Figuring out Organizations

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Introduction

A remarkable amount of formally structured information is now routinely shared among firms, industries, and a broad range of research agencies. While there has been a "rediscovery" of the economy and of economic organisations by a wide range of social scientists across the past two decades, the economic and technological models that facilitate this cooperation have been given insufficient attention to date (Djelic and Sahlin-Andersson, 2006; Drori et.al., 2003; MacKenzie, 1996, 2006; Miller, 2001, 2008; Miller and O'Leary, 2007; Powell, Koput and Smith-Doerr, 1996). Sociologists and organisation theorists have depicted economic action as socially situated, and as embedded in interactions with other individuals and within institutional networks (Barley et. al., 1992; Granovetter, 1985; Powell, 1985, 1987, 1990; Fligstein, 1990, 2001). Yet they have only very recently started to address the roles of the calculative practices that provide the infrastructure which enables some markets to operate (Callon, 1998; Callon et. al., 2007; Mackenzie, 2006; Mennicken, 2007; Miller, 2008; Miller and O'Leary, 1997, 2007). Economists have argued for the need to develop an economic analysis of institutions and novel organisational forms based on complementarities (Hart, 1995; Roberts, 2004), and have suggested the importance of diverse social norms in the behaviour of agents (Bénabou and Tirole, 2006). To date, however, they have paid relatively little attention to information exchanges that occur without vertical integration (Holmström and Roberts, 1998). The attentiveness across the social sciences to the variability of organizational forms and behavioural norms during the past two decades or so should be matched, we suggest, by a similar attentiveness to the information exchanges and calculative practices that link and stabilize the actors and entities that make up the modern economy, and that provide the infrastructure within which economic action occurs.

This paper takes these infrastructural practices and metrics as its principal focus, and pays particular attention to the mediation between technological and economic trajectories and models. It addresses these issues in three stages. First, it considers the literature on intermediate or network organisational forms that has emerged from a range of social scientists, noting its primary focus on the organizations, institutions and networks that populate the economic domain. Second, it considers the recently emerging literature that addresses the constitutive nature of calculative practices, and their roles in the formation of markets and economic relations more generally. Third, it illustrates the significance of such infrastructural calculative practices by reference to the microprocessor industry, and the roles of "Moore's Law" and "technology roadmaps" in shaping the fundamental expectations of an entire set of industries and firms.

Networks and Hybrids

Social scientists became interested in network and hybrid organisational forms just as important changes were occurring in the nature of economic life. The increasing globalisation of the world economy, shorter product life-cycles, the emergence of new hi-technology industries, an increasing customisation of demand, the growth of flexible specialisation, together with altered competitive conditions all helped bring about changes to traditional modes of organising production. The 'quasi-firm' (Eccles, 1981) in the construction industry was identified as a distinctive organisational form and governance structure that had the characteristics of both markets and hierarchies. Dense networks of personal ties were viewed as characteristic of the academic publishing industry (Coser, Kadushin & Powell, 1982; Powell, 1985). In the German textile industry, production systems were observed and analysed that linked small and medium-sized firms in extensive subcontracting systems (Piore & Sabel, 1984). More generally, and in industries as varied as commercial aircraft manufacture, oil extraction, chemical and pharmaceutical research, microelectronics, telecommunications and biotechnology, researchers provided increasing evidence of modes of organising economic activity that did not fit the conventional antinomies of markets and hierarchies (Powell, 1987).

By the late 1980s, a substantial body of research had already emerged which suggested that hybrid organisational forms were a new and distinctive feature of the socio-economic landscape. Powell (1987) argued that to view economic organisation as a choice between markets and hierarchies was to fail to appreciate the rich variety of organisational arrangements that are possible. He went so far as to speak of a 'stampede' into various alliance-type combinations, linking large generalist firms and specialised entrepreneurial start-ups. Granovetter (1985) went further, and suggested a more general argument concerning economic behaviour. He proposed that all economic behaviour, whether it takes place within markets or hierarchies, is 'embedded' in interpersonal and social networks. Subcontracting relationships based on strong interpersonal relations and shared norms are, according to this diagnosis, not intermediate organisational forms but indicative of the fundamental 'embeddedness' of economic transactions in social life (Granovetter, 1985).

