Citizen Science: Enabling Participatory Urbanism

Book Chapter for *Urban Informatics: Community Integration and Implementation*

Eric Paulos
Intel Research
2150 Shattuck Avenue #1300
Berkeley, CA 94704
USA
eric@paulos.net

RJ Honicky
Department of Electrical Engineering and Computer Sciences
University of California, Berkeley
Berkeley, CA 94720-1776, USA
honicky@cs.berkeley.edu

Ben Hooker
Intel Research
2150 Shattuck Avenue #1300
Berkeley, CA 94704
USA
ben.hooker@gmail.com

Tell me, I forget.
Show me, I remember.
Involve me, I understand.
— Chinese proverb

ABSTRACT

In this chapter we present an important new shift in mobile phone usage – from communication tool to "networked mobile personal measurement instrument". We explore how these new "personal instruments" enable an entirely novel and empowering genre of mobile computing usage called *citizen science*. We investigate how such citizen science can be used collectively across neighborhoods and communities to enable individuals to become active participants and stakeholders as they publicly collect, share, and remix measurements of their city that matter most to them. We further demonstrate the impact of this new *participatory urbanism* by detailing its usage within the scope of environmental awareness. Inspired by a series of field studies, user driven environmental measurements, and interviews, we present the design of a working hardware system that integrates air quality sensing into an existing mobile phone and exposes the citizen authored measurements to the community – empowering people to become true change agents.

Keywords

Mobile Sensors, Air Quality, Global Warming, Street Science, Sustainability, Green, Urban Computing.

MOTIVATION

Mobile phones are powerful tools indeed – collapsing space and time by enabling us to reach out to contact others at a distance, to coordinate mico-planning events, and to reschedule activities at a moment's notice. But with all of their abilities they lack the superpower we perhaps need most – the ability to measure and understand the real world around us.

We carry mobile phones with us nearly everywhere we go; yet they sense and tell us little of the world we live in. Look around you right now. How hot is it? Which direction am I facing? Which direction is the wind blowing and how fast? How healthy is the air I'm breathing? What is the pollen count right now? How long can I stay outside without getting sunburned? Is the noise level safe here? Were pesticides used on these fruits? Is this water safe to drink? Are my children's toys free of lead and other toxins? Is my new indoor carpeting emitting volatile organic compounds (VOCs)? Now look to your phone for answers about the environment around you. What is it telling you? For all of its computational power and sophistication it provides us with very little insight into the actual conditions of the atmospheres we traverse with it. In fact the only real-time environmental data it measures onboard and reports to you is a signal to noise value for a narrow slice of the electromagnetic spectrum (Figure 1).

Certainly one could imagine accessing the web or other online resource to find an answer to some of these questions. But much of that online data is calculated and published for general usage, not for you specifically. For example, the civic government may say that the temperature is currently 23ºC by taking one measurement at the center of the city or averaging several values from multiple sites across town. But what if you're in the shade by the wind swept waterfront where it is actually 17ºC or waiting underground for the subway where it is a muggy 33ºC. The measurement that means the most to you is likely to be the one that captures the actual conditions you are currently experiencing, not citywide averages.

Imagine you are deciding between walking to one of two subway stations and could gather live data from the passengers waiting on the platform at each stop about the temperature and humidity of each station at that very moment? What if you were one of the 300 million people who suffer from asthma (WHO, 2006b) and could breath easily as you navigated your city with real-time pollen counts collected by your fellow citizens? What if you could not just be told the level of noise pollution in your city but measure and publish your own actual decibel measurements taken in front of your home? What if you were one of the more than 3 billion people, nearly half the world's population, that burned solid fuels, including biomass fuels (wood, dung, agricultural residues) and coal, for their energy, heating, and cooking needs indoors and yet had no way to monitor the health effects of the resulting pollutants on yourself and your family even though nearly 2 million people die annually from indoor air pollution (Ezzati & Kammen, 2002)?

Mobile technology is with us and is indeed allowing us to communicate, buy, sell, connect, and do miraculous things. However, it is time for this technology to empower us to go beyond finding friends, chatting with colleagues, locating hip bars, and buying music. We need to expand our perceptions of our mobile phone as simply a communication tool and celebrate them in their new role as personal measurement instruments capable of sensing our natural environment and empowering collective action through everyday grassroots citizen science across blocks, neighborhoods, cities, and nations. Our goal is to provide our mobile devices with new superpowers and "super-senses" by outfitting them with novel sensors and providing an infrastructure for public sharing and remixing of these personal sensor measurements by experts and non-experts alike. The overall long-term goal is to enable actual and meaningful local and global changes driven by the desires of everyday citizens. Our work is but a small effort towards this end.

INTRODUCTION

We have already seen the early emergence of sensor rich mobile devices such as Apple's Nike+iPod Sport Kit (music player + pedometer), Apple's iPhone (mobile phone + proximity sensor and accelerometer), Nokia's 5500 (mobile phone +

Figure 1: The only real-time environmental data displayed on a mobile phone – a narrow slice of the electromagnetic spectrum with a tiny readout of cell tower signal strength.

pedometer), Samsung's S310 (mobile phone + 6 axis accelerometer), LG Electronics LG-LP4100 (mobile phone + breathalyzer), t+ Diabetes (mobile phone + blood glucose sensor), and Samsung's planned body fat (K. K. Park & Hwang, 2007) and fertility monitoring phone (J. J. Park, Lee, Jung, & Kim, 2007). Similarly, we have seen the "Web 2.0" phenomenon embrace an approach to generating and distributing web content characterized by open communication, decentralization of authority, freedom to share and re-use, and "the market as a conversation" (Beer & Burrows, 2007; Josef & Hermann, 2006; O'Reilly, 2005).

We assert that there are two indisputable facts about our future mobile phones: (1) that they will be equipped with more sensing and processing capabilities and (2) that they will be driven by an architecture of participation and democracy that encourages users to contribute value to their tools and applications as they use them as well as give back collective value to the public. There are countless examples already in existence of such systems from Flickr to Wikipedia to Creative Commons (Lessig, 1994) to open source movements such as FLOSS (Free/Libre/Open-Source Software) where the *de facto* moral etiquette of openly contributing and sharing the collective repository of knowledge is upheld as the foundational and driving principle of the technology. What if we simply enable mobile phones to more easily participate in this emerging computing paradigm? There is an inevitable and powerful intersection of people-centric sensing with the current online remix culture.

More specifically, what happens when individual mobile phones are augmented with novel sensing technologies such as noise pollution, air quality, UV levels, water quality, *etc*? We claim that these new mobile "sensing instruments" will promote everyday citizens to uncover and visualize unseen elements of their own everyday experiences. As networked devices, they reposition individuals as producers, consumers, and remixers of a vast openly shared public data set. By empowering people to easily measure, report, and compare their own personal environment, a new citizen driven model of civic government can emerge, driven by these new networked-mobile-personal-"political artifacts" (Winner, 1999).

Our strategy is to design and deploy a series of networked measurement instruments that are embedded within our everyday places as well as coupled to personal mobile devices to collectively capture a view of our environment. More importantly, our research positions citizens as the driving element for collecting, reporting, interpreting, and collectively improving the health of our natural environment. Our hypothesis is not only that a wealth of novel and important untapped computing interactions exist in this research space, but that such experiences are certain to become a dominant paradigm in our evolving relationship with technology.

