Platform Ecosystem: ARM’s answer to Intel’s dominance

by
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SDM Thesis
Platform Ecosystem: ARM’s Answer to Intel’s Dominance

Abstract
The personal computing industry has witnessed significant changes with more users moving from desktop PCs to battery-operated mobile devices. These dynamics have prompted chip-design companies to evaluate ways to lower the power consumption of devices, thereby elongating battery life. With its lower power microprocessor-core architecture, a newer and smaller company, ARM Holdings, has been able to challenge the much bigger incumbent Intel and capture significant market share by creating a powerful ecosystem based on strategic partnerships.

This thesis will evaluate how ARM’s ‘design and license’ business model based on a platform ecosystem-partnerships with Original Equipment Manufacturers (OEMs), semiconductor companies, and software developers, has been able to counter Intel’s vertically-integrated business model. This thesis will discuss the details of underlying technologies - Intel’s high speed vs. ARM’s low power architectures, and further evaluate how ARM gives its partners more customizing power and the ability to differentiate its products with respect to competitors that also use the ARM architecture.

Thesis Supervisor
Prof. Michael A. Cusumano
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Chapter 1 Introduction

1.1 Motivation

In the age when the PC market is shrinking and users are rapidly switching to smartphone and tablet devices, there has been a significant change in the industry dynamics. A powerful ecosystem has developed around the devices, especially of new operating systems and software applications.

ARM Holdings has become a first mover in this space with the key enabler being its low power ARM core architecture. This architecture, being entirely different from Intel’s x86 core, has reaped substantial first mover advantages, especially with ARM’s ‘design and license’ business model. Hugely popular operating systems such as the Android and the more recent, Windows RT have been designed especially for ARM architectures.

Will the $53B giant Intel, with its long-time partner Windows, years of research in new technologies and newly minted Atom processor, be able to counter the ‘open’ platform ecosystem that $900M ARM has created?

1.2 Thesis Statement & Primary Research Objectives

ARM, through its ‘design and license’ business model, has been able to create a revenue stream based on licensing and royalties for its processor design architecture. It has also managed to create a unique network wherein its partnerships with multiple OEMs (e.g. Nokia, Apple and Samsung), semiconductor companies (e.g. TI, ST) and software developers have enabled it to ‘pull’ demand for new products and ‘push’ to semiconductor companies designs that satisfy the
demand. In contrast to Intel’s proprietary business model of selling physical chips, ARM’s distinctive partnership model enables it to create ‘reference’ designs for and transfer crucial information to OEMs/semiconductor companies, which can then highly customize the design by adding company-specific and demand-focused layers, thereby differentiating w.r.t. competitors while using the same underlying ARM architecture.

This thesis will focus on Intel and ARM’s business strategies. More specifically:

- Assess how ARM enables its unique business/partnership model.
- The industry they are competing in
- The evaluation of the differences in their platform ecosystems and its relevance to today’s industry
- Intel and ARM’s partners and their industry dominance.
- Evaluate how ARM gives its partners more customizing power and the ability to differentiate its products w.r.t. competitors’ that also use ARM architecture
- The underlying technologies and evaluation of their disruptiveness- Intel’s high speed vs. ARM’s low power architectures. Future- Intel’s claim of catching up on low power vs. ARM’s ability to increase core speed
1.3 **Summary of Chapters**

Chapter 2 will define a microprocessor and explore its applications and market trends. Various players in this segment will be discussed, with focus on Intel and ARM. A brief description of these companies will be subsequently presented.

Chapter 3 will compare the Intel's x86 CISC architecture and ARM's latest RISC based core, focusing mainly on the power consumption. Two levels of hierarchy will be considered for the comparison, Central Processing Unit (CPU) and System on Chip (SoC) and various methods to optimize power will also be discussed.

Chapter 4 will begin with a short description of the business models of Intel and ARM. It will eventually dive deep into the ARM ecosystem-its partnership with various players in the semiconductor industry: Semiconductor companies, Foundry, Electronic Design Automation (EDA) vendors and Software Developers (OS and Apps). Finally, this chapter will explore the ARM licensing model in detail and look at how Apple benefits from this model.

Chapter 5 will look into the future trends of the microprocessor industry from the perspective of Intel and ARM. New avenues to generate extra revenue streams, be it new growth markets or a modified business model of leasing Intel's foundry and new technology trends such as 3-D transistors will be discussed.

Chapter 6 will summarize and conclude the thesis.
Chapter 2  Analysis of the Mobile Microprocessor Segment

2.1 What is a microprocessor?

A microprocessor is also known as the Central Processing Unit (CPU) of all computers and other electronics items\(^1\). It is a programmable device that accepts digital data as input, processes it according to instructions stored in its memory, and provides results as output. Microprocessors process numbers and symbols in the binary numeral system and outputs data in the same binary format. The modern day microprocessor unit is contained in an Integrated Circuit (IC).

General purpose microprocessors are used for computation, text editing, multimedia display, and communication over the Internet. Many more microprocessors are part of embedded systems, providing digital control over myriad objects from appliances to automobiles to cellular phones and industrial process control.

The first microprocessor was introduced by Intel in 1971, which had a 4-bit computing architecture. Evolution of its design led to 8-bit, 12-bit, 16-bit, 32-bit and 64-bit architectures.

\(^1\) What is a Microprocessor? [Intel]
http://download.intel.com/newsroom/kits/40thanniversary/pdfs/What_is_a_Microprocessor.pdf
Today, multi-core processors, which use parallel computing to harness the power of several cores, are widely used. Dual-core and quad-core processors are widely used in home PCs and laptops while quad, six, eight, ten, twelve, and sixteen-core processors are common in the professional and enterprise markets with workstations and servers\(^2\).

### 2.2 Microprocessor Market

![Image 2013 MPU Sales by Applications (Fct, $65.38)](image)

*Figure 1 Microprocessor Sales (2013) Source: IC Insights*

![Image Microprocessor Revenue ($US Billion) Forecast (2003-2017)](image)

*Figure 2 Microprocessor Revenue ($US Billion) Forecast (2003-2017) Source: ITCandor, 2012*

\(^2\) Microprocessor [Wikipedia, December 2013]

[http://en.wikipedia.org/wiki/Microprocessor#64-bit_designs_in_personal_computers](http://en.wikipedia.org/wiki/Microprocessor#64-bit_designs_in_personal_computers)
The microprocessor market is expanding fast. As figures 1 and 2 imply, this growth is mainly driven by the expansion of the mobile devices, server markets and the already penetrated PC market. IC Insights\(^3\) expects the market for tablet processors to rise 54 percent to $3.5 billion this year. The market for cellphone application processors will grow 30 percent to $16.1 billion. This market mainly consists of mobile devices (smartphones, tablets), embedded Main Processing Units (eMPU), PCs and servers. Figure 2 shows the trends and forecast of the various market segments. The PC market, though generating the highest revenues, is declining fast and the mobile devices market, which is still nascent, is growing at a rapid rate.

\textit{Table 1 Worldwide Device Shipments by Segment (Source: Gartner\(^4\))}

<table>
<thead>
<tr>
<th>Application</th>
<th>Sales (#million units)</th>
<th>Annual Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year 2012</td>
<td>Year 2013 (projected)</td>
</tr>
<tr>
<td>Smartphone</td>
<td>600</td>
<td>900</td>
</tr>
<tr>
<td>PC (Desk based and Notebook)</td>
<td>341</td>
<td>303</td>
</tr>
<tr>
<td>Tablet</td>
<td>120</td>
<td>184</td>
</tr>
<tr>
<td>Mobile Phone (including smartphone)</td>
<td>1746</td>
<td>1810</td>
</tr>
<tr>
<td>Feature phone</td>
<td>1080</td>
<td>840</td>
</tr>
</tbody>
</table>

Table 1 shows the growth and decline of the mobile devices segment, in terms of the number of units sold annually. As expected, the sales of smartphones and tablets dominate this segment. Due to its increasing affordability and more value, smartphones are rapidly replacing feature phones. It accounted for more than 55% of the total mobile shipments\(^5\). Tablet processor shipments are expected to grow 62 percent to more than 300 million units and cellphone application processor shipments increasing 11 percent to 1.5 billion units. Mobile

\(^3\) Report Contents and Summaries [IC Insights] \url{http://www.icinsights.com/services/mcclean-report/report-contents/#10}

\(^4\) Gartner Says Worldwide PC, Tablet and Mobile Phone Shipments to Grow 4.5% in 2013 as Lower Priced Devices Drive Growth [Gartner] Oct 2013 \url{http://www.gartner.com/newsroom/id/2610015}

\(^5\) Gartner Says Smartphone Sales Accounted for 55 Percent of Overall Mobile Phone Sales in Third Quarter of 2013 [Gartner] Nov 2013 \url{http://www.gartner.com/newsroom/id/2623415}
processors are becoming more significant in an expanding microprocessor market, because the traditional PC market is in the doldrums\(^6\).