During the 1990s, the literature on intermediate organisational forms burgeoned, with Powell (1990) arguing that the term hybrid was an inappropriate and inaccurate way of characterising the diverse forms of collaboration that have existed historically. Rather than presuming markets as the starting point, and viewing other forms of exchange as arrayed on a continuum with hierarchies at the other end, Powell called for attention to be directed at networks as a distinctive mode of coordinating economic activity. Network forms of exchange are characterised by individuals engaging in reciprocal and mutually supportive actions, and effectively foregoing the right to pursue individual interests at the expense of others. Biotechnology, for instance, is an industry in which innovation does not arise exclusively from individual firms, but typically emerges out of the relations among firms, universities, research laboratories, suppliers and customers (Powell, Koput & Smith-Doerr, 1996). This suggested a more general argument: when knowledge is broadly distributed and may bring competitive advantage, innovation is likely to be located in a network of inter-organisational relationships. Others argued similarly, focusing on the social networks that enable and shape strategic alliances (Barley, Freeman & Hybels, 1992; Gulati, 1995; Nohria & Eccles, 1992). Teece, together with colleagues, developed a related argument that the linking of firms with complementary capabilities and capacities represented a significant organisational innovation, and made

possible the development of ‘dynamic capabilities’ based on the ability of firms to integrate, build and reconfigure internal and external competences to address rapidly changing environments (Teece, 1996; Teece, Pisano and Shuen, 1997).

Across roughly the same period, economists were also pointing to, and seeking to theorise hybrid organisational forms. As early as 1979, Williamson argued that much economic activity takes place via governance structures that are intermediate between markets and hierarchies (Williamson, 1979). While markets and hierarchies represent two of the principal governance structures for organising transactions, Williamson proposed that a third type which he called “semi-specific” also existed (Williamson, 1979). A little over a decade later, he used the term “hybrids” to refer to one of three alternative modes of governance (Williamson, 1991). This meant putting hybrids on a similar footing to markets and hierarchies, rather than viewing them as a loose amalgam of the features of markets and hierarchies. According to this view, the firm is depicted as the governance structure “of last resort” (Williamson, 2002, p. 183), driven largely by asset specificity, while hybrids are conceived as “market-preserving credible contracting modes that possess adaptive attributes located between classical markets and hierarchies” (Williamson, 2002, p.181).

Hart (1995) bemoaned the rudimentary state of the economic analysis of institutions, and put forward a framework that placed centre stage the notions of contractual incompleteness and power. Firm boundaries, he argued, are chosen to allocate power optimally among the various parties to a transaction, where power is not understood as simply market power, i.e. the ability to affect price. While principal-agent theory leads, Hart suggested, to a richer and more realistic portrayal of firms than neoclassical theory, it leaves unresolved the basic issue of the determinants of firm boundaries. To understand firm boundaries, Hart proposed that a central factor is whether assets are highly complementary (synergistic). Where assets are complementary, integration is more likely. This line of argument suggests that when an industry contains a small number of firms, complementarities are likely to be great since there are few alternative trading partners. However, when the market is large enough to support many purchasers and suppliers, complementarities between any single purchaser and supplier become smaller, and non-integration is then more likely. Hart suggested that this may

help us understand the trend towards de-integration during the 1980s and 1990s – increased flexibility in technology means that assets are becoming less complementary, since an asset can be more easily modified to be suitable for a new trading partner.

