



# Health Sensing

## 6.810 Engineering Interaction Technologies

Prof. Stefanie Mueller | HCI Engineering Group







# Health Sensing

## 6.810 Engineering Interaction Technologies

Prof. Stefanie Mueller | HCI Engineering Group

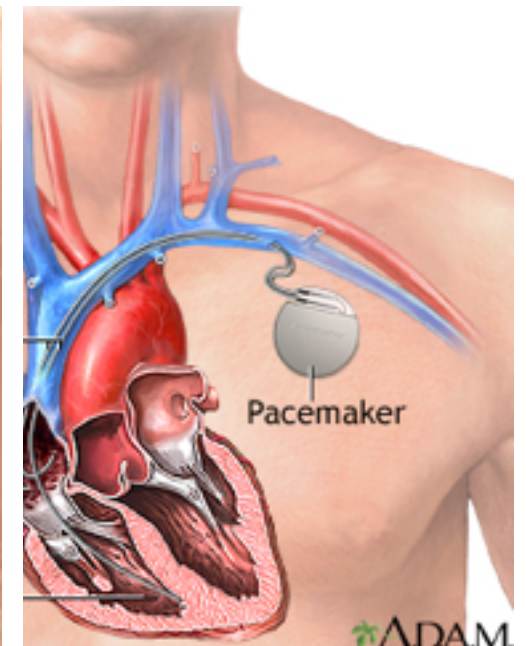
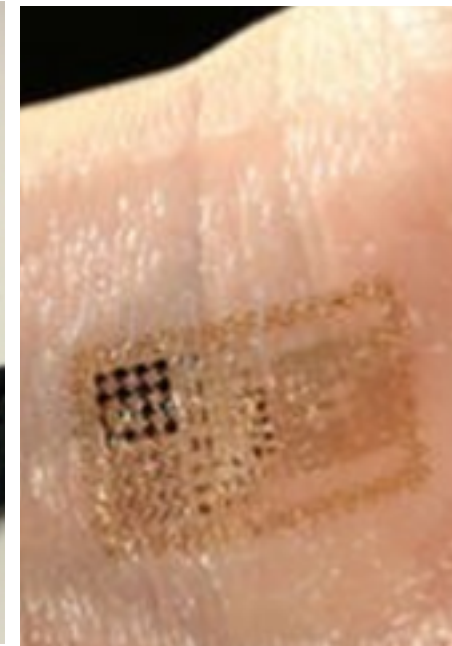
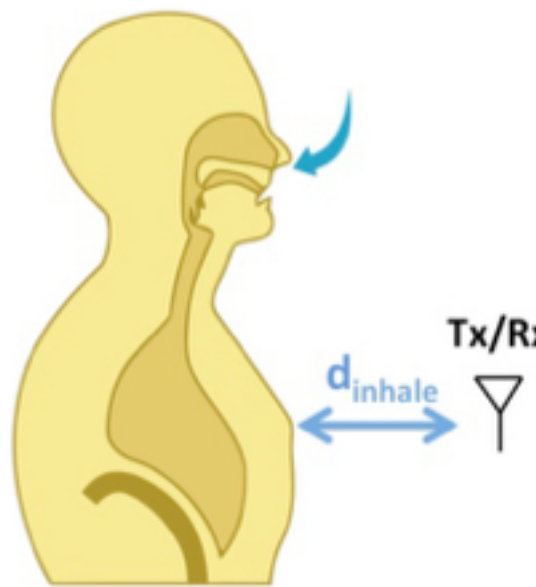


**traditional health sensing:** visit doctor once a year...  
very few data points, often only reactive not preventive





**novel health sensing:** measure anywhere & all the time  
-> many more data points, can generate warnings upfront



wireless

phone

wearable

tattoo

implanted



closeness to body

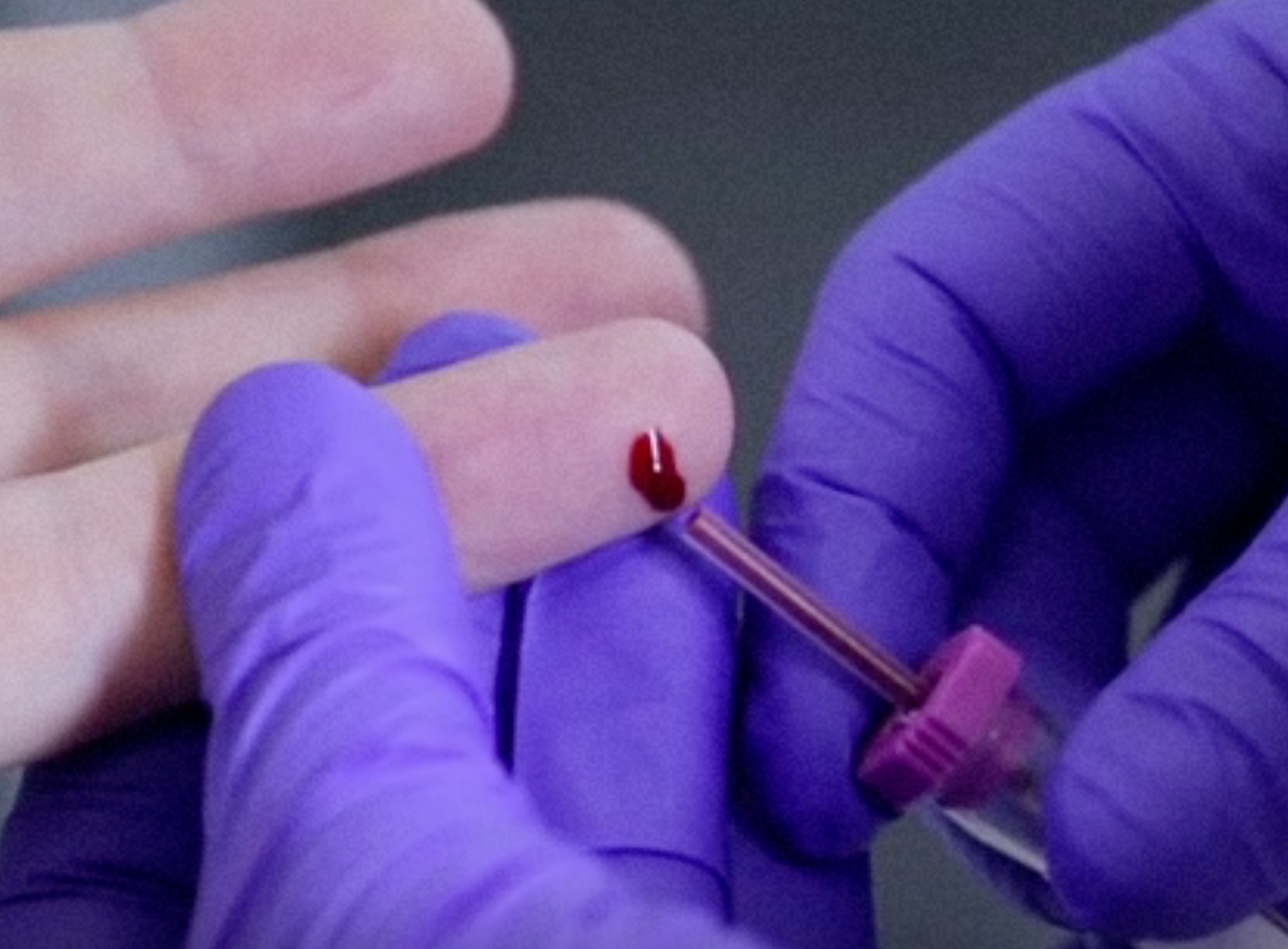


how can we detect **body signals**  
with cheap consumer technology  
accurately?

**smart-phone based**



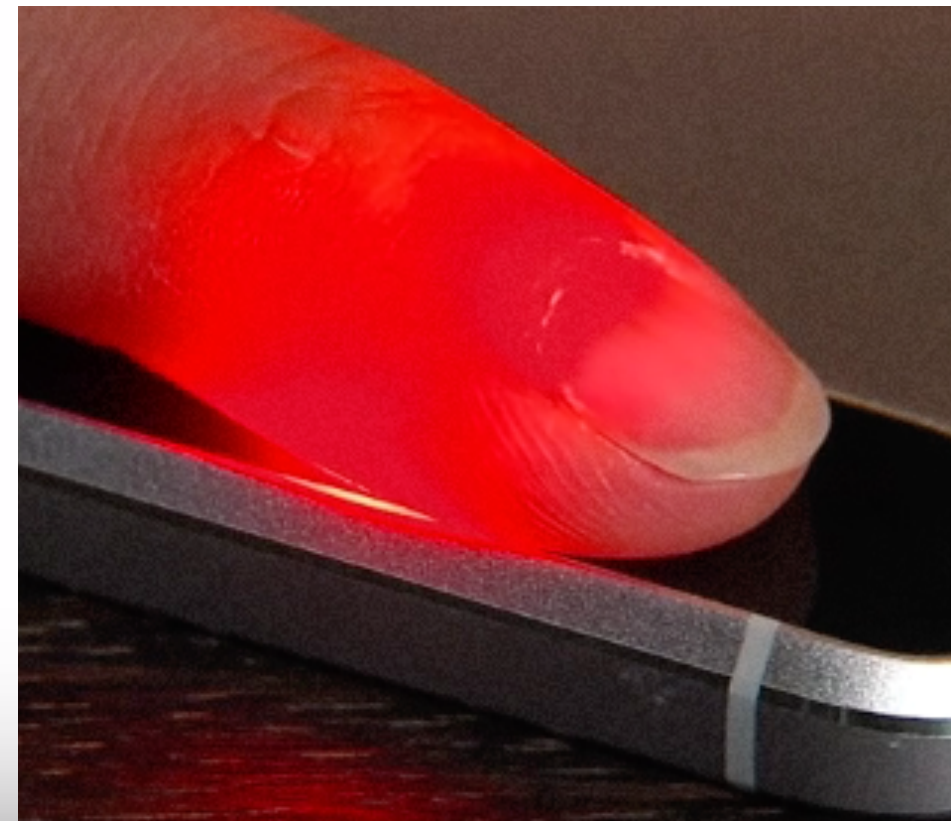
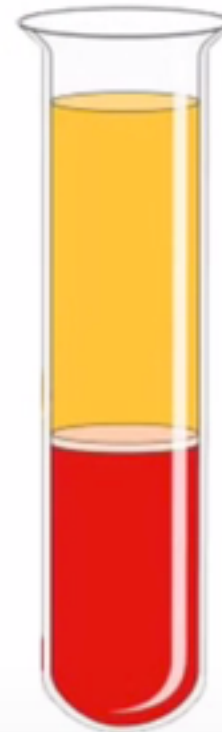
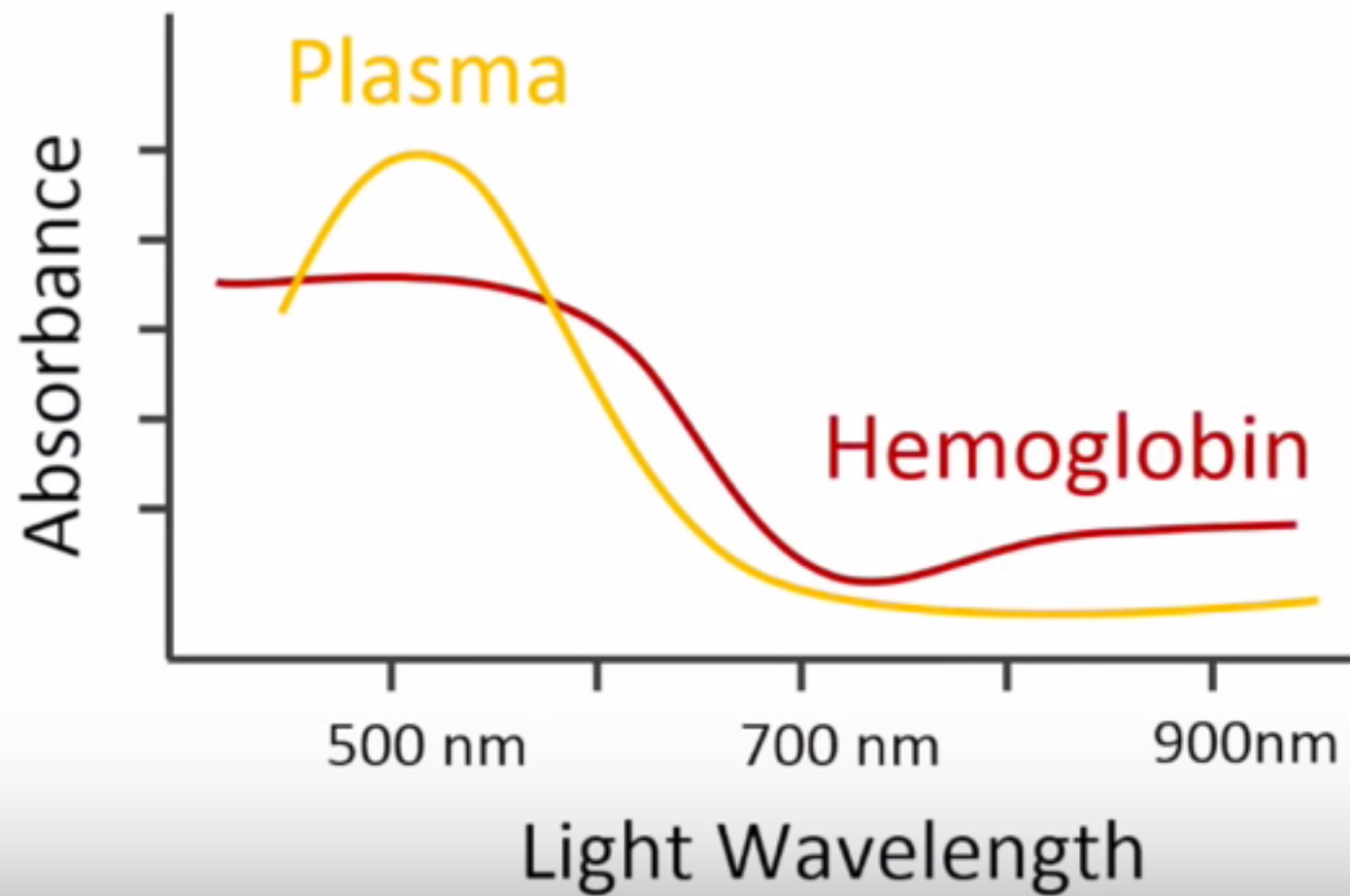
**86% of people own smart phone**  
(compared to 21% for a smart watch)...



## **child mal-nutrition**

- Hemoglobin (gives blood its red color)
- responsible for carrying oxygen around the body
- too little Hemoglobin -> too little oxygen
- blood tests are difficult in developing countries especially in rural areas (infections etc.)





- hemoglobin has different light absorption
- the more hemoglobin, the more red your blood
- put **finger on cellphone camera**
- light illuminates finger
- finger absorbs certain wavelength
- analyze image & match against database



- results in clinical test are comparable



# HemaApp: Noninvasive Blood Screening of Hemoglobin using Smartphone Cameras

Edward Jay Wang<sup>1</sup>, William Li<sup>1</sup>, Doug Hawkins<sup>4</sup>, Terry Gernsheimer<sup>3</sup>,  
Colette Norby-Slycord<sup>3</sup>, Shwetak N. Patel<sup>1,2</sup>

<sup>1</sup>Electrical Engineering, <sup>2</sup>Computer Science &  
Engineering, <sup>3</sup>Division of Hematology

Seattle, WA 98195

{ejaywang<sup>1</sup>, wli<sup>1</sup>, bldbuddy<sup>3</sup>, coletten<sup>3</sup>,  
shwetak<sup>1,2</sup>}@uw.edu

<sup>4</sup>Seattle Children's Hospital  
4800 Sand Point Way NE  
Seattle, WA 98105

<sup>4</sup>doug.hawkins@seattlechildrens.org

## ABSTRACT

We present HemaApp, a smartphone application that noninvasively monitors blood hemoglobin concentration using the smartphone's camera and various lighting sources. Hemoglobin measurement is a standard clinical tool commonly used for screening anemia and assessing a patient's response to iron supplement treatments. Given a light source shining through a patient's finger, we perform a chromatic analysis, analyzing the color of their blood to estimate hemoglobin level. We evaluate HemaApp on 31 patients ranging from 6 – 77 years of age, yielding a 0.82 rank order correlation with the gold standard blood test. In screening for anemia, HemaApp achieve a sensitivity and precision of 85.7% and 76.5%. Both the regression and classification performance compares favorably with our control, an FDA-approved noninvasive hemoglobin measurement device. We also evaluate and discuss the effect of using different kinds of lighting sources.

## Author Keywords

Hemoglobin; Mobile Health; Photoplethysmography; Anemia; Camera; Blood Screening

## ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

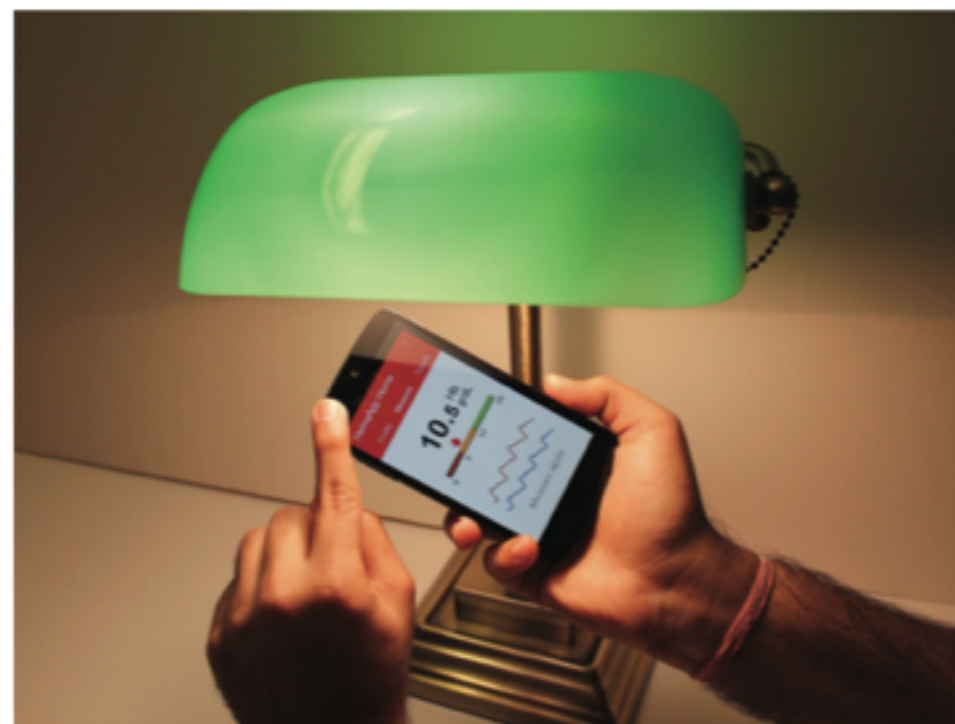


Figure 1: HemaApp is a smartphone application that noninvasively estimates blood hemoglobin concentration using a smartphone camera. Analysis of the color of the blood in a user's finger yields an estimate of the user's hemoglobin level. We evaluated the system using the smartphone's LED flash and incandescent light bulbs as illuminating sources.

candidates for clinical and remote healthcare platforms. A number of applications have even leveraged only the existing sensors on a smartphone to achieve results similar to those



# Noninvasive Hemoglobin Measurement Using Unmodified Smartphone Camera and White Flash

Edward J. Wang *Member IEEE*, William Li, Junyi Zhu, Rajneil Rana, and Shwetak N. Patel *Member IEEE*

**Abstract**— We show that a mobile phone can measure hemoglobin levels using the built-in RGB camera and white LED without modification. Prior work has demonstrated that a smartphone using the built-in RGB camera with the aid of visible and IR lights can achieve a Pearson correlation results between 0.69-0.82 and an RMSE value between 1.26-1.56 g/dL. Our system builds upon the prior work and demonstrates that with only the built-in white LED, the estimation of hemoglobin level has a Pearson correlation of 0.62 with an RMSE of 1.27 g/dL. This extension work demonstrates that it is feasible to measure hemoglobin without using an IR source.

## I. INTRODUCTION

The combination of a smartphone camera and flash LED to measure the blood pulses from the fingertip, known as photoplethysmograph (PPG), is a well-established technology. Apps on smartphones are available to consumers to test their heart rate and track their cardiovascular health. These apps work by having the user place their finger over the camera and flash to measure the absorption of blood as it fluctuates each time the heart beats. Optical measurement using a smartphone has also been demonstrated for measuring the blood oxygenation and hemoglobin concentration when used in conjunction with a custom light attachment on the phone.