2.3 Players in this segment

There are several big players in the segment that cater to the end applications market. As shown in Figure 3, apart from Intel, Qualcomm, Samsung and AMD lead the pack with a combined market share of 24% (as of 2012). However, Intel is way ahead of the rest with 65% market share.

<table>
<thead>
<tr>
<th>2012 Rank</th>
<th>Company</th>
<th>2011</th>
<th>2012</th>
<th>Percent Change</th>
<th>Percent Market Share</th>
<th>Main Product Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Intel</td>
<td>37,435</td>
<td>36,892</td>
<td>-1%</td>
<td>65.3%</td>
<td>x86 PC, server MPUs</td>
</tr>
<tr>
<td>2</td>
<td>Qualcomm</td>
<td>4,152</td>
<td>5,322</td>
<td>28%</td>
<td>9.4%</td>
<td>ARM mobile app processors</td>
</tr>
<tr>
<td>3</td>
<td>Samsung (+Apple)*</td>
<td>2,614</td>
<td>4,664</td>
<td>78%</td>
<td>8.2%</td>
<td>ARM mobile app processors</td>
</tr>
<tr>
<td>4</td>
<td>AMD</td>
<td>4,552</td>
<td>3,605</td>
<td>-21%</td>
<td>6.4%</td>
<td>x86 PC, server MPUs</td>
</tr>
<tr>
<td>5</td>
<td>Freescale</td>
<td>1,210</td>
<td>1,070</td>
<td>-12%</td>
<td>1.9%</td>
<td>ARM and embedded MPUs</td>
</tr>
<tr>
<td>6</td>
<td>Nvidia</td>
<td>591</td>
<td>764</td>
<td>29%</td>
<td>1.4%</td>
<td>ARM mobile app processors</td>
</tr>
<tr>
<td>7</td>
<td>TI</td>
<td>510</td>
<td>565</td>
<td>11%</td>
<td>1.0%</td>
<td>ARM mobile app processors</td>
</tr>
<tr>
<td>8</td>
<td>ST-Éricsson**</td>
<td>660</td>
<td>540</td>
<td>-18%</td>
<td>1.0%</td>
<td>ARM mobile app processors</td>
</tr>
<tr>
<td>9</td>
<td>Broadcom</td>
<td>295</td>
<td>345</td>
<td>17%</td>
<td>0.6%</td>
<td>ARM mobile app processors</td>
</tr>
<tr>
<td>10</td>
<td>MediaTek</td>
<td>280</td>
<td>325</td>
<td>16%</td>
<td>0.6%</td>
<td>ARM mobile app processors</td>
</tr>
</tbody>
</table>

sales have been on a decline with the advent of substitutes like tablets and smartphones, it has impacted the company’s growth rate.\(^7\)

Intel has a wide range of products catered to different target market segments. Its CORE series (i3, i5 and i7) is catered towards PCs (desktops and laptops). The Intel Atom is Intel’s line of low-power, low-cost and low-performance x86 and x86-64 microprocessors, geared towards the mobile devices market. The Xeon is a brand of multiprocessing or multi-socket-capable x86 microprocessors from Intel Corporation targeted at the non-consumer workstation, server, and embedded system markets.\(^8\)

As seen in Figure 3, ARM Holdings Inc. does not appear in the rankings because it does not sell its own chips but designs and licenses its architectures to semiconductor companies. Its architecture’s value can be judged by the fact that it is the basis for processor chip designs of 8 of the top 10 microprocessor suppliers. Its largest business is designing and licensing processors as intellectual properties (IP), targeted to the application segment of processors for mobile phones (smartphones or otherwise) and tablets.

ARM architectures, adopted by processor system-on-chip companies, are used in all classes of computing devices from microcontrollers in embedded systems to smartphones (Apple’s iPhones), tablets (Apple’s iPads), laptops (some Chromebook versions), desktops, servers and supercomputers/HPC.

http://www.forbes.com/sites/greatspeculations/2013/03/06/whats-impacting-intels-notebook-processor-market-share/

ARM's main competitors in GPU or processor businesses include Imagination Technologies, Nvidia (for mobile GPUs, but customer for processors) and increasingly Intel\(^9\).

Chapter 3 Technology

3.1 ARM’s low power architecture strategy vs. Intel’s

ARM’s competitive advantage is its low power architecture. It is due to its low power design that ARM has been able to become a favorite in the mobile devices space (tablets, smart phones), which uses battery as its main power source. The time for a battery to drain off depends on the power consumption when applications such as 3G/4G, Bluetooth, video, apps and actual calls are used (dynamic power consumption), when the phone is in standby/idle and when the phone is switched off (leakage power consumption). It is believed that ARM’s processor architecture inherently implies low dynamic power consumption, leading to a long lasting battery.

*How does ARM achieve low power?*

To answer this question, we will look at two levels of hierarchy- Central Processing Unit (CPU) and System on Chip (SoC)

**CPU**

*Instruction Set Architecture (ISA)*

The two most popular ISAs are Reduced Instruction Set Computers (RISC) and Complex Instruction Set Computers (CISC). ARM uses RISC, while a majority of other companies such as Intel (x86) and AMD use CISC.
In early computers, memory was expensive, so minimizing the size of a program to make sure it would fit in the limited memory was often central. Thus the combined size of all the instructions needed to perform a particular task, the code density, was an important characteristic of any instruction set. Computers with high code density often have complex instructions for procedure entry, parameterized returns, loops etc.; therefore retroactively named Complex Instruction Set Computers.

Reduced instruction-set computers, RISC, were first widely implemented during a period of rapidly growing memory subsystems. These instruction-sets sacrifice code density in order to simplify implementation circuitry and thereby try to increase performance via higher clock frequencies and more registers. RISC instructions typically perform only a single operation, such as an "add" of registers or a "load" from a memory location into a register; they also normally use a fixed instruction width, whereas a typical CISC instruction set has many instructions shorter than this fixed length. Fixed-width instructions are less complicated to handle than variable-width instructions.²⁰

It is widely studied and published that RISC, due to its simple instruction set, consumes much less power than CISC. As RISC instruction sizes are fixed, fetching is simpler and both op-code and operand can be simultaneously accessed (because they are in a known memory position), thus simplifying the design of the control unit and requiring less power.²¹ CISC has a variable-length instruction set and complex addressing modes, making it difficult for fetching and

---

decoding operations. Moreover, due to x86's legacy, it uses just 25% of the available instruction set frequently\textsuperscript{12}.

However, pure RISC or CISC architectures are rarely used today. The gap between these architectures has narrowed significantly because, to achieve better performance and power, each of them has adopted features from the other. Typical CISC and RISC systems use out-of-order and in-order execution respectively, but the Atom processor uses in-order execution\textsuperscript{13}. Modern day x86 processors can operate on instructions out of program order. Processors that are capable of out of order execution can, instead of waiting for the data that is not available in its caches, execute other instructions that are ready while waiting for the required data to be fetched from memory. Although this instruction reordering in out of order processors speeds up the CPU, it also increases power consumption. The x86 Atom is Intel's in-order CPU, incapable of executing instructions out of program order\textsuperscript{14}.