More recently, Holmström and Roberts (1998) have also revisited the classic question in the economics of organisations of why firms exist, and what determines their scope. If, as Coase (1937) argued, firm boundaries and integration can be explained by efficiency considerations, Holmström and Roberts ask why so much economic activity takes place outside the umbrella of the organisation. Noting the lack of theoretical foundations, and the anecdotal nature of their evidence, they suggest that a much broader view of the firm and the determination of its boundaries are needed than is offered by transaction cost economics and property rights theory. The theory of the firm, they argue, has become too narrowly focused on the hold-up problem and the role of asset specificity. Only a small part of the organisational change taking place today, Holmström and Roberts suggest, can be readily understood in terms of traditional transaction cost theory in which hold-up problems are resolved by integration. Many of the hybrid organisations that are emerging, they argue, are characterised by high degrees of uncertainty, frequency of transaction and asset-specificity, yet they do not result in integration. Indeed, they suggest, mutual dependency seems to support rather than hinder ongoing cooperation across firm boundaries. While Holmström and Roberts do not advance a specific or singular explanation for the phenomena they identify, it is clear that they regard organisational knowledge and information transfer as key. Leading economic theories of firm boundaries, they argue, have paid almost no attention to the role of organisational knowledge. Moreover, information and knowledge are at the heart of organisational design, because they lead to contractual and incentive problems that challenge both markets and firms.

Roberts (2004) argued in similar terms, describing the changes in the organisation of the firm during the past two decades as comparable to the invention of the M-form structure early in the last century. The refocusing on core businesses, and the outsourcing of many activities previously regarded as central has, Roberts argues, led to a shift in the nature of relationships between firms and their customers and suppliers, with simple arms length relationships being replaced by long-term partnerships. Layers of management

have been eliminated, functional units dispersed to business units, and the authority and accountability of line managers increased. To facilitate coordination and learning in this novel organisational form, Roberts suggests that firms have experimented with ways of linking people through horizontal rather than hierarchical communication. These organisational innovations, he argues, are ongoing and offer the opportunity for improved economic performance, while also altering the way work is done and changing people's lives in fundamental ways.

Taken together, these writings by economists, organization theorists, sociologists and others have extended considerably our understanding of the novel organisational forms that have proliferated across the past two decades. Empirically, these have been shown to be both novel and relatively enduring features of economic life. Conceptually, they have been shown to require modifications and extensions of existing theoretical frameworks, and that work is ongoing. Yet, despite this expansion of the domain of analysis, the focus has remained largely restricted to organisational forms and inter-organisational relations, with relatively little attention to those infrastructural calculative practices and models that link firms, industries and other agencies, and that help frame the capital spending decisions of individual firms. It is to these that we draw attention in this paper, but before turning to them we consider the ways in which calculative practices have very recently been accorded significance at the interface between sociology and science studies.

Calculative Practices, Models, and Instruments

An unlikely encounter between science studies and accounting, and subsequently between science studies and finance, has brought about a renewed interest in the roles of calculative practices in shaping and forming, rather than measuring and mirroring economic relations. Whereas the early writings in economic sociology, and particularly those of Weber and Sombart, placed the calculative practices of accounting at the heart of capitalist development, there followed virtual silence on this issue on the part of social scientists for approximately half a century (Miller, 2008). Only in the past decade or so has this renewed interest spilled over beyond the somewhat specialist domains in which it emerged, and come to be recognised once again as a topic of more general sociological

interest, even if in some quarters this recognition is still rather belated (Smelser and Swedberg, 2005).

The rediscovery of accounting by sociologists and others across the past quarter century can be attributed in part to a refocusing of interest among scholars of science on practices and instruments. Over two decades ago, Hacking (1983) argued for studying 'representing' and 'intervening' as joint processes, contrasting this with the traditional preoccupations of philosophers of science with theories and representations only. The study of representing, Hacking argued, needed to be linked with the study of instruments as modes of intervening. Approximately a decade later, Pickering (1992) argued in similar terms, proposing that scholars of science should focus on 'science-as-practice', rather than 'science-as-knowledge'. This meant attending to the intricate work of building instruments, planning and running experiments, and the panoply of activities that make up the doing of science. Meanwhile, Latour (1987) called for attention to 'science in action', or 'science in the making'. This took science studies beyond the laboratory, and also broadened the definition of instruments to include the various 'inscription devices' employed by sociologists, political scientists, economists and others, in so far as they provide a visual display of information for articles written in a range of scientific journals and used by others. While Latour was not alone in calling for attention to these issues, much of the sociological interest in his arguments came from his proposition that such inscriptions – to the extent that they were mobile, stable and combinable – allowed 'centres of calculation' to form which could exert power over others (individuals, territories or whatever) that were distant. The task of dominating a country's economy was thus put on a more or less equal footing to the task of dominating the earth or the seas.

