An Ecosystem Strategy for Intel Corporation to drive adoption of its embedded solutions

by

Prashant Paliwal

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Signature of Author ______________________________

Prashant Paliwal
System Design and Management Program
May 2010

Certified by ______________________________

Alan MacCormack
Thesis Supervisor
Technology Innovation and Entrepreneurship Group, MIT Sloan School of Management

Certified by ______________________________

Patrick Hale
Director
System Design & Management Program

Abstract

With time, successful companies and businesses grow to create a network of partners and stakeholders that work very closely with them. The very survival and growth of these companies is dependent on this ecosystem network around them. The ecosystem thrives on stakeholders mutually benefiting from each other while contributing to growth of the ecosystem itself. Every now and then business growth of such big companies with powerful ecosystems of their own is disrupted by relatively small players when incumbents have to respond.

Intel, world's largest semiconductor company, has seen tremendous growth in its business since its inception. While Intel focused on continuously innovating and delivering great products for the personal computer industry, it chose not to compete in low margin embedded computing markets. Advanced RISC Machines (ARM Holdings Ltd.), a small semiconductor company during early nineties developed architecture for low power embedded computing markets that with time became the dominant architecture for mobile computing. As demand in the personal computer industry and consumer interest shifted towards portable and mobile computers, Intel delivered products for these markets. In recent years Intel, the incumbent is being threatened by ARM, the disruptor because mobile embedded platforms based on ARM architecture have encroached Intel's territory. Intel at the same time has its sight at the high growth embedded markets dominated by ARM. Today, both these players with their mature ecosystems are facing each other as they try to enter each other's territories.

This Thesis analyses this classic battle for ecosystem leadership for embedded markets by Intel and ARM. Software and platform leadership is analyzed in detail and an Ecosystem strategy for Intel to drive adoption of its embedded solutions is devised in later chapters.

Acknowledgements

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1 Chapter 1 - Introduction

In the technology industry, Incumbent dominant [4] players like Intel have been managed very well till date where the technology giant has instilled a culture of continuous innovation to deliver breakthrough products throughout its history. However, a relatively little known player in the semiconductor industry during early nineties – Advanced RISC Machines (ARM) came up with a revolutionary low power chip architecture. ARM's initial focus was very low power, low cost embedded products but during its course it ended up heavily disrupting [5] Intel's business as it became the dominant architecture in the fastest growing segment of programmable chips, the Mobile phone. ARM, A relatively less complex architecture that first found its entry into simple mobile phones with an entire focus on lower power and low cost segments has found its way into increasingly complex mobile computing devices today and is directly threatening Intel, the dominant incumbent in mobile notebook and netbook segments.

Technology plays a very important role in our everyday lives today. From Personal Computers to mobile phones, from intelligent TV screens to intuitive in-car infotainment systems we are constantly using technology to enable our lives. All these very easy to use devices and systems at the core are powered by tiny logic circuits in form of semiconductor chips. Overall semiconductor industry has adopted two principal processor architectures; Intel Architecture (X86) that is driven by Intel Corporation and ARM that is driven by ARM Holdings Corporation. Figure 1 shows the worldwide semiconductor leaders for 2009 and the primary processor architecture used by the leading companies.

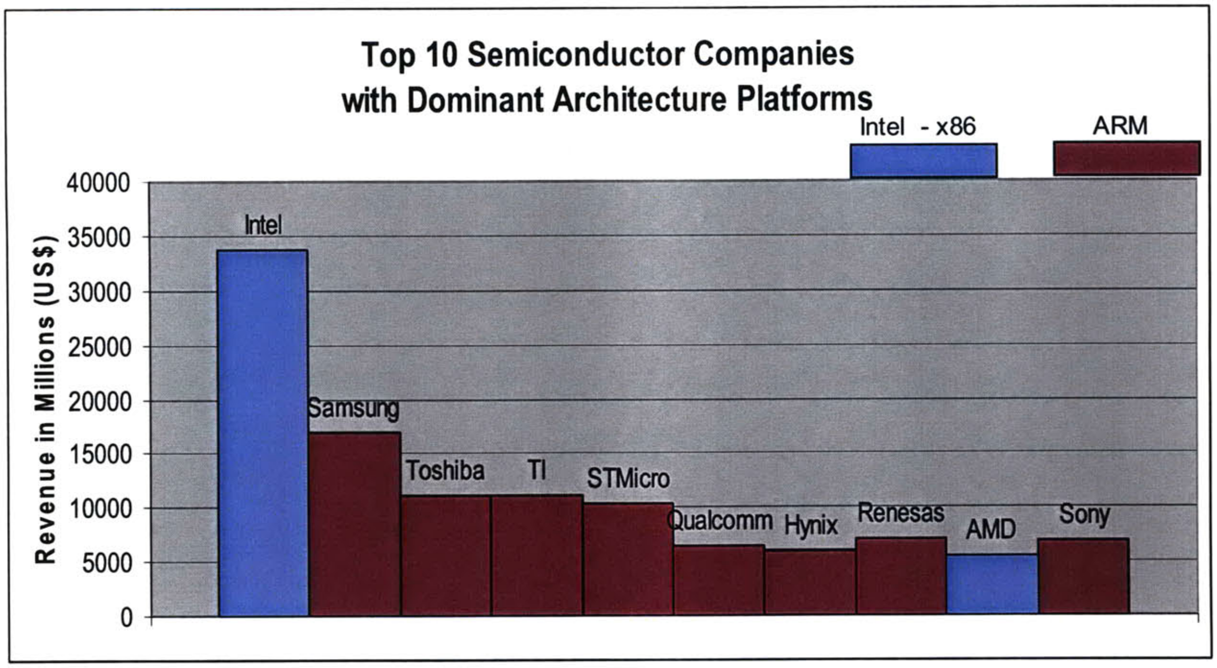


Figure 1: Principal Architecture platforms by Leading Semiconductor Vendors – 2009 (Data sourced from IDC)

Though most of the vendors showed in Figure 1 have been active in all types of semiconductor markets including memory and other microcontrollers, the figure shows primary architecture in usage. The type of devices served by these two very different architectures depends upon the nature of power and performance requirements of the platform. Low power embedded platforms like the mobile phones and vehicle control systems have been dominated by ARM architecture while compute intensive devices like Personal Computers and Advanced Server systems have been dominated by Intel Architecture. Over the years, both these architectures have developed into thriving ecosystems of their own dominated by the respective keystones [2], Intel and ARM. Both Intel and ARM have followed different ecosystem strategies till date. Intel focused on becoming the largest semiconductor player driven by the PC industry while ARM focused on Intellectual property development licensing its architecture to leading semiconductor vendors for various embedded markets. This thesis analyses these two different ecosystems and platforms in detail. Based on the analysis a strategic framework and methodology is developed to devise ecosystem strategies for Intel through which it could penetrate the ARM ecosystem with its architecture and platform offerings. This Chapter provides a Background and Motivation for this Thesis in Section 1.1 followed by thesis outline and formation described in Section 1.2.

1.1 Background and Motivation

Intel Corporation has been considered a platform leader [1] in the overall personal computer industry. Intel has been able to maintain its leadership dominant position with continuous innovation in microprocessor technology over the years. Its close alliances with other key ecosystem players like the Software giant Microsoft has enabled Intel to complement [1] its technology effectively to provide a comprehensive platform to the PC industry. While Intel dominated the PC Industry with the Wintel (Microsoft Windows and Intel) alliance during 1990's, a new platform – ARM based mobile phone was just emerging. ARM's model of open architecture and open innovation where the OEMs and customers have been instrumental in feeding back the intellectual property (IP) back into the company has fueled an embedded revolution. Adoption of ARM into low power mobile chipsets coupled with aggressive growth of mobile phones in late 90's catapulted ARM as the de-facto standard for low power embedded devices.

While ARM continued to proliferate in embedded devices, Intel continued to prove its dominance in high performance, relatively high power computing platforms driven by the growth of personal computer. This started to change during early years of the 21st century when driven by market needs for greater power efficiency, Intel started to focus more on overall performance of the computing platforms with its "Core" architecture greatly improving the power envelope for its platforms. At the same time, a seismic shift started to happen where mobile laptop platforms started to see greater growth than traditional desktop platforms thus leading Intel to innovate in high performance low power processors that would power the next generation mobile platforms.

1.2 Ecosystems Colliding – Intel's move into ARM's Territory

The requirements of computing and embedded platforms have been evolving over the years, with the traditional PC platforms becoming more portable and power efficient and the embedded platforms like smart mobile phones becoming more intelligent and compute intensive. As traditional PC industry is maturing, Intel is finding ways to capture these adjacent low power embedded markets, while ARM is evolving its architecture to capture compute intensive markets.

Continued innovation in low power high performance processors led to the birth of "Atom", a low power relatively high performance processor that revolutionized the computing industry powering the low cost laptops called "netbooks" and announced Intel's entry into embedded markets. The strong software ecosystem around established Intel Architecture made it easier for customers and OEMs to adapt their designs to platforms built around Atom. Today, with continued innovation and a comprehensive roadmap for embedded devices, Atom is being looked as a major competitor and threat in the established ARM territory and ecosystem. Atom continues to find new applications ranging from industrial automation to in-vehicle infotainment. While Intel is focusing on extending its market share in the embedded markets, ARM is not sitting quietly and is continuously working on evolving ARM architecture into something that could take more and more compute intensive tasks while keeping the low power requirements. Most popular Smartphone's today with intuitive user interfaces like the ones provided by Apple

Corporation are all powered by ARM architecture. ARM's strong network of partners with close allies like Qualcomm has resulted in pushing compute intensive chips like the Snapdragon into the market today that are directly going to compete with Intel's Atom.

Following Figure 2 shows how these two very disjoint ecosystems are now colliding as ARM is trying to respond back by offering high performance ARM based solutions that would directly compete with Intel's Atom line of processors and products.