A CISC processor takes instructions called micro-codes while a translator unit receives CISC commands and converts them into micro-codes, which are similar to RISC instructions, making them hybrid RISC/CISC architectures.

These trends points out that today, the power consumption figures should not be very different for latest ARM (such as cortex A9) and Intel (such as Atom) architectures. Blem et al\textsuperscript{15} prove that power consumption is independent of the underlying instruction sets. They show, through

\textsuperscript{12} T. Jamil, RISC versus CISC: why less is more, IEEE Potentials 14 (1995) 13–16
\textsuperscript{15} Blem et al, Power Struggles: Revisiting the RISC vs. CISC Debate on Contemporary ARM and x86 Architectures, 19th IEEE International Symposium on High Performance Computer Architecture (HPCA 2013)
experiments conducted on ARM Cortex A9/A8 and Intel Atom, that ‘so-called’ RISC and CISC architectures have similar power figures (see Figure 4). They conclude that ISA evolution has focused on specialization, not on the philosophies of RISC or CISC.

![Figure 4 Technology and Frequency Independent Power Normalized to A8](source: Blem et al)

**System on Chip (SoC)**

ARM provides Intellectual Properties to semiconductor companies, whereas Intel provides complete chips. ARM provides design licenses to SoC design companies and it is up to them to take full advantage of the flexibility of custom-building its system around the ARM core. The following lists some of the power saving techniques that have been used by ARM's licensee systems such as TI's OMAP and NVIDIA's TEGRA SoCs\(^\text{16}\).

\(^{16}\) Wei Wang, Tanima Dey, A Survey on ARM Cortex A Processors [Univ. of Virginia]
1. **Power Gating**

   Power gating is a technique used in integrated circuit design to reduce power consumption, by shutting off the flow of current to blocks of the circuit that are not currently in use.

2. **Clock Gating**

   Clock gating is a popular technique used in many synchronous circuits for reducing dynamic power dissipation. Pruning the clock disables portions of the circuitry so that the flip-flops in them do not have to switch states. Switching states consumes power. When not being switched, the switching power consumption goes to zero, and only leakage currents are incurred.

3. **Dynamic voltage and frequency scaling (DVFS)**

   DVFS, a power management technique in computer architecture, where the voltage used in a component or the frequency of the microprocessor is increased or decreased, depending upon the circumstances.

4. **Multiple Threshold-Voltage ($V_T$) transistors**

   High $V_T$ transistors consume lower power but work at relatively lower frequencies, whereas low $V_T$ transistors work at high speed but consume higher power. Power consumption of an SoC can be optimized by placing these transistors according to their frequencies of operation.

5. **Different modes of operation**
These SoCs operate at four different modes: Run, Standby, Dormant, Shutdown. To save power, for instance, a sub-system can be put into standby/dormant state it is not required to work or when idling.

6. Application specific SoC design

ARM gives SoC designers the flexibility to design their system according to their needs, optimizing the chip’s power/performance parameters in accordance with its application.

TI’s OMAP has full-chip retention/OFF in idle and suspend modes of operation. It also has, among other features, state-of-the-art power management features such as DVFS, Adaptive Voltage Scaling (AVS), Dynamic Power Switching (DPS), Power Gating and Clock Gating.

Intel Atom processors also have power gating, clock gating and a basic DVFS solution.

One of the best examples of ARM providing the flexibility to design a low-power chip comes from a start-up in Austin, Texas, called Calxeda. The fabless firm ships chips for servers based on 32-bit ARM mobile processor designs. The dual core processor consumes about 1.5 watts of power, less than a tenth as much as a comparable Intel Xeon chip. The energy savings comes not from the capability of the ARM cores, but from the integration of cores, cache, and sophisticated network switches onto a single chip. Designing such system-on-a-chip (SoC) cuts

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17 Power-Management Techniques for OMAP35X Application Processors- White Paper
down the power consumed by data lines in the computer and makes it easier to implement power management techniques\(^{18}\).

3.2 Key Findings

1. In CPU designs, the boundary between RISC and CISC has become blurred. Each instruction-set uses several features of the other. In such a circumstance, empirical evidence shows that Intel’s Atom (x86, CISC) and ARM’s Cortex A9 (RISC) have similar performance and power consumption figures.

2. If the underlying ISA is irrelevant to making a low power design, it all boils down to the design and optimization of the SoC.

3. Intel designs SoC in-house, optimizing for performance, power and energy. Whereas, ARM, being an IP provider, provides the flexibility and choice to its licensees to optimize for power, performance or ‘performance per watt’. This flexibility on customization of its IP from the perspective of its licensee’s SoC gives ARM has an upper-hand in becoming a part of a customer-focused improved system.

\(^{18}\) The Battle Between ARM and Intel Gets Real [IEEE Spectrum] April 2012
Chapter 4  Ecosystem

4.1  Business Models

4.1.1  ARM Holdings

ARM operates as a fabless semiconductor firm. To reduce manufacturing setup and operating costs, some semiconductor companies (called fabless) create all of the designs for their chips, but physically manufacture them at a foundry (e.g. TSMC, Global Foundries, Samsung). However, ARM goes beyond the fabless model by designing IP (instruction set architecture, microprocessor, graphics, interconnects) and licensing it to anyone who wants to use it, called

\[\text{http://www.arm.com/annualreport10/download-centre/PDF/ARM%20AR%202020%2020vision.pdf}\]
Partners. ARM's Partners will then take the IP they've licensed and design it into silicon. These Partners pay ARM a license fee for the original IP and a royalty on every chip or wafer produced.

4.1.2 Intel

Intel has, throughout its history, invested in building a vertically integrated business (Figure 6). It has its own design units and state-of-the-art manufacturing facilities and controls the assembly, packaging and distribution of chips. These microprocessor chips are used by Original Equipment Manufacturers (OEM) such Dell and HP as the CPU. Not surprisingly, a significant source of its revenue comes from the PC Client market of Notebooks and Desktops (Figure 7). Intel's partnership with Microsoft (Windows) has, historically, given both companies a tremendous lead in the PC market. If we consider this specific market, Intel and Microsoft are
complementors and platform leaders at the same time. OEMs critically need both these products; hence each one complements the other. They are platform leaders because both these companies have dominated the market over other complementors. This leadership was possible because of 'network effects', in the sense that as more people use it, the more incentives there are for complementors to build their product\textsuperscript{20}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Intel's Revenue sources 
Source: Trefis.com\textsuperscript{21}}
\end{figure}

\textsuperscript{20} MIT SLOAN MANAGEMENT REVIEW, Spring 2002 & Platform Leadership: How Intel, Microsoft and Cisco Drive Industry Innovation – Annabelle Gawer and Michael Cusumano
\textsuperscript{21} Intel [Trefis.com] \url{http://www.trefis.com/company?hm=INTC.trefis#}
4.2 ARM Ecosystem

ARM licenses its designs to several different types of companies

1. Silicon on Chip (SoC) design companies such as Qualcomm, Texas Instruments and Nvidia
2. Semiconductor foundries such as Taiwan Semiconductor Manufacturing Company (TSMC)
3. EDA Vendors such as Cadence Design Systems and Synopsys
4. Software companies such as Operating System developers
4.2.1 SoC design companies

A system on a chip or system on chip (SoC or SOC) is an integrated circuit (IC) that integrates all components of a computer or other electronic system into a single chip. It may contain digital, analog, mixed-signal, and often radio-frequency functions—all on a single chip substrate. More than 95% of the application processors going into mobile devices (smartphones and tablets) are ARM based (CNN Money Feb 2013). Apple iPhone/iPad and Samsung Galaxy phones and tablets use ARM processors. ARM only designs the chip core and licenses it to semiconductor companies that build an SoC around it (for example, Texas Instruments’ OMAP, Figure 9). Table 2 shows the companies that make SOCs for mobile devices and the underlying CPU architectures.