These arguments had important implications for debates about the governing of economic life. The interplay between representing and intervening was characterised as one between 'programmes' and 'technologies' (Miller and Rose, 1990, 2008)[1]. The term programmes referred to the discursive nature of modes of governing, the conceptualising and imagining of the economic domain and its constituent components and associated

[1] This has similarities to the arguments put forward by Meyer and Rowan (1977) that researchers should attend to the interplay between the idea or 'myth' of rationality, and the rationalized practices and procedures that organizations come to deploy.

problems as something that could be acted upon and calculated. The term technologies referred to the various calculative devices and instruments that made it possible to operationalise these aspirations, and to act upon others whether in attempts to enhance output, improve competitiveness, facilitate empowerment or encourage monitoring. The links between programmes and technologies were not conceived as a matter of 'implementing' idealised schemes, but as a matter of assembling and adjusting diverse components and practices into some sort of working ensemble. As Power (1997) demonstrated convincingly with respect to audit, at issue here is both the generalised idea or programmatic view of audit, the notion that audit is defined to a large extent by what it *could* or *should* be, and its capacity to make activities and domains *auditable*, as well as through the plethora of devices that inhabit the domain of auditing practice. This dual aspect of audit, and of accounting more generally, is important for it alerts us to the ways in which broader policy and political ambitions can be linked to such a wide range of apparently mundane and neutral calculative practices.

This way of thinking about the governing of economic life placed accounting practices centre stage within an expanded economic sociology (Hopwood and Miller, 1994). While analogous to Callon's (1998) call to consider the interrelations between economics as a discipline and the economy as a thing, the literature on accounting suggested a more differentiated notion of calculation. This included consideration of the important roles played by economic models, not least in the formation of some of the key concepts and calculative practices of accounting, but it also suggested careful attention to the distinctions between, *inter alia*, accounting, actuarial science, economics and finance. This differentiation is significant if we are to understand the roles and scope of these distinct disciplines in shaping the economic domain, but it is important in a further sense. It alerts us to the extent to which modes of expertise can hybridise, or adapt and borrow from other modes of expertise at the 'margins' (Kurunmäki, 2004; Miller, 1998), and it alerts us to the ways in which certain instruments or models can 'mediate' between actors and arenas such as science and the economy (Miller and O'Leary, 2007). As Wise (1988) demonstrated, with respect to the steam engine and the electric telegraph, instruments can mediate between social context and the "everyday doings" of practitioners. Put differently, if social context affects those working in areas involving

mathematics or measurement, it does so in a mediated form. In so far as machines carry with them a set of ideas that explain their physical operation, and a set of ideas that explain their social function, the embedding of physical and social ideas requires a mutual adaptation of the one to the other.

This notion of mediation has been extended recently by Morrison and Morgan (1999), who have suggested that "models" can function as mediating instruments. They suggest that models – neither just theory nor data – are one of the critical instruments of modern science. While an instrument is independent of the thing it operates on, it nevertheless connects with it in some way and acts as both means of representation and means of intervention. This, they suggest, holds for both the natural and the social sciences, which places models of superconductivity or quark conferment on the same footing as the Leontief input-output model and multivariate structural time-series models.

The concept of "techno-economic networks" (Callon, 1991; Callon, Larédo and Mustar, 1997) reinforced this line of argument. Here, the emphasis was on the triptych formed between scientific knowledge, technical instruments and market forming activities. Rather than viewing the economic domain as made up of firms and markets only, it is viewed as made up in important part out of the complex links formed among university laboratories, technical research centres, companies and customers. The emphasis here is on the "intermediaries" that link the various constituent elements, such as written documents, technical artefacts, individuals or money.

Most recently, these arguments have been extended with respect to financial markets and financial knowledge. Mackenzie and Millo (2003) have addressed the role of economics and economic theory in the context of the Chicago Board Options Exchange, while Beunza and Stark (2004) and Kalthoff (2005) have called for economic sociology to focus more on problems of calculation and valuation. The term 'market devices' has been used to refer to the range of instruments, models and tools that make it possible to represent markets and intervene in them (Callon, Millo and Muniesa, 2007), while Mackenzie (2006) has ably demonstrated the validity of the awkward neologism 'performativity' in a study of the co-emergence of financial economics and contemporary financial markets.

