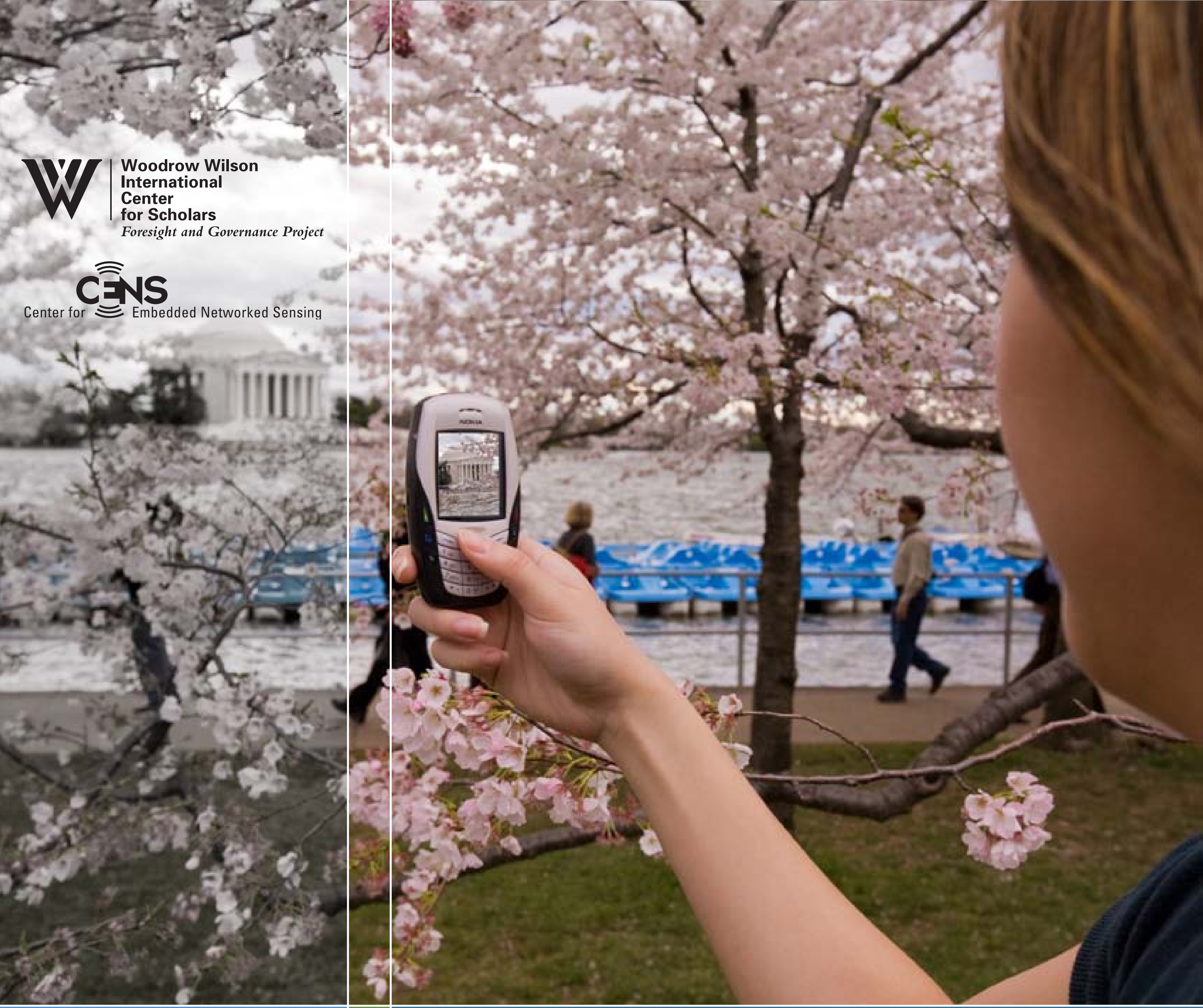

Woodrow Wilson International Center for Scholars
Foresight and Governance Project

CENS
Center for Embedded Networked Sensing

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WHITE PAPER

Participatory Sensing

A citizen-powered approach to illuminating the patterns that shape our world

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ABOUT CENS

UCLA's Center for Embedded Networked Sensing (CENS) is a major research enterprise focused on developing wireless sensing systems and applying this revolutionary technology to critical scientific and societal pursuits. In the same way that the development of the Internet transformed our ability to communicate, the ever-decreasing size and cost of computing components is setting the stage for detection, processing, and communication technology to be embedded throughout the physical world and, thereby, fostering both a deeper understanding of the natural and built environment and, ultimately, enhancing our ability to design and control these complex systems.

The **Urban Sensing** program area envisions a future in which we - individuals, neighbors, friends, and relatives - can use the technology around us to observe, discover, and act on the patterns that shape our lives. Whether your passion is personal or global, whether your interest is in health or the environment, whether you act alone or in a group, Urban Sensing is a new approach that empowers all of us to illuminate and change the world around us.