![Figure 9 Texas Instruments' OMAP SOC using 2 ARM Cortex A9 Cores](http://www.ti.com/lit/ml/swpt034b/swpt034b.pdf)

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22 Wikipedia, December 2013 – System on a chip  
Table 2 SOCs and utilizing products *(Source: Wikipedia, December 2013)*

<table>
<thead>
<tr>
<th>Semiconductor Company</th>
<th>CPU</th>
<th>System-On-Chip</th>
<th>Products Mobile / smart phones</th>
<th>Products Tablets and others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas Instruments (TI)</td>
<td>ARMv7</td>
<td>OMAP (Figure 9)</td>
<td>Nokia N&amp;E series mobile phones, Motorola Droid series, Palm Pre, Sony Ericsson Satio, Vivaz &amp; Idou, Samsung Omnia HD</td>
<td>Nokia 800, 810, 900, Pandora, Touch Book Nook Color, Kindle Fire HD, Blackberry Playbook, Kobo Arc, B&amp;N Nook HD</td>
</tr>
<tr>
<td>Apple</td>
<td>ARMv6, ARMv7, ARMv7s</td>
<td>A4, A5, A5X, A6, A6X</td>
<td>iPhone all series</td>
<td>iPad, iPod Touch &amp; Nano, Apple TV</td>
</tr>
<tr>
<td>Qualcomm</td>
<td>ARMv6, ARMv7</td>
<td>Snapdragon Scorpion &amp; Krait</td>
<td>Samsung Galaxy S line, Sony Xperia, HTC One, Nokia Lumia, Motorola RAZR, Google Nexus 7 (2013), Blackberry Bold/Torch</td>
<td></td>
</tr>
<tr>
<td>Samsung</td>
<td>ARMv7</td>
<td>Exynos</td>
<td>Samsung Galaxy S2, S3 (Europe/Asia/South</td>
<td>Samsung Galaxy Tab, Chromebook, Nexus</td>
</tr>
</tbody>
</table>
It is clearly seen that the majority of mobile devices currently in the market are ARM based. Intel has found a few takers mainly in the tablet segment with its latest Atom processor. Intel has claimed that its next-generation Atom CloverTrail+ SOC is better than the latest ARM-Cortex processor in terms of both speed and low power performance. Further investigation by other analysts has blown serious holes in the ABI Research report. Not only does it focus on a single, highly questionable benchmark (AnTuTu), the x86 version of that benchmark is running different code than the ARM flavors. Furthermore, the recently released Version 3.3 of the test is much faster on Intel hardware than on any of the other platforms. As analyst Jim McGregor

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nvidia</td>
<td>ARMv7</td>
<td>Tegra</td>
<td>Google Nexus 7 (2012)</td>
</tr>
<tr>
<td>Intel</td>
<td>x86</td>
<td>Atom</td>
<td>Lenovo K900, Lava XOLO, Motorola Razr i</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Asus VivoTab, Lenovo ThinkPad Tab, HP ElitePad, Samsung Series S Slate, Lenovo IdeaTab</td>
</tr>
</tbody>
</table>

24 'A Technical Analysis of Performance and Power Consumption of Lenovo K900, Samsung Galaxy S4 (two variants), Samsung Nexus 10 and Asus Nexus 7', ABI research whitepaper, June 2013
writes, "The only clear conclusions that should be drawn are that the leading ARM-based processors still have a performance lead over the latest Intel processor."25

Customization flexibility to ARM’s partner companies

By providing its partner companies design intellectual properties of its processor, ARM gives them the flexibility to build their own SOCs having their own advantages. For example, ARM-Cortex A9 is used in Ti’s OMAP-4 (Figure 8), Qualcomm’s Snapdragon (Scorpion, Krait) and Nvidia’s Tegra-3, but each SOC’s performance in significantly different (Refer to Table 3)26. Each company has the flexibility to choose the number of ARM cores, amount of memory (RAM and Cache) and other features such as signal processing (DSP) and wireless radio capabilities. As a result, while they have the same ARM processor, the partner companies still have significant competitive advantages in the mobile devices market.

Apple has taken customization to a new level. It jointly developed with ARM a new version of instruction set architecture- ARMv7s. It is the architecture of the A6 processor in the iPhone 5.

Table 3 Core Performance at a given clock rate: Arithmetic (Source: tomshardware.com26)

<table>
<thead>
<tr>
<th></th>
<th>OMAP 4430</th>
<th>Tegra 3 (T30L)</th>
<th>S3 (APQ8060)</th>
<th>S4 Plus (MSM8960)</th>
<th>S4 Pro (APQ8064)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>2 Cortex-A9</td>
<td>4 Cortex-A9</td>
<td>2 Scorpion</td>
<td>2 Krait Cores</td>
<td>4 Krait Cores</td>
</tr>
</tbody>
</table>

25 New Analysis Casts Doubt on Intel’s Smartphone Performance vs. ARM, July 2013

26 Snapdragon S4 Pro: Krait and Adreno 320, Benchmarked, Oct 2012
http://www.tomshardware.com/reviews/snapdragon-s4-pro-apq8064- msm8960t.3291-4.html
4.2.2 Foundries

Foundries are fabrication facilities dedicated to research and manufacturing of cutting edge semiconductor process nodes such as 45nm, 28nm and 22nm. A pure-play semiconductor foundry is a company that does not offer a significant amount of IC products of its own designs, but instead operates semiconductor fabrication plants focused on producing ICs for other companies. Examples of such companies are Taiwan Semiconductor Manufacturing Corporation (TSMC), Global Foundries and United Microelectronics Corporation (UMC). Integrated device

<table>
<thead>
<tr>
<th></th>
<th>Cores @ 1 GHz</th>
<th>Cores @ 1.3 GHz</th>
<th>Cores @ 1.2 GHz</th>
<th>@ 1.5 GHz</th>
<th>@ 1.5 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dhrystone (MIPS/MHz)</td>
<td>2.34</td>
<td>2.21</td>
<td>1.92</td>
<td>2.55</td>
<td>2.64</td>
</tr>
<tr>
<td>Whetstone Double (FLOPS/MHz)</td>
<td>0.023</td>
<td>0.021</td>
<td>0.012</td>
<td>0.15</td>
<td>0.015</td>
</tr>
<tr>
<td>Whetstone Float (FLOPS/MHz)</td>
<td>0.031</td>
<td>0.029</td>
<td>0.016</td>
<td>0.16</td>
<td>0.022</td>
</tr>
<tr>
<td>Whetstone Float/Double (FLOPS/MHz)</td>
<td>0.026</td>
<td>0.025</td>
<td>0.011</td>
<td>0.15</td>
<td>0.018</td>
</tr>
</tbody>
</table>
manufacturer (IDM) semiconductor foundry is where companies such as Texas Instruments, IBM, and Samsung join in to provide foundry services as long as there is no conflict of interest between relevant parties.

Table 4 Top 12 Semiconductor Foundries of 2012 [Source: IC Insights]

<table>
<thead>
<tr>
<th>2012 rank</th>
<th>Company</th>
<th>Foundry type</th>
<th>HQ</th>
<th>2010 sales ($M)</th>
<th>2011 sales ($M)</th>
<th>11/10 change (%)</th>
<th>2012F sales ($M)</th>
<th>12/11 change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TSMC</td>
<td>Pure-play</td>
<td>Taiwan</td>
<td>13307</td>
<td>14600</td>
<td>10</td>
<td>16720</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>GlobalFoundries</td>
<td>Pure-play</td>
<td>US</td>
<td>3510</td>
<td>3480</td>
<td>-1</td>
<td>4285</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>UMC</td>
<td>Pure-play</td>
<td>Taiwan</td>
<td>3965</td>
<td>3760</td>
<td>-5</td>
<td>3775</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Samsung</td>
<td>IDM</td>
<td>South Korea</td>
<td>1205</td>
<td>2190</td>
<td>82</td>
<td>3375</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>SMIC</td>
<td>Pure-play</td>
<td>China</td>
<td>1555</td>
<td>1320</td>
<td>-15</td>
<td>1625</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>TowerJazz</td>
<td>Pure-play</td>
<td>Israel</td>
<td>510</td>
<td>611</td>
<td>20</td>
<td>655</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>Grace/HHNEC</td>
<td>Pure-play</td>
<td>China</td>
<td>630</td>
<td>565</td>
<td>-10</td>
<td>605</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>Vanguard</td>
<td>Pure-play</td>
<td>Taiwan</td>
<td>508</td>
<td>519</td>
<td>2</td>
<td>540</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>Dongbu</td>
<td>Pure-play</td>
<td>South Korea</td>
<td>475</td>
<td>500</td>
<td>5</td>
<td>540</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>IBM</td>
<td>IDM</td>
<td>US</td>
<td>430</td>
<td>420</td>
<td>-2</td>
<td>435</td>
<td>4</td>
</tr>
</tbody>
</table>