HemaApp is a cellphone-based application that uses the camera on the back of the phone to measure the PPG signal from a user's finger (Figure 1) to measure the hemoglobin level of a person noninvasively. In our previous work [8], we proposed HemaApp as a system that utilized the unmodified back camera with a custom attachment that is placed over the phone camera to provide a spectrum of illumination using a white LED, IR LEDs, or an incandescent bulb. To use the attachment, the user's finger is placed over the LED attachment and the camera. Each light source is cycled through in sequence, and the resulting PPG is recorded for each light source. The hemoglobin level is then computed based on the



Figure 1. HemaApp is a smartphone application that measures the hemoglobin level using the phone's built-in camera and white flash LED.

RMSE = 1.27 g/dL when compared with another optical hemoglobin measurement device, the Masimo Pronto 7. For comparison, HemaApp V.1 using a white LED and IR LED in a similar study achieves a correlation result between 0.69 – 0.82, with an RMSE value between 1.26 – 1.56 g/dL. This result gives evidence that using an unmodified phone is possible with the new gain balancing technique.

## II. BACKGROUND

### A. Hemoglobin Screening

Hemoglobin is the protein molecule in the blood that carries oxygen throughout the body. Conceptually, the measure of hemoglobin is a representation of the oxygen carrying capacity of the patient's blood. This is distinct from



# Jaundice

- yellow or greenish appearance of skin and eyes
- due to high bilirubin levels
- occurs in  $>$  half of babies in first week after birth
- it often goes away on its own, but if too high for a long time, leads to brain damage
- how yellow is too yellow?
- + only way to test today is to draw blood...





- calibration card to compensate for lighting
- take multiple pictures to compensate for blood flushes
- software does the color-matching





- for adults, it is easier to see bilirubin levels in eyes
- (bilirubin is also a sign for pancreatic cancer in adults)



# BiliCam: Using Mobile Phones to Monitor Newborn Jaundice

Lilian de Greef<sup>1</sup>, Mayank Goel<sup>1</sup>, Min Joon Seo<sup>1</sup>, Eric C. Larson<sup>2</sup>,  
James W. Stout MD MPH<sup>3</sup>, James A. Taylor MD<sup>3</sup>, Shwetak N. Patel<sup>1</sup>

<sup>1</sup>Computer Science & Engineering, DUB Group

<sup>3</sup>Department of Pediatrics  
University of Washington  
Seattle, WA 98195

<sup>2</sup>Computer Science & Engineering  
Southern Methodist University  
Dallas, TX 75205

{ldegreef, mayankg, minjoon, shwetak, jstout, uncjat}@uw.edu, eclarson@lyle.smu.edu

## ABSTRACT

Health sensing through smartphones has received considerable attention in recent years because of the devices' ubiquity and promise to lower the barrier for tracking medical conditions. In this paper, we focus on using smartphones to monitor newborn jaundice, which manifests as a yellow discoloration of the skin. Although a degree of jaundice is common in healthy newborns, early detection of extreme jaundice is essential to prevent permanent brain damage or death. Current detection techniques, however, require clinical tests with blood samples or other specialized equipment. Consequently, newborns often depend on visual assessments of their skin color at home, which is known to be unreliable. To this end, we present BiliCam, a low-cost system that uses smartphone cameras to assess newborn jaundice. We evaluated BiliCam on 100 newborns, yielding a 0.85 rank order correlation with the gold standard blood test. We also discuss usability challenges and design solutions to make the system practical.

## Author Keywords

Health sensing, mobile phones, neonatal jaundice, bilirubin, image processing.

## ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI):



**Figure 1.** Parents or medical practitioners can monitor a newborn's jaundice with their smartphones through BiliCam.

monitoring [30], pulmonology [18,19], point-of-care diagnostics [14,33], and various other health applications [1]. They demonstrate how the capabilities and ubiquity of modern smartphones make them excellent candidates for clinical and health platforms, despite their inherent sensing limitations. In this paper, we present the design and critical evaluation of assessing newborn jaundice using a smartphone in a study with 100 newborns. Our prototype, BiliCam, is a smartphone-based medical device that uses the embedded camera and a paper-based color calibration



# BiliScreen: Smartphone-Based Scleral Jaundice Monitoring for Liver and Pancreatic Disorders

ALEX MARIAKAKIS, MEGAN A. BANKS, LAUREN PHILLIPI, LEI YU, JAMES TAYLOR, and SHWETAK N. PATEL, University of Washington

---

Pancreatic cancer has one of the worst survival rates amongst all forms of cancer because its symptoms manifest later into the progression of the disease. One of those symptoms is jaundice, the yellow discoloration of the skin and sclera due to the buildup of bilirubin in the blood. Jaundice is only recognizable to the naked eye in severe stages, but a ubiquitous test using computer vision and machine learning can detect milder forms of jaundice. We propose BiliScreen, a smartphone app that captures pictures of the eye and produces an estimate of a person's bilirubin level, even at levels normally undetectable by the human eye. We test two low-cost accessories that reduce the effects of external lighting: (1) a 3D-printed box that controls the eyes' exposure to light and (2) paper glasses with colored squares for calibration. In a 70-person clinical study, we found that BiliScreen with the box achieves a Pearson correlation coefficient of 0.89 and a mean error of  $-0.09 \pm 2.76$  mg/dl in predicting a person's bilirubin level. As a screening tool, BiliScreen identifies cases of concern with a sensitivity of 89.7% and a specificity of 96.8% with the box accessory.

CCS Concepts: • **Human-centered computing** → **Smartphones**; • **Applied computing** → **Consumer health**;

Additional Key Words and Phrases: Health sensing; smartphones; jaundice; bilirubin; image processing

## ACM Reference format:

Alex Mariakakis, Megan A. Banks, Lauren Phillipi, Lei Yu, James Taylor, and Shwetak N. Patel. 2017. BiliScreen: Smartphone-Based Scleral Jaundice Monitoring for Liver and Pancreatic Disorders. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 2, Article 20 (May 2017), 26 pages.  
<https://doi.org/10.1145/3090085>

---

## 1 INTRODUCTION

Among all forms of cancer, Pancreatic cancer has one of the worst survival rates [2]. Many attribute this statistic to the fact that the symptoms associated with pancreatic cancer often go unnoticed until the cancer is in a later stage; 80-85% of patients present themselves with tumors so advanced that they cannot be removed completely through surgery [5, 34]. One of the earliest symptoms to appear is jaundice, a yellow discoloration of the skin and eyes. In the case of pancreatic cancer, jaundice occurs because a cancerous growth obstructs the common bile duct, causing a buildup of bilirubin in the blood [11]. Being able to detect the very first signs of jaundice when levels of bilirubin are minimally elevated could enable an entirely new screening program for at-risk individuals. Jaundice also manifests as a symptom for a variety of other conditions, such as hepatitis and Gilbert's syndrome, but we are primarily motivated by the link between jaundice and pancreatic cancer for the purpose of this paper.



## **asthma monitoring / lung function**

- lung diseases cause 10% of deaths worldwide
- in spirometry, a patient forcefully exhales into a tube
- tube measures flow + exhaled volume





- use built-in microphone
- evaluate audio not air flow
- **model of the user's vocal tract + reverberation of sound around user's head**
- evaluated on 52 subjects, mean error 5.1%
- problem: user's hold phone at different distances (influences the audio)



# SpiroSmart: Using a Microphone to Measure Lung Function on a Mobile Phone

Eric C. Larson<sup>1†</sup>, Mayank Goel<sup>2†</sup>, Gaetano Boriello<sup>2</sup>, Sonya Heltshe<sup>3</sup>, Margaret Rosenfeld<sup>3</sup>, Shwetak N. Patel<sup>1,2</sup>

<sup>1</sup>Electrical Engineering,

<sup>2</sup>Computer Science & Engineering,

DUB Institute, University of Washington

Seattle, WA 98195

{eclarson, mayankg, gaetano, shwetak}@uw.edu

<sup>3</sup>Seattle Children's Hospital

Center for Clinical and Translational Research

4800 Sand Point Way NE

Seattle, WA 98105

{sonya.heltshe, margaret.rosenfeld}@seattlechildrens.org

## ABSTRACT

Home spirometry is gaining acceptance in the medical community because of its ability to detect pulmonary exacerbations and improve outcomes of chronic lung ailments. However, cost and usability are significant barriers to its widespread adoption. To this end, we present SpiroSmart, a low-cost mobile phone application that performs spirometry sensing using the built-in microphone. We evaluate SpiroSmart on 52 subjects, showing that the mean error when compared to a clinical spirometer is 5.1% for common measures of lung function. Finally, we show that pulmonologists can use SpiroSmart to diagnose varying degrees of obstructive lung ailments.

## Author Keywords

Health sensing, spirometry, mobile phones, signal processing, machine learning.

## ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

## INTRODUCTION

Spirometry is the most widely employed objective measure of lung function [37] and is central to the diagnosis and management of chronic lung diseases, such as asthma, chronic obstructive pulmonary disease (COPD), and cystic fibrosis. During a spirometry test, a patient forcefully exhales through a flow-monitoring device (a tube or mouth-piece), which measures instantaneous flow and cumulative



Figure 1. Subjects using SpiroSmart (left) and a clinical spirometer (right) and example curves from each device.

exacerbations, more rapid recovery, reduced health care costs, and improved outcomes [15,23,34,35]. However, challenges currently faced by home spirometry are cost, patient compliance and usability, and an integrated method for uploading results to physicians [9,12]. Importantly, while office-based spirometry is coached by a trained technician, current home spirometers have no coaching, feedback, or quality control mechanisms to ensure acceptable measurements.

In this paper, we present *SpiroSmart*, a smartphone-based approach that measures lung function using the phone's built-in microphone (*i.e.*, a complete software-enabled solution). SpiroSmart requires the user to hold the smartphone



# SpiroCall: Measuring Lung Function over a Phone Call

Mayank Goel<sup>1</sup>, Elliot Saba<sup>1</sup>, Maia Stiber<sup>2</sup>, Eric Whitmire<sup>1</sup>, Josh Fromm<sup>1</sup>,  
Eric C. Larson<sup>3</sup>, Gaetano Borriello<sup>1</sup>, Shwetak N. Patel<sup>1</sup>

<sup>1</sup>Computer Science and Engineering,  
Electrical Engineering  
DUB Group  
University of Washington  
Seattle, WA 98195

<sup>2</sup>Inglemoor  
High School  
Kenmore, WA 98028  
mwstiber@gmail.com

<sup>3</sup>Computer Science and Engineering  
Southern Methodist University  
Dallas, TX 75205  
eclarson@lyle.smu.edu

{mayankg, sabae, emwhit, jwfromm, gaetano, shwetak}@uw.edu

## ABSTRACT

Cost and accessibility have impeded the adoption of spirometers (devices that measure lung function) outside clinical settings, especially in low-resource environments. Prior work, called SpiroSmart, used a smartphone's built-in microphone as a spirometer. However, individuals in low- or middle-income countries do not typically have access to the latest smartphones. In this paper, we investigate how spirometry can be performed from *any* phone—using the standard telephony voice channel to transmit the sound of the spirometry effort. We also investigate how using a 3D printed vortex whistle can affect the accuracy of common spirometry measures and mitigate usability challenges. Our system, coined SpiroCall, was evaluated with 50 participants against two gold standard medical spirometers. We conclude that SpiroCall has an acceptable mean error with or without a whistle for performing spirometry, and advantages of each are discussed.

## Author Keywords

Health sensing; spirometry; mobile phone sensing; signal processing; machine learning.

## ACM Classification Keywords



**Figure 1.** A user using SpiroCall on a feature phone (Sony w580i) with, and without a SpiroCall whistle.

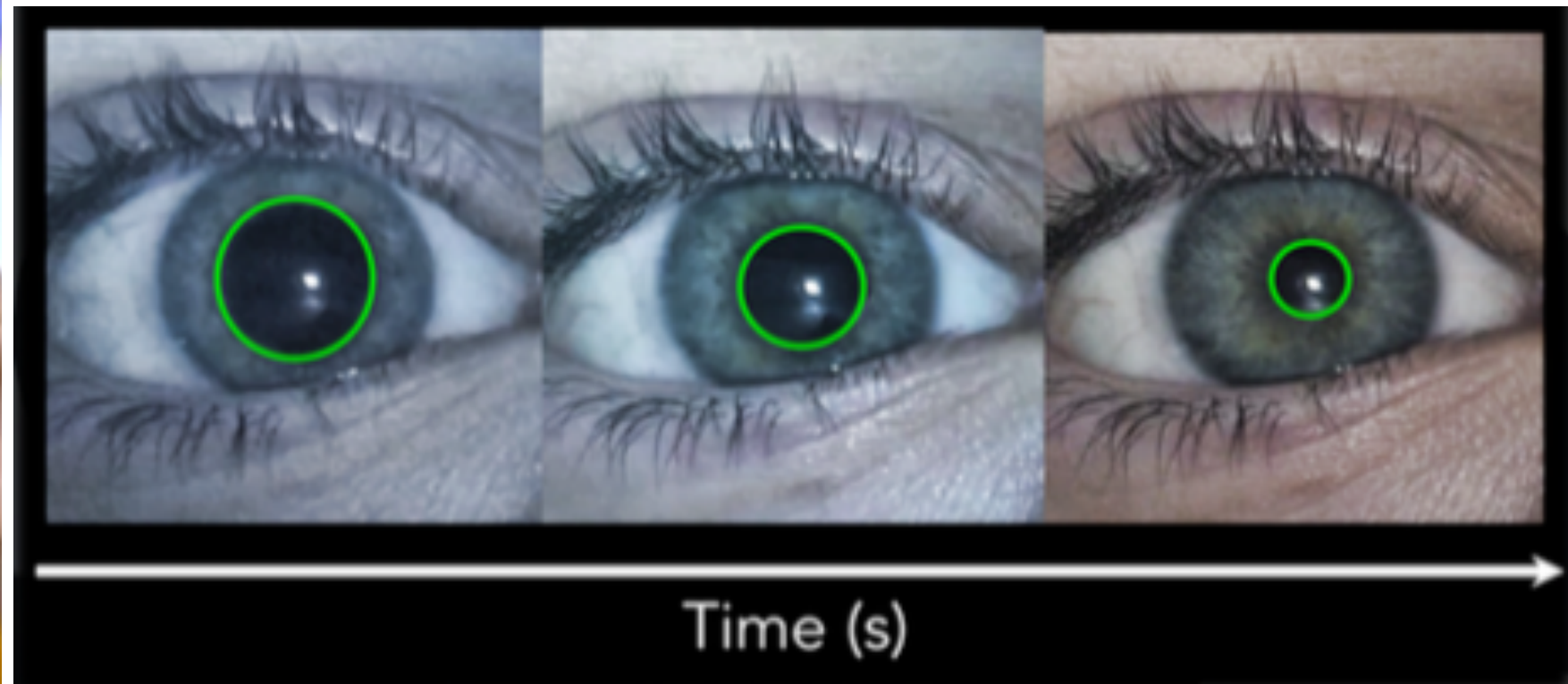
Recently, a number of health applications have been developed to estimate physiological measures such as





## **traumatic brain injury:**

- 3.8 million concussions in the US every year (e.g. sport)
- many cases remain undiagnosed
- can lead to permanent cognitive deficits
- pupillary light reflex: how much light the eye reflects
- with concussions, the reflex is diminished or disappears



- use flashlight to stimulate athletes eye
- take pictures with the camera
- analyze picture sequence over time



# PupilScreen: Using Smartphones to Assess Traumatic Brain Injury

ALEX MARIKAKIS, JACOB BAUDIN, ERIC WHITMIRE, VARDHMAN MEHTA, MEGAN A. BANKS, ANTHONY LAW, LYNN MCGRATH, and SHWETAK N. PATEL, University of Washington

---

Before a person suffering from a traumatic brain injury reaches a medical facility, measuring their pupillary light reflex (PLR) is one of the few quantitative measures a clinician can use to predict their outcome. We propose PupilScreen, a smartphone app and accompanying 3D-printed box that combines the repeatability, accuracy, and precision of a clinical device with the ubiquity and convenience of the penlight test that clinicians regularly use in emergency situations. The PupilScreen app stimulates the patient's eyes using the smartphone's flash and records the response using the camera. The PupilScreen box, akin to a head-mounted virtual reality display, controls the eyes' exposure to light. The recorded video is processed using convolutional neural networks that track the pupil diameter over time, allowing for the derivation of clinically relevant measures. We tested two different network architectures and found that a fully convolutional neural network was able to track pupil diameter with a median error of 0.30 mm. We also conducted a pilot clinical evaluation with six patients who had suffered a TBI and found that clinicians were almost perfect when separating unhealthy pupillary light reflexes from healthy ones using PupilScreen alone.

CCS Concepts: •Applied computing →Consumer health; •Human-centered computing →Smartphones;

Additional Key Words and Phrases: Health sensing, smartphones, pupillometer, pupillary light reflex, pupil dilation, convolutional neural network

## ACM Reference format:

Alex Mariakakis, Jacob Baudin, Eric Whitmire, Vardhman Mehta, Megan A. Banks, Anthony Law, Lynn McGrath, and Shwetak N. Patel. 2017. PupilScreen: Using Smartphones to Assess Traumatic Brain Injury. *PACM Interact. Mob. Wearable Ubiquitous Technol.* 0, 0, Article 0 (2017), 27 pages.  
DOI: 0000001.0000001

---

## 1 INTRODUCTION

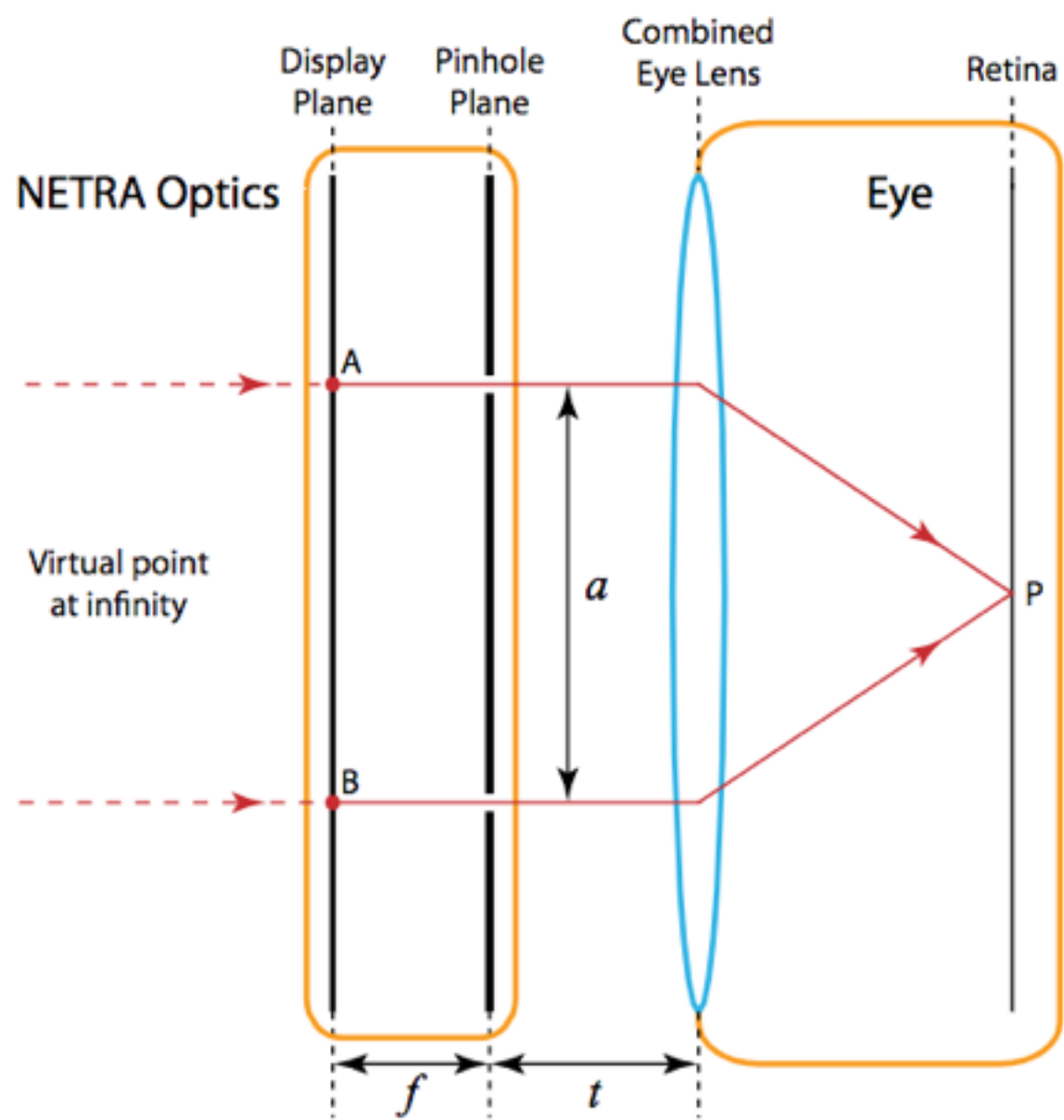
Traumatic brain injury (TBI) accounts for 30% of all injury-related deaths in the United States [9]. TBI can occur in a variety of situations, including car accidents, falls, and blunt force trauma. A concussion is a specific form of TBI caused by a swift blow to the head; these injuries tend not to be life-threatening, but can have serious and long-term effects on a person's memory, motor abilities, and overall cognition [37]. One area in which concussions have garnered national attention is sports, particularly contact sports such as boxing, hockey, and