Taken together, this recent body of work is further evidence of the need for economic sociology to complement existing research on the embedding of markets in institutions, networks and personal interactions with attention to the roles played by systematic forms of knowledge and their technological infrastructures that shape and are deployed in markets. It is to a consideration of these issues that we now turn, taking the roles of Moore's Law and technology roadmaps in the microprocessor industry as exemplars.

Figuring out Science and the Economy

"Moore's Law" is the label that has been given to a set of predictions, based on flimsy data, made by Gordon E. Moore in April 1965. Moore, who was then R&D Director at Fairchild Semiconductor, had been asked to predict what would happen to the semiconductor components industry during the next ten years. Reflecting back on these predictions three decades later, Moore commented as follows:

> "I did not expect much precision in this estimate. I was just trying to get across the idea this was a technology that had a future and that it could be expected to contribute quite a bit in the long run." (Moore, 1995, p. 2)

Imprecise or not, these predictions have proved to be enduring, and they now underpin the expectations of an entire set of industries about rates of increase in the power and complexity of semiconductor devices, and the timing of those increases. Fundamentally, the predictions suggested also that the massive increases in device complexity over the next ten years would be accompanied by corresponding reductions in cost. Taking 1959 as the base year for the data, these predictions have proved robust for nearly half a century, with only relatively minor inflections.

Moore had extrapolated in a straight line based on a handful of observations pertaining to rates of increase in device complexity, which led him to envision a thousand-fold increase across the next decade in the number of components in the most complex circuits available commercially. If the predictions were accurate, he suggested that this meant a massive increase in the number of electronic components that could be

“crammed” on a single semiconductor device. Whereas in 1965 that number was only 50 or 60, he predicted that this would be approximately 65,000 by 1975. But, even more fundamentally, he predicted that this would be paired with corresponding cost reductions, arising primarily from advances in lithography and reductions in defect density. This meant that, for each ‘generation’ of products, the costs of adding electronic elements to a device would decline until one reached the limits of current manufacturing capabilities. Beyond some level of density, the benefit of adding more elements would be offset by the extra expense of manufacturing a defect-free product in any given generation of technology. By 1975, Moore had revised his projections for the slope of the rate of increase in device complexity, indicating that the slope might approximate to a doubling of device complexity for minimum cost every two years, rather than every year as originally indicated. It is this particular prediction that came to be termed Moore’s Law in subsequent years.

These predictions of product and process improvements, paired with reduced cost, can appear even today as implausible. But they were even more so at the time they were first made. In 1965, integrated circuits formed on a semi-conductor substrate such as silicon were only a few years old, and the first manned moon landing was still four years away. Many in the industry continued to think that the role of the semiconductor industry was to produce individual elements such as transistors, diodes and capacitors, rather than the integrated circuits themselves. In his 1965 article, Moore argued strongly and persuasively in favour of integrated circuits, yet in terms that must have sounded like science fiction to many of his contemporaries:

> “Integrated circuits will lead to such wonders as home computers – or at least terminals connected to a central computer – automatic controls for automobiles, and personal portable communications equipment.” (Moore, 1965, p. 114)

At the time, integrated circuits were limited mainly to the military, but Moore envisaged a massive increase in their use in a range of personal, commercial and governmental applications:

> “Integrated electronics will make electronic techniques more generally available throughout all of society, performing many functions that presently are done inadequately by other techniques or not done at all.” (Moore, 1965, p. 115)

He went on to state that the biggest potential resided in the production of large systems, remarking portentously that “Integrated circuits will also switch telephone circuits and perform data processing” (Moore, 1965, p. 114). This, combined with reduced cost, gave rise to the astounding predictions made by Moore:

> “Reduced cost is one of the big attractions of integrated electronics, and the cost advantage continues to increase as the technology evolves toward the production of larger and larger circuit functions on a single semiconductor substrate.” (Moore, 1965, p. 115)

To demonstrate this, Moore graphed the relations over time between the number of electronic elements on a semiconductor, which he termed device complexity, and cost. The resultant series of u-shaped curves, shifting downward and to the right over time, is reproduced in Figure 1, while Figure 2 shows the predicted straight line increase in device complexity.