ARM is involved in mutually beneficial partnerships with several of these foundries that manufacture ARM's latest core processors. ARM gets to show to the partner semiconductor companies that the latest core designs have been 'silicon-proven' and ready for incorporation into the next generation mobile devices. The foundries, on the other hand, prove their manufacturing capabilities in the latest semiconductor process nodes and designs. The success of this partnership also gives the confidence to design companies such as TI that using ARM's IP in their SOCs and manufacturing it in the partner foundry would have a high probability of first-time silicon success. Manufacturing ARM's IP in the foundries of IDMs such as Samsung validates the latest ARM architecture that Samsung might use in the near future.

One example of such partnerships is between ARM and TSMC. Earlier in the year 2013, ARM and TSMC taped-out an ARM Cortex-A57 processor on the latest FinFET process technology. The Cortex-A57 processor is ARM's highest performing processor, designed to further extend the capabilities of future mobile and enterprise computing, including compute intensive applications such as high-end computer, tablet and server products. This was the first milestone in the collaboration between ARM and TSMC to jointly optimize the 64-bit ARMv8 processor series on TSMC FinFET process technologies.\(^{29}\)

\(^{29}\) 'ARM and TSMC Tape-Out First ARM Cortex-A57 Processor on TSMC's 16nm FinFET Technology' – TSMC, April 2013
In another such partnership, ARM and GlobalFoundries launched in June 2013 the ARM Cortex-A12 processor, in the new power, performance and cost-optimized POP technology offerings for the ARM Cortex-A12 and Cortex-A7 processors for GlobalFoundries 28nm-SLP High-K Metal Gate (HKMG) process technology.\(^3^0\)

ARM-Foundry partnerships get complicated when the foundry is a part of IDMs such as Intel and Samsung. Although Intel may not be operating its foundry at full capacity and might be willing to open it to other design companies, it will not be glad to manufacture ARM's IPs because it competes directly with Intel's own x86 core processor.

A recent press release says– 'Intel has a 22nm Atom architecture that is itching to pitch at the smartphone market. Fabricating ARM chips for Apple could cripple that processors' reception who's going to believe it's a top-notch design if you're simultaneously building ARM processors for the most-visible smartphone vendor in the United States.'\(^3^1\)

### 4.2.3 Electronic Design Automation (EDA) Vendors

Electronic design automation is a category of software tools for designing electronic systems such as printed circuit boards and integrated circuits. The tools work together in a design flow that chip designers use to design and analyze entire semiconductor chips. These software tools are used mainly for design (behavioral synthesis, logic synthesis, schematic capture and layout), simulation of the design (transistor simulation, logic simulation, technology CAD and

\(^3^0\) ARM and GLOBALFOUNDRIES to Optimize Next-Generation ARM Mobile Processors for 28nm-SLP Process Technology', -Global Foundries, June 2013

field solvers), analysis/verification (clock domain, functional) and manufacturing preparation (mask generation, built-in self-test).

Since its inception, ARM has been into long term partnerships with leading EDA vendors such as Synopsys and Cadence Design Systems. ARM needs the EDA tools right from the design phase of core processors to validating its performance in partner-companies’ SOCs. On the other hand, EDA vendors benefit by the need of partner-companies to validate their SOCs using the same EDA technology and tools.

ARM has partnered with Cadence to develop its latest processor ARM Cortex A57 in a technology node that is not under market production. Fulfilling the promise of performance and power scaling at 16nm, ARM and Cadence announced a design suite, ARM Artisan standard cell libraries and TSMC’s memory macros. 32

ARM has similar collaboration agreements with other EDA vendors too. In 2011, it had signed a multi-year agreement with Synopsys to develop ARM Cortex A15, state of the art core processor architecture at that time. The agreement aimed to maximize SoC performance and energy efficiency while shortening the development time of the SoC. The following were the highlights of the agreement33

- Synopsys and ARM have signed a multi-year expanded EDA tools agreement providing ARM engineering teams extended access to Synopsys’ leading-edge EDA technology.

32 ‘ARM and Cadence Partner to Implement Industry’s First Cortex-A57 64-bit Processor on TSMC 16nm FinFET Process’, ARM, April 2013

33 ‘ARM and Synopsys sign Multi-Year EDA Tools and ARM Cortex A15 Access Agreements’, Synopsys, June 2011
• ARM will also provide Synopsys with access to ARM Cortex-A15 processor intellectual property (IP) to maximize performance and energy efficiency of SoCs built by ARM’s Partners using this advanced ARM processor and Synopsys tools.

• The agreement will enable design teams to rapidly deliver products to market by taking advantage of processor cores and EDA tools optimized to work well together.

4.2.4 Software Developers

To get an idea of the partnership between software developers and ARM, we should consider looking at the relationship among ARM, Operating Systems such as Android and iOS and Mobile Apps. The hypothesis is that if there is a high switching cost from ARM-Android/iOS to x86-Android/iOS for a firm, then the first to lock-in will gain a significant advantage. The following section will go into the details of the various operating systems, apps and the underlying processors.

<table>
<thead>
<tr>
<th>Operating System</th>
<th>2Q13 Unit Shipments</th>
<th>2Q13 Market Share</th>
<th>2Q12 Unit Shipments</th>
<th>2Q12 Market Share</th>
<th>Year-over-Year Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Android</td>
<td>187.4</td>
<td>79.3%</td>
<td>108</td>
<td>69.1%</td>
<td>73.5%</td>
</tr>
<tr>
<td>iOS</td>
<td>31.2</td>
<td>13.2%</td>
<td>26</td>
<td>16.6%</td>
<td>20.0%</td>
</tr>
<tr>
<td>Windows Phone</td>
<td>8.7</td>
<td>3.7%</td>
<td>4.9</td>
<td>3.1%</td>
<td>77.6%</td>
</tr>
<tr>
<td>BlackBerry OS</td>
<td>6.8</td>
<td>2.9%</td>
<td>7.7</td>
<td>4.9%</td>
<td>-11.7%</td>
</tr>
<tr>
<td>Linux</td>
<td>1.8</td>
<td>0.8%</td>
<td>2.8</td>
<td>1.8%</td>
<td>-35.7%</td>
</tr>
<tr>
<td>Symbian</td>
<td>0.5</td>
<td>0.2%</td>
<td>6.5</td>
<td>4.2%</td>
<td>-92.3%</td>
</tr>
<tr>
<td>Others</td>
<td>N/A</td>
<td>0.0%</td>
<td>0.3</td>
<td>0.2%</td>
<td>-100.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>236.4</strong></td>
<td><strong>100.0%</strong></td>
<td><strong>156.2</strong></td>
<td><strong>100.0%</strong></td>
<td><strong>51.3%</strong></td>
</tr>
</tbody>
</table>

Source: IDC Worldwide Mobile Phone Tracker, August 7, 2013

*Figure 10* Top Smartphone Operating Systems
Android

Android is not just an operating system. It is a robust software stack that includes an operating system, middleware and applications. Android is developed and maintained as an open source project by Google with contributions from members of the Open Handset Alliance (OHA)\(^{34}\), including ARM. Android has been designed and built for the ARM architecture, and continues to be the primary development platform of the OHA with hundreds of companies contributing to the Android on ARM codebase.\(^{35}\)

Figure 11 shows the Android system architecture, which uses the standard software stack with Linux as its kernel. The top of the stack is what end users see as user-interface and applications such as email, calculator and calendar. The bottom of the stack is the Linux kernel, which interfaces with the hardware, ARM processor in this case, with its Instruction Sets specific to the processor architecture. There are significant differences in the assembly language (the low level language used to interact with a processor) for ARM and x86, such as interrupt model and instruction size\(^{36}\). The assembly language for ARM is simpler to write (RISC-Reduced Instruction Set) than that for x86 (CISC-Complex Instruction Set). These reasons make Android developed for ARM processors locked to it. To make Android switch to (or compatible with) x86 architectures requires a substantial programming effort. Notwithstanding, there have been continued efforts to port Android to x86 based processor architectures\(^{37}\).