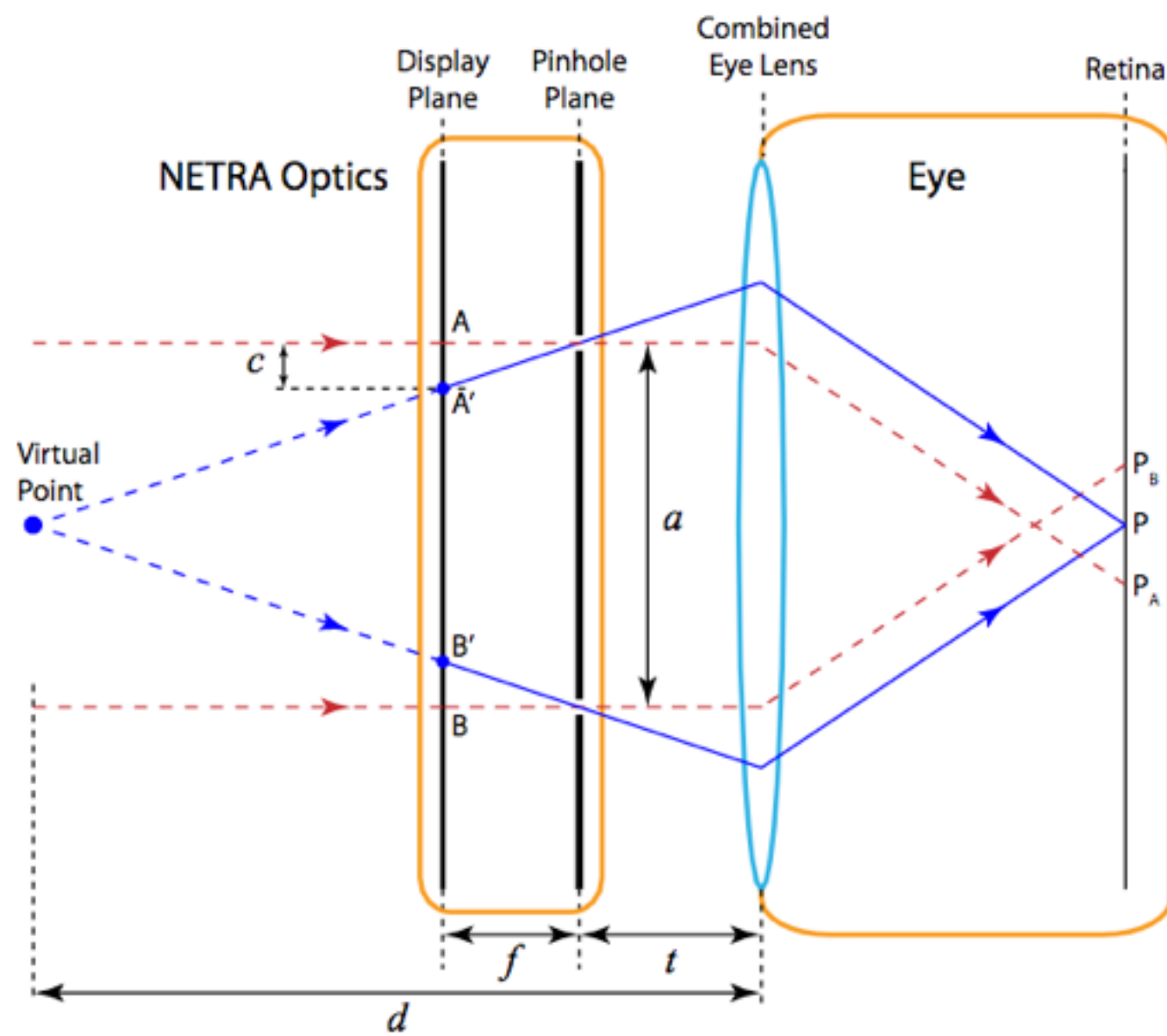


## **eye prescription / optometry:**

- rather than using big setup
- measure with mobile phone



(b) Perfect Eye



(c) Myopic Eye



# NETRA: Interactive Display for Estimating Refractive Errors and Focal Range

Vitor F. Pamplona<sup>1,2</sup>

Ankit Mohan<sup>1</sup>

Manuel M. Oliveira<sup>1,2</sup>

Ramesh Raskar<sup>1</sup>

<sup>1</sup>Camera Culture Group - MIT Media Lab

<sup>2</sup>Instituto de Informática - UFRGS

<http://cameraculture.media.mit.edu/netra>

## Abstract

We introduce an interactive, portable, and inexpensive solution for estimating refractive errors in the human eye. While expensive optical devices for automatic estimation of refractive correction exist, our goal is to greatly simplify the mechanism by putting the human subject in the loop. Our solution is based on a high-resolution programmable display and combines inexpensive optical elements, interactive GUI, and computational reconstruction. The key idea is to interface a lenticular view-dependent display with the human eye in *close range* - a few millimeters apart. Via this platform, we create a new range of interactivity that is extremely sensitive to parameters of the human eye, like refractive errors, focal range, focusing speed, lens opacity, etc. We propose several simple optical setups, verify their accuracy, precision, and validate them in a user study.

**Keywords:** optometry; light-field display; computer-human interaction; refractive errors; visual accommodation.

## 1 Introduction

Measuring refractive properties of imaging systems is a common task in many applications ranging from industrial ones to optometry. The majority of these use sophisticated hardware to precisely estimate these aberrations. Emerging trends in high-resolution displays and interactive software in portable devices provide a new opportunity. In this paper, we explore novel estimation techniques based on interaction with a view-dependent display. Instead of an automated system, we put the user in the loop. This approach intriguingly is highly suitable for estimating refractive errors in the human eye. Although the majority of the paper deals with focusing abilities, aberrations, and range in a human eye, the techniques are also applicable to other optical systems. Our estimation method is not intended to replace the need for optometrists. Instead, the goal is to build a handy refraction screening tool, similar to modern electronic tools used to measure body temperature, blood oxygenation, or blood sugar that promote self-awareness.

We measure the refraction deviations using the dual of a Shack-Hartmann wavefront sensing approach by placing a microlens ar-



**Figure 1:** Can a person look at a portable display, click on a few buttons and recover his refractive fidelity? Our solution combines inexpensive optical elements, programmable display and interactive software components to create the equivalent of a parallax barrier display that interfaces with the human eye. Using this platform, we create a new range of interactivity for measuring several parameters of the human eye, such as refractive errors, focal range, and focusing speed.

paper, we explore the design parameters of our novel device as well as smart patterns to maximize its usability.

### 1.1 Contributions

We propose a novel device based on a view-dependent display to measure focusing abilities of an optical system. Our approach (called *NETRA*) exploits alignment rather than blur as an indicator of misfocus. The main contributions of our paper include:

- A co-design of optics and interactive software to create an effective, low-cost interface sensitive to refractive parameters of the human eye. We create an unusual optical configuration for a programmable display, which is the dual of a Shack-

besides 'serious' diseases,  
sensing technology can also be used for  
**behavior analysis**





## **stress:**

- pressure sensitive keyboard + capacitive mouse
- during stress
  - people use more pressure
  - have more contact with the mouse



# Under Pressure: Sensing Stress of Computer Users

Javier Hernandez<sup>1</sup>

Pablo Paredes<sup>2</sup>

Asta Roseway<sup>3</sup>

Mary Czerwinski<sup>3</sup>

<sup>1</sup>MIT Media Lab, 75 Amherst Street, Cambridge, MA 02139, USA

<sup>2</sup>EECS UC Berkeley, 387 Soda Hall, Berkeley, CA 94720-1776, USA

<sup>3</sup>Microsoft Research, One Microsoft Way, Redmond, WA 98052-6399, USA

javierhr@mit.edu, pablo.paredes@berkeley.edu, {astar, marycz}@microsoft.com

## ABSTRACT

Recognizing when computer users are stressed can help reduce their frustration and prevent a large variety of negative health conditions associated with chronic stress. However, measuring stress non-invasively and continuously at work remains an open challenge. This work explores the possibility of using a pressure-sensitive keyboard and a capacitive mouse to discriminate between stressful and relaxed conditions in a laboratory study. During a 30-minute session, 24 participants performed several computerized tasks consisting of expressive writing, text transcription, and mouse clicking. During the stressful conditions, the large majority of the participants showed significantly increased typing pressure (>79% of the participants) and more contact with the surface of the mouse (75% of the participants). We discuss the potential implications of this work and provide recommendations for future work.

## Author Keywords

Stress measurement; pressure-sensitive keyboard; capacitive mouse; Affective Computing.

## ACM Classification Keywords

H.5.2. Information interfaces and presentation: User Interfaces.

## INTRODUCTION

Do you remember the last time you felt genuinely stressed in front of the computer? Maybe you had a pressing deadline and very little time to write a report or perhaps you received an unpleasant e-mail you had to reply to. Although you might not have been completely aware about feeling stressed, your body was experiencing a chain of physiological changes: pupil dilation, deeper respiration,

computer mouse more actively. This chain of physiological changes and their associated behavioral effects (also known as the fight or flight response), has evolved to help us face life-threatening situations. However, repeated triggering of this stress reflex during daily activity can result in chronic stress, leading to a large array of adverse health conditions such as depression, hypertension and various forms of cardiovascular diseases [21].



Figure 1. Pressure-sensitive keyboard (left), and capacitive mouse (right).

A first step towards preventing this type of condition consists in being able to detect when a person is stressed. Ideally, stress measurement systems should be continuous and unobtrusive so that they can capture the responses of people throughout the day without creating additional stress. If a person could know, for instance, that during the last week s/he experienced more stress than usual, the person could gain more awareness and incorporate behavioral changes to reduce unnecessary stressors (e.g., increase the number of breaks, change the type of work activity, or socialize more). Computers could also take advantage of this type of information to produce more complex forms of human-computer interaction [24]. For instance, if a computer user is feeling stressed, the





## **sleep quality:**

- movement
- audio (snoring)
- battery level of phone (to check if you used it at night ;))



# Intelligent Sleep Stage Mining Service with Smartphones

Weixi Gu<sup>†</sup>, Zheng Yang<sup>†</sup>, Longfei Shangguan<sup>‡</sup>, Wei Sun<sup>‡</sup>, Kun Jin<sup>†</sup>, Yunhao Liu<sup>†</sup>

<sup>†</sup> School of Software and TNLIS, Tsinghua University, China

{guweixigavin, evilying2016}@gmail.com, {yang, yunhao}@greenorbs.com

<sup>‡</sup> CSE, Hong Kong University of Science and Technology, Hong Kong

longfei@greenorbs.com, wsunaa@cse.ust.hk

## ABSTRACT

Sleep quality plays a significant role in personal health. A great deal of effort has been paid to design sleep quality monitoring systems, providing services ranging from bedtime monitoring to sleep activity detection. However, as sleep quality is closely related to the distribution of sleep duration over different sleep stages, neither the bedtime nor the intensity of sleep activities is able to reflect sleep quality precisely. To this end, we present Sleep Hunter, a mobile service that provides a fine-grained detection of sleep stage transition for sleep quality monitoring and intelligent wake-up call. The rationale is that each sleep stage is accompanied by specific yet distinguishable body movements and acoustic signals. Leveraging the built-in sensors on smartphones, Sleep Hunter integrates these physical activities with sleep environment, inherent temporal relation and personal factors by a statistical model for a fine-grained sleep stage detection. Based on the duration of each sleep stage, Sleep Hunter further provides sleep quality report and smart call service for users. Experimental results from over 30 sets of nocturnal sleep data show that our system is superior to existing actigraphy-based sleep quality monitoring systems, and achieves satisfying detection accuracy compared with dedicated polysomnography-based devices.

## Author Keywords

Smartphones; sleep stage; sensors.

## ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

the distribution of different sleep stages rather than the time of sleep [7]. Even though people experience a full night's sleep, they may still feel fatigued after being woken up. A longer deep sleep period contributes to a better sleep. Moreover, a proper wake-up time is also helpful for mental and physical health [38]. Comparing with other sleep stages, people woken up in light sleep stage feel more refreshed generally.

Sleep quality monitoring requires a careful observation of individuals' sleep stages. The approaches to recording sleep stages are divided into two categories. The first category is based on polysomnography [32]. The methods in this category leverage electroencephalograph (EEG) to observe brain waves and then recognize sleep stages accurately. EEG systems, *e.g.*, Zeo [41], however, are usually limited to medical and physiological studies. High cost and complicated operations make them hard to be accepted by the public. The approaches in the second category are based on actigraphy [1] utilizing some certain physical activities such as body movement or snore to predict sleep stage. The detection performance based on these approaches, *e.g.*, Jawbone up [16] and Sleep As Android [37], has not yet been evaluated against medically accepted methods. In this paper, we show their performance to be substantially lesser than the methods used in physiological studies.

In this paper, we present Sleep Hunter, a sleep stage detection system based on actigraphy that predicts sleep stage transitions by smartphone. The information collected by Sleep Hunter can be used to evaluate human sleep quality and provide smart call service, which wakes up users in light sleep stage intelligently. The principle behind our system is that apart from implicit brain wave changes, individuals usually exhibit distinguishable physical



# Toss 'N' Turn: Smartphone as Sleep and Sleep Quality Detector

**Jun-Ki Min, Afsaneh Doryab, Jason Wiese, Shahriyar Amini, John Zimmerman, Jason I. Hong**

Human-Computer Interaction Institute, Carnegie Mellon University

{loomlike, adoryab, jwwiese}@cs.cmu.edu, shahriyar@cmu.edu, {johnz, jasonh}@cs.cmu.edu

## ABSTRACT

The rapid adoption of smartphones along with a growing habit for using these devices as alarm clocks presents an opportunity to use this device as a sleep detector. This adds value to UbiComp and personal informatics in terms of user context and new performance data to collect and visualize, and it benefits healthcare as sleep is correlated with many health issues. To assess this opportunity, we collected one month of phone sensor and sleep diary entries from 27 people who have a variety of sleep contexts. We used this data to construct models that detect sleep and wake states, daily sleep quality, and global sleep quality. Our system classifies sleep state with 93.06% accuracy, daily sleep quality with 83.97% accuracy, and overall sleep quality with 81.48% accuracy. Individual models performed better than generally trained models, where the individual models require 3 days of ground truth data and 3 weeks of ground truth data to perform well on detecting sleep and sleep quality, respectively. Finally, the features of noise and movement were useful to infer sleep quality.

## Author Keywords

Smartphone; sleep; machine learning; sensors

## ACM Classification Keywords

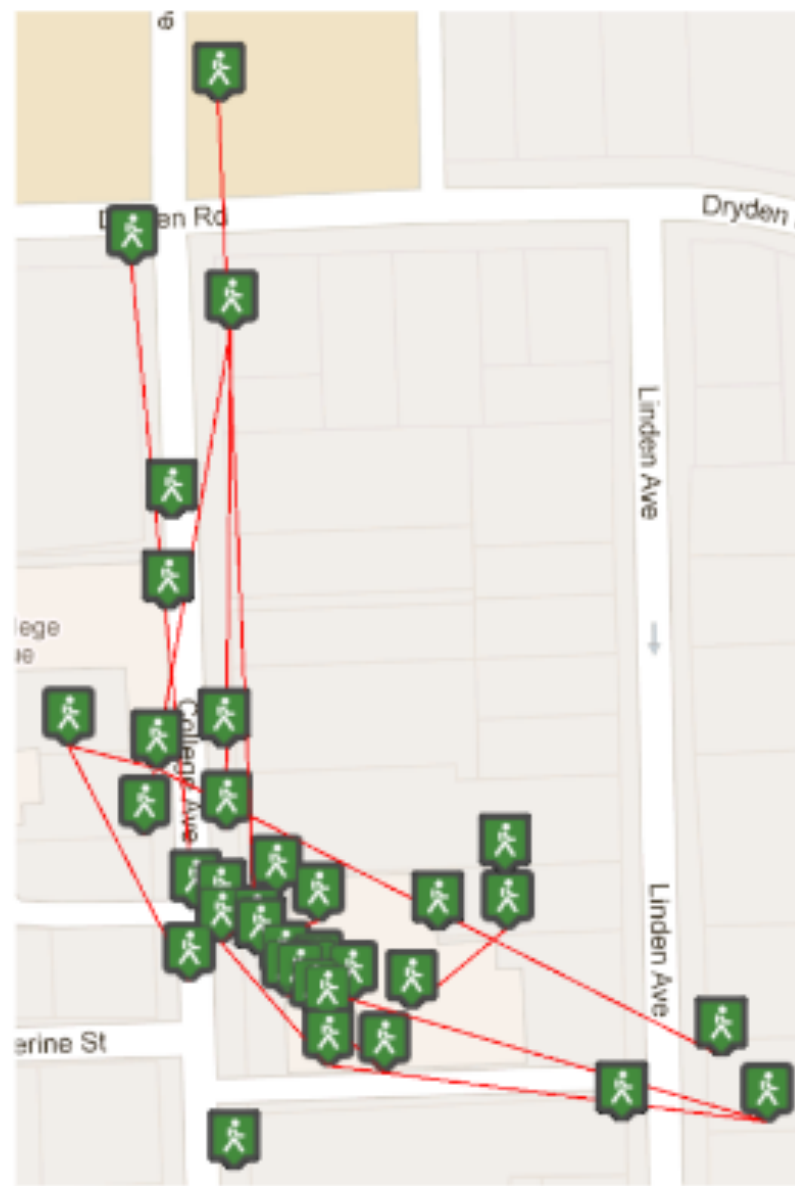
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

## INTRODUCTION

tracking people's daily sleep behaviors without the need for additional hardware or for a significant change in behavior.

From a broader perspective, monitoring a person's sleep patterns offers three opportunities for the HCI community. First, sleep can be considered important context information for UbiComp systems. Having these systems model if a person is asleep or awake could allow them to modify their behavior to act more appropriately. Second, there is a growing interest in HCI around personal informatics and quantified self, where people are increasingly engaged in tracking and visualizing their personal behaviors [15]. The ability to detect and log sleep and sleep quality can add to this growing area of interest. Third, sleep and sleep quality have a strong connection to healthcare. Chronic sleep problems have been associated with diabetes, heart disease, and depression. In addition, even a few nights of poor sleep can impact alertness, memory, mood, and cognitive function [2,30,34,45]. Better tools for monitoring sleep could help improve diagnoses as well as help people understand their own needs and trends.

The goal of our work is to investigate how well a commodity smartphone can sense and model sleep and sleep quality without requiring significant changes in people's behavior. More specifically, we built Toss 'N' Turn (TNT), an Android app that logs seven different sensor inputs (an accelerometer, microphone, ambient light sensor, screen proximity sensor, running process, battery



# obesity:

- behavior analysis, how much you walk etc.
- uses IMU data from phone
- analyze e.g. where you tend to stay stationary
- suggests to take small walks around it



# MyBehavior: Automatic Personalized Health Feedback from User Behaviors and Preferences using Smartphones

Mashfiqui Rabbi<sup>1</sup>, Min Hane Aung<sup>1</sup>, Mi Zhang<sup>2</sup>, Tanzeem Choudhury<sup>1</sup>

<sup>1</sup>Cornell University, <sup>2</sup>Michigan State University

ms2749@cornell.edu, msa242@cornell.edu, mizhang@egr.msu.edu, tanzeem.choudhury@cornell.edu

## ABSTRACT

Mobile sensing systems have made significant advances in tracking human behavior. However, the development of personalized mobile health feedback systems is still in its infancy. This paper introduces MyBehavior, a smartphone application that takes a novel approach to generate deeply personalized health feedback. It combines state-of-the-art behavior tracking with algorithms that are used in recommendation systems. MyBehavior automatically learns a user's physical activity and dietary behavior and strategically suggests changes to those behaviors for a healthier lifestyle. The system uses a sequential decision making algorithm, *Multi-armed Bandit*, to generate suggestions that maximize calorie loss and are easy for the user to adopt. In addition, the system takes into account user's preferences to encourage adoption using the *pareto-frontier* algorithm. In a 14-week study, results show statistically significant increases in physical activity and decreases in food calorie when using MyBehavior compared to a control condition.