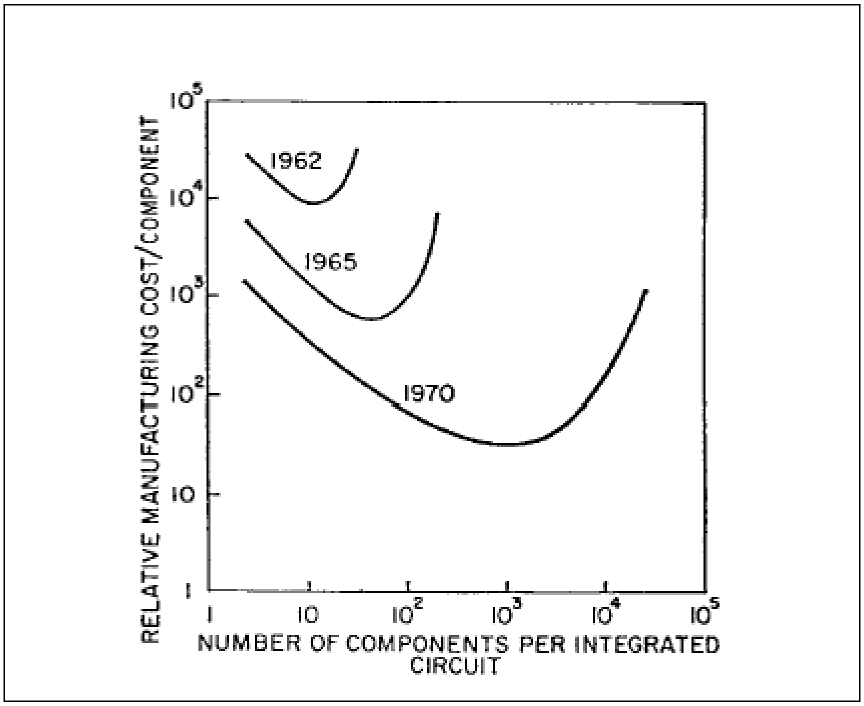

Fig. 1. Curves of Device Complexity for Minimum Cost.

(Adapted from Moore, 1965, p. 115)

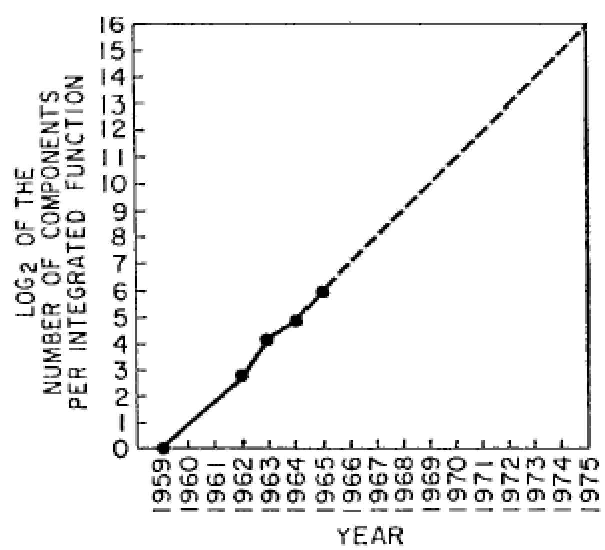

Fig. 2. Number of Electronic Elements "Crammed" on an Integrated Circuit

(Adapted from Moore, 1965, p. 116)

This was more than a "technological trajectory" (Mackenzie, 1996), a persistent pattern of technological change that is explained by the fact that technologists and others believe it will persist. For at its heart was a prediction not only about technological developments, but about the powerful and beneficent links between science and the economy, a "mediating instrument" in the strong sense (Miller and O'Leary, 2007). In so far as its basic assumptions held, more powerful semiconductors would be available for an ever increasing array of applications affecting private life, business and government. And these applications would be increasingly attractive because of the large cost reductions that went with the increases in complexity.