The technological debate radically expands from beyond simply how to design a few functional mobile applications that satisfy the needs of thousands of people (such as a location service, a friend finder social networking system, or a mapping overlay tool) to how thousands of mobile individuals can measure, share, and remix publicly sampled data into a wide variety of more personally meaningful mobile experiences and tools. Large-scale services, while tremendously important, often suffer from lowest common denominator effects as they seek to make a single system satisfy the needs of everyone. We see our future technologies as a mixture of large-scale systems and personally customized small tools. In this chapter we are interested in exploring this new model of citizen measuring, public sharing, and personal remixing of the environment driven by personal experiences and measurements. The result is a technological future that hopefully conveys personal meaning to citizens, a more informed and responsive civic government unburdened from its reliance on low resolution, generic, and filtered data driven solutions, and a better place for us all to live. By elevating everyday citizens into the role of data collector, commentator, and policy maker, we hope to directly empowering such individuals to act as change agents within their world.

Outline

In this chapter we define the territory of *citizen science* along with the challenges to its adoption, introduce the mobile phone as a measurement instrument for environmental sensing, and outline a taxonomy of sensor and mobile phone interactions. In the second half of the chapter we explore the measurement of air quality specifically, discuss current techniques in use for measuring and presenting air quality, report results from an air quality awareness survey, present a field study using several human driven atmospheric environmental sensors carried across the capital city of Ghana, and present a specific instantiation of a working system for *citizen science* – personal environmental monitoring with air quality sensors integrated with a mobile phone.

CITIZEN SCIENCE

Citizen Science builds upon a large body of related projects which enable citizens to act as agents of change. There is a long history of such movements from grassroots neighborhood watch campaigns to political revolutions. Some of the more well known movements are the National Audubon Society's Christmas Bird Count (CBC) where a census of birds in the Western Hemisphere is performed annually by citizens since 1900 (LeBaron, 2006). More recently, the success of online approaches such as SETI@Home and “The Great World Wide Star Count” an international event that encourages everyone to go outside, look skywards after dark, and report the count of stars they see, inform us that there is an immense public interest in such collective movements.

Our work leverages Corburn’s “street science” framework, which emphasizes local urban insights to improve scientific inquiry and environmental health policy and decision-making. Corburn underscores the importance of local community knowledge as “the scripts, images, narratives, and understandings we use to make sense of the world in which we live” (Corburn, 2005). Even more emphatically he states that a community's “political power hinges in part on its ability to manipulate knowledge and to challenge evidence presented in support of particular policies” (p. 201). While such local knowledge and community-based practices are sometimes labeled as romantic or populist, Corburn insists that such views overlook the structural and global dimensions of problem solving for urban communities. Corburn believes that “street science” leverages community power imbalances, and can increase agency or decision maker understanding of a community's claims, thereby potentially increasing public trust. He insists that such local knowledge informs environmental health research and environmental policy making in four distinct ways: 1) by making a cognitive contribution by rectifying the tendency towards reductionism; 2) by fostering of a “hybridization” of professional discourse with local experience; 3) by pointing out low-cost and more effective interventions or remedies; and 4) by raising previously unacknowledged distributive justice concerns that disadvantaged communities far too often face.

We also draw from the work of German sociologist Ulrich Beck who postulates that as people become less constrained by social institutions, they are in a position to mold the process of modernization rather than remain passive observers of a system in which they hold no stake (Beck, Giddens, & Lash, 1994). In Beck’s world, individuals have the opportunity to become change agents by way of information. For him information is key to the (re)shaping of the social and political world. For us the creation, sharing, and remixing of information is a fundamental component of our citizen science design approach.

Finally, in *The Death and Life of Great American Cities* Jane Jacobs writes (Jacobs, 1961) that to understand cities we need to “reason from the particulars to the general, rather than the reverse [and] to seek ‘unaverage’ clues involving very small quantities, which reveal the way larger and more ‘average’ quantities are operating” (p. 440). Jacobs continues, “Quantities of the ‘unaverage’, which are bound to be relatively small, are indispensable to vital cities” (p. 443). Citizen science attempts to elevate the local expertise of citizens and their personal, small, unusual, local, particular experiences across urban life.

URBAN COMPUTING

Urban Computing captures a unique, synergistic moment - expanding urban populations, rapid adoption of small, powerful, networked, mobile devices, bluetooth radios, tiny ad hoc sensor networks, and the widespread influence of wireless technologies across our growing urban landscapes. According to the United Nations, 2007 marks the first point in human history that over half of the world’s population live in urban areas (UN, 2003). In developed nations the number of urban dwellers is even more dramatic, often exceeding 75%. The very essence of person, place, and community are being redefined by personal wireless digital tools that transcend traditional physical constrains of time and space. New metaphors for visualizing, interacting, and interpreting the real-time ebb and flow of urban places are emerging. The large population densities of cities, the widespread proliferation of wireless and digital infrastructure, and the early adoption of mobile and wireless technologies by its inhabitants make such urban landscapes a rich territory for researching emerging social and technological phenomena. Urban Computing strives to expose, deconstruct, and understand the challenges of this newly emerging moment in urban history and its dramatic influence on technology usage and adoption. Several bodies of collected work outline this research frontier (Dave, 2007; Kindberg, Chalmers, & Paulos, 2007; Shklovski & Chang, 2006).

What is <u>not</u> Urban Computing?

Urban Computing focuses on our lifestyles and technologies within the context of public urban spaces. Its research challenges differ from those found within the home where technologies readily intermingle across our intimate relations with friends and family members. It diverges from office and work environments where productivity and efficiency often dominate our computing tools. Urban Computing is **not** a disconnected personal phone application, a domestic networked appliance, a mobile route planning application, an office-scheduling tool, or a social networking service. Urban Computing is also not simply concerned with mobile computing which is actually a misnomer for “nomadic computing” in which people interface with a “computing device” from a finite set of discrete places such as “at the park”, “on the bus”, and “in the cafe”. Rather we are concerned with the continuous needs, opportunities, and styles of interactions that arise not just within the scope of these nomadic places but across the full range of places, transitions, and flows. Finally, while cities are places of dynamic social interactions, Urban Computing is not focused on simply solving the challenges of social networking in public places, but exploring a much wider gamut of urban live from the personal to the social, from the solitary to the crowd, from emphasizing connectivity to celebrating the disconnect, from promoting passivity to inspiring activism, curiosity, and wonderment (Paulos, Jenkins, Joki, & Vora, 2008).

Urban Computing Framework

Urban Computing establishes an important new framework for deconstructing and analyzing technology and urban life across five research themes - *people*, *place*, *infrastructure*, *architecture*, and *flow*. The diversity of these important themes promotes rich interdisciplinary research within the field of Urban Computing. The authors assert the following key themes for Urban Computing.

People – Who are the people we share our city with? How do they influence our urban landscape? Where do we belong in this social space and how do new technologies enable and disrupt feelings of community and belonging?

Place – How do we derive the meaning of various public places? What cues do we use to interpret place and how will urban technologies re-inform and alter our perception of various places? How does technology create new places?

