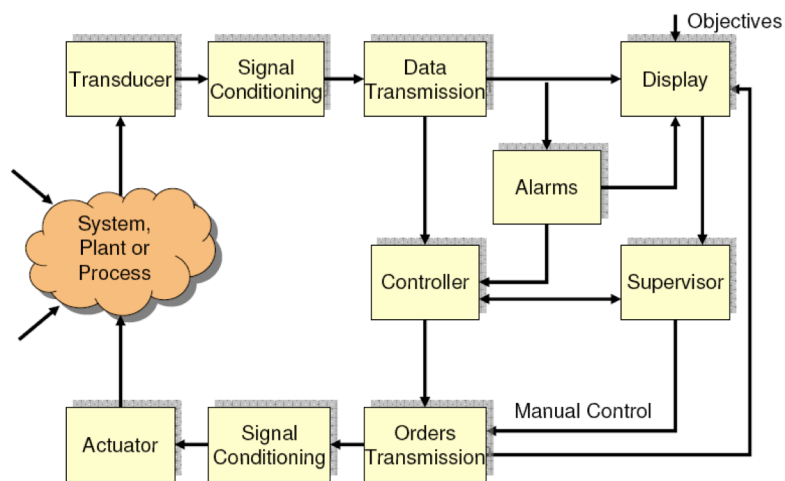
| Visual Sensor | Ultrasound Sensor | Infrared Sensor |

Sensor/Actuator System

Sensor-to-Signal Interface

- Action of environment on a sensor causes it to **generate** an electrical signal directly
  - voltage source (V), current (I), or charge (Q) source

- Action of environment on sensor **changes** an electrical parameter that we can measure
  - **Resistance:** V = I * R
  - **Capacitance:** C = ε * A / d
  - **Inductance:** V ~ dI/dt, I ~ ∫V dt
    - I = current, V = voltage, R = resistance, A = area, d = distance, ε = permittivity

Analog-to-Digital Converter (ADC)

- Successive approximation ADC
  - Binary search algorithm
- Q = resolution in volts per step
- M = resolution in bits
- N = Number of intervals (steps)
- E_{FSR} = Full scale voltage range
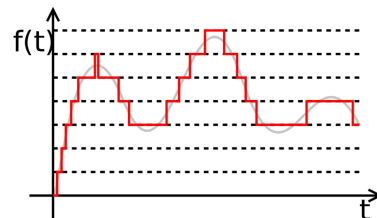
$$Q = \frac{E_{FSR}}{2^M} = \frac{E_{FSR}}{N}$$

- Voltage range 0 – 10V; M = 12 bits
- N = 4096 intervals (steps)
- Q = 2.44 mV/code

- Quantization error depends on resolution Q

Sensor Types: HW & SW

- **Hardware**-based sensors
  - Physical components built into a device
  - They derive their data by directly measuring specific environmental properties
- **Software**-based sensors
  - Not physical devices, although they mimic hardware-based sensors
  - They derive their data from one or more hardware-based sensors

Sensor Types: Function Type

- Motion sensors
  - Measure acceleration forces and rotational forces along three axes, e.g., accelerometer, gyroscope, etc.
- Position sensors
  - Measure the physical position of a device, e.g., GPS, proximity sensor, etc.
- Environmental sensors
  - Measure various environmental parameters, e.g., light sensor, thermometer, etc.

Sensor List

| Sensor	Function Type	Software-based or Hardware-based
Accelerometer	Motion Sensor	Hardware-based
Gyroscope	Motion Sensor	Hardware-based
Gravity	Motion Sensor	Software-based
Rotation Vector	Motion Sensor	Software-based
Magnetic Field	Position Sensor	Hardware-based
Proximity	Position Sensor	Hardware-based
GPS	Position Sensor	Hardware-based
Orientation	Position Sensor	Software-based
Light	Environmental Sensor	Hardware-based
Thermometer	Environmental Sensor	Hardware-based
Barometer	Environmental Sensor	Hardware-based
Humidity	Environmental Sensor	Hardware-based

Smartphone Sensing

- Light
- Proximity
- Cameras (multiple)
- Microphones (multiple)
- Touch
- Position
  - GPS, Wi-Fi, cell, NFC, Bluetooth
- Accelerometer
- Gyroscope
- Magnetometer
- Pressure
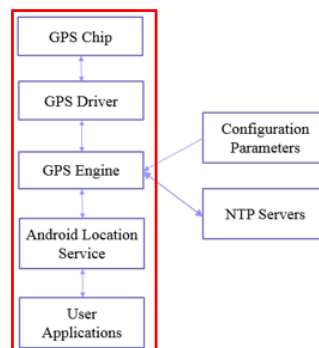- Temperature
- Humidity
- Fingerprint sensor

Sensor: GPS (Recap)

- Need signals from 3 satellites for 2D positioning, 4 satellites for 3D positioning
- More visible satellites increase precision
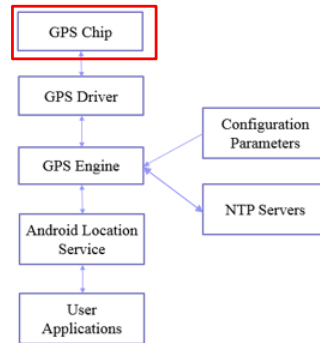- Based on concept of trilateration
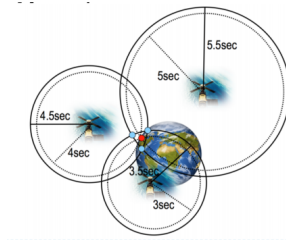
GPS in Smartphones

- Location service using GPS in Android consists of five architectural components
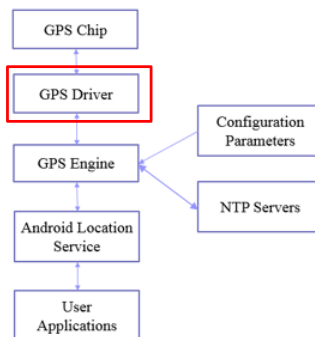
GPS in Smartphones

- GPS chip: Radio frequency receiver that obtains signals from GPS satellites

GPS in Smartphones

- GPS driver communicates with GPS chip, provides low-level APIs to high-level software
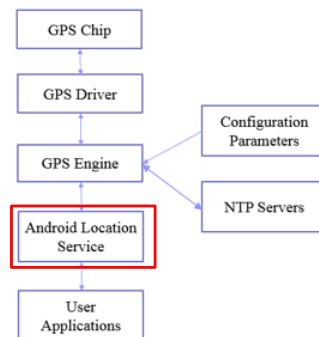
GPS in Smartphones

- GPS engine: The heart of the system; uses configuration parameters to configure GPS; instructs GPS driver to detect satellites; gets timing data from NTP servers (fast) or Internet (slow)
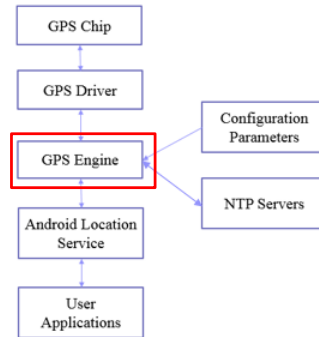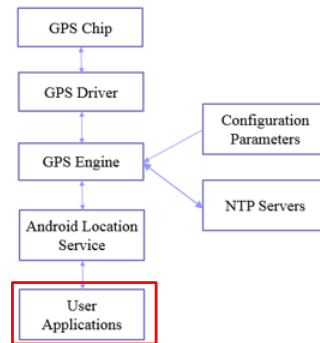

GPS in Smartphones

- Android Location Service: consists of Android framework classes like Location Manager that provides data/services to applications
- Also integrations location data from multiple sources (Wi-Fi, cellular, etc.)
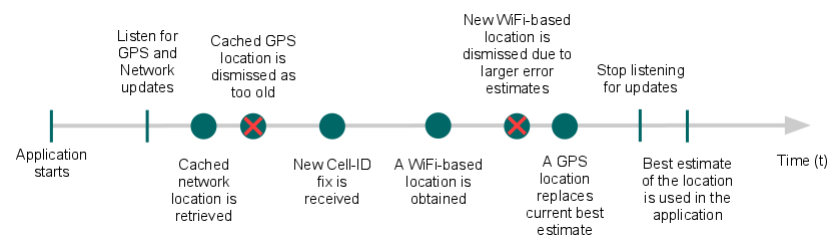
GPS in Smartphones

- Applications: Location-based applications and services (Google Maps, navigation, location tagging, etc.)