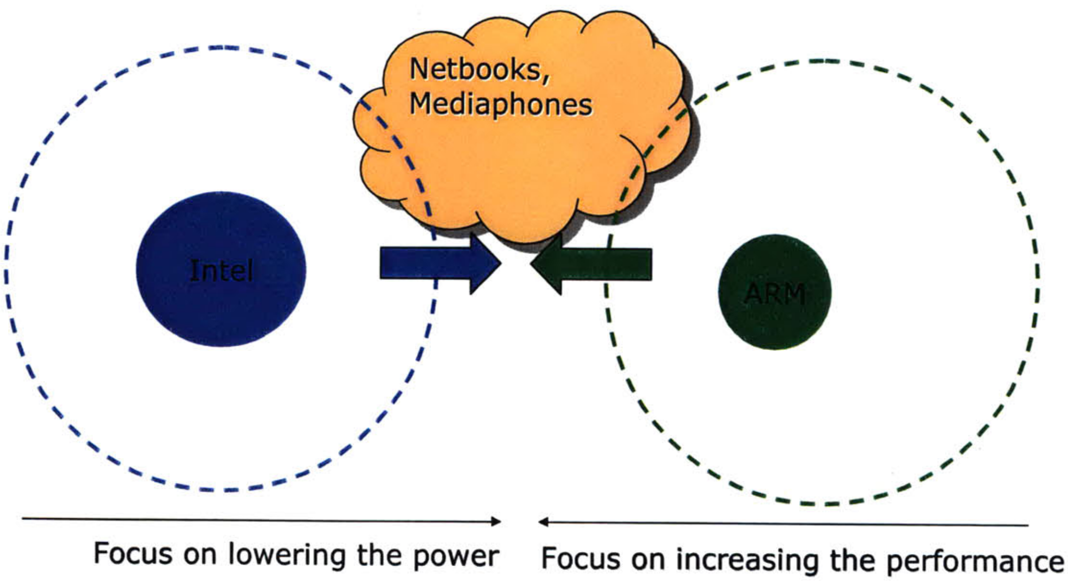


Figure 2: Competing Platforms

Detailed work in this thesis analyses platform capabilities and offerings provided by these disjoint ecosystems. These architectures might be very different but Software is that common glue that is abstracting the differences in the architectures from the end users who use them in various devices. Next section looks at this most important common ingredient, Software.

1.3 Software, Key Ingredient of the Platform

With time, computing has evolved to meet the ever increasing needs of the end user with better applications, greater content, and fast response times. Intel has played a very important role in reshaping the personal computer industry by addressing the needs of its customers with processors that have been consistently providing better speeds and performance required by complex application workloads. Figure 3 below illustrates the key platform ingredients for Intel.

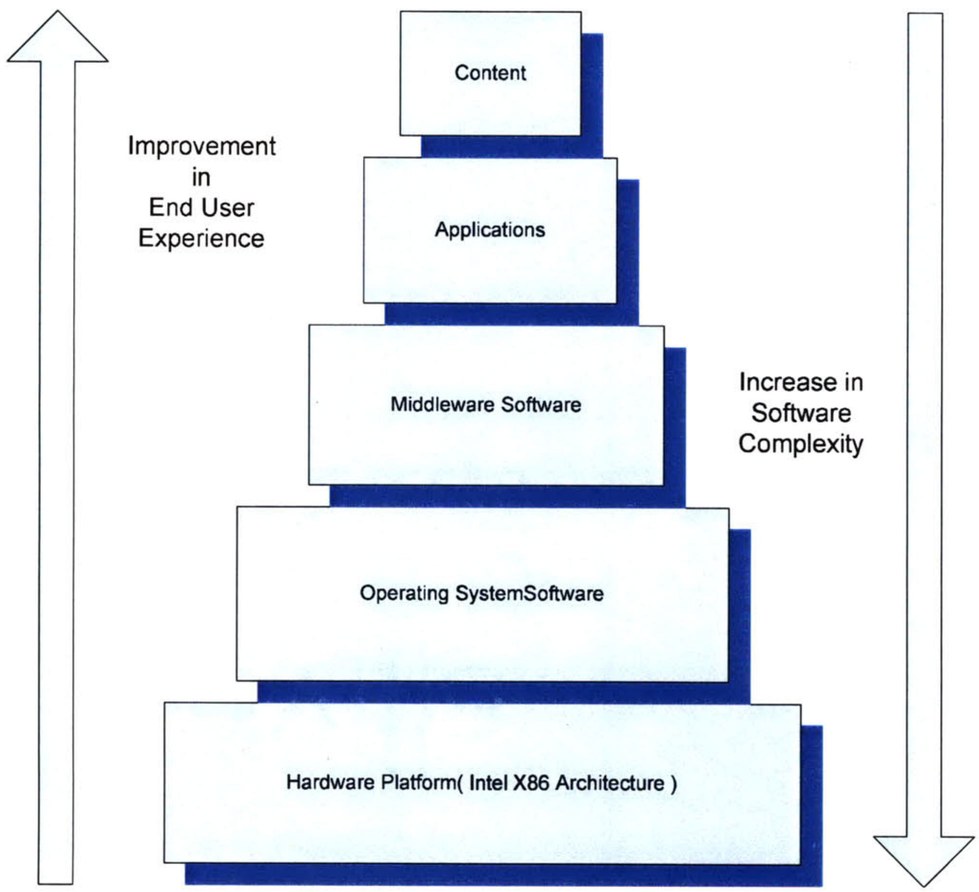


Figure 3: Intel Platform Ingredients enabling the End User Experience

It's notable, that layers closer to the hardware get increasingly complex when it comes to implement the software required to enable the stack. As we move up the stack, the complexity in software decreases while improving the user experience at the highest level. A user watching a high definition video on a powerful laptop system may not notice the sheer complexity of the hardware and software platform beneath it that brings him the great user experience. Intel and ARM are two very different architectures and thus follow very different instruction sets that are abstracted through the higher software layers. Software application layers at the highest level that provide the end user experience are abstracted by the underlying platform layers. Whether an end user uses an Apple iPad that is powered by ARM architecture or a powerful notebook computer that is powered by Intel architecture, software is that common glue that abstracts the differences between the architectures.

As ARM architecture dominated the early mobile phone platforms, Advent of Linux, an open source operating system provided the software support, flexibility and scalability needed to make these small embedded devices workable and manageable with a wide range of applications required for such low power platforms. ARM's symbiotic relationships with key ecosystem players in the software arena fueled the growth of ARM architecture into adjacent embedded markets.

As Intel's embedded offerings tries to find new markets, Intel needs to enable this key ingredient, Software in a scalable way to effectively enable its various embedded segments. A very strong incumbent software ecosystem around the ARM devices also poses a significant challenge. Software ecosystem around embedded devices is fragmented in general with many small to medium independent software vendors playing in a range of embedded markets. Intel will need to rethink its embedded strategy to come up with a scalable and attractive software platform that would bring these fragmented markets together. Future growth of Intel's embedded offerings like Atom into embedded markets also requires a seamless transition for ARM based embedded software to Intel Architecture while maintaining the platform performance and compatibility.

Intel needs to rethink its platform architecture and strategy for the software ecosystem around it as it tackles incumbent embedded offerings. Further work in this thesis investigates some of these platform ideas and proposes a framework to effectively achieve platform leadership in embedded segments.

1.4 Thesis Objective

Sections above have outlined some basic differences between these two very powerful but disjoint ecosystems. Today, these ecosystems are facing each other head on as they try to compete in each other's spaces. Software and Platform ecosystem strategy is critical as Intel and ARM move forward in each other's territories. Looking back at history though, ARM has come a long way from being a small disruptive player to having a fully grown mature ecosystem of software and hardware vendors and partners. How did ARM manage to do it? How did ARM manage to challenge a thriving and dominant ecosystem of Intel? What should Intel do to overcome the challenges posed by ARM?

This thesis is an attempt to go in depth into the detailed analysis of these ecosystems, and address these key questions and issues by

- Characterizing the existing ecosystems and strategies and their differences
- Deliver a framework and software ecosystem strategy for Intel to counter the threats against its ecosystem

1.5 Thesis Outline

Chapter 2 analyses and explains differences between the ARM and Intel business models and markets

Chapter 3 analyses ecosystem Partners Strategy and Software ecosystem for Intel and ARM

Chapter 4 analyses the software ingredients around the Intel embedded platforms in detail and provides recommendation for an ecosystem strategy and software framework for its embedded segments

Chapter 5 concludes the thesis with recommendations and learning's based on this work

2 Chapter 2 – Intel and ARM: Technology, Markets and Business Model

Intel has long been a dominant player in the microprocessor industry and has developed a vast network of ecosystem suppliers and partners. However, Intel has never dominated the low power embedded markets where ARM has been a solution of choice. Intel chose not to compete with ARM in these embedded markets due to low margins on small-embedded parts but has been seriously thinking its strategy as embedded markets fueled by the growth in mobile phones presents Intel with a very lucrative market. At the same time, ARM has found an entry through powerful mobile phones into popular low power laptop markets that has always been Intel's territory. For the purpose of this thesis, this chapter compares Intel and ARM in this growing embedded space. An analysis of the strengths and weaknesses of these players is presented in different areas like Products, Business model, Software and Ecosystem network, respectively in the following sections.

2.1 Technology

As far as technology is concerned ARM and Intel differ greatly at the core architecture level. Microprocessors are today the smallest self-sufficient computing units of a computer or any intelligent computing device. Microprocessors typically implement the functionality of a central processing unit (CPU) on a single integrated circuit. They implement an Instruction set architecture (ISA) [11], a set of instructions at the lowest level to achieve most of their functionality. These instructions are represented in form of bits at the core logic level. For example Intel has evolved its 32-bit x86 instruction set and architecture starting out with 16-bit

8086 microprocessor in the beginning. Intel's architecture has evolved to support ever increasing complexity to address growth in computing with an instruction set that has grown over the years. Specifically, complexity has evolved at a single instruction level where an instruction usually has dependency on multiple CPU components for its execution. Computing devices based on such complex ISA are called complex instruction set computers (CISC). Intel has managed to hide this complexity by consistently innovating in the way sub components communicate with each other and by optimizing the process through which underlying circuitry is laid out. Operating systems like Microsoft's Windows and Linux has kept pace with Intel's ISA implementing the x86 instruction set at the lowest level.