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INTRODUCTION

Today, people are increasingly able to create and share written and recorded media via the Internet. This phenomenon, now evident in the explosion of blogs and online social networks, is often called Web 2.0, or *the new media*. It has created compelling new avenues for public discourse, creative expression, and electronic commerce. The same forces that have given rise to these trends in media—affordable personal computers and cameras; pervasive connectivity; and consolidated data centers—are acting to create a public that can objectively record, analyze, and discover a variety of patterns that are important in their lives. Through the use of sensors (e.g., cameras, motion sensors, and GPS) built into mobile phones and web services to aggregate and interpret the assembled information, a new collective capacity is emerging—one in which people participate in sensing and analyzing aspects of their lives that were previously invisible. In this document, we introduce the concept of Participatory Sensing, explore five hypothetical situations in which it might have real-world influence, and suggest short- and long-term measures that can promote our vision.

First, consider a pair of illustrative examples:

- A group of citizens, organized through a social network, could use their mobile phones to take geotagged images as they move about town. Images of community assets—automatically uploaded and displayed on an interactive map—could be used to promote neighborhood identity and local services. Images of safety hazards could help prioritize maintenance services. Runners could use similar techniques to document and select scenic and shaded running routes away from roadways and combine their shared data with personal fitness journaling.
- Using the same mobile + web capabilities, each member of a family could monitor his or her travel and activity patterns for a few days to allow for reflection and discussion of daily routines. In concert with engaging visual displays of similar information about their peer groups and neighborhoods, family-wellness coaches could provide highly personalized guidance. Because so many people already have mobile phones with these capabilities, the promise of Participatory Sensing is remarkably affordable and scalable.

Participatory Sensing defined

At its heart, Participatory Sensing is data collection and interpretation. The motivations, governing social processes, and outcomes of these activities, however, are quite different from what one would encounter in, for example, a typical university research laboratory.

Participatory Sensing emphasizes the involvement of citizens and community groups in the process of sensing and documenting where they live, work, and play. It can range from private personal observations to the combination of data from hundreds, or even thousands, of individuals that reveals patterns across an entire city. Most important, Participatory Sensing begins and ends with people, both as individuals and members of communities. The type of information collected, how it is organized, and how it is ultimately used, may be determined in a traditional manner by a centrally organized body, or in a deliberative manner by the collection of participants themselves. The latter case, in particular, emphasizes the novelty of Participatory Sensing as an approach and underscores the importance of using widely available and familiar technology in the process.

Participatory Sensing can draw on a variety of data collection devices, such as home weather stations and water quality tests, but several features of mobile phones make them a special and unprecedented tool for engaging participants in sensing their local environment. The first is their sheer ubiquity across the demographic and geographic spectrum. The broad proliferation of cellular infrastructure and mobile phone usage makes it possible to collect data over large areas for little incremental cost. Through the global wireless network, participants scattered across a city or the world can easily coordinate activities and upload data to servers that can process it and integrate it with other data, such as GIS map layers and weather reports, that a variety of organizations publish on the web. Most modern phones, and certainly phones of the future, can record images, motion, and other signals, automatically associating them with location and time. New data-modeling techniques can infer a lot about individuals and the places they inhabit. Aggregated across populations, the information reveals large-scale patterns that can help address regional issues such as transportation planning, public health maintenance, disease management, and environmental sustainability.

Approaches to Participatory Sensing are numerous and participation patterns vary. Here, we discuss three models.

Collective Design and Investigation. A group of individuals collaborate to define what, where, and why to sense and then collectively design a data collection system, conduct an investigation, interpret the data, and act on the results. In this case, the community of participants owns the entire process and is vested in its outcome, whether it is research and discovery or effecting change in the community. By combining local knowledge and individual empowerment with widespread technology, this approach develops a community's potential for self-determination. As in community-based participatory research, a well-established model of research engagement, individuals play an active role in the investigative process rather than serving merely as research subjects.

Public Contribution. Individuals collect data in response to inquiries defined by another individual or organization. Participants are actively involved in the collection of data, but not necessarily in the definition of research questions or use of the results. By recruiting interested individuals in this way, organizers can acquire data at a scale unachievable by professionals acting alone, and participants can contribute to an effort they find meaningful.

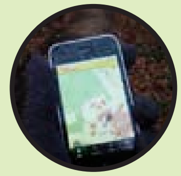
Personal Use and Reflection. Individuals log information about themselves and use the results for personal discovery. Images, sounds, and travel records contain information that, when analyzed and visualized, reveal hidden habits and patterns in one's life related to health, safety, social dynamics, and cultural identity. In this sense, Participatory Sensing can open a window onto life that allows one to reflect on, evaluate, and perhaps change patterns that were previously overlooked. A person may wish to keep these newly

THE RISE AND SPREAD OF THE MOBILE PHONE

It's hard to understate the worldwide rate of mobile phone adoption. With over 3 billion subscriber lines active today, nearly half the world's population, including citizens in every country, uses mobile phones. Once used exclusively for voice communication, mobile phones can now be used to transmit text messages, take and send pictures, and detect motion. Prompted by emergency services, such as E911, many mobile phones and phone systems now have standard location services (either radiolocation or GPS) built in. These additional features are now common on even low-end phones, making Participatory Sensing a reality for the vast majority of mobile phone users. The power and capability will only increase as more sophisticated smartphones, which can run software applications to access and process the data collected by these various sensors and detectors, spread to the masses.

PARTICIPATORY SENSING IN ACTION

Participate. People can initiate a Participatory Sensing exercise for a variety of reasons. The first step is to organize the participants—whether individuals acting alone or a large group acting in concert—to determine the goals and data collection plan.



Mobile personal data devices. Using mobile phones, participants collect data automatically (e.g., location logging) or manually (e.g., taking pictures).