Infrastructure – How will existing urban systems such as power, water, subways, public transportation, signal lights, toll booths, etc be used and re-appropriated by emerging technologies?

Architecture – What new techniques and smart surfaces will emerge for interacting with buildings, public surfaces, sidewalks, benches, and other "street furniture"? What role will new structures, shapes, and forms play?

Flow – What is a path or route through a city using these new urban tools? How will navigation and movement, either throughout an entire city or within a small urban space, be influenced by the introduction of computing technologies?

PARTICIPATORY URBANISM

Inspired directly by citizen science and in the spirit of Urban Computing (Paulos & Jenkins, 2005), *participatory urbanism* is more directly focused on the potential for emerging ubiquitous urban and personal mobile technologies to enable citizen action by allowing open measuring, sharing, and remixing of elements of urban living marked by, requiring, or involving participation, especially affording the opportunity for individual citizen participation, sharing, and voice. Participatory urbanism promotes new styles and methods for individual citizens to become proactive in their involvement with their city, neighborhood, and urban self-reflexivity. Examples of *participatory urbanism* include but are not limited to: providing mobile device centered hardware toolkits for non-experts to become authors of new everyday urban objects, generating individual and collective needs based dialogue tools around the desired usage of urban green spaces, or empowering citizens to collect and share air quality data measured with sensor enabled mobile devices.

A clear research challenge is to understand the roll that emerging *in situ* mobile technologies will play in promoting citizen science. Using only text and picture messaging, citizens have already initiated several significant citizen science themed actions.

- **People Power 2**: a four-day popular revolution that peacefully overthrew Philippine president Joseph Estrada in January 2001 where text messaging played a leading role (Mydans, 2001).
- **Orange Revolution**: a series of protests and political events coordinated using text messaging that took place in the Ukraine in 2004 that exposed massive corruption, voter intimidation, and direct electoral fraud between candidates Viktor Yushchenko and Viktor Yanukovych (Myers & Mydans, 2005).
- **TXTmob**: a open source text messaging system used to coordinate protests during the United States Republican Presidential Convention in 2004 (Justo, 2004).
- **Hollabacknyc.com**: A blog where women "holla back" at harassers by taking their pictures with camera phones and post them online. Inspired by Thao Nguyen's Flickr image of Dan Hoyt indecently exposing himself to her on a New York public subway in 2005 (May, 2007)
- **Parkscan.org**: a system setup in 2003 allowing people voice concerns on park maintenance by uploading information about public park conditions as text and pictures from mobile devices and the web (Farooq, 2006).

Several research projects have also begun to explore technology's role in promoting citizen science such as Equator's Ambient Wood Project (Randell, Phelps, & Rogers, 2003) using PDAs for sampling the environment by children and White's LeafView mobile phone system for capturing, logging, and cataloging plants in the field (White, Feiner, & Kopylec, 2006) by non-scientists. More recently, UCLA's Center for Embedded Network Sensing has setup a research initiative called "Participatory Sensing" that is developing infrastructure and tools to enable individuals and groups to initiate their own public "campaigns" for others to participate in by using networked mobile devices (Burke et al., 2006). Similarly, the

MetroSense project outlines an exciting opportunistic "people-centric" approach to mobile phone sensing including several deployments with bicycles (Campbell et al., 2008). As strong advocates of such participatory models, our work complements this research by 1) focusing on an initial capstone application of air quality sensing, 2) emphasizing the measure-share-remix metaphor for "on-the-go" citizen participation, and 3) expanding the integration of new sensors for mobile devices. We have also seen exciting new work that addresses sensor data sharing and remixing with Microsoft's SenseWeb (Santanche, Nath, Liu, Priyantha, & Zhao, 2006), Nokia's SensorPlanet (Balandina & Trossen, 2006), Platial (www.platial.com) and SensorMap (Nath, Liu, Miller, Zhao, & Santanche, 2006), Mappr (www.mappr.com), Swivel (ww.swivel.com), and IBM's ManyEyes (Viégas, Wattenberg, Ham, Kriss, & McKeon, 2007).

MOBILE DEVICE AS MEASUREMENT INSTRUMENT

One major vector of citizen science is the enabling of networked, personal, mobile devices to become easily augmented with novel sensors that empower individuals to personally collect, share, compare, and participate in interpreting the personal measurements of their everyday life. As we stated in the introduction, our future mobile devices will have not only more processing power but also a wealth of new sensing capabilities. These new personal mobile sensors open up a rich new design territory. We envision a taxonomy of sensors and mobile devices as follows:

Onboard – Sensors that are physically built into the mobile device. Examples are the onboard accelerometer in the Apple iPhone and Nokia 5500 and the existing microphone and camera on today's mobile phones. In the future it could include mobile phone capable of measuring carbon monoxide, pollen, radiation, epidemiological viruses or wind speed and direction for a golfer.

Worn – Sensors that are worn on the body or clothing and are wirelessly connected to the user's mobile phone using a personal area network (PAN) such as Bluetooth. Examples, are the shoe worn pedometer in the Nike+iPod Sports Kit, personal heart rate monitors, to perhaps a leg kick sensor for dancers, a hat mounted UV sensor, or a wristwatch sulfur dioxide sensor. We can envision a new genre of environmentally conscious fashion designed around air quality sensing enabled clothing.

Left Behind – In the spirit of sensor networks (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002) very low-power and low-cost sensors that are left behind to collect measurements which are retrieved upon the users next visit or encounter with the sensor. Examples include an ambient temperature logger left under a bus seat, a UV light detector left in a park, a soil moisture sensor stuck in a public planter, and a nitrogen dioxide sensor attached to a street sweeper.

Temporarily Scattered – Sensors that are spread out within a nearby area and used by an individual while they are within that given context. Later they are typically collected and taken away by the user. Examples include a hall-effect spoke counter by a bike messenger on her bicycle, a motion sensor used by a group playing soccer to demarcate the goal and side lines, and accelerometers mounted on a skateboard for "recording" the acceleration profile of a "casper stall" trick.

Infrastructure – Sensors, typically powered, highly calibrated, and static in the urban environment that broadcast their sensor data via a global network and/or a personal area network such as Bluetooth or Wibree. Typically these sensors are operated by reliable agencies and used as a public resource for authenticating and calibrating the mobile sensor platforms carried by individual citizens. Examples include a carbon monoxide sensor in a subway station, a temperature sensor at a bus stop, and pollen count logger in a park.

BARRIERS TO CITIZEN SCIENCE

While sensor rich mobile devices usher in a compelling series of new mobile device usage models that place individuals in the position of influence and control over their urban life, there are a number of important barriers to the development and adoption of such systems. These research challenges are presented below:

Hardware Extensibility – Currently, attaching new devices and sensors is a skill reserved for experts and scientists. In order to gain widespread usage non-experts must be able to easily attach new sensors to their mobile phones. Standard connectors, for providing power (i.e. 500mA), and standard protocols for communication with sensors need to be adopted. Most mobile devices provide RS-232 serial, USB, and/or Bluetooth as external communication mechanism to attached sensors. But standards across vendors for pins and power are lacking. Nokia has initiated research into this problem with N-RSA (Nokia Remote Sensing Architecture) (Balandina & Trossen, 2006).

