Smarter Communities:

Community-Based Sense and Respond Systems

A smart system is a system that senses what is going on in its environment and responds effectively. A community-based sense and response (CBSR) system is a system that enables the community as a whole to sense and respond smarter. CBSR systems depend on resources and time volunteered by ordinary people who provide sensors, responders and computational and communication resources.

There are several examples of CBSR systems and there will be many more in the next decade. Information aggregated from mobile phones equipped with global positioning system capability help monitor road traffic congestion in projects at the University of California at Berkeley, Microsoft Research, and Air Sage Inc. in Atlanta. A Purdue University project is fusing information from mobile phones provided with radiation-detection sensors to locate and identify harmful radiation sources. Inexpensive accelerometers connected to computers in people's homes are being integrated to form earthquake warning systems in the Quake-Catcher Network at Stanford and a shakemap generation network at the California Institute of Technology. The Center for Embedded Network Sensing (CENS) at UCLA has several examples of applications of CBSR and is the pioneer in the area.

What's New about Community-Based Sense and Response?

Community-based applications have been available on the Web for several years. The term "Web 2.0" is often associated with applications that depend on community volunteers. Wikipedia is a superb example of such an application. Peer-to-peer systems, such as BitTorrent, exploit computing provided by users. Community-based computational systems, such as folding@home and seti@home, have been used for several years; these systems carry out massive computational tasks by parceling small pieces to different participants. Community-based image-analysis systems, such as the Peekaboom system developed at Carnegie Mellon University, identify images by having groups of people participate in a game.

So, what's new about community-based sense and response?

Earlier applications enabled volunteers to improve computational resources and the quality of information available to the community. ***CBSR takes the next step: It enables communities to <u>sense and respond</u> to events collaboratively.***

CBSR Systems in History and Nature

CBSR systems are common in nature. White-tailed deer raise their tails to signal danger and prairie dogs give warning barks to signal different predators. Fish in schools and whales in pods signal each other about threats and food sources. Many species, including *homo sapiens*, survive because groups sense and respond collectively.

In the Iliad, Homer writes about bonfires used to signal events such as the approach of ships, and the English lit bonfires to warn about the approach of Viking raiders and the Spanish Armada. People in the Great Plains of North America signaled their tribes when they located buffalo herds. Throughout history, individual members of communities have raised alerts when they detected threats or opportunities, and individuals responded by stopping routine activities to deal with the events. Now communities "see" further and respond faster. We are doing what our ancestors did, but better. Issues in designing digital CBSR systems today are much the same as they were centuries ago.

Combinations of Central Management and Individual Initiative
CBSR systems combine some degree of central management with individual initiative. Though individuals lit signal bonfires, the collective had to agree on what the bonfires meant and what to do when alerts were generated. Wikipedia and SourceForge channel individual initiative through centralized management structures; likewise, CBSR systems have centralized managements that specify types of sensors, responders, analysis engines, and data schemas. The challenge is to encourage participation.

Incentives and Disincentives for Participation in Community Systems

Members of a community can benefit from most CBSR applications without contributing to it. For example, an individual can get alerts from an earthquake-warning CBSR system without contributing accelerometers or computers. What's the incentive to contribute when "free riders" get the same benefit as contributors? This question arises in all community-based systems including community-based computation, but there are a few issues particular to CBSR.

One approach to providing incentives to contributors is to give no benefits to free riders; however, society will not tolerate systems that conceal information about impending earthquakes, floods, and fires to those who cannot afford to buy sensors. The more critical the response, the greater the necessity for providing value to free riders.

What to do to Encourage Participation
One can argue that the rational choice is to be a free rider when contributions entail additional costs but no additional benefits. Empirical evidence shows, however, that many people do volunteer time and resources to the community. CBSR system designers can take steps used in other community-based systems to encourage volunteers:

1. A contributor of resources should be impacted only very slightly by the contribution. In an earthquake warning application, people buy and connect accelerometers to their computers, but the continuous operation of accelerometers and computers should have little discernable impact on the contributor's operations. Most importantly, a CBSR system must not crash a participant's computing system!
2. A contributor with minimal skill should be able to install a CBSR application. For example, designers of earthquake warning systems should not expect contributors

to fix their accelerometers so that they are totally flat and oriented precisely along true North-South and East-West directions.

3. Each volunteer should be able to see how his or her contribution matters. Knowing that one's contribution makes a difference is a powerful incentive. For example, a participant in a road-congestion system should be able to see a dot indicating the participant's location and should have a mechanism to relate the participant's dot to the overall service provided by the application. A contributor's visibility within the community is an additional incentive; so, CBSR systems should identify the contributors who contributed most to successful responses.