ARM architecture on the other hand has been based on the philosophy that to achieve majority of simple computing tasks, complex instructions are generally not needed. By dramatically simplifying the interactions of an instruction that require its execution, an instruction can be executed quickly. Simple targeted computing tasks thus can be run more efficiently and quickly on a reduced instruction set computer (RISC). ARM is thus based on the RISC architecture. There are many other notable RISC architectures like the PowerPC from IBM and the SPARC from Sun Microsystems (now merged with Oracle Corporation), but ARM ended up being the most popular and widely used RISC architecture with instruction set level innovations that made the overall microprocessor a high performance, power efficient design. Advanced RISC Machines (ARM), the company that redefined RISC architecture with simple instruction modifications and intelligent instruction management techniques, went on to capture the majority of embedded market.

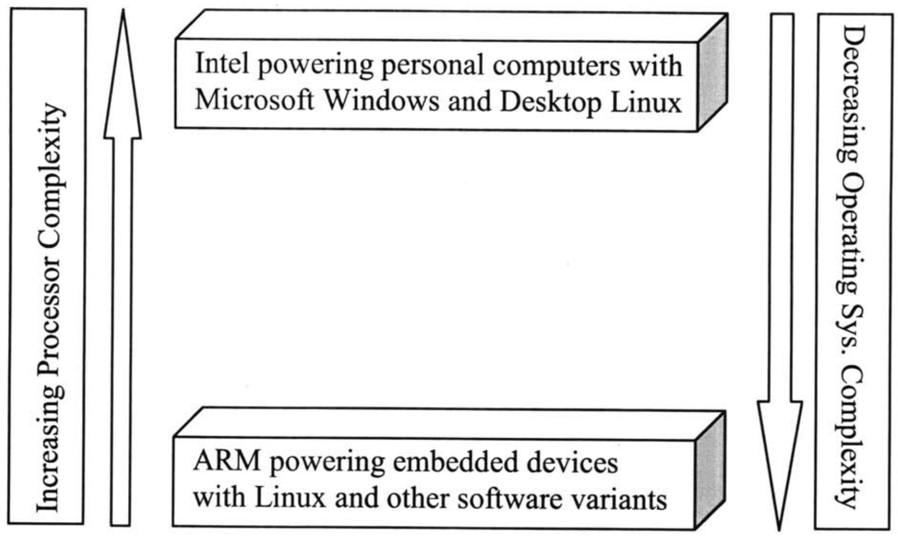


Figure 4: Intel and ARM technology – Enabling Computing

Simple RISC architectures like ARM as shown in Figure 4 have thus enabled a variety of embedded devices. Linux and its open source variants complemented ARM with their modular offerings and thus fit very well for embedded markets that require flexible designs. Intel on the other hand dominated the relatively high end computing market with its complex microprocessors complemented with desktop Linux variants and Microsoft's windows operating system. ARM continued to grow in the lower strata of the embedded computing market while Intel continued to grow in the higher strata of the overall computer market.

2.2 Licensing – ARM's Reuse Strategy

Intel's x86 instruction set is available for implementation, where competitors like AMD have implemented it in their processors but the architecture and microprocessor circuitry is completely proprietary and is never shared with customers or OEMs. ARM in contrast licenses both the instruction set as well as the implementation for the microprocessor cores to its customers. ARM is in the business of licensing microprocessor cores in two forms, Soft Cores and Hard Cores respectively:

- Soft Cores – Soft cores are generally microprocessor designs that are still in register description language form and have not been fabricated or manufactured into finished chips. By licensing microprocessor designs in this form, ARM offers its OEM customers maximum flexibility in enhancing the core feature set of its microprocessors. This offers customers a highly customizable core that results in product chips which customers can independently develop and resell to grow their business. Soft cores offer a level of customization needed by customers who want to take the silicon design to the next level.
- Hard Cores – Hard cores are usually ready-to-go integrated circuits without the packaging that OEMs could repackage for their needs. Hard cores cannot be customized or changed but can be extended upon with other processor cores and technologies. As ARM captured most of the embedded market, it offered hard cores for almost all segments enabling vast set of OEM customers. Hard cores are also very standard in terms of silicon design and software required to enable it. OEMs and Silicon vendors have largely benefited from this standardization.

Each of these cores, carry a small licensing fee that drive the revenue stream for the company. Clearly, ARM is very focused in helping its customers ramp up products based on its processor cores. OEM customers in turn, do not have to reinvent the wheel and get readymade optimized embedded microprocessors for their products. This symbiotic relationship driven by ARM's flexible licensing strategy has helped the company with widespread adoption in embedded markets.

2.3 Products and Markets

The embedded computing industry covers a broad segment of computing devices. Figure 5 represents the primary embedded market segments for the embedded industry today. Clearly, Communications and Networking that include products like Wi-Fi routers in our homes to the network gear that powers today internet is the leading embedded segment. Automotive controllers that control the highly functional vehicles follow the communications market. The mobile handset, consumer electronics and Industrial automation contribute equally to the overall significant embedded markets.

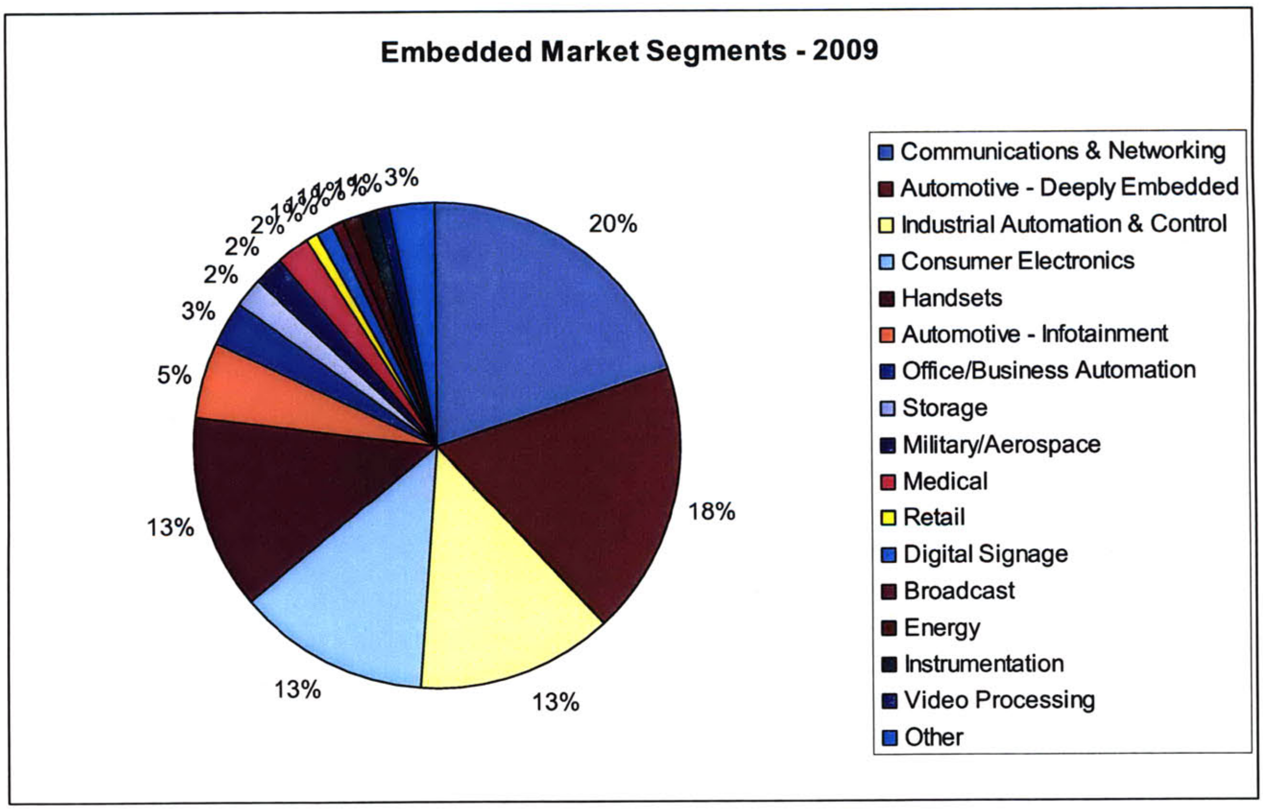


Figure 5: Embedded market segments by US dollar shipments 2009 (Adapted from IDC data)

Today ARM architecture dominates all these segments while Intel is still trying to establish itself in these segments. Figure 6 below represents the total volume market share by major players in these embedded segments.

