Taking technological infrastructure seriously

Mair, C.S.

CHAPTER 5

INTEL, ARM AND PRIVATE ORDERING APPROACHES TO TECHNOLOGICAL INFRASTRUCTURE

I. INTRODUCTION

This chapter focuses on the role of business model innovation in ensuring the open access of technological infrastructure. Unlike previous chapters, which have focussed on the interaction between private ordering with an additional institution, such as competition law (chapters 1-2), public R&D subsidies (chapter 3), or the demand-side instrument of public procurement (chapter 4), this chapter argues that business model innovation and private ordering alone are sufficient to sustain the infrastructural approach of 'if infrastructure, then open access'. In particular, this chapter examines the CPU 'standards war' in the market for smartphones and embedded devices, including the evolving 'Internet of Things'. It looks in detail at the very different business models of ARM and Intel in this market, and analyses the extent to which ARM's infrastructural approach to IP licensing is helping it consolidate its position as the de facto CPU standard.

In June 2014, the General Court of the European Union ('EU') issued its decision in the *Intel* antitrust case.[867] The decision threw out in its entirety an action for dismissal brought by Intel Corporation ('Intel') against the European Commission's 2009 decision to fine Intel 1.06 billion Euros for anticompetitive practices. That decision was remarkable both for the magnitude of the fine (still the largest to date under Art 102 TFEU in the field of antitrust[868]) and for demonstrating the Commission's willingness to intervene in a market characterised by exponentially falling prices[869] and product performance increases. [870]

From the vantage point of 2017 (the time of writing), the decision is also remarkable for what it does not contain. Nowhere in its 517 pages does the original decision make even a passing reference to the company whose CPU designs have come to dominate the space for personal mobile devices ('PMD'), the ultra-portable form of personal computing which is eating up the market once dominated by the traditional PC. That company- ARM Holdings ('ARM')[871]- is now widely acknowledged to be the nimblest and most formidable challenger for Intel's

867. Case T-286/09 *Intel v Commission* (12 June 2014).

868. Damien Geradin, and Katarzyna Sadrak, 'The EU Competition Law Fining System: A Quantitative Review of the Commission Decisions between 2000 and 2017' (April 25, 2017). Available at SSRN: https://ssrn.com/abstract=2958317

869. Wouter P J Wils, 'The Judgment of the EU General Court in Intel and the So-Called "More Economic Approach" to Abuse of Dominance' (2014) 37(4) World Compet. Law Econ. Rev. 405.

870. Intel , 'Why the European Commission's Intel Decision is Wrong', <http://www.intel.com/pressroom/legal/docs/EC_response092109.pdf> accessed 14 October 2016, 2.

("[i]t is perhaps most remarkable that the Commission's decision essentially ignored the undisputable fact that microprocessor prices have declined significantly year over year, while innovation has proceeded at a stunning pace, and output has been expanding rapidly, more than tripling in recent years.")

871. In 5 September 2016, ARM Ltd was acquired by the Japanese company SoftBank Group < http://www.reuters.com/article/us-arm-holdings-m-a-softbank-group-idUSKCN0ZY03B>

respective home-turfs of personal computing and business servers, while currently powering 85% of all PMDs and upwards of 90% of 'wearables'.[872]

That the Commission decision failed to mention ARM as a potential competitor or dynamic constraint on Intel[873] is only remarkable from the vantage point of the time of writing. The process of dynamic competition in high technology is inherently disruptive.[874] At the time of the 2009 decision, the PMD sector was promising, but essentially restricted to smartphones[875]; in 2006- when the empirical surveys informing the decision were undertaken, the few PMDs which did exist were focused almost solely on commercial customers[876]; and in 2000, it didn't yet exist.

Although the prediction of technological trends can be a dangerous exercise[877], it is clear that the space of personal computing is rapidly changing – and in the direction of increased mobility. New constraints on CPU design (such as requirements of portability and power efficiency) have caused major disruption to the traditional PC research and development ('R&D') trajectory of ramping up raw processor power on the coat-tails of Moore's law.[878] ARM's mastery of these design constraints within the PMD space threatens to spill over into the whole (post-) personal computing market, as consumers and software developers place their bets on a single dominant microprocessor platform to harvest the positive network effects of the platform leader.[879] ARM's PMD market dominance also threatens to spill over into the evolving 'Internet of Things' ('IoT')- the networks of ultra low-power embedded devices, which seem to bestow sentience on an increasing array of everyday objects.[880] The battle for the microprocessor 'infrastructure' of the IoT, however, (unlike the PMD space) is

---

872. ARM Strategic Report 2015 <http://ir.arm.com/phoenix.zhtml%3Fc%3D197211%26p%3Dirol-reportsannual> accessed 14 October 2016.
873. For understanding of 'dynamic constraint', see Guidance on the Commission's Enforcement Priorities in Applying Article 82 of the EC Treaty [2009] OJ C45/02, para 16 ("[c]ompetition is a dynamic process and an assessment of the competitive constraints on an undertaking cannot be based solely on the existing market situation. The potential impact of expansion by actual competitors or entry by potential competitors, including the threat of such expansion or entry, is also relevant.").
874. Baker, 'Dynamic Competition'.
875. *i.e.,* the market for tablet devices was still underdeveloped
876. *i.e.,* mainly Blackberries and Nokia devices, as the iPhone of 2007 was not yet released. <https://www.canalys.com/newsroom/64-million-smart-phones-shipped-worldwide-2006> accessed 14 October 2016.
877. See Wu, 'Intellectual Property', 103 ("[i]n the 1980s, the Japanese government, consulting with experts, predicted where computer technology would be in ten years. The government then launched a huge national effort to build the predicted technologies, hoping to leapfrog other countries… The project was, unfortunately, centred on the mistaken belief that mainframe computers would remain dominant and that parallel supercomputing was the key to the future. It completely missed other less grandiose innovations, like the personal computer, the graphical user interface on the Apple Macintosh, and the computer networking now called the Internet. The project was an abject failure that damaged the Japanese computer industry.")
878. Daniel Nenni and Paul McLellan, *Fabless: The Transformation of the Semiconductor Industry* (SemiWiki 2013).
879. Lao, 'Terminal Railroad to Microsoft '.
880. David Rose, *Enchanted Objects: Innovation, Design, and the Future of Technology* (Scribner 2014) ("Rose, 'Enchanted Objects'").

still very much alive. Both Intel and ARM are heavily investing in attempting to become the *de facto* standard technological infrastructure, by scaling down their microprocessor designs to meet the extremely small power 'footprint' requirements of IoT devices, together with developing and supporting the tiny Operating Systems ('OS') needed to power them.[881]

This chapter argues that a large component of this 'standards war' will be determined by these two companies' very different approaches to innovation (including business model innovation), intellectual property, and industry partnerships. While ARM is essentially a pure IP company, engaging solely in R&D and liberally licensing its IP for (comparatively) razor-thin profit margins[882], Intel is a vertically integrated R&D and microprocessor fabrication company, which does not usually license its IP except by court order[883], and is used to raking in significant profits.[884]

The distinction between these two approaches to innovation and intellectual property licensing- one comparatively 'open', the other comparatively 'closed'- is argued to be a main determinant in the battle for the emerging post-PC marketplace. ARM's openness with respect to licensing its IP (often dubbed a 'partnership approach') has enabled it to become a key supplier of microprocessor designs across the semiconductor industry and have arguably helped it to become a *de facto* standard in both the 'embedded' and PMD spaces. ARM's approach can be viewed as a special case of the 'infrastructural approach' developed in this thesis, where ARM has used an open licensing business model to establish itself as the de facto CPU infrastructure of the PMD space; superficially, at least, reversing the logic of the infrastructural approach. [885]

This IP licensing strategy has permitted ARM to rapidly develop an 'installed base'[886] and leverage the power of 'indirect' network-effects[887] to ensure a vibrant downstream software

881. In many cases, these OS's are simply scaled-down versions of the open source embedded Linux operating systems, as discussed in Part IV

882. See Charlie Demerjian, 'How ARM Licenses its IP for Production' (*SemiAccurate* 8 August 2013) <http://semiaccurate.com/2013/08/08/how-arm-licenses-its-ip-for-production/>.

883. Such as toVIA and AMD, the only two companies who maintain a license to Intel's proprietary 'X-86' CPU architecture. See discussion in Greg Tang, 'Intel and the x86 Architecture: A Legal Perspective', (*Jolt Digest* 2011) http://jolt.law.harvard.edu/digest/patent/intel-and-the-x86-architecture-a-legal-perspective-2> accessed 14 October 2016. See also discussion of the X-86 architecture as an 'essentialy facility, W. Greg Papciak 'Intergraph Corp. v. Intel Corp.', 14 Berkeley Tech. L.J. 323 (1999).

884. Intel's Gross Margin Percentage for 2016 was 60.90%. See Intel Annual Report https://s21.q4cdn.com/600692695/files/doc_financials/interactive/2016/index.html

885. As will be developed further in this chaper, ARM's CPU designs have infrastructural characteristics (by being generic, non-rivalorous, and able to support downstream production); however, open access licensing are helping it establish the status of technological infrastructure *in fact*.

886. For importance of quickly establishing an installed base in network industries, see generally Annabelle Gawer, *Platform Leadership: How Intel , Microsoft and Cisco Drive Industry Innovation* (Harvard Business School Press 2005).

887. As mentioned in chapter 4, 'indirect network effects ' are simply the positive effects which the development of the downstream markets for complementary products (and services) have on the upstream technical platform. See

ecosystem making use of its CPU designs, such as its strong relationship with the open source Android software platform.[888] By contrast, Intel's historically closed approach to IP licensing has enabled it eat up the whole value chain from CPU design all the way to the final (CPU) product, and contract directly with device makers or Original Equipment Manufacturers ('OEMs'). However, by walling up the garden around its microprocessor architecture, Intel has prevented independent semiconductor design houses from using its designs as inputs to downstream products. This has so far (at least in the PMD market) arguably prevented Intel from being able to flood the market with compatible CPU architectures in the way ARM has, and thus has arguably prevented it from leveraging the indirect network effects in complementary software and hardware platforms to establish itself as the dominant technological infrastructure.

To briefly preview this chapter's conclusion: ARM's open approach to IP licensing enables its CPU designs to scaffold genuine 'bottom up' innovation, by permitting downstream semiconductor companies to easily and quickly configure and adapt ARM's designs to new use-cases and applications, as well as providing device makers with a genuinely competitive and diverse market of suppliers. It is argued that if scholars and observers of the rapid expansion of the PMD market have learnt anything from the dual PMD successes of ARM and the open source mobile OS, Android[889], it is that diversity, complexity and proliferation of successful solutions is scaffolded by an open and decentralised approach to technological infrastructure.

The chapter will be structured as follows. After this introduction, Part II will begin by a brief overview of the nature of the semiconductor industry (Section A) followed by a survey of IP licensing approaches in high-technology markets (Section B). Part III will then provide a historical and technical review of Intel (Section A) and ARM (Section B), linking their business models to their approach to IP licensing in both the PMD market and the nascent IoT space. Part IV will then provide an analysis of the complex relationship between microprocessor architecture, software OSs, and IP licensing strategies. This will include taking a close look at Google's open source Android platform (Section A), the feasibility of 'porting' an OS to a non-native microprocessor architecture (Section B), and an analysis of what the findings from these two sections mean for ARM and Intel's battle for the evolving IoT space (Section C). This last section will also draw some important distinctions between the PMD and emerging IoT markets, suggesting that ARM's model of 'bottom up' innovation is uniquely suited to the requirements of the IoT market. Part V will conclude.