## Author Keywords

Mobile Phone Sensing, Machine learning, Mobile Health, Health Feedback

## ACM Classification Keywords

H.1.2 User/Machine Systems; I.5 Pattern Recognition

## General Terms

Systems, Design, Experimentation, Scalability, Performance

## INTRODUCTION

In 2007, the World Health Organization (WHO) declared obe-

that fit well into a users's routine. Feedback is often limited to either overall statistics [11][25], visualization of entire self-tracked data [33][15] or generic suggestions [24][46] that are not personalized to a user's behaviors and lifestyle. However, we can go beyond these paradigms and take advantage of more fine-grained information contained in the data. With a deeper analysis of the self-tracked data, patterns that characterize both healthy and unhealthy behavior can be revealed. These patterns then can be leveraged to generate personalized and actionable suggestions that relate to a user's behaviors.



Figure 1: Visualization of user behaviors over a week (a) Heatmap of places a user stayed stationary (b) Location traces of frequent walks for the same user (c) Location traces of frequent walks for another user.

To this end, we created a mobile application called MyBehavior. The novel functionality is an intelligent engine that provides personalized suggestions by learning a user's physical activity and dietary behaviors. For example, Figure 1(a-b) show learnt behaviors of one user's stationary locations and the routes of frequently taken short walks over a week. Then





## StudentLife Study

StudentLife is the first study that uses passive and automatic sensing data from the phones of a class of 48 Dartmouth students over a 10 week term to assess their mental health (e.g., depression, loneliness, stress), academic performance (grades across all their classes, term GPA and cumulative GPA) and behavioral trends (e.g., how stress, sleep, visits to the gym, etc. change in response to college workload -- i.e., assignments, midterms, finals -- as the term progresses).

Much of the stress and strain of student life remains hidden. In reality faculty, student deans, clinicians know little about their students outside of the classroom. Students might know about their own circumstances and patterns but know little about classmates. To shine a light on student life we develop the first of a kind StudentLife smartphone app and sensing system to automatically infer human behavior. Why do some students do better than others? Under similar conditions, why do some individuals excel while others fail? Why do students burnout, drop classes, even drop out of college? What is the impact of stress, mood, workload, sociability, sleep and mental health on academic performance (i.e., GPA)? The study used an android app we developed for smartphones carried by 48 students over a 10 week term to find answers to some of these pressing

**Dartmouth used it to access student life quality**  
(you can download the data set from their website)

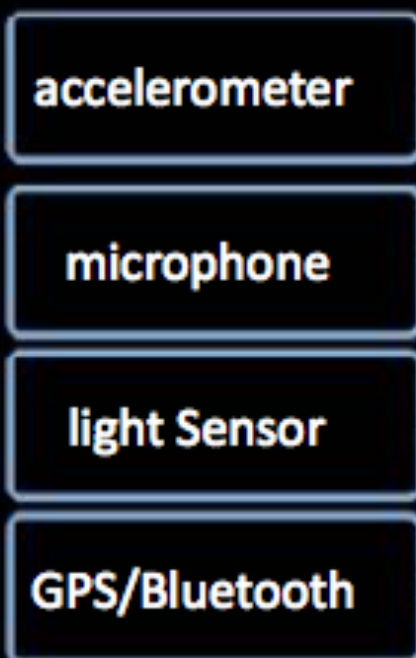


sleep, sociability, activity, etc.) The StudentLife app that ran on students' phones automatically without any user interaction:

- bed time, wake up time and sleep duration
- the number of conversations and duration of each conversation per day
- physical activity (walking, sitting, running, standing)
- where they were located and how long they stayed there (i.e., dorm, class, party, gym)
- the number of people around a student through the day
- outdoor and indoor (in campus buildings) mobility
- stress level through the day, across the week and term
- positive affect (how good they felt about themselves)
- eating habits (where and when they ate)
- app usage
- in-situ comments on campus and national events: dimension protest, cancelled classes; B



### automatic continuous sensing



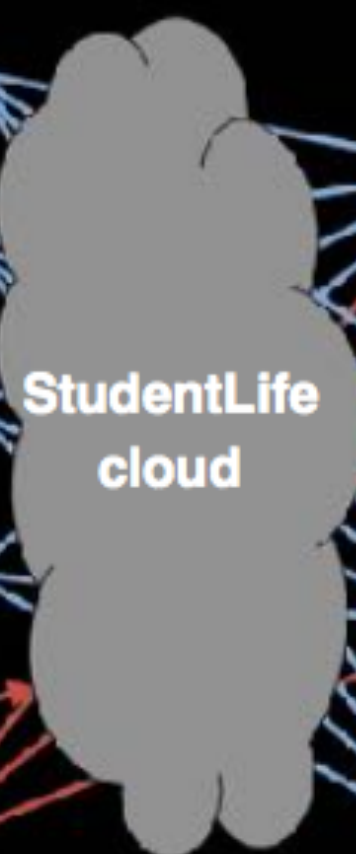
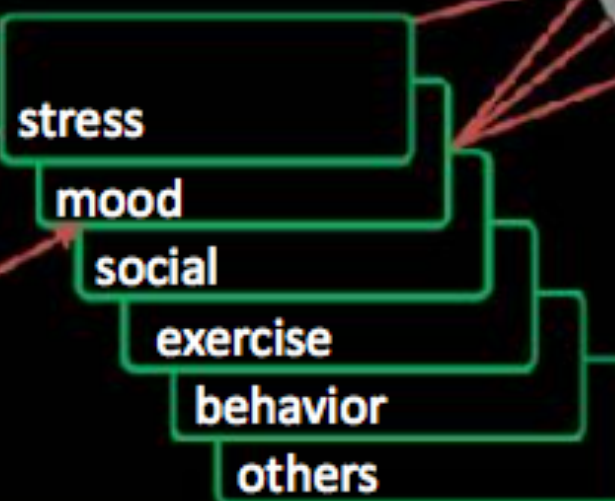
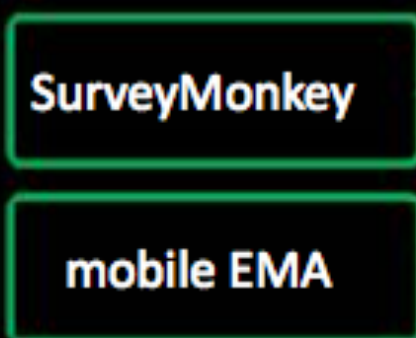
### behavioral classifiers



### statistical analysis



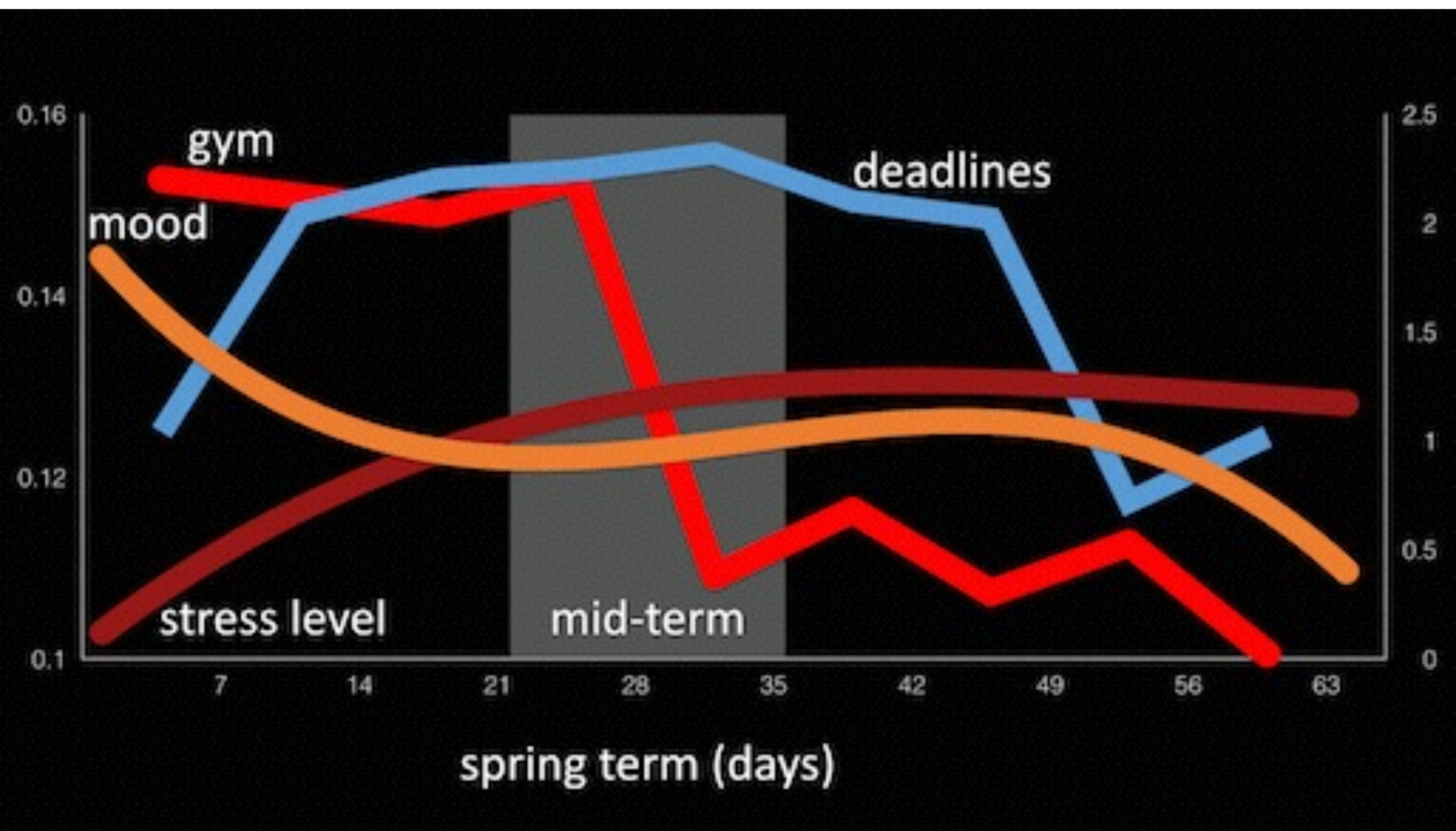
### self-reports

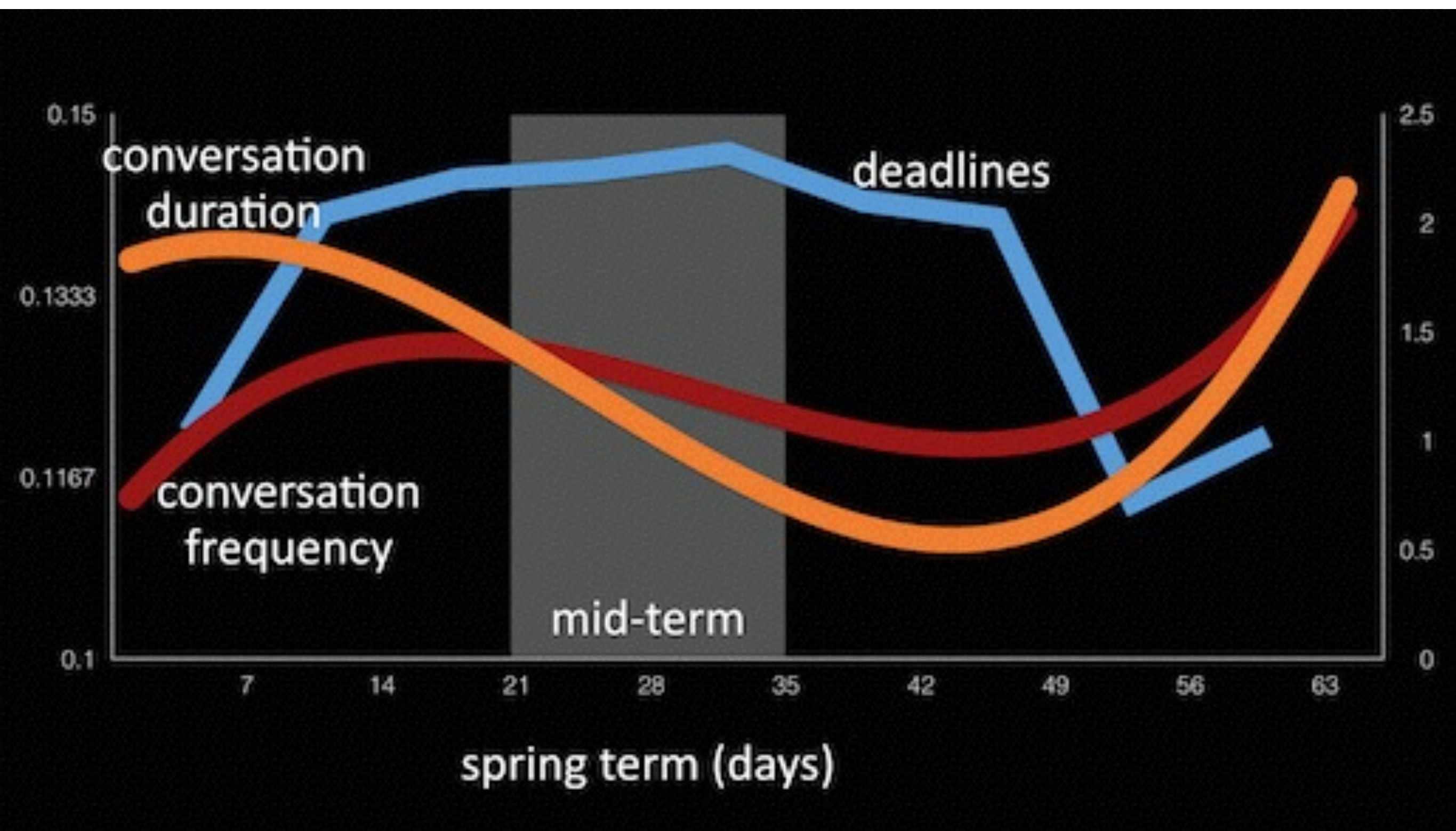


Android phone

cloud









how do you feel about doing the  
**survey with sensors** rather than  
with questionnaires?

do you have **any concerns**?

**<30 sec brainstorming>**

# StudentLife: Assessing Mental Health, Academic Performance and Behavioral Trends of College Students using Smartphones

Rui Wang<sup>†</sup>, Fanglin Chen<sup>†</sup>, Zhenyu Chen<sup>†</sup>, Tianxing Li<sup>†</sup>, Gabriella Harari<sup>‡</sup>,  
Stefanie Tignor<sup>\*</sup>, Xia Zhou<sup>†</sup>, Dror Ben-Zeev<sup>†</sup>, and Andrew T. Campbell<sup>†</sup>

Dartmouth College<sup>†</sup>, The University of Texas at Austin<sup>‡</sup>, Northeastern University<sup>\*</sup>

{ruiwang, chentc, zhenyu, ltx, xia, campbell}@cs.dartmouth.edu,  
gabriella.harari@utexas.edu, tignor.s@husky.neu.edu, dror.ben-zeev@dartmouth.edu

## ABSTRACT

Much of the stress and strain of student life remains hidden. The *StudentLife* continuous sensing app assesses the day-to-day and week-by-week impact of workload on stress, sleep, activity, mood, sociability, mental well-being and academic performance of a single class of 48 students across a 10 week term at Dartmouth College using Android phones. Results from the StudentLife study show a number of significant correlations between the automatic objective sensor data from smartphones and mental health and educational outcomes of the student body. We also identify a Dartmouth term lifecycle in the data that shows students start the term with high positive affect and conversation levels, low stress, and healthy sleep and daily activity patterns. As the term progresses and the workload increases, stress appreciably rises while positive affect, sleep, conversation and activity drops off. The StudentLife dataset is publicly available on the web.

## Author Keywords

Smartphone sensing; data analysis; mental health; academic performance; behavioral trends

## ACM Classification Keywords

H.1.2 User/Machine Systems; I.5 Pattern Recognition; J.3 Life and Medical Sciences

smartphones carried by students to find answers to some of these pressing questions.

Consider students at Dartmouth College, an Ivy League college in a small New England college town. Students typically take three classes over a 10-week term and live on campus. Dartmouth classes are generally demanding where student assessment is primarily based on class assignments, projects, midterms and final exams. Students live, work and socialize on a small self-contained campus representing a tightly-knit community. The pace of the 10 week Dartmouth term is fast in comparison to a 15 week semester. The atmosphere among the students on campus seems to visibly change from a relaxed start of term, to an intense midterm and end of term. Typically classes at Dartmouth are small (*e.g.*, 25-50 students), but introductory classes are larger (*e.g.*, 100-170), making it difficult for a faculty to follow the engagement or performance of students on an individual level. Unless students contact a student dean or faculty about problems in their lives, the impact of such challenges on performance remains hidden.

To shine a light on student life we develop the *StudentLife* smartphone app and sensing system to automatically infer human behavior in an energy-efficient manner. The StudentLife app integrates MobileEMA, a flexible ecological momentary

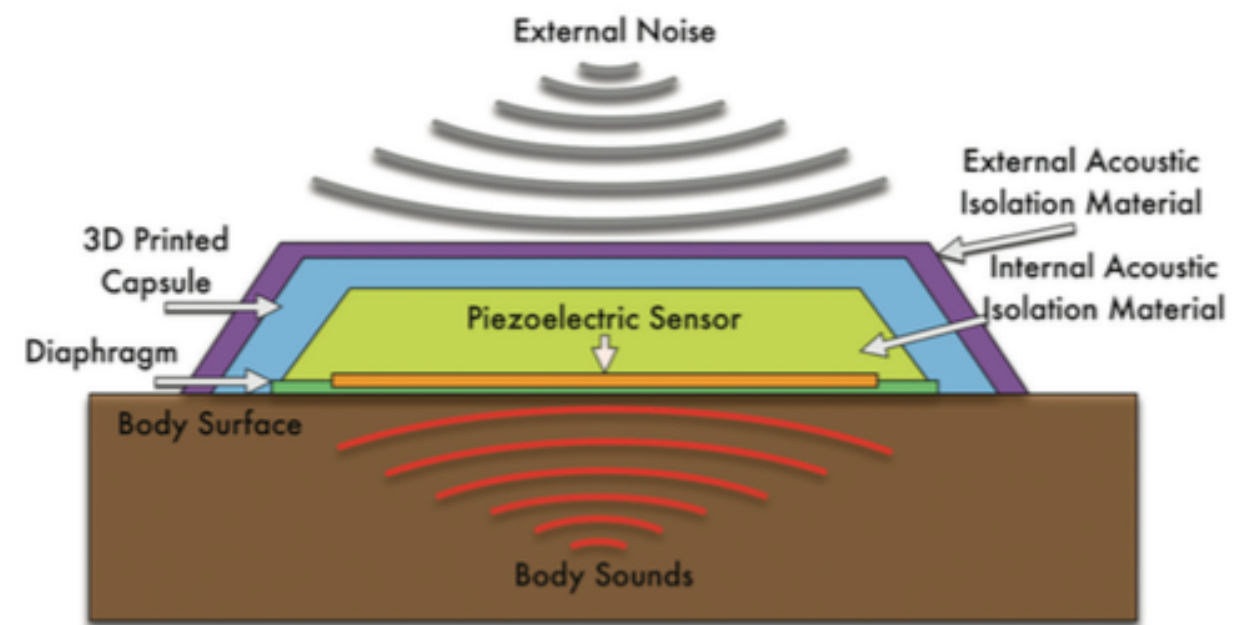


**wearables**

for measuring signals of the body,  
**the closer the device is to the body**  
the better...