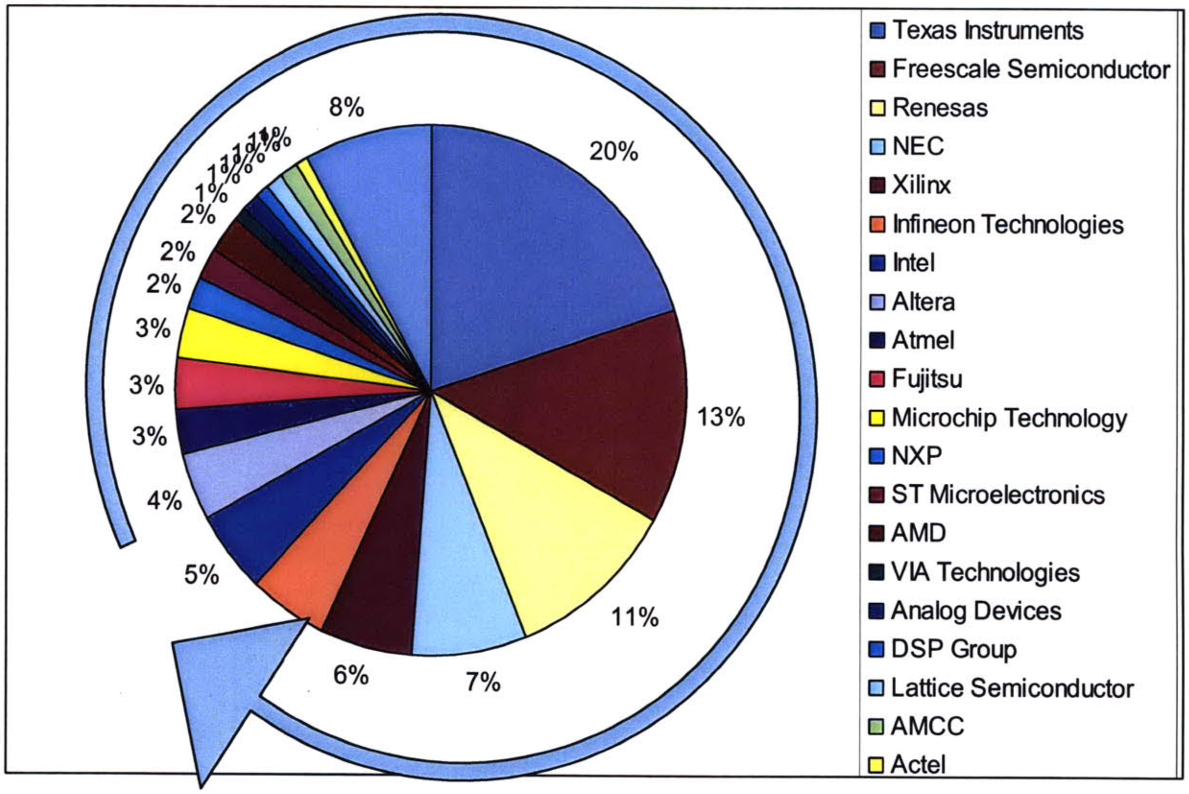


Figure 6: Embedded market segments by volume shipments for major OEMs (Adapted from IDC data)

Clearly, Intel is far behind with a mere 5% market share in the overall embedded market by volume. The blue arrow in Figure 6 shows the massive market share for ARM players compared to Intel. The top 5 players, Texas Instruments, Freescale Semiconductor, Renesas Technologies, NEC and Xilinx are all powered by the dominant ARM architecture.

Even though Intel is trying to catch up with ARM in the embedded segments, it is still the largest semiconductor company by revenue in the world. Intel has dominated this high margin lucrative business starting out with microprocessors for the PC industry and continued to dominate the platforms as they became smaller with laptops and now netbooks and nettops.

Figure 7 shows the netbook market for 2009, where Intel has a lion share of the market at 90% followed by the only other players who are all using ARM based architecture platforms.

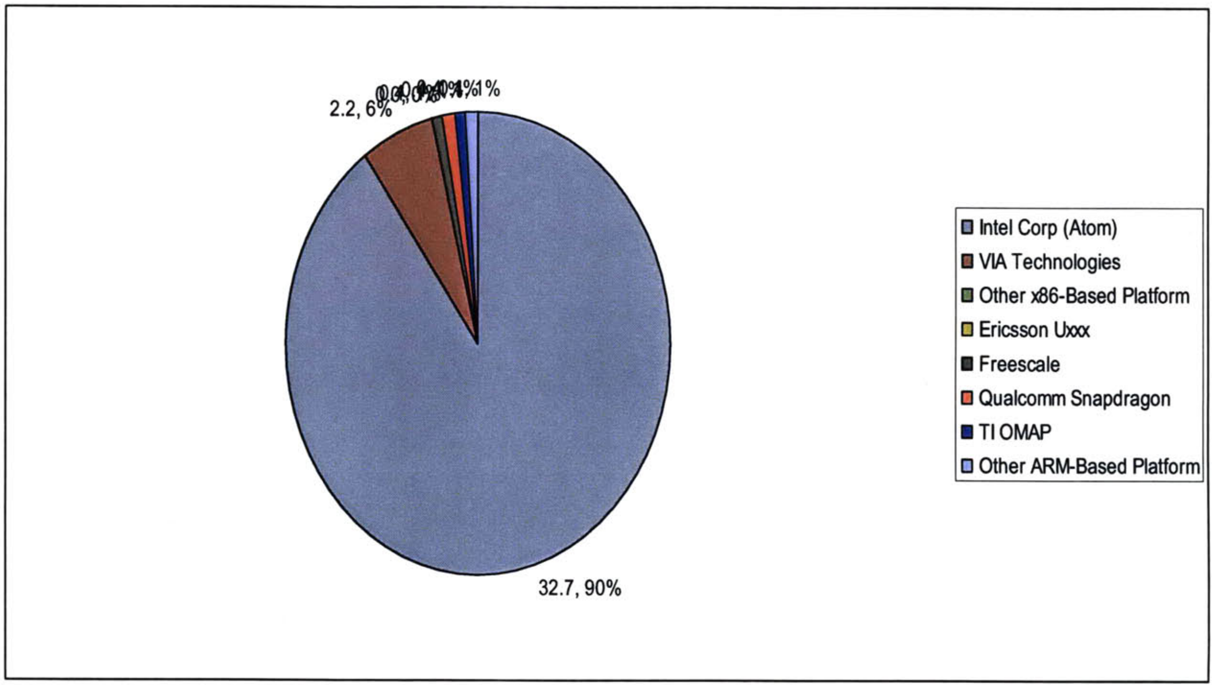


Figure 7: Netbook shipments by volume units (millions) by Platform

Though Intel is leading the netbook market, other ARM players are getting there as they have been dominating in the adjacent mobile phone markets for a while as shown in Figure 6. Apple's latest foray into the overall netbook and nettop market with a popular platform called iPad is an example of just that. Apple in iPad's case has reportedly licensed soft IP from ARM and has extended the design with its homegrown silicon expertise to come up with a powerful and efficient platform like iPad with a focus on user experience.

The classic battle comes into play in markets where Intel is the incumbent, like netbooks, ARM is coming in as a capable entrant with a wide and proven experience with mobile platforms. On the other side, markets where ARM thinks that it is the dominant incumbent, Intel is coming in as an entrant where it's trying to come up with lower power and efficient chips that has created a niche in the netbook segment adjacent to the mobile platform segments.

So, why is it that these two classic players have dominated their respective segments for a while and continued to do so as this battle took shape? The answer and possible explanation lies in the strong ecosystem strategies that Intel and ARM have followed over the years. Following sections will compare the business models and software strategies employed by these two dominant players.

2.4 Business Model

It's clearly seen in Figure 6 that ARM dominates the embedded markets while ARM by the company name, ARM Holdings Ltd. is nowhere to be seen. Instead major players like Texas Instruments and Freescale are the dominant OEMs (Original Equipment manufacturers) that have adopted the ARM architecture. Then what is ARM? ARM Holdings today is a very small company that licenses its intellectual property that is used by leading OEMs like Texas Instruments in their breakthrough products. But how can a small company like ARM continue to invent intelligent embedded designs that have dominated the embedded markets for so long? The answer to this puzzle lies in the business model of this powerful design house. Figure 8 shows the business model employed by ARM, where it licenses the technology and the intellectual property to its customers, the major embedded OEMs like Texas Instruments. In return though ARM establishes strict rules where any modifications and enhancements to its intellectual property are fed back into ARM through its close relationships with the OEMs.

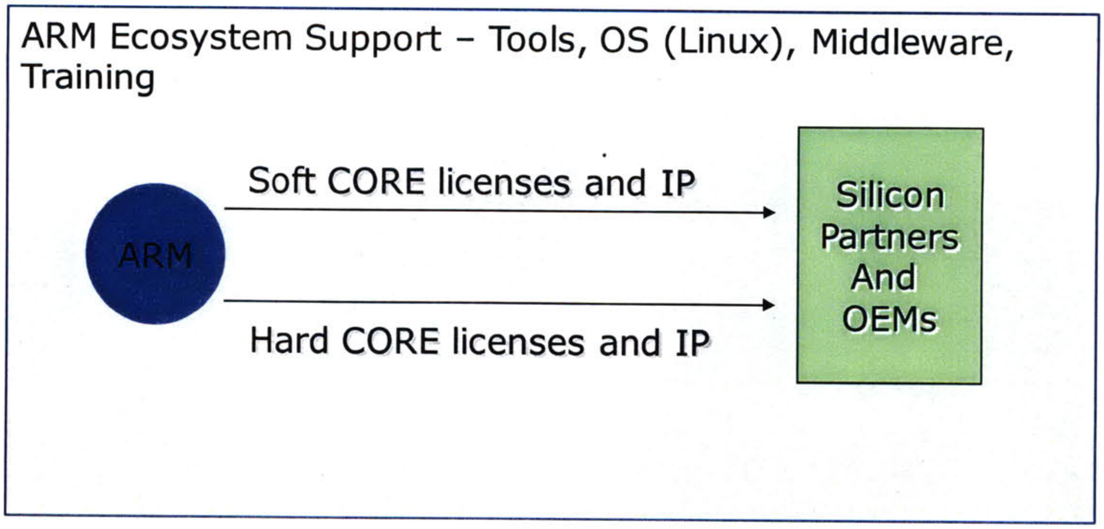


Figure 8: ARM's business model

ARM with its open licensing model has been able to create an ecosystem of tool suppliers, Operating System vendors and Middleware software vendors in its ecosystem. Silicon Partners and OEMs have benefited from the flexibility offered in the ARM licensing model in choosing soft and hard cores as they productized ARM based designs. ARM in turn has continued to focus on architectural innovation and standardization of its modular platform. Per license revenue for ARM is not close to what Intel gets in terms of margin per chip sale but ARM has managed to keep its operations lean and small while focusing entirely on research and development.

This model of open innovation where ARM continued to diffuse its technology into its ecosystem while continuing to benefit by the feedback loop of intellectual property enhancements is key to the dominance of this architecture seen in Figure 6.

Intel on the other hand prides itself in doing everything on its own. From very hefty Research and Development budgets to continuously innovate cutting edge architecture to designing and fabricating the chips in their own fabrication units, Intel owns the entire process. Intel in contrast with ARM is a product company and generates huge revenues and margins with its dominance in the microprocessors for personal computers. Over the years, Intel has been investing a lot of capital into their advanced fabrication units resulting in the most advanced silicon manufacturing fabrication units in the world. Figure 9 shows the manufacturing and revenue model for Intel.