---

generally Economides, 'Competition Policy in Network Industries'. See also Lao, 'Terminal Railroad to Microsoft '; Mair, 'Taking Technological Infrastructure Seriously'.

888. However the actual openness of the Android OS in practice has been brought into question by a recent EU Commission antitrust investigation, see Commission, *Press Release MEMO-16-1484*.

889. Therefore also Linux OS, on which Android is based.

II. SEMICONDUCTOR INDUSTRY: OVERVIEW AND THEORY OF IP LICENSING

The semiconductor industry has long been a subject of study for both legal and economic scholars due to a number of unique characteristics. Over the last decades, the industry has been radically transformed by processes of deep vertical 'dis-integration'[890] and disaggregation, which has led to the creation of hyper-specialised niche companies focused on tightly specified tasks. The highly fragmented industry structure that has emerged has necessitated a unique approach to knowledge sharing, collaboration and intellectual property licensing, leading to a web of interdependence, referred to as the 'semiconductor ecosystem'.[891]

As will be shown in Section A below, much of the driving force behind this dis-integration has been due to the unforgiving economics of semiconductor R&D, which has required the mobilisation of enormous financial and human capital resources to keep up with the market demand for continuous innovation. The highly complex pattern of interdependence and knowledge sharing that has emerged as a result of these forces has also interested IP scholars, who focus their analysis on the unique types of intellectual property licensing in this knowledge-intensive industry.[892] In a seminal 2001 paper by Bronwyn Hall, the semiconductor industry was found to embody what was identified as a 'patent paradox': the wide-spread use and density of patenting behaviour despite strong empirical data that patents are peculiarly ineffective at driving innovation in the semiconductor domain.[893] This finding has led other scholars[894] to investigate the idiosyncratic ways patents and other semiconductor intellectual property are used in practice- called 'IP block licensing'- as will be discussed in Section B.

A. Semiconductor industry overview

In many ways, the semiconductor industry stands out as an anomaly in traditional theories of innovation and the innovative process. Innovation is often said to be stochastic and disruptive, yet semiconductor innovation seems to operate much like clockwork –with

890. Here this term is used to contrast with the more familiar term of 'vertical integration', meaning that large companies 'spinoff' components of the supply-chain which used to be subsumed under one company structure/
891. See Global Semiconductor Alliance, 'Collaborative Innovation in the Global Semiconductor Industry' <http://www.gsaglobal.org/gsa-resources/reports/collaborative-innovation-in-the-global-semiconductor-industry/>.
892. For a detailed discussion of IP licensing approaches in the semiconductor industry see Barnett, *supra* note. See also Grindley and Teece, 'Managing Intellectual Capital'; Deepak Somaya, David Teece and Simon Wakeman, 'Innovation in Multi-Invention Contexts: Mapping Solutions to Technological and Intellectual Property Complexity' (2011) 53(4) Cal Management Rev 47.
893. Hall and Ham, 'The Patent Paradox Revisited' (2001) RAND Journal of Economics Vol. 32, No.1
894. Tansey *et al.,* 'Patent Aggression'; Galasso, 'Cross-License Agreements in the Semiconductor Industry'; Ikka Tuomi, 'The Future of Semiconductor Intellectual Property Architectural Blocks in Europe' (JRC Scientifc and Tehnical Reports, Economic Commission 2009); Greenbaum, 'Open Source Semiconductor Core Licensing'.

not one, but two, empirical 'laws' describing its technological progress. There is "Moore's Law"- which states that 'computing power, as measured by the density of the silicon chips … doubl[es] about every eighteen months'[895], and the lesser known "Rock's Law" which observes that the cost of setting up a semiconductor manufacturing plant or 'foundry' doubles every four years.[896] This 'clockwork' analogy of semiconductor innovation has been taken a step further by Intel, which has built its development model on a two-stage innovation strategy called 'Tick-Tock'.[897] Each 'tick' corresponds to a microprocessor architectural innovation, and the 'tock' refers to an innovation in manufacture process.[898] As will be discussed in Part III, Section A, Intel is unique in the semiconductor industry by being able to innovate on both these fronts simultaneously, by maintaining vertical integration of semiconductor design and manufacture. Its status as an Integrated Device Manufacturer ('IDM') sets it apart from the majority of semiconductor companies, which tends to concentrate on highly specialised components of the semiconductor value ecosystem.

Broadly speaking, this ecosystem consists of individual companies providing electronic design automation tools ('EDA's) for designing integrated circuits ('IC') (*e.g., Cadence*[899]); pure-play IC design houses (also known as 'fabless'[900] design houses) who focus on the development of microprocessor architectures and other 'logic units' for specific purposes (*e.g., ARM* and *Qualcomm*); pure-play IC manufacturers or 'foundries' (also known as 'fabs') who manufacture the ICs (*e.g., TSMC*[901] Global Foundries[902]), as well as pure-play manufacturing tool suppliers who provide cutting-edge *e.g.,* photolithography technology to foundries (*e.g., ASML*[903]). The final product company that ends up integrating the microprocessors into a finished product is known as the Original Equipment Manufacturer ('OEM'), and here the company names become more familiar, as they are the consumer—facing Apple, HTC and Samsung.

The above-described fragmentation of the semiconductor value chain is generally ascribed to the extreme economics associated with semiconductor foundries, which are assessed as costing upwards of 10 billion USD to set-up[904]; are almost entirely fixed-cost assets with an

895. Ceruzzi, *A History of Modern Computing*, 297.
896. See IEEE http://spectrum.ieee.org/semiconductors/materials/5-commandments accessed 14 October 2016.
897. Actually, Intel 's "Tick-Tock "model has been replaced by a new model better characterised by "Tick-Tick-Tock", see Peter Bright, 'Intel Retires "Tick-Tock" Development Model, Extending The Life of Each Process" (*arsTechnica* 24 March 2016) <http://arstechnica.com/information-technology/2016/03/intel-retires-tick-tock-development-model-extending-the-life-of-each-process/> accessed 14 October 2016.
898. See Intel , 'The Tick-Tock Model' <http://www.intel.com/content/www/us/en/silicon-innovations/intel-tick-tock-model-general.html> accessed 14 October 2016
899. See Cadence <https://www.cadence.com/en/default.aspx> accessed 14 October 2016.
900. *i.e.,* no 'fabrication' plant or foundry
901. See TSMC, <http://www.tsmc.com/> accessed 14 October 2016.
902. See https://www.globalfoundries.com/ accessed 14 October 2016
903. See ASML, https://www.asml.com/ accessed 14 October 2016.
904. Nenni and McLellan, *Fabless.*

amortisation rate of approximately 50% of production costs; and which must be kept at full capacity at all times otherwise they will run at a loss.[905] This unforgiving economics has led the majority of semiconductor companies that were originally IDMs- such as *e.g.,* AMD - to 'spin off' their 'fabs' as independent manufacturers.[906] This trend, in turn, has opened up the possibility of 'fabless' IC design houses, and has triggered the subsequent hyper-specialisation and dis-integration of the other components in the supply chain, such as EDAs, design, and manufacturing tools development.

Of course, not all of the distinct semiconductor specialisations identified above are dis-integrated by every company, and there is still some degree of consolidation and integration of these tasks. For example, Samsung, is both a foundry and an OEM, and despite often being engaged in acrimonious patent lawsuits[907] with rival OEM and PMD company, Apple, is also Apple's chief supplier of manufactured microprocessors. Likewise, Apple is Samsung's largest foundry customer.[908] In addition, high value OEMs may try to get more control over their supply chains and essential technologies by either buying them up, or eliminating them from the supply chain and moving production in-house, such as recently happened in the case of Apple and Imagination Technologies.[909]

Furthermore, within the category 'pure-play IC design house' there is also a supply chain of some depth. For example, while Qualcomm is a pure-play IC design house designing microprocessors for the PMD space, core components of its designs are licensed directly from ARM.[910] ARM's CPU designs also provide the core logic units that power Apple's "A-series" CPU[911], as well as the other major PMD OEM CPUs such as those of HTC, Samsung, Huawei and LG, either directly, or via an intermediate fabless design house, like Qualcomm.[912]

As will also be discussed in Section B below, the complex web of partnerships and collaboration that sustains the semiconductor ecosystem is driven by a unique approach to intellectual property licensing, called 'IP block licensing'. Here, the term 'IP' differs from its normal use by lawyers and economists. An 'IP block' or 'IP core' refers to a 'functional module'

905. Ibid, 75. Also see Jim Turley, 'The Business of Making Semiconductors' (*InformIT*, 28 March 2003) <http://www.informit.com/articles/article.aspx?p=31338&seqNum=4> accessed 14 October 2016.
906. The 'fab' spun off is called Global Foundries, see <http://www.globalfoundries.com/> accessed 14 October 2016.
907. Such as during the so-called 'smartphone patent wars', see Thomas H Chia, 'Fighting The Smartphone Patent War With RAND-Encumbered Patents' (2012) 27(4) Berkeley Tech LJ 211; Lim, 'Misconduct in Standard-Setting'; Jones, 'Standard-Essential Patents'.
908. Nenni and McLellan, *Fabless*, 79.
909. See https://techcrunch.com/2017/05/04/imagination-technologies-starts-dispute-with-apple-over-graphics-chips/> accessed 7 May 2017
910. See ARM <http://www.arm.com/markets/mobile/qualcomm-snapdragon-chipset.php> accessed 14 October 2016.
911. See <http://www.anandtech.com/show/9686/the-apple-iphone-6s-and-iphone-6s-plus-review/4>
912. See ARM <http://www.arm.com/markets/mobile/qualcomm-snapdragon-chipset.php> accessed 14 October 2016.

which represents, in an abstract yet implementable form, the underlying logic of the IC, and integrates patented inventions, copyrights, as well as trade secrets.[913] Such IP cores may either be 'soft' or 'hard'. 'Soft' IP cores are delivered to customers in a form that looks like software source code- called hardware description language ('HDL')[914]- and which can be further configured and customised by the licensee. 'Hard' IP cores are delivered to customers already 'pre-compiled'[915] and cannot be further configured. When ARM licenses its microprocessor designs to downstream design houses or OEMs, its IP is provided in one of these two forms, depending on the requirements of the customer- and on the extent of the customer's in-house customisation capacities.

The reason why ARM is able to sustain such a diverse network of partners is due to the 'open' modularisation of semiconductor design- something widespread in the embedded and PMD spaces, but not yet fully embraced by Intel (see Part III, Section A). Open modularisation is a result of a push in the semiconductor industry towards the "System on a Chip" ('SoC') approach to PMD IC design. SoCs pack onto the same IC multiple hardware components, such as microprocessors, power management, memory, and external interfaces. [916] SoCs cut down on cost, increase the speed and efficiency of the logic units,[917] improve time to market,[918] and allow semiconductor design houses to leverage network partners' expertise in the creation of complex products- in the form of third party IP 'blocks'- in what is also a paradigm case of 'open innovation'[919] (see Section B below).