Open Platforms – Developers need access to all of the features and hardware on mobile devices. This does not imply that such open platforms are prone to open hacking and are inherently insecure. In fact recent work on embedded OS device isolation and virtual machines such as J2ME, Parallels, and VMware demonstrate strategies for designing secure, open systems. Mobile phones must adopt these established computing practices to insure open sensor development for citizen science.

Software for Sharing – The need for common file formats and internet protocols like Google maps, geo-tagged images, XML-schema, and RSS/ATOM for "on-the-go" devices must be established. Microsoft's SenseWeb (Santanche et al., 2006) has outlined an approach to sharing sensor data from fixed sensor deployments. Without common formats, the growth and adoption of grassroots citizen science efforts will be stunted.

Power – The addition of new hardware, new sensors, more data logging, and more radio power for sharing this data, puts extreme demands on power management for these new mobile devices. Creative strategies for opportunistic sampling, sharing, and processing of these new data feeds must be developed. Delay Tolerant Networks (DTN) and similar approaches currently hold much promise (Fall, 2003).

Privacy and Anonymity – Users may desire to participate in this public data collection but not at the expense of publicly disclosing their daily location traces and patterns. We need mechanisms to insure privacy and guarantee a level of anonymity for users and yet enable communities to make connections and foster open debates with their data.

Authentication and Trust – Erroneous or intentionally bogus measurements by an adversary need to be easily detected and flagged as such for removal from the system. The validity and integrity of the entire system are based on insuring this fundamental level of trustworthy data.

Calibration – Citizen science by definition explicitly enables the use of scientific data collection equipment by non-experts. The handling and usage of the sensors and measurement conditions will vary wildly – in and out of elevators, handbags, pockets, subway stations, *etc*. How can we attempt to calibrate these sensors "in the wild"?

Sensor Selection – What are the reasonable set of sensors to use and what conditions make sense to measure? Where should the sensors be mounted and in what contexts and positions are they best sampled?

Super Sampling – Intuitively, millions of mobile sensors should be better than a single fixed sensor. What are the algorithmic techniques that can provide a mechanism to use the sensor data to super sample locations and activities? How can this super sampling enable detection of anomalous or adversarial sensor readings and improve overall sensor calibration.

Environmental Impact – Finally, perhaps of greatest importance, while the vision is to provide millions of sensors to citizens to empower new collective action and inspire environmental awareness by sampling our world, the impact of the production, use, and discarding, of millions of pervasive sensors must be addressed. Does the overall benefit of citizen science enabled by these new devices offset their production, manufacturing, and environmental costs?

MEASURING ENVIRONMENTAL AIR QUALITY

The World Health Organization reports that 2 million people now die each year from the effects of air pollution, two times the number of deaths from automobile accidents (WHO, 2006a). Direct causes of air pollution related deaths include aggravated asthma, bronchitis, emphysema, lung and heart diseases, respiratory allergies, visual impairment, and even Sudden Infant Death Syndrome (SIDS) (Klonoff-Cohen, Lam, & Lewis, 2005).

How is Air Quality Measured and Reported?

The main method of measuring and reporting air quality is the Air Quality Index (AQI). The AQI is a standardized indicator of the air quality in a given location based on United States federal air quality standards for six major pollutants as regulated by the Environmental Protection Agency (EPA). The AQI is primarily an 8-24 hour moving average weighted measurement of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ground-level ozone (O_3), 2.5 micron particulate matter ($PM_{2.5}$), and 10 micron particulate matter (PM_{10}). A non-gas, particulate matter is the term for tiny particles of solid (a smoke) or liquid (an aerosol) suspended in the air and is a major contributor to lung tissue damage, cancer, and premature death. The AQI translates these daily air pollution concentrations into a number on a scale between 0 and 500 which is reported to the public along with a standardized color indicator: 0-50 good (green), 51-100 moderate (yellow), 101-150 unhealthy for sensitive groups (orange), 151-200 unhealthy (red), 201-300 very unhealthy (purple), and 301-500 hazardous (maroon).

Many of these measured pollutants are generated as byproducts of fuel combustion from vehicles, smelting, and other industrial processes. In cities, automobile exhaust alone can contribute to as much as 95 percent of all CO emissions (EPA, 2007). Recent studies have also revealed that 97 percent of European citizens living in urban areas are exposed to pollution levels that exceed EU limits (EU, 2004).

Currently, citizens must defer to a small handful of civic government installed environmental monitoring stations. For example, the entire San Francisco Bay Area in California, the sixth-largest consolidated metropolitan area in the United States, home to more than seven million people, composed of numerous cities, towns, military bases, airports, and associated regional, state, and national parks sprawled over nine counties and connected by a massive network of roads, highways, railroads, and commuter rail contains only 40 measurement stations (Figure 2). However, not every pollutant is measured at every site. For example, the Bay Area Air Quality Management District reports dangerous $PM_{2.5}$ at only 6 locations (Figure 2) and ozone (O_3) at 21 (AirNOW, 2006).

For locations away from these stations, a Gaussian dispersion model extrapolation technique called ASPEN (Assessment System for Population Exposure Nationwide) is used by the EPA. However, there are numerous citizen science projects that have exposed the inaccuracies contained in the ASPEN model. For example, in 1995 the EPA ASPEN model estimated the expected outdoor concentration of a toxic nonflammable carcinogenic liquid used as an industrial and organic solvent and as a dry-cleaning agent called *perchloroethylene* to be less than 2 ppb (parts per **billion**) across the Greenpoint-Williamsburg area of Brooklyn, NY. However, a citizen science community group called the "Watchperson Project" investigated areas of odor complaints, canvassed neighborhoods, and conducted studies documenting (1) 39 of 40 apartments in excess of 100 ppm (parts per **million**), (2) one site with levels at 197,000 ppm, and (3) 24 of 29 apartments above dry cleaners with a eight-day average concentration above 1,000 ppm (Wallace, Groth, Kirrane, Warren, & Halloran, 1995).