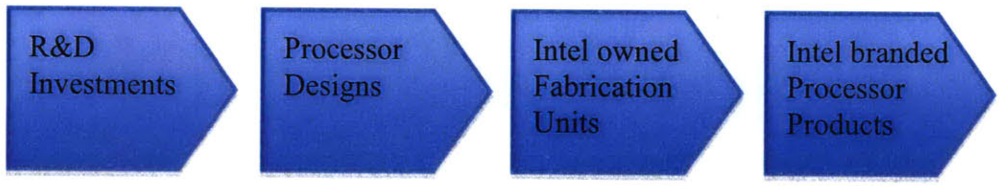


Figure 9: Intel Manufacturing Machine

Intel owns and manages the entire life cycle of products from concept to market delivery as shown in Figure 9

ARM, as shown in Figure 10 licenses the designs to OEM's like Texas Instruments that use their own branding and sales channel to productize the designs.

Figure 10: ARM's Product Flow

As described in section 2.2, ARM's focus on providing flexible licensing options to its customers have enabled it to focus its energies into research and development activities that has resulted in continuous optimization of its architecture. Unlike Intel, ARM manages to keep relatively low R&D budgets as its processor cores are evangelized and virally adopted by its close ecosystem partners.

To summarize, ARM has managed to be a very small research and development firm that has focused entirely on generating architecture and designs that were adopted and productized by its vast network of OEMs and other partners. Willingness to open its architecture to its partners has led to viral proliferation of the architecture and its designs into almost all segments of the embedded world.

Intel, in contrast continues to be a one-stop shop with advanced Research and Development of Intel Architecture based designs, world class manufacturing capability and a powerful marketing and branding machine.

3 Chapter 3 - Intel and ARM: Ecosystem Partners and Software

Intel and ARM have both developed into thriving keystones [4] where each of them comprise of powerful networks of partners and stakeholders called nodes [4]. Both these thriving ecosystems comprise of self-sustaining nodes with a symbiotic relationship between the partner nodes resulting in co-operative and mutually beneficial business relationships. Section 3.1 analyzes the partner ecosystems for these respective keystones. Section 3.2 delves deeper into the software analysis for ARM that has played a very important role in the proliferation of its ecosystem.

3.1 Ecosystem Partners

Figure 11 shows various types of partners that Intel needs in order to carry its business and sustain the manufacturing machine.

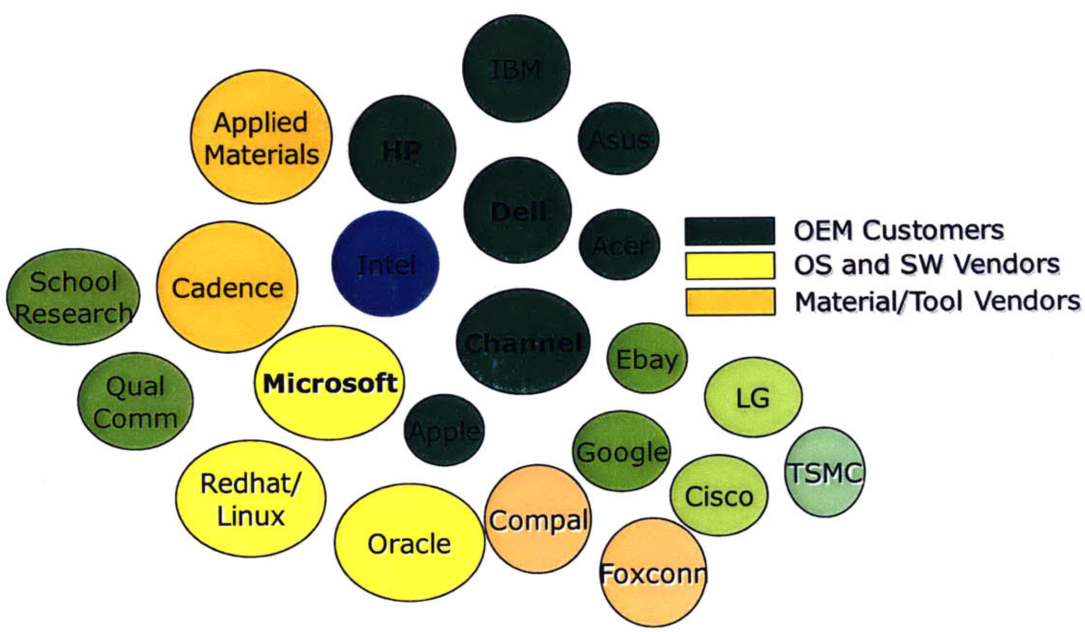
Partner Type	Partner Detail
Material Vendors	Suppliers for raw material like silicon and chemicals. E.g. Applied Materials
Design Tool Vendors	Chip Design tool vendors like Cadence and Mentor Graphics
Intellectual Property Vendors	IP used by Intel from outside vendors like Qualcomm and University networks
Operating System Vendors (OSVs)	Operating System enabling partners like

	Microsoft
OEM Customers (System Builders)	Major customers that use Intel products to build systems like Dell, Hewlett-Packard
Distributors	Direct distributors in the Channel (network of Small and medium enterprises that directly source Intel products)
Sub-component OEMs	Vendors supplying peripheral components like Chipsets that complete Intel products
Embedded OEMs	OEM customers and Vendors with a focus on embedded designs like Cisco, WindRiver (now part of Intel)
Contract OEMs	OEM customers that partner on specific or custom designs adopting Intel products. Examples include major players in Taiwan and Asia Pacific like Compal and Foxconn
Enterprise Customers	Primarily large scale enterprise software firms that source Intel Server technologies to run the internet and backend offices. Examples include Google and Ebay
Foundry Partners	Though Intel solely operates its own fabrication units, Intel has started to engage and outsource selected few designs to fabrication units like Taiwan

	Semiconductor Manufacturing Corporation (TSMC), the largest Fabrication company after Intel

Figure 11: Intel Ecosystem Partners

Out of all these major partners there are some prominent partners that play a key role in Intel's ecosystem. Operating System and Software partners like Microsoft have worked very closely with Intel in customizing their operating system to run best on Intel processors. There is a direct relationship between these partners at the core research and development level where collaboration and co-operation starts much early in the architecture and design phase of Intel's products. Figure 12 shows the prominent partners in Intel's ecosystem by vicinity to the Intel bubble.



Microsoft: By vicinity in this diagram is a major software partner for Intel
Oracle: Being farther in this diagram holds indirect relationship with Intel

Figure 12: Major Partners in Intel Ecosystem

Similarly, OEM customers like Dell and HP directly collaborate with Intel and feed in processor product requirements. Customers like Apple exclusively use Intel products and have thus far helped Intel fend off competition from the likes of Advanced Micro Devices (AMD) in the premium processor market for laptops.

Intel also has business relationships with material vendors like Applied Materials being one of the largest consumers of silicon and chemical raw materials.

ARM has a very similar network of partners and suppliers in its ecosystem but given the size and the nature of its business model the closest partners and collaborators are its direct licensing customers. Material vendors like Applied Materials for example doesn't have to deal directly with ARM because ARM is not a manufacturing house like Intel.

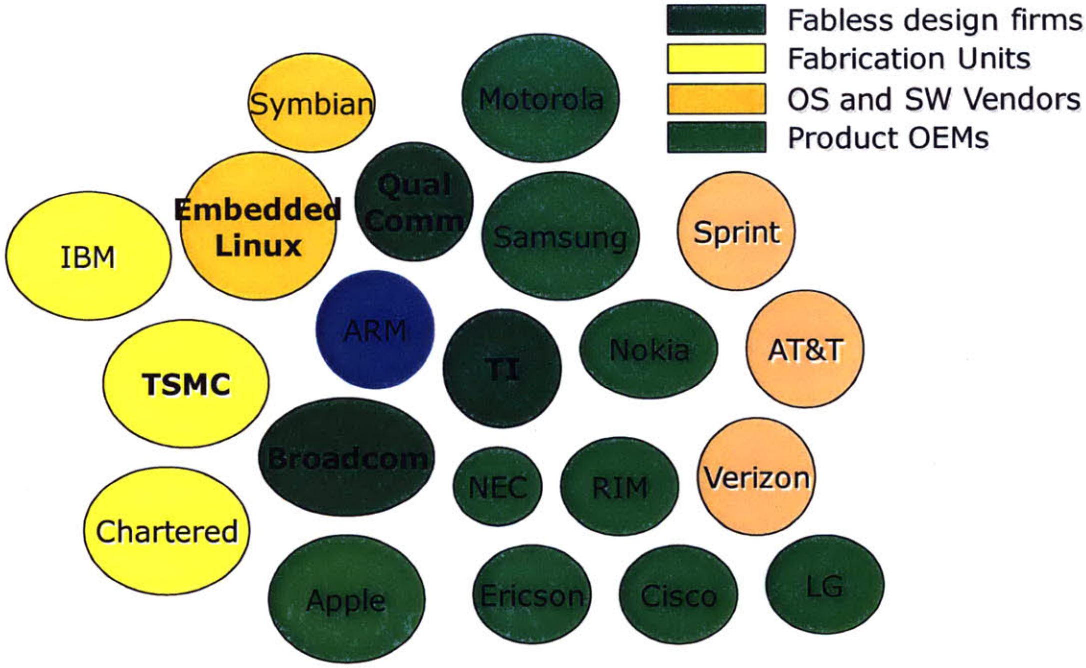
Figure 13 shows the type of partners that comprise the ARM ecosystem, from Fabless design companies to the operating system and software vendors.

