A Thesis

entitled

Optimizing Android Memory Management by Predicting User Behavior

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Masters of Science Degree in Engineering

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An Abstract of

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With the advent of increase in the amount of RAM available in Android smart-phones, there is a case to be made that this additional memory availability can be put to better use. By default, every Android application runs in its own Linux process. Android starts the process when any of the application's components need to be executed, then shuts down the process when it's no longer needed or when the system must recover memory for other applications. When a smart-phone that runs on the Android operating system is active (turned on), the RAM contains all the active processes and services (processes that run in the background). In addition to these processes and services, the RAM also contains cached background processes. These processes are kept in memory so that in the event the user clicks any of these applications, they can be loaded onto the screen quickly as they're already in memory and don't have to be fetched from the disk. If Android needs to reclaim memory for other processes, it eliminates cached background processes through an LRU scheme. Ideally we would like every application the user clicked to be present in memory but due to constraints in RAM availability, Android employs the LRU scheme to decide which processes to retain. I postulate that looking into user behavior could help us better determine which applications to cache in memory, as cached background processes. I parse the user's Calendar for contextual clues and gather information

that could help me predict which application a user is about to use. I measure the cache efficiency (Cache hits and misses, CHR) for the default CRA Android employs (LRU), a pure prediction based CRA and finally a hybrid approach that combines the LRU approach with the prediction approach. I also demonstrate why the hybrid CRA is the most efficient one.

To my parents who've always put my needs ahead of theirs.

Acknowledgments

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I'd like to thank all my friends and family for supporting me throughout my time here at UT but I'd like to especially mention Sandy Stewart for everything she's done for me. This page is'nt enough to expound on the details but it suffices to say I would'nt be here without her and she is like a second mother to me.

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List of Abbreviations

RAM	Random Access Memory
LRU	Least Recently Used
CHR	Cache Hit Ratio
CRA	Cache Replacement Algorithm
OS	Operating System
AOSP	Android Open Source Project
APK	Android Package
IPC	Inter Process Communication
IC	Integrated Circuits
MB	Mega-Byte
GB	Giga-Byte
APC	Android Process Cache

List of Symbols

‡ ..... the degree to which the flayrod has gone out of skew on tredel
△ ..... the ratio of the M2 monetary aggregate to the Monetary Base

α ..... angle of rotation around internal rotation axis
β ..... the number of people named "Bob"

Q ..... Tobin's q; the ratio of the market value of installed capital to the replacement cost of capital
Y ..... Gross Domestic Product (adjusted for inflation)

Preface

This thesis is original, unpublished, independent work by the author, Srinivas Muthu under the tutelage of Dr. Jackson Carvalho.

Chapter 1

Introduction

1.1 Android Operating System

1.1.1 Overview of the Android OS

Android is a mobile OS (Operating System) based on the Linux kernel and designed primarily for touchscreen devices such as smart-phones and tablets [1]. In addition to touchscreen devices, Android TV, Android Auto and Android Wear are emerging technologies with specialized user interfaces. Globally, it is the most popular mobile OS [2]. Android has an active community of developers and enthusiasts who use the AOSP (Android Open Source Project) source code to develop and distribute their own modified versions of the operating system [4]. Android homescreens are typically made up of app icons and widgets. App icons launch the associated app, whereas widgets display live, auto-updating content such as the weather forecast, the user's email inbox, or a news ticker directly on the homescreen [5].

Internally, Android OS is built on top of a Linux kernel. On top of the Linux kernel, there are the middleware, libraries and APIs written in C and application software running on an application framework. Development of the Linux kernel continues independently of other Android's source code bases.

Figure 1-1: [3] Android System Architecture

1.1.2 Applications, Activities and Services

1.1.2.1 Applications

Android apps are written in the Java programming language. The Android SDK tools compiles the code, along with any data and resource files into an APK (Android Package), which is an archive file with an .apk suffix. One APK file contains all the contents of an Android app and is the file that Android-powered devices use to install the app [6]. The Android operating system is a multi-user Linux system in which each app is a different user. Each process has its own virtual machine (VM), so an app's code runs in isolation from other apps. By default, every app runs in its own Linux process.

1.1.2.2 Activities

An Activity is an application component that provides a screen with which users can interact in order to do something, such as dial the phone, take a photo, send an email, or view a map [7]. An application usually consists of multiple activities that are loosely bound to each other. Typically, one activity in an application is specified as the main activity, which is presented to the user when launching the application for the first time. Each activity can then start another activity in order to perform different actions.

1.1.3 Services

A Service is an application component that can perform long-running operations in the background and does not provide a user interface [8]. Another application component can start a service and it will continue to run in the background even if the user switches to another application. Additionally, a component can bind to a service to interact with it and even perform IPC (Inter Process Communication). For example, a service might handle network transactions, play music, perform file I/O, or interact with a content provider, all from the background.