Example of Sensing Procedure

Sensor: Motion and Orientation

- Most of the sensors use the same **coordinate system**
- When a device's screen is facing the user
  - The X axis is horizontal and points to the right
  - The Y axis is vertical and points up
  - The Z axis pints toward outside of the screen face

Sensor: Accelerometer

- Measures proper acceleration (acceleration it experiences relative to freefall)
- Units: g

| Example	G Force
Standing on earth at sea level	1g
Bugatti Veyron from 0 to 100 km/h (2.4s)	1.55g
Space Shuttle, maximum during launch and reentry	3g
Formula 1 car, peak lateral in turns	5-6g
Death or serious injury	50g
Shock capability of mechanical Omega watches	5000g

Sensor: Accelerometer

- Acceleration is measured on 3 axes
- Note that the force of gravity is always included in the measured acceleration
  - When the device is sitting on the table stationary, the accelerometer reads a magnitude of 1g
  - When the device is in free fall, the accelerometer reads a magnitude of 0g
- To measure the real acceleration of the device, the contribution of the force of gravity must be removed from the reading, for example, by calibration

Sensor: Accelerometer

- When the device is lying flat
  - gives +1g (gravitational force) reading on Z axis
- Stationary device, after 45 degree rotation
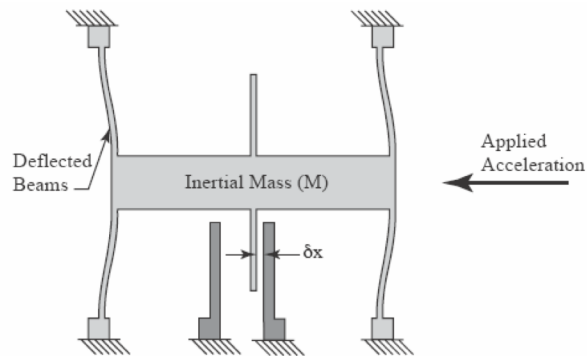 - Same magnitude, but rotated

$$a_x = a_y = 0$$
$$a_z = g$$

$$a_y = 0$$
$$a_z = -a_x = g/\sqrt{2}$$
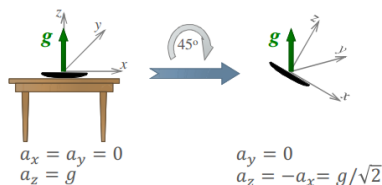
Accelerometer: Inner Working (1 of 2)
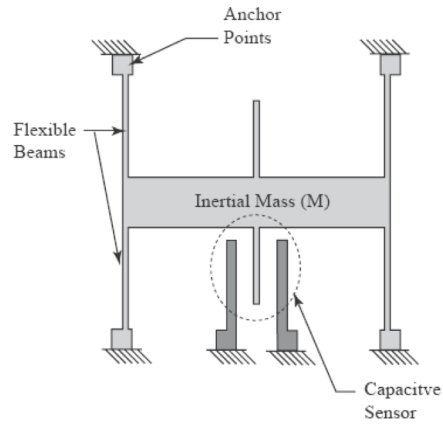
It consists of beams and a capacitive sensor with some anchor points
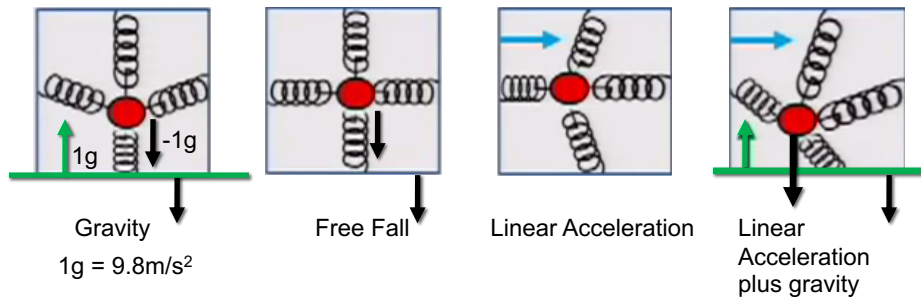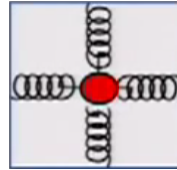
Accelerometer: Inner Working (1 of 2)

On applying the acceleration, the beams deflect and cause the change in capacitance.
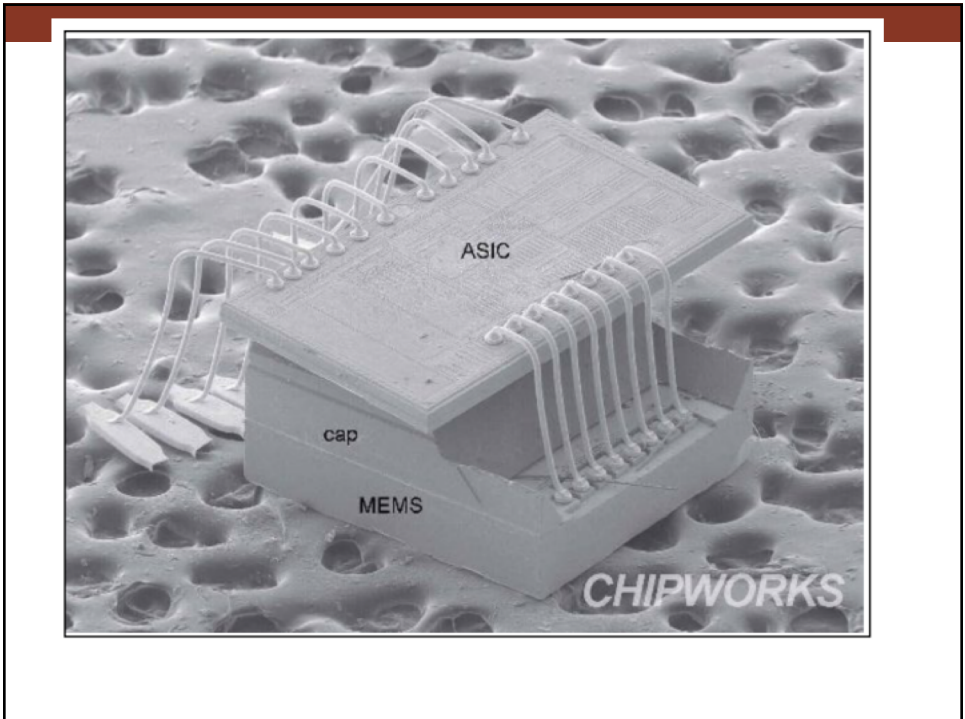
Accelerometer

Mass on spring

Gravity
1g = 9.8m/s^2

Free Fall

Linear Acceleration

Linear Acceleration plus gravity

Smartphones: MEMS Sensors

- Micro Electro-Mechanical Systems
- Term coined in 1989
- Describes creation of mechanical elements at a scale more usually reserved for microelectronics
- MEMS use cavities, channels, cantilevers, membranes, etc. to imitate traditional mechanical systems
- Small enough to be integrated with the electronics