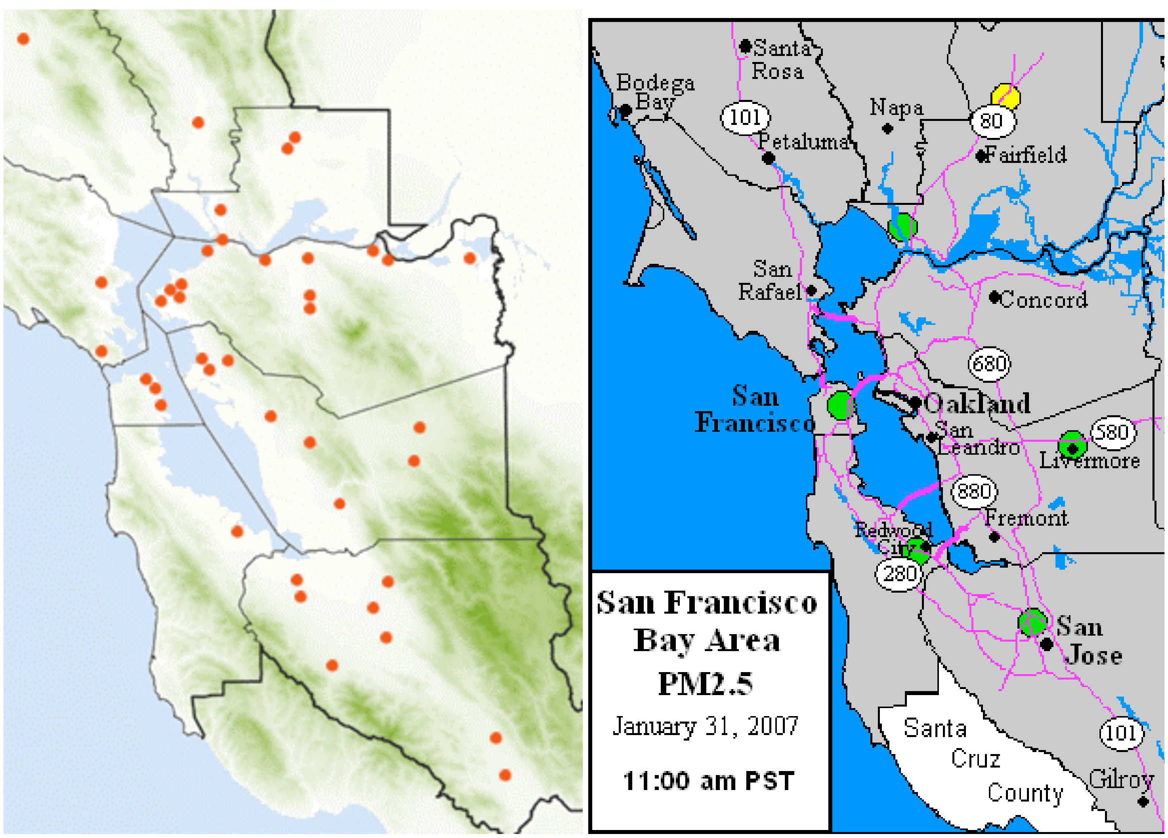

Figure 2: Map of the 40 air quality monitoring sites (left) and air quality map for the 6 locations where ($PM_{2.5}$) is reported (right) for the San Francisco Bay Area.

Clearly, this sparse sensing strategy and dispersion modeling technique do little to capture the dynamic variability arising from urban micro-climates, daily automobile traffic patterns, human activity, and smaller industries. Are we to believe that the park, subway exit, underground parking lot, building atrium, bus stop, and roadway median are all equivalent environmental places? A geo-logged path of more fine grain ozone measurements across Las Vegas, Nevada begins to expose the detailed dynamic range of ozone across a city (Figure 3) (DAQEM, 2005).

Finally, these measurements only address outdoor air quality. However, every year, indoor air pollution is responsible for the deaths of 2 million people – that's one death every 20 seconds (Ezzati & Kammen, 2002). Indoor air pollution is caused by the burning of solid fuels which over half of the world's population rely on for cooking and heating. More than half of this burden is borne by developing countries. This means that there is an opportunity for not just civic change but the creation of significant life saving technologies for emerging regions and rural villages worldwide. Even in developed nations there is significant indoor air pollution from smoke, radon, paints, carpets, and even toner particles expelled from laser printers (Kay, 2007). However, there are no EPA monitoring stations indoors. Air quality needs to be measured where people go and this includes indoors. Our solution is to integrate air quality sensing with a technology already carried indoors and outdoors by billions of people everyday – their mobile phone.

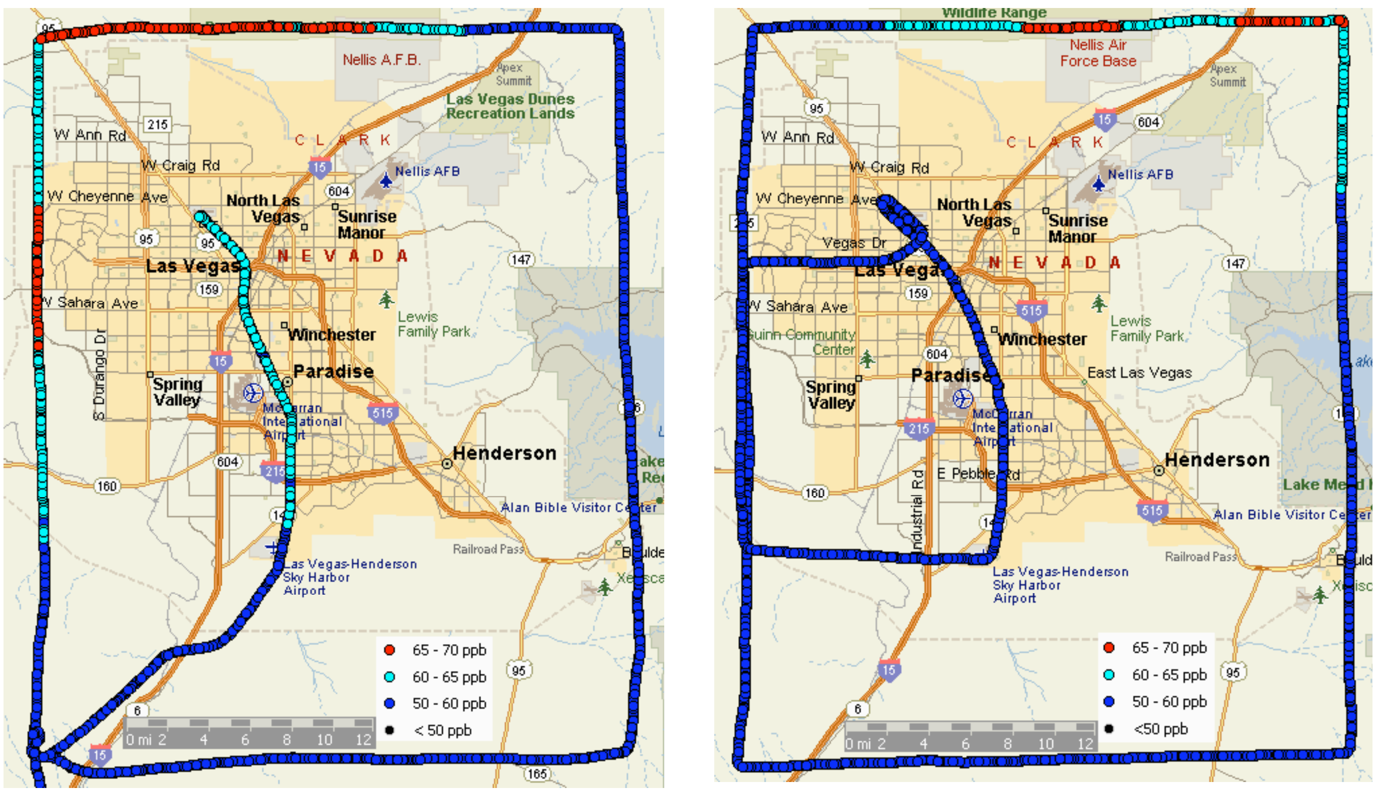

Figure 3: Geo-logged ozone measurements over Las Vegas, Nevada on 21 August 2005 @ 3:30PM (left) and 22 August 2005 @ 3:00PM (right), measured at 1500 meters. Colors indicate wide variations expressed in parts per billion.