Disincentives

Participants in some CBSR applications are faced with disincentives. For example, global infectious disease surveillance and response is an important CBSR system, but there are powerful disincentives for reporting illness. Reports to public health authorities about individuals suffering from avian flu may result in destruction of their poultry. Regions that report outbreaks of infectious disease are likely to see reductions in tourism and business traffic. The aphorism, "Don't kill the messenger," is a warning about disincentives in CBSR.

The CBSR designer's challenge is to provide incentives that overcome the disincentives. For example, an incentive in the infectious-disease surveillance application is free expert medical care coupled with compensation for destruction of poultry or swine and other losses. CBSR systems should guarantee privacy to the extent possible since loss of anonymity is a serious disincentive.

Designs of CBSR Systems

Designs of CBSR systems have many points in common with designs of other sense and respond systems. There are, however, a few points that are characteristic of CBSR; next, I'll review some of these characteristics.

Sense and Response using Dynamic Infrastructure

Contributors to a CBSR system can start and stop participating at any time. They may accidentally turn off computers, unplug sensors or damage responders. The number of contributors, their locations, their devices, and the communication network may change from instant to instant. A challenge in CBSR systems is to sense and respond to events when the underlying information infrastructure is highly dynamic.

CBSR is harder than Parallel Computation

Design Constraints Imposed by Timeliness: Designers of CBSR have much to learn from community-based computation such as folding@home, but there's more to CBSR design. The challenge of an uncertain and time-varying information infrastructure is more severe for CBSR systems than for computational systems for several reasons. When a contributor withdraws computational resources from a community-based computational system, the tasks assigned to that contributor are reassigned to others who complete the tasks later. Reassigning responsibilities from contributors who withdraw is not an option in an earthquake warning system because contributors are needed when the earthquake strikes, not at some later time.

Variety of Components: Community-based computational systems can assign tasks to any computer that has certain basic features. Many more features are required to describe sensors and responders in CBSR systems. Parameters for describing an accelerometer in an earthquake warning system include the location of the accelerometer and its make and model number because different model numbers have different calibrations. Many CBSR applications need to have sensors and responders in specified locations; for example, a traffic congestion application requires sensors on all the important roads. By contrast, location is immaterial for computational applications. The age of sensors and actuators, their physical environment (humidity and temperature ranges), and other factors are important for CSBSR systems but are unimportant for purely computational systems.

Pathological Failure Modes
Designers of CBSR systems must guard against failure modes common to devices used in a system. For example, an earthquake warning system for the LA Basin will be ineffective if most accelerometers or communication links fail when devastating earthquakes strike. Homogeneity of devices considerably simplifies designs of CBSR systems but may lead to correlations in system-wide component failures.

Problems of Scale
The scale of CBSR systems requires different designs than conventional centrally-deployed systems. Seismic sensor networks run by government geological services have hundreds of seismometers but community-based networks may have tens of thousands of accelerometers. The growth of a government seismic network can be managed by a geological service to ensure that there are no bottlenecks and that the network remains secure at every step. The growth of CBSR seismological networks cannot be managed in the same way; the system grows and shrinks as people decide to contribute and withdraw sensors. Similarly, government-run traffic congestion monitoring systems, with fixed sensors strategically placed on roads by transportation authorities, have different design considerations than systems based on GPS reports of tens of thousands of cars. The scale of CBSR systems requires massive distribution of computing resources and more adaptive networks connecting sensors, processors and actuators. CBSR systems will rely on cloud computing such as Google App Engine, distributed data storage such as Hadoop, and peer-to-peer networks such as Boinc, to deal with organic growth.

Models of the Environment
Models of the environment used in centrally deployed systems are different, and sometimes more sophisticated than, models used in CBSR systems. For example, a government traffic authority can use detailed models of traffic patterns between critical measurement points on roadways; it can use models tailored to the region – Los Angeles, London, or Stockholm – based on a great deal of local knowledge. Seismologists use detailed models for fault regions, such as the Los Angeles basin, based on measurements

carried out over decades; they tune parameters associated with each sensor because the sensors are stationary and placed carefully in locations that can be analyzed over time. By contrast, organic growth of CBSR systems makes tuning of each sensor difficult; models cannot be based on careful locations of sensors; and rapid, organic growth of CBSR systems in different parts of the world may require that systems operate without the benefit of detailed, region-specific models. For example, scientists have developed detailed models of the Hudson River for decades whereas scientifically-verified models of water quality do not exist for rivers in some parts of the world.