1.2 Growth of available RAM over the years

1.2.1 Advances in Technology

RAM (Random Access memory) is a form of computer data storage. A RAM device allows data items to be accessed (read or written) in almost the same amount of time irrespective of the physical location of data inside the memory. The overall goal of using a RAM device is to obtain the highest possible average access performance while minimizing the total cost of the entire memory system. Today, random-access

memory takes the form of IC (Integrated Circuits)(s).

1.2.1.1 Moore's Law

Moore's law is the observation that the number of transistors in a dense IC doubles approximately every two years.

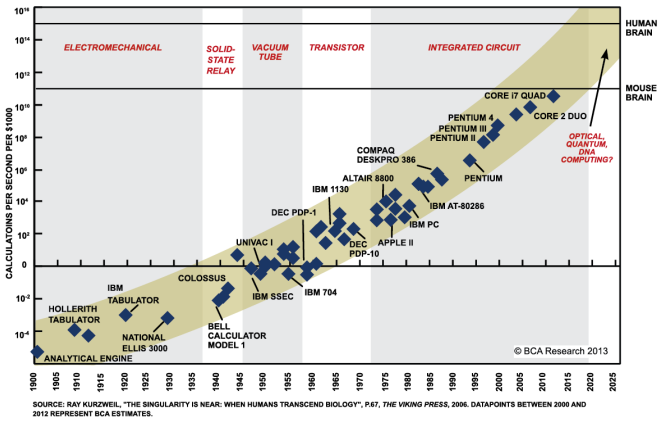

Figure 1-2: [9] Moore's Law

Advancements in digital electronics are strongly linked to Moore's law, especially in the context of memory capacity. T-Mobile G1, the very first Android smart-phone to be released back in 2008 [10] has a 256 MB (Mega-Byte) RAM [11]. In comparison, the Nexus 6P that was released in September 2015 has a 3 GB (Giga-Byte) RAM and some devices like the LG T585 have a 16 GB RAM [12][13], which amounts to 64 times the memory capacity of the T-Mobile G1. The rapid growth in the amount of RAM available to Android devices has in part led to newer possibilities and in our case, a better CRA (Cache Replacement Algorithm) for determining which processes (in the context of Android applications) remain in memory.

1.2.2 Demise of Task Killers

One of the main benefits of the Android OS is the fact that unlike certain other OS(s), it can run apps in the background. This enables us to have multiple applications open at the same time which results in true multitasking. Thus, RAM availability is highly desirable [14]. A popular misconception is that forcibly removing applications from memory in order to 'free up RAM' will result in increased performance. In fact, several task-killer applications promise to do precisely that. With the advancement in the amount of RAM available, the debate should be about how to better use all this extra space, not killing applications to 'free up' more space. In fact, the Android OS can go one step further and pro-actively cache applications that the user might use in the near future. We'll analyze this prospect in more detail in the upcoming chapters.

1.3 How Android Manages Processes

1.3.1 Android Process Lifecycle

A Android process can be in one of five different states at any given time, from most important to least important [15]:

- Foreground process: A foreground process is one that is required for what the user is currently doing.
- Visible process: A visible process is one holding an Activity that is visible to the user on-screen but not in the foreground.
- Service Process: Service processes are not directly visible to the user, they are generally doing things that the user cares about (such as playing music in the background).

- Background process: A background process is one holding an Activity that is not currently visible to the user. They are kept in an LRU (Least Recently Used) list to ensure the process that was most recently seen by the user is the last to be killed when running low on memory.

- Empty process: An empty process is one that doesn't hold any active application components. The only reason to keep such a process around is as a cache to improve startup time the next time a component of its application needs to run.

Every Android smart-phone user is capable of checking the processes that currently reside in physical memory. The Application Manager which is part of the Settings app shows a list of running processes and cached background processes. Additionally, it breaks down the composition of RAM usage by the System applications and user installed applications.

