

# Smartphone Evolution and Reuse: Establishing a more Sustainable Model

(Invited Paper)

Xun Li   Pablo J. Ortiz   Jeffrey Browne   Diana Franklin   John Y. Oliver\*

Roland Geyer<sup>‡</sup>   Yuanyuan Zhou<sup>†</sup>   Frederic T. Chong

*Department of Computer Science, University of California, Santa Barbara*

*{xun, portiz, jbrownne, franklin, chong}@cs.ucsb.edu*

<sup>†</sup> *Department of Computer Science and Engineering, University of California, San Diego*

*yyzhou@cs.ucsd.edu*

<sup>\*</sup> *Department of Electrical Engineering, Cal Poly San Luis Obispo*

*jyoliver@calpoly.edu*

<sup>‡</sup> *Donald Bren School of Environmental Science and Management, University of California, Santa Barbara*

*geyer@bren.ucsb.edu*

**Abstract**—The dark side of Moore’s Law is our society’s insatiable need to constantly upgrade our computing devices. The high cost in manufacturing energy, materials and disposal is more worrisome the increasing number of smartphones. Repurposing smartphones for educational purpose is a promising idea and shown success in recent years. Our previous work has shown that although different components in smartphones degrade from use, their functionalities, available resources and power supplies are still able to satisfy the requirement of educational applications. In this study, we demonstrate the potential benefits of reusing smartphones by analyzing their manufacturing and life-time energy. The key challenge is the design of software that can adapt to extreme heterogeneity of devices. We also characterize different types of heterogeneities among different generations of smartphones from HTC and Apple, including processing capability, storage resource and various features. We propose insights to aid establishing a sustainable model of designing mobile applications for phone reuse.

**Keywords**—Sustainable Computing; Education; Smartphone Evolution

## I. INTRODUCTION

The current trend of more and more powerful mobile devices has shifted the computing market from personal computers to smartphones. Companies such as Apple, HTC and Microsoft are pushing the smartphone technology so hard that new smartphones with higher speed and more features are coming out every year. The smartphones now are equipped with high-end processors, rich storage resources, multiple sensors, touch-screens with fancy human interface and different network connections capabilities. The power of such smartphones can be equivalent to low-end personal computers, but with lower cost and better portability. The superiority of smartphones indicates that the smartphone market is going to increase even faster and dominate the mobile device market.

However, such a high speed of evolution in smartphones does not come for free. People upgrade their phones an

average of every 18 months, either because of the incentives in provider contracts or to keep up with the newest generation. Over 300,000 iPads were sold in the first day that they were sold in stores and apple sold 1.5 million of iPhone 4G on launch day. Most of the smartphones are still computational powerful and hence not fully utilized when they are thrown away. As pointed out by our initial work [7], the manufacture energy and the life-time energy of smartphones are extremely imbalanced. This has a tremendous environmental impact given the energy costs to manufacture the components in a cellphone in the first place and the problem of disposing them.

One intuitive way to maximally utilize the computation power of smartphones is to reuse smartphones for other purposes. Our previous study in characterizing educational applications running on smartphones has shown that recycled smartphones can be a good fit for elementary school education [3]. We showed that the resources remaining in recycled smartphones are enough for reusing for another five years.

However, though the hardware is adequate, the key challenge in our strategy is the design of software that can adapt to the extreme heterogeneity of devices. Handsets could be running diverse operating systems and possess different hardware capabilities. Worse yet, re-used handsets may have worn out peripherals or be deployed with intermittent power sources and connectivity. Such heterogeneity poses challenges for developing mobile applications.

Mobile applications are designed for the current generations of devices; running applications on reused devices which might be one or two generations older could cause compatibility problems since current applications might be using some features that do not exist in older devices or such features are not functional any more. Old devices could also be slow, lack resources or have a short battery lifetime. On the other hand, certain types of applications such as educational applications are mostly non-profit, which might

not be continuously maintained by the original developers. Running such applications developed years ago on new devices could also lead to inefficiency: new features and new resources might not be fully utilized.

To make smartphone reuse feasible, it is important to first understand how smartphones evolve in terms of technology and how to design mobile applications with such knowledge in mind. In this paper we analyze the heterogeneity of smartphones by modeling the evolution of smartphones from different brands and generations, and discuss how to design mobile applications with such information and potential solutions to existing challenges. Specifically we make the following contributions:

- We analyze the potential benefits of reusing mobile devices by comparing the energy cost of manufacturing mobile devices with their lifetime energy, concluding that there is, indeed, a compelling environmental benefit to repurposing used cell phones. We also look into the extension to the battery life of smartphones when switching from the cellphone network to the WiFi network.
- We model how the device features and operating systems from different brands and generations of smartphones evolve, and propose insights on how to help design mobile applications compatible with all types of devices by utilizing the knowledge of smartphone evolution.
- We discuss the challenges and potential solutions of designing life-cycle aware cellular phones for educational applications, raising the technical problems to be solved in order to maximize the benefit of a second smartphone use.