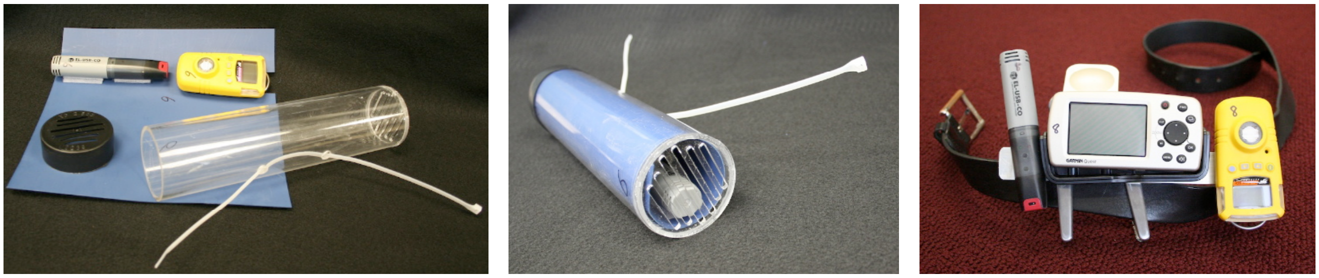

Figure 4: Taxi mounted tube with carbon monoxide, sulfur dioxide, and nitrogen dioxide sensors exposed (left) and packaged (center). Also, the student worn setup containing similar air quality sensors and GPS unit (right).

Environmental Health Related Work

Historically there have been grassroots efforts by communities to address environmental issues, often when conditions become extreme. In 1988 "The Toxic Avengers" (Yahr, June 2001), a group of 15 high school students, operating under the belief that people should have a right to live in a safe environment, successfully canvassed their community about the myriad of risks inherent in having toxic industrial pollutants and a large capacity incinerator in close proximity to residences and schools. In direct response to the citizens, the government eventually took action and many of the polluting sites were cleaned up and the incinerator shutdown.

However, in general the individual citizen has very little direct awareness of the air quality that they encounter daily and almost no public forum to debate strategies for change. Several recent projects have explored citizen measurement of air quality such as Hooker's Pollution e-Sign (Hooker, Gaver, Steed, & Bowers, 2007), Preemptive Media's AIR (Areas Immediate Reading) mobile device (Costa, Schulte, & Singer, http://www.pm-air.net/index.php), Proboscis' Snout (http://socialtapestries.net/snout, 2007), Millecevic's Neighborhood Satellites (Milicevic, 2007), the Everyday Learning Lab's Smoke Rings (Foley-Fisher & Strohecker, 2005), Jeremijenko's Feral Robotic Dogs (Jeremijenko, 2005), EQUATOR's e-science project which included extensive carbon monoxide samples taken by people across several streets in London (Milton & Steed, 2007), and a more recent deployment of such bike based mobile air quality sensing by Cambridge Mobile Urban Sensing (CamMobSens) (Kanjo & Landshoff, 2007).

STUDY 1: PERCEPTIONS OF AIR QUALITY

What does "air quality" mean? How is it measured? Where? How often do people think about their air quality? Where can you find the reported/forecast air quality? We were interested in understanding people's perceptions of air quality and their interest in taking personal measurements. We conducted personal interviews with 12 residents (9M/3F 23-56 years old) who were approached on public streets of a major metropolitan US city using the questions above as well as others. The small sample size prohibits statistically significant data but several insights can be drawn. Mentioning the term "air quality" elicited responses such as pollution, smog, Los Angeles, Athens, soot, pollen, asthma, vehicles, breathing, smells, cleanliness, quality of life, and even global warming. None of the participants had a clear understanding of how and where air quality was measured in their own city and only one knew that reported forecasts could be found in the weather section of the local newspaper. When participants speculated on where air samples were taken, the dominant model was *samples at multiple locations* such as "at least in every district in the city", "hundreds if not more near factories, close to highways, etc", and "all around". Some voiced concern over the management of the data, commenting, "I don't trust the government to collect and report air quality". However, every participant expressed some degree of interest in personally being able to sample air quality, most of them enthusiastically positive responses such as "definitely...what a cool idea", "absolutely", "yes, it has a lot to do with how we breath", "I would try to spread the new across the world", "I want to be part of the solution", "I am concerned and want to be involved and monitor it", "yes, especially if it was useful to other people", "that would be cool ... I'd love to do that", and "definitely but only if it could bring about some global change in policy or action". This led us to further understand the existing air quality system and how we could enable personal sampling.

Ergo: Air Quality On-the-Go

To further study the experience of receiving air quality data on a mobile platform while on-the-go, we designed a public tool called Ergo. Ergo is a simple SMS system that allows anyone with a mobile phone to quickly and easily explore, query, and learn about his or her air quality on-the-go. Ergo uses data from the United States Environmental Protection Agency (EPA) based on fixed metropolitan air quality measurement stations. Sending a text message containing a zip code causes Ergo to deliver current air quality data (usually less than 20 minutes old) and up to three days of forecast for the area. Similar SMS commands to Ergo allow users to request the worst thee polluted locations within the United States that day as well as schedule daily air quality reports to be delivered to their mobile device at any specified frequency. Ergo has delivered nearly 10,000 air quality reports and generated a range of positive feedback including comments from individuals with respiratory problems. For example, several individuals have reported on how the system has improved their lifestyle and provided them with easy access while on-the-go to real-time geographically measured air quality reports.

STUDY 2: AIR QUALITY SENSING FIELD STUDY

What would be the experience of daily living with a personal environmental monitoring mobile device? How can we understand the challenges associated with large, distributed, geo-logged data collection schemes by non-expert users across everyday urban life?

We recruited 7 taxi drivers and 3 students in Accra, Ghana to participate in a two week long study to collect air quality data. We chose Accra because of its poor air quality and common practice of domestic cooking outside using wood, charcoal, and other biofuels. Subjects were modestly compensated even if they did not participate in the full study. Each taxi driver was provided with a dash mounted GPS logger and a tube to hang from their passenger window that contained a carbon monoxide sensor and (a sulfur dioxide sensor or a nitrogen dioxide sensor). At the end of each day, the sensor tube was dropped off at a convenient location where the data was extracted and the sensors charged. Similarly, 3 students were each given a mobile clip sensor pack containing a GPS logger, carbon monoxide sensor and (a sulfur dioxide sensor or a nitrogen dioxide sensor). Similarly, at the end of each day the unit was collected, data extracted, and batteries charged. Both systems are shown in Figure 4. The system was setup to automatically log sensor data every second. Subjects were asked to carry the sensor/GPS loggers as much as possible and during normal everyday activities, including those surrounding work, family, and relaxed social activities. This study allowed us to collect actual geo-logged air quality sensor data by citizens across an urban landscape and influence our design for an integrated air quality sensor into a working mobile phone.