Ubiquitous wireless transfer. Data are moved from anywhere in the world via wireless infrastructure.

Data processing in "the Cloud." Data from a variety of sources and locations are collected and processed to reveal patterns that were previously invisible.

Learn and act. Participatory Sensing systems digest the results of analyses into simple visualizations that can be shared and used to make change.

discovered patterns private or, like reflections written in a blog, share them with family, friends, and the public.

Mobilizing today's technologies

Despite the diversity in why and how individuals engage in Participatory Sensing, the basic process is similar across the approaches. The sensing process can be broken down into the following steps, each of which is facilitated by corresponding technology: coordination, capture, transfer, storage, access, analysis, feedback, and visualization.

Coordination involves recruiting and communicating with participants to explain the sensing effort and provide necessary guidance. Such communication is assisted by existing social networks, which can be accessed via computers, mobile phones, or face-to-face gatherings.

Capture is the acquisition of data on a mobile phone or other device. In addition to standard capabilities of mobile phones, specialized software applications[1] can be downloaded to phones in project-specific configurations or be programmed directly by participants.

Transfer takes place using mobile phones and wireless networks. Mobile phone software can make data uploading transparent to the participant and tolerant of inevitable network interruptions. Depending on the approach and the purpose of a project, either the participants or the organizers can bear the cost of data transfer.

Storage occurs on servers distributed across the Internet: privately owned servers, commercially managed but privately accessed storage services such as Google, and sharing-oriented services such as Facebook.

Access is managed according to policies written by project organizers and participants. It is difficult to overstate the importance and intricacy of data security and privacy. Currently, many people entrust their private e-mail and other data to website providers because standard access controls make them comfortable that their accounts are safe and private. It is also common for people to choose to share their information with other trusted members of a network according to a specific and user-controlled set of rules (for example, "Only designated individuals may view my profile"). These same systems are used in Participatory Sensing. However, Participatory Sensing data often include particularly sensitive information such as images of one's family and friends, and the participant's location collected over time. This information could be used to infer a participant's identity, where he or she lives, or when he or she is away from home. It is thus extremely important that the participant take a role in determining what type of information to share and with whom. Techniques currently exist and are being developed to allow participants to, for instance, automatically ab-

PARTICIPATORY PRIVACY

Negotiations over privacy touch on all phases of the sensing process. Control over data capture is part of defining collection requirements. Decisions about data specificity relate to presenting project results. Data sharing and retention are central to decisions about a project's goals and outcomes. The process of negotiating privacy is an indelible part of Participatory Sensing.

Our approach to Participatory Privacy incorporates privacy concerns into the very design of sensing systems so that groups and individuals decide the limits of disclosure. We argue that sensing systems should be designed so that people can negotiate social sharing and discretion much as they do in other parts of their lives. Awareness of, and participation in, the entire sensing process can help users understand a system's information flow, weigh the costs and benefits of sharing information, and make informed, context-specific decisions to disclose or withhold data. Allowing user discretion and autonomy in these functions can help all parties build trust in each other and their technology.

> Participatory Sensing can open a window onto life that allows one to reflect on, evaluate, and perhaps change patterns that were previously overlooked.

[1] See, for example, Campaignr: http://wiki.cens.ucla.edu/wiki/index.php/Campaignr.

stract their precise location to an area the size of, say, a neighborhood or zip code. Participants can also use computer-vision techniques to blur any faces in shared images. While many privacy mechanisms can already be put in place, this is clearly a crucial issue that requires continual attention and improvement to reduce the risks associated with abuse and misuse.

Analysis includes a wide variety of data-processing methods, from aggregation of contributed data for display to the participant, to higher-level analysis of data to classify a participant's activity (walking, riding a bus, etc.), to image processing that automatically eliminates blurry or poorly exposed images. Analysis also includes the calculation of group statistics and the integration of contributed data into statistical and spatial models that can be used to determine patterns in space and time.

Feedback may be required during a project to trigger manual or automatic events. Systems can use contributed data and mobile phone messaging to deliver such triggers in context-dependent ways. For example, when a person travels to a location of interest, the systems can trigger a message for the person to respond to ("Please take a picture here") or for the phone to answer automatically (to record sounds when the participant stops walking).

Visualization goes hand-in-hand with analysis and is the step in which data are displayed in a legible format to the participant or project organizers. The effectiveness of any project depends on how well its results are understood by the target audience. Excellent methods for mapping, graphing, and animation make this a rich area to develop in the context of Participatory Sensing.

All the technologies that power the individual steps in the process exist today. What we need now is to extend and combine them in innovative and informative ways that engage individuals as active members of society and to nurture the culture of participation that is taking root around these transformative technologies.

The following hypothetical scenarios envision a variety of ways in which Participatory Sensing can have a profound influence on individuals and on society at large. It is a realizable vision of what could exist in the near future, without the need for additional research and development. In fact, some of the systems described in these stories already exist[2], and all will be enhanced in the long term by the emergence of new devices and web technologies. The ideas presented below are only a starting point. How would you use Participatory Sensing to make a difference in your world?

[2] See, for example, http://urban.cens.ucla.edu.