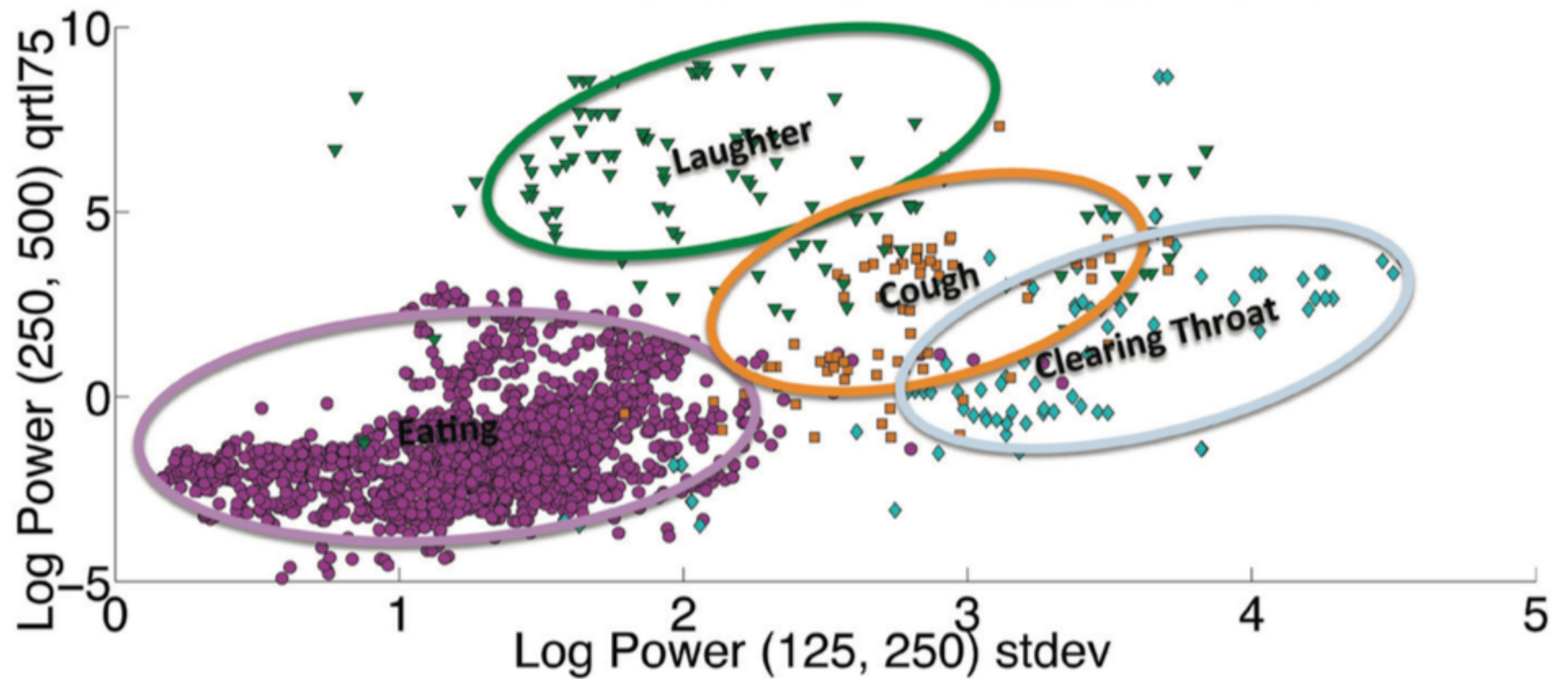
smart phone vs. wearable...





## measuring your throat:

- internal body sounds + external surrounding sounds
- eating - dieting
- coughing - lung diseases and infections
- laughter - emotional well being
- breathing - stress levels



- clearly distinguishable with the device



# BODYBEAT:

## Eavesdropping on our Body Using a Wearable Microphone

**F**rom munching on a piece of toast and swallowing a sip of coffee to deep breathing after a few laps of running, our body continually makes a wide range of non-speech body sounds, which can be indicative of our dietary behaviour, respiratory physiology, and affect. A wearable system that can continuously capture and recognize different types of body sound with high fidelity can also be used for behavioural tracking and disease diagnosis. BodyBeat is such a mobile sensing system that can detect a diverse range of non-speech body sounds in real-life scenarios. The BodyBeat mobile sensing system consists of a custom-built piezoelectric microphone and a distributed computational framework that utilizes an

smartphone. The custom-built microphone is designed to capture subtle body vibrations directly from the body surface without being disturbed by external sounds. The ARM embedded system and the Android smartphone processes the acoustic signal from the microphone and identifies non-speech body sounds.

Speech is not the only sound generated by human. Non-speech body sounds such as sounds of food intake, breath, laughter, yawn, and cough contain invaluable information about people's health and wellbeing. With regard to food intake, body sounds enable us to discriminate characteristics of food and drinks [1, 2]. Longer term tracking of eating sounds could be very useful in dietary monitoring

the friction caused by the airflow from our lungs through the vocal organs (e.g., trachea, larynx, etc.) to the mouth or nasal cavity [3], are highly indicative of the conditions of our lungs. Sounds of laughter and yawns are good indicators of people's affect states such as happiness and fatigue. Therefore, automatically tracking these non-speech body sounds can help in early detection of negative health indicators by performing regular dietary monitoring, pulmonary function testing, and affect sensing.

We have designed, implemented, and evaluated a mobile sensing system called BodyBeat, which could continuously keep tracking of a diverse set of non-speech body sounds. BodyBeat consists of a custom-made piezoelectric sensor-based

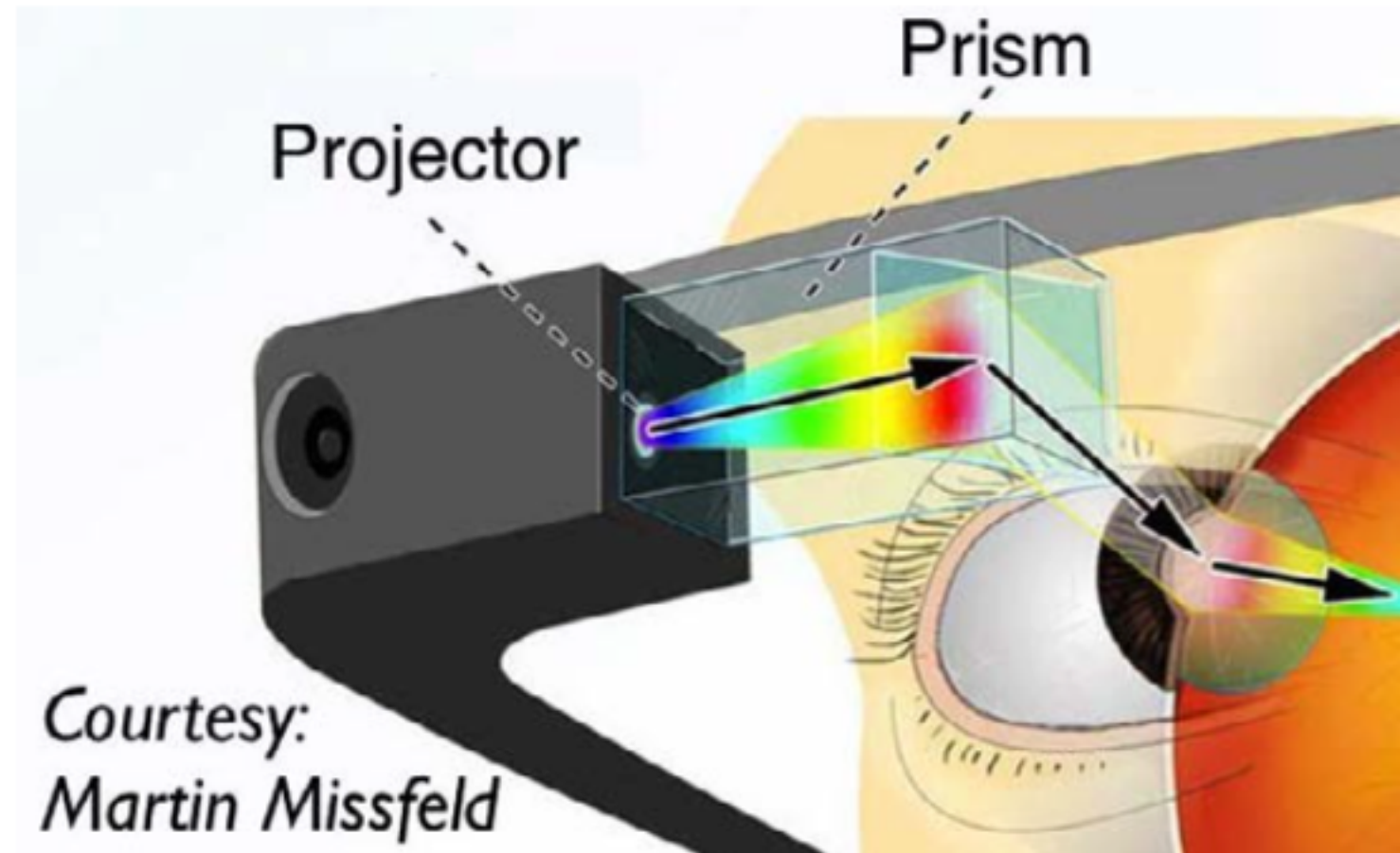
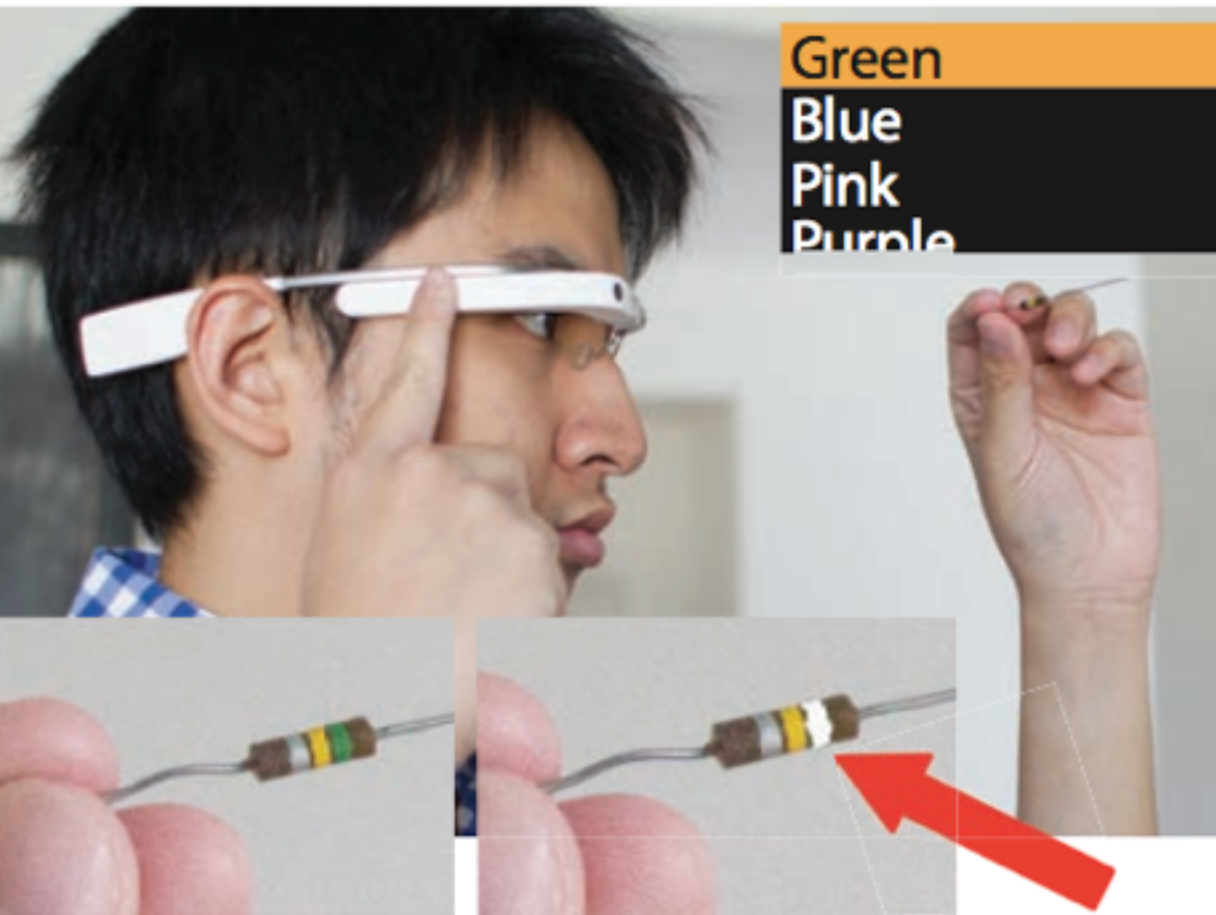




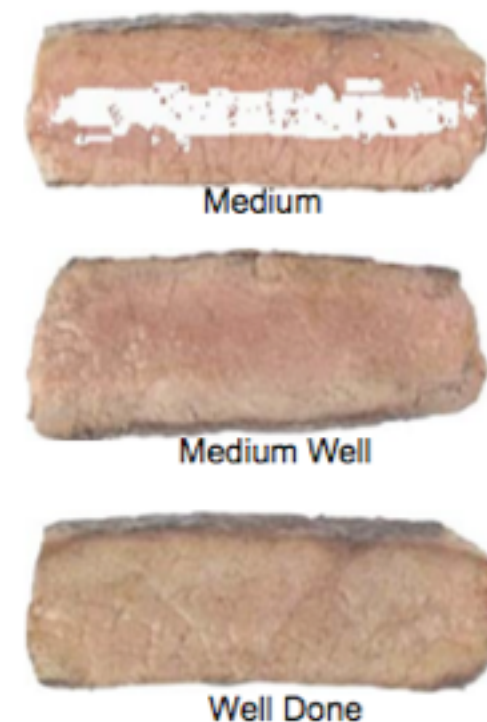
## color blindness:

- inability to distinguish between different colors
- ca. 8% of males, 0.5% of females
- different categories of color blindness





- use google glass
- capture image
- perform color analysis
- display new image for the user





# Chroma: A Wearable Augmented-Reality Solution for Color Blindness

Enrico Tanuwidjaja, Derek Huynh, Kirsten Koa, Calvin Nguyen, Churen Shao, Patrick Torbett, Colleen Emmenegger, Nadir Weibel

Department of Computer Science and Engineering,  
University of California San Diego, La Jolla, CA 92093, USA

{etanuwid, dbhuynh, kkoa, cbn004, cshao, ptorbett, cemmenegger, weibel}@ucsd.edu

## ABSTRACT

Color blindness is a highly prevalent vision impairment that inhibits people's ability to understand colors. Although classified as a mild disability, color blindness has important effects on the daily activity of people, preventing them from performing their tasks in the most natural and effective ways. In order to address this issue we developed Chroma, a wearable augmented-reality system based on Google Glass that allows users to see a filtered image of the current scene in real-time. Chroma automatically adapts the scene-view based on the type of color blindness, and features dedicated algorithms for color saliency. Based on interviews with 23 people with color blindness we implemented four modes to help colorblind individuals distinguish colors they usually can't see. Although Glass still has important limitations, initial tests of Chroma in the lab show that colorblind individuals using Chroma can improve their color recognition in a variety of real-world activities. The deployment of Chroma on a wearable augmented-reality device makes it an effective digital aid with the potential to augment everyday activities, effectively providing access to different color dimensions for colorblind people.

## Author Keywords

Augmented-reality; Glass; Wearables; Color blindness

## ACM Classification Keywords

are deuteranomaly (56% of all colorblind individuals) and protanomaly (15%) the "less severe" versions of protanopia (14%) and deuteranopia (13%). Tritanomaly and tritanopia along with other specific deficiencies are more rare. Figure 1 shows the color spectrums as seen by people with six different types of colorblindness with respect to standard vision. A common misconception about colorblindness is that colorblind people are unable to see certain colors or some colors appear grey for them. Colorblind people are actually unable to *distinguish* certain colors. As evident in the figure, colorblind people can see a variety of colors, but depending on the type of colorblindness, some colors are off. For example, a person with deuteranopia sees red as a shade of green and people with deuteranomaly often misclassify brown as red.

Color blindness affects people on a daily basis since many daily activities require the ability to distinguish colors. For example, while cooking, colorblind people have difficulties distinguishing cooked meat from raw meat. They often use other factors to guide their assessments, such as cooking time and amount of charring. However, burnt meat does not always mean that the meat is cooked. Many colorblind individuals have problems with other activities, such as identifying colors in art and fashion (flowers, photography, etc.), reading color legends (maps, medical charts, etc.). Also, many tasks require the ability to distinguish colors in real-time. Preparing food or drink, driving, and first-aid operations are example activities





## **stress:**

- physiologically and psychologically damaging
- impairs real-time performance, reduces creativity
- directly facilitates illness, e.g. cancer, heart disease, autoimmune conditions
- real-time awareness prevents stress from getting worse



- measure signals
- EDA: electrodermal activity (skin conductance, e.g. sweat)
- ECG: electrocardiogram (how fast heart beats, is it regular)
- flap wings of butterfly (shape memory alloy)
- result? **users were more stressed** (monitoring effect)



# MoodWings: A Wearable Biofeedback Device for Real-Time Stress Intervention

Diana MacLean<sup>1,2</sup>, Asta Roseway<sup>1</sup> and Mary Czerwinski<sup>1</sup>

<sup>1</sup>Microsoft Research, One Microsoft Way, Redmond, USA

<sup>2</sup>Stanford University

## ABSTRACT

Stress has a wide range of negative impacts on people, ranging from declines in real-time task performance to development of chronic health conditions. Despite the increasing availability of sensors and methods for detecting stress, little work has focused on automated stress interventions and their effect. We present MoodWings: a wearable butterfly that mirrors a user's real-time stress state through actuated wing motion. We designed MoodWings to function both as an early-stress-warning system as well as a physical interface through which users could manipulate their affective state. Accordingly, we hypothesized that MoodWings would help users both calm down and perform better during stressful tasks. We tested our hypotheses on a common stressful task: driving. While users drove significantly more safely with MoodWings, they experienced higher stress levels (physiologically and self-perceived). Despite this, users were enthusiastic about MoodWings, expressing several alternative contexts in which they would find it useful. We discuss these results and future design implications for building externalized manifestations of real-time affective state.

## Author Keywords

Affective computing; stress; stress intervention; biofeedback; butterfly

## ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI):

stressed, could we use that information to deflect or prevent an acute stress episode? One can imagine that the ability to ward off stress could make us more productive and

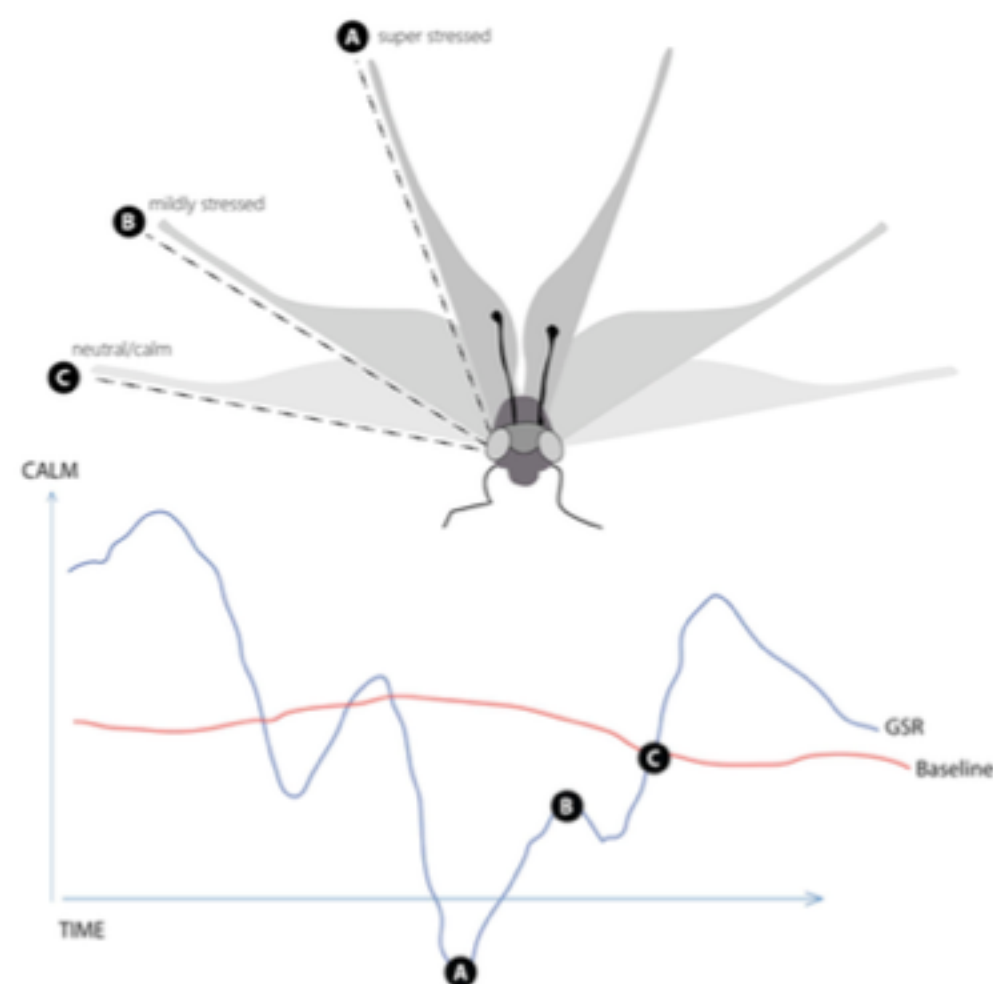


Figure 1: MoodWings' response to changes in user arousal. A high state of arousal precipitates a large flap, while a calmer state results in a gentle hover.