\(^{34}\) Open Handset Alliance [http://www.openhandsetalliance.com/](http://www.openhandsetalliance.com/)

\(^{35}\) mobile.arm.com


\(^{37}\) Android-x86 Project- Run Android on your PC [http://www.android-x86.org/](http://www.android-x86.org/)
There’s another reason for the lock-in. Android’s market share in the smartphone operating space is almost 80% (Figure 10). Everyday almost 1 million Android devices are activated worldwide. On the processor hardware side, ARM is being used in 95% of the mobile devices currently being sold. The large market size of both ARM and Android, and the high switching costs make the environment conducive for a partnership with a strong growth curve for both.
iOS

iOS (previously iPhone OS) is a mobile operating system developed and distributed by Apple Inc. Originally unveiled in 2007 for the iPhone, it has been extended to support other Apple devices such as the iPod Touch, iPad, iPad Mini and second-generation Apple TV.

Figure 12 shows the software system architecture of iOS. The core operating system interfaces with the iDevice hardware in the bottom of the stack. Because all iOS devices use CPUs based on the ARM architecture, the core OS has been programmed specially for ARM.

![iOS System Architecture Diagram](image)

*Figure 12 iOS system architecture*

iOS is the second largest smartphone operating system by market size (Figure 10), making ARM a partner of a large market.

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38 iOS [Wikipedia](http://en.wikipedia.org/wiki/iOS)
Microsoft has traditionally been the partner of Intel. Consequently, its operating system was specifically made for the x86 architecture. Even Windows 8, launched recently, runs on a 64-bit x86 processor architecture.

However, things are changing for Microsoft too. After the emergence of ARM as a leader in the mobile devices processor architecture, Microsoft has tried to cater to both x86 and ARM space.

In 2011, it was officially announced that the next version of Windows would provide support for the ARM architecture. Microsoft demonstrated an early version of a Windows port for the architecture, codenamed Windows on ARM (WoA), running on prototypes with Qualcomm Snapdragon, Texas Instruments OMAP, and Nvidia Tegra 2 chipsets. In 2012, it launched Windows RT, which is a variant of the Windows 8 operating system designed for mobile devices that use the ARM architecture. Microsoft intended for devices with Windows RT to take advantage of the ARM platform’s power efficiency to allow for longer battery life, to use system-on-chip designs to allow for thinner devices, and to provide a "reliable" experience over time.\(^3\)

While Windows RT tablets (Surface RT) and mobile phones haven’t done well in the market, we can expect a decent growth, especially after the acquisition of Nokia Mobile by Microsoft. ‘Windows Phone’ has a 4% market share, but it has the potential to grow in the European market.

markets.\textsuperscript{40} Windows Phone uses Qualcomm Snapdragon processor SoC, which is based on ARM, benefiting the company directly.

\textbf{App Developers}

Apps is the highest level in the software stack. Some apps, which are light and designed using Java or .NET, are cross-platform, i.e., they can run unmodified on x86 or ARM processor based operating systems. However, those apps that are memory intensive and require compiling on x86 or ARM, have to be used in that machine.

How does the popularity of iOS, Android, Windows Phone and Windows RT, which are designed for ARM based processors, and Windows 8 Operating System, which is designed for x86/64 processors, impact the mobile app development space? To answer that, we need to understand the different types of mobile apps being developed and the extent of their dependence on the phone’s hardware.

\textbf{Native Apps}: These mobile apps are developed for a particular device and operating system. Because they use the phone’s specific hardware capabilities and application programming interfaces (API: interface between hardware and software), these mobile applications are fast, reliable, and powerful, but are tied to a mobile platform. Therefore, in order to use the same app in a different mobile platform, the developer has to build it in the appropriate programming language\textsuperscript{41}.

\textsuperscript{40} Record Share for Windows Phone [Kantar Worldpanel] Feb 2013 http://www.kantarworldpanel.com/global/News/Record-share-for-Windows-phone
\textsuperscript{41} Pavel Smutny - Mobile development tools and cross-platform solutions [IEEE 2012 13\textsuperscript{th} International Carpathian Conference]
**Hybrid Apps**: These apps use both phone features and the web, that is, they require both advanced user interaction and core phone features. These mobile apps offer a compromise because they ensure cross-platform compatibility and can access the mobile device’s hardware (camera, GPS or user’s contacts). Special cross-platform tools such as Phonegap, Rhomobile and Titanium are required to develop this type of app.

**Web Apps**: Mobile web apps require internet access to display the application. Generic web apps such as HTML5 work seamlessly across devices and platforms.

Figure 133 describes the three types of apps in detail with axes showing their capability and cross-platform portability.

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42 Mobile Applications: What type is right for you? [Freeman Marketing] May 2013
http://www.freemanhelp.com/different-types-of-mobile-apps/

43 Mobile Strategy Handbook 6: How to Choose the Right Technology? Native, HTML5 and more... , July 2013
http://www.mobilemarketinguniverse.com/mobile-strategy-handbook-chapter-6-how-to-choose-the-right-technology-native-html5-and-more/
Figure 14 shows that for consumer applications, Native and Hybrid apps still dominate the market. These apps require varying amounts of different programming skills defined by the platform specific Software Development Kit (SDK). For example, iOS, Android and Windows Phone require Objective C/C++, Java and Visual C++ respectively. These programming languages are needed to access the particular device’s hardware such as sensors and accelerometers. In addition, developers of native applications must expect restrictions and costs associated with developing and deploying to certain platforms, such as needing an Apple developer license and Apple’s approval to distribute applications to iTunes Apps Store. These act as major barriers in the seamless portability of native apps.

This problem has been somewhat bypassed in Hybrid apps where cross-platform porting tools are used to code the bulk of the app. Only a small portion of ‘native’ coding is required to access the device’s specific hardware. Although the user interface is reusable across different platforms, Hybrid apps are inferior in performance and lack the look and feel of native apps.

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65 Writing Small - tools and toys [IEEE Spectrum] June 2010
A new approach, Cross Compiled Application, has been described\(^{47}\) where the cross compiler converts the source code to native binaries and hence increases the portability and performance of apps, but it still has some shortcomings.

**Windows 8 (x86) vs. Windows RT (ARM)**

Microsoft’s Windows 8 is an operating system based on x86/64 (CISC) whereas Windows RT and Windows Phone are based on ARM processors (RISC). ARM processors have new requirements for security and power management (such as *Connected Standby*\(^{48}\) mode) and Microsoft meets those needs via Windows Phone and RT. And like iOS, Windows RT will be available only preinstalled, which will simplify the hardware combinations that can become a support nightmare. Also, Windows RT will only run software delivered through Windows Update or the Windows Store. About porting apps from x86 to ARM based Windows operating system, Microsoft Windows former chief Steven Sinofsky said, ‘If we enabled the broad porting of existing code we would fail to deliver on our commitment to longer battery life, predictable performance, and especially a reliable experience over time.’\(^{49}\) As per its original plans, Windows on ARM would not support emulation and would not enable existing x86/64 applications to be ported because it would run counter to its goal of system reliability and predictability. The emulated software would not have been optimized for the platform and would consume system resources, including battery life and CPU, at unacceptable levels\(^{48}\). In

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\(^{47}\) Rahul Raj C.P. and Seshu Babu Tolety - A study on approaches to build cross-platform mobile applications and criteria to select appropriate approach [IEEE India Conference 2012]


\(^{49}\) Microsoft bans Firefox on ARM-based Windows, Mozilla say [CNET News] May 2012
other words, users would be able to use only those apps that Microsoft has approved, and is selling through the Windows Store.