SCENARIO 1

PERSONAL REFLECTIONS ON ENVIRONMENTAL IMPACT AND EXPOSURE

Last night's Personal Environmental Impact Report (PEIR) interest group meet-up was at a local pub, and conversations ranged from discussions of the most carbon-efficient route to the community pool to the high density of fast-food restaurants near the city's high school. At one crowded table, a woman boasted that shifting her work schedule by one hour significantly reduced her particulate exposure score (the time she spends exposed to unhealthy particles generated by car and truck exhaust). A curious friend responded, "But how much did it reduce your carbon impact?"

Spurring the PEIR group's conversations is more than a casual interest in the environment and members' health. All the people at last night's gathering are using a new online service that interacts with their mobile phones to give them detailed personalized information about their effect on the environment, and their environment's effect on them. Worrying about the environment is not new, but the kind of information that people can gather about it is. PEIR complements and extends carbon footprint calculators, which use information about the size of your home, the setting on your air conditioning, and other static factors to estimate your carbon emissions. PEIR takes a more personal approach by considering your location and travel patterns to provide information not only on environmental impacts, such as carbon emission, but also on environmental exposure, such as breathing unhealthy air. With a simple, free download, anyone can use the mobile phone stashed in their pocket to access information about their personal relationship with the environment. Now there are answers to the question, "What can I do about the environment, and how much does it matter?" Here's how PEIR works.

The PEIR dashboard maps your travel habits in colors corresponding to environmental factors. Other elements of the dashboard (not shown) graph daily totals over the previous week to help individuals identify patterns and discover the results of changes they make in their travels. *Image: PEIR website.*

A PEIR day

After opening the program on your phone in the morning, you go about your routine. Perhaps you jog in a quiet residential area in the morning, take the bus to and from work on congested highways, and then run errands in your car in the evening. Using GPS and cell towers, your phone records and uploads your location every few seconds to a secure server. Based on these time-location traces, the PEIR system can infer your activities (walking, biking, driving, riding the bus) and log them throughout the day.

> Like an instant, daily utility bill, PEIR allows you to monitor, reflect on, and change your behaviors, and to observe their effect on yourself and the environment.

As your data streams in, PEIR maps this combination of location, time, and activity to regional air quality data and weather data to estimate your personal carbon footprint and your exposure to particulate matter. Perhaps your trip to work on congested highways exposes you to high levels of particulate matter, even while your choice to take public transportation reduces your contribution to harmful emissions. Perhaps you have found a side route that shaves valuable minutes during your evening errands, but that takes you past a day care center as children wait outside for their parents. The PEIR system tells you how your car contributes to the levels of particulate matter (smog)

PEIR users can investigate their impact and exposure metrics and compare their results with others in their social network. *Photo: Cat Deakins (CENS).*

to which these children are exposed. You examine how these patterns change as you vary your routine by logging in to your personal, secure PEIR website. A travel diary with maps of your daily routes, as well as displays of your emissions and exposure to particulate matter, helps you interpret what your actions mean for your health, the health of others, and the environment. Because information about your location and daily habits is very sensitive, PEIR encrypts the data and allows you to share it only with people you trust. You can also choose to compare aggregate, less-sensitive information about your emissions and exposure to friends using social networking sites like Facebook. PEIR empowers you to decide whether different routes can make a positive difference in environmental impact and exposure.

Impacts and exposures

Currently, PEIR reports on two kinds of environmental impact and two kinds of exposure, though others can be developed. One impact factor is a total of the carbon dioxide emitted during your car travel. The other impact factor is the amount of car emissions you generate near schools, hospitals, and other places where sensitive groups of people congregate. The measures of exposure reveal how long you are exposed to unhealthy levels of particulate matter during the day and how much time you spend in areas with a lot of fast-food restaurants. This last exposure factor makes people aware of how their food choices, and by extension their health, may be influenced by what is around them. Environmental information is derived from data gathered and continually updated by government, scientific, and commercial organizations. The analyses already account for current weather conditions and time of day, and can be further refined to include real-time traffic and other sensor data.

Why PEIR?

PEIR provides you with personalized information about your relationship with the environment and serves as a counterpoint to the general, summarized environmental information that is typically available in the media or from government agencies. Like an instant, daily utility bill, PEIR allows you to monitor, reflect on, and change your behaviors, and to observe their effect on yourself and the environment.

There is also considerable scientific value in collecting the data. Better estimates of traffic patterns in an area, for example, can help transportation scientists refine usage models that in turn yield better estimates of environmental impacts. Similar technologies that utilize mobile phones as location sensors for self-discovery can build personal photo-stream diaries or serve as tools for discovering and documenting neighborhood culture. Urban planners can use secure location-tracking systems to better understand land-use patterns and neighborhood dynamics. Epidemiology, health sciences, sociology, or any domain concerned with the movements of people (and the impacts of these movements) could be explored using this technology.