MEMS Accelerometer
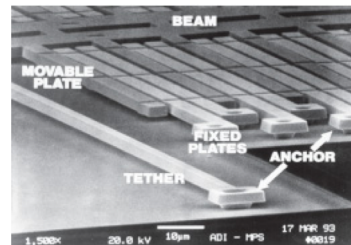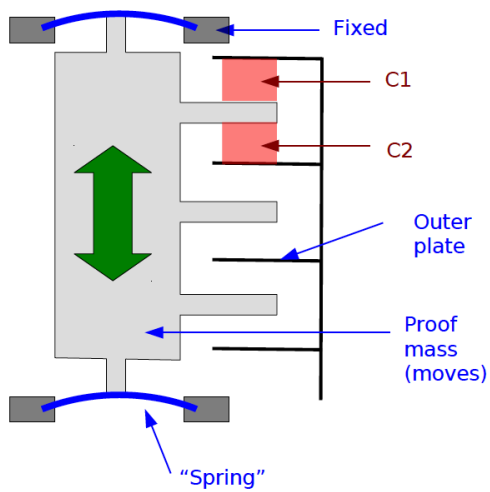
- Have a proof mass between springs and a series of 'plates'
- Measure deflection via capacitance changes
- 1-D only

Sensor: Gyroscope

- Measures the rate of rotation (angular speed) around an axis
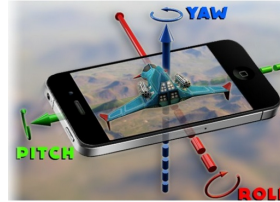- Speed is expressed in rad/s on 3 axis
- When the device is not rotating, the sensor values will be zeros
- It gives us 3 values
  - Pitch value (rotation around X axis)
  - Roll value (rotation around Y axis)
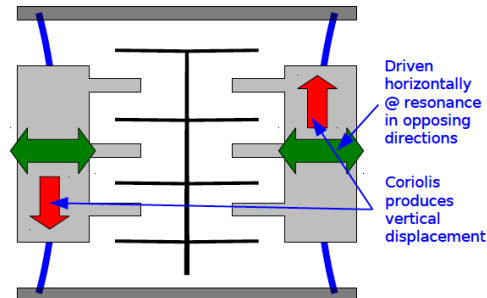 - Yaw value (rotation around Z axis)

- Unfortunately, gyroscope is error prone over time.
- As time goes, gyroscope introduces drift in result
- By sensor fusion (combining accelerometer and gyroscope), results can be corrected and path of movement of device can be obtained correctly

Gyroscope
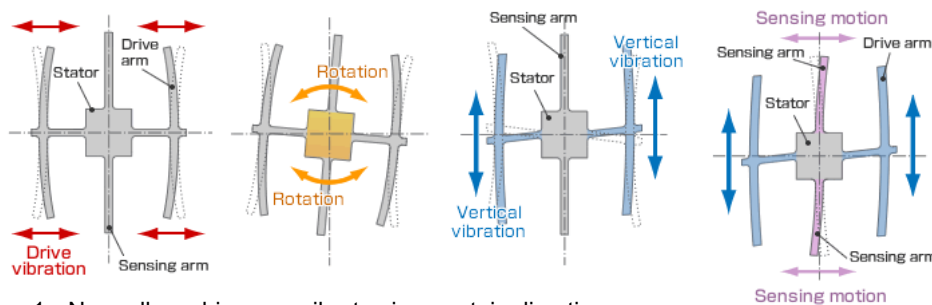
1. Normally, a drive arm vibrates in a certain direction.
2. Direction of rotation
3. When the gyro is rotated, the Coriolis force acts on the drive arms, producing vertical vibration.
4. The stationary part bends due to vertical drive arm vibration, producing a sensing motion in the sensing arms.
5. The motion of a pair of sensing arms produces a potential difference from which angular velocity is sensed. The angular velocity is converted to, and output as, an electrical signal.

MEMS Gyroscope

Driven horizontally @ resonance in opposing directions

Coriolis produces vertical displacement

$$\vec{\Omega}_z$$
$$\vec{v}$$
$$\vec{F}_{Coriolis} = -2m\vec{\Omega} \times \vec{v}$$
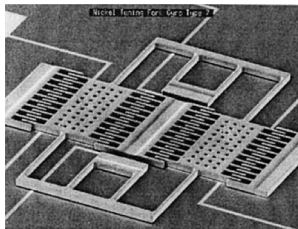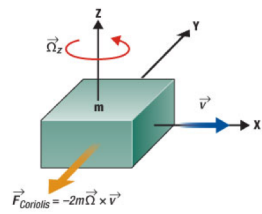
- Based on measuring Coriolis force as experienced by a moving object in a rotating frame of reference
- Many implementations, but the "tuning fork" method is most common

Accelerometer vs. Gyroscope

- Accelerometer
  - Senses linear movement: not good for rotations, good for tilt detection
  - Does not know difference between gravity and linear movement
- Gyroscope
  - Measures all types of rotations
  - Not movement
- A+G = both rotation and movement tracking possible

Sensor: Magnetic Field

- Measures direction and strength of earth's magnetic field
- Strength is expressed in tesla (T)

| Example	Field strength
Earth's magnetic field on the equator (0° latitude)	31μT (0.00031T)
Typical fridge magnet	5mT (0.005T)
Strong neodymium magnet	1.25T
MRI system	1.5T – 3T

Compass

- Magnetic field sensor (magnetometer)

Magnetic declination   Magnetic inclination
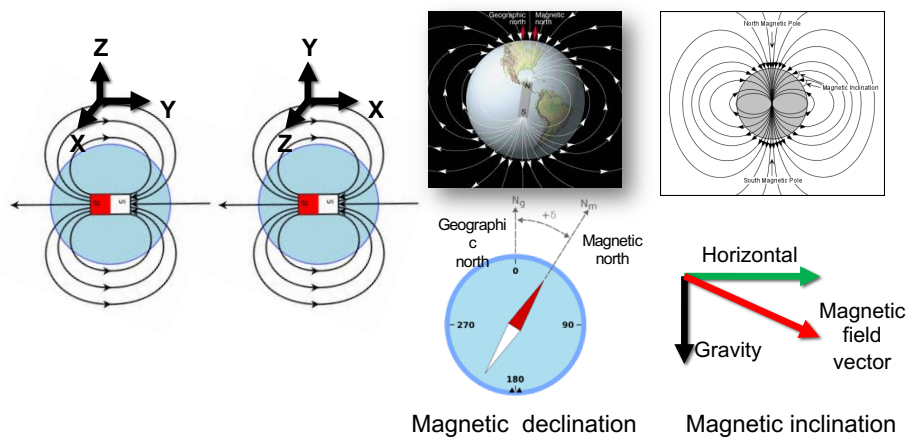
MEMS Compass

- Most use Lorentz Force
- A current-carrying wire in a magnetic field experiences a perpendicular force
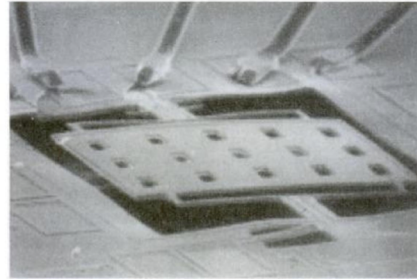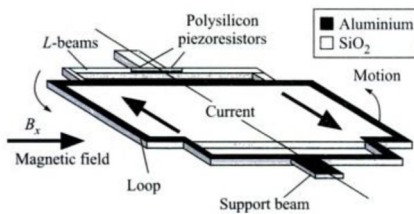
Sensor: Proximity

- A proximity sensor can detect the presence of nearby objects without physical contact
- It emits an **infrared signal** that gets bounced back by objects nearby
- It is usually used by mobile device to determine how far a person's head is from the face of a handset
  - For example: is the user is making a phone call; is the device near the ear?
- The measured results could be different based on different devices
  - Most proximity sensors return the absolute distance in centimeters (cm)
  - Some return binary information only

Sensor: Light

- It gives a reading of the **ambient light level** detected by the light sensor of the device
- Located at front of mobile device near to front facing camera
- The device uses the data to adjust the display's brightness automatically
  - When ambient light is plentiful, the screen's brightness is pumped up and when it is dark, the display is dimmed down

Other Smartphone Sensors

- **Fingerprint sensor** or a **facial recognition system:**
  - Used for authentication purposes
  - Alternative to PIN (Personal Identification Number)
  - Fingerprint options:
    - Optical (scanning with light)
    - Capacitive (scanning with electronic capacitors)
    - Ultrasonic (scanning with sound waves)
  - Facial sensor options:
    - Normal camera lens
    - Infrared sensor