We begin with a motivation and background for reusing smartphones in Section II. Related work is presented in Section III. Section IV provides the potential benefits obtained by reusing mobile devices. Section V analyzes how different brands and generations of smartphones evolve in terms of device and system. Section VI presents how we could utilize the knowledge of smartphone evolution to help design mobile applications. Section VII discusses the potential solutions to the challenges of lifecycle-aware design of mobile devices and Section VIII concludes.

## II. MOTIVATION

### A. Smartphones

A smartphone is considered to be a mobile phone that offers more advanced computation ability and connectivity than basic feature phones. It is normally equipped with cameras, WiFi connectivity, an interface for installing new applications, comprehensive user interfaces such as touchscreens and other equivalent functions and computation abilities as personal computers. With the rapid improvement in the technology, the mobile device market is currently

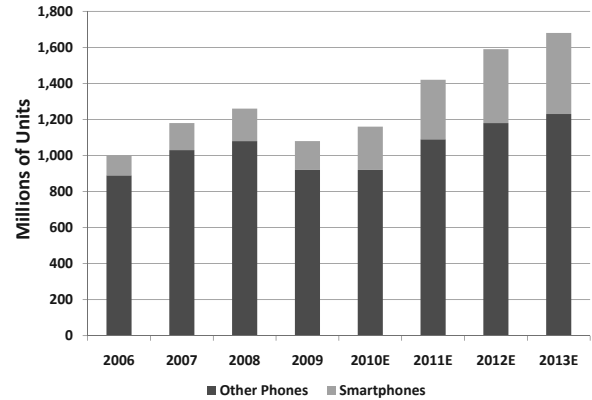


Figure 1. Worldwide production of all mobile phones and the breakdown: The portion of smartphones is increasing fast recent years

shifting from conventional cellphones to smartphones. Vendors shipped a total of 174.2 million units in 2009, up 15.1% from the 151.4 million units in 2008. Figure 1 shows that among all mobile phones, smartphones accounted for 15.4% shipped in 2009, up slightly from 12.7% in 2008, but is estimated to grow quickly during the next 3 years. It is also estimated that almost all handsets sold will be smart by the year of 2015 [2].

However, the environmental impact of the increasing number of smartphones has been a pressing problem. More toxic chemicals are generated, and the disposal cost is increasing. To achieve sustainable computing, discarded smartphones have to be either reused or recycled. Reuse in the broadest sense means any activity that lengthens the life of an item. Recycling, on the other hand, is the reprocessing of an item into a new raw material for use in a new product. Recycling has been used for a long time and benefits from regaining the materials for manufacturing. However, reusing achieves the goal of sustainable manufacturing more efficiently than recycling due to the fact that recycling will always generate waste regardless of the recycling technology, and it also costs money and energy to recycle. Hence there is a high incentive of reusing mobile devices into other purposes. In addition, when the phone becomes too old for educational use, it can still be recycled.

### B. Potential Applications for Reusing

Reuse is nothing new. What is new is the need to reuse.

One natural reuse of mobile handsets would be the formation of a robust and self-maintaining environmental monitoring infrastructure. We envision a network of distributed nodes that monitor a physical region of interest, where visual or data can be gathered, aggregated to increase accuracy and completeness, and processed to locate events or objects of interest. Specific deployment scenarios include home alarm systems, wildlife detection and tracking systems, or emergency reporting systems for monitoring

earthquakes along fault lines or the spread of wildfires. Leveraging the large number of repurposed devices allows us to mask intermittent and permanent failures with redundancy and transparently failover. The software infrastructure would monitor nodes and perform adaptive load-maintenance on a per-resource basis, dynamically reassigning tasks away from failed components while leveraging resource rich nodes to their fullest.

Another compelling application would involve the reuse of handsets as GPS trackers for mobility measurement and trace gathering. Current research on mobile networks such as MANETs or vehicular networks are severely constrained by the lack of representative mobility models [1]. While recent work shows theoretical mobility models such as Random Walk or Random Waypoint to be inaccurate, measurement of real mobility models is constrained by the size, cost and availability of wireless computing clients. Repurposed handsets would provide a scalable, low-cost solution that minimizes inconvenience to participants. Handsets can use GPS-locators or cellular triangulation to compute, track and record their movements. Measurement data can be aggregated, filtered, compressed and anonymized in-network before being gathered by wired basestations. For vehicular networks, distributed sensors can not only build accurate mobility models, but also provide a distributed monitoring network that measures and predicts traffic patterns, even detecting and alerting authorities to accidents in real-time [6]. Finally, accurate, large-scale mobility measurements would not only fill a critical need for networking researchers, but also provide invaluable insights into the optimization and design of transportation infrastructures.

