# Rebooting Discarded Smartphones

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> The consumer economy loves a product that sells at a premium, wears out quickly or is susceptible to regular improvement, and offers with each improvement some marginal gain in usefulness.
> —Jonathan Franzen

**Abstract**

Electronic waste is a growing problem as the rapid pace of technological improvements drives consumer appetites for the latest and greatest devices. The result is millions of tons of e-waste, much of it containing hazardous chemicals and difficult to dispose of safely. Smartphones are already part of this problem, and given the rate of progress in the smartphone technologies, it seems reasonable to expect that consumers will dispose of these devices at rapid rates, spurred on by new features and discounts offered by carriers.

Fortunately, the capabilities, connectedness, and platform homogeneity of smartphones make discarded devices ideal *building blocks* for many second uses. Instead of ending up in a landfill, a discarded smartphone could be transformed into a sensing device monitoring infrastructure or a health care device for the elderly or disabled. **We propose to improve smartphone sustainability by addressing the challenges inherent in turning techno-trash into treasure.**

## 1 — Goals

The Problem: **The progress of smartphone technologies produces growing amounts of electronic waste.**

Smartphone technologies are advancing rapidly, bringing new power into users pockets and changing the way that we live and work. The rapid rate at which consumers purchase new smartphones can be seen as primarily a response to the rate at which this technology is improving. Short device lifetimes, while unfortunate from a sustainability perspective, help support companies that build and sell smartphone hardware and software. Unfortunately smartphones, like most other electronics, are difficult to dispose of properly. Many end up in landfills or shipped to poor countries where they are dangerously dismantled in an effort to collect precious materials.

Given the potential of the smartphone to bring about transformative technological change, it becomes difficult to reduce *demand* by arguing that consumers should hang on to outdated devices in the name of sustainability. Instead, we propose to focus on the *supply* of fully- or partially-functional outdated devices that society currently struggles to put to use, and explore how this growing volume of techno-trash can be efficiently reused.

There are three reasons why the time is right for this effort. First, unlike previous generations of "feature phones", the current smartphone market is coalescing around a small set of common platforms such as Android. This platform homogeneity reduces the burden of supporting large numbers of discarded devices. Second, current smartphones have an attractive feature set for many non-phone applications: size and power requirements facilitating easy deployment, microphones and cameras allowing them to double as sensors, touch screens for interfacing with users.

Finally, smartphones are well-integrated into the existing communication infrastructure. They can transmit data via text messages, over WiFi networks, and via high-speed mobile communication technologies like 3G. If WiFi is available, no service plans are required to allow recycled smartphones to become part of the "Internet of Things". And with carriers increasingly interested in "machine-to-machine" applications, we expect to see increasing service flexibility allowing discarded devices to be cheaply connected to pervasive mobile cellular and data networks.

To provide an idea of the potential of discarded devices, the U.S. Environmental Protection Agency (EPA) estimated that 141 million mobile devices became ready for end-of-life management in 2009, of which only 11.7 million (8%) were collected for recycling [3]. The 129 million phones discarded in 2009 would be enough to place an average of *200 phones* on all 600,000 bridges in the United States, or every *2 feet* on every stretch of highway in the 46,876 mile interstate highway system.

THE OUTCOME: **Several successful demonstrations of both *how* to transform discarded smartphones and *what* to transform them into.**

Working with a supply of "discarded" smartphones left over from a previously-funded project, we will build several prototypes demonstrating how to efficiently repurpose discarded phones. We currently have several ideas for how to use recycled smartphones, including:

- At campus bus stops monitoring rider volumes and performing on-demand bus routing.
- Bolted to stop lights helping improve traffic flow in congested corridors.
- At nearby farms tracking animal behavior.
- Providing the basis for verifiable location services.
- Fitted to rowing shells and providing data improving crew performance.
- As special-purpose devices assisting the disabled or elderly.

The specific projects tackled will be a function of student interest and the specifics of different opportunities that present themselves. But the goal is to demonstrate two things conclusively. First, we want our case studies to show that discarded smartphones **are still useful devices**. Second, we want to demonstrate **how to use discarded phones as building blocks** to enable new applications or lower the cost of existing ones. In contrast with existing work [2], which explored reusing phones *as phones*, we plan to focus on transforming smartphones into sensors and actuators integrated with existing infrastructure.

Any code or tools produced will be open-sourced and made available for collaborative development. In addition, short videos describing the process and results of recycling smartphones will be posted on a project website for public viewing. Finally, papers and posters will be presented at appropriate venues including new forums emerging to share results on sustainable computing.

## 2 — Challenges

There are several challenges that must be overcome in order to enable efficient reuse of discarded smartphones. One is **power efficiency**. Many of our imagined reuses of discarded phones place them far from the existing power infrastructure, meaning that they will have to continuously harvest power and conserve energy during use. The mobile systems and sensor networking communities have been studying power conservation in many similar settings, and we expect to be able to reuse many existing ideas while inventing new solutions when necessary.