Other Smartphone Sensors

- Google **Soli** sensor
  - Radar module
  - Detects movement near the phone (start activities such as muting sounds or face unlock quicker)
  - https://atap.google.com/soli/technology/

- Apple **LiDAR**
  - Laser light scanning technology that can judge depth and map out a room very accurately
  - Augmented reality apps

- Apple **U1 chip**
  - Communications antenna; can help determine location and the direction you're pointing your phone in

Other Smartphone Sensors

- **Barometer**
  - Air pressure
  - Detecting weather changes & altitude

- **Thermometer**
  - Ambient temperature outside of the device
  - Internal temperature to prevent overheating or adjust clock speed
  - A temperature sensor detects a change in a physical parameter such as resistance or output voltage that corresponds to a temperature change
  - Contact (direct physical contact) vs. non-contact (radiant energy of a heat source)

Other (Smartphone) Sensors

- **Pressure**
  - Barometer
  - Transduces pressure into electrical quantity
  - Pressure exerts force which can be converted to electrical voltage using various methods
  - **Strain Gauges**
    - Based on the variation of resistance of a conductor or semiconductor when applied to mechanical stress
  - **Capacitive diaphragms**
    - Diaphragm acts as one plate of capacitor
    - The stress changes the space between capacitor plates
  - **Piezo-resistive**
    - Micro-machined silicon diaphragms
    - Piezo-resistive strain gauges diffused into it
    - Very sensitive to pressure

Piezoelectric Sensors

- Device that measures changes in pressure, strain, force, etc. by converting them to an electrical charge.
- Typically crystals or ceramics.
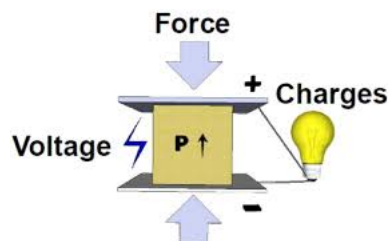
Sensor: Sound

- A **microphone** is an acoustic to electric transducer that converts sound into an electrical signal.

- Microphones **capture sound waves with a thin, flexible diaphragm**. The vibrations of this element are then converted by various methods into an electrical signal that is an analog of the original sound.

- Most microphones in use today use electromagnetic generation (**dynamic microphones**), capacitance change (**condenser microphones**) or **piezo-electric generation** to produce the signal from mechanical vibration.
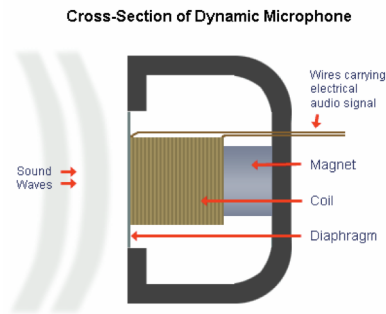
Condenser (or Capacitor) Microphones

- In a condenser microphone, the diaphragm acts as one plate of a capacitor, and the vibrations produce changes in the distance between the plates.

- Since the plates are biased with a fixed charge (Q), the voltage maintained across the capacitor plates changes with the vibrations in the air.
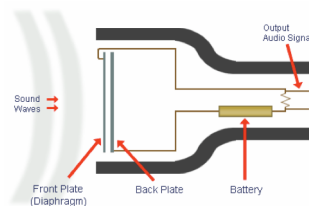
Dynamic Microphones

- In a dynamic microphone, a small **movable induction coil**, **positioned in the magnetic field of a permanent magnet**, is attached to the diaphragm.

- When sound enters through the windscreen of the microphone, the sound wave vibrations move the diaphragm.

- When the diaphragm vibrates, the coil moves in the magnetic field, producing a varying current in the coil through **electromagnetic induction**.

Cross-Section of Dynamic Microphone

Wires carrying electrical audio signal

Sound Waves

Magnet

Coil

Diaphragm

Microphones in Smartphones

- Almost all new handsets use MEMS microphones (often plural!)
- Two conducting membranes, one on top of the other, acting as a capacitor
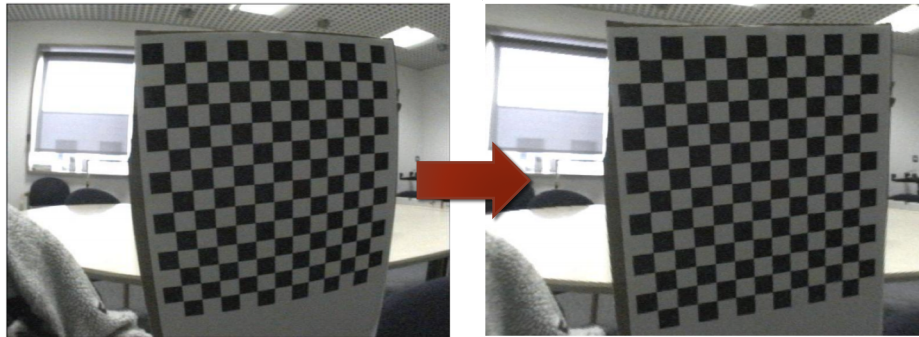- Vibrations cause the capacitance to change
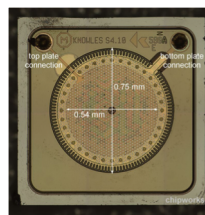
Sensor: Cameras

- These vary, but more and more make use of MEMS for (auto)focus
- The underlying light sensor is no different from 'normal' cameras
- However the small, cheap lenses inevitably suffer from distortion
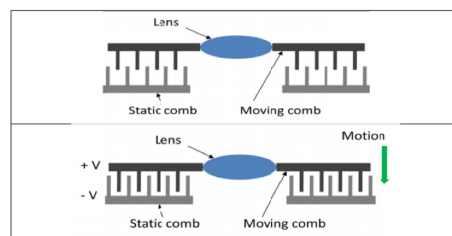
Distortion Correction

- Calibrate lens -> Remove distortion
- But this is a costly process

Camera Sensor

- With such small apertures, longer exposures are needed to get good output
- Hence phone cameras suffer from extensive noise in low light levels
  - Photon shot noise

Accessing Sensors (Android)

- We register for a particular sensor and provide a hint for the rate required

```java
public class SensorTestActivity extends Activity implements SensorEventListener {

  private SensorManager sensorManager;

  public void onCreate(Bundle savedInstanceState) {
    //...
    sensorManager = (SensorManager) getSystemService(SENSOR_SERVICE);
  }

  public void onSensorChanged(SensorEvent event) {
    if (event.sensor.getType() == Sensor.TYPE_ACCELEROMETER) {
      // Do something
    }
  }

  public void onAccuracyChanged(Sensor sensor, int accuracy) {
    // May be blank
  }

  protected void onResume() {
    //...
    sensorManager.registerListener(this,
        sensorManager.getDefaultSensor(Sensor.TYPE_ACCELEROMETER),
        SensorManager.SENSOR_DELAY_NORMAL);
  }

  protected void onPause() {
    //...
    sensorManager.unregisterListener(this);
  }
```

Get sensor service

Handle new sensor event

Register for specific sensor only on resume

Deregister all sensors if we're paused

Continuous Sensing

- Most of the smartphone OSes assume you don't want to register for 24/7 sensing events
- If you do, watch out that the OS doesn't require some extra action on your part
  - e.g., some versions of Android put the CPU into a low power state after a certain time of screen inactivity. The lowest power states preclude polling the sensor data...!
- You might have to hold a wake lock on the CPU if you want to do this (which means the battery will deplete faster!)