Finally, reusing smartphones for educational purpose has been an emerging research and shown to be more efficient than conventional education. With a cellular phone in each child's hands, the problem sets being taught can also be personalized to each student. One advantage this offers is that short math problems can be tweaked so that the collaboration between two students with slightly different problems becomes more an interaction of, "How did you get your answer?" rather than, "What answer did you get?" Another advantage personalization offers is the ability to match problem difficulty more closely to a student's abilities, making the learning process less daunting (or less trivial) for individual students. Participatory interaction is encouraged by working through distributed devices, since students who are shy in a traditional setting are more inclined to collaborate via text or graphical annotations. Also, due to the nature of online interaction, every student's input is weighed equally since no single comment will interrupt or "talk over" another comment.

These devices also offer an availability of resources that has been traditionally infeasible. If enabled with WiFi access points, the phones have a constant connection to the web for reference materials. For some students, the phone may

even be their only access to the Internet, especially if the school serves a disadvantaged community. Even without constant connectivity, the mobile devices have advantages in terms of their compact form factor. Students can do their homework assignments practically anywhere, while pen-and-paper methods require an amount of preparation and commitment beforehand. Lastly, smartphones equipped with sensors such as cameras and GPS allow students to create their own learning experiences through constructive activities. Students can collect data and present on open-ended social studies or science questions, or express themselves creatively through videos and photos. In this sense, the devices open up new ways of learning previously unavailable.

### *C. Feasibility of Reusing*

To show that smartphone have enough computation capability for reusing, our recent work [3] characterized the resource usage of running popular educational applications on the HTC Nexus One. We also modeled the degradation of smartphones and compare the remaining resource of reused devices with the demand of educational applications. We made the following observations:

- In terms of device functions, most applications only need around 3 in all 10 device features, so that damage to any single component will not affect the use of most other applications. Although mobile devices will wear out during use, they can still be reused in most scenarios as long as the network adapter remains functional along with at least a few other components.
- In terms of storage requirement, a reused Nexus One is still capable of installing more than 30 applications without any difficulty.
- In terms of memory usage, around 200MB of memory is still available for running userspace applications in reused smartphones, which is certainly enough for running educational applications.
- In terms of battery life, a battery could be reused for another 2.3 years after 18 months of regular use. For a five-year reuse, one battery replacement might be necessary.
- In terms of network requirement, the average network requirement is 655bytes/second, and the peak network bandwidth requirement can be as high as 160KB per second. Assuming a big classroom with 40 students, a maximum of 6.4MB/s bandwidth network is needed.

For each different type of resource, we observe that the computation capability of reused smartphones is always more than enough to support running educational applications, hence reusing smartphones for education purpose can be a promising research field.

### III. RELATED WORK

The current smartphones develop so quickly that most mobile devices are discarded every 18 months on average despite the high costs associated with manufacturing these devices. Our initial work [7] proposes the notion of life cycle aware computing and provides a framework for designing embedded microprocessors for reuse. Zadok [12] also points out the fact that the growing trends of the smartphone market make sustainability in mobile computing an urgent problem to address, and they propose the Green Switch as a new product and service design methodology to assess the environmental impact of mobile products.

Researchers have been trying to model the evolution of personal computers and wireless devices. Authors in [4] posit Bell's Law as a general theory for the creation, evolution, and death of various priced-based computer classes that have come about through circuit and semiconductor technology evolution from 1951. Such observations can potentially be used to help predict the future of smartphones too.

Approaches to increase the existing computation power of smartphones have also been proposed. [5] introduces a novel architecture that can off-load execution from the smartphone to a computational infrastructure hosting a cloud of smartphone clones to achieve better energy efficiency.

### IV. POTENTIAL BENEFITS OF REUSE

In order to evaluate the energy savings in reusing cell phones, we need pieces of information - energy for manufacturing, use, and disposal. We begin by estimating, based on published data, the energy required for these three phases in a cellular phone's lifetime. We pay particular attention to the ratio between the energy used during the phone's lifetime and the energy required to manufacture the cell phone, with the belief that a low ratio represents a waste of energy because the manufacturing cost dominates the energy. We then incorporate the energy values we gathered (that are presented in the following sections) to estimate how much this ratio increases, leading to a more palatable energy profile that is less dominated by the production costs.

A Recent study on the environmental impacts of mobile devices from Nokia [8] indicates that the total energy consumption for creating, using and recycling a typical Nokia mobile device is 270 MJ. The breakdowns are shown in Figure 2. They assume the phone is used for 3 years, while in reality they will probably be used only for an average of less than 2 years. The calculated energy for each portion is shown as Basic Energy in Figure 3. The *Total Cost* is calculated by adding up the *Manufacturing Energy* and *Transport Energy*. As can be seen from the figure, the basic *User Phase Energy* is far below the *Total Cost* of producing mobile devices. The ratio between the product use energy and the total energy cost (the sum of manufacturing energy and transport energy), is as low as 0.28.