SCENARIO 2

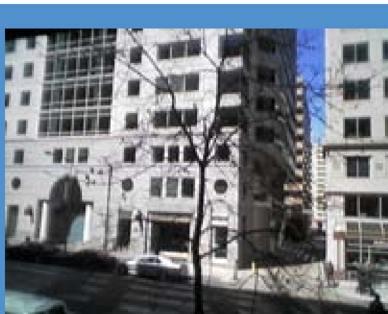
PARTICIPATORY SENSING OF THE IMPACTS OF CLIMATE CHANGE

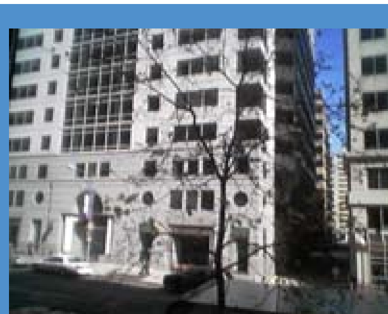
Scientists have unveiled new evidence that a changing climate is affecting our ecosystems. The latest data, however, come from an unusual source: hundreds of amateur botanists using their mobile phones to photograph and send pictures of plants to researchers for analysis. Their ongoing study in phenology examines the link between increasing temperatures attributed to global warming and the timing of specific events in the lives of some critical plant species. These events include the emergence of the first leaf, the appearance of the first flower, and when fruits or seeds drop from the plant. Scientists fear that changes in the timing of these events will disrupt ecosystem synchrony in natural and agricultural systems, with resultant, and unknown, changes in agricultural productivity, species ranges, and food webs.

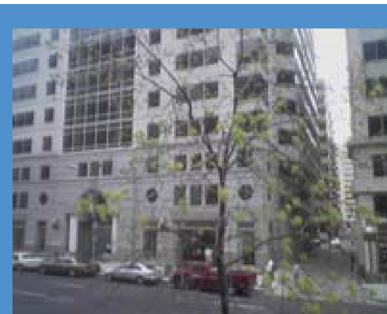
Scientific studies that take advantage of knowledgeable amateurs to collect data are certainly not the norm, but events such as the Audubon Society's Christmas Bird Count, World Water Monitoring Day, and the University Corporation for Atmospheric Research's Project BudBurst have successfully involved the public in the scientific processes of data collection and interpretation.

Out in the field

Participants in this latest study have searched their yards, neighborhoods, and trails for individual plants from a list of species selected for monitoring. After locating plants with the help of reference material such as full-color images delivered by the scientists to their mobile phones, participants are observing their subjects every day, noting each of the life cycle events. Text message reminders help scientists keep everyone engaged. On the big day—for example, when all of the leaves emerge from their buds—participants take photographs of the plant and apply descriptive keyword tags, such as the name of the plant and the observed life stage. Meanwhile, the phone records the location of the plant using its built-in GPS. The data are then uploaded to a personal participant website. If a plant happens to grow in a "dead zone" with no cellular coverage, the phone simply stores the data and sends it along the next time it connects.


APRIL 6


APRIL 11


APRIL 12

The greening up of deciduous trees is one marker of spring. Here, an office worker used a mobile phone to

To coordinate all the volunteer field workers, the scientists have set up an interactive web portal where participants can learn about the project's goals, register, access software, undergo online training, and view the data they contribute. Inside the portal, groups of users share photographs and compare data with friends.

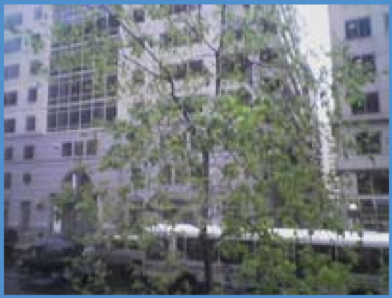
Text message reminders help scientists keep everyone engaged.

Teachers have designed lesson plans in which students become data collectors and compare their results with those from classes in different regions to observe how the change of season varies geographically. Participants maintain profiles that allow them to set their privacy preferences, including which of their data is used and who can view it. Information about the location of plants is of special concern since it can be used to identify personal information about the participants, for example, where they live. Participants can set limits on the level of detail reported, sharing, for instance, only that a plant is in a particular neighborhood without pinpointing the exact location in their backyard.

Participants in the study tend to be interested in their local natural history before becoming involved, and many are school children involved because of interested teachers. Some are gardeners and nature lovers who like the idea of contributing to science and also enjoy sharing their interest in plants with others through the web portal. Most don't mind the small expense associated with transmitting their data. Using mobile phone technology means participants can collect data if they happen upon a new plant of concern during the course of their day, and can contribute immediately upon observing a sought-after plant.

Meanwhile, by coordinating this effort, scientists benefit from data gathered over a far larger geographic range than would otherwise be feasible. And while the project provides a huge number of photographs to sort through, researchers are aided by image-processing software that filters out poorly exposed, blurry, or duplicate images. Other data processing tricks help prioritize images for viewing based upon patterns observed in previously processed images. Scientists are also developing measures to document the reliability of individual data collectors; information that can be used to estimate and account for the uncertainty inherent in the large-scale use of citizen-gathered data. Enabled by common and abundant mobile phones, this ongoing citizen science project gives researchers access to a unique data set that sheds further light on the environmental impacts of climate change while simultaneously building hobbyist communities of gardeners and plant enthusiasts.

APRIL 14



APRIL 17

APRIL 21

photograph the tree outside his window as its first leaves appeared. *Photo: flickr/sudama.*

Fruiting is a key event in the life cycle of many plants. Large-scale citizen-generated information on the timing of such key events can be an indicator of climate change. Photo: Alex Parlini.

A new tool for science

Researchers are quick to point out that plant phenology is just one research topic that lends itself to participatory data collection. Using people's everyday mobile phones to collect data in a coordinated manner could be applied to scientific studies of various sorts, such as accessing fishermen's extensive knowledge to identify and locate fish pathologies in the field or documenting the spread of an invasive species. The prospect of working with citizens interested in a topic who are near critical points of measurement and who already have powerful measurement abilities (but who happen not to be scientists) is becoming a reality.