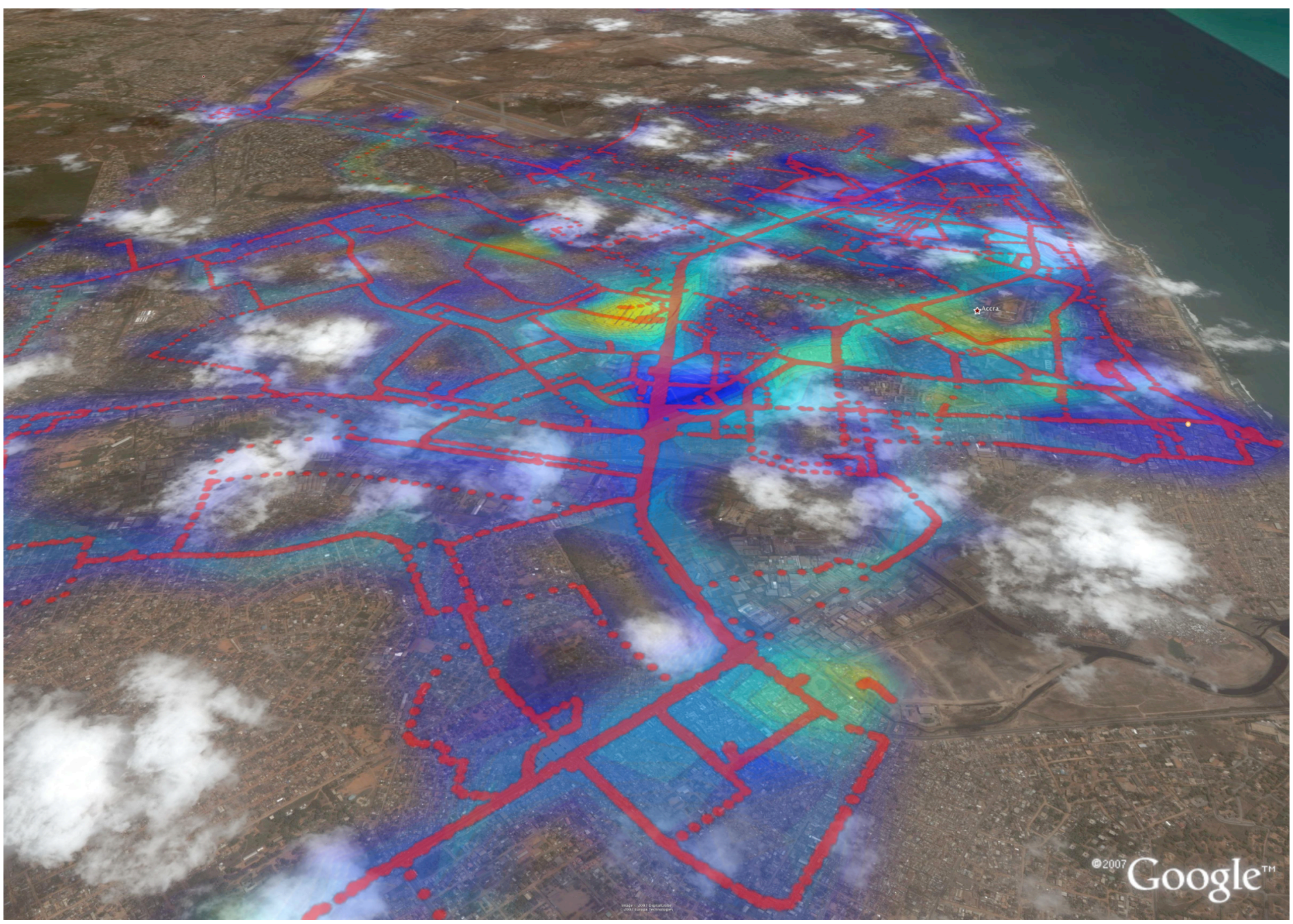

Figure 5. A heat-map visualization of carbon monoxide readings across Accra, Ghana rendered atop Google Earth. Colors represent individual intensity reading of carbon monoxide during a single 24-hour period across the city. Red circles are locations were actual readings were taken.

Over the two-week period we collected an impressive and diverse collection of air quality data, reveling dynamic ranges of air quality across neighborhoods and over time. Looking only at CO, for which safe levels are defined as 9 ppm for 8 hours and 35 ppm for 1 hour, our participants logged frequent readings around 30 ppm with many samples ranging up to 75 ppm and some as high as 200 ppm. A heat-map visualizing only the CO values over one 24-hour period captures the dynamic range of air quality across the city as never before seen (Figure 5).

While the rich data sampled from our two-week study in Accra provided hard evidence for the need for citizen science air quality sampling, there were even more revealing and unexpected social effects that resulted. Recall that we provided the participants only with the technology and instructions to carry it during their everyday activities. At the end of each day they dropped of the gear where it was charged and the data extracted. When we conducted exit interviews, it was clear that, although it was not our intention to provide any humanly readable output on the devices, the participants had begun to look at the numbers and piece together a personal view of the areas of toxic air across Accra. Many discussed how they watched to see how parts of their city changed as they traveled through neighborhoods at different times of day and how they discussed air quality and passed on their new knowledge of hazardous locations to their friends and family. Subjects who thought about air quality once every few months before the study were now thinking about it hourly. Even more interesting, our subjects reported changing their routes through the city, choosing different times to travel downtown, walking further from roadways, being outside later in the day rather than during high pollution times, and even taking their own automobile in for inspection to insure they were not contributing to the problem they were measuring. Several of the participants encountered each other when dropping of their equipment for charging and, although they did not know each other, many of them reported discussing the data they were measuring each day, where they had captured dangerously high readings, alternate routes they had found to be less polluted, and compared graphs from each day's journey.

Most participants reported that the most important thing they learned from the study was that there were extremely unsafe levels of air quality in their city beyond what any government or news agency had reported to them before. Many expressed anger and distrust in their civic leadership for not informing them of such a hazardous condition nor enacting legislation to improve it in the name of public health. Remember, there was no formal networked, real-time sharing mechanism or informed interface for this study and yet spectacular elements of citizen science emerged.

AIR QUALITY SENSING WITH A MOBILE PHONE

Informed by our studies, we designed, built, and integrated various air quality sensors into a mobile phone. We iterated several designs based on various sensors and communications standards such as wired RS-232 and Bluetooth. The resulting 2x4cm hardware combines a carbon monoxide, nitrogen dioxide, and temperature sensor with Bluetooth wireless communication to the mobile phone (Figure 6). The CO/NO_X sensor is small scale, low power (< 350 microamps) and designed to be maintenance-free and stable over long periods. The sensor only needs to be turned on for a few milliseconds while taking a measurement, further reducing overall power consumption. These sensors have a direct response to volume concentration of gas rather than partial pressure and are ideally suited for integration into mobile devices. We chose this sensor combination not only for its small size, low-power, and cost ($60USD), but because they measure two important gases strongly associated with air pollution primarily from automobiles and diesel exhaust.