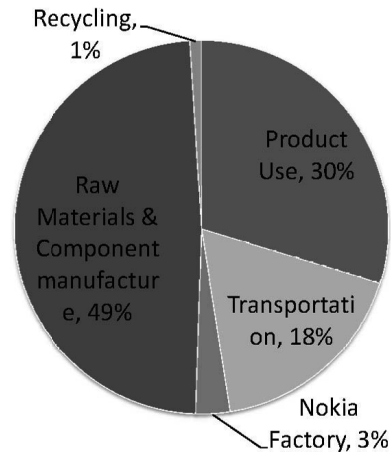


Figure 2. Energy breakdown for a typical Nokia phone in which 3 years of use time is assumed. The total energy consumption for creating, using and recycling a typical Nokia mobile device is 270 MJ

We now analyze, using experimental results presented later in the paper, how reusing the phones for educational applications will increase this ratio. If we are able to reuse the mobile device for another 5 years, the energy consumed per year can be greatly reduced. When a device is reused, more *User Phase* energy will be introduced compared with the energy cost to manufacture and transport the device. We assume 1.7% of the total energy is needed to recycle a smartphone, since most of the components do not require replacement except the batteries, which accounts for 0.7% of total manufacturing energy [9]. The production cost also increases due to the repurposing costs in collecting, reprogramming, and distributing the phones to schools. The total distance of transportation for reuse is calculated as twice the average distance from any two places in the United States, which can be estimated as the sum of the east-west distance (2900 miles) and the north-south distance (1500 miles) for the United States divided by 2. The unit transportation energy for airplanes is approximated to be 6900 kJ per tonne kilometre according to the US Transportation Energy book [11]. For an example smartphone, the HTC Nexus One with weighs 0.13kg, resulting in a total transportation energy of  $6900 \times 0.00013 \times 7081 = 6352kJ = 6.35MJ$ . During the reuse phase, assuming that a mobile device can be used for 1.6 days without recharging according to our power analysis in the following sections, another 5 years using of the phone will consume a total of 120MJ. As shown in Figure 3, the total cost energy and the use phase energy becomes more balanced, and the ratio between them increases to as high as 0.87. Such a prominent increase in this ratio shows that repurposing can substantially improve the utilization of the energy used to manufacture and transport the mobile devices.

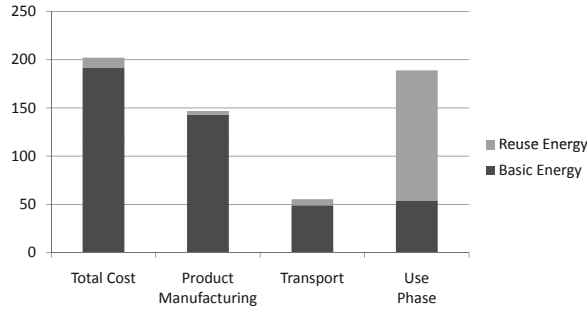


Figure 3. Manufacturing, Transport and User phase energy for regular use and recycling. Total Cost is calculated by adding the Manufacturing Energy and Transport Energy. Basic Energy gives the energy for manufacturing, initial transportation and regular use of the phone, while Reuse Energy indicates the extra energy required to reuse the phone

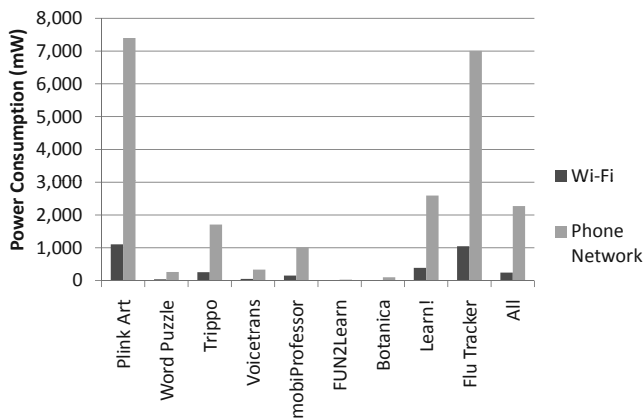


Figure 4. Power consumed by the network communication for each application through WiFi and phone network

#### A. WiFi Energy and Cellphone Network Energy

When smartphones are reused for educational purpose, no cellphone services should be provided, due to the high cost of cellphone contracts, prohibitions of cellphone use in schools, and the nonnecessity of giving cellphone service to students for education purpose. Hence WiFi network or other approaches such as bluetooth will be used for establishing a communication network in the classroom. By switching from cellphone network to WiFi, we observe that substantial energy can be saved, hence the battery lifetime can also be extended.