SCENARIO 3

GRASSROOTS SENSING OF POLLUTION SOURCES BY COMMUNITY GROUPS

Prompted by local residents armed with compelling new data, city leaders voted to pursue a comprehensive study of diesel truck traffic on residential roads that may be unduly affecting area neighborhoods. Worries about environmental hazards and high pollution levels found in low-income communities prompted local activists, who say their goal is to reduce asthma cases by routing truck traffic away from houses, schools, and businesses. The city council released funding for this project after reviewing convincing data gathered through a unique community-university collaboration. Inspired by T.S. Lena's Columbia University investigation of diesel truck traffic in the South Bronx[3], a community group launched a similar project augmented with new, mobile phone-based technologies to increase the number of participants and the geographic reach. Neighbors came together to convince the city council to take the region's diesel truck traffic seriously.

GPS-equipped mobile phones can be used to photograph diesel trucks as part of a campaign to understand community exposure to air pollution. *Photo: Iris Helfer (CENS).*

Making their case

Using data-gathering software run on residents' mobile phones, the community organization initiated data collection, recruited and coordinated participants, and analyzed the resulting data to make the case that diesel truck traffic on neighborhood streets created unexpected "hot spots" of traffic near homes and schools. The community organization recruited neighborhood residents to photograph diesel trucks that passed their homes, or to photograph trucks they witnessed as they walked around the neighborhood over the course of a day. After snapping a photo of a truck with a camera phone, the phones used cell tower triangulation to identify the location of the photograph and used the camera's clock to record the time. The grassroots sensing system automatically uploaded each photograph, along with its time and location, to a secure server.

By logging in to a website, campaign organizers and participants could view a customized, continually updated traffic map of their neighborhood, making the geographic distribution of heavy truck traffic immediately visible. They could also view the map according to time of day to pinpoint hours when truck traffic was highest. As the system alerted campaign organizers about areas of the city or times of day when more photographs were needed, it sent text message requests and reminders to the volunteers near these particular places at the right time ("Can you watch for trucks at the corner of Main and Green Street today?" or "Can you take pictures on First Street between 5 and 6 p.m. tonight?") Over just a few days, community organizers and volunteers had completely surveyed the neighborhood.

Community organizers and participants found their map of the city's diesel truck traffic very valuable. But they were worried about the privacy of project participants, many of whom took photographs outside their homes. System designers encouraged community members to use system tools to protect their privacy. For example, the system could be set to map a photograph to a location no more specific than a four-block radius: small enough to indicate increased truck traf-

[3] Lena, T. S., Ochieng, V., Carter, M., Holguin-Veras, J. and Kinney, P.L. "Elemental Carbon and PM2.5 in an Urban Community Heavily Impacted by Diesel Truck Traffic". *Environmental Health Perspectives*, 110, 10 2002, 1009-1015.

fic in a neighborhood, but general enough to protect the identity of the volunteer. The system also enabled individual participants or campaign organizers to automatically detect and blur the faces of any people captured in photographs. Some residents who worried about revealing too much about their daily routines or who feared repercussions for being a whistle-blower, chose to contribute their data anonymously. This way, organizers displayed photographs and maps for the city council without identifying any individuals who did not explicitly provide permission. Documenting local diesel truck traffic, a primary source of airborne particulate matter, enabled community members to assess the amount of traffic relative to zoning and regulatory requirements. When presented with evidence that diesel truck traffic may exceed allowable levels, the council decided to undertake a city-sponsored survey of traffic conditions in residential areas.

Some residents who worried about revealing too much about their daily routines or who feared repercussions for being a whistle-blower, chose to contribute their data anonymously.

Expanding possibilities for grassroots sensing

This story of empowered residents documenting their environments and making a case for action is just the beginning. Similar grassroots sensing projects can take place anywhere, thanks to software that transforms the mobile phone network into a platform for data gathering, analysis, and presentation.

Consider a community affected by unregulated flaring at an oil refinery, or by incineration at a factory. Documenting the impact of these environmental hazards on local people could instigate new understandings of cumulative environmental impacts. And grassroots sensing isn't useful only to document hazards and health risks; it can also help communities explore their assets. Imagine groups of volunteers toting cell phones to map, with the push of a button, things like street-lighting conditions, scenic views, and social hubs, which cannot be discovered with current Internet-based mapping tools. School projects could encourage students to record, upload, and organize oral histories of community elders using phones as recorders. Coordinating mobile phones for grassroots sensing promises to make data collection and presentation accessible and available to communities for whom it was once prohibitively labor-intensive and expensive.

SCENARIO 4

PERSONAL HEALTH MONITORING USING MOBILE PHONES IN ELDERCARE

The Jansen family is breathing a sigh of relief now that Grandpa Jansen's weight is back up to normal after weeks of being dangerously low. The weight loss was a side effect of depression, though neither family members, doctors, nor Grandpa Jansen himself noticed either symptom right away. The tip-off ultimately came from a high-tech personal health monitor built into Grandpa Jansen's cell phone. But don't assume that Grandpa Jansen is a technology wizard: he simply carries a standard-issue mobile phone. The breakthrough lies in the way the phone is programmed to collect and send information from its microphone and GPS and the way the information is analyzed and reported back to Mr. Jansen and the family members and doctors he designates. The role of Mr. Jansen and his family in deciding what to measure, and how to respond to the information returned, marks this as an innovation in the approach to health-related technology as well.

