Center for Wearable Sensors

UC San Diego
Jacobs School of Engineering

Wearable Chemical Sensors: Opportunities and Challenges

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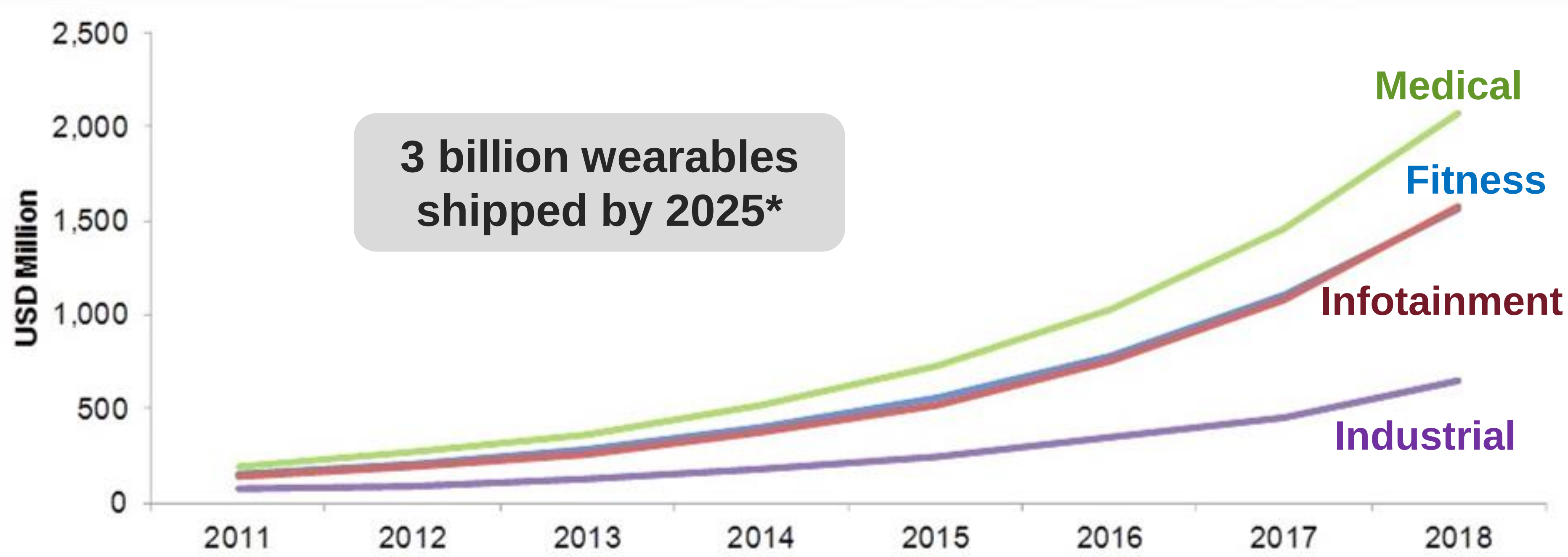
UC San Diego

Wearables:
an exciting high-growth market







*IDTechEx 2015 Report

Source: Transparency Market Research

Why aren't we there now?

Size & Usability:

Need to develop sensors that are small & seamlessly integrated into daily life

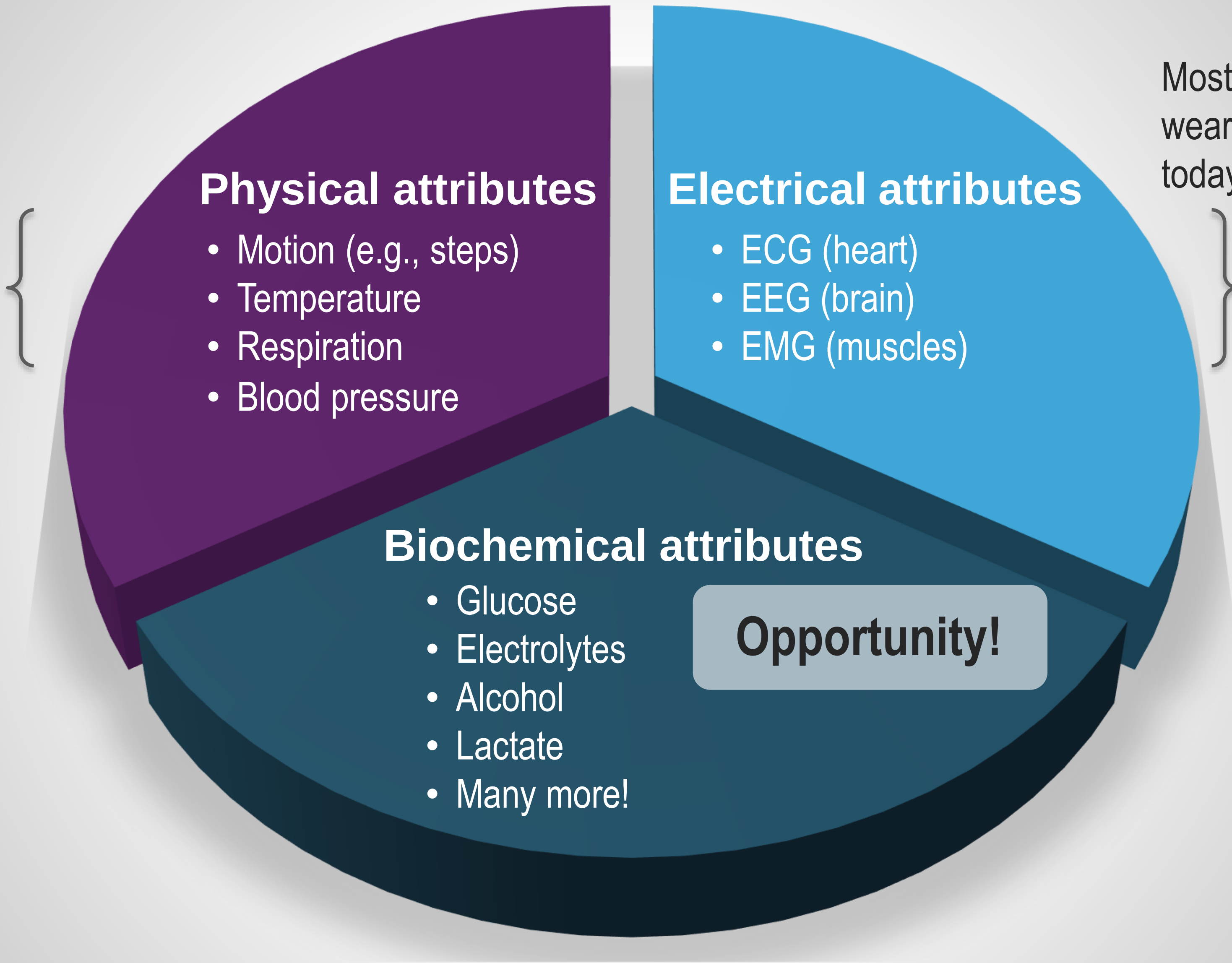
Battery Life:

Need ultra-low-power and/or energy harvesting to minimize re-charging

Utility:

Need to develop sensors that are actually useful

Wearable sensing opportunities



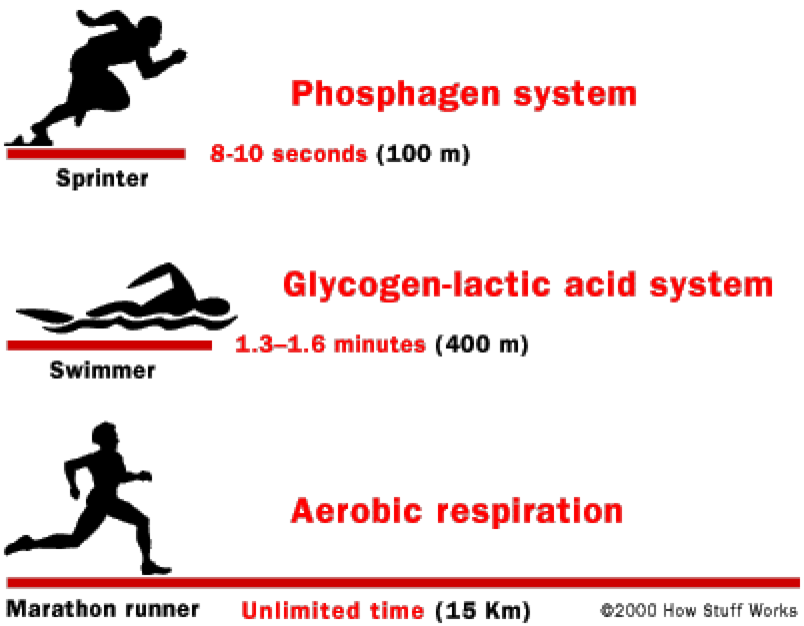
Most of the wearables market today

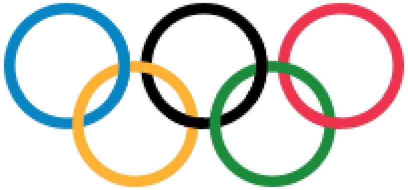
Chemical analysis: current practice

Painful / inconvenient blood draws

Example: lactate monitoring for athletes

Staying below the "lactate threshold" important for endurance training



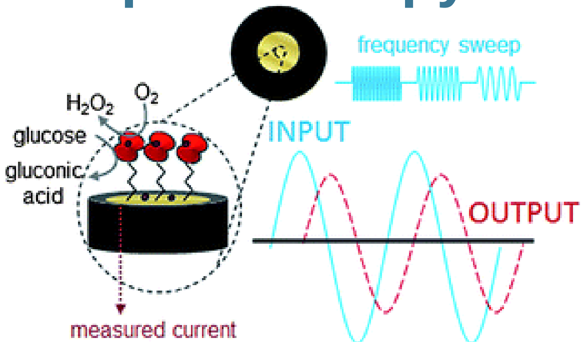


Current state-of-the-art testing method:

Non-invasive and/or continuous sensing is required

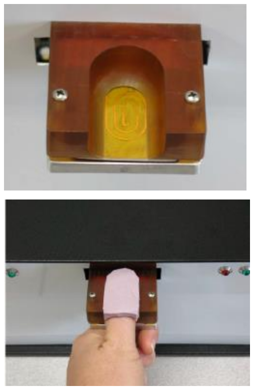
Non-Invasive Chemical Biosensing Techniques

Bioimpedance Spectroscopy



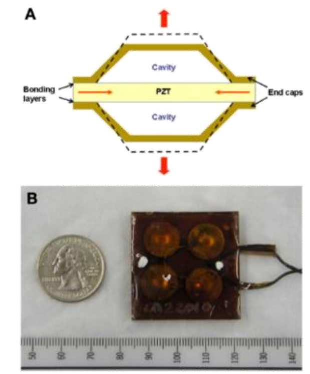
Adamson et. al. Analyst 2012

mm-wave Detection



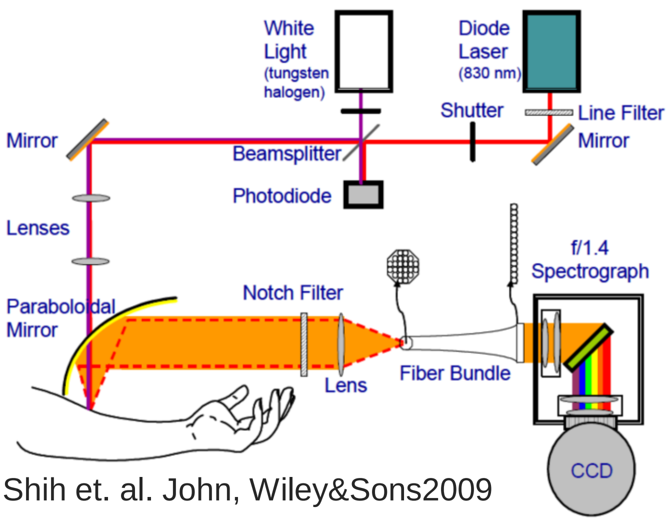
Jean et. al. SAS IEEE 2008

Ultrasound



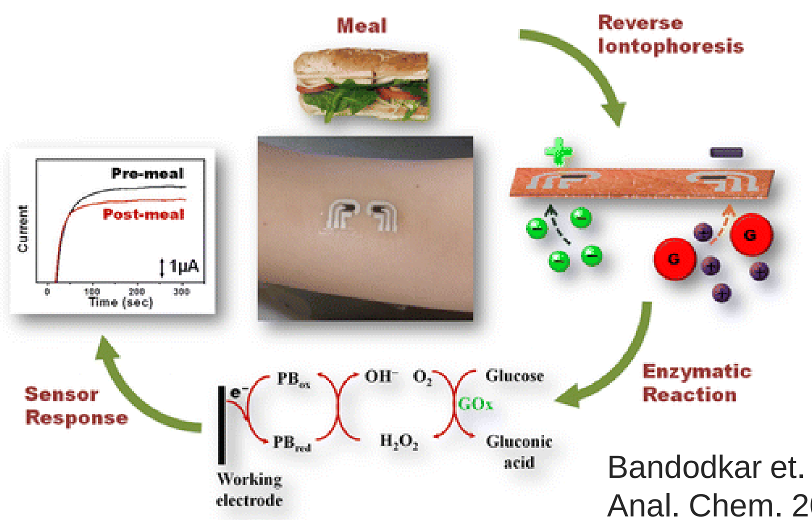
Park et. al. J Diabetes Sci Technol, 2009