According to the power breakdown for typical mobile devices derived by [10], WiFi consumes 0.518 mW/byte compared with 3.47 mW/byte for the phone network. As shown in Figure 4, the power consumed by network communications for each application can reduce by 90% through using WiFi connections in average. Based on our previous study, an average of 5.9MB of data will be transmitted everyday. Hence by switching the internet access from the phone network to the WiFi network during using those applications, 12MJ of energy can be saved everyday.

	Brand	Release Date
HTC	HTC Dream	Oct 2008
	HTC Magic	Mar 2009
	HTC Hero	Oct 2009
	HTC Nexus One	Jan 2010
	HTC Desire	Mar 2010
	Droid Incredible	Apr 2010
	HTC Evo 4G	Jun 2010
Apple	iPhone Original	Jun 2007
	iPhone 3G	Jul 2008
	iPhone 3GS	Jun 2009
	iPhone 4G	Jun 2010

Table I  
LIST OF DIFFERENT GENERATIONS OF SMARTPHONES IN OUR STUDY

## V. SMARTPHONE EVOLUTION

One of the challenges of reusing smartphones is the high heterogeneity from different brands of devices and even different generations of the same brand. In this section we model the evolution of different smartphones from different brands and generations and seek to obtain useful insights to help software designers design applications which are able to run on reused smartphones. The heterogeneity of smartphones can be mainly divided into two parts: hardware heterogeneity and software (operating system) heterogeneity.

#### A. Hardware Heterogeneity

A typical smartphone usually consists of an embedded processor, random access memory, flash storage, camera, touch-screen, sensors such as GPS and compass, and WiFi/Bluetooth connectivity. We study how different smartphone brands and generations evolve on those different device features. Specifically, we choose devices from HTC and Apple as our target since they are two of the most popular smartphone brands been used. Table I lists all the different generations of smartphones we are analyzing.

- **Processor** We first look at the computation ability of the processor in different smartphone generations. Figures 5 shows the processor frequency of different generations from HTC and Apple. As can be seen from the figure, smartphones from the two brands share similar trends: during the first one or two years the processor frequency remains the same due to technical immaturity, while after that it starts to increase according to the Moore's Law. Hence the first observation

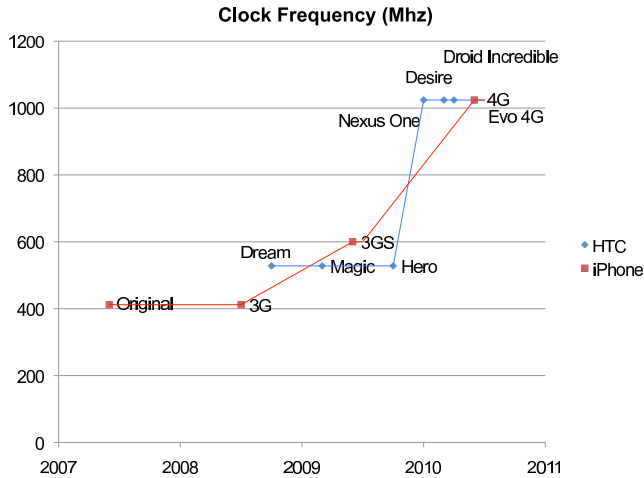


Figure 5. Smartphone processor frequency of different generation from HTC and Apple

we make is that we can predict the future processor frequency for smartphones based on Moore's Law, until it reaches the power wall. The power wall for smartphones has not been heavily studied yet and will depend on the technology of portable batteries.

Our second observation is that although the two different brands start with different frequencies, they have merged to the same level in 2010. To maintain enough compatibility, we can predict that in the future smartphones from different brands should have equivalent or comparable processor computation ability, except that the power consumption reaches a certain level such that people have to make trade-off between the computation ability and the battery lifetime.

- **Memory** Both of the devices from Apple and HTC have the RAM for running applications. Figure 6 gives the RAM capacity for different generations of smartphones from HTC and Apple. The observation here is similar as the processor evolution: the capacity of RAM increases based on the Moore's Law and the capacities of the current up-to-date device versions from HTC and Apple are the same.
- **Storage** For any type of smartphone, a big (several GB right now) flash storage will be equipped to store user space files such as pictures, music, videos and other personal files. The capacity of such storage for devices from both HTC and Apple turns out to be changing in the same way. For earlier versions of the devices, the flash storage capacity is 16GB, and for newer versions it is 32GB. The speed of evolution is doubling every two year, fit to Moore's Law again. For devices from HTC, they have special flash ROM which is used for storing user-space applications for security reasons. The capacity of such storage evolves in the similar speed as the RAM.