Partner Type	Partner Detail
Fab-less Design Companies	Fab-less semiconductor design houses and giants like Texas Instruments directly license ARM architecture for their processors.
OEM Customers	OEM Customers like Motorola and Apple who deliver the finished products like mobile phones that use products from Design houses like Qualcomm and Texas

	Instruments
Semiconductor Manufacturers and Foundry Partners	Semiconductor outsourcing fabrication units like Taiwan Semiconductor Manufacturing Corporation (TSMC), the largest Fabrication company after Intel manufactures processors by taking designs from Fab-less design houses like TI
Operating System Vendors (OSVs)	Operating System enabling partners like MontaVista and RedHat Linux
Service Providers	End consumer service providers like mobile phone services companies that provide network and communication services on top of the finished products like mobile phones produced by OEMs like Apple

Figure 13: ARM Ecosystem Partners

Figure 14 shows the prominent ecosystem partners for ARM by vicinity. Fabless Design houses that license ARM architecture to evolve them into processor designs that can be manufactured at outsourced fabrication units like TSMC play a very important role in the ARM ecosystem.



Nokia: By vicinity in this diagram is a major mobile phone OEM with ARM designs LG: Being farther in this diagram is not as big as Nokia but does use ARM in consumer electronics

Figure 14: Major Partners in ARM Ecosystem

Perhaps the most important role in ARM's ecosystem is played by the operating system and software ecosystem enabled by Linux. Product OEMs like Apple and Nokia are the customers for ARM based processors and come up with user-friendly designs that make use of the underling ARM technology. Such OEMs also have significant in-house software capabilities that enable their products like the mobile phones. Apple iPhone, a popular smart phone is a great example of a finished product that has its own software ecosystem around it and was developed ground up by Apple. Figure 15 shows the hardware capabilities of Apple's iPhone powered by ARM technology.

Figure 15: ARM architecture in Iphone (Source: ARM Holdings Ltd.)

Almost all processor capabilities in iPhone as shown in Figure 15 are based on ARM architecture. From the core multimedia processor from Samsung to the wireless processing chipset from Marvell, all of them are based on ARM architecture. Most of these OEMs have reused ARM hard or soft IP cores to come up with productized versions of these processors.

It's evident that popular OEMs like Apple and Motorola have very successfully incorporated ARM architecture into their products, but the common glue that has made all this possible is the software ecosystem around ARM, based on open source Linux. Section 3.2 details the software capabilities around ARM architecture in general.

3.2 Software: Enabling ARM Architecture

During early nineties; as ARM was emerging as a major player in the low power embedded industry, cost of the finished product - be it an embedded part within an automobile or a low cost mobile phone, always played a very important and deciding role for the OEM companies. Emergence of Linux as an open source, free operating system at that time provided ARM and its

OEM partners with a viable platform of choice. On top of it the modular design and flexibility offered by Linux operating system and surrounding libraries provided the embedded OEMs with greatest flexibility in tailoring their embedded designs. The sheer variety of embedded segments and the custom nature of processor designs asked for a flexible software solution and Linux satisfied that need from all perspectives.

ARM's business model of open innovation with its partners fit extremely well with the open source model of development provided by the Linux community.

Figure 16 provides a snapshot of Linux development model and the open source community around ARM architecture.

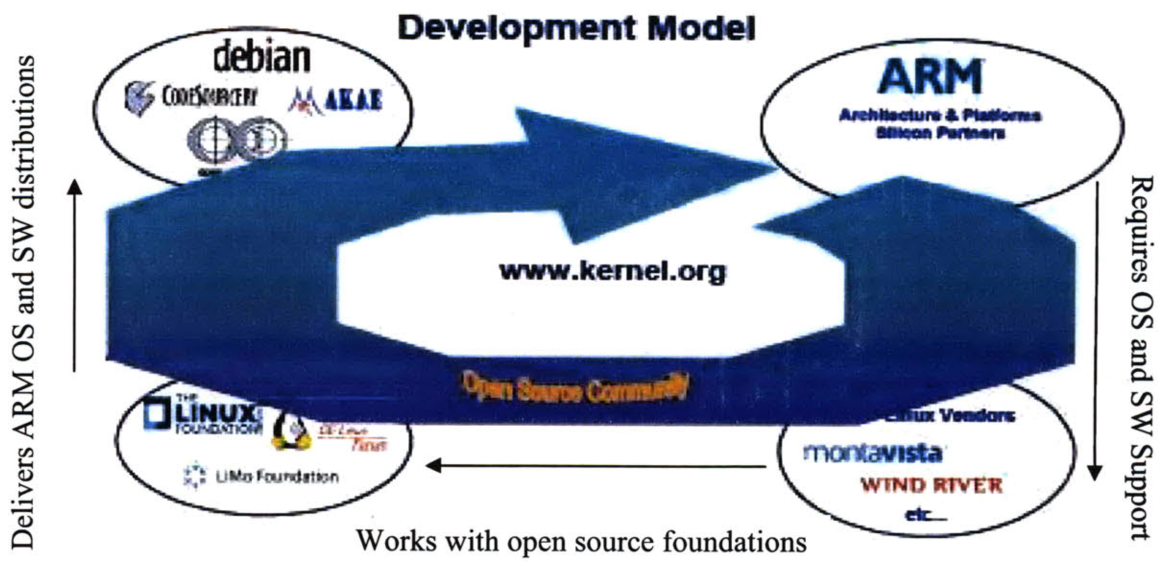


Figure 16: Linux Software Ecosystem around ARM (Adapted from ARM Holdings)

ARM directly works with open source community at all the levels. Its close OEM and silicon customers and partners directly work with individual Linux vendors. These vendors in turn contribute to the core changes in the Linux kernel working with Kernel.org while at the same time work with the Linux foundation to contribute to the foundation libraries that take advantage of ARM architecture. These changes and enhancements are subsequently picked up by open source Linux distributions like Debian that is customized by Open source software vendors like MontaVista for major product OEMs like Motorola. Google's latest mobile operating system – Android is based on open source Linux derivatives as well. The operating system and software libraries that power the user friendly user interface (UI) for Android based smart phones today are all based on open source Linux derivatives and libraries.

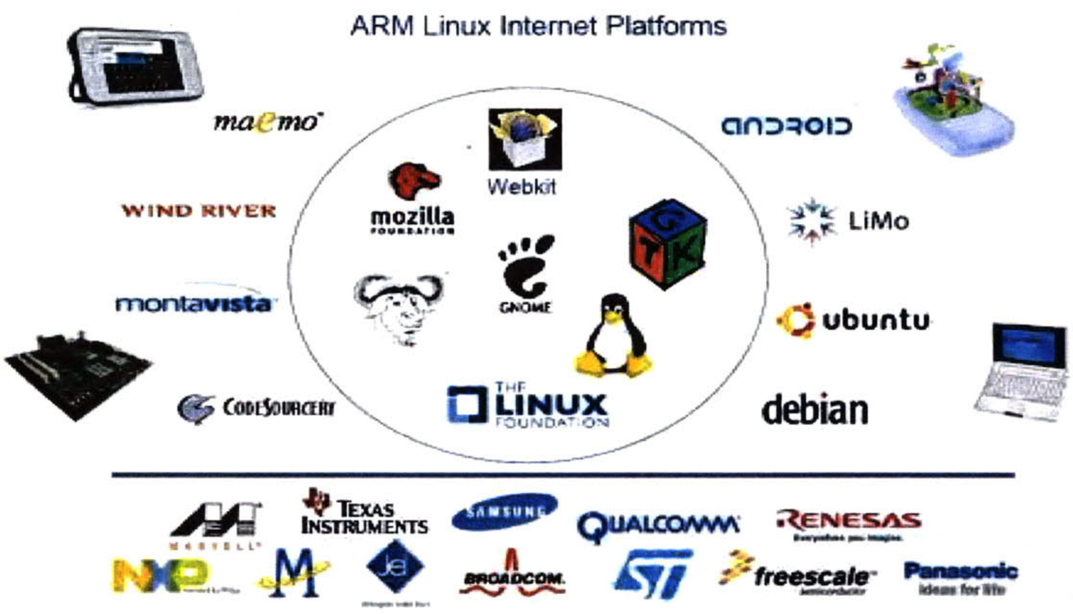


Figure 17: Prominent Linux Platforms for ARM (source: ARM Holdings Ltd.)

Figure 17 provides a snapshot of operating systems and software development platforms that are all based on Linux and are powered by ARM based architecture and processors underneath. Android for example is a new operating system entrant driven by Google in the Smartphone space and has been quite successful in leveraging its open source development capabilities to create a thriving ecosystem of application developer community around it. Maemo, a derivative

Linux platform developed by Nokia found its way into Linux based Smartphone's pushed by Nokia in the mobile space.

ARM's business model and open model of development around its architecture is a classic example of how open innovation percolates [9] to subsequent innovation platforms. Open source development community [6] around Linux operating system has taken Internet and the underlying software powering it to great levels; it has helped ARM achieve its goals of proliferation into the embedded world in similar fashion.

While ARM has tremendously benefited with the power of open source Linux, Intel has always had its own connections with Linux and the open source community. Chapter 4 analyses Intel's open source software capabilities and recommendations based on this thesis work in detail.

4 Chapter 4 – Intel: Embedded Software Analysis, Delivering value to Silicon

Intel has had great relationships with the Operating System and Software vendors like Microsoft, who have played a major role in the overall success of Intel based platforms. The Microsoft Windows and Intel alliance, called Wintel [1] has long dominated the PC industry with easy to use personal computers affecting everyday lives of people in all segments of computing. Microsoft has been the dominant player in the operating systems for personal computers and its alliance with Intel worked very well all these years, however advent of Linux during nineties did provide Intel with a viable OS alternative.

4.1 Background: Linux at Intel

The flexibility and positive cost factors of enterprise Linux that power most server computers in world today led Intel to develop in-house Linux capabilities to support its platforms. Since the very early days of Linux, Intel has been a very active contributor to the Linux kernel and today houses one of the most talented open source developer and Linux community contributors at its facilities.