An essential factor of any SoC design is the means by which the different components of the SoC communicate, especially if those components are third party. The means by which SoCs coordinate the timing and interaction between SoC modules is by the use of 'interconnects' or 'buses'. In order for OEMs to be able to pick and choose among different modules for their customised SoCs, it is essential that the buses are standardised. The current industry standard for SoC buses is ARM's open protocol called the 'Advanced Microcontroller Bus Architecture' ('AMBA'). Intel's PMD SoCs currently utilise a proprietary 'chassis' known as the 'Intel On-Chip System Fabric' ('IOSF'). Since Intel's system of interconnects differs from the industry standard it means that Intel's customers are not able to pick and choose among different modules to the same extent as those of ARM. Furthermore, as will be discussed in

913. Such as implementation details which are not covered by IP.
914. Like *e.g.,* RTL or Verilog.
915. In the sense of already specifying particular electronic components, or by being specified into non-reversible 'netlists', see discussion and description of the latter in Greenbaum, 'Open Source Seminconductor Core Licensing'.
916. *e.g.,* like USB.
917. Due to closer proximity between components since on a single IC.
918. As can be 'printed' onto a single wafer.
919.Marcel Bogers, Rudi Bekkers and Ove Granstrand, 'Intellectual Property and Licensing Strategies in Open Collaborative Innovation' in C de Pablos Heredero and D López (eds), Open Innovation in Firms and Public Administrations: Technologies for Value Creation (Hershey, PA: IGI Global, 2012) 37-58.

Part III below, Intel's refusal to license its CPU architecture to downstream IC design houses means that OEMs generally receive a fully integrated SoC product from Intel. This means that Intel's PMD SoCs tend to be complete solutions, decided via a 'top down' 'exclusive property' approach, rather than by the 'bottom up' approach of 'open innovation', provided by ARM's more 'inclusive' property approach.

The relationship between the SoC design model and the various approaches to IP management and licensing will be discussed in Section B below, which will also engage a more general survey of approaches to IP management and licensing in high-tech industries.

B. Survey of IP licensing strategies in high technology

1. The closed 'exclusive' property approach to IP licensing

The two approaches to IP licensing identified in the introduction, and essentially summarised as 'open' and 'closed' also summarise the main approaches adopted by high technology companies to the problem of how to manage and stimulate innovation. Research and Development ('R&D')- the production of new knowledge assets, such as product and process innovations- is extremely costly. For example, in 2014, Intel's R&D budget exceeded 11 billion USD (over a net revenue of 55billion USD)[920], whereas ARM's 2015 R&D budget was 215 million USD (over a net revenue of 1.4 billion USD.[921]) Given the R&D intensity of high technology markets (15-20% of revenue in these two examples), companies must make decisions over protecting the investment, monetising it, and stimulating further innovation.

When companies like Intel adopt a closed approach, they have chosen to solve these problems by heavily patenting their innovations, guarding the exclusivity of their rights by refusing to license IP, and litigating against infringers, as well as often providing 'complete solutions' to their end-customers, with little use of third-party IP.

The economics behind this 'exclusive property' approach to managing innovations constitutes the prevailing 'orthodoxy' in IP theory. In brief, it recruits the idea that unprotected knowledge assets engender 'market failure' due to the extremely high ratio of sunk R&D costs to marginal costs of reproduction of R&D results: unless such assets are protected, they won't be produced. Empirical evidence shows that in markets where the protected asset is relatively 'simple', then this economic reasoning is fairly robust.[922] However, as the complexity[923] of

920. See Intel Annual Report, 2014 <http://www.intc.com/intel-annual-report/2014/index.html> accessed 14 October 2016.
921. ARM Strategic Report 2015.
922. Lemley, 'Ignoring Patents '.
923. von Graevenitz, Wagner and Harhoff 'Incidence and Growth of Patent Thickets'.

the product increases, the picture becomes murkier. A 2001 study of the use of patents in the semiconductor industry discovered that while patenting rates are unusually high in this industry, their perceived effectiveness at both incentivising and protecting innovations are rated relatively low.[924] This 'gap' is explained by the use of such patents 'strategically', either as 'defensive mechanisms' or to engage in cross licensing.[925] Furthermore, when the 'exclusive property' approach predominates in a particular high technology market with complex products, companies may find themselves in a so-called 'patent thicket',[926] 'an overlapping set of patent rights'[927] requiring extensive licensing, cross licensing and sometimes litigation in order to bring products to market, as discussed further from a game theoretical perspective in chapter 3 of this thesis.

According to some scholars- some of whom explicitly base their analysis on the semiconductor industry[928]- not only does the adoption of the exclusive property approach to knowledge assets actually not encourage innovation, it may retard it. There are at least two components to this criticism of the exclusive property approach. The first component appeals to the economics of 'transaction costs', and argues that in high technology markets the costs of monitoring, enforcement, secrecy (when relevant), and licensing negotiations (in case of patent thickets) are significant (and significantly higher) than an 'inclusive' property regime[929], such as a 'commons' or 'open access' (as will be discussed in Section B(2) below). In this case, innovation may proceed slower due to diversion of resources away from R&D and towards the transaction costs of infringement monitoring and litigation.[930] The second component is a broadly empirical argument and is strongly contingent on the character of the underlying knowledge assets. It argues that in many cases the adoption of an exclusive property regime

924. Hall and Ham 'The Patent Paradox Revisited' 102 ("the gap between the relative ineffectiveness of patents (as reported in surveys) and their widespread use is particularly striking.")

925. Ibid; Barnett, 'Property as Process'.

926. Clarkson and DeKorte, 'The Problem of Patent Thickets in Convergent Technologies'; Ralph Siebert and Georg Von Graevenitz, 'Does Licensing Resolve Hold Up in the Patent Thicket ?'; Shapiro, 'Navigating the Patent Thicket'; Adam Mossoff, 'The Rise and Fall of the First American Patent Thicket: The Sewing Machine War of the 1850s' (2009) 53 Arizona L Rev 165.

927. Shapiro, 'Navigating the Patent Thicket'.

928. Barnett, 'Property as Process'; Hall and Ham, 'The Patent Paradox Revisited';

929. Ibid.

930. Kapczynski, 'The Cost of Price', 990 ("[t]ransaction cost and externality concerns are important components of the recent debates about the potential for an anticommons in information goods. If information is subject to especially high transaction costs, then in this context, price is also particularly problematic"); Samuels Bowles and Jung-Kyoo Choi, 'Coevolution of Farming And Private Property During The Early Holocene', (2013) 110(22) Proceedings of the National Academy of Sciences 8830. (Though not directly concerned with intellectual property or information resource management, Bowles suggested that the model developed in this paper concerning the emergence of the institution of property may be applied to intangible resources, and specifically intellectual property.) This insight has also been developed by Bowles in a talk given to the Berkman Klein Centre For Internet & Society at Harvard university 'Kudunomics: Information and Property Rights in the Weightless Economy, where it was suggested that open access approaches to information resources would be more efficient than exclusive rights approaches in today's knowledge economy <https://cyber.law.harvard.edu/interactive/events/luncheons/2009/11/bowles> accessed 13 October 2016

is mismatched to the natural process of cumulative and sequential innovation that drives development in complex product industries, such as high technology.[931] This is because R&D outputs are often simultaneously 'inputs' for future industry-wide innovative activity, such that 'locking' them up in exclusive rights harms that process. As a corollary to this last point, in markets characterised by sequential and cumulative innovation (such as high technology) exclusive ownership of critical[932] R&D outputs, such as the 'technological infrastructure', may facilitate a kind of 'centralisation' of industry-wide R&D investment decision-making. As put by Tim Wu[933]:

> Even accepting that useful incentives can be created by intellectual property, the effects on decision-making suggest a reason to be cautious about the assignment of broad rights. The danger is that centralization of investment decision-making may block the best or most innovative ideas from coming to market.

In other words, under certain conditions, it is possible for the IP system in high technology markets to put pressure on the decentralised 'bottom up' character of the innovative process and transform it into something more centralised and 'top down'. Such a system may permit 'a single private company…[to]… make decisions for all participants…[and]…unconstrained by market forces, such a private company is no more likely to perform well than government regulators.'[934] This is maybe particularly the case in relation the nascent IoT market, which is characterised by numerous cooperatively-set and de facto standards, creating a number of choke-points for private companies to exert control. IoT devices are in many ways the product of a drive towards technological convergence, and so must interoperate with a diversity of host devices, servers, and network hubs[935], implicating a 'jungle of standards'[936]. As argued in chapters 1 and 2 of this thesis, such standards operate in markets of relatively inelastic demand, creating incentives for private right holders to leverage their market control in exploitative or exclusionary ways. In relation to cooperatively-set standards, chapter 1 has already explained the ex ante and ex post legal approaches to ensuring 'open access' licensing.

931. Bessen and Maskin, 'Sequential Innovation'.
932. Lee, 'The Evolution of Intellectual Infrastructure'.
933. Wu, 'Intellectual Property'.
934. Lemley, 'The Regulatory Turn'
935. Jason R. Bartlett and Jorge L. Contreras 'Rationalizing FRAND Royalties: Can Interpleader Save the Internet of Things' (October 4, 2016). Review of Litigation, Forthcoming; University of Utah College of Law Research Paper No. 185. Available at SSRN: https://ssrn.com/abstract=2847599 3 ("…standards that will link a bewildering array of devices in vehicles, buildings and the environment known as the "Internet of Things."")
936. Nicolo Zingales, 'Of Coffee Pods, Videogames, and Missed Interoperability: Reflections for EU Governance of the Internet of Things' (2015) TILEC Discussion Paper No 2015-026, 31 <http://papers.ssrn.com/abstract=2707570> accessed 14 October 2016 ("a 'jungle of standards', generating confusion for their proliferation and the lack of certainty as to which standards provide adequate levels of interoperability and security.")

Although chapter 2 developed in detail the ex post competition law approach to managing de facto standards, it left to one side the various ex ante private-ordering approaches available to companies to ensure that the 'if infrastructure, then open access' model is applied in relation to technological infrastructure. The following section will develop some of these in detail, before exploring how ARM and Intel are choosing to self-organise in the standards war for the IoT CPU infrastructure.

2. Open approaches to IP licensing

Within the broad category of 'inclusive property' are a number of heterogeneous approaches to achieving 'openness' in high technology markets.

The most well known 'inclusive' property or 'openness' regime in high technology is the use of open source licenses over software. As will be discussed in more detail in Part III in relation to the PMD space, the Android mobile Operating System ('OS') is a Linux-based open source OS that currently powers more than 85% of all PMDs. The 'core' or 'kernel' of this OS is based on a pared-down distribution of the Linux OS kernel, and is specifically designed for embedded microprocessors, such as which power PMDs. The parts of the OS that expressly derive from Linux are licensed under the General Public License ('GPL' v 2) copy-left[937] style open source license, while the Android specific parts developed by Google and its partners are licensed under the 'permissive'[938] Apache License 2.0.[939] Open source licensing- particularly under 'permissive' terms- can be conceptualised as creating a kind of 'virtual commons', since all companies or individuals are permitted access and modification rights to the software source code[940] once published, provided the contractual terms of the license agreement are adhered to. In the case of Android, the code is also available for view, including use for projects and commercial applications, on the open source software repository website, Github.[941] Although the economics of open source software is still in a state of some theoretical uncertainty[942], it is clear that the main drivers for open source licensing models include (for companies), inter alia, the indirect value appropriation[943] via sale of complementary assets, and the fostering of interoperability between different systems and devices.[944] Aside from the efficiencies that arise from an OS being open source, (which

937. 'Copyleft' refers to an open source license which requires all derivative works to also follow the same licensing terms as the 'in-coming' code

938. 'Permissive' means that the licensing terms of derivative works can diverge from that of the 'in-coming' code provided that certain minimal criteria are met.