Nominal Rates

- The sensor hardware samples at a constant ('nominal') rate but timestamping is error-prone
- Hence most smartphone APIs shy away from numerical rates. Android uses:

```
case SENSOR_DELAY_FASTEST:
    delay = 0;
    break;
case SENSOR_DELAY_GAME:
    delay = 20000;
    break;
case SENSOR_DELAY_UI:
    delay = 66667;
    break;
case SENSOR_DELAY_NORMAL:
    delay = 200000;
```

Sampling

- Smartphone OSes are not real-time. Most sensors regularly update a register with values. The updates produce interrupts and eventually the OS gets around to collecting the value.
- If the OS is busy already, a new value could come in before we've read the last!
- Dropped readings...
- More recent sensors use a ring buffer so we don't drop any, but...
- The timestamps are currently of the time the datum was collected and not the instant it was created...
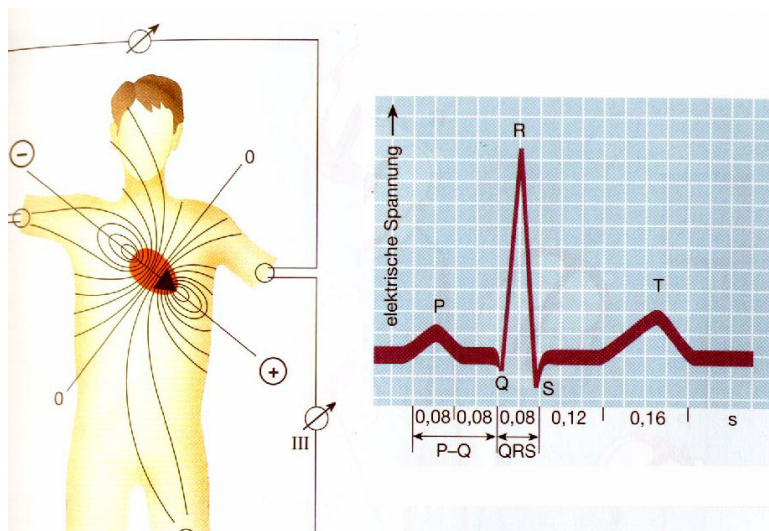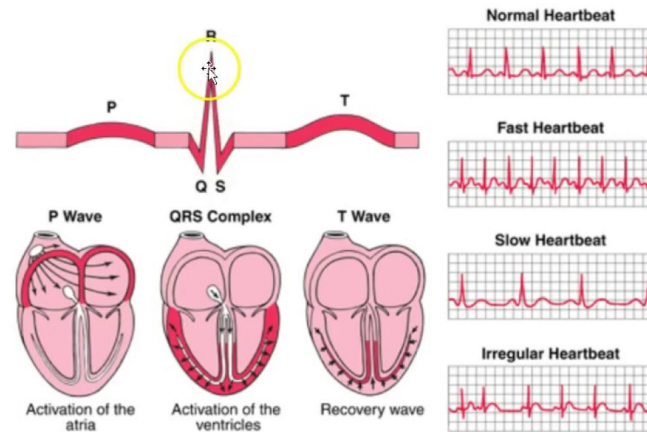
Nominal Rate Example (Nexus S)
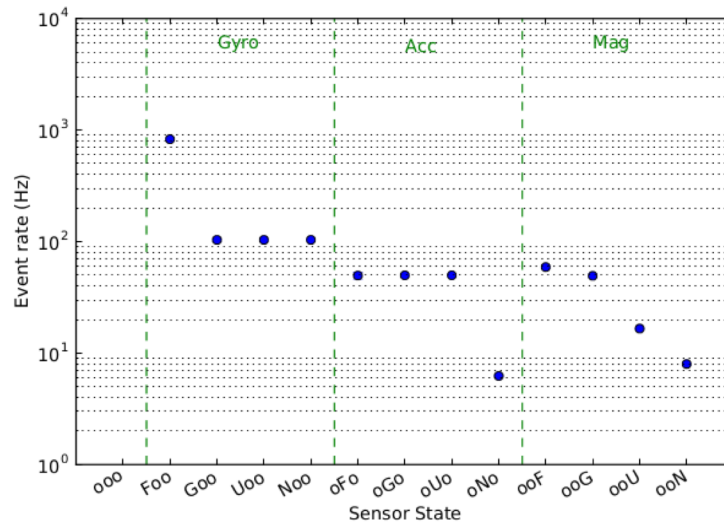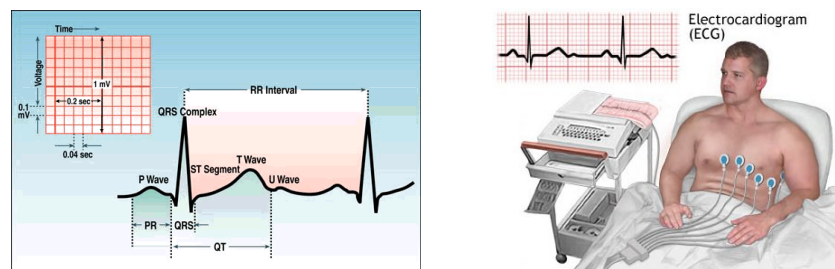
Power Draw (Nexus S)
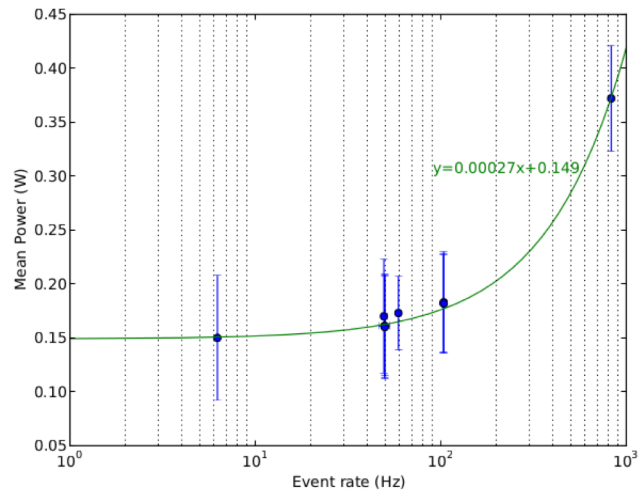
Electrocardiogram (Heart Activity)

Electrocardiogram (Heart Activity)

Electrocardiogram (Heart Activity)

The P wave is associated with the contractions of the atria (the two chambers in the heart that receive blood from outside)
The QRS is a series of waves associated with ventricular contractions (the ventricles are the two major pumping chambers in the heart)
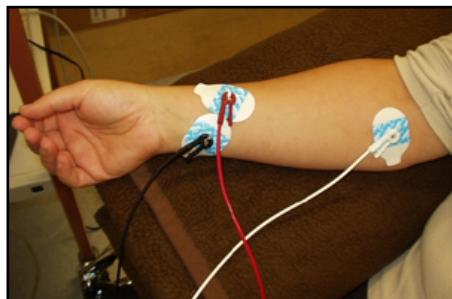The T and U waves follow the ventricular contractions

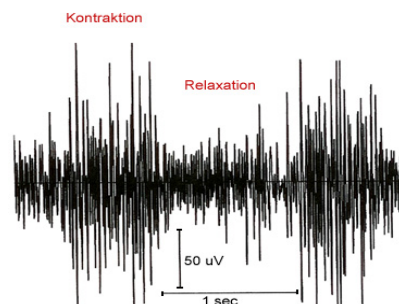https://www.youtube.com/watch?v=gWakpOAxWAU

ECG Applications

- Diagnostics
- Functional analysis
- Implants (pace maker)
- Biofeedback (heartrate variability, HRV)
- Peak performance training, monitoring

Electromyogram (Muscle Movement)