CBSR systems obtain situation awareness by using orders of magnitude more sensors and often simpler models than centrally deployed systems. Simpler models of traffic congestion can be used when there are tens of thousands of cars, equipped with GPS, sending data about local congestion than when there are only hundreds of stationary sensors. Likewise, simpler models of ground shaking can be used in an earthquake warning system fed by tens of thousands of accelerometers than a hundred seismometers. Simpler models of water quality can be used when volunteers make hundreds of thousands of measurements. Since CBSR systems rely on simple models they can be deployed rapidly in parts of the world that have not been studied by scientists for decades.

CBSR systems are characterized by massive uncertainty; so CBSR applications have to be designed from the ground up to cope with this uncertainty. This requires new kinds of models that are more data-driven and more adaptive than the fine-tuned models in place.

Noise and Calibration

Sensors and responders deployed by volunteers have poorer signal to noise ratios than those purchased and deployed by central agencies. For example, there are many varieties of accelerometers with different sensitivities. The performance of sensors may degrade over time; requiring volunteers to recalibrate their instruments periodically places an added burden. CBSR systems sense and respond to the environment based on data obtained from more noisy, and more poorly calibrated instruments than systems deployed by central agencies. Measurements of pollutants in the water made by scientists are likely to be more comprehensive and accurate than those made by volunteers. The challenge of CBSR systems is to use automatic calibration and large numbers of devices to overcome these problems.

Security

CBSR systems are more vulnerable to attack than centrally-managed systems with secure dedicated devices and communication links. A seismic network implemented by a geological service can place seismometers in secure areas where they cannot be tampered with; however, anybody can attach an accelerometer to a CBSR system. Dedicated communication links can be used in centrally-managed systems whereas everybody has have access to a URL of a server in a CBSR system making the system more susceptible to denial-of-service attacks.

Attackers may attempt to trick contributors into running viruses by pretending to be the sites that coordinate volunteer efforts. Coalitions of attackers in local regions can generate cascades of false measurements. They can send erroneous messages indicating massive shaking of the earth when there is no shaking, or traffic congestion when there is none, or absence of pollutants in water systems when, in reality, the water is indeed polluted. Nevertheless, community-based systems do provide valuable sense and response capability even though they are attacked. For example, Wikipedia provides (almost always) accurate, valuable information though attackers attempt to pervert the service; CBSR systems should be designed using similar principles of self-monitoring and self-correction. The challenge for CBSR systems, unlike Wikipedia, is to *neutralize attackers in real time.*

Response Mechanisms

Community-based response mechanisms vary significantly from application to application. A response of an earthquake-warning system is to use a larger fraction of a contributor's computer immediately after an apparent earthquake is detected to calculate the location and intensity of the quake. A response when pollutants are detected in the water may be to send alerts to members of the community and the local water-management board.

One of the most important responsibilities of CBSR systems is to monitor and coordinate responses by individuals in the community. For example, after an emergency in a building, occupants of the building are expected to go to safe evacuation points; CBSR systems using mobile-phone technology and other devices can be used to identify missing people. Photographs posted by individuals after a crisis, such as an earthquake or hurricane, help the community's first responders go to where they are most needed. Continued monitoring by volunteers in the community, as responses to crises play out, help ensure effective collective response.

The Future

Next I'll discuss the technology drivers and consumer demand for CBSR systems. Then, I'll summarize the disadvantages of CBSR systems. Finally, I'll describe how I think CBSR systems will evolve over the next decade.

Technology Drivers for CBSR Systems

Next, I'll identify developments in some of the technologies that foster the development of CBSR systems:

- Mobile phones
- Video cameras
- Decreasing costs of sensors – GPS, stethoscopes, EKG devices, accelerometers, strain gauges, etc.
- Cloud computing

- Peer-to-peer systems
- Social Networks

Mobile phones and CBSR
People in every country, even in remote areas, use mobile phones. Many companies offer phones that accept sensor data through USB and Bluetooth in addition to microphones. This allows phones to acquire and transmit data from thermometers, electrocardiographs, stethoscopes, radiation measurement devices, accelerometers and other instruments. Phones have substantial computational capability and vendors are providing increasingly sophisticated application-development environments.