The system uses snippets of sound and trends in travel patterns to draw inferences about aspects of Mr. Jansen's life that are indicative of his health, but that are also difficult for family members and doctors to monitor continuously. Jansen, who is in his 80s and lives alone in his longtime home, receives visits from his family quite frequently, and this always perks him up—so much so that the family didn't notice the onset of depression or the gradual weight loss associated with it. Using the GPS and microphone, Jansen's mobile phone was keeping track of and reporting the amount of time he spent at home and the types of social interaction he was having. Based on these reports, family members were able to see that Jansen had stopped making his daily visit to the local bakery, that he only rarely had conversations with people, and that his TV watching was way up. These indicators were enough to get Mr. Jansen into the doctor for diagnosis and treatment, which quickly stabilized his depression and weight. His doctors say that relatively minor health problems in older people often become severe and dangerous before they are treated.

> Mobile phone and web technology are now being used to provide information to elders, their families, and doctors about changes in lifestyle that are early warnings of diminishing health.

Technology to aid aging in place

Increasingly, seniors are living longer and wanting to remain at home among friends and familiar patterns in their community, while still having access to support services appropriate to the changes they are undergoing. This trend, called "aging in place," gives seniors a well-deserved degree of independence, but can also increase the risk that declines in health may not be noticed early enough to provide the most favorable intervention.

Mobile-to-web systems can be tools to encourage and support aging in place, while giving families confidence that their loved ones are safe. *Photo: flickr/kiddharma.*

Mobile phone and web technology are now being used to provide information to elders, their families, and doctors about changes in lifestyle that are early warnings of diminishing health. The system aggregates the information on a daily or weekly basis, stripping out anything that the elderly individual or the family deems too personal, and presents it in a visually intuitive report on a private, secure, personal web portal that highlights unusual changes. The system uses the mobile phone's standard features and a variety of methods to draw inferences related to a person's health without requiring the person to do anything and without compromising privacy. For instance, the GPS in the mobile phone keeps track of its owner's location throughout the day but sends back the results of a mobility analysis that shows how often and how far the individual travels away from home, but not exactly where the person has gone. Likewise, the microphone samples sounds periodically during the day to determine whether its holder is engaged in conversation, watching television, or spending time outdoors. But it records only one second of sound every minute so that what is being said cannot be deciphered. With these safeguards in place, Jansen and his family saw the value in giving up some privacy in return for continued independence.

The system is being praised not only by doctors and families with elderly members but also by companies whose employees are often called on to take care of elderly parents. Companies increasingly recognize that using the systems to catch health problems before they become severe benefits worker productivity. Insurance companies are also in favor of the system, although others are quick to point out that one of the important advantages is that the system can be used at almost no cost and does not require involvement of insurance companies.

Personal health monitoring

Eldercare is just one application of the growing trend of using mobile-to-web systems for personal health monitoring. Other systems use mobile phone–containing motion sensors to provide extensive feedback to people, young and old, about their activity levels, which is related to important public health issues such as obesity and diabetes. In a time when lack of access to health care is all too common, approaches that encourage individuals to play an active role in their own health maintenance can have a large effect. The mobile phones we began to carry around for communication are rapidly becoming an important tool for healthy living.

SCENARIO 5

DISTRIBUTED SENSING FOR BIKE COMMUTERS

As gasoline prices rise, commuters are turning to alternative forms of transportation. More residents are beating fuel costs while getting their exercise by setting off to work on a bicycle. But bike commuting in the city can be as complicated as it is rewarding: road and path availability, air quality, traffic and accidents, and bright sunlight all affect the quality of the ride.

Just in time to help these new bicycle commuters is CycleSense: a new Participatory Sensing service jointly designed by bicyclists and university researchers. This convenient, web-based technology is designed to give bike commuters daily feedback on the quality and safety of their preferred routes and to suggest quality-of-ride modifications in route and time of day. Using their mobile phones as data-gathering devices, bike commuters work together to find great routes, document changing hazards, and meet other bikers.

Improving the commute

Cyclists must find feasible, pleasant routes where they can easily connect with public transportation and arrive at work safely. A ride's safety is affected by such variables as the incidence of traffic and bike accidents along a route, the traffic congestion of a route depending upon time of day, and the average air quality of a route. A ride's quality is dependent upon factors such as available shade, condition of the path or road, and availability of connections to public transportation.

CycleSense users carry a GPS logger or a mobile phone equipped with GPS technology during their commute. These tools automatically upload their routes to a secure website. Participants log in to their private website and see their route combined with existing data, including air quality, time-sensitive traffic conditions, and aggregate traffic accidents along the

Bicycle commuting is healthy and environmentally-sound but not always safe or enjoyable. CycleSense is a personal tool for tracking commuting and can also tap into the collective wisdom of cyclists in an area to help find high-quality commuting routes. *Photo: Cat Deakins (CENS)*

Photo: Cat Deakins (CENS)

route. Participants also use mobile phone technologies to help improve their routes. Bikers document hazards and impediments along their way by taking photos with a mobile phone or sending a text message to the CycleSense server. This information helps CycleSense improve its maps and models so that all bikers in the region benefit from other cyclists' updates. By combining existing Los Angeles conditions with biker-contributed data, CycleSense allows area bikers to plan routes with the least probability of traffic accidents or the best air quality, or according to personal preferences, such as maximum shade, best road or path surface quality, or connections with public transportation.