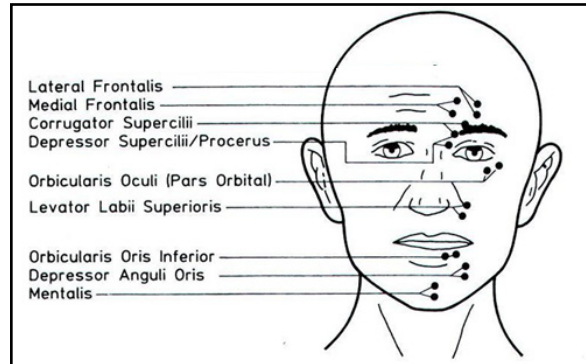**EMG surface (glue-)electrodes**

EMG - signal (up to 3mV, 1kHz)
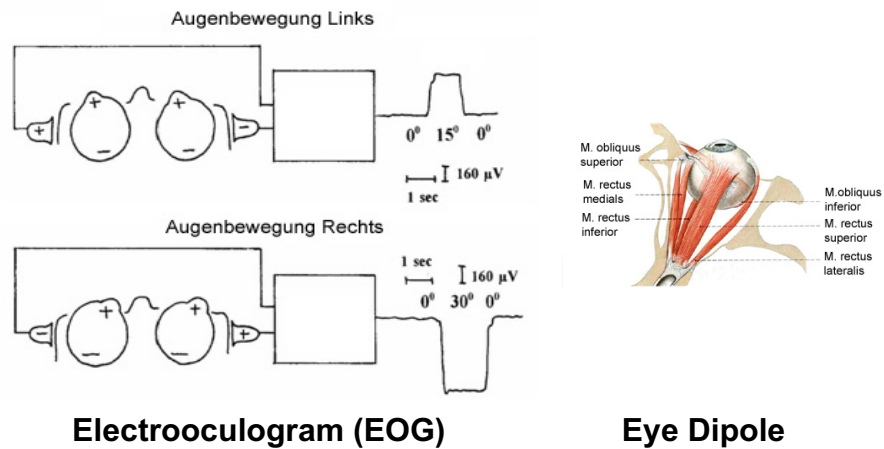
Electromyogram (Muscle Movement)

Recording locations for facial EMG

EMG Applications

- Rehabilitation
- Functional analysis
- Active prosthetics
- Biomechanics, sports medicine

Electrooculogram (Eye Movement)
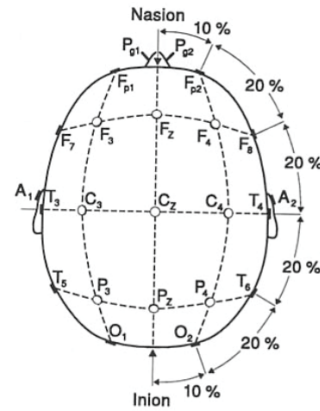

Electrooculogram (EOG)　　　　**Eye Dipole**

EOG Applications

- Diagnostics
- Functional analysis
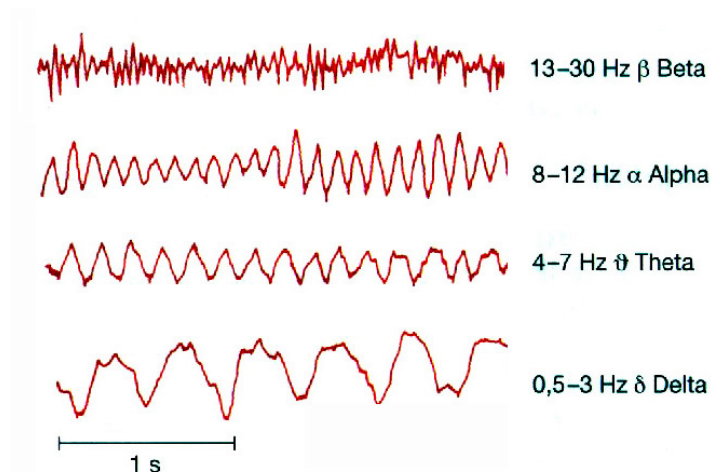- Human-computer interfaces

Electroencephalogram (Brain Activity)

EEG electrode cap system

Locations of 10/20

Electroencephalogram (Brain Activity)

13–30 Hz β Beta

8–12 Hz α Alpha

4–7 Hz ϑ Theta

0,5–3 Hz δ Delta

1 s

Electroencephalogram (Brain Activity)

- Delta (up to 4Hz)
  - Front in adults, back in children
  - Sleep, babies, during some continuous attention tasks
  - (subcortical lesions, diffuse lesions, …)
- Theta (4-8Hz)
  - Locations not related to task at hand
  - Young children, drowsiness or arousal, idling
  - (focal subcortical lesions, deep midline disorders, …)
- Alpha (8-13Hz)
  - Posterior regions, both sides
  - Relaxed, reflecting, closing eyes, inhibition control
  - (coma)
- Beta (13-30Hz)
  - Both sides, symmetrical distribution
  - Alert/working; active, busy or anxious thinking, active concentration
  - (benzodiazepines)
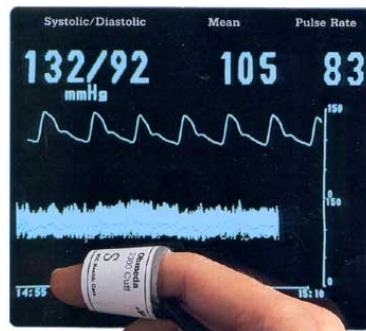
Electroencephalogram (Brain Activity)
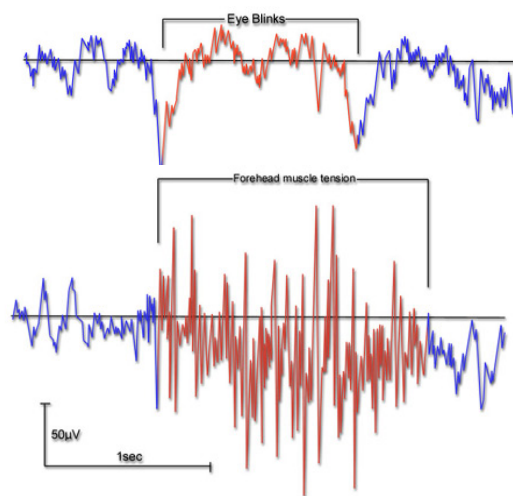
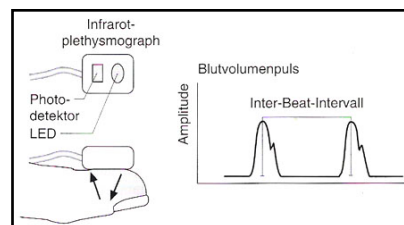EEG artifacts: Eye blinks, muscle tension

EEG Applications

- Diagnostics (epilepsy, oncology, ..)
- Cognitive sciences
- Sleep analysis
- Human computer interfaces (BCIs)
- Pharmacology
- Intensive care, monitoring

Other Biosignals

Blood volume   Infrared plethysmography

Other Biosignals

- Pulse oximeter
- Non-invasive technology used to measure the **heart rate (HR)** and **blood oxygen saturation (SpO$_2$)**
- Project infrared and near-infrared light through blood vessels near the skin
- Detect the amount of light absorbed by hemoglobin in the blood at two different wavelengths to help determine level of oxygen
- Blood vessels contract and expand with the patient's pulse which affects the pattern of light absorbed over time
- Computation of HR and SpO$_2$ from the light transmission waveforms can be performed using standard DSP algorithms

Other Biosignals

Breathing sensors
(thermal/optical/mechanoresistive)
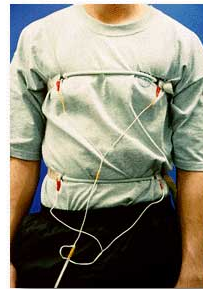
Other Biosignals

Galvanic skin response (GSR)
Electrodermal activity (EDA)
Skin conductance level (SCL)

**Peripheral body
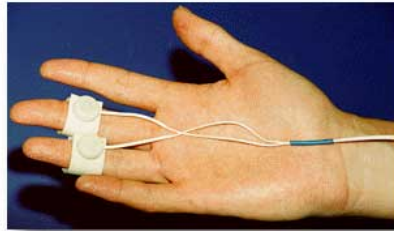temperature**

Biomedical Measurements

Biomedical measurements	Voltage range (V)	Number of users = K (sensors)	Bandwidth (Hz)	Sample rate (samples/s) = (Hz)	Resolution [b/sample]	Information rate [b/s]
ECG	0.5–4 m	5–9	0.01–250	1250	12	15,000
Heart sound	Extremely small	2–4	5–2000	10,000	12	120,000
Heart rate	0.5–4 m	2	0.4–5	25	24	600
EEG	2–200 μ	20	0.5–70	350	12	4200
EMG	0.1–5 m	2+	0–10,000	50,000	12	600,000
Respiratory rate	Small	1	0.1–10	50	16	800
Temperature of body	0–100 m	1+	0–1	5	16	80