People can wear or deploy sensors that operate continuously and send data to phones. Phones detect significant events in incoming data and send the data to experts for further analysis. For example, medical sensor data generated while a patient is sleeping, eating, and exercising can be recorded and analyzed by the phone, and sent to doctors when an anomaly is detected. Organizations can train people in remote villages to use sensors to record and analyze vital medical signs of villages on a mobile phone; if a villager has anomalous vital signs or is ill, the villager's medical measurements are sent to a doctor by the phone. The doctor can talk to the health worker and decide next steps.

People on boats in rivers and lakes can connect sensors immersed in water to mobile phones. The phones can periodically send summarized data to servers. Accelerometers in phones can detect shaking indicative of earthquakes. Photographs taken with mobile phones are used to distribute information about events ranging from landslides to political demonstrations.

Phones equipped with sensors are ideal sense and respond devices.

Video Cameras and CBSR
People in a community can collaborate to direct video cameras at parks, roads, landslides, fires, tornadoes, and bridges and analyze the images they see. The *Los Angeles Times* reported on June 21, 2009, that civilians in Lancaster, Pennsylvania can orient the city's video cameras and report suspicious activity. Airports, train stations and shops have used video cameras for many years, but what's relatively new is that individuals in the community – rather than governments or companies – are contributing and controlling them. (The issue of privacy will be discussed in a later note.) Many communities have had "neighborhood watch associations" for decades; now these associations can use increasingly sophisticated technology to make them more effective.

Images from cameras and video cameras coupled with community-based analysis of imagery, such as the Peekaboom system developed at Carnegie Mellon, are powerful tools for CBSR systems.

Inexpensive Sensors

A cellphone medicine project at Caltech is carrying out useful analysis on data obtained from a $5 stethoscope. Inexpensive EKG devices that produce useful data have been constructed for under $10. Of course, these devices are not as powerful as devices used by medical professionals; however, they may be adequate to carry out initial filtering of normal from anomalous measurements. Prices of a variety of sensors from accelerometers and strain gauges are decreasing relative to the costs of experts. GPS devices and location-based sensing technologies enable people to collaborate based on where they are and where they are going. The continuing drop in prices allows more people to buy sensors, and enables more CBSR systems.

Cloud Computing
Google, Amazon, IBM, Microsoft and many other companies provide services that enable computations to be carried out on scalable compute engines. Sensors connected to the Internet can send messages to a cloud computing system. Anybody, anywhere in the world (with Internet access) can connect sensors and actuators to a CBSR system by merely linking the devices to a Web site that accepts input for a cloud computer. Water quality sensors in all the rivers of the world can be connected to a CBSR merely by linking the sensors to a Web site. An accelerometer in Lima, Peru can be connected to a CBSR as easily as an accelerometer in Tokyo or Los Angeles, because all those locations have Internet access and therefore access to a cloud computing system.

Cloud computing systems enable anybody anywhere in the world (provided they can pay for it) to get access to immensely powerful, scalable distributed computation and storage systems; they also enable rapid deployment of worldwide CBSR systems.

Peer to Peer Systems
Peer-to-peer systems such as BOINC enable CBSR systems to use hundreds of thousands of computers around the world. Peer to peer systems enable CBSRs to use computers provided by volunteers in addition to sensors and actuators contributed by individuals. Peer to peer systems have been used for several years for a variety of applications. People now understand that contributions of their computing resources have significant benefit for the community.

Social Networks
Social networks such as Facebook, MySpace, and LinkedIn allow individuals to keep track of what their “friends” are doing. This, in turn, enables communities of friends to detect events based on data provided by members and to respond as a group.

Demand for CBSR Systems

Now I’ll discuss some of the situations that benefit from CBSR systems:

- Citizen science projects
- Responding to crises
- Social interaction and community action

Citizen Science Projects: Community-Based Scientific Research

Communities around the world are more aware of environmental issues than they were in the past. Citizen-science projects are harnessing the intelligence, observational capacity, and science tools of ordinary people to carry out important and exciting scientific research. These include projects Citizens and Remote Sensing Observation Network, CARSON in which people measure environmental parameters such as ozone levels and nitrogen levels in streams, Earth by Aura in which participants measure ultra-violet radiation, the Christmas Bird Count in which people identify and count birds during the Christmas holiday season, the Great Sunflower Project in which people report on the activity of bees, and the American Association of Variable Star Observers (AAVSO). CBSR systems can provide the informational infrastructure that supports citizen science projects.