939. See Android , https://source.android.com/> accessed 14 October 2016.

940. Provided it has been 'published' or distributed.

941. See Android , <https://github.com/android> accessed 14 October 2016.

942. Josh Lerner and Jean Tirole, 'The Economics of Technology Sharing: Open Source and Beyond' (2005)19(2) J Econ Perspectives 99, 100 ("[t]he open source process of production and innovation seems very unlike what most economists expect.")

943. Benkler, 'Coase's Penguin'; Benkler, 'Free as the Air to Common Use'.

944. Benkler, *The Wealth of Networks.*

are in some ways very unique to 'platform' economics[945]) companies may also choose to release open source software 'libraries'- tools or development frameworks that implement specific functionalities. Projects such as Facebook's *react*[946], which is a JavaScript framework for building sophisticated user interfaces, and Twitter's *bootstrap*[947] (a framework for speeding up web development) are just two examples of commercial companies leveraging open source development models to sharpen their software as well as the Web generally.[948] The 'force' such companies are trying to harness has been elsewhere dubbed 'Linus's law', and represents the idea that the bigger the user/developer group of a project, the faster new features are added and bugs eliminated due to powerful positive feedback loop and network effects.[949] Furthermore, since these two libraries are in many ways 'infrastructural' components of Websites, both Twitter and Facebook stand to gain from a faster, more efficient Web, under a principle called the 'Cooking Pot Model'[950], which can be summarised by the expression 'a rising tide lifts all boats'.

Another 'inclusive' property approach that is commonly used in high technology markets is often referred to by the buzzword of 'open innovation'[951], but can be more intuitively dubbed 'innovation partnership' or 'cooperative innovation'.[952] In essence, the approach enshrines the use of 'third party' IP as central to the innovation process, and by consequence, replaces the heroic model of a company which can do all its innovation in-house, by that of a 'network of innovators'.[953] Unlike the open source software model of inclusive property, cooperative innovation relies on a bedrock of exclusive intellectual property rights which support the development of pure-play IP licensing business models. As already discussed in Section A above, the dis-integrated character of the semiconductor ecosystem encourages strong partnerships and collaboration among semiconductor companies, and has resulted in the unique 'IP block'

945. Robin S Lee, 'Competing Platforms' (2014) 23(3) J Econ & Management Strategy 507.
946. See React, <http://facebook.github.io/react/> accessed 14 October 2016.
947. See Bootstrap, <http://getbootstrap.com/2.3.2/> accessed 14 October 2016.
948. These Web development tools actually help web apps to run faster. Another reason for Twitter and Facebook to release these open source tools is because they are the indirect beneficiaries of a faster Web. Indeed, everyone benefits from a faster Web, but Twitter and Facebook do not benefit any less just because others do too.
949. Eric S Raymond, *The Cathedral and the Bazaar*, 12 ("[g]iven a large enough beta-tester and co-developer base, almost every problem will be characterized quickly and the fix obvious to someone. Or, less formally, 'Given enough eyeballs, all bugs are shallow.' I dub this: 'Linus's Law' […]").
950. See Rishab Aiyer Ghosh 'Clustering and Dependencies in Free/Open Source Software Development: Methodology and Tools' (2002) Working Paper UNU MERIT available at http://www-siepr.stanford.edu/programs/OpenSoftware_David/Ghosh.pdf> accessed 7 May 2017, 2 ("The "cooking-pot" model hypothesises that participants contribute their products to a delineated commons, or "cooking-pot", in a sort of exchange with implicit one-to-many transactions of the one-time production cost with the value gained from individual access to a diversity of products contributed by others. There are other parallel motives for contribution, but this is one of the main economic ones, and also happens to be in some sense quantifiable.")
951. See generally Henry Chesbrough, *Open Innovation: The New Imperative for Creating and Profiting from Technology* (Harvard Business School Press 2003).
952. Bogers, Bekkers and Granstrand, 'Intellectual Property and Licensing Strategies'.
953. Ikka Tuomi *Networks of Innovation: Change and Meaning in the Age of the Internet* (OUP, 2002).

licensing approach. ARM is an example of a company using this approach and business model, although primarily as a licensor rather than as a licensee of IP semiconductor cores, which are then usually incorporated into SoCs. Despite having important differences from the open source model, ARM's 'open innovation' approach does have some strong commonalities with that model, such as the availability and re-use of configurable and modifiable IP 'blocks' to its downstream partners, which in many ways, function analogously to software libraries.

The final 'inclusive' property model to be discussed derives from the legal regime which has been developed by standard-setting organisations ('SSO's) in conjunction with competition regulators and the EU Courts[954], as described in detail in chapter 1 of this thesis. When companies engage in cooperative standard-setting, they are usually required to offer a contractual commitment to license any standards-essential patents ('SEP') on Fair, Reasonable and Non-Discriminatory conditions ('FRAND').[955] Once this commitment has been given, such companies are then compelled to enter into FRAND licenses with licensees, and at the same time lose the right to deny access to the SEPs to willing licensees.[956] Given the ubiquitous requirements of interoperability of high technology devices, standards and SEPs abound in both the PMD and the nascent IoT markets.[957] The FRAND IP licensing model is therefore a dominant 'open access' approach to ensuring an 'inclusive' property regime, as will be discussed in Part IV.

It is submitted that the open approach to IP licensing as summarised above is particularly suited to complex high technology markets, where markets are at risk of tilting in the direction of over-propertisation resulting in patent thickets and patent wars, as discussed in chapter 3. Indeed, the success of both ARM and Android in the PMD space is argued to be no accident, but the result of open' approaches permitting the creation of multiple 'nodes' of innovative activity (in the form of independent companies innovating around a particular open microprocessor infrastructure or open software platform). When property rights are decentralised via an open approach, the potential for independent companies to 'explore' innovative possibilities is liberated while maintaining interoperability. As developed further in Part III and IV of this chapter, this is argued to create a system of 'bottom up' innovation, which can result in products of considerable diversity and complexity, as upstream inputs are available for downstream mixing-and-matching.[958]

954. See *Huawei*. See also Commission, 'Guidelines on the Applicability of Article 101'.
955. See the European Telecommunications Standard Institute Rules of Procedure (19 November 2014).
956. See *Huawei*, para 51 ("[…] the patent at issue obtained SEP status only in return for the proprietor's irrevocable undertaking, given to the standardisation body in question, that it is prepared to grant licences on FRAND terms").
957. Nicolo Zingales, 'Of Coffee Pods, Videogames, and Missed Interoperability: Reflections for EU Governance of the Internet of Things' (2015) TILEC Discussion Paper No 2015-026, 31 <http://papers.ssrn.com/abstract=2707570> accessed 14 October 2016 ("a 'jungle of standards', generating confusion for their proliferation and the lack of certainty as to which standards provide adequate levels of interoperability and security.")
958. This position assumes that the exclusive property approach to IP only has a muted effect on incentivising pro-

A useful way of summarising the above approaches to IP management and licensing in the high technology sector is to imagine them on a spectrum from the 'pure commons' approach of open source software, to the 'exclusive property' approach, as shown in Fig. 1 below. As the approach to IP licensing becomes more open, the productive inputs get distributed among potentially more nodes of innovative activity (which nonetheless remain interoperable), leading to a scenario of 'bottom up' innovation. Conversely, as the approach becomes more exclusive, the number of potential nodes decreases, leading to 'top down' innovation. Although top down innovation may still produce products of considerable value, the 'combinatorial' effect of a multi-node approach is lost, leading to potentially less complexity and product diversity. [959]

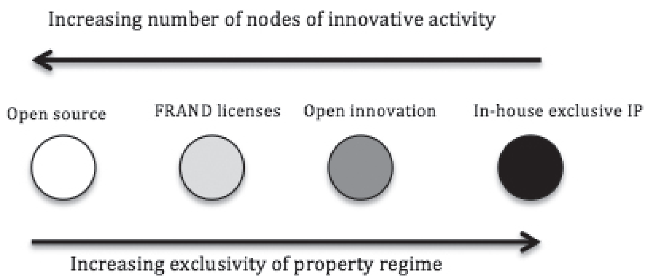

Figure 1. (adapted from Jonathan M Barnett)[960]

Another way to visually conceptualise the above is by means of nodes in a network. Under a decentralised approach, where the essential technological infrastructure is liberated by open licensing, the latter is free to scaffold multiple nodes of innovative activity without top-down control. Examples of the latter include the evolution of the Web (as discussed in chapter 4) and the Linux kernel, which is licensed under the GPL open source license, and has spawned a number of competing Linux 'distributions' (some of which have gone on to generate new innovations, which have then been fed back into the Linux 'ecosystem'[961]). Linux RedHat[962], Android, Ubuntu[963], and Tizen[964] are just four separate well-known nodes of innovative

duction. This seems empirically robust (see Hall and Ham, 'The Patent Paradox Revisited') although it bears repeating that even where the above does not hold true, it would only result in a single-node of innovative activity compared to the multi-node approach of open access regimes.

959. See generally William Brian Arthur, *The Nature of Technology: What It Is and How It Evolves* (Penguin 2009).

960. Barnett, 'Property as Process' 401

961. Developed first by RedHat, the concept of containers is a way of creating virtualisations of separate instances of an OS within a single OS and has now become part of the overall Linux system. LinuxContainers <https://linuxcontainers.org/> accessed 14 October 2016.

962. RedHat <https://www.redhat.com/en> accessed 14 October 2016.

963. Ubuntu <http://www.ubuntu.com/> accessed 14 October 2016.

964. Tizen <https://www.tizen.org/> accessed 14 October 2016.

activity within the Linux ecosystem. In the diagram Figure 2 below, one can imagine each of these as forming one of the main nodes in the right hand side of the diagram ('decentralised'). The microprocessor designs of ARM are another example of a decentralised approach to innovation. ARM-based[965] chips now currently power all the major PMD devices, including Apple iPhone 7's A10 'Fusion' CPU, Qualcomm's 'Snapdragon'[966] and Kirin 950[967], all of which could be similarly imagined as forming the nodes on the right hand side of the diagram. The centralised approach to innovation, such as evidenced by both Intel and *e.g.,* Microsoft, can be imagined as forming the nodes (perhaps linear[968] or sometimes parallel versions[969]) as shown by the 'centralised' network on the left hand side of the diagram, which demonstrates strong top-down control by the central node.