Bandwidth = $f_{max} - f_{min}$
Sample rate = 5_f_{max}
Information rate = R_b = Resolution_Sample rate

S. Arnon, et al., "A Comparative Study of Wireless Communication Network Configurations for Medical Applications," IEEE Wireless Communications, pp. 56-61, February 2003
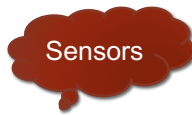
From Smart Devices to Crowdsensing
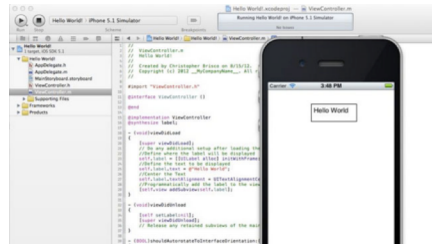

MCS (Mobile Crowdsensing)

Technical Enabler 1: Powerful Embedded Sensors in Smartphones

Sensors

- Ambient light
- Proximity
- Dual cameras
- GPS
- Accelerometer
- Dual microphones
- Compass
- Gyroscope

Technical Enabler 2: Open and Programmable

Technical Enabler 3: App Store
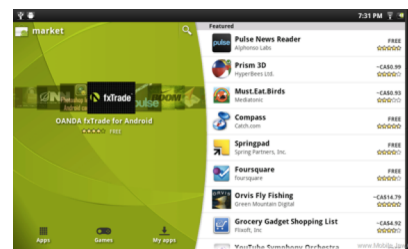
Technical Enabler 4: Mobile Computing Cloud

MCS Paradigm

Participatory	Opportunistic
Users actively engage in the data collection activity.	Takes random sample which is application defined.
Users manually determine how, when, what, where to sample.	Easy to gather large amount of data in short time.
Can avoid phone context issues.	Can't avoid phone context issues.
Higher burdens or costs.	Lower burdens or costs if contextual problems are handled.

Filtering Data by Handling Privacy Issues & Localization.

Dataset is ready for research!!!

Sensing Paradigms

- Participatory Sensing
  - Users actively engage in the "sensing process"
  - Human intelligence can be leveraged for complex tasks
  - More costs or incentives are needed to keep humans involved
  - Privacy issues
- Opportunistic Sensing
  - Fully automated and no user involvement
  - Less burden and costs on the user
  - Detect the phone context
  - Humans are underutilized
 - Privacy and energy issues

MCS: Unique Characteristics

- Multi-modal sensing capabilities
- Deployed in the field (remote sensing/management)
- Device diversity; resource limitations
- Dynamic conditions
- Privacy concerns
- Energy consumption
- Amounts of data
- Effort/cost vs. incentives; compliance
- False data
- Labeling/annotations
- Localized/aggregate analytics

Sensing

- Programmability:
  - Lack of low level sensor control
  - Different vendors offer different APIs
- Continuous sensing:
  - Need to support multitasking and background processing
  - Limited battery power on mobile phones
- Phone context:
  - Phones are used on the go and in different contexts (e.g., in vs. out of pocket)
 - Anticipating all possible different phone usage scenarios is very difficult

Learning

- Human behavior and context modeling
  - Supervised learning (small scale)
  - Semi-supervised/Unsupervised (medium to large scale)
  - Learn activities (e.g., brushing teeth, driving, running)
  - Learn places (e.g., work, home, coffee shop)

Raw data → Extracted features → Classification inferences
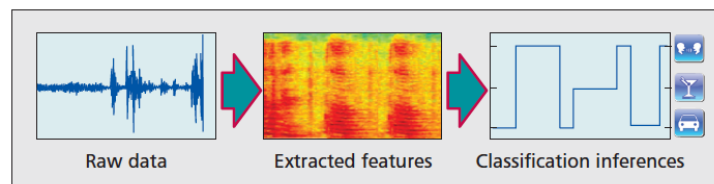
Urban Sensing Apps

- Noise mapping
- Emotion mapping
- Congestion charging
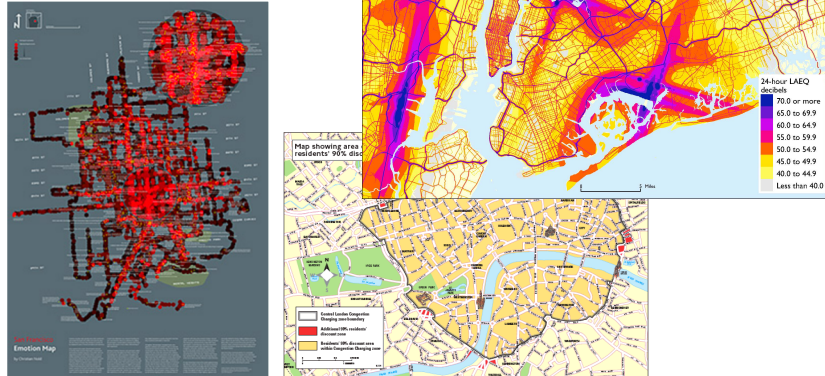
NetHealth Study

- Smartphone Sensor Data

Device	Data Type	Sampling Period (Min.)
iPhone	Location (Latitude, Longitude, Accuracy)	2.75
Fitbit	Step Counts, activity levels (sedentary, light, fair, high), Calorie burn, Heart rate	1

- Subjects
  - 467 iPhone users (on-campus freshmen)
  - Avg. age ~17y 11m (SD = 11m)
  - Fall 2015 – Fall 2016