However, there have been numerous successful attempts at achieving cross-compatibility of apps between Windows 8 and Windows RT. In one such instance, a member of the XDA-developer forum has designed an emulation layer, currently in beta phase, that emulates x86 instructions and passes Windows API calls to the WinRT kernel with necessary modifications. In other words, the tool allows x86 apps to be run successfully on Windows RT. The emulation software, though, has some limitations.

Key Insights:

- The portability of mobile apps largely depends on the type of app (Native, Hybrid or Web) and the programming language used to build the operating system. Processor-defined special features are best used by native apps, which have the lowest rank in portability. However, because apps are typically small in size, duplicating them in a new language for a different platform takes less effort once the features have been defined.

- Windows has restricted the portability of apps between its x86 operating system, Windows 8, and ARM based operating system, Windows RT. However, some unofficial emulators have been developed that allows the portability of legacy apps, although with some restrictions.

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4.3 ARM Licensing Model

ARM’s licensing model is tiered as shown in Figure 15. It is illustrated as a pyramid with the ‘architectural license’ at the top and ‘Academic License’ at the bottom. Figure 15 also mentions that as we move up the pyramid, technical/business flexibility of licensees increases, number of partners reduces and the fee increases. In terms of numbers, ARM has around 1000 licenses in the market spread across 320 licensees/partners. Of those 320 licensees, only 15 of them have architecture licenses.\(^53\)

http://www.anandtech.com/show/7112/the-arm-diaries-part-1-how-arms-business-model-works/1

\(^{54}\) Licensing ARM IP [ARM]
Academic/Research Licenses

These licenses are for research purposes only and given to academic institutions. The designs might not work on silicon, if manufactured.

DesignStart

These licenses are for non-commercial use in academic institutions, startups and research arm of bigger firms. ARM claims that these designs, when manufactured, will show full functionality.

Multiple/Single Use Licenses

Multiple or single use licenses have some upfront fees and are given for a pre-specified number of uses. This type of license is for commercial use by the licensee and is ideal for startups making their first products.

Term Licenses

Term licenses are for unlimited use but within a pre-defined period (e.g. 1 year). The fees for this type of license is higher than that of single/multi use licenses.\(^55\)

Perpetual Licenses

These licenses are very similar to Term but without the term. A firm that designs numerous SOCs and wants to use the core for a larger period of time (e.g. 10-20 years) opts for perpetual licenses. These licenses are typically used by large companies in industrial applications.\(^56\)

Subscription Licenses

Subscription licenses, though more expensive, give the licensee much more flexibility. Under this agreement, the licensee can get access to multiple products that ARM has got in its repository of designs. Large companies, which need greater flexibility in designing SOCs, opt for this type of license.

Architecture License

The flexibility that ARM gives to its licensees is epitomized by this license-model. Partner companies get access to the latest microprocessor architecture ARM starts working on before any other licensee (in other license models). ARM and the licensee work on the architecture together, the latter getting a significant advantage (customization and fast time-to-market) in this process. The licensees manufacture the design and test it, and provide feedback directly to ARM. Not surprisingly, this is the most expensive type of licensing model (runs into tens of millions of dollars) and only a few companies are partners with ARM.

Historically, Apple licensed its core processors from ARM. These processors were used in iPhones, iPad and other mobile devices. This trend continued till Apple’s A4 processors. Apple changed its strategy moving forward to A6, its latest processor. Apple acquired PA Semi in 2008 with the intention of making its own customized microprocessor architecture. It signed a deal with ARM for an architectural license soon after and engaged its newly acquired processor team to work with ARM in developing the next generation A6.

A6 was successfully tested a year later and went into production as Apple’s own processor in iPhone 5.

Why did Apple change to ARM architecture for A6?

ARM had used off-the-shelf licensed ARM processors in all its iPhones, iPods and iPads prior to A6. The next design in line from ARM was A15, which was focused on improving computing performance while keeping total power consumption as a second priority. A15’s deeper machine and much wider execution engines would have driven both power and performance up. It was only through some added complexity (e.g. big.LITTLE) that Cortex-A15 would have been suitable for smartphones. Given Apple’s intense focus on power consumption and its newly acquired prowess in designing processors, it decided to skip Cortex A15 and instead took

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57 How Apple Designed Own CPU For A6 [Linley Group] Sept 2012
an architectural license to develop its own processor based on ARM’s Instruction Set Architecture (ISA)\(^5^9\).

The other benefits that Apple received by switching to an architectural license were:

- **No disclosure of CPU architecture**: By just using the ISA from ARM and developing its own processor, Apple had the option of not disclosing the processor’s architecture. This flexibility gives Apple a competitive advantage over other ARM based players in the market.

- **Time to market**: By licensing ARM architecture, Apple got the advantage of building its SoC (A6) much ahead of its competitors, who waited till the A15 was designed and released by ARM. Interestingly, Qualcomm also purchased an architectural license from ARM to build its processor, Krait, competing with Apple’s A6 on an even platform.

**Pricing**

ARM’s license and royalty fees depend on

- **CPU performance**: Higher performing CPUs typically have higher license fees and royalty than lower performing cores.

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\(^5^9\) The iPhone 5’s A6 SoC: Not A15 or A9, a Custom Apple Core Instead [AnandTech] Sept 2012

Table 5 Royalty Structure w.r.t. Core  Courtesy: AnandTech

<table>
<thead>
<tr>
<th>IP</th>
<th>Royalty (% of chip cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM7/9/11</td>
<td>1%-1.5%</td>
</tr>
<tr>
<td>ARM Cortex A-series</td>
<td>1.5%-2%</td>
</tr>
<tr>
<td>ARMv8 Based Cortex A-series</td>
<td>2% and above</td>
</tr>
<tr>
<td>Mali GPU</td>
<td>0.75%-1.25%</td>
</tr>
<tr>
<td>Physical IP Package (POP)</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

- Moving up the license pyramid (Figure 15): Higher the flexibility the core IP gives to the licensee, higher the license fee. For commercial uses, architecture license has the highest upfront fees, while single use the lowest. However, the royalty fees have the opposite trend moving up the pyramid. While ARM charges 2-2.5% for multi/single use licenses, this figure drops to around 1% per chip in case of architecture licenses.

Table 6 Fee Structure w.r.t. license segment (Cortex A Class)  Courtesy AnandTech

<table>
<thead>
<tr>
<th>License Tier</th>
<th>Est. Upfront License Fees</th>
<th>Est. Royalty (% chip cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>&gt;$10M</td>
<td>1%</td>
</tr>
<tr>
<td>Subscription</td>
<td>$10M</td>
<td>1-2% (lower end)</td>
</tr>
<tr>
<td>Perpetual</td>
<td>No Data</td>
<td>1-2%</td>
</tr>
<tr>
<td>Term</td>
<td>No Data</td>
<td>1-2% (higher end)</td>
</tr>
</tbody>
</table>

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http://www.anandtech.com/show/7112/the-arm-diaries-part-1-how-arm-s-business-model-works/2

http://www.anandtech.com/show/7112/the-arm-diaries-part-1-how-arm-s-business-model-works/3
<table>
<thead>
<tr>
<th>Multi/Single Use</th>
<th>$1M (single use)</th>
<th>2-2.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>DesignStart</td>
<td>ARM foundry sponsored Physical IP - (free to end user) Applications optimized Physical IP - &quot;Try Before You Buy&quot; (low license fee)</td>
<td>Commercialization Not Allowed</td>
</tr>
<tr>
<td>Academic/Research</td>
<td>Free</td>
<td>Commercialization Not Allowed</td>
</tr>
</tbody>
</table>
Chapter 5 Future Trends

5.1 New Revenue Sources

ARM is currently eyeing the growing enterprise and data center market. One of the major initiatives in this direction was the recently announced partnership of ARM and Oracle in catering to the needs of this market. This agreement reflects the increasing applicability of the combination of ARM and Oracle technology in server and network infrastructure. In this multi-year agreement, ARM will provide architectural support and Oracle will optimize its existing Java Platform, Standard Edition (Java SE) for ARM 32 bit platforms and to upgrade Java SE to support ARM 64-bit architectures, providing efficient scalability for ARM-based multi-core systems. In addition, Oracle’s Java Virtual Machine (JVM) helps in increasing the performance of Java applications used in ARM-based multicore systems in enterprise servers and embedded systems. Furthermore, these two companies will work together in improving boot-up performance, power savings and library optimization- essential factors for the enterprise and embedded markets.\(^{62}\)

According to Ian Drew, Executive Vice President, Business Development and Chief Marketing Officer, ARM, this extended relationship with Oracle to enhance Java SE is an important step in growing the ARM ecosystem, coinciding with the inflection point that enterprise infrastructure, including servers and network routers, has reached.