## **anxiety:**

- we derive emotions from body signals
- heart beat up -> I must be excited, anxious, in love?
- the device fakes a slow heartbeat using vibrators
- vibrators vibrate at a certain rhythm
- makes you feel more relaxed



# EmotionCheck: Leveraging Bodily Signals and False Feedback to Regulate our Emotions

**Jean Costa**  
Information Science  
Cornell University  
jmd487@cornell.edu

**Alexander T. Adams**  
Information Science  
Cornell University  
ata56@cornell.edu

**Malte F. Jung**  
Information Science  
Cornell University  
mfj28@cornell.edu

**François Guimbertière**  
Information Science  
Cornell University  
francois@cs.cornell.edu

**Tanzeem Choudhury**  
Information Science  
Cornell University  
tanzeem.choudhury@cornell.edu

## ABSTRACT

In this paper we demonstrate that it is possible to help individuals regulate their emotions with mobile interventions that leverage the way we naturally react to our bodily signals. Previous studies demonstrate that the awareness of our bodily signals, such as our heart rate, directly influences the way we feel. By leveraging these findings we designed a wearable device to regulate user's anxiety by providing a false feedback of a slow heart rate. The results of an experiment with 67 participants show that the device kept the anxiety of the individuals in low levels when compared to the control group and the other conditions. We discuss the implications of our findings and present some promising directions for designing and developing this type of intervention for emotion regulation.

## Author Keywords

Emotion Regulation; Intervention; Interoceptive; Emotion; Anxiety; Stress; Heart Rate; Feedback; False Feedback.

## ACM Classification Keywords

H.5.m Information Interfaces and Presentation: Misc.

## INTRODUCTION

these emotions is called 'emotion regulation' [13]. As we mature, we learn how to employ different strategies to effectively regulate our emotions. However, in many cases we are not able to regulate our emotions properly, which can negatively influence our mental health, relationship satisfaction, work performance and physical well-being [25].

The past years have seen enormous growth in research on emotion regulation [14]. While research in psychology has focused mostly on understanding the phenomenon of emotion regulation and the impact that different emotion regulation strategies have on cognitive and affective processes, research in HCI and Ubicomp has focused on designing and developing technologies to help people regulate their emotions.

One popular theme in HCI and Ubicomp is the design and development of technologies for mood regulation, such as systems that focus on improving our awareness of our affective states. Although 'mood' and 'emotion' are used interchangeably, both in everyday language and in research, they refer to different experiential phenomena [9]. While emotions are often elicited by specific events and trigger behavioral response tendencies relevant to these events, moods tend to last longer than emotions [15], for hours, days or weeks. Moods can be considered the "persistent and sustained emotional

**wireless sensing**

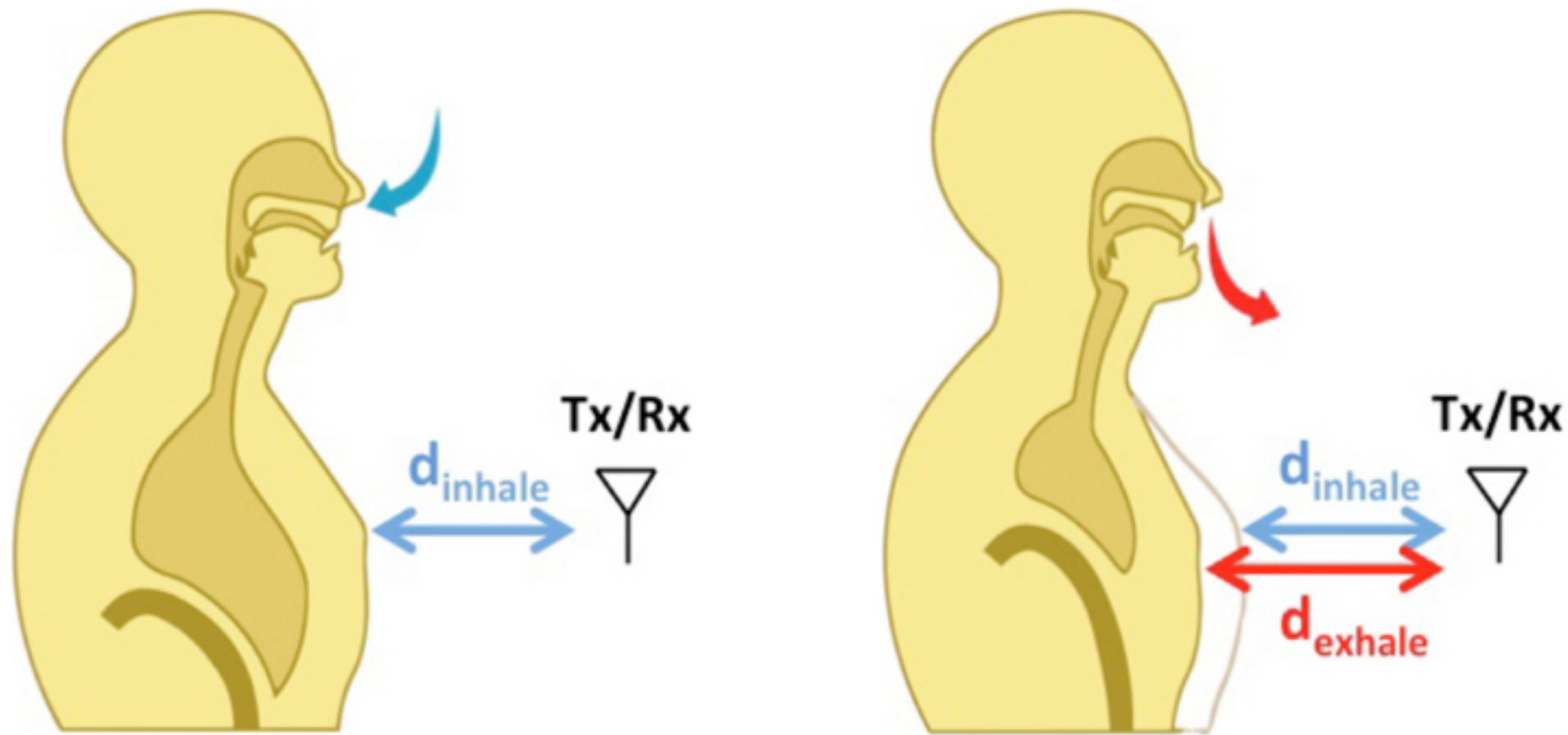


**wearable** - on body

**smartphone** - arm distance from body

**wireless** -

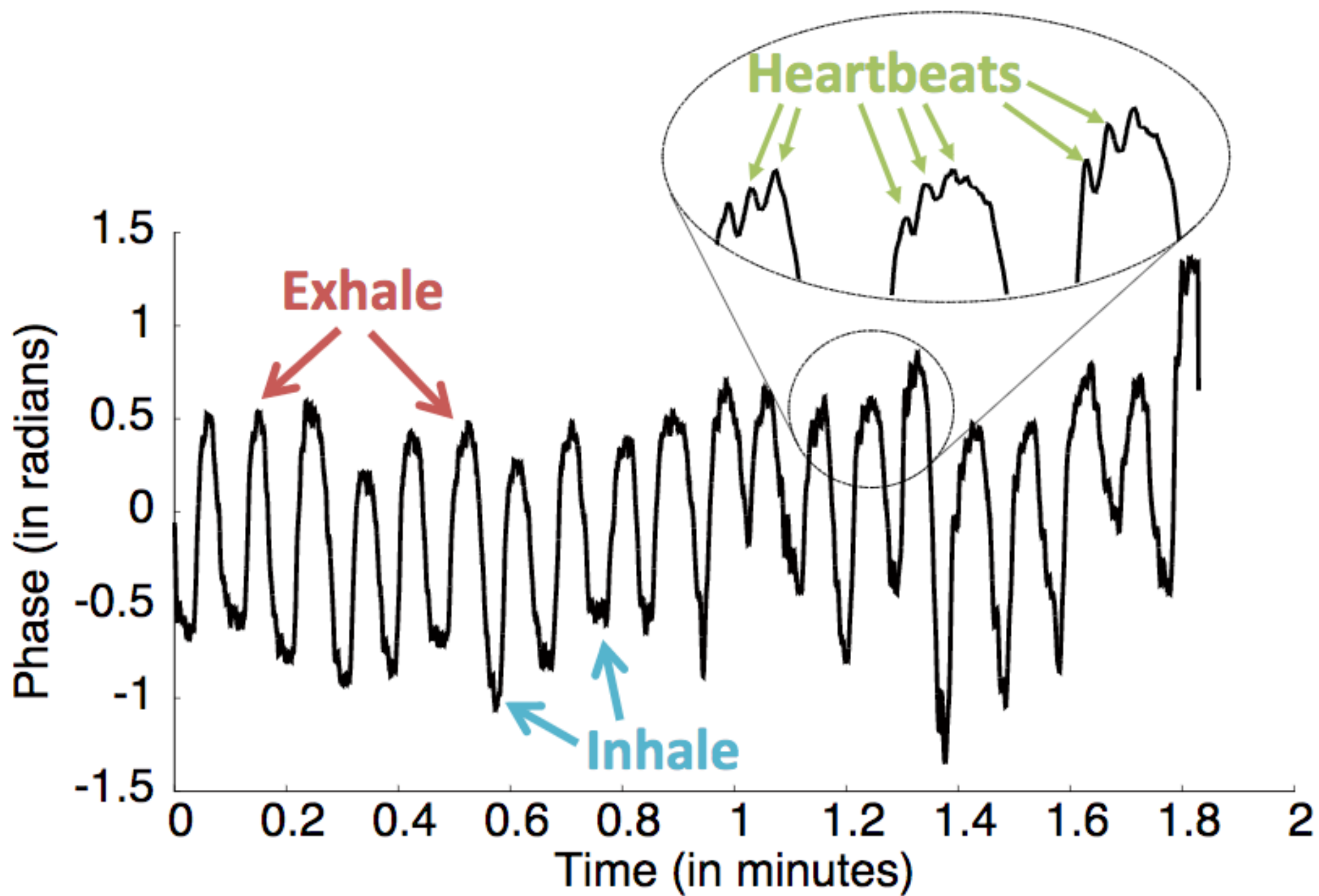
sensing is even further away from the user  
but **does not require any instrumentation**  
of the user's body!



## breathing and heart rate:

- wifi signal
- chest expansion changes signal reflection time
- remove other reflecting objects from the reflected signal
  - each object's reflections come back at a different time
  - sort them into buckets, then identify user





# Smart Homes that Monitor Breathing and Heart Rate

Fadel Adib Hongzi Mao Zachary Kabelac Dina Katabi Robert C. Miller

Massachusetts Institute of Technology  
32 Vassar Street, Cambridge, MA 02139  
{fadel,hongzi,zek,dk,rcm}@mit.edu

## ABSTRACT

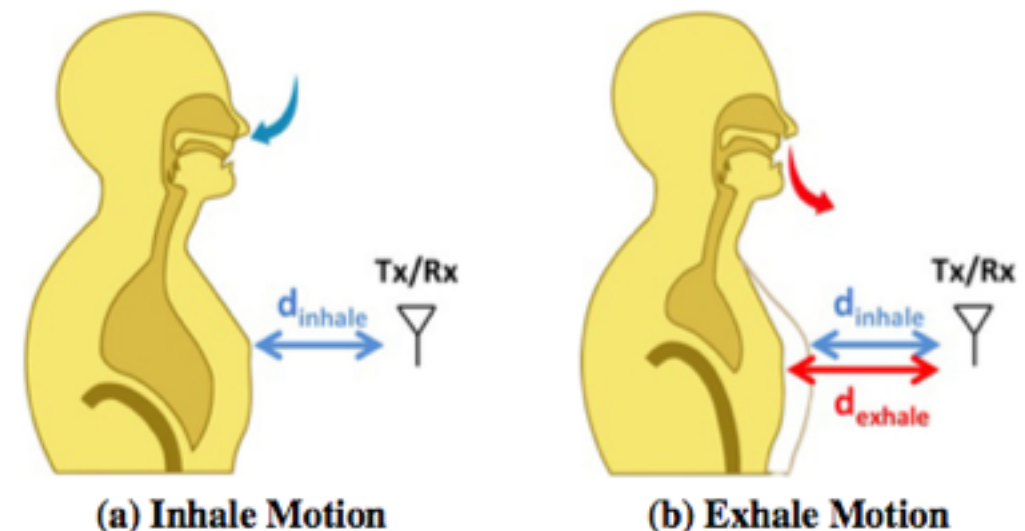
The evolution of ubiquitous sensing technologies has led to intelligent environments that can monitor and react to our daily activities, such as adapting our heating and cooling systems, responding to our gestures, and monitoring our elderly. In this paper, we ask whether it is possible for smart environments to monitor our vital signs remotely, without instrumenting our bodies. We introduce Vital-Radio, a wireless sensing technology that monitors breathing and heart rate without body contact. Vital-Radio exploits the fact that wireless signals are affected by motion in the environment, including chest movements due to inhaling and exhaling and skin vibrations due to heartbeats. We describe the operation of Vital-Radio and demonstrate through a user study that it can track users' breathing and heart rates with a median accuracy of 99%, even when users are 8 meters away from the device, or in a different room. Furthermore, it can monitor the vital signs of multiple people simultaneously. We envision that Vital-Radio can enable smart homes that monitor people's vital signs without body instrumentation, and actively contribute to their inhabitants' well-being.

**Author Keywords** Wireless; Vital Signs; Breathing; Smart Homes; Seeing Through Walls; Well-being

**Categories and Subject Descriptors** H.5.2. Information Interfaces and Presentation: User Interfaces - Input devices and strategies. C.2.2. Network Architecture and Design: Wireless Communication.

## INTRODUCTION

The past few years have witnessed a surge of interest in ubiquitous health monitoring [22, 25]. Today, we see smart homes that continuously monitor temperature and air quality, and



**Figure 1—Chest Motion Changes the Signal Reflection Time.** (a) shows that when the person inhales, his chest expands and becomes closer to the antenna, hence decreasing the time it takes the signal to reflect back to the device. (b) shows that when the person exhales, his chest contracts and moves away from the antenna, hence the distance between the chest and the antenna increases, causing an increase in the reflection time.

heartbeats?" Furthermore, if non-intrusive in-home continuous monitoring of breathing and heartbeats existed, it would enable healthcare professionals to study how these signals correlate with our stress level and evolve with time and age, which could have a major impact on our healthcare system.

Unfortunately, typical technologies for tracking vital signals require body contact, and most of them are intrusive. Specifically, today's breath monitoring sensors are inconvenient: they require the person to attach a nasal probe [19], wear a chest band [43], or lie on a special mattress [3]. Some heart-rate monitoring technologies are equally cumbersome since they require their users to wear a chest strap [18], or place a pulse oximeter on their finger [21]. The more comfortable technologies such as wristbands do not capture breathing and



# WiBreathe: Estimating Respiration Rate Using Wireless Signals in Natural Settings in the Home

Ruth Ravichandran<sup>1</sup>, Elliot Saba<sup>1</sup>, Ke-Yu Chen<sup>1</sup>, Mayank Goel<sup>1</sup>, Sidhant Gupta<sup>2</sup>, Shwetak N. Patel<sup>1</sup>

<sup>1</sup>University Of Washington  
Seattle, WA, US

{vinisha, sabae, kychen, mayankg, shwetak}@uw.edu

<sup>2</sup>Microsoft Research  
Redmond, WA, US  
sidhant@microsoft.com

**Abstract**— Sensing respiration rate has many applications in monitoring various health conditions, such as sleep apnea and chronic obstructive pulmonary disease. In this paper, we present WiBreathe, a wireless, high fidelity and non-invasive breathing monitor that leverages wireless signals at 2.4 GHz to estimate an individual's respiration rate. Our work extends past approaches of using wireless signals for respiratory monitoring by using only a single transmitter-receiver pair at the same frequency range of commodity Wi-Fi signals to estimate the respiratory rate of an individual. This is done irrespective of whether they are in line of sight or not (e.g., through walls). Furthermore, we demonstrate the capability of WiBreathe in detecting multiple people and by extension, their respiration rates. We evaluate our approach in various natural environments and show that we can track breathing with the accuracy of 1.54 breaths per minute when compared to a clinical respiratory chest band.

**Keywords**—health sensing, wireless, respiration rate, non-invasive.

## I. INTRODUCTION

Continuous, non-invasive, and unobtrusive sensing of various health metrics has the potential to improve an individual's well being and quality of life. This information not only provides them with timely feedback on their overall physiological condition but also helps detect abnormalities in trends over prolonged periods of time. Of the many health metrics, detecting respiration rate in a home environment has significant impact in determining potential pulmonary exacerbations in advance. In general, respiration rate in



Figure 1: WiBreathe can detect a person's respiration rate from anywhere in a house without any instrumentation on the body. The system only requires a pair of transmitter and receivers that can be placed anywhere in the house.

behind walls. Specifically, our algorithm clusters and chooses between multiple respiratory rate extraction algorithms, and adapts to a dynamically changing environment. Using a single transmitter-receiver pair (see Figure 1), we show the ability to detect breathing during various activities such as reading, typing at a desk, watching television, and lying down. Given the ubiquity of wireless signals (e.g., Wi-Fi), such an approach can enable true continuous breathing detection throughout the day at various locations in a home, obviating the cost and



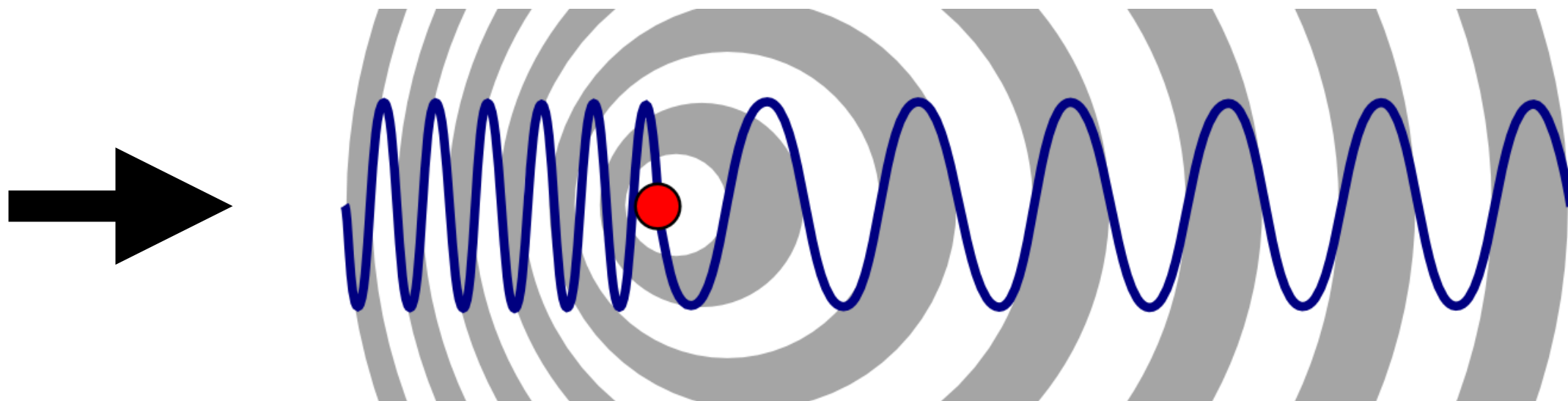
## **sleep interruptions:**

- use the Doppler effect
- module transmits a single tone
- analyze the phase shift



# Doppler effect (from sound lecture):

- if an object moves towards you, the distance between successive wave fronts decreases = denser
- high frequency = high pitch sound
- low frequency = low pitch sound
- think emergency vehicle high pitch when close to you
- direction and speed of hand gesture can be sensed



# DoppleSleep: A Contactless Unobtrusive Sleep Sensing System Using Short-Range Doppler Radar

Tauhidur Rahman<sup>1</sup>, Alexander T. Adams<sup>1</sup>, Ruth Vinisha Ravichandran<sup>2</sup>, Mi Zhang<sup>3</sup>, Shwetak N. Patel<sup>2</sup>, Julie A. Kientz<sup>2</sup>, Tanzeem Choudhury<sup>1</sup>

<sup>1</sup>Cornell University, <sup>2</sup>University of Washington, <sup>3</sup>Michigan State University  
tr266@cornell.edu, ata56@cornell.edu, vinisha@uw.edu, mizhang@msu.edu, shwetak@uw.edu,  
jkientz@uw.edu, tkc28@cornell.edu

## ABSTRACT

In this paper, we present DoppleSleep – a contactless sleep sensing system that continuously and unobtrusively tracks sleep quality using commercial off-the-shelf radar modules. DoppleSleep provides a single sensor solution to track sleep-related physical and physiological variables including coarse body movements and subtle and fine-grained chest, heart movements due to breathing and heartbeat. By integrating vital signals and body movement sensing, DoppleSleep achieves 89.6% recall with Sleep vs. Wake classification and 80.2% recall with REM vs. Non-REM classification compared to EEG-based sleep sensing. Lastly, it provides several objective sleep quality measurements including sleep onset latency, number of awakenings, and sleep efficiency. The contactless nature of DoppleSleep obviates the need to instrument the user's body with sensors. Lastly, DoppleSleep is implemented on an ARM microcontroller and a smart-phone application that are benchmarked in terms of power and resource usage.