The second is **device capability determination and characterization.** To efficiently reuse large numbers of discarded phones, the cost of the transformation must be as low as possible. This cost includes the process of identifying the phone and determining its capabilities. We expect the pool of discarded devices to eventually include many different models of smartphone with different features. In addition, there will be process variation between identical phones as well as additional variation caused by phone usage. Certain parts of the phone may not be working well; others may be entirely broken. Matching phones with any number of intended second uses will require new testing procedures that can accurately identify what phone features are available and how well they are functioning.

A third challenge is **how to create a single-purpose device from a multi-purpose phone.** Imagining the phone as a powerful building block for new devices, we must determine what the interfaces will be that will allow the phone core to be attached to whatever special-purpose peripherals the device needs to function. In cases where the phone is replacing special-purpose hardware we must determine how to transform the existing software to run on the recycled phone. And if new software is being developed, the problem includes the continuation of work on making smartphone programming easier.

In addition, it may be necessary to research the structure of an appropriate computing platform for smartphone recycling. Smartphones are considered general-purpose computing platforms, but many of our recycling ideas put them to more specific uses. It is possible that the existing smartphone software platform is too general purpose to efficiently support these new classes of recycled uses, and must be refactored to be more efficient at a small set of core tasks.

Finally, recycled devices must be integrated into the existing communications infrastructure. While the large number of different communication protocols integrated into typical smartphones makes this possible, the power requirements and deployment locations may make efficient integration challenging. Carrier flexibility will also be necessary, since keeping the cost of applications using recycled devices down will require new service plans tailored to their communication patterns.

## 3 — Investigator Qualifications

Geoffrey Challen has deployed sensor networks on active volcanos [4], developed new solutions for managing energy in distributed systems [5, 1], and is currently building a 750 phone public participatory smartphone testbed called PHONELAB at SUNY Buffalo. The challenges inherent to smartphone recycling lie in the intersection of his previous work on sensing, his current work on smartphones, and his developing interests in sustainability and infrastructure. Through the Google- and NSF-funded PHONELAB project he has developed local contacts at Sprint necessary to the success of the proposed research.

## 4 — Budget

| Type | Description | Price ($) | × | Quantity | = | Total ($) |
|---|---|---|---|---|---|---|
| **Equipment** | Nexus S Solar Panel Charger | 40[1] | | 20 | | 800 |
| **Student Support** | 2012–2013 Salary | 28,625 | | 2 | | 57,250 |
| | 2012–2013 Tuition | 10,602 | | 2 | | 21,204 |
| | | | | | **Total:** | **$79,254** |

[1] Price retrieved from `thepocketsolution.com` on 4/13/2012.

**Table 1 — Line item budget for our proposal.**

Our budget includes support for two graduate research assistants. Students will be assigned recycling projects based on their interests and will also be engaged in proposing new ideas of how to reuse discarded smartphones. For phones we will reuse the 40 phones we received from Google last year through the University Award program. Given that one requirement of this project is determining how to provide power for recycled smartphones deployed in areas were power infrastructure is not available, we budget a small amount of equipment money to purchase 20 Nexus S solar panel chargers for outdoor use.

## REFERENCES


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[5] Geoffrey Werner-Allen, Stephen Dawson-Haggerty, and Matt Welsh. Lance: Optimizing high-resolution signal collection in wireless sensor networks. In *Proc. of the 6th ACM Conference on Embedded Networked Sensor Systems (SenSys'08)*, Raleigh, NC, USA, November 2008.

## RESULTS FROM PRIOR GOOGLE SUPPORT

Geoffrey Challen was a co-investigator on a project entitled "PhoneLab: A Participatory Smartphone Cloud Testbed" which received $60,994 from the Google University Award program in 2011.

We used this funding to purchase 40 Nexus S 4G smartphone from Sprint and equip them with voice and data service. In addition, two students were supported during the 2011–2012 academic year. Equipment and student support were used to design a small prototype of the large open-access smartphone testbed called PhoneLab which SUNY Buffalo will open in the fall of 2012. During the last nine months, our team has focused on building the software necessary to control testbed-attached devices, log data, reliably collect data at central servers, and manage the testbed. At this point we have a working set of tools in continuous use managing our prototype testbed.

In addition to the core infrastructure work, a series of research projects were initiated last fall as part of a graduate-level systems research class that focused on smartphone research and development, and these early projects provided valuable insights into the features that the testbed would need to support to accelerate smartphone research. While they have yet to produce results, several projects are ongoing.

With support from Google, Sprint, and many of our research colleagues at other institutions, the PhoneLab project recently received a 3 year 1.3 million dollar Computing Research Infrastructure (CRI) grant from the National Science Foundation. This funding will allow us to open PhoneLab this fall with 250 phones and eventually scale the testbed to 750 connected devices by 2015. A stated goal when we applied and received money previously from Google to support PhoneLab was to eventually scale it to a size that the University Awards program would have been unable to support, and we are pleased that we have been able to use the initial seed funding from Google to do so.