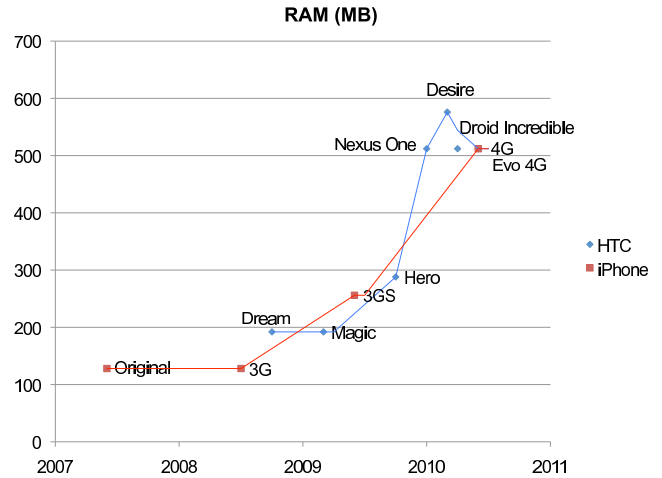


Figure 6. Smartphone RAM capacity of different generation from HTC and Apple

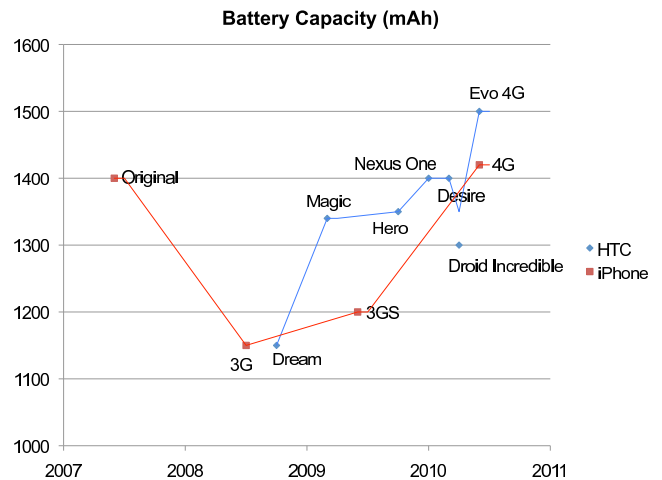


Figure 7. Smartphone battery capacity of different generation from HTC and Apple

- **Connectivity** All smartphones support the same types of connectivity features: cellphone network, WiFi network and Bluetooth although the protocol versions differ trivially. The network bandwidth usually depends on the environment instead of the devices.
- **Battery Capacity** Figure 7 gives the battery capacity of different generations of smartphones from HTC and Apple. Although there is no well defined method for predicting the evolution of battery capacity, it happens to share the similar trend as in silicon technology.
- **User Interface** Different from conventional cellphones which are mostly operated by keyboards or at most special pens, smartphones all have touch-screens as the user interface. Furthermore, except the original iPhone, all smartphones from both HTC and Apple support multi-touch. Hence there should be no obvious heterogeneity in the user interface in terms of hardware,

although there can be operating system heterogeneity that provides different features using the user interface. The screen of the device, however, only remains the same size for all generations of iPhones, and differ for most of the generations for HTC (from 3.2inch to 4.3 inch).

- **Other Features and Sensors** Several others features and sensors are all included in some of the devices: all the generations of smartphones have GPS sensor except the devices prior to 2008; all the generations have at least one built-in camera for taking pictures, and all current versions can record videos too. The newest version from Apple, the iPhone 4G have two cameras such that one can video chat using the phone; all the generations have a built-in compass sensor except the iPhone Original and iPhone 3G.

### B. System Heterogeneity

The heterogeneity of devices include both the device variation and also the system difference. The major focus of changes made in operating systems on mobile phones at present and in the past seems to be the improvement and addition of features to an existing feature set. This focus does not always keep performance a priority. In the case of Google's Android, performance typically improves or stays the same with an expanded set of features. For them, it is important to do so because many Android phones that are currently in circulation receive update to the operating system (obviously, without a hardware update to go with it) when it becomes available, and consumers expect to maintain their phone's current level of performance, at the very least. A performance boost is generally seen from an upgrade of Android 1.5 to 2.1, but it is often the case that there is a performance hit from Android 2.0.1 to 2.1. In the case of Apple's iPhone, major OS updates are clearly designed for a new model of the phone. For example, when comparing iOS 3 and iOS 4 on the iPhone 3G, the iOS 4 typically does not perform as well. The reason why there was a significant hardware update in the iPhone 4G was to make up for the slowdown caused by the new multitasking feature in iOS 4. Since there is no other company besides Apple that manufactures models of iPhones, Apple does not have to cater the design of their OS to update and maintain the performance of other models of iPhones currently in circulation. It can simply be assumed that people will upgrade to the new phone. As is normally the case when competing brands focus on expanding the features of their products, the popular features added to the OS of one company will inevitably appear in some form in the OS of its competitors.