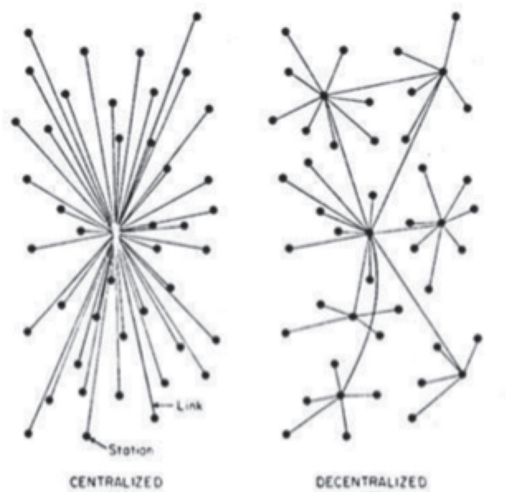

Figure 2. (adapted from Paul Baran[970])

The description of these different approaches to openness and control also links up with the analysis in chapter 3 of this thesis, which discussed the strategic dynamics in high technology as being characterised by an 'assurance game'. By adopting an open approach to their IP,

965. Specifically, the ARM instruction set architectures of ARMv7 and ARMv8.
966. Qualcomm, <https://www.qualcomm.com/products/snapdragon> accessed 14 October 2016.
967. Wikipedia, 'HiSilicon' <https://en.wikipedia.org/wiki/HiSilicon#Kirin_950> accessed 14 October 2016.
968. *i.e.,* gradual evolutions of a software platform, such as Windows 7, Windows 10 etc.
969. *i.e.,* slight divergences in *e.g.,* chip design depending on product market, so high-powered Intel chips versus those for low-powered uses. However, the divergences here are very limited compared to those available under a decentralised approach.
970. Paul Baran, 'On Distributed Communications', Memorandum RM-3420, RAND Corporation 1964, <http://www.rand.org/content/dam/rand/pubs/research_memoranda/2006/RM3420.pdf>

Linux (and to a lesser extent,[971] ARM) are also serving to create an open access equilibrium, which avoids the social costs of the 'strong IP' approach.

Having now outlined the unique character of the semiconductor industry (Section A) and surveyed the various approaches to IP management and licensing in high technology (Section B), Part III delves into more detail about the specific business and IP licensing approaches of Intel and ARM. This is intended to help set up the baselines for the more complex discussion of software and microprocessor platform interdependence and IP licensing contained in Part IV.

III. A CLOSER LOOK AT INTEL AND ARM

Below, Section A will briefly describe the history and business model of Intel. Particular emphasis will be given to the historically 'walled garden' approach to its microprocessor IP, and how this may play out (and has played out) in the PMD and IoT markets. Section B will then apply the same analysis to ARM, focusing instead on how its open approach to its microprocessor IP has helped to pave the way to its current dominance in the PMD space. A projection of how these approaches may play out in the nascent IoT space will also be included. Part IV will then discuss the intimate relationship between microprocessor architecture, IP licensing strategy and software platforms.

A. Intel's History, Business Model and IP Licensing Approach

Below, Intel's origin story (1), approach to IP licensing and the establishment of the 'walled garden' (2), and experience in the PMD and nascent IoT spaces (3) are briefly reviewed.

1. Intel's origin story

The relevant part of Intel's history begins in 1982 with the release of IBM's PC incorporating the Intel 8086 microprocessor, the ancestor to Intel's current 'x86' PC CPU *de facto* standard.[972] In order to speed up time to market and guarantee a reliable pool of component suppliers, IBM's approach to the PC was to have a modular 'open architecture', whereby suppliers got to keep control of their IP, and the hardware interfaces were open and standardised. At that time, IBM's policy was also to ensure at least two suppliers for every hardware component, and so 1982 was also the birth of AMD as a competing CPU supplier.[973] In

971. ARM, unlike Linux, of course still sues companies who infringe its patents without a license. It is position on the spectrum in Figure 1 as 'open innovation' means however that it generally always responds positively to license requests by practically every company, including competitors.
972. Ceruzzi, *A History of Modern Computing.*
973. Intel was forced by IBM to grant a license to the essential x86 patents to AMD, see ibid.

addition to IBM's open approach to hardware, the supplier of its OS (at that time, MS DOS) by the Microsoft Corporation was also able to retain control over its IP. As history has subsequently demonstrated, IBM's 'open architecture' approach had profound effects on the computer industry. As owner of neither the hardware nor software IP making up its PCs, IBM's hold over the PC market was weak.[974] Eventually, IBM's limited monopoly gave way to the proliferation of IBM-compatible PCs[975], tipping the market to the standard platforms owned by its suppliers who did retain IP rights: Intel's x86 microprocessor combined with Microsoft's MS-DOS (later, Windows). 'Wintel' is still the dominant combined software/hardware 'platform' in the PC market today, with more than 80% of total PC OS market share.[976]

Despite being a virtual monopolist in the market for x86 microprocessors, Intel has continued to innovate at an astonishing rate. Due to a process called CMOS scaling[977] and innovations on the level of the microarchitecture, Intel has increased its microprocessor performance by a factor of 100 every decade in rough accordance with 'Moore's law', while consistently improving on the performance-cost ratio. Central to Intel's ability to ramp up processor speeds so consistently is due to an essential aspect of its business model which is rare in the semiconductor sector, and strongly differentiates it from ARM. In a world where most semiconductor companies have become 'fabless' or 'fab-lite' (see Part II, Section A), Intel both designs and manufactures its microprocessors. Intel's enduring status as an IDM has enabled it to innovate simultaneously on microprocessor design as well as manufacturing process, according to the development model dubbed "Tick-Tock", as discussed in Part II, Section A. This vertical integration of both microprocessor design and manufacture has allowed the two R&D trajectories to tightly co-evolve.[978] It has also allowed any IP in the form of trade secrets and confidential information over design and manufacture to remain entirely in-house, and not spill over into the industry.[979]

Indeed, Intel's exclusive property approach to its IP has meant that its patents and copyrights are generally only licensed in the context of cross-license agreements following legal proceedings. This approach to IP means that Intel's relationship with its customers is generally in the form of the sale of completed semiconductor products to OEMs, usually with very high profit

974. Gawer, *Platform Leadership*.
975. *e.g.,* DELL and HP, Compaq.
976. See NetMarketshare, 'Analytics Without the Bots' <https://www.netmarketshare.com/operating-system-market-share.aspx?qprid=10&qpcustomd=0> accessed 14 October 2016.
977. John Hennessy and David Patterson, *Computer Architecture* (Morgan Kaufmann 2012).
978. Of course, fabless companies have strong partnerships with foundries, but nothing comparable to Intel 's scale and integration.
979. Although, *e.g.,* via employee mobility it is impossible to contain spillovers completely, see Lemley and Frischmann, 'Spillovers'.

margins due the significant added value and the absence of vigorous competition. As will be discussed below, this approach has also meant that innovation around Intel's x86 CPU's has proceeded in a largely 'top-down' way, which, while resulting in a high-value product, has also resulted in a limitation in diversity, especially since the effective exit of Intel's main competitors from the market.

2. Approach to IP Licensing and Establishment of the 'Walled Garden'

Intel's dominance in the PC CPU microprocessor market has in many ways derived from its total commitment to the exclusivity of its x86 CPU 'instruction set architecture' ('ISA'). Put simply, an ISA is the set of machine-readable instructions which software source code must be compiled down to in order for the software to be able to tell the microprocessor what to do.[980] Because these instructions are shared by all microprocessors in a particular ISA 'family', software written for one microprocessor can (generally) also run on other microprocessors in the same family.

Due to the legacy of IBM requiring AMD as a second supplier of x86 CPUs, Intel and AMD entered a cross-licensing deal with respect to the x86 ISA in 1982. In the years while IBM was still the pre-eminent PC company, Intel continued to stick to the letter of the cross-license agreement by continuously updating the agreement to include subsequent extensions to the x86 design. During this time, Intel also maintained an effectively 'open architecture', meaning that the technical specifications relating to the way the CPU interacted with peripheral hardware (referred to as the 'bus') conformed to a standard used throughout the industry. This permitted OEMs who used the Intel chip to substitute the CPUs of other companies (such as AMD, VIA and NVIDIA) without the risk of "lock-in." However, with the virtual demise of IBM in the late 1980s due to the proliferation of 'PC clones', Intel sought to become the sole supplier of x86 chips in the burgeoning PC market by refusing to continue the technology exchange with AMD. In addition, Intel subsequently embarked on a legal crusade against all other, already marginalised, x86 manufacturers by suing for both patent and copyright infringement of the x86 ISA.[981] Intel's refusal to continue the cross license agreement with AMD eventually led to further litigation, concluding with a US Supreme Court Decision in 1994 granting AMD a time-limited license to new x86 extensions. An eventual settlement between the parties in 1995 secured AMD's continued viability in the x86 marketplace but ended the cross license agreement. With Intel's 1997 introduction of the x86 Pentium II microprocessor, Intel's hither-to comparatively open architecture, switched to one that

980. See *Intel* Commission Decision.
981. Greg Tang, 'Intel and the x86 Architecture: A Legal Perspective', (*Jolt Digest* 2011) http://jolt.law.harvard.edu/digest/patent/intel-and-the-x86-architecture-a-legal-perspective-2> accessed 14 October 2016.

was completely closed, and fenced around with Non Disclosure Agreements ('NDAs') and patents.[982]

What this meant in practical terms was that OEM's that utilised the Pentium family of CPUs would be unable to substitute CPUs designed by other companies. This decision kicked off a new era of litigation in the market for x86 CPUs, as rival x86 CPU makers found themselves cut out of the new generation x86 marketplace, which was rapidly adopting the Intel product as the *de facto* standard. Given Intel's steadily accumulating market share (90% of all x86 processors by late 1990s[983]), the legal arguments against Intel's exclusive IP licensing practices began to be couched in antitrust terms. In 1999, a US District Court even ruled that the proprietary information covering the closed Intel architecture constituted an 'essential facility' demanding compulsory licensing to competitors.[984] Although this decision was eventually quashed on appeal, a number of similar cases lodged by x86 CPU suppliers –also demanding access to the new x86 CPU architecture- followed in swift succession. In particular, lawsuits involving two x86 CPU markers, VIA technologies and NVIDIA- resulted in, respectively, a license to the x86 ISA but not to the proprietary architectural extensions (VIA),[985] and a monetary settlement of USD1.5 billion but no access to the x86 ISA (NVIDIA).[986] From Intel's now super dominant position in the market for x86 CPUs, its strategy against the main competitor who still retained an x86 ISA license- AMD- transformed from one of asserting IP rights to that of business tactics, involving, inter alia, extensive loyalty rebates in return for exclusive supply agreements with OEMs. These business tactics subsequently came under review, and sanction, in the 2009 EU competition case, whose decision to fine Intel 1.06 billion Euro was recently confirmed by the General Court in June 2014, although perhaps too late for AMD whose market share took a drastic tumble due to Intel's illegal practices, leading it to eventually switch focus from the PC CPU market to that of gaming consoles.[987]

The upshot of the above-abbreviated history of Intel's x86-related litigation is that Intel now holds the undisputed dominant position for the supply of x86 CPUs for PCs. Its main competitors have either been marginalised in the x86 PC market (VIA), sought greener pastures in gaming console CPU design (AMD)[988], or have been nudged out of the market