But if others were to be persuaded, and if the appropriate levels of investment were to be achieved, something more was needed than the fantastic claims and predictions made by Moore. The imperative to innovate technologically, and the promise of associated cost improvements, had to be articulated in such a way that all those who were needed for such an endeavour could be persuaded to contribute. To put this differently, in so far as Moore's Law is a 'mediating instrument' linking science and the economy, something more – a programmatic ambition and a set of instruments to realise it – was needed to mobilise the wide range of actors and aspirations needed to make it a reality.

By the mid 1980s, however, it was not at all clear that American firms and research agencies shared the beliefs embodied in Moore's law. Indeed, the semiconductor industry was referred to in the report of an advisory committee to Congress at the end of the 1980s as a "strategic industry at risk". The committee chairman, Ian Ross of AT&T, declared to President Bush in November 1989 that the "semiconductor industry in the United States is in serious trouble" (Ross, 1989, introduction). By this time, all of the advanced industries of the Unites States relied on products incorporating the latest integrated circuits, but the country had lost its leadership in semiconductor design and production. Revenues of American semiconductor firms were losing out badly to Japanese competitors, while 80% of the rapidly growing DRAM market had been ceded to Japan. This had not only damaged manufacturers of integrated circuits, but had all but eliminated US suppliers of the materials and equipment used for semiconductor production. By the end of the 1980s, the US was importing 97% of the

most advanced silicon wafers and 68% of the highest specification lithography machines from overseas suppliers (National Advisory Committee on Semiconductors, 1989, pp. 8-9).

The diagnosis of the causes of this decline and its perceived remedies shared many of the refrains that were familiar from the wider debates about the decline of American manufacturing in the 1980s (Cohen and Zysman, 1987; Dertouzos, Lester and Solow, 1989; Miller and O'Leary, 1993, 1994a). Capital investment was pointed to as a central issue, with US semiconductor firms consistently investing less than their Japanese counterparts (National Advisory Committee on Semiconductors, 1990b). This inferior commitment to technology development was held to have been a key factor in the loss of world market share to Japan. Ross's committee pointed to this, and also to the need to correct certain perceived deficiencies in the workings of the nation's capital markets, with Japanese firms being able to obtain capital at lower cost that their US counterparts and being willing to invest longer term. This had, it was argued, lowered the risks and increased the time-horizons for capital budgeting decisions, a key issue in a capital intensive industry. The committee proposed that low-cost, long-term capital should be made available through a consortium of industry, government and private and institutional sources (National Advisory Committee on Semiconductors, 1990b, p. 22).

Almost as soon as this proposal was announced, it was rendered irrelevant. By the time Ross's committee presented its final report to Congress in 1992, American semiconductor firms were regaining market share. This was a consequence of a change in strategy for the industry, rather than any action directed at US capital markets. One particular type of semiconductor – the microprocessor – was substituted for another – the DRAM or memory device. This allowed American firms and research agencies to focus their efforts on skills on an area of relative advantage, one that also offered significantly higher margins and in a market that was increasing significantly overall. By 1997, US firms held over 50% of the total world market for semiconductors, with Japanese firms' share reduced to just 29% (Macher et al., 1998, p. 112).

A separate proposal of Ross's committee, however, was to have enduring consequences. The committee expressed concern at the lack of coordination among firms and research agencies of their capital spending on "pre-competitive" R&D. This referred

to investments in common underlying technologies for the US semiconductor industry as a whole, excluding proprietary products and components. Such investments were needed years before products are ready for markets, but the total amount of such investments nationally was insufficient, despite the amount of investment needed increasing each generation (National Advisory Committee on Semiconductors, 1989, p. 20). Despite relaxations in anti-trust law, the nation was held to be lagging its Far East rivals in such cooperative endeavours. Firms undertook research projects and appraised investment opportunities independently, thereby limiting the financial resources that could be applied to any single R&D effort. There was little sharing of non-proprietary information and expertise to manage and coordinate the development of new technologies that would benefit all in the industry.