Android phones running Android 2.1+ and the iPhone 4G currently share many of the same features (though implemented differently). However, in past versions there were significant differences in what features were available

on each of these platforms. Android phones have supported third party applications from the beginning, but Apple has only been supporting them since the iPhone 3G. Also, the iPhone only recently obtained a multitasking feature, while Android has had one for quite some time. As for interoperability, Android apparently is quite good at working with other devices/services since version 2.0. The iPhone does not work quite so readily with many devices. The services it does work well with are those services that Apple has deemed beneficial for their business.

Not like the devices, the OS variation for different brands and generations is more than random and hard to predict. Despite the phones these OS versions were tested on had different CPU frequencies (the differences were not that large), one can see a clear difference in performance of the OS from one major release to the next. In this case, a major release would be going from a 1.x to a 2.x instead of going from a 1.x to 1.y. Following are the detailed examples on how features change from Android 1.5 to 1.6 and from Android 1.6 to 2.0/2.1.

Features added from Android 1.5 to 1.6:

- An improved Android Market experience
- An integrated camera, camcorder, and gallery interface
- Gallery now enables users to select multiple photos for deletion
- Updated Voice Search, with faster response and deeper integration with native applications, including the ability to dial contacts
- Updated search experience to allow searching bookmarks, history, contacts, and the web from the home screen
- Updated technology support for CDMA/EVDO, 802.1x, VPNs, and a text-to-speech engine
- Support for WVGA screen resolutions
- Speed improvements in searching and camera applications
- Gesture framework and GestureBuilder development tool

Features added from Android 1.6 to 2.0/2.1

- Optimized hardware speed
- Support for more screen sizes and resolutions
- Revamped UI
- New Browser UI and HTML5 support
- New contact lists
- Better white-black ratio for backgrounds
- Improved Google Maps 3.1.2
- Microsoft Exchange support
- Built in flash support for Camera
- Digital Zoom
- MotionEvent class enhanced to track multi-touch events[43]
- Improved virtual keyboard
- Bluetooth 2.1

- Live Wallpapers

## VI. SMARTPHONE APPLICATION DESIGN

To enable running applications in smartphones with high heterogeneity, the knowledge of smartphone evolution can be used to aid designing mobile software. In this section we propose several insights to designing mobile software for sustainable computing.

As mentioned in the previous section, the heterogeneity of smartphones includes both the device heterogeneity and system heterogeneity. The device heterogeneity comes from three different types of causes.

- **Brand Heterogeneity** As we analyzed in the previous section, the device variation among different brands only exists in earlier years when all the companies are starting up developing their new devices. After the technology for smartphones gets more mature, such variation has shown to be largely reduced and become trivial. Some brands might introduce some new features faster than others, but all devices will have the same feature in the next generation. For some of the technologies such as display technology and touch sensitivity, some device can be more advanced than others. However such types of heterogeneity will not affect how users use the device in general. In conclusion, the heterogeneity generated by different brands is not the main issue of designing smartphones for sustainability, and the heterogeneity generated when some devices advance faster than others can be treated the same as generation heterogeneity.
- **Generation Heterogeneity** As shown in the previous section, the heterogeneity across different generations can be substantial. First of all, the computation capability and the resource capacity are both determined by the fabrication technology, hence the evolution of most of the device parameters can be predicted by the Moore's Law. For other components in smartphones such as batteries that can not be based on silicon technology, also have their own methodologies for projection and prediction. The only thing that is non-predictable is the features and sensors added to smartphones. Most of the smartphones are provided with cameras, GPS and compass from the earliest generations, while it is uncertain that whether and what new features and sensors will be added in the future. Even if we know that some specific sensor is going to be added, there is no way to predict how such sensor will interface with devices and applications.
- **Wear-out heterogeneity** Smartphones can degrade quickly, and the processing capability might decrease substantially. Some of the features or sensors might even stop working while being reused. For reusing smartphones in education, one of the distinguished

characteristics of the classroom is that a group of devices will be used at the same time and they essentially form a distributed network infrastructure. To enable running applications on old devices, one interesting solution is to offload computations or sensing needs to neighbor devices through WiFi or Bluetooth. It is also worth noting that even the WiFi capability which is required by most of the applications, can also be offloaded to other devices through Bluetooth. In such a way, reused smartphones could support a much wider range of applications by collaborating with each other. Our future work seeks to provide a mobile application design framework that supports such distributed collaboration.

On the other hand, system heterogeneity is generally random and can not be taken any advantage of. Fortunately, approaches already exist to support running applications on different platforms by using virtual machines. Applications can automatically take advantage of the system improvement without any modification on applications but only the virtual machines need to be updated.

## VII. DISCUSSION

In our previous study, we outlined several challenges that software developers are facing in order to effectively use recycled devices, including the high heterogeneity of different models of devices and significantly degraded reliability.

To address the challenges above, we propose and discuss several possible solutions.