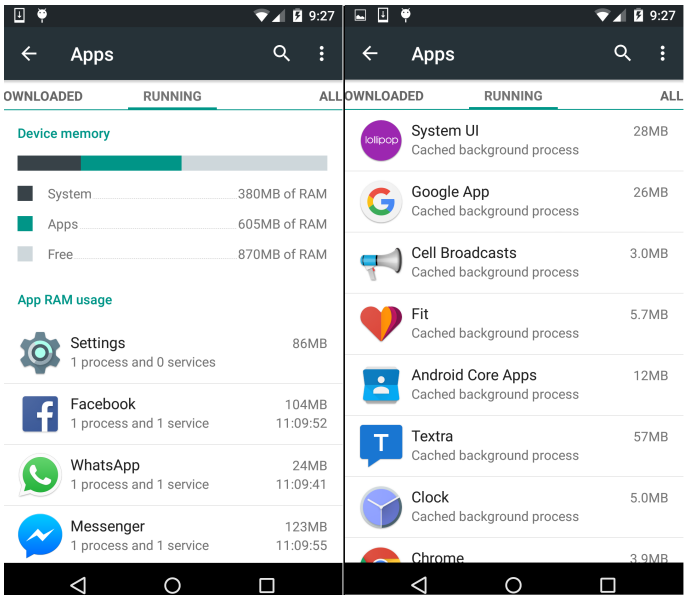

Figure 1-3: Left - List of Running Applications (Active Processes and Services)
Right - List of Cached Background Processes

1.3.2 LRU Cache

LRU is a CRA that discards the least recently used items first. This algorithm requires keeping track of what was used when, which is expensive if one wants to make sure the algorithm always discards the least recently used item [17]. Android keeps processes that are not hosting a foreground app component in a LRU cache. As the system runs low on memory, it may kill processes in the LRU cache beginning with the process least recently used, but also giving some consideration toward which processes are most memory intensive [16].

1.4 Goals and Objectives

1.4.1 A User-Centric CRA

The main benefit of caching processes (components of applications recently clicked by the user) in memory is to improve startup time (of the application), the next time a component of the application needs to run. This greatly enhances the usability experience and therefore it's in Android's best interests to increase the efficiency of this cache i.e. improve its CHR (Cache Hit Ratio). In addition to recency of application usage (which is what Android currently relies on in the form of LRU as a CRA), there is scope to potentially infer what application a user may click in the near future. A more user-centric CRA could look into contextual clues and deduce patterns in user behavior to better the decision making involved in determining which applications to cache in memory.

We will explore in theoretical detail many such possibilities for user behavior inference and as a proof of concept, read the user's Calendar application and parse for contextual information that could help in improving the CHR of the APC (Android Process Cache).

1.5 Organization of Thesis

Several works in the past have focused on context-aware applications and ways to observe user behavior patterns. We'll explore some these works and how this contextual data was put to use in Section 2. In Section 3, we'll take a look at some of the challenges in collecting cache metrics like detecting what's in the RAM, detecting when the user clicks a new application, whether to approach the problem at the user level or the system level, to list a few. Section 4 elaborates on the setup of the experiment and analyzes the design of the applications used to collect these metrics. We dive into the data in Section 5 and summarize its ramifications. We also investigate how certain factors could explain the variation in data. Section 6 talks about scope for future work and explores some of the possibilities of directly adding to this work. We conclude the thesis with Section 7.

Chapter 2

Related Work

2.1 Context Patterns in Application Usage

Several works have attempted to collect user behavior data and they've accomplished this in unique ways. Hannu Verkasalo, in his 2007 paper titled *Contextual Patterns in Mobile Service Usage* analyzes how mobile services are used in different contexts [18]. Usage contexts were divided into *home, office* and *on the move*. A specialized algorithm tracked user's location patterns over a period of time to determine whether the user was at home or at work. Furthermore, changes in location data revealed whether the user was in transit between home and work. There was a correlation between the mobile services requested by the user and the user's physical location, which enabled the algorithm to understand the user's context quite well. It was also observed that certain services were requested more during the weekends as opposed to certain others being requested more during the weekdays i.e. days with office hours.

2.2 Context Phone

Mika Raento, Antti Oulasvirta, Renaud Petit, and Hannu Toivonen, in their paper titled *ContextPhone: A Prototyping Platform for Context-Aware Mobile Applications*

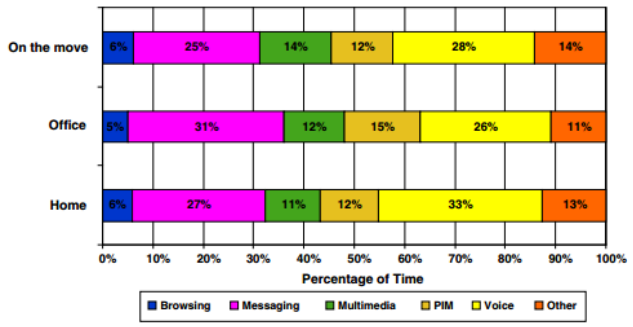

Figure 2-1: By classifying user context into three distinct entities namely *home, work* and *on the move*, the author managed to infer which services were requested more in a given context. For e.g. Voice services i.e. calling was predominantly requested while the user was at home. This type of information can be very useful.

proposed that mobile phones are well suited for context aware computing due to an intimate relationship between the user and the phone [19].

Chapter 3

Challenges in Collecting the Desired Metrics

3.1 What are the desired metrics?

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