This indicates the limits of Moore's Law, or rather its need for complementary instruments. Moore had sketched out a possible future for microprocessors, in terms of the rate and timing of increased complexity, and had modelled a very happy coincidence of technological development and cost reductions. But to make that imagined future a reality required an instrument that would facilitate the coordination and alignment of investments among firms, research agencies and universities. The task of devising such an instrument fell to a group chaired by Gordon Moore himself, and he set about this in November 1992. That month, Moore – who then was President and CEO of Intel – convened a meeting in Irving, Texas, of almost 200 scientists, engineers and semiconductor technologists. Moore was acting as chairman of the Semiconductor Industry Association's technology committee. Those attending represented major US semiconductor firms, their suppliers and customers, as well as representatives of universities, government agencies and national laboratories. The aim of the meeting was to create a "common vision" of the future of semiconductor technology for a fifteen year period. A set of charts was to be made available to all participants to help coordinate and time their investments in research and development of advanced technologies. Ross's committee had argued that significant capital misallocations resulted from isolated and un-coordinated decisions of individual firms and agencies. Moore's group sought to rectify that, by creating an instrument that would mediate between the multitude of distinct investment decisions, aligning them without breaching the confidentiality of

individual companies' capital budgeting processes, and without seeking to determine their technology choices.

The first set of charts was published in 1992, as a US National Technology Roadmap for Semiconductors. Two revised versions – published in 1994 and 1997 – were also developed by the American industry alone, but subsequent versions have been international, bringing in the other four key semiconductor regions of the world (Europe, Japan, Korea and Taiwan). From 1998, pre-competitive scientific and R&D programs were to be coordinated internationally. While the initial premise – that the solution for US industry could be found within the US alone – was altered, the fundamental commitment to Moore's Law and its assumptions of continuing cost reductions per function combined with continued scaling of electronics has remained. As the 2007 edition of the industry roadmap states:

> "Thus the Roadmap has been put together in the spirit of a challenge – essentially, 'What technical capabilities need to be developed for the industry to stay on Moore's Law and the other trends?'" (International Technology Roadmap for Semiconductors, 2007, p. 1).

Table 1 summarises top-level data from the 2001 edition of the Roadmap for illustrative purposes. Each of the columns refers to a 'technology node' or generation, the year by which more advanced types of semiconductor products were expected to be available for

Table 1. International Technology Roadmap for Semiconductors, 2001 Edition, Data Adapted from Top-Level Charts[2]

Year of first production:	**2001**	**2004**	**2007**	**2010**	**2013**	**2016**
Technology node:	**(TN_0)**	**(TN_1)**	**(TN_2)**	**(TN_3)**	**(TN_4)**	**(TN_5)**
Expected shifts in product functionality & manufacturing cost - high volume microprocessors						
Number of electronic elements per chip at introduction (billions of transistors): *Multiple per 3 year technology cycle:*	**0.193**	**0.386** ***2***	**0.773** ***~2***	**1.546** ***2***	**3.092** ***2***	**6.184** ***2***
Affordable production cost per element at introduction (micro cents): *Rate of cost reduction per cycle (%):* *Annualized cost reduction (%)*	**176**	**62** ***~65%*** ***~29%***	**22** ***~65%*** ***~29%***	**7.78** ***~65%*** ***~29%***	**2.75** ***~65%*** ***~29%***	**0.97** ***~65%*** ***~29%***
Chip size at introduction (mm^2):	**280**	**280**	**280**	**280**	**280**	**280**
Innovations in lithographic equipment for microprocessor manufacture						
Electronic feature size ½ pitch (nm):	**150**	**90**	**65**	**45**	**32**	**22**
Type of lithographic technology:	**Deep ultraviolet (DUV)**			**Extreme-ultraviolet (EUV) *Or* Electron projection (EPL)**		
Innovations in raw materials						
Silicon wafers Wafer diameter (mm) in high-volume production	**300**	**300**	**300**	**300**	**450**	**450**

sale. The timing of each node, and the expected levels of product functionality (number of electronic elements per chip), and desired cost reduction (per cycle and per annum) are derived from Moore's Law, albeit with some adjustments. According to Moore's Law, a new semiconductor should provide twice the functionality every two years at a constant cost *per chip*. This means that, if the number of electronic elements per chip doubles every two years, total manufacturing cost *per element* should reduce by