982. Ibid.
983. Richard Gray and David Banie, 'Intergraph Corporation v. Intel Corporation' (2000) 16(2) Santa Clara High Tech LJ 437.
984. Ibid.
985. See Agam Shah, 'Intel, Settle All Patent Cases' (*Computerworld,* 8 April 2003) <http://www.computerworld.com/article/2581013/technology-law-regulation/intel--via-settle-all-patent-cases.html> accessed 14 October 2016.
986. See Ryan Smith, 'Intel Settles With NVIDIA: More Money, Fewer Problems, No x86' (*Anandtech*, 10 January 2011) <http://www.anandtech.com/show/4122/intel-settles-with-nvidia-more-money-fewer-problems-no-x86> accessed 14 October 2016.
987. See <http://www.moorinsightsstrategy.com/the-real-reasons-microsoft-sony-chose-amd-for-the-xbox-one-and-ps4/> accessed 14 October 2016.
988. AMD has now moved into the PS4 and Xbox console CPU market, CrimsonRayne, 'Why PS4 and Xbox One

entirely (NVIDIA). Intel's x86 IP strategy has finally resulted in a 'walled garden' around its CPU architecture. Although Intel has never stopped innovating- and indeed is still at the forefront of semiconductor innovation (perhaps due to the phenomenon of 'self-competition' in durable goods monopolies[989] as well as its status as an IDM) its exclusivity over the x86 ISA means that its customers only benefit from a single 'node' of innovation, compared to the multi-node system resulting from ARM's open innovation approach, as discussed in Section B below. Since Intel is continuing to use its x86 architecture in both the PMD market (cf. Intel 'Atom') and IoT (cf. Intel 'Quark'), it is likely that this 'exclusive' property approach- and thus its 'top down' approach to CPU innovation- will continue as the status quo.

3. Intel's Experience in the PMD and Nascent IoT markets

Intel entered the market for PMDs substantially unopposed in the x86 CPU space, as one of only three[990] companies in the world still using the ISA. However, although the strategy of eliminating competition in the PC market bore fruits for Intel in the already mature PC market where x86 had already achieved status of *de facto* standard, Intel entered a very different market structure in the PMD space. As will be discussed below in relation to ARM's IP strategy, Intel entered a market replete with suppliers of ARM's competing CPU. Because ARM is an IP company and not a product company, ARM's CPU designs had rapidly achieved status of *de facto* standard on PMD SoCs, in part due to the sheer depth of the CPU's design supply base in the form of intermediate IP design houses supplying ARM-based microprocessors, as in the example of Qualcomm (see Part II, Section A).

Intel's entry into the PMD space began in 2012 with its release of the Intel 'Atom' SoC based upon the so-called 'Medfield' platform.[991] Like other companies in the PMD market, Intel's SoC also included some third party IP – already a milestone for a company that famously liked to develop all its IP in-house under its walled garden approach.[992] However, unlike ARM, Intel still refused to license its CPU architecture to downstream design houses, except perhaps for one example of the Chinese company *Spreadtrum*, although details are unclear[993]. In practice, this approach meant that Intel remained the sole supplier of x86-based SoCs, meaning that OEMs which adopted the SoC risked vendor "lock in", as well as a lack of diversity and depth

Moved to X86-64' (*RedgamingTech* 20 September 2013) <http://www.redgamingtech.com/why-ps4-and-xbox-one-moved-to-x86-64/> accessed 14 October 2016.

989. The concept that Intel must keep on innovating in order to entice consumers to keep upgrading their existing products based on Intel's previous generation. Ronald Goettler and Brett Gordon, 'Does AMD Spur Intel to Innovate More?' (2011) 119(6) J Pol Econ 1141.

990. Others include AMD and VIA, although the last two are on longer running ISA's compatible with Intel's.

991. See Intel <http://www.intel.com/content/www/us/en/processors/atom/atom-processor.html> accessed 14 October 2016.

992. Tassey, 'Standardization in Technology-Based Markets'.

993. See Usman Pirzada, 'Intel Looking to Grant x86 ISA License to a Third Company - Chinese CPU Maker Spreadtrum' (*WCCFTECH*, 2014) <http://wccftech.com/intel-x86-isa-license-spreadtrum/> accessed 14 October 2016.

in terms of power and efficiency options as well as SoC customisability. Unlike with ARM, where OEMs had a range of suppliers with a number of different ARM-based SoCs touting varying specifications, Intel's PMD customers were tied to the innovative capacity of a single company. This approach arguably invited potential customers into a new space of 'top down' innovation compared to the 'bottom up', multi-nodal R&D trajectories of a truly competitive market place (see Part II, Section B). Perhaps for this reason, Intel's entry into the PMD space has been assessed as more-or-less a failure, as currently only low-end smartphones- ASUS and Lenovo- are powered by Intel's x86-based SoCs, and it has failed to make any headway with the major OEMs[994]. However, as will be discussed in Part IV, some of this failure may be attributed to Intel's complicated relationship with software platforms, due to its late-starter status.

Given Intel's discouraging entry into the PMD space, its approach to the nascent IoT market has been somewhat more hands-on. Intel has continued in its reversal of its traditional R&D trajectory of ramping up raw power in its x86 architecture, by scaling back the power 'footprint' even further than its PMD-friendly 'Atom' SoC. For the IoT market, Intel has produced the 'Quark'-line of SoCs, designed to consume considerably less power and function as the logic 'chip' on miniaturised embedded devices.[995] Intel is even taking an active hand in developing and supporting a promising new OS for the IoT, Zephyr,[996] - an open source minimalist OS based on Linux- which will help it face the hurdles it encountered in the PMD space (see Part IV). As demonstrated by its Whitepaper, *The Intel IoT Platform*[997], Intel's approach to the IoT is an all-inclusive strategy to leverage first-mover advantages to try to get the Quark-line SoCs as a *de facto* standard technological infrastructure for the IoT.

However, so far all indications are that its IP licensing approach to its x86 architecture will remain an 'exclusive property' approach. This would mean that downstream IP design houses will not have access to the architecture in order to engage in 'bottom up' multi-nodal SoC innovation, thus arguably depriving OEMs of the diversity, complexity, and configurability which characterises the ARM-based approach, as discussed below. As further discussed in Part IV, this may have negative consequences for its ability to attract the depth of installed-

---

994. See Micah Singleton, 'Lenovo's P90 is the First Smartphone with 64-bit Intel Atom Processor' (*The Verge*, 5 January 2015) <http://www.theverge.com/2015/1/5/7490143/lenovo-ces-2015-p90-vibe-x2-pro-vb10-intel-atom> accessed 14 October 2016. See also Intel, 'Smartphones For the Speed of Life' <http://www.intel.com/content/www/us/en/smartphones/smartphones.html> accessed 14 October 2016.
995. See Intel <http://www.intel.com/content/www/us/en/embedded/products/quark/overview.html> accessed 14 October 2016.
996. See 'The Linux Foundation Announces Project to Build Real-Time Operating System for Internet of Things Devices' (*Link Foundation,* 17 February 2016) <http://www.linuxfoundation.org/news-media/announcements/2016/02/linux-foundation-announces-project-build-real-time-operating-system> accessed 14 October 2016.
997. See Intel, 'Architecture Specification White Paper Internet of Things' http://www.intel.com/content/www/us/en/internet-of-things/white-papers/iot-platform-reference-architecture-paper.html accessed 14 October 2016.

based required for driving the achievement of *de facto* standard status as microprocessor infrastructure for the nascent IoT.

B. ARM's History, Business Model and IP Licensing Strategy

Below, ARM's origin story is briefly sketched (1) before taking a closer look at its IP licensing and business model (2), and finally its experience in the PMD and the nascent IoT spaces (3).

1. History of ARM

The relevant history of ARM Holdings begins in 1991, when it entered into a partnership with Apple Corporation ('Apple') to power the Apple Newton Personal Digital Assistant ('PDA').[998] Although this device was not a success, it formed a sufficient proof-of-concept of the technology to trigger its adoption as the microprocessor platform for Nokia's 2G mobile phones in the mid 1990s.[999] This 'design win' was quickly repeated by a number of other mobile phone OEMs, until by 2005, ARM-based microprocessors powered 90% of all mobile phones.[1000] In addition to mobile phones, ARM technology was chosen to power Apple's 2001 breakthrough product, the Apple iPod (and all subsequent versions) and now also powers all Apple iPhones and iPads and the majority of other leading smartphones, tablets and handheld devices. As of 2016, ARM-based microprocessors also power 90% of all hard drives, 40% of digital TV's and set-top boxes, and 15% of microcontrollers. [1001] ARM-based microprocessors currently outnumber Intel microprocessors by around four to one. This wide diversity of implementations and partnerships is what ARM calls its 'ecosystem approach' to computing and is only possible because of ARM's very different business model and approach to IP licensing, which will be discussed below.

2. ARM's open approach to IP licensing and business model

As a pure-play semiconductor IP company, ARM sits at the top of the semiconductor value chain, focusing the bulk of its R&D resources on microprocessor design. ARM's business model takes one of two main forms. Either ARM licenses out a microprocessor design (such as *e.g.,* the ARM-Cortex A9[1002] or Cortex A15[1003] which may then be implemented into SoCs as the CPU.) In such cases, both the microarchitecture and instruction set architecture are designed by ARM. The OEM or downstream semiconductor company (like *e.g.,* Texas Instruments) will then configure the CPU module into the SoC. Alternatively, ARM may just license out

998. Nenni and McLellan, *Fabless*.
999. Ibid.
1000. Ibid.
1001. ARM Strategic Report 2015.
1002. See ARM ,'Cortex-A9 Processor' <http://www.arm.com/cortex-a9.php> accessed 14 October 2016.
1003. See ARM ,'Cortex-A15 Processor' <https://www.arm.com/products/processors/cortex-a/cortex-a15.php> accessed 14 October 2016.

the ARM instruction set (usually the ARM v7 or v8[1004] ISA), and the OEM or downstream semiconductor company will be responsible for designing the microarchitecture of the microprocessor, such as is the case with Qualcomm and its 'Snapdragon' microarchitecture SoC.[1005] The downstream semiconductor companies or OEMs then usually make use of a third party foundry (which is often also in a partnership with ARM[1006]) to manufacture the completed SoC design.[1007] In consideration for its IP, ARM receives both an upfront licensing fee as well as a per-unit royalty over every chip sold.[1008] The licensing fees and royalties ARM reaps from licensing its IP cores are famously low[1009], although the precise royalty fee depends on the complexity of the microprocessor.[1010]

Given ARM's monolithic focus on microprocessor designs and the flexibility of its IP licensing arrangements- which permit high configurability of the end-product SoC- it has built up an ecosystem of unparalleled depth and range. This strategy has enabled its customers to simply 'slot in' the desired microprocessor according to use-case, or otherwise customise the microprocessor specifications according to need. Furthermore, given the fact that ARM's CPU designs tend to share an ISA, customers are able to choose between chip designs from either ARM or various intermediate suppliers without concern of compatibility problems with other hardware peripherals or downstream software platforms. This uniformity of ISA allows OEMs to benefit from competition between intermediate suppliers, including the continued innovation drive and improving cost-performance ratios across a number of different innovation nodes (see Part II, Section B).