September 2016

Iranda

Basilica

Student Center

Dorm

Gym

Stadium

Dining

Class

Basilica

Theater

Library

Dorm

Student
Center

Tennis
Court

Gym 1

Stadium

Gym 2

Dining
Hall

Swimming
Pool

Lecture
Hall

Basketball
Court

88
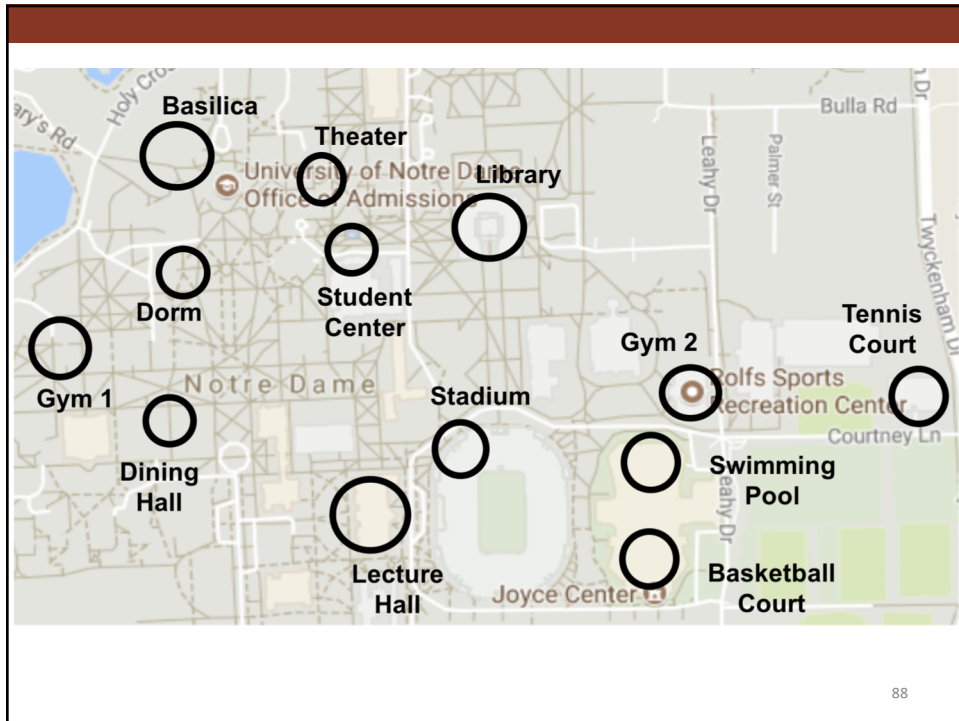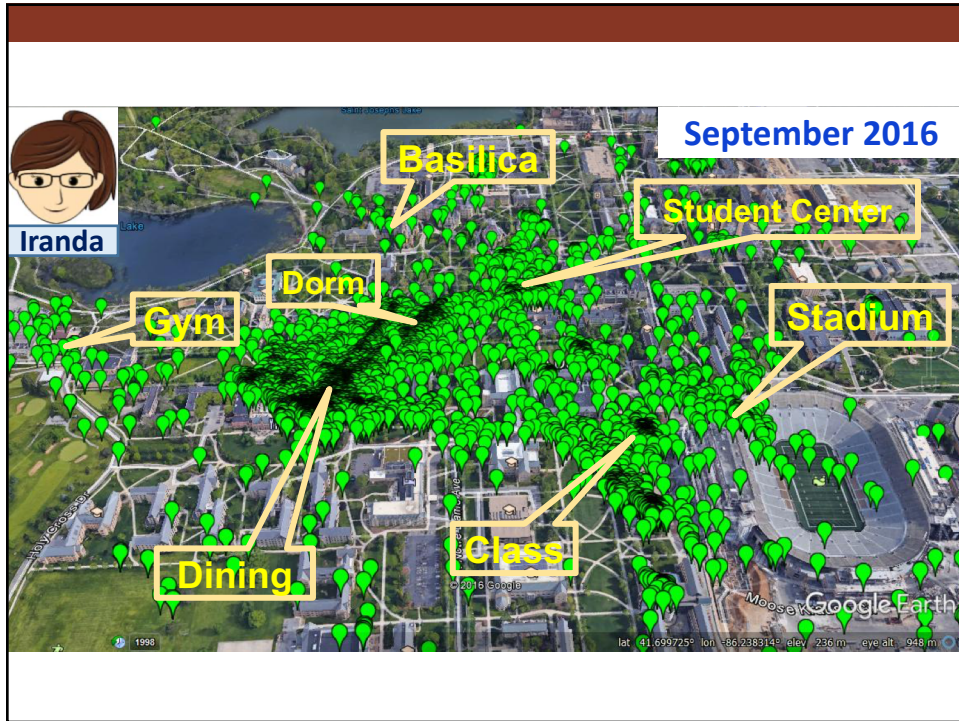
Sensing Example: Location Hotspots
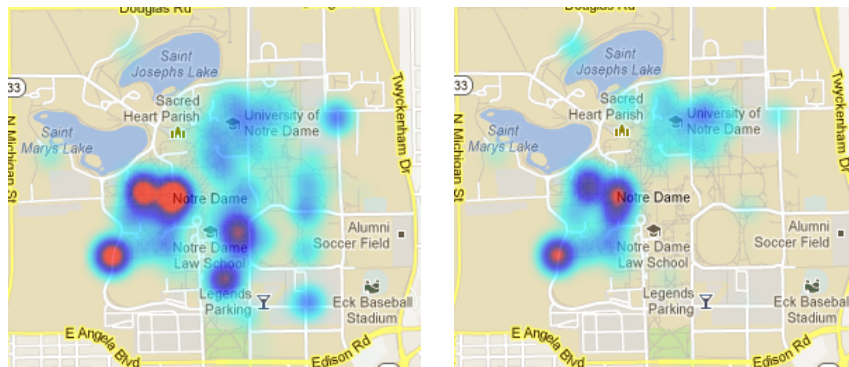
Subjects' locations during
daytime hours

Subjects' locations during
nighttime hours

Motivation

- Assess a user's **quality of life** through analysis of
  - Place visits and mobility patterns, social interactions, and levels of physical activity
- Researchers and healthcare providers can monitor **patient behavior** remotely
  - E.g., assess the effectiveness of stroke therapy
- Deliver place-specific mobile **health interventions**
  - E.g., encourage individuals to work out when near gyms or parks
- Deliver **customized surveys** to an individual's phone
  - E.g., social interaction surveys, or mood surveys

90

Continuous Health Monitoring

- Opportunities of continuous monitoring:
  - Identify mobility patterns
    - Time spent indoors/outdoors; type of transportation; locations visited
  - Recognize social interactions
    - Electronic communications (email, phone, SMS, chat)
    - In-person meetings (individual/group, type of meeting, venue)
  - Identify activities
    - Healthy/unhealthy habits, routine household activities, physical activities
  - Other health-related information and events
    - Sleep times/quality, stress, moods, falls and other injuries


Continuous Health Monitoring
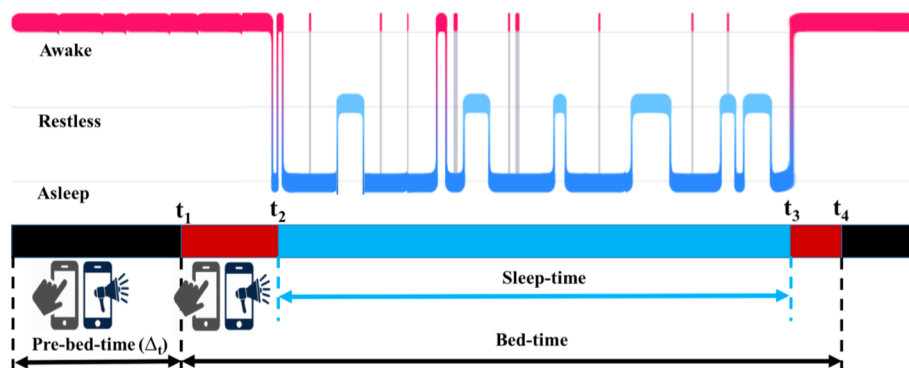
Examples of Sensing Capabilities

Sensor Type	Sensing Examples
GPS & Triangulation	Locations, routes, indoor/outdoor time
Accelerometer	Mode of transportation, activities, step counters
Gyroscope	Type of activities, unusual events (falls)
Wi-Fi Proximity	Locations, routes
Bluetooth Proximity	Proximity to friends, family, coworkers, etc.
Magnetometer	Type of activities
NFC/RFID	Locations (supermarket, library, etc.)
Barometer	Locations (floor of building)
Applications	Preferences, moods, interests/hobbies
Phone, EMail, SMS	Communication patterns, moods
Media (Music, Pictures, …)	Preferences, interests, moods

Technical Challenge: Battery Life
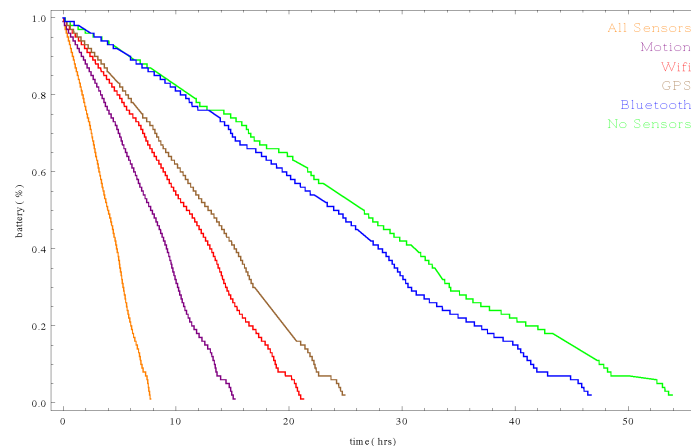
Current research focus: *collect maximum amount of data at highest quality possible, while making sure that device will last 14-16 hours* (typical time between recharging)

CIMON Sensing App: Labeling Interface

- Allows subjects to track common types of activities

- Used for development of activity detection algorithms

- In addition to pre-defined activities, subjects can add custom activities