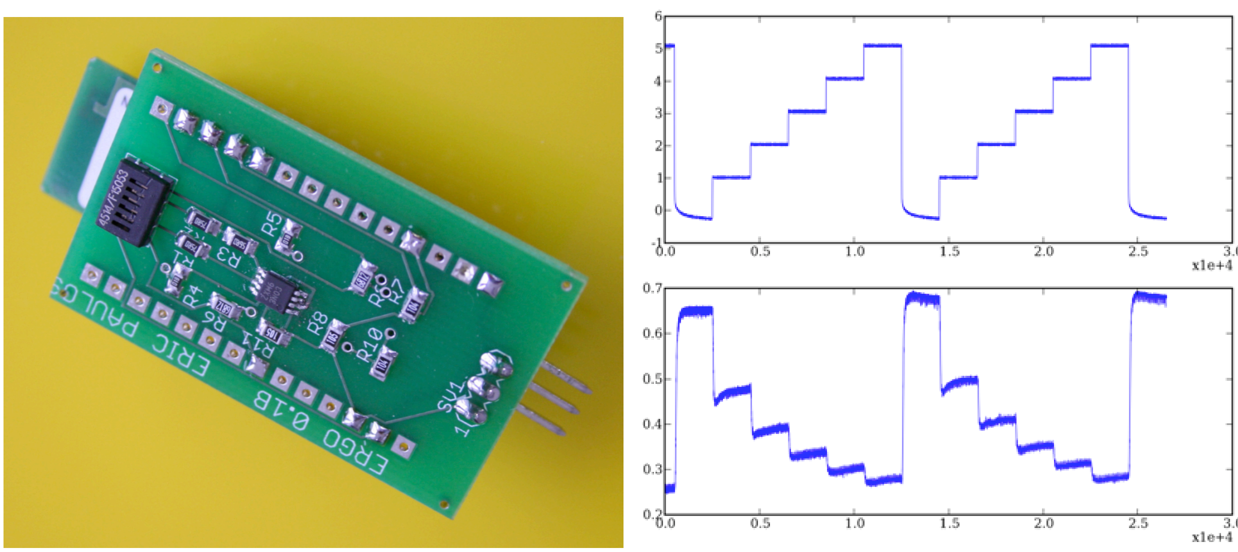

Figure 6: A wireless Bluetooth based sensor board with a carbon monoxide and nitrogen dioxide sensor (black rectangle in upper left of board) and a graph depicting nitrogen dioxide values from 0-5ppm (top graph) and the measured signal from the sensor (bottom graph).

The sensor board is powered separately and captures measurements when polled by the mobile phone via Bluetooth. It can be attached to the mobile phone, worn, or carried on a purse or backpack. The complete system uses either a Bluetooth mobile phone with assisted GPS (AGPS) or a standard Bluetooth phone without location technology. With a GPS phone, the sensor data is geo-logged at regular intervals with a bias towards taking measurements during voice calls and text messaging usage (ensuring adequate exposure of the carbon monoxide sensor to ambient air samples when the sensor is mounted on the phone). We also wanted to explore the value of using such sensors without any location information using only time. In both conditions the collected data is sent using SMS. SMS was chosen over other data transport mechanisms because of its wide adoption and its use of the carrier's control channel rather than data channel, allowing data to be sent even during voice calls. The format of sampled sensor and corresponding meta-data is in a standardized XML schema. It is shared publicly via a web-based interface with a standardized SQL database backend. This allows the public to query and use the data within the repository.

It is not uncommon for people to use Bluetooth headsets (exposed to ambient air) while their mobile phone is in their bag or pocket (not exposed to ambient air). Similarly, we can imagine the use of various Bluetooth based air quality sensors attached to clothing, body, or backpacks for sampling the ambient atmosphere. We are also in the process of developing a wristwatch version of the hardware with a numeric output on a watch face. A sketch of this design concept is shown (Figure 7).

Figure 7: A wristwatch form factor design currently under development integrating air quality sensing and output

INTERACTING WITH AIR QUALITY MEASUREMENTS

While we have addressed many of the technical challenges associated with the engineering of the overall system from circuit design to the construction of the SMS relay service for handling data to the XML database schema, it is the overall user experience of everyday life capturing, sharing, and comparing air quality data that is fundamental to the success of citizen science. We concentrate our discussion here for the mobile on-the-go experience rather than the online web interaction that is more straightforward. It is the on-the-go experience that promotes curiosity, reflection, learning, and awareness of a user's immediate surroundings and perhaps influences their actions in the moment. In the rest of this section we sketch out several design concepts currently under development for interacting with live air quality data sampled from citizens.

Figure 8: Mobile interactions and visualizations of air quality (a) taking an air quality measurement, (b) sensor buddies, (c) daily graphed sensor buddies, (d) air journal, (e) my air journal, (f) cleanest route signage, (g) dynamic real-time air quality map, (h) bus stop air quality mashup

Either prompted by a user's request or triggered automatically by the act of preparing to make a phone call when the device is best exposed to the atmospheric air, the system powers up, captures a CO sample, and displays the numeric value in ppm to the user (Figure 8a). We want to use real values rather than arbitrary ones to preserve the scientific element of the task as well as encourage awareness of air quality based on real numbers. In the same way living with Celsius temperature measurements promotes a clear understanding of the relationship of the values to the feeling of temperature, we want to build a connection of air quality values to user perceptions.

Once the data is uploaded it can be shared with others. An obvious sharing mechanism acts much like a buddy list where you can see a listing of your "sensor buddies" with real-time comparison not of online status but of their current and daily cumulative (*i.e.* dosimeter) air quality exposure (Figure 8b). It also shows up/down trends and a current ranking by exposure level, including the forecast and officially reported levels by the government. A related "sensor buddies" view shows graphs for each person over the course of the day (Figure 8c). This promotes reflection about your exposure compared to others through the day. Why is my exposure so much higher in the morning? Lower at lunch? My office air quality seems worse than my friends? What's my child's exposure today? While your "buddies" could be located across your own city, it is also interesting to compare your values to people in other parts of the world? How does my exposure compare to my friend in Rome? A mother in Shanghai? My parents in Los Angeles?

As you start to log more data it becomes interesting to look for trends and longer patterns. The "air journal" mechanism allows a user to look at hourly, daily, weekly, monthly, and yearly cycles (Figure 8d). How does my weekend exposure differ from the weekday? What was a trip to Rome look like? My vacation in Montana? Again the focus is on promoting awareness and reflection to motivate discussions and lifestyle changes within individuals and groups using persuasive technologies.

It is important that individuals are provided feedback that their own measurements are important and making a significant contribution to their community. The "my air space" tab affords a visualization of the location of their own measurements atop a map with data from others. It is a visual reward system that their data is providing vital coverage for a specific neighborhood or subway stop as well as a simple reputation model for publicly showcasing their contributions (Figure 8e).

One of the themes of citizen science is allowing others to remix the public data for other applications. For example, new signage or mobile route planning software could provide, not the quickest or shortest route, but the cleanest (Figure 8f). Similarly, users could not only create visual heat-map style graphs (Figure 8g) but also mashups more specifically tuned to various activities such as creating an air quality mashup of bus stops for a bus line (Figure 8h).

CONCLUSION

We have presented a transformation of the mobile phone from solely communication tool to that of a sensor rich personal measurement instrument that empowers individuals and groups to more easily gain an awareness of their surroundings, engage in grassroots efforts to promote environmental change, and enables an important social paradigm – *citizen science*. Through a series of investigations, interviews, and user field studies around the measurement of air quality by individuals, we designed and built a series of functional air quality hardware solutions integrated with a mobile phone. Finally, we sketched a series of design scenarios around various, on-the-go, mobile interactions with an overall system. We believe that such systems can elevate individuals to have a powerful new voice in society, to act as citizen scientists, and collectively learn and lobby for change within their block, neighborhood, city, and nation.

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