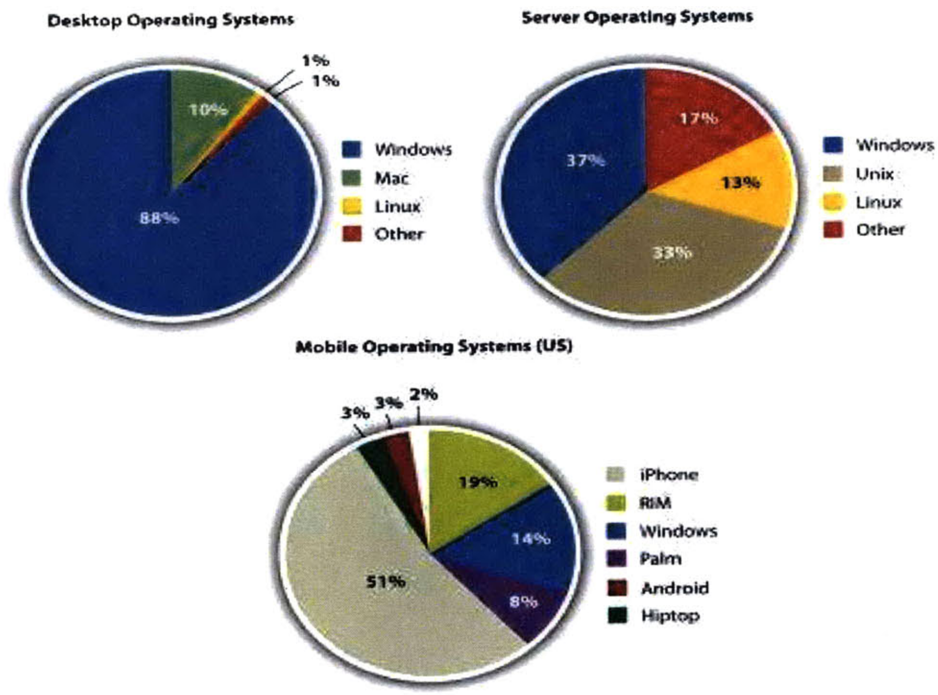


Figure 18: Operating System Market Shares by Platforms [10]

Figure 18 provides a snapshot of market shares for different operating systems by Platforms. Clearly, Windows from Microsoft dominates in the Desktop segment. However, Linux and Unix based open source distributions dominate Server operating systems. Linux based derivatives also continue to dominate the mobile Smartphone space. Intel being a processor company never overlooked the flexibility and customizable nature of Linux that suited server product lines very well and took advantage by having direct relationships with open source vendors like RedHat to enable Red Hat Linux Enterprise distributions. Intel continues to maintain and contributes heavily to a number of open source projects, however Intel had limited success in the mobile phone and embedded markets that has always been dominated by ARM architecture. In recent years, Intel has jumpstarted its efforts to go after the lucrative mobile platform markets and had seen initial success in its low power Atom based product lines that power most netbooks and nettops in the world today.

4.2 Moblin.org: Intel's Mobile OS Distribution

As Intel ventured into creating a segment for its low power Atom line of processors, it realized that the segment would entail easy to use portable devices whose form factor would reside between a laptop computer and a mobile phone. Given, that it was an entirely new category; Intel went on to come up with its own mobile Linux distribution. Moblin was devised for Intel Architecture based mobile internet devices and has been maintained and run by Intel as an open source project at Moblin.org.

Figure 19 provides a snapshot of the Moblin Software stack. Moblin is based on Linux kernel and leverages the capabilities provided by the open source operating system and middleware libraries. The Linux kernel modules and drivers power the software stack at the lowest level. Application services layer is highly modular in nature as well. A low cost, power efficient Netbook requires an OS that could be customized by the product OEMs based on the targeted segment. Platform capabilities to add or subtract components based on the power and space requirements for the target device were also added to the OS. Application Services thus comprise of separate modules for core services like the network connection services, Web services and Graphics services for example. User Interface libraries take advantage of the underlying graphics capabilities of the platform and power the multimedia applications for the platform.

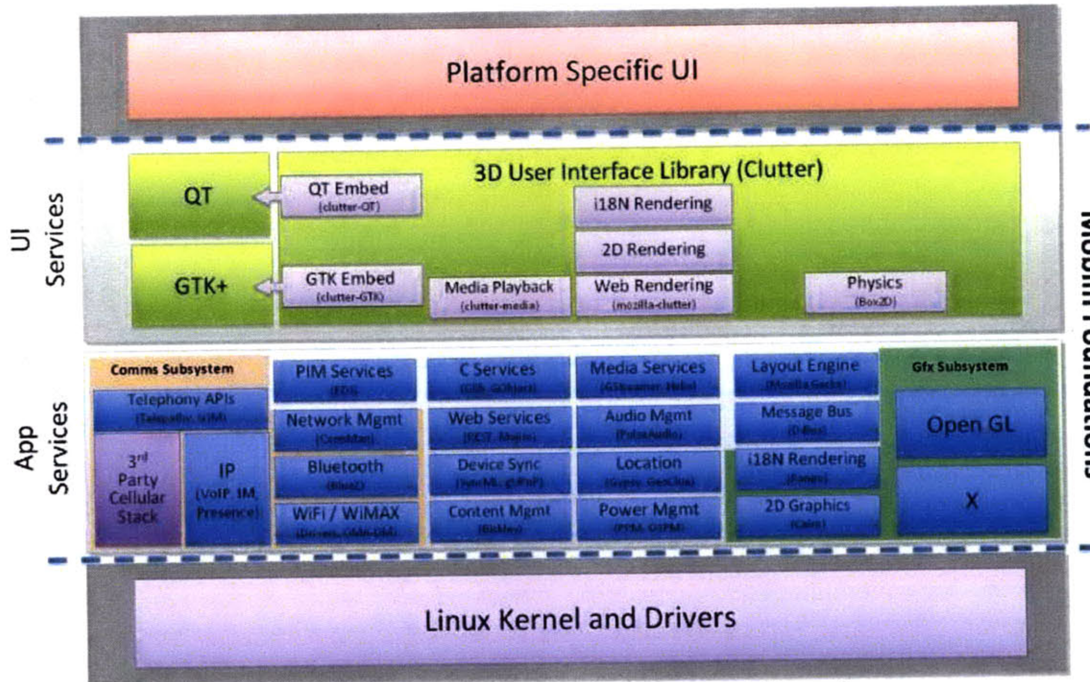


Figure 19: Intel's Moblin Software Stack (source: www.Moblin.org)

Moblin being an open source operating system also enables an ecosystem of software developers that want to tweak or customize the operating system based on their preferences. For easy development of Moblin based applications for mobile internet devices, a Moblin Application Software Development Kit (SDK) is also provided. Overall, Moblin and its derivatives played a key role in giving Intel a significant lead as it pushed its low power Atom based products into newly created segments like netbooks.

4.3 Embedded Segments: Rapid Enabling Needs

As Intel tries to grow its market share in the embedded markets, which are dominated by ARM, Intel needs a comprehensive software strategy. With significant success in the low power netbook market, Atom and its derivatives being developed at the Embedded and Communications group at Intel has now found its way into emerging embedded segments that have been primarily dominated by ARM. Some of these notable segments are as following:

- In-Vehicle Infotainment – This segment includes Intel platform powered easy to use touch based devices that provide vehicle users with vehicle diagnostics, relevant information and entertainment inside the vehicle on the go. This usually involves a very easy to use touch-based interface on the vehicle dashboard giving power to the vehicle owner to control most features in the vehicle.
- Mediaphones – This segment involves intelligent mediaphones with touch-based user interface that are way smarter than the traditional handset based phones. Mediaphones provide a dashboard inside the home to access information, entertainment as well as manage household tasks. These are usually always on, always connected devices and utilize the internet backbone for connectivity and information.
- Digital Signage – Digital Signage represents a highly lucrative but fragmented digital signs market. Intel embedded platforms could use Intel's technology to remotely manage and control electronic displays of variable sizes. Content and advertising information could be pushed to these signs depending upon surrounding conditions and factors like the time of the day, vicinity of end users and location of the signs.
- Premises Services gateway – Premises Service Gateway is another high growth segment that would be an efficient home gateway device managing and controlling the inflow and outflow of information in an household. As traditional home internet routers become more intelligent by the day, they are going to be replaced by these service gateways that bring capabilities like local home storage, on demand backup, home energy control and many other household services based on Intel platforms

These high growth segments have rapid enabling needs that cannot be met by traditional software enabling practices. It becomes strategically all the more important as the segments grow by the day. From energy control to industrial automation, Intel's low power embedded offerings have an opportunity to positively impact the company's ecosystem and the bottom line.

Other important notable factor for all these segments is the involvement of end consumer. Latest mobile smartphones like the iPhone are a good example of devices that carry a great ecosystem of applications and application developers with them. Over time consumers have asked for more control and more applications and it has become all the more important for product OEMs to device downloadable application stores. This in turn has helped major OEMs like Apple to strategically earn recurrent revenues per device by selling targeted content and applications through their stores. From In-vehicle Infotainment to Premises Services gateway, consumers want control over applications and features to manage these devices. Section 4.4 proposes a software architecture and methodology to accelerate rapid enabling for these embedded segments based on experiments done with the software stacks for this thesis.

4.4 Leveraging Software Modularity for Embedded Segments

Figure 19 provides a generic stack for the Moblin OS Framework. Moblin is a modular operating system platform powered by the flexible Linux kernel and libraries. The modularity of the platform could be leveraged to add and subtract the libraries based on the platform segment that needs to be enabled. Modular architecture could be advantageous for enabling platform segments that require same core capability while differ in peripheral capabilities.

For example, Premises services gateway (PSG) is a headless device without any core UI capabilities but could have a web browser interface. Thus for PSG, Moblin stack can be reused for the core underlying Intel Atom platform capabilities while direct graphics support can be removed. At the same time a PSG device will need home control capabilities and sensor features that would require extra middleware requirements.

Figure 20 shows an adapted Moblin SW stack for the PSG segment. Graphic capabilities are removed from the software stack while sensor control capabilities are added.