- **Common virtual platforms to support portability across heterogeneous devices**  
To support applications to run seamlessly on devices with different architecture and configurations, virtual platforms similar to Java virtual machines or even browser-based OS can be exploited, of course with special extensions and adaptations to handle issues that are more unique to recycled, old devices, such as drastically reduced memory sizes and old interfaces. Applications could be distributed via bytecodes that would then be executed on such virtual platforms.
- **Acceptable computing via component service level requirements (SLRs) or acceptance tests**  
As some devices may not be fully configured or may run slowly, it is hard to support all functionalities in some applications. To allow applications running on such partially configured devices, it would be beneficial if software components could be decoupled based on functionalities and importance. Each component would provide a service level requirement for configurations and performance. Furthermore, manufacturers could provide an acceptable test suite to run on each device to measure the level of acceptability. They may also need to identify critical components and specify inter-component dependencies. Of course, it is also possible

to infer such independencies automatically through in-house profiling. All these information would be used to dynamically select devices and match application functionalities to devices.

- **Application-level auto-adaptation**

Since different devices may have different types of configurations (screen sizes, memory sizes, etc), applications need to do certain (hopefully automatic) adaptation based on each device. For example, some documents can appear differently depending on whether it is shown on a desktop or a smart phone. Similarly, some communication protocols, policies and optimizations can be disabled/enabled or adapted based on the underlying device's capabilities.

- **Coordinated computation**

Besides the above methods, we can also selectively migrate certain functionalities to other neighboring devices to jointly support the target application. For example, functions requiring intensive computation can be migrated from older, slower devices to newer, faster ones or even desktops/notebooks/netbooks nearby. Applications requiring cameras/video-recorders can run on a device without such capability by leveraging neighboring devices with such capability. Such coordination could be dynamically adaptive to the spatial environment just like in ubiquitous computing. To decide which computation to migrate and its destination, the run-time system needs to consider components' SLRs and each device's configuration, capable "services" and current loads.

- **Error detection and recovery in the core design of run-time systems and applications**

To handle significantly degraded reliability in many old devices, intensive error detection and recovery mechanisms need to be built into the run-time systems or applications. For example, some invariant-based error detection can be enabled for early error detection. Similarly, redundancy (running a shadow copy in another device) could also be used to detect and recover from errors. In most usage scenarios, applications need to be designed in a way with full expectation for errors and need to provide mechanisms to tolerate or recover in case of errors. In other words, reliability should be a major part of the core design instead of an after-thought like how existing applications/systems are designed today.

## VIII. CONCLUSION

Our society faces a severe environmental challenge posed by the rapid advance of Moores Law technology scaling and the equally rapid proliferation of computing devices in the world. Our solution to this problem is to reuse obsolete devices for new applications that can be satisfied with older, less reliable technology. The key challenge in this approach,

however, is the design of software that can adapt to extreme heterogeneity of devices.

Our previous work has shown that although different components in smartphones degrade from use, their functionalities, available resources and power supplies are still able to satisfy the requirement of educational applications. In this paper, we explore different types of heterogeneities among smartphones from different brands and different generations. We then discuss potential solutions to address the challenges that software developers need to consider to effectively use recycled devices. Our future work seeks to propose more concrete design details and implementations.

## REFERENCES

- [1] Modeling mobility for vehicular ad hoc networks. In *Proc. of VANET*.
- [2] Cleverly simple. *The Economist*, October 2009.
- [3] A case for smartphone reuse to augment elementary school education. *The Work in Progress in Green Computing (WIPGC)*, 2010.
- [4] Gordon Bell.
- [5] Byung-Gon Chun and Petros Maniatis. Augmented smartphone applications through clone cloud execution, 2009.
- [6] T. ElBatt, S. Goel, G. Holland, H. Krishnan, and J. Parikh. Cooperative collision warning using dedicated short range wireless communications. In *Proc. of VANET*, 2006.
- [7] R Geyer, J Oliver, R Amirtarajah, V Akella, and FT Chong. Life cycle aware computing: Reusing silicon technology. *IEEE Computer*, 40(12):56–61, 2007.
- [8] Nokia. Life cycle thinking. <http://www.nokia.com/environment/we-create/creating-our-products/life-cycle-thinking>.
- [9] Nokia. Integrated product policy pilot project, stage i final report: Life cycle environmental issues of mobile phones, 2005.
- [10] Alex Shye, Benjamin Scholbrock, and Gokhan Memik. Into the wild: Studying real user activity patterns to guide power optimizations for mobile architectures. In *Proceedings of the International Symposium on Microarchitecture (MICRO 2009)*, December 2009.
- [11] U.S. Department of Energy. Transportation energy data book, 2009.
- [12] Galit Zadok and Riikka Puustinen. The green switch: Designing for sustainability in mobile computing. In *The First USENIX Workshop on Sustainable Information Technology*, February 2010.