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**Research Interests**

Energy management, computer systems, smart phones, embedded and distributed systems, sensor networks, resource management, sustainability.

**Education**

- **Ph.D. in Computer Science,** Harvard University, May 2010
  Adviser: Matt Welsh. Thesis title: "Data Fidelity and Resource Management for Data-Rich Sensor Networks."
- **A.B with Honors in Physics,** Harvard University, June 2003

**Experience**

- **Assistant Professor**, University at Buffalo, State University of New York, August 2011–
- **Post-Doctoral Assistant**, Massachusetts Institute of Technology, September 2010–June 2011
  Working with Hari Balakrishnan, studied ways to reduce 802.11 power consumption in the context of the AirBlue FPGA-based software-radio platform.
- **Research Assistant,** Harvard University, June 2003 - May 2010
  Working with Matt Welsh, designed sensor network systems supporting the scientific study of active volcanoes. Developed the Lance architecture for optimizing high-resolution signal collection. Participated in the design of the Pixie operating system and the Mercury architecture for medical monitoring. Designed and built the IDEA sensor network service enabling coordinated distributed energy management. Deployed and maintained MoteLab, a wireless sensor network testbed.

**Publications**

- **The Case for Power-Agile Computing**
  Geoffrey Challen and Mark Hempstead. In *Proceedings of the 13th Workshop on Hot Topics in Operating Systems* (HotOS'11).
- **IDEA: Integrated Distributed Energy Awareness for Wireless Sensor Networks**
  Geoffrey Werner Challen, Jason Waterman and Matt Welsh. In *Proceedings of the 8th Annual International Conference on Mobile Systems, Applications and Services* (MobiSys'10).
- **Mercury: A Wearable Sensor Network Platform for High-Fidelity Motion Analysis**
  Konrad Lorincz, Bor-rong Chen, Geoffrey Werner Challen, Atanu Roy Chowdhury, Shyamal Patel, Paolo Bonato and Matt Welsh. In *Proceedings of the Seventh ACM Conference on Embedded Networked Sensor Systems* (Sensys'09).
- **Peloton: Coordinated Resource Management for Sensor Networks**
  Jason Waterman, Geoffrey Werner Challen, and Matt Welsh. In *Proceedings of the 12th Workshop on Hot Topics in Operating Systems* (HotOS'09).
- **Lance: Optimizing High-Resolution Data Collection in Wireless Sensor Networks**
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- **Deploying a Wireless Sensor Network on an Active Volcano**
  Geoffrey Werner-Allen, Konrad Lorincz, Mario Ruiz, Omar Marcillo, Jeff Johnson, Jonathan Lees and Matt Welsh. In *IEEE Internet Computing*, Special Issue on Data-Driven Applications in Sensor Networks, March/April 2006.
- **Firefly-Inspired Sensor Network Synchronicity with Realistic Radio Effects**
  Geoffrey Werner-Allen, Geetika Tewari, Ankit Patel, Radhika Nagpal and Matt Welsh. In *Proceedings of the Third ACM Conference on Embedded Networked Sensor Systems* (Sensys'05).
- **MoteLab: A Wireless Sensor Network Testbed**
  Geoffrey Werner-Allen, Pat Swieskowski, and Matt Welsh. In *Proceedings of the Fourth International Conference on Information Processing in Sensor Networks* (IPSN'05), Special Track on Platform Tools and Design Methods for Network Embedded Sensors (SPOTS).
- **Monitoring Volcanic Eruptions with a Wireless Sensor Network**
  Geoffrey Werner-Allen, Jeff Johnson, Mario Ruiz, Jonathan Lees, and Matt Welsh. In *Proceedings of the Second European Workshop on Wireless Sensor Networks* (EWSN'05).
- **Simulating the Power Consumption of Large-Scale Sensor Network Applications**
  Victor Shnayder, Mark Hempstead, Bor-rong Chen, Geoffrey Werner-Allen, and Matt Welsh. In *Proceedings of the Second ACM Conference on Embedded Networked Sensor Systems* (SenSys'04).

**Books and Book Chapters**

- **Wireless Sensor Networks: Deployments and Design Frameworks**
  Elena Gaura, Mike Allen, Lewis Girod, James Brusey, Geoffrey Werner Challen. Springer Publishing, 2010. Book co-editor and chapter co-author.

**Professional Activities**

- **Program Committee Member** for the Sixth IEEE International Workshop on Sensor Networks and Systems for Pervasive Computing (PerSeNS 2010); the 9th ACM Conference on Embedded Networked Sensor Systems (SenSys 2011); the 10th ACM Conference on Embedded Networked Sensor Systems (SenSys 2012).
- **External Reviewer** for IPSN'10, IPSN'08, EWSN'06, Sensys'05, and others.