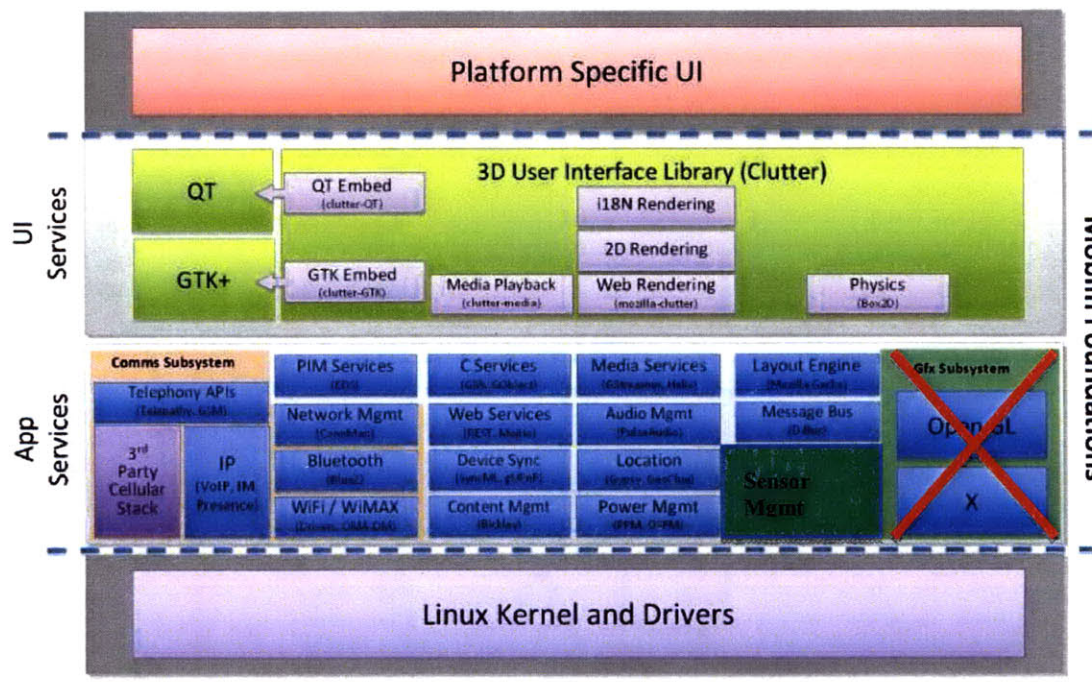


Figure 20: PSG Platform stack evolved from Moblin (Adapted from Moblin.org)

Similarly, other embedded segment software stacks for mediaphones etc. can be derived from the original Moblin stack.

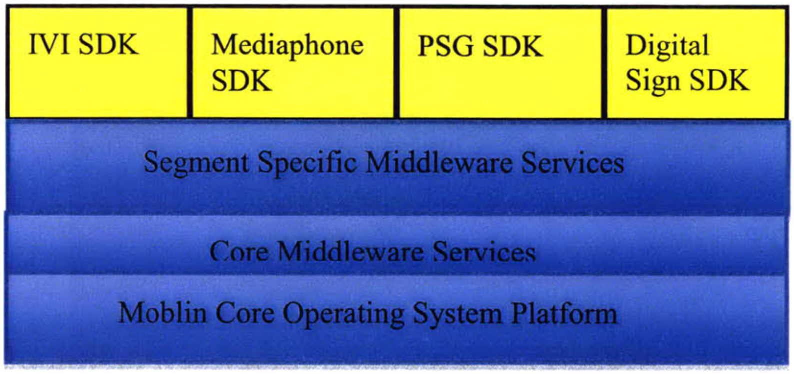


Figure 21: Embedded SDK's for various segments

Figure 21 provides an architecture where Segment specific middleware services can serve specific needs to enable a segment on top of the core middleware services provided by the Moblin Platform. These SDKs could be published to the developer community and Intel's customers that could take advantage of the Application Programming Interfaces (APIs) to develop segment specific applications.

A modular SDK architecture and software methodology [2] is critical for Intel to grow its embedded segments and close in the time to market with competition. Meanwhile the embedded ecosystems continue to evolve with mobile segment showing the most rapid growth. Chapter 5 in conclusions section relates this work to the current context for Intel and ARM

5 Chapter 5 - Conclusions

The following sections conclude this thesis with two four takeaways for Intel's ecosystem strategy. The recommendations are compared with the current context as the embedded revolution is dynamic in nature and is very current to this thesis work.

5.1 Need for a collaborative ecosystem

Analysis in this thesis has shown how an open licensing model along with symbiotic relationship with its partners catapulted ARM into a dominant embedded architecture leadership position. Intel has long preserved its intellectual property and does not have a functional licensing model for its architectural designs. While, this has worked well for Intel from a business perspective and Intel may very well continue to do so, Intel's foray into mobile and embedded markets require new thinking. Intel's Atom processor line of products for mobile and embedded computing has made some good inroads but establishment of cross-licensing agreements to leverage the design would enable customers who have been looking for flexibility and customization in the embedded markets. Intel could learn this well from the way ARM manages its partners. Atom line of processors have worked well for netbook segment but portable mobile smart phones today require even greater power optimized cores that are catered by ARM. Intel needs that technical knowledge and foundry expertise from ARM manufacturers to do advanced power optimized designs.

5.2 Winning with Software: Reverse Disruption

Recently, Intel and Nokia announced a major collaboration agreement. The agreement was around joining forces behind a common operating system software platform for mobile Internet devices. The new venture is called MeeGo. MeeGo combines Moblin and Nokia's flagship Maemo software platform. MeeGo will continue to be an open source platform like Moblin but will bring in the greater mobile know-how and expertise from Nokia's software development community.

It remains to be seen whether MeeGo is able to enable Intel to advance into various embedded segments but the initial architecture supports and validates the work in this thesis. In the current context ARM is the incumbent while Intel is trying to disrupt [5] its territory by innovating a competitive mobile software platform. In the current context this is a case of reverse disruption by a dominant player like Intel.

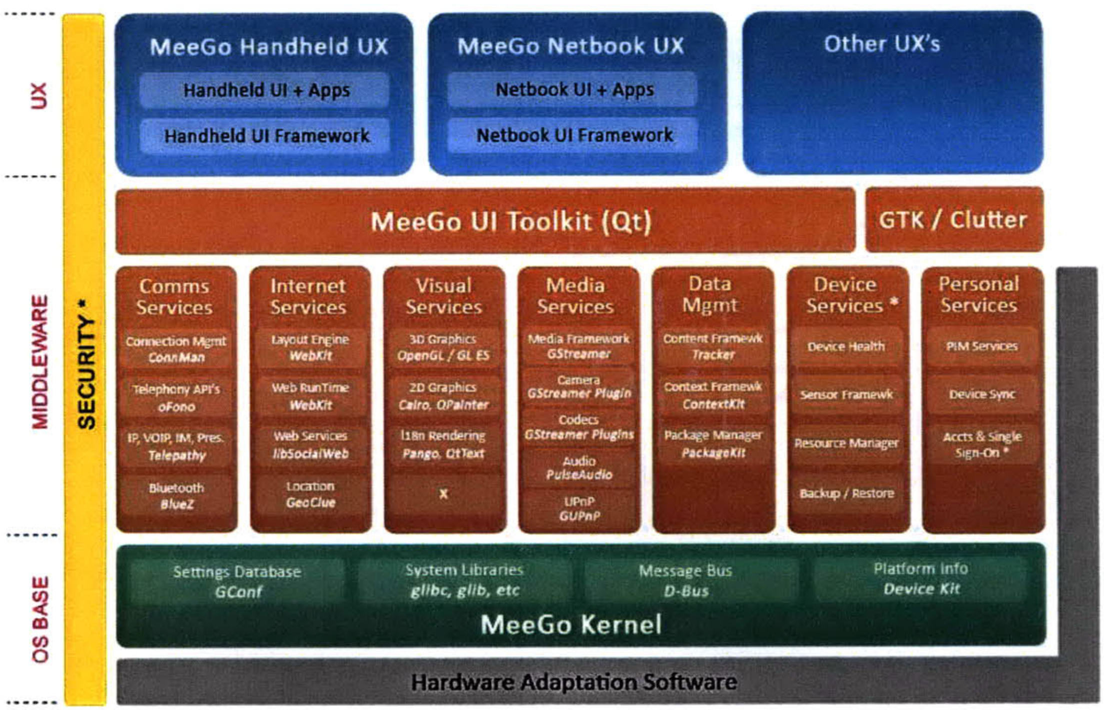


Figure 22: MeeGo Architecture – Intel Nokia Alliance (source: www.meego.com)

It should be noted in the Figure 22 that not only MeeGo provides more modularity then compared to Moblin but it takes the modularity down to the hardware level where MeeGo unlike

Moblin will run all various hardware platforms. Hardware Adaptaion Software layer provides an additional layer of abstraction to the underlying hardware thus enabling software application developers irrespective of the platform specifics.

5.3 Application Ecosystem

Intel has come a long way in developing core software competency around its platforms, but as Intel tries to enter the mobile and embedded ecosystem; its platforms will need a comprehensive application development environment. Today popular mobile platforms like the iPhone and Android deliver value to end customers through the rich application ecosystem around the platform. Intel with its MeeGo alliance has a chance to evangelize an application developer community around its platforms. Intel Atom developers program is a step in this direction but more needs to be done soon. The application store strategy could also be driven in partnership with notable OEMs for Atom platforms. It's important to excite the application ecosystem developer community even if it requires collaboration and licensing arrangements with its OEM partners rather than waiting for its own Application store strategy to pick up one day.

5.4 Open Innovation: From in-house to outsourced fabrication

Intel has always had its own homegrown fabrication units and has never licensed its architecture or designs to any other firm. However, as Intel tackles the challenge of highly customizable embedded hardware – Intel needs support from ecosystem partners of ARM who have the expertise and experience in the embedded space. Recently, Intel has entered an agreement to selectively license some of its Atom based system on chip designs for fabrication at Taiwan Semiconductor Manufacturing Corporation (TSMC). This is a major step from Intel in opening up its architecture to a limited audience. In return, Intel is going to benefit with the years of

ARM based embedded manufacturing experience that TSMC brings to the table. Intel in this case is trying to partner with a major node [4] in the ARM ecosystem. This is a breakaway from the legacy strategy of exclusively using their own fabrication units by Intel, in the long term however open exchange of technology between these players will evangelize the adoption of Intel architecture into ARM embedded territories.

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