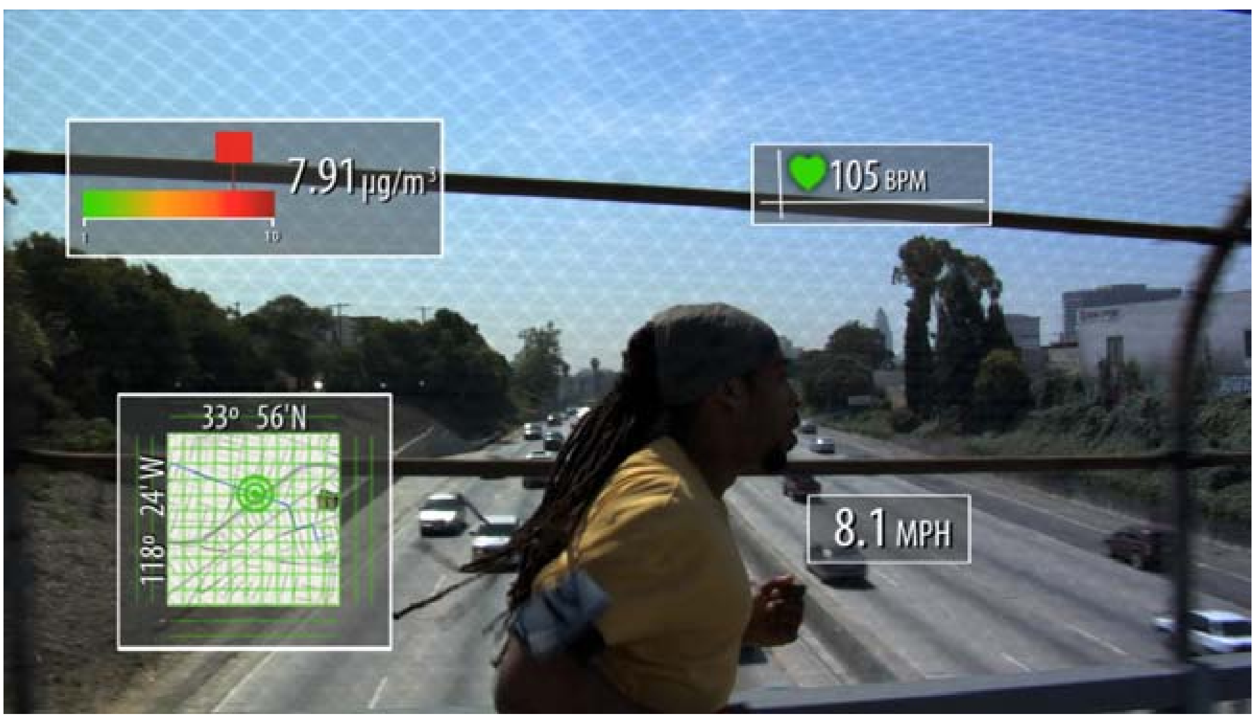
Using their mobile phones as data-gathering devices, bike commuters work together to find great routes, document changing hazards, and meet other bikers.

REALIZING THE VISION OF PARTICIPATORY SENSING

Participatory Sensing's *innovation* lies in how people can use today's technologies to observe, document, and act on issues that matter to them. Participatory Sensing's potential *power* comes from the already widespread adoption of the technologies by people across many demographics. Where many technologically enabled innovations require significant time for development and adoption before they become significant change agents, we can realize the benefits of Participatory Sensing virtually immediately and, over time, increase them as the technology industry produces ever-more-capable mobile devices and researchers discover how to harness them.

To truly empower people as envisioned here—to create opportunities for community and personal discoveries and foster positive changes in peoples' lives—will require short- and long- term investments. The uncertain market size and profit opportunity associated with Participatory Sensing currently constrain significant commercial investment and limit progress. Therefore, the responsibility for making Participatory Sensing a reality falls to forward-looking organizations and agencies working in concert with community organizations and academic institutions. *Resources are needed now to facilitate collaborations between community members, subject experts, and technologists. In addition, support for professional software developers is required to create the large-scale, robust Participatory Sensing systems described above.*

Over the longer term, the Participatory Sensing approach will drive fundamental technology research across a number of areas, including new system architectures to promote security and privacy and reduce risks inherent in collecting extremely personal data; enhanced analytical techniques to make more-accurate inferences from mobile phone–supplied data such as location and images and to automatically detect and respond to subtle events; expanded data analysis and visualization techniques to focus on providing relevant and easily interpreted data for the general public; engaging and efficient mobile device interfaces to support effective, real-time user interaction; new personal-scale sensors to expand the range of information that individuals can track and use; and next-generation network infrastructure to support Participatory Sensing services, like intelligently recruiting collaborators and deploying data collection protocols. Investments in fundamental research and development in Participatory Sensing, like those once made in the Internet, will enable unanticipated capabilities and uses and will empower people to better understand and react to their environments.



The mobile phone is well on its way to becoming a personal sensing platform in additon to a communication device, as depicted in this image from a video envisioning the near future of participatory sensing. See http://urban.cens.ucla.edu/video.

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