Meanwhile, Intel is exploring the foundry business by opening up its chip manufacturing facilities to third party customers. The company has expanded its chip-to-order business by signing up additional customers to take advantage of its 22-nanometer process facilities. This move has been a surprise to the semiconductor company because Intel has historically known to be using its fab just for its own chips. It doesn't expect to become a large-scale foundry company like its rivals Taiwan Semiconductor Manufacturing Corporation (TSMC), UMC (United Microelectronics Corp.) and GlobalFoundries, but Intel's executives say there are strategic advantages in opening up its manufacturing facilities.

The manufacturing costs in the latest technology nodes such as 22nm are very high and it is becoming increasingly difficult for a company to own and run its foundry for itself. This is especially true in light of its latest 3D (tri-gate) transistors. Therefore, this move will spread manufacturing costs over several partners (Intel and third party companies) and run the fab at full capacity even during lean periods.

There could be another strategic advantage in opening up its fab from 22nm, in which Intel has introduced a new type of device, 3-D transistors (in contrast with 2-D in older generations). Intel believes that this technology will not only provide them a manufacturing edge over its rivals such as TSMC but also will enable Intel to attract OEM partners using this technology.

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64 Silicon-on-Insulator at ST and IBM Closing Gap With Intel [EE Times] April 2012
done successfully, network externalities will make it hard for rivals such as ST and IBM, who are pursuing a competing technology - FD-SOI⁶⁵.

However, Intel’s move to opening up its foundries to third party companies could result in difficult encounters between ARM and Intel. Altera, a leading manufacturer of Programmable Logic Devices (PLDs), had signed a deal with Intel to produce its Field Programmable Gate Array (FPGA) devices in 14nm (next generation technology node) using Intel’s fabrication facility. However, Altera later announced that it is using ARM’s 64-bit cores (ARM Cortex A53) in its chip, Altera Stratix 10. This has resulted in a situation where Intel is the manufacturer for ARM-based chips. To date, Intel has experimented with offering its leading-edge fab processes as foundry services to a handful of chip designers, Altera being one of its largest planned customers to date. However, this situation might make Intel rethink its foundry-outsourcing strategy⁶⁶.

5.2 Technology Trends

For over 50 years, semiconductor manufacturers had used planar transistors for its chips (Fig. 16). With every shrinking technology node, the transistor dimensions followed Moore’s law, which predicts the doubling of number of transistors present in a chip every two years. It had become increasingly difficult to follow this law in the latest processes, but Intel’s 22nm and below will use an entirely different geometry of transistors, making use of the third dimension and fueling Moore’s law for years to come. Intel is using the revolutionary 3-D transistor design called Tri-Gate (Figure 17), first disclosed by Intel in 2002, into high-volume manufacturing at the 22-nanometer (nm) node in an Intel chip codenamed "Ivy Bridge."\(^{67}\)

According to Intel, tri-gate transistor’s reduced current leakage results in a substantial performance gain at low operating voltage. The new transistors consume less than half the

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power when at the same performance as 2D planar transistors on 32nm chips and are also better equipped to save power on standby\(^68\).

These advancements announced two years ago have come to show results in the latest ‘Ivy Bridge’ SoC of Intel. Ivy Bridge is claimed to be 19\% more efficient than its previous generation SoC, Sandy Bridge\(^69\). However, what is important is whether Intel can leverage its advancements in manufacturing to compete in the mobile devices market, where low power consumption is of utmost importance.

On the other hand, ARM has also been continuously evolving to support deployment of energy-efficient computation devices in a growing spectrum of applications. It has added several features to its application processor 32-bit/64-bit architecture (ARMv7-A and ARMv8-A). However, it has made significant progress in real-time processors, ARM Cortex-R\(^70\). According to ARM, this architecture will let companies make embedded chips that are faster and more power-efficient. The need for faster chips is essential as small electronic devices in hospitals, vehicles, factories and even casinos take on multimedia, wireless communication and other tasks. The chips based on this new architecture will be able to automate more operations and handle more advanced communication features\(^71\).

\(^{69}\) Review: Intel Core i7-3770K (22nm Ivy Bridge) - http://hexus.net/tech/reviews/cpu/37989-intel-core-i7-3770k-22nm-ivy-bridge/
Chapter 6 Conclusion

In the age when PC was the dominant and the highest growing market segment, Intel capitalized on it by providing the OEM industry high performance x86 based microprocessors. Its partnership with Microsoft, who provided the Windows operating system, fueled this growth. Growing number of users of Intel-Windows combination (‘Wintel’) of hardware and software led to more value which in turn led to more users. This self-reinforcing loop virtually eliminated all players from the market who came up with a different architecture or design (read Macintosh) and built an ecosystem around x86 based microprocessors- the dominant design. 

However, in the last decade, with the tremendous growth of mobile devices – smartphones and tablets, and its encroachment into the PC space leading to its gradual decline, the microprocessor market is witnessing new dynamics. The foremost concern of mobile-devices OEM is a combination of battery life and performance, placing a premium on low power components. A microprocessor is one of the most crucial components and low-power architecture has become imperative. ARM Holdings, well known for its low-power microprocessor designs and flexible architecture, fit the bill perfectly. It was broadly assumed that the underlying RISC instruction set of ARM and CISC of Intel x86 made all the difference in the power consumption figures. This led to its rapid rise in the mobile devices market, where 95% of smartphones and tablets today are based on ARM.

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ARM had the right technology/design focus to benefit from being the first mover in this market segment. However, what stands today, is completely different.

Empirical evidence shows that Intel’s Atom (x86, CISC) and ARM’s Cortex A9 (RISC) have similar performance and power consumption. Over the years, ARM’s processor architecture, though RISC, has added features that were predominantly observed in Intel’s x86 CISC and vice versa. This has made the boundary between RISC and CISC blurred and the underlying Instruction Set irrelevant to making low-power designs. To the first order and given technology node, the optimization of the system (SoC) is what impacts the total power consumption of the processor.

While it is true that the being RISC or CISC based (ARM and Intel respectively) will not directly impact the power performance of the processor, the fact that ARM provides just the Intellectual Property (design) of the core makes the difference. It offers flexibility to the SoC makers to customize their SoC design and meet the end-user needs, whether it is power figures, performance, or a combination of both.

ARM was the first to demonstrate value of its microprocessor in the mobile devices segment and was rapidly adopted in smartphones and tablets. This has given ARM a significant first mover advantage in terms of the synergistic relationships it has forged with semiconductor companies, EDA vendors, software companies and large foundries. As mentioned earlier, semiconductor companies build SoCs using ARM core licenses and ARM builds its next generation core based on the end-user application requirements that these semiconductor companies target. Software companies, especially operating system developers such as Android and iOS, have built their operating systems on ARM instruction set. This is reminiscence of the
Windows-Intel complementarity, although this time ARM has a bigger ecosystem of several players. In particular, the large market size of both ARM and Android and the high switching costs make the environment conducive for a partnership with a strong growth curve for both.

New market trends such as enterprise and data center growth, change in business models such as opening up foundries to fabless companies and technology trends such as 3-D transistors might usher in a different set of dynamics. However, given the current market drift toward mobile devices and erosion of the PC market, ARM Holdings is definitely in the driver’s seat.
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