The above 'open' approach to IP licensing can be contrasted with Intel's relatively closed 'walled garden' approach. The disaggregation of microprocessor design from the final product essentially allows PMD CPUs and peripheral hardware to evolve in a 'decentralised' manner, permitting the developmental trajectories to develop via a 'bottom up' process akin to some aspects of the open source software development mode, which, incidentally (or not[1011]), is also present in the approach of the dominant PMD software platform (see Part IV).[1012] It is

1004. ARMv8 is ARM 's 64-bit architecture, which the latest generation of PMD CPU's are migrating to, such as the iPhone 7's 'A10 Fusion' chip.
1005. Qualcomm, <https://www.qualcomm.com/products/snapdragon> accessed 14 October 2016.
1006. *e.g.,* ARM's foundry program ARM, <http://www.arm.com/products/buying-guide/licensing/processor-foundry-program.php> accessed 14 October 2016., since needs a license to ARM's IP in order to manufacture.
1007. In many cases, this will be TSMC.
1008. ARM Annual Report 2011.
1009. See Charlie Demerjian, 'How ARM Licenses it's IP for Production' (*SemiAccurate* 8 August 2013) <http://semiaccurate.com/2013/08/08/how-arm-licenses-its-ip-for-production/> accessed 14 October 2016.
1010. See <http://www.arm.com/products/buying-guide/licensing/> accessed 14 October 2016.
1011. In Part II, Section B it is argued that the dual dominance of both an open source software platform as well as an open innovation approach to CPU design is not an accident.
1012. In terms of permitting companies access to pre-designed modules which can be customised.

submitted that a decentralised approach, where the essential IP is available for customisation and integration by a variety of different parties- both intermediate and end product- permits the formation of multiple nodes of innovative activity, leading to products of a greater complexity and diversity than the 'single node' approach of fully integrated solutions.

3. ARM's experience in the PMD and nascent IoT spaces

In 2015, ARM reported that its network of partners had shipped a total of 15 billion ARM-based microprocessors, half of which went into PMDs.[1013] This brings the total number of shipped ARM-based chips to 75 billion since its inception. For the sake of comparison, Intel's number of shipped chips in 2013 for the PMD market was an order of magnitude less, at 10 million.[1014] Although comparison between these figures must take into account ARM's first mover advantage, which has allowed it to become the technological infrastructure and *de facto* standard in the PMD space, ARM's success is nevertheless astounding. One major reason for its success may be attributed to the fact that its IP licensing model is particularly suited to the nature of the PMD semiconductor market, whose extreme complexity and rapid pace of evolution arguably requires high flexibility and customisability of microprocessor and SoC designs, as discussed in Part II, Section B.

With respect to the nascent IoT market, ARM already has its foot in the door with its current dominance of the 'wearables' market.[1015] As with IoT, the wearables market requires heavily reduced power 'footprint' CPUs. ARM's microprocessor Cortex-M-series is already powering smart watches and intelligent parking meters.[1016] As with the PMD space, all of ARM's Cortex M-series architectures are individually licensable by design houses and integrated OEMs for the creation of fully customisable SoCs.[1017] Furthermore, as with Intel's support of the embedded Zephyr OS, ARM has its own open source IoT-specific minimalist OS, called mbed.[1018] Like Android, mbed is licensed under the permissive Apache 2.0 open source software license, and is available on the Github open source repository.[1019]

Given that the IoT market is still in in its infancy, one has to look to the example of the PMD space in order to try to discern some patterns as to how it may evolve. Since both Intel and ARM have either adopted or plan to adopt an open source OS for the software platform,

1013. ARM Annual report 2014, 16.

1014. Getting sales figures for more recent years was more difficult, perhaps due to the failure of Intel to thrive in these markets and hesitancy to publish. See Intel Annual Report 2013 <http://www.intc.com/intel-annual-report/2013/#> accessed 14 October 2016.

1015. See <https://www.arm.com/markets/wearables>

1016. See ARM , 'Internet of Things' <https://www.arm.com/markets/internet-of-things-iot.php> accessed 14 October 2016.

1017. See ARM , 'IoT System for Cortex-M' <http://www.arm.com/products/internet-of-things-solutions/iot-subsystem-for-cortex-m.php> accessed 14 October 2016.

1018. See ARMmbed, <www.mbed.com> accessed 14 October 2016.

1019.See ARMmbed, <https://github.com/ARMmbed/mbed-os> accessed 14 October 2016.

this shows that the astounding success of the open source Android platform in the PMD space may have been used as a model. As will be shown in Part IV below, once an application ecosystem grows up around a particular OS, this can drive demand for the underlying OS via the economics of two-sided markets.[1020] Such demand can also then feedback onto the underlying microprocessor infrastructure to create a situation of 'derived demand', whereby the demand for the user-facing apps 'reaches through' to drive demand for the CPU the OS is built on. In what follows, the example of software platforms in the PMD market will be examined in detail before distilling some take-home points for the importance of software platforms and open IP licensing in the battle for the future IoT microprocessor infrastructure.

IV. MICROPROCESSOR INFRASTRUCTURE AND SOFTWARE PLATFORMS

A crucial component in the success of a microprocessor platform is the depth and range of the software ecosystem associated with it.[1021] Software may be divided into two main categories[1022], operating systems and applications. By intermediating between the hardware and higher-level software, OS's provide the foundation upon which downstream applications ('apps') can be built. Like microprocessor families, OS families can also therefore be described as platforms. Software developers (often third parties) need to write apps according to specific rules unique to the OS, known collectively as 'Application Programming Interfaces' ('APIs'). Since these APIs are unique to the platform, apps written for a particular software platform cannot usually function on other software platforms. The software ecosystems of different platforms do not therefore overlap, and a user's choice between different platforms is generally mutually exclusive.

Just as apps are written to work on specific software platforms, software platforms are generally[1023] written to function on specific CPU architectures. In addition to working with peripheral hardware[1024], OS's must be organised to work with the instruction set of the underlying microprocessor. These one-way relationships (Apps→OS→CPU) might lead one to conclude that apps written for a particular software platform can only work on specific CPU architectures. Although this has often been the case in practice, it is possible for some applications to work across microprocessor platforms, provided the software platform remains constant, and various other technical conditions are met (see Section A below).

1020. Rochet and Tirole, 'Platform Competition in Two-sided Markets'.
1021. Barnett, The Host's Dilemma'.
1022. There also 'drivers' etc, but these are low-level software controlling the interaction between software and (peripheral) hardware.
1023. Two main caveats here. The web, and browser or internet based apps which work according to web and internet protocols independent of the hardware. And software which work via virtual machines, as will be discussed.
1024. *E.g.,* cameras, sensors, gyroscopes etc.

In what follows, we will examine the case of Intel attempting to enter the PMD space by reconfiguring key aspects of the ARM-based Android platform to work on Intel's x86 microprocessor (referred to as 'porting'). Given the fact that Android is open source (and thus freely available for such an endeavour)- as well as the fact that a port of Apple's iOS would have been impossible due to Apple's status as an integrated software and device company, such a port was Intel's best bet for success in the PMD market. This will be the subject of Section B below. Section A will be begin by an examination of the dominant PMD software platform- Android- in order to illustrate the crucial relationship between microprocessors and OSs. Section C will then aim to tie the various threads together, before Part V of this chapter will conclude.

A. The Dominant PMD Software Platform: Android

The Android mobile OS is the dominant software platform in the market for smartphones, with a market share currently exceeding 85% (compared to Apple's 13%).[1025] In the tablet market, Android's lead is less pronounced due to its reasonably late start, but is still 60% compared to Apple's 33%.[1026] Arguably, a significant component of the success of this platform is due to its 'openness', whereby any OEM may implement the platform into their devices without any significant intellectual property restrictions. As already mentioned in Part II, Section B, the IP licensing regime behind Android is governed by a variety of open source licenses, but mainly the GPL v2 (the kernel) and Google's (and partners') additional extension libraries under the Apache 2.0, both of which enable royalty-free use, modification and distribution of the software source code. Furthermore, the platform sponsors- Google and the Open Handset Alliance- provide OEMs with free compatibility guidelines, a test suite, and a verification suite, to ensure that particular implementations of the software platform retain cross-device interoperability. This policy has enabled Android to work across a diversity of different devices by different OEMs, ranging from Samsung, HTC, Motorola, Amazon, in both smartphone and tablet form. This approach contrasts sharply with, for example, Apple's tightly controlled iOS (permitted only to work on Apple hardware) and is arguably a major reason why Android was able to establish an installed base so quickly and accelerate its uptake.[1027]

The above cross-device compatibility has been driven significantly by the fact that all the above Android devices are running ARM-based CPUs with the same microprocessor

1025. See IDC, 'Smartphone OS Market Share, 2016 Q2' <http://www.idc.com/prodserv/smartphone-os-market-share.jsp> accessed 14 October 2016.

1026. See NetMarketshare, 'Analytics Without the Bots' <https://www.netmarketshare.com/operating-system-market-share.aspx?qprid=8&qpcustomd=1> accessed 14 October 2016.

1027. See Jack Wallen, 'Android is Winning the Platform Race' (*TechRepublic* 11 August 2014) <http://www.techrepublic.com/article/android-is-winning-the-platform-race/> accessed 14 October 2016.

instruction set architecture. This close coupling between the Android OS and ARM has arguably been both the cause and the result of a positive feedback loop (otherwise called 'network effects'[1028]) of the following (rather complicated) form: the open availability of Android led to high adoption rates by OEMs, which led to more Android devices, which in turn attracted third party app developers to the size of the user-base, which led to more apps, which attracted more users, which led to more Android devices etc. Clearly, a prime driver of this feedback loop was the openness of the Android OS, which permitted OEMs to easily adopt the OS. However, underwriting this entire feedback loop is ARM's open approach to its CPU architecture, which enabled Android to run on all the different devices in the first place.

The fast establishment of the Android installed base due to the open approach of both Android and the underlying ARM microprocessor infrastructure enabled it to create the vibrant application ecosystem embodied in its app store, 'Google Play', which has fuelled the further growth of the platform due to network- effects. As already mentioned, third party application developers are attracted by the platform's large installed base, and thus create more apps; meanwhile, the blossoming array of apps attract more users to the installed base, in a virtuous cycle. The growth of this two-sided market is also aided by the platform sponsors' relatively open attitude to granting developers access to the Google Play app store API, by only charging a one-time fee of USD25[1029], compared to Apple's USD99 fee.[1030] The current population of apps in the Google play store now exceeds 1.6 million, having recently overtaken Apple Appstore's 1.5 million.[1031]

Since apps unlock for users the real functionality of their PMDs or other embedded devices, a microprocessor platform which intends to break into the PMD market (or any dominant software platform which may arise in the nascent IoT space) will need to 'port' the dominant OS to its microprocessor infrastructure in order to participate in the network effects of the dominant app ecosystem. In the case of the IoT market, the two most likely software platforms to battle it out will likely be ARM's mbed and the Intel-supported Zephyr. Although both these software platforms are open source (see Part III, Sections A and B), they will still require significant reconfiguration to operate on a different microprocessor infrastructure, so as to unlock any eventual app ecosystem associated with them.