## Author Keywords

Sleep Sensing; Doppler radar; Vital Sign Monitoring

## ACM Classification Keywords

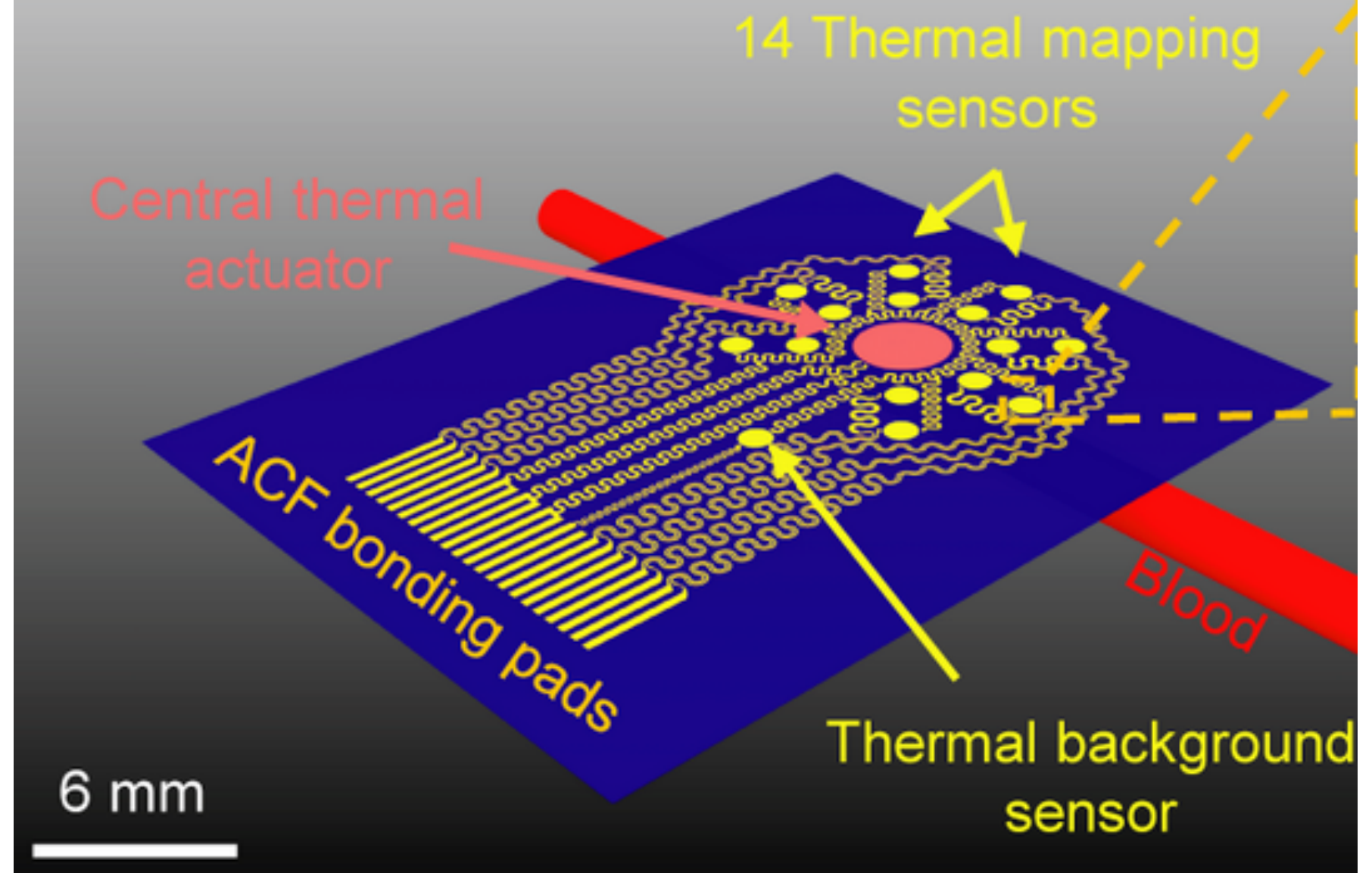
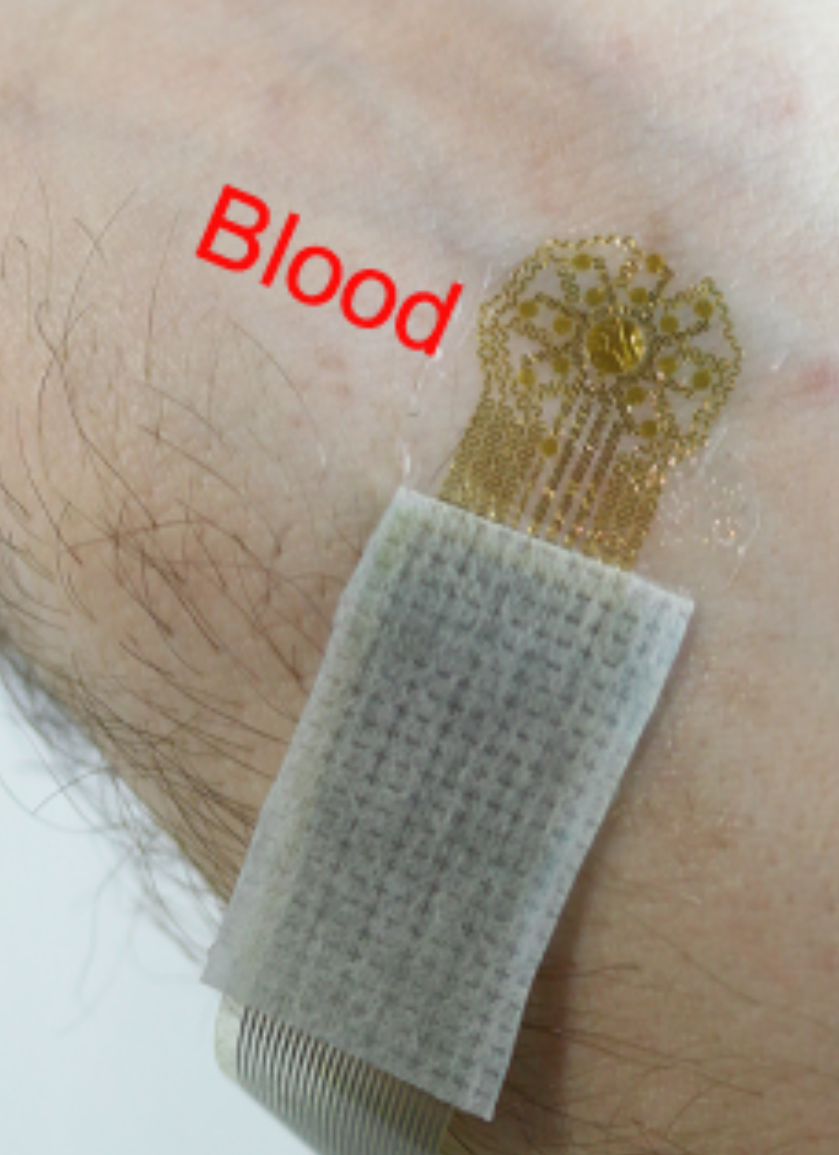
C.3 Special-Purpose and Application-Based Systems: Signal Processing Systems

suspected of having sleep disorders such as sleep apnea or narcolepsy may be advised by physicians to undergo sleep studies in a laboratory, which consists of a single, highly studied night. However, many people with poor sleep quality have more long-term sleep issues such as insomnia or delayed sleep phase syndrome that require longer term monitoring to diagnose, monitor, and treat. A sleep monitoring system that can unobtrusively and objectively measure sleep quality over the long term could provide users with valuable insights into their sleep habits, help them take corrective measures such as improving their sleep hygiene, and ultimately help with identifying more sleep disorders, which often go undiagnosed.

Apart from short-term diagnostic systems like polysomnography, there is a wide variety of commercial long-term sleep monitoring devices. An overview of the state of art in sleep sensing can inform us of the existing gaps in the practical usage of sleep sensing systems. At one end of the spectrum is polysomnography (PSG), which is regarded as the medical gold standard for assessing sleep quality and for diagnosing sleep-related disorders such as sleep apnea [15]. By instrumenting patients with at least 7 different sensors and electrodes that track various sleep-related physiological parameters throughout the night, PSG provides fine-grained sleep quality assessment. PSG is considered a highly obtrusive sleep sensing system due to its expense, impracticality for home-based use, and comfort-level for the patient, and



**the future:  
health-sensing tattoos**

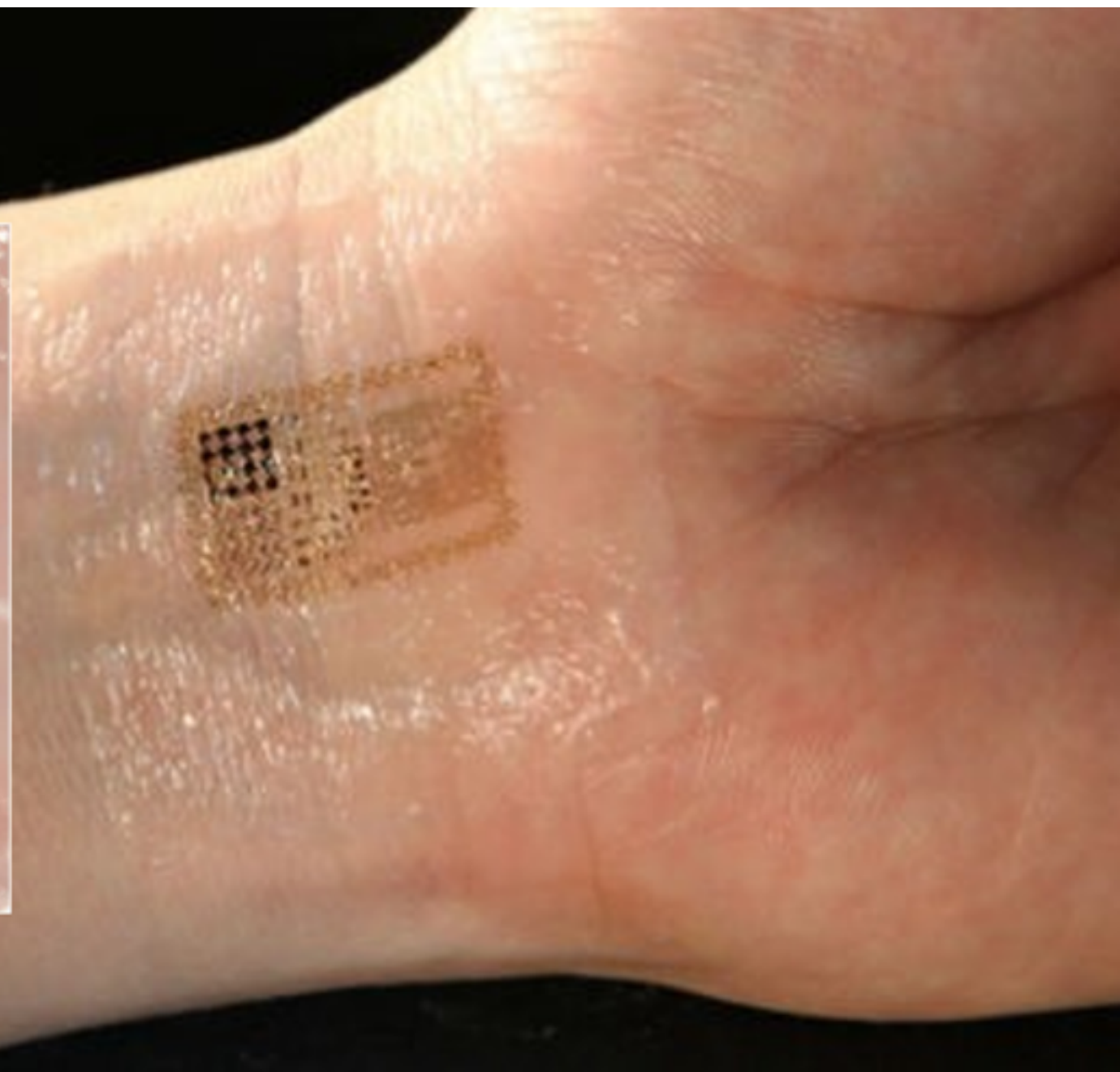
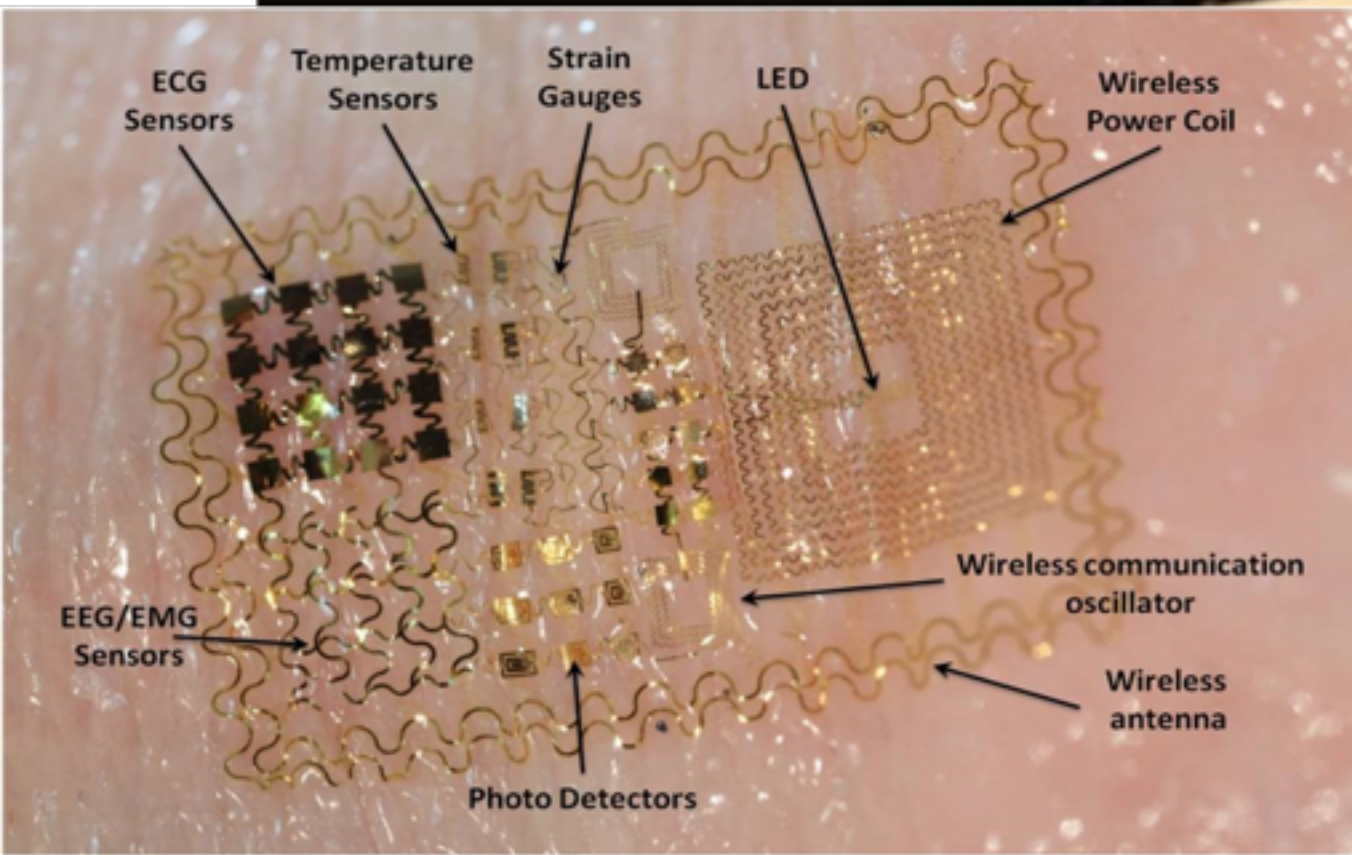


## vascular health & blood flow:

[Rogers, IUIIC]

- heat actuator generates heat
- blood carries heat away
- outer sensors measure direction of blood flow and how quickly heat dissipates
- thin layers of: gold, chromium, copper on silicone



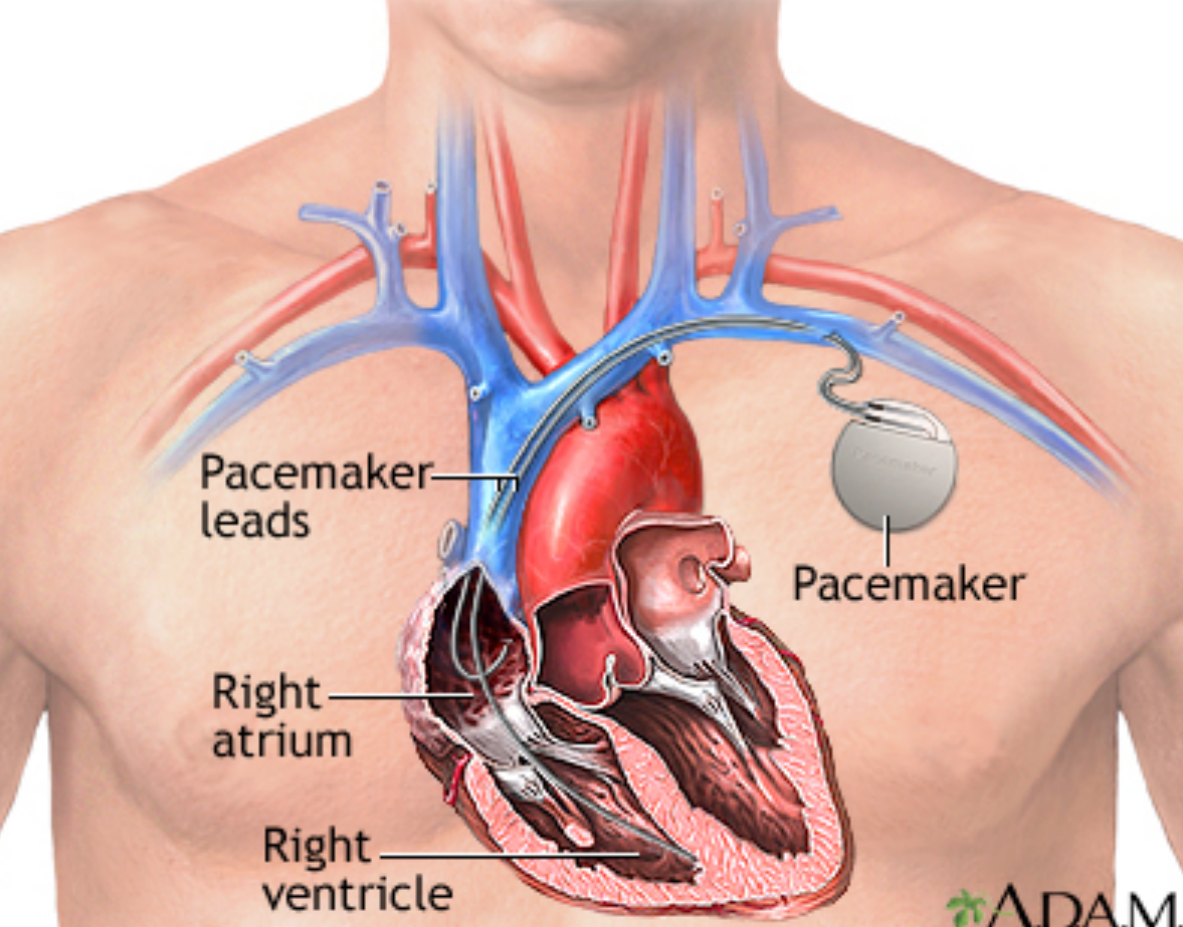


[Coleman, UCSD]

- includes energy transfer (power coil)
- includes information transmit (wireless antenna)
- different sensors

**the future:  
implanted**





## **implanted:**

- most direct effect on body
- best to take close measurements
- measure heart muscle directly rather than indirectly

**challenges**



- make it **easy to access** (e.g. low-cost)
- make it **easy to use**
- **ground-truth** is hard
  - everyone is different
  - even the same person can vary on a daily basis
  - factors such as food intake influence values
- **not everything** is directly measurable
  - chronic pain, mental health

# Detection of behavior change in people with depression

Afsaneh Doryab, Jun Ki Min, Jason Wiese, John Zimmerman, Jason Hong

Carnegie Mellon University, Pittsburgh, PA, USA  
{adoryab, loomlike, jwwiese, johnz, jasonh}@cs.cmu.edu

## Abstract

Major Depressive Disorder (MDD) is the most common mental health disorder and remains a leading cause of disability and lost productivity with huge costs for society. MDD has high rates of relapse and recurrence, and it has strong correlations with feelings of low social support and disrupted sleep. However, MDD is also commonly misdiagnosed by primary care providers, which leads to delayed treatment and unnecessary suffering. Changes in technology now make it possible to cheaply and effectively monitor social and sleep behaviors, offering the potential of early detection of the onset of MDD. We report on the design of Big Black Dog, a smartphone-based system for gathering data about social and sleep behaviors. We also report on the results of a pilot evaluation to understand the feasibility of gathering and using data from smartphones for inferring the onset of depression.