Responding to Crises using CBSR

CBSR systems are already used in responding to crises such as fires, floods, earthquakes, and chemical spills. The most widely used sensor devices are cameras on mobile phones that capture images of impacted areas. A common response is to pass information to, and get advice from, trusted sites. The adoption of mobile phones, computers and the Internet in developing countries is outpacing the rates at which governments can install sensors and actuators to help manage crises. CBSR systems will be set up by volunteer organizations and non-governmental organizations (NGOs) to address needs for community-based sense and response.

Many communities in different parts of the world are increasingly concerned about security of their families and homes. The story about citizens in Lancaster, Pennsylvania orienting video cameras on community property and reporting suspicious activity gives one example of people collaborating to improve security by using information technology. Communities collaborate in reducing fire hazards to their homes. More types of sensors and actuators (particularly mechanisms for automatic alerting of security personnel) will be used security in the future.

Social Networks and CBSR

The economic and social drivers for the use of CBSR systems in crisis management also apply to social networks. Members of a social network can sense what others are doing, or where others are located, and respond by carrying out joint actions. Applications provide simple responses such as: "17 of your friends have volunteered to help in responding to an oil spill at Walrus Beach on Sunday. Would you like to join them? Click here."). In the future, sensor data, such as local temperature and rainfall, may be fed to personal pages on social networks. These developments enable groups of "friends" in social networks to sense and respond collectively.

Brief Review of Advantages and Disadvantages

CBSR systems enable communities to respond collectively to threats, opportunities and important events better and smarter. CBSR systems have advantages and disadvantages when compared with more traditional systems that are deployed and managed by centralized agencies. The advantages and disadvantages are not primarily the consequences of technology; rather they stem from the distribution of responsibilities for sensing, analyzing and responding to individual volunteers, and the manner in which systems grow organically. The benefits and failings are similar across all CBSR systems whether they use primitive technologies such as bonfires or sophisticated technologies such as accelerometers and cloud computing.

A major benefit is that CBSR systems harness the intelligence, time and resources of ordinary citizens. This not only leads to powerful systems but also helps to build community. Citizen science projects such as the Christmas Bird Count and the Great Sunflower Project are inspiring and they also produce valuable research results. Another important advantage is the ease with which CBSR systems can be started anywhere in the world without governmental approval and massive installed infrastructure. CBSR systems exploit the widespread deployment of the Internet, mobile phones and inexpensive computers to enable communities to respond to events.

A disadvantage is that organic growth is unpredictable. CBSR systems with too few contributors are unreliable; people are more likely to contribute time and resources to CBSR systems when they know that there already are, or soon will be, enough other contributors to make the system useful. CBSR systems can more quickly reach the tipping point where organic growth is sustained by seeding the system with a large-enough group of initial contributors to provide some value.

CBSR systems can reduce a citizen's privacy because these systems use technology effectively. Neighborhood-watch associations in which people use technology, such as remotely-controlled video cameras, may make some individuals feel a greater loss of privacy than associations in which people report what they see with their naked eyes.

CBSR systems must sense and respond effectively even though some sensors and actuators are not installed or maintained carefully. Moreover, some participants may attack the system by providing false information or carrying out denial of service irruptions. CBSR systems exploit their size to overcome these difficulties and to provide value in situations in which conventional systems are not viable.

The Future Evolution of CBSR Systems

CBSR systems will be used for many more applications in the coming decade. Community-based computing systems such as folding@home and citizen science projects such as the Christmas Bird Count have demonstrated the benefits of contributions of intelligence, time and resources by ordinary people. The next step in evolution of community-based systems is to monitor and coordinate responses as well as obtain sensor data and carry out distributed computation. Sensing and analysis are important steps, but responses complete the loop. Understanding and measuring earthquakes are important activities, but responding to them is important too.

Many CBSR applications will extend existing or planned traditional, centralized schemes. Community-based applications for detecting and responding to water pollution will build upon existing systems where possible, and will start from scratch in other areas of the world. CBSR systems need a critical mass of participants to operate reliably; so extending existing systems is the quickest way to add value.

CBSR systems will increasingly use cloud computing or peer-to-peer systems because of the simplicity of connecting sensors to cloud computers to actuators anywhere in the world, using only the Internet, mobile phones or computers. Cloud computing and peer-to-peer systems help to deal with organic growth and very dynamic loads.

Many centralized applications deployed by companies will have the characteristics of CBSR systems. The smart grid will use sensors (smart meters) in people's homes, but the sensors will be deployed over many years and will not all be identical. Individual responses to high load or high prices for power will vary widely. Issues of security and senor calibration arise in the smart grid just as they do in CBSR systems. So, design methodologies for CBSR systems and sense and respond applications deployed by companies will converge.