Raman Spectroscopy



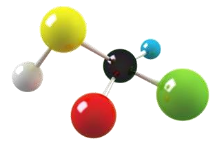
Shih et. al. John, Wiley&Sons2009

Electrochemical



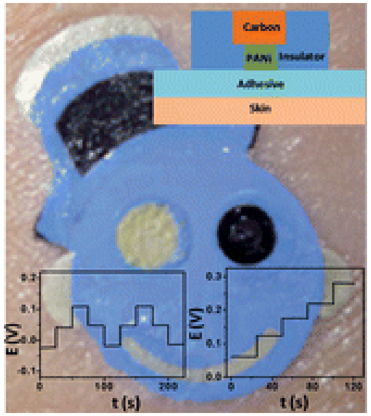
Bandodkar et. al., Anal. Chem. 2015

Electrochemical Biosensors

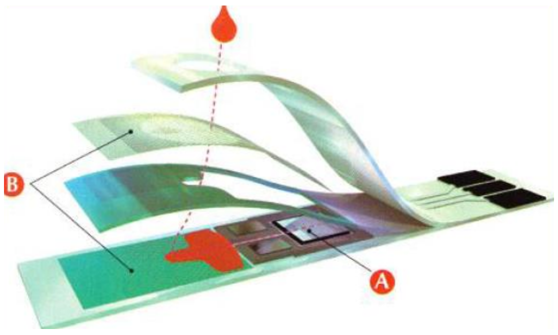


Chemical communicate via ions, electronics via electrons. Electrochemical biosensors operate by measuring electrons as the output of redox reactions. Three main types of sensors:

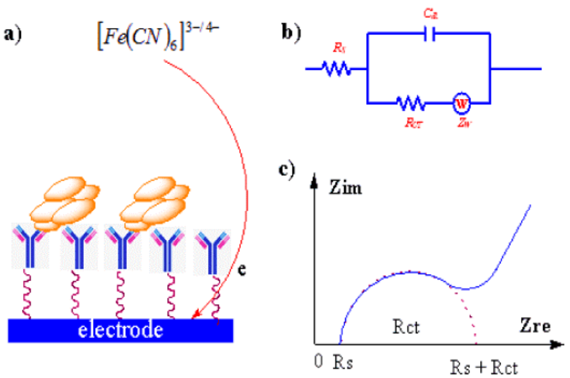
Potentiometric	Amperometric	Electrochemical Impedance Spectroscopy (EIS)



Bandodkar et. al., Analyst. 2013



Wang, Chem. Rev. 2008

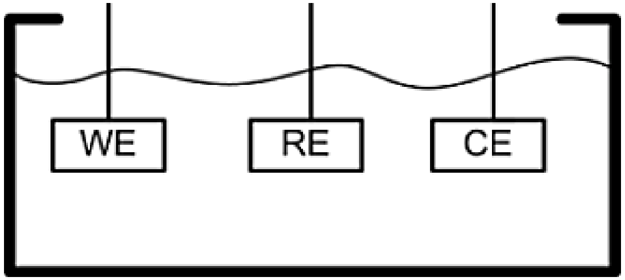


Lien et. al., Biosensors & Bioelectronics, 2011

Measures:	Voltage	Current	Complex Impedance

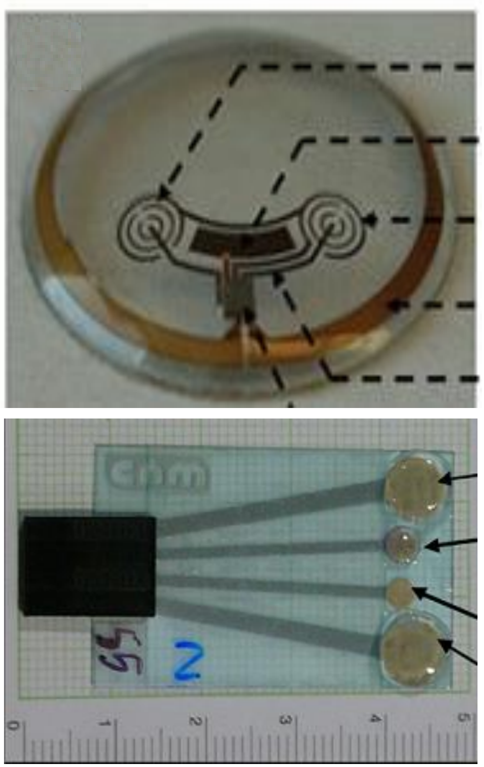
Proportional to underlying concentration of chemical analyte

Biosensor Fabrication

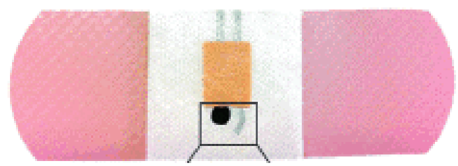


Most electrochemical biosensors rely on two- or three-electrode systems: a working electrode (WE), a reference electrode (RE), and sometimes a counter electrode (CE). Electrodes are functionalized for analyte specificity, and can be fabricated on many different materials:

Plastics

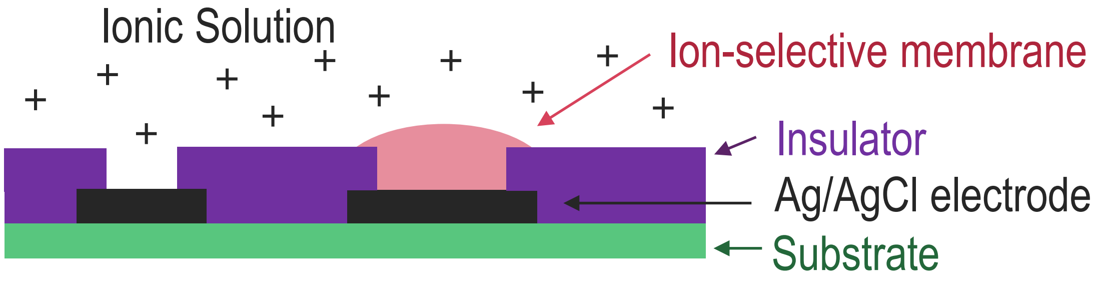


Textiles

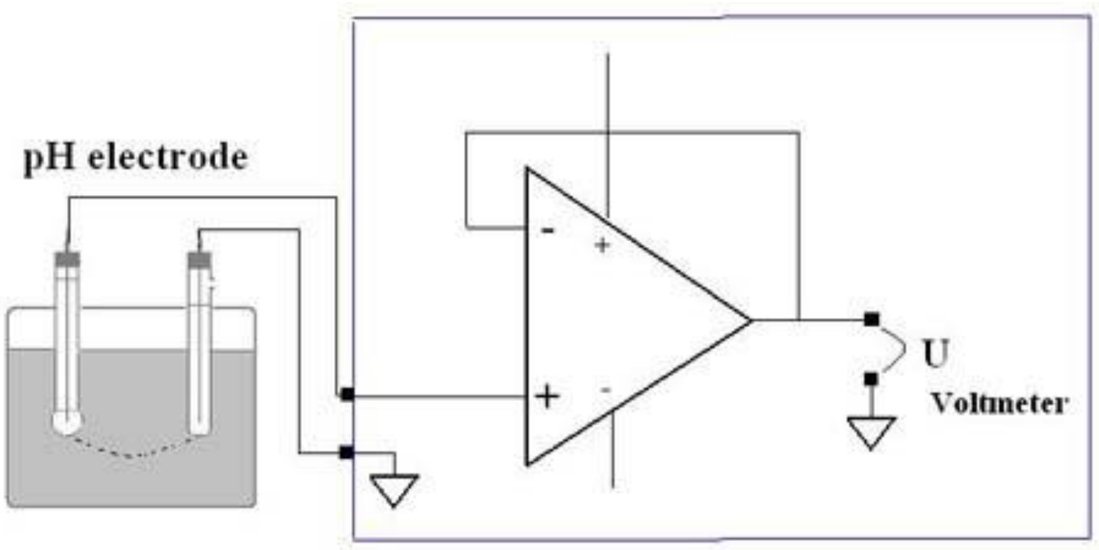


Temporary Tattoos

Example: measure the voltage between a reference electrode and an electrode with an ion-selective membrane coating



Applications: pH, K^+, Na^+, Cl^-, etc…

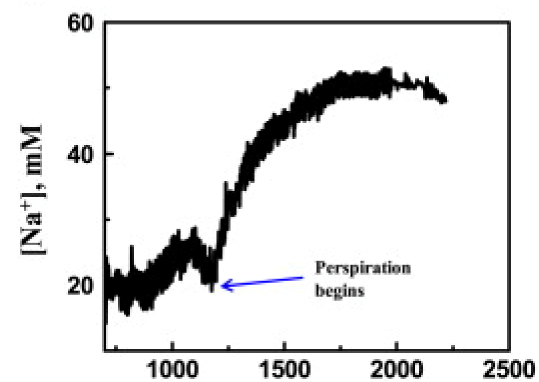


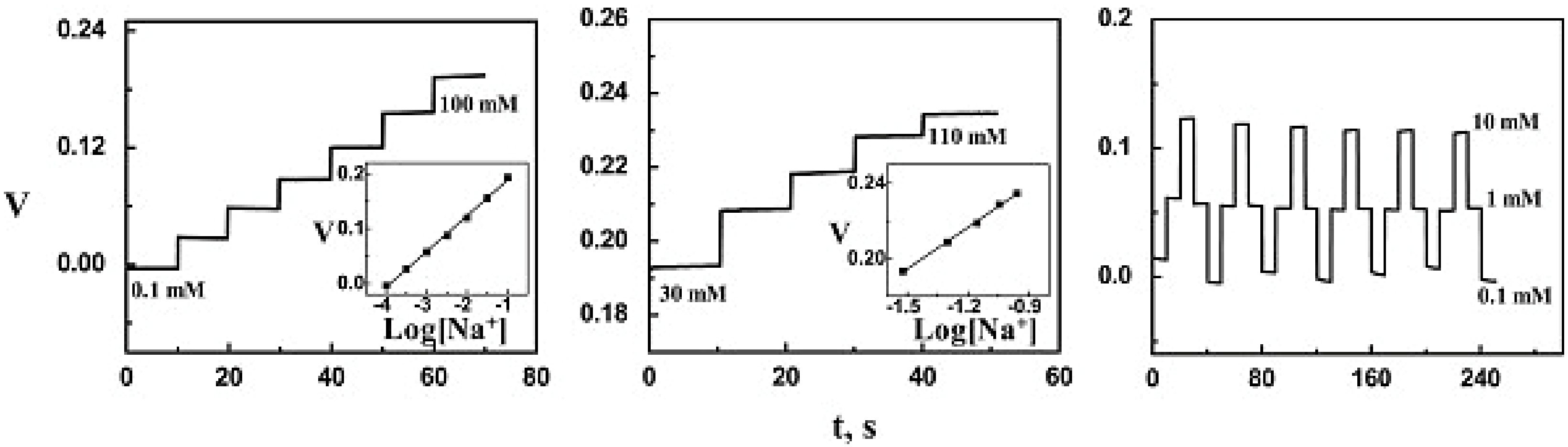
Typical Instrumentation Amplifier Requirements:

- **Voltage range:** 0-400mV
- **Noise:** several µV
- **Bandwidth:** < 100Hz

Example: a wearable sodium sensor tattoo

Enables real-time measurement of sodium in sweat

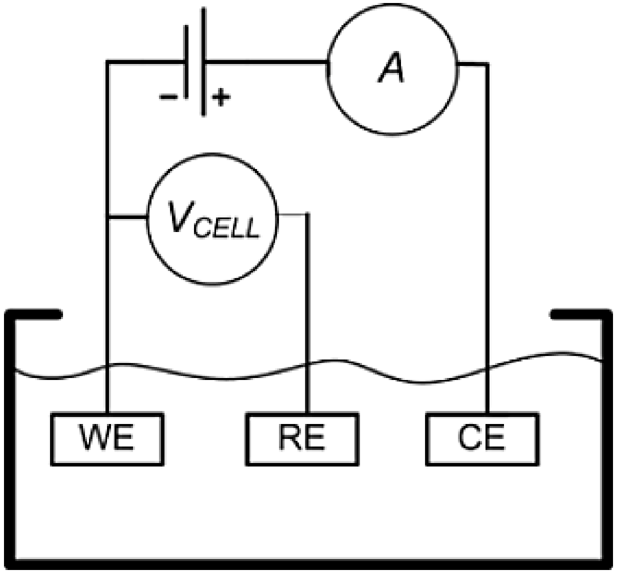




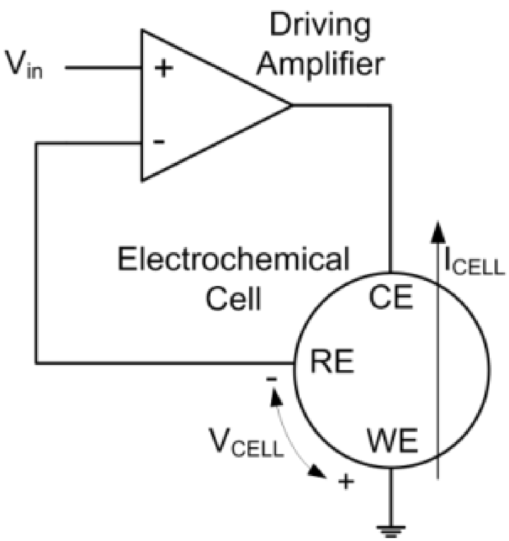
Bandodkar et al., Biosensors & Bioelectronics, 2014.

Amperometric biosensors: sensing metabolites

Selectivity: working electrode functionalized with an enzyme that catalyzes a reaction with the metabolite to be sensed, which then transfers e^- to an ISE underneath



Operating principal: enzymatic reaction occurs at specific voltage → apply voltage, measure resulting current → proportional to analyte concentration

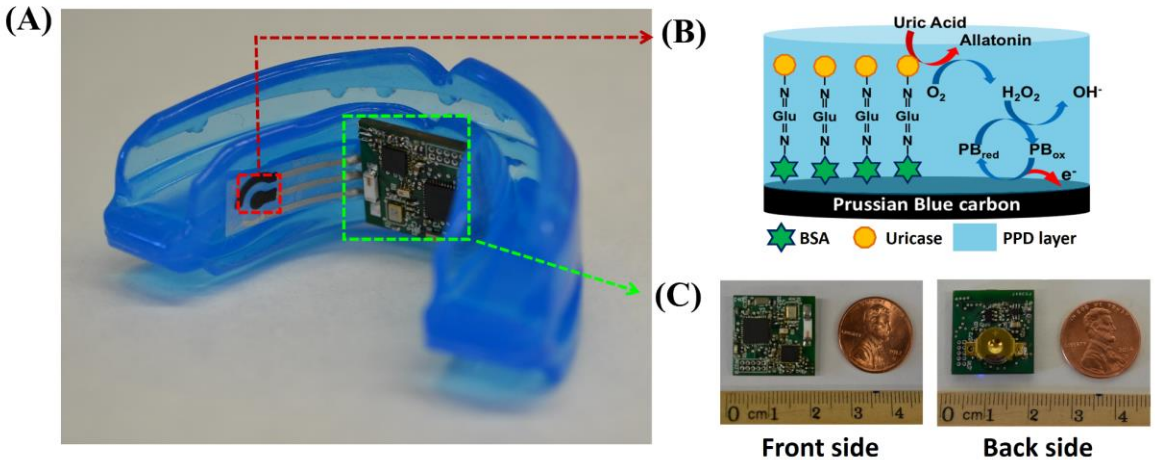


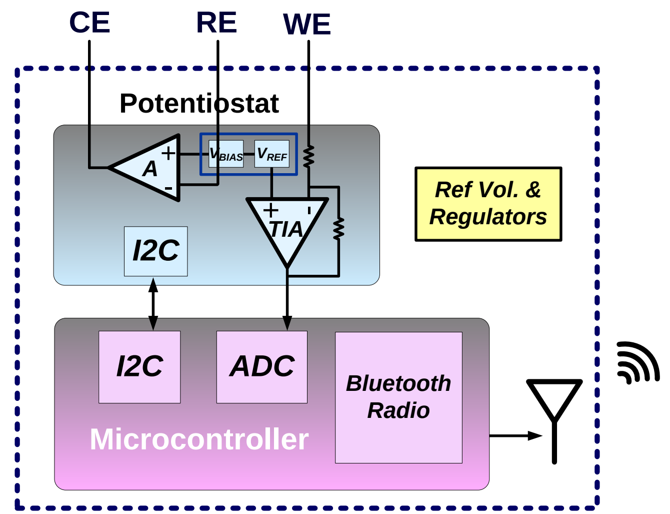
Circuit: potentiostat used to condition the cell; current sensor (e.g., TIA) to sense current, often through the counter electrode to not disturb cell potential

Typical Requirements:

- ❑ **Voltage range:** ±1V
- ❑ **Current range:** fA - µA
- ❑ **Noise:** lower current range
- ❑ **Amp. voltage gain:** > 10^4

Example System: A Saliva-Sensing Mouthguard (1)





J. Kim et al., Biosensors & Bioelectronics, 2015

Fitness applications

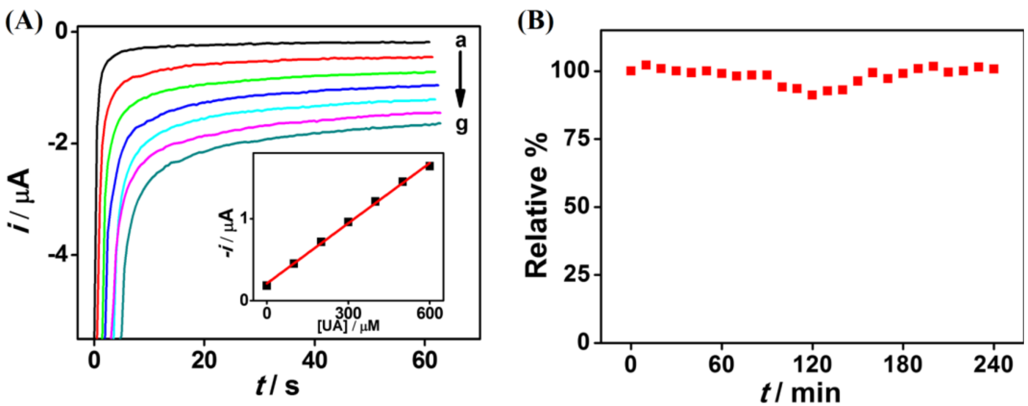
Measure Lactate for Stress / Exertion

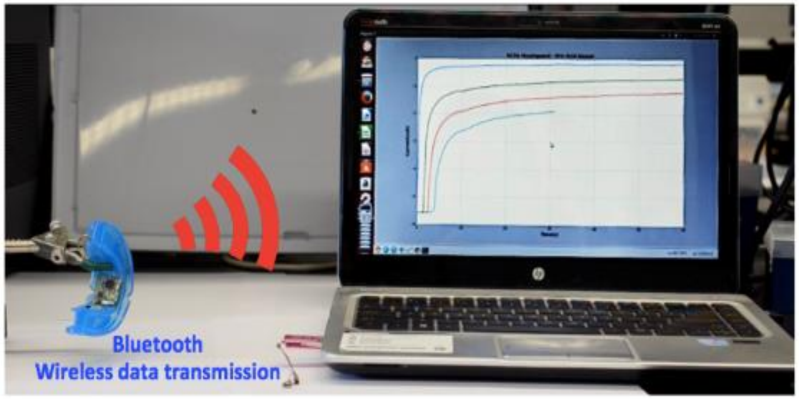
Health applications

Measures Uric Acid for Hyperuricemia

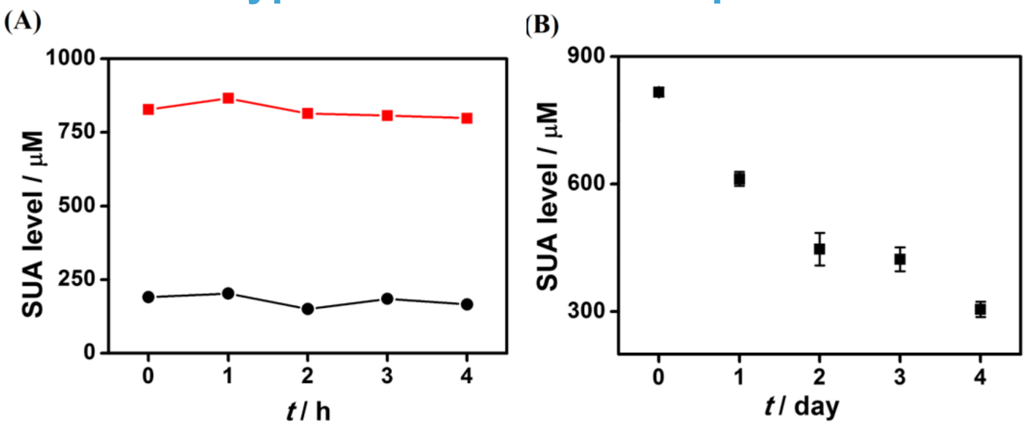
Example System: A Saliva-Sensing Mouthguard (2)

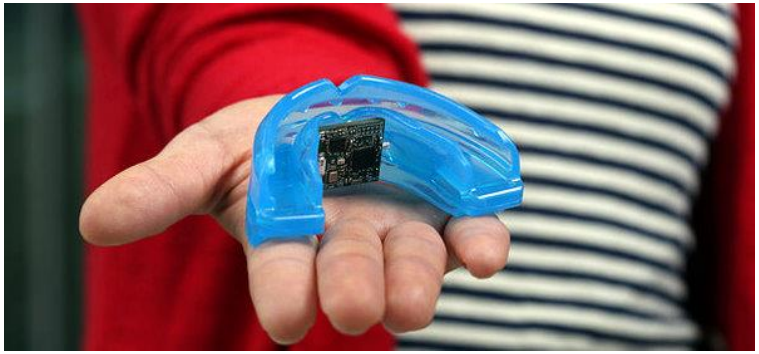
Characterization of integrated wireless mouthguard biosensor



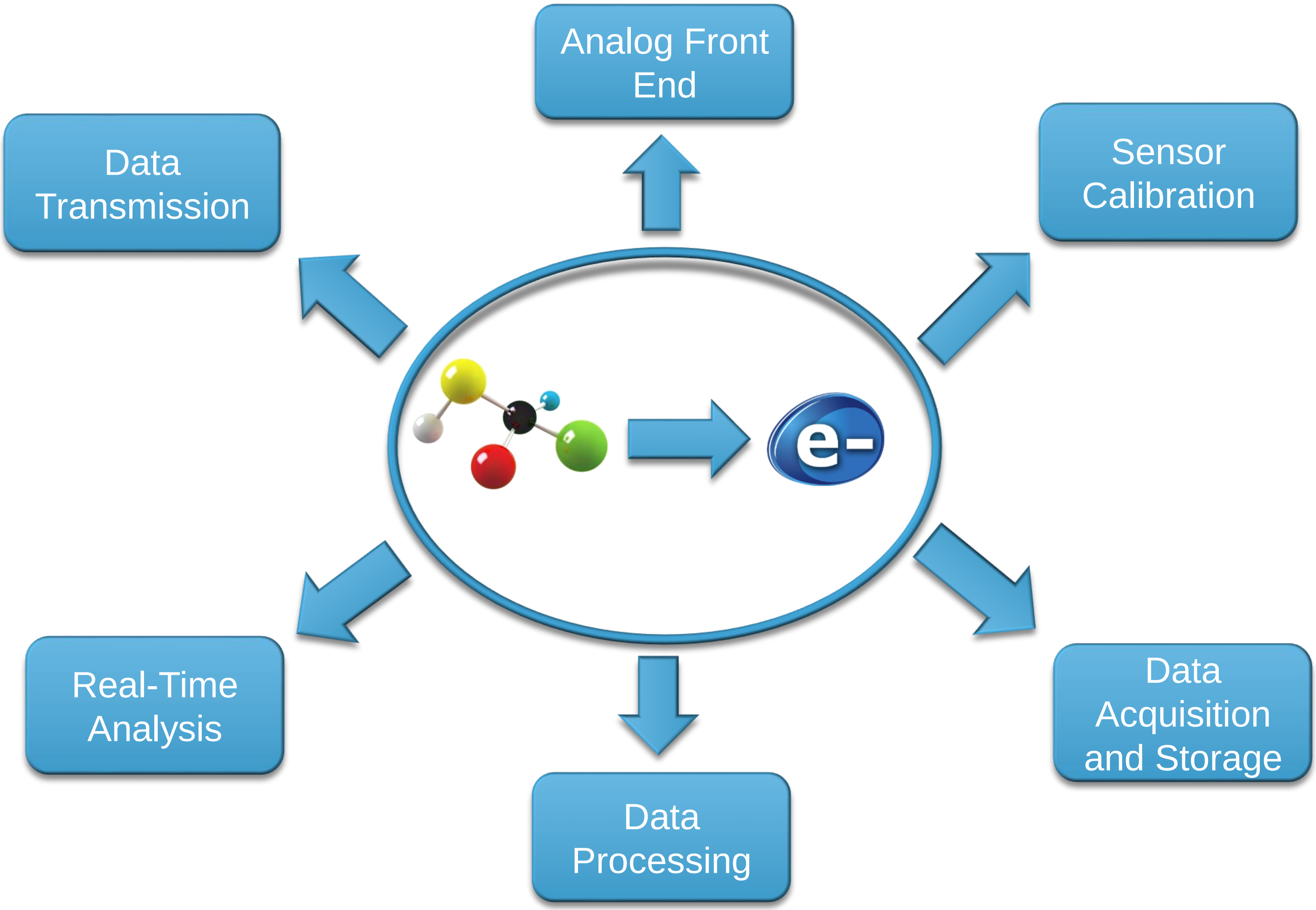


Monitoring treatment of hyperuricemia with Allopurinol®





Chemical biosensing system considerations

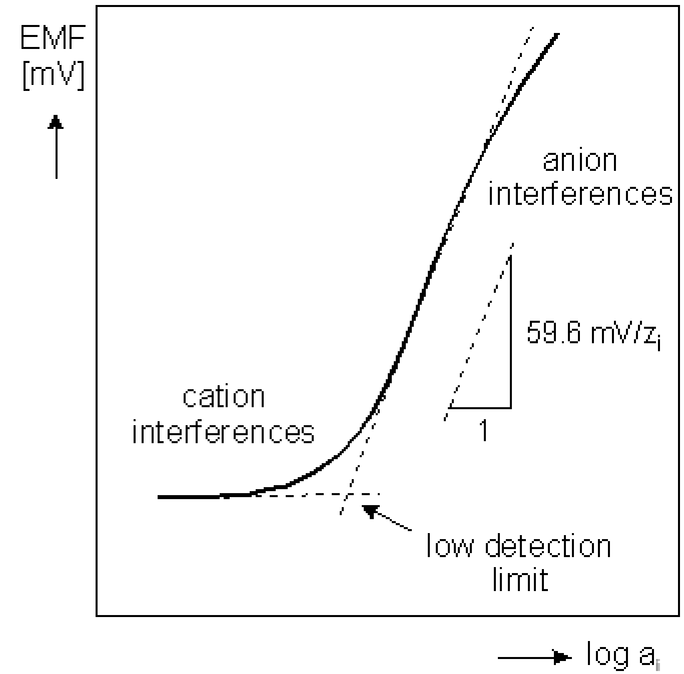


Challenge: Efficient Calibration for Operation in Complex Fluids

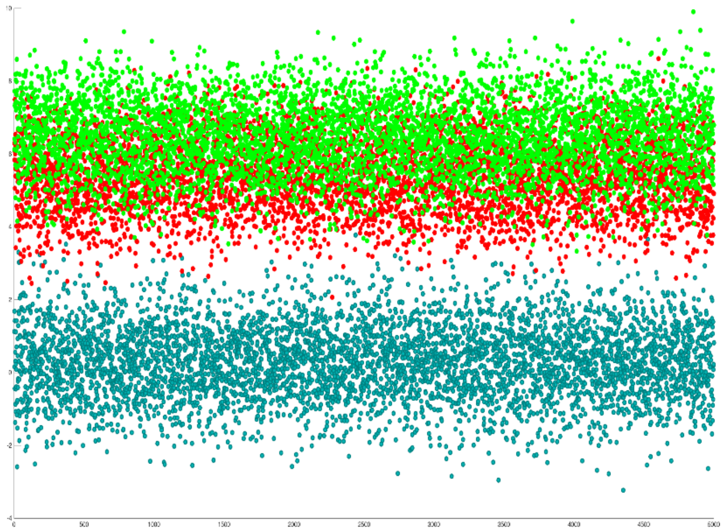
Selectivity: ISEs are not perfectly selective → other ions in solution will affected measured potential

$$V = V_0 + \frac{RT}{z_i F} \ln\left(a_i + \sum_j k_{ij} a_j^{\frac{z_i}{z_j}} \right)$$

↑ Finite selectivity coefficients



Challenge: may require significant calibration with many analytes to represent real (complex) fluids



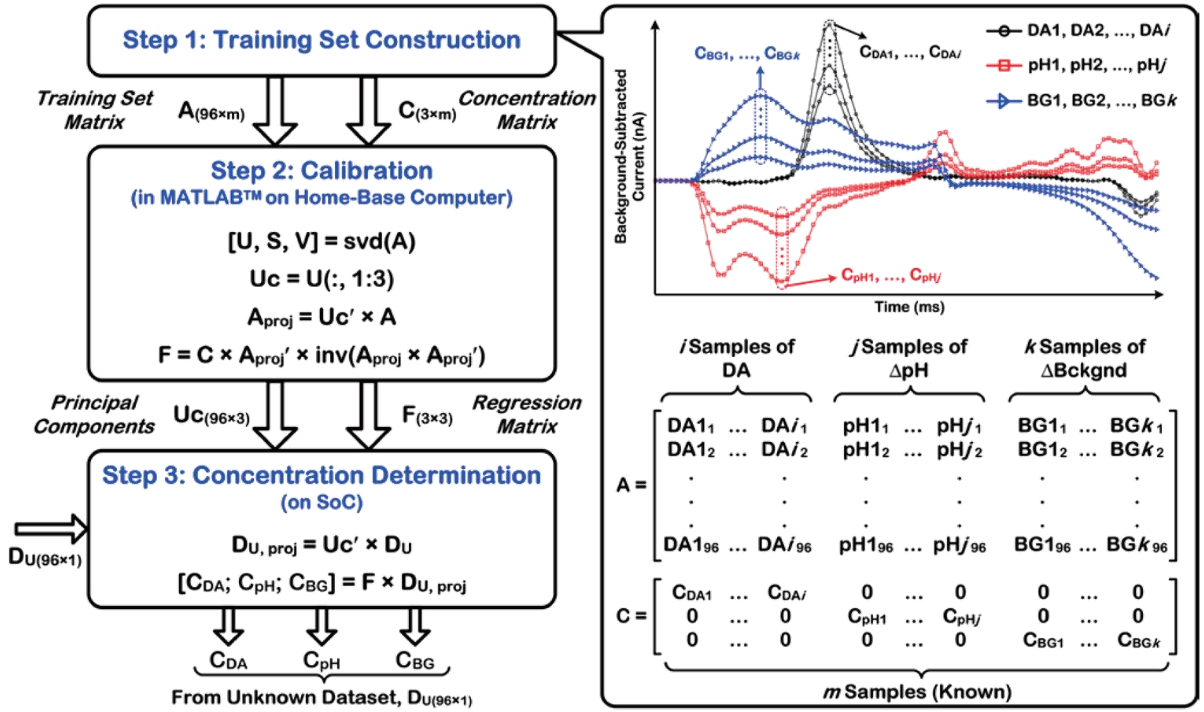
Opportunity: leverage machine-learning to quickly infer selectivity coefficients

Location: calibrate and/or process on-device, in the fog, or in the cloud

Example: dopamine monitoring in complex fluids

Challenge: dopamine sensors vary with pH and background interferers

Solution: in-sensor principal component regression (PCR)-based chemometrics to infer dopamine concentration



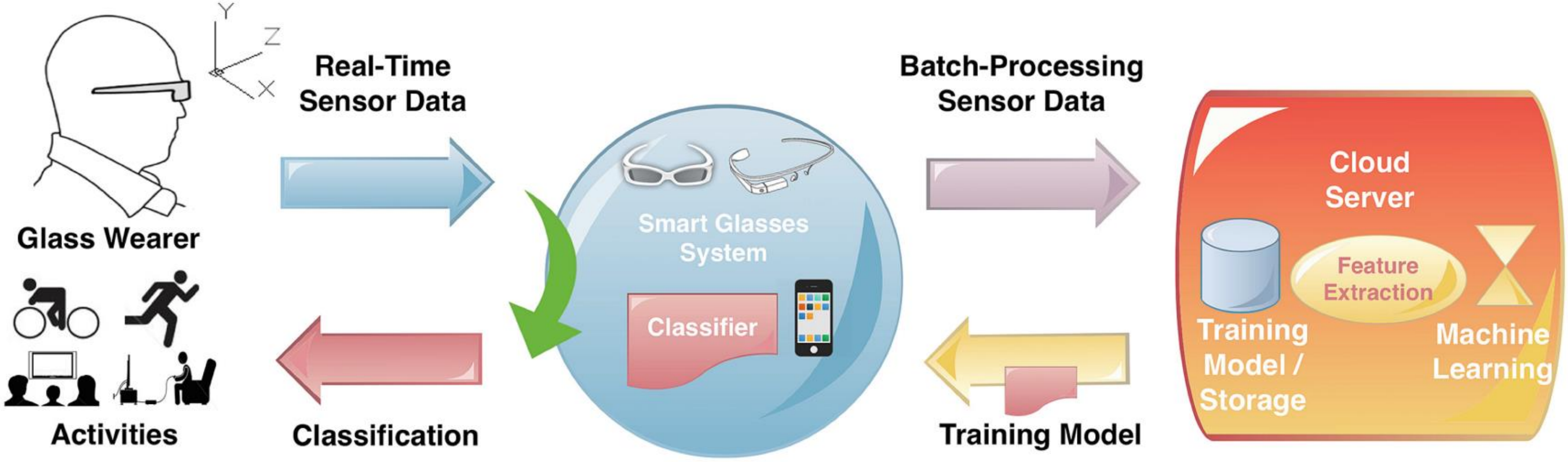
Bozorgzadeh et. al., VLSI, 2015

Leverage multi-variate analysis to improve specificity in complex environments

Data analytics

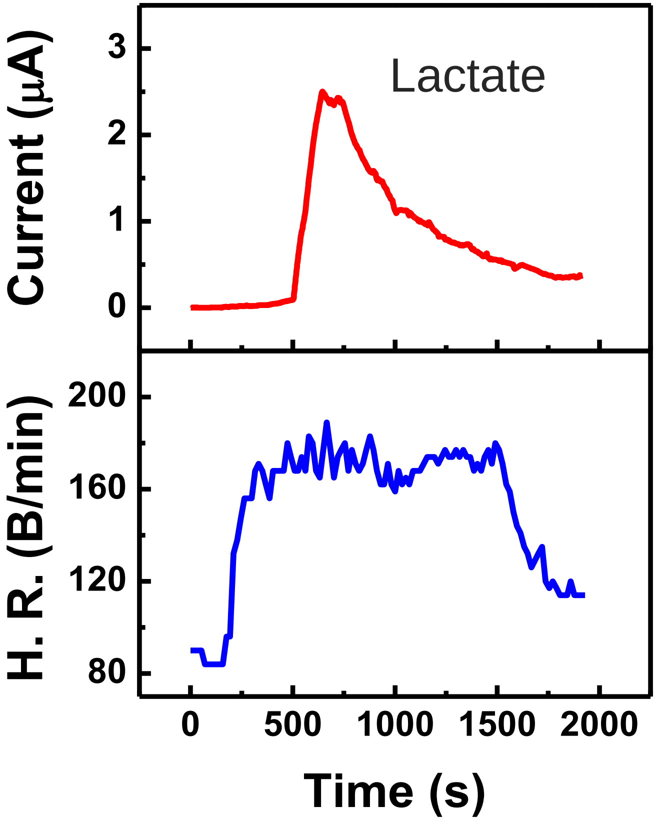
- Real-time chemical data is generally not available today. We don’t know what kind of correlations to expect – analytics will help

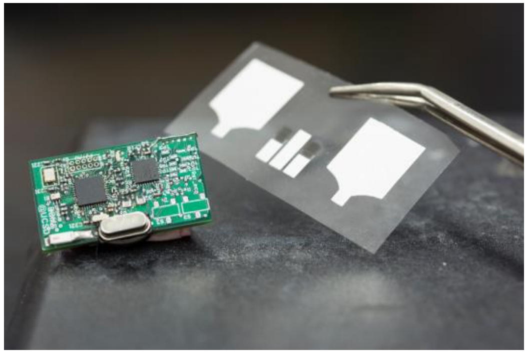
Example: classifying user’s head motions to recognize activities according to wearable sensor data from the smart glasses

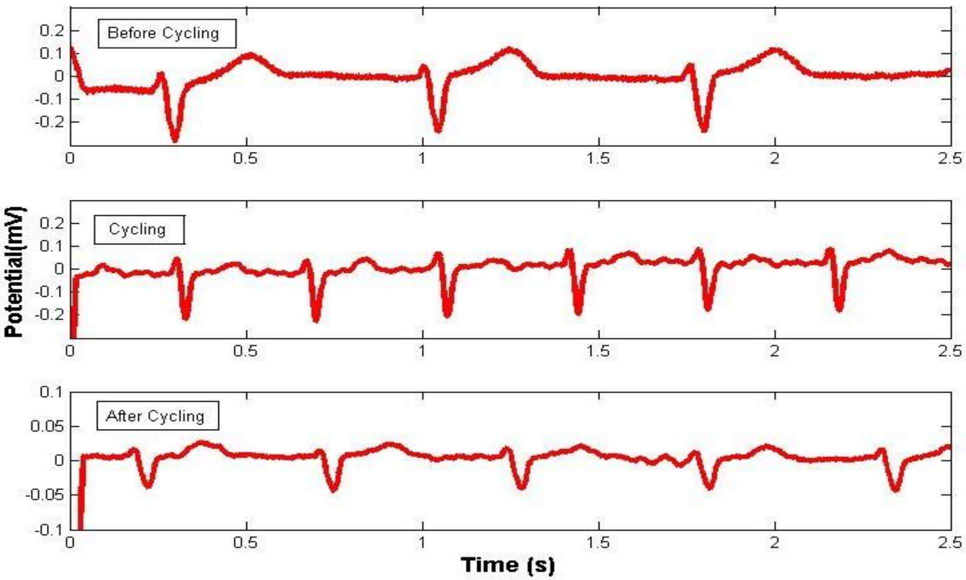


Ho and Wang, User-Centric and Real-Time Activity Recognition Using Smart Glasses, 2015

Simultaneous & continuous, real-time lactate and ECG sensing







First demonstration of simultaneous chemical+electrophysiological sensing in a wearable patch

Opportunities for data analytics

S. Imani et al., Nature Communications, May 2016

Conclusions

- Current wearable sensors have limited utility
- Introduction of chemical sensing can augment utility across a number of applications spaces:
  - High-end athletes
  - Diabetic patients
  - General-purpose "tricorder-like" monitoring
- There are many challenges:
  - Sensor fabrication on soft wearable materials
  - Miniaturized, low-power electronics
  - Low-cost calibration
  - Interference & longevity
  - Analytics & inference

} Can be solved with big-data analytics & machine learning (Low-cost calibration; Interference & longevity; Analytics & inference)

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