## Introduction

Each year 7% of Americans experience an episode of major depression [NIMH, 2011]. As a leading disability, depression has huge costs in terms of reduced productivity and absenteeism [RAND, 2008]. Most people seek help from their primary care provider (PCP); however, PCPs fail to recognize depression symptoms 65% of the time [Jencks, 1985; Coyne et al, 1995]. The delay in diagnosis and treatment increases the time people suffer from this condition. Research has shown that early detection of a first episode or of a recurrent episode can have a major positive impact [Halpin, 2007; Kupfer et al., 1989].

MDD has high rates of relapse and recurrence, and it has strong correlations with feelings of low social support and disrupted sleep. For example, a lack of social support has been found to predict depression as well as many other

## Related Work

Researchers have investigated a number of behavioral signals to detect the mental state of people, using such approaches as brain signals (Stewart et al., 2010), heart rate (Vikram et al. 2002) blood pressure (Shinn et al., 2001), voice prosody (Cohn et al., 2009; France et al., 2000), and facial expression (Cohn et al., 2009) as proxies for psychophysiological information. EEGs, heart rate trackers, and skin conductors provide rich streams of data; however they are cumbersome to wear, often difficult to use, and typically limited to being used in clinics.

Text mining has also been investigated as a method to detect depression. De Choudhury et al. used tweets to detect depression (De Choudhury et al., 2013). Important indicators included a decrease in social activity, raised negative affect, highly clustered ego networks, heightened relational and medicinal concerns, and greater expression of religious involvement.

Smartphones offer rich a set of built-in sensors including accelerometers, location (GPS, WiFi ID, signal strength), light, and microphone. In past work, we used call logs, text logs, and contact list data to model social behaviors. In other past work, we used smartphone sensor data to model sleep quantity and sleep quality. BBD uses many of the same features from these two systems and applies them in a pilot study specifically for depression.

The most relevant piece of past work is Mobilyze (Burns et al., 2011), a smartphone app that collects sensor data to detect the user's cognitive state. Mobilyze uses machine



# Designing Mobile Health Technology for Bipolar Disorder: A Field Trial of the MONARCA System

Jakob E. Bardram, Mads Frost,  
Károly Szántó

The Pervasive Interaction Technology Laboratory  
IT University of Copenhagen, Denmark  
{bardram,madsf,ksza}@itu.dk

Maria Faurholt-Jepsen, Maj Vinberg  
and Lars Vedel Kessing

Psychiatric Center Copenhagen,  
University Hospital of Copenhagen, Denmark  
<firstname.lastname>@regionh.dk

## ABSTRACT

An increasing number of pervasive healthcare systems are being designed, that allow people to monitor and get feedback on their health and wellness. To address the challenges of self-management of mental illnesses, we have developed the MONARCA system – a personal monitoring system for bipolar patients. We conducted a 14 week field trial in which 12 patients used the system, and we report findings focusing on their experiences. The results were positive; compared to using paper-based forms, the adherence to self-assessment improved; the system was considered very easy to use; and the perceived usefulness of the system was high. Based on this study, the paper discusses three HCI questions related to the design of personal health technologies; how to design for disease awareness and self-treatment, how to ensure adherence to personal health technologies, and the roles of different types of technology platforms.

## Author Keywords

Bipolar disorder; mental health; personal health systems; mobile application

## ACM Classification Keywords

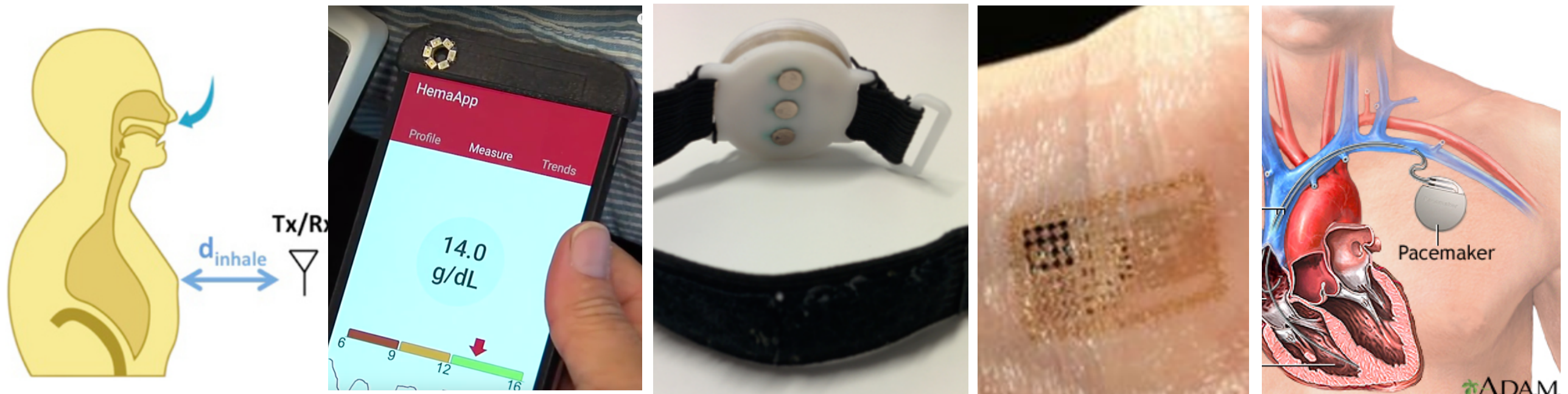
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Consequently, a number of personal monitoring and feedback systems have been suggested for the management of a wide range of health-related conditions. In general, these types of systems help users by enabling them to monitor and visualize their behavior, keeping them informed about their physical state, reminding them to perform specific tasks, providing feedback on the effectiveness of their behavior, and recommending healthier behavior or actions.

However, introducing new technology for patients with psychiatric disorders, who often have a low coping ability, may be stressful for them and introduce a high cognitive load. Unfortunately, mentally ill patients tend to be socially challenged as well, having a larger tendency for unemployment and alcohol or substance abuse [14]. As such, designing for this group of users is challenging, and the introduction of new technology may not be well adopted and used. Hence, a core research question is to what degree systems for mentally ill patients can be designed, to what degree such technologies will be adopted and used, and how it will lead to new ways for the patients and clinicians to treat this group of patients, compared to the existing approaches.

In this study, we examined the use of a personal health monitoring and feedback system for patients suffering from bipolar disorder, called the MONARCA system [1]. The system lets





wireless

phone

wearable

tattoo

implanted

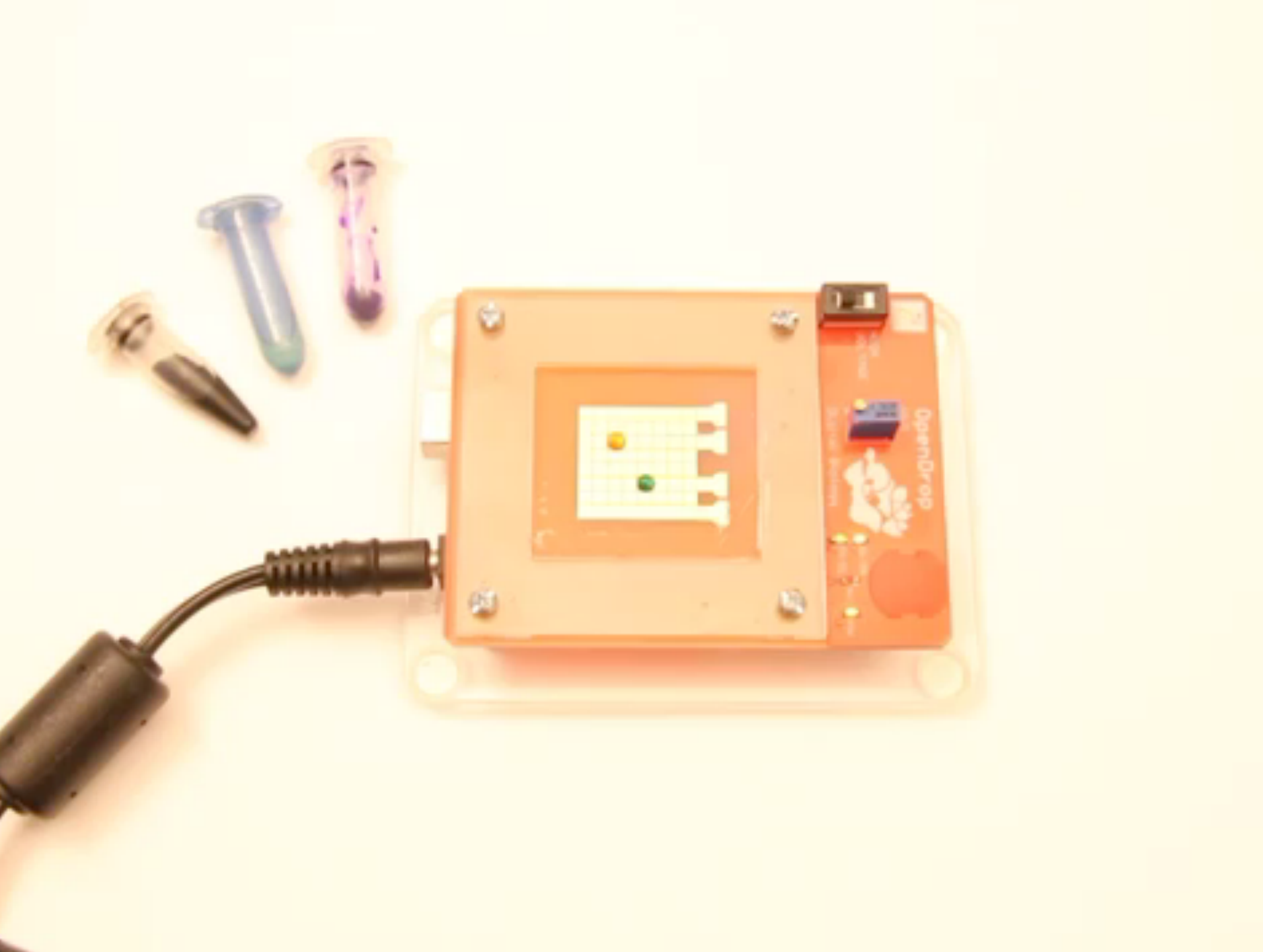


closeness to body

**novel health sensing:** measure anywhere & all the time  
 -> many more data points, can generate warnings upfront



**many more areas  
in health...**



## micro-fluidics:

- analyzing probe data in-situ
- mixing medicine on the fly





**OpenDrop**  
Desktop Digital Biology Laboratory

HOME

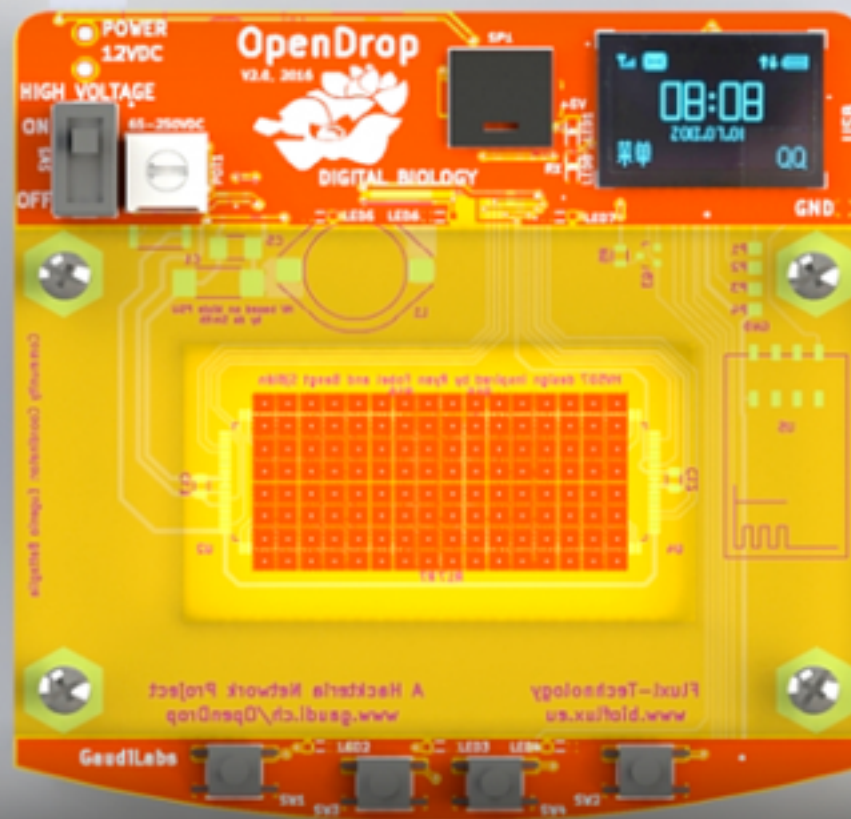
ABOUT

DEVICES >

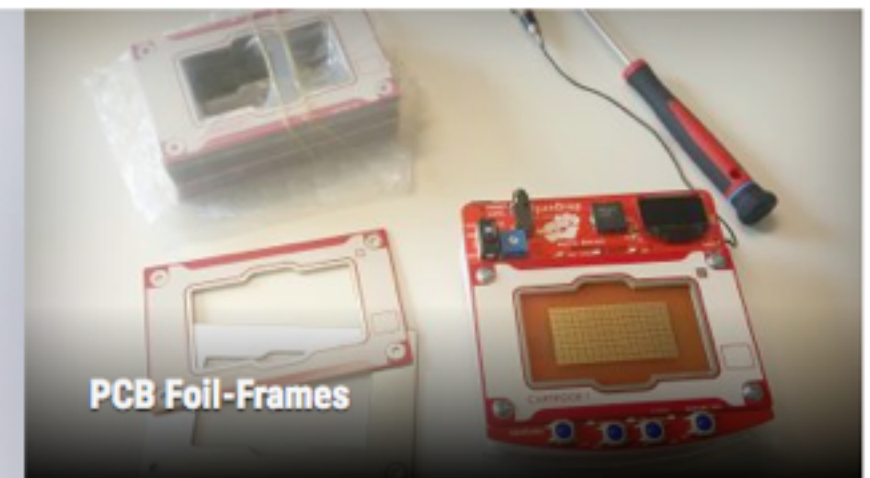
RESEARCH

COMMUNITY

GITHUB



OpenDrop V2



PCB Foil-Frames

OPENDROP

CONTACT

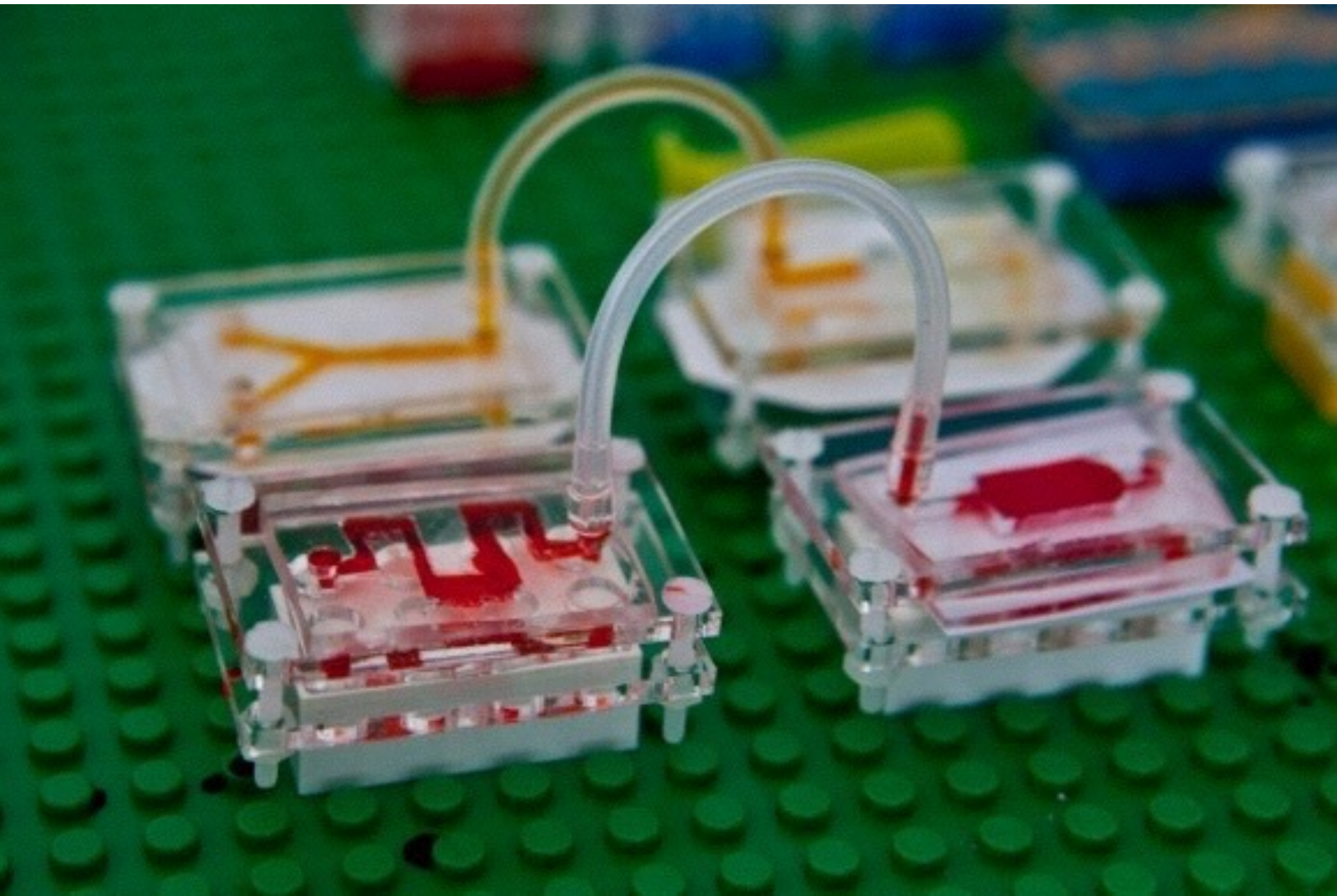
OpenDrop is a development part of a bigger ecosystem around digital biology with the aim of making personal

Urs Gaudenz – GaudiLabs



**Little Devices Group at IDC:**  
affordable health & rapid diagnostics





**Little Devices Group at IDC:**  
affordable health & rapid diagnostics



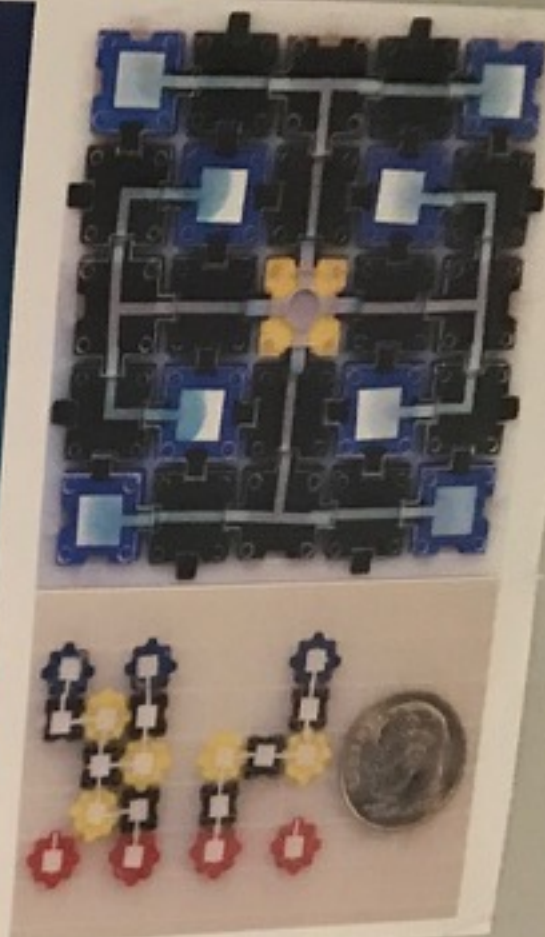


# LITTLE DEVICES LAB

We explore the design, invention and policy strategies for DIY health technologies around the world.

What happens in a healthcare system as it learns to prescribe a prototype? We work at the intersection of biomedical design and user-generated medical devices. The goal is to radically democratize the process of medical fabrication and create more transparent medical hardware tools that engage many types of users innovators. The research outcomes do not prioritize the creation of final devices but instead a platform of instrumentation and design patterns that enable everyone to be a health maker. The performance of our medical making instruments are measured by a metric we define as Design for Hack: an engineered structure and experience where the device encourages users to become the final and primary architects of a medical device.

Our work spans fields such as open source infectious disease diagnostics for viruses like RNA viruses such like dengue and ebola; sensorized medical devices; the discovery of novel user innovator behavior for health; prototyping tools and instrumentation with consumer materials; and the design of construction sets and medical makerspaces that facilitate medical invention in hospital and home settings.





end.