1028. Farrell and Klemperer, 'Coordination and Lock-in'.
1029. See Google , 'How to Use the Google Play Developer Console' <http://support.google.com/googleplay/android-developer/bin/answer.py?hl=en&answer=113468> accessed 14 October 2016.
1030. See Apple Developer, 'Choosing a Membership' <https://developer.apple.com/support/compare-memberships/> accessed 14 October 2016.
1031. See Statista, 'Number of Apps Available in Leading App Stores as of June 2016' <http://www.statista.com/statistics/276623/number-of-apps-available-in-leading-app-stores/> accessed 14 October 2016.

Below, Intel's experience with porting Android to its x86 microprocessor infrastructure will be discussed as a possible template for any such endeavour in the future evolution of the IoT. Section C will then aim to integrate the findings of Section A and B, before Part V concludes.

B. Intel x86 and Android: Possibility of 'Porting'

As has already been explained in Section A above, for software to function on microprocessors it must to be compiled down to the set of instructions understood by the ISA of the microprocessor. Although this is particularly crucial for the operating system, the great majority of application-level software must also meet a similar requirement via the APIs set by the OS. What this generally means is that applications do not work across software platform (due to different APIs) or across microprocessor platform (due to different ISAs). However, there are some important exceptions to this rule, such as in the case of cross-platform technologies like Java, Qt[1032] or HTML5.[1033] Fortunately for Intel, Android makes use of a Virtual Machine ('VM') called the Android Run-Time ('ART'), which can execute Java 'bytecode'. Applications built within the ART framework do not require apps to be compiled down to the microprocessor ISA in order to be executed, but instead compile down to an 'intermediate' 'bytecode' which runs on a 'simulated' ISA called a VM. ART (like the Java VM) acts to 'shield' the application source code from the microprocessor ISA via an intermediate translation step[1034], which can then be easily modified to match the ISA. This action enables all apps written to the ART API to work with any microprocessor, provided the VM is correctly configured for the particular microprocessor ISA. To achieve cross-microprocessor app compatibility, all that is required is a 'porting' of the VM to the new microprocessor infrastructure, rather than an individual porting of each individual app, which would otherwise be the case.

In 2011, Intel successfully ported the ART VM to the x86 architecture.[1035] Android on Intel is apparently able to run around 95% of all Android apps.[1036] However, there is a minority of Android apps, which for performance reasons do not make use of the ART VM, and instead are written according to the Native Development Kit ('NDK'). Since these apps compile directly to the native Android architecture (ARM ISA), Intel's ART VM port does not assist with compatibility. Instead, Intel has had to create some extremely sophisticated translation

---

1032. See QT, <http://www.qt.io/> accessed 14 October 2016.
1033. *i.e.,* Web-based applications require only browsers which are compatible with the HTML5 standard in order to run the apps.
1034. *i.e.,* the compilation down to Java or ART bytecode.
1035. See Android , 'Android-x86 Open Source Project Announcement' <http://www.android-x86.org/> accessed 14 October 2016.
1036. See Lawrence Latif, 'Intel Claims Its Atom Chip Can Run 95 per cent of Android Applications'(*The Inquirer* 6 June 2012) <http://www.theinquirer.net/inquirer/news/2182314/intel-claims-atom-chip-run-cent-android-applications> accessed 14 October 2016.

software directly between the x86 and ARM binaries,[1037] which app developers have to make use of themselves if they want cross-platform interoperability of their Android apps.[1038] Whether NDK developers will find it worth their while, is another question, and depends on the number of design wins Intel can secure with its Atom SoC in the PMD space. What Intel has proven, however, is that mere technical barriers to interoperability are surmountable, and therefore have made their microprocessor a serious option to OEMs, at least on technical grounds.

Given the above template of OS 're-porting' to a different microprocessor architecture, it is conceivable that in the event that either ARM or Intel backed-OSs lose the IoT software platform standards battle, the open source nature of these OSs will enable the loser to play 'catch-up' in much the sane way Intel did in the PMD space. However, the technical viability of this approach will strongly depend on the way IoT apps interact with their native OS's (i.e whether they are *e.g.,* web-based HTML5 apps, or native apps) and cannot be predicted without further development on this front.[1039]

However, what it is clear from the nature of the feedback-loop discussed in Section A above, is that one of the prime drivers for Android's dominance in the PMD space was ARM's open approach to its microprocessor architecture. The openness of ARM's microprocessor architecture was what drove its adoption among device makers, which, when coupled with the openness of Android, drove the feedback loop between consumers and third party app developers. Of course, Intel's approach to its x86 infrastructure- even in the pared-down architectures powering its IoT-friendly 'Quark' SoC- still lacks this openness, so according the analysis in this chapter, Intel will still remain on the back-foot in an all-out standards war.

C. Integrating the software and microprocessor platform approaches with IP licensing strategies

Most software platforms are tightly coupled to the underlying microprocessor platform, and require significant adaptation ('porting') if they are to function on non-native platforms. Once a software platform has been ported to a new microprocessor, its value is only transferred if the app ecosystem associated with it is also transferred. Whether apps can also be transferred to a newly-ported software platform depends on the technology embodied in their APIs. If the APIs include cross-platform technology such as HTML5 or Java (or ART, in the case of Android), then it is possible for a non-native microprocessor platform to also inherit the ecosystem of apps, and thus inherit the true value of software platform. Since

1037. See Intel , 'NDK Android Application Porting Methodologies' (27 November 2013) <http://software.intel.com/en-us/articles/ndk-android-application-porting-methodologies/> accessed 14 October 2016.
1038. See Android , 'x86 Support' <http://developer.android.com/ndk/guides/x86.html> accessed 14 October 2016.
1039. The market is still too fragmented to see how this interaction will take place, as too many competing solutions

software platforms are user facing, it is easier for new entrant microprocessors that port dominant software platforms to gain market share (Android on Intel example) than for new entrant software platforms which port to dominant microprocessor platforms. This is due to the economics of two-sided markets and network-effects, which rewards first movers and interoperable products and punish late starters and incompatible products.[1040]

In the nascent IoT market, there is currently a huge amount of fragmentation along most axes of infrastructural components, including microprocessor infrastructure, OS's, radio communication protocols[1041], security measures, sensors, application-level APIs etc. While some of these components may not need standardisation due to the development of 'middleware' which are argued to ensure interoperability[1042], such middleware itself will still require standardisation, such as, for example, 'Alljoyn' (as is being currently developed by the AllSeen Alliance industry consortium[1043]) as well as 'open interconnects' (via the 'Open Interconnect Consortium'[1044]). Indeed, there are currently dozens of formal and informal SSOs promulgating hundreds of possible IoT standards.[1045] Perhaps the problem of fragmentation in the IoT market is due to having too many standards, not too few, creating a 'jungle of standards'.[1046]

However, given that, as with the PMD market- the main driver of demand will almost certainly be consumer applications- it will most likely be rich app ecosystems which will 'pick winners' among the lower-level infrastructures, via the forces of derived demand and network effects. If this is the case, then software platforms (and hence microprocessor infrastructures) will play a determinative role in the battle of the standards, due to the complex feedback loops and derived demands described in Section A above.

Given that the two likely contenders in the IoT software platform space- mbed and Zephyr- are both open source (and not therefore constrained anymore than Android was), to a particular microprocessor infrastructure, it is submitted that success in the microprocessor infrastructure 'battle of the standards' will be driven equally (if not more) by the diversity, range, and depth of the *hardware* ecosystem making up the IoT. In contrast to the PMD space, where, although SoC variety and diversity was argued to be central to ARM's success (see

1040.Farrell and Klemperer, 'Coordination And Lock-In'.
1041. For example, between Bluetooth Low Enery (otherwise known as 'Bluetooth Smart'), Zigbee, Z-Wave, or DECT.
1042. IEEE, 'IEEE Standards Association (IEEE-SA) Internet of Things (IoT) Ecosystem Study' (2015) <http://www.sensei-iot.org/PDF/IoT_Ecosystem_Study_2015.pdf> accessed 14 October 2016.
1043. See Allseen Alliance, <https://allseenalliance.org/framework> accessed 14 October 2016.
1044. See Wikipedia, 'Open Connectivity Foundation' <https://en.wikipedia.org/wiki/Open_Interconnect_Consortium> accessed 14 October 2016.
1045. Zingales, 'Of Coffee Pods, Videogames, and Missed Interoperability'.
1046. Ibid.

Part III, Section B), PMD diversity is still roughly limited by PMDs' status as a 'universal'[1047] device, rather than being task-specific. Not so with the IoT. Indeed, the IoT will arguably be completely defined by its diversity and specificity of its hardware. As stated by ARM in its analysis of the market potential of the IoT[1048]:

> If the mobile Internet is 10 billion units, the Internet of Things is 100 billion units…if mobile computing had tens of form factors, then IoT will have millions of form factors.

If the above is an accurate analysis of the way the IoT will evolve, then the truly crucial component of microprocessor infrastructure success will be the ability to combine a common software platform with a rich ecosystem of apps *and* a cornucopia of diverse task-specific devices with a variety of form factors.[1049]

In order to achieve this outcome, what is required is an approach to innovation and IP licensing which fosters diversity, complexity and configurability of end products. In short: an approach which favours innovative 'bottom up' exploration of the technological frontier, where key infrastructural inputs are distributed over multiple nodes of potential innovative activity. As argued in Part II, Section B, such an approach will most likely be encouraged by IP licensing models which favour openness over exclusivity, such open source, or the FRAND-based approach to technological standards, or the 'open innovation' regime of ARM's 'ecosystem' of downstream partners, each of which implements the infrastructural approach of 'if infrastructure, then open access'.

V. CONCLUSION

This chapter has attempted to outline in broad strokes some key considerations for the evolution of microprocessor infrastructure in the nascent IoT market. By examining the nature of the semiconductor industry and dominant IP licensing models, it developed the argument that Intel and ARM's respective fortunes in the PMD market were tightly interwoven with their approaches to IP. It further argued that these approaches can be projected- with some caveats- into the evolution of the IoT market in order to assess likely outcomes in the battle for microprocessor infrastructure.

1047. *i.e.* all PMDs such as smartphones and tablets are essentially personal computers, with sophisticated user interfaces and the ability to run millions of different apps.
1048. See ARM, 'Internet of Things' <https://www.arm.com/markets/internet-of-things-iot.php> accessed 14 October 2016.
1049. Ibid.

With respect to the PMD market, it concluded that the principal driver of ARM's success was its open approach to its IP, which scaffolded 'bottom up' innovation via the creation of multiple nodes of innovative activity around the core technological infrastructure of its microprocessor designs. This was contrasted to Intel's IP more closed, 'top down' approach, which although yielding extremely high-value products (due also to Intel's status as an IDM) can only provide a single node of innovative activity, thus limiting diversity, configurability and complexity.

While the PMD space- including its dominant software platforms- rewarded ARM and its partners' ability to produce highly diverse, configurable, and complex PMDs, it is argued that the IoT market may turn this reward into an economic bonanza. Unconstrained by requirements of 'universality' like PMDs, IoT devices are likely to be extremely diverse and highly task-specific. If ARM and Intel persist in their approaches to IP and business models in this new market of 'enchanted objects'[1050], then it is predicted that ARM's 'infrastructural approach' to its IP licensing will be a strong driver of its success.

1050. Rose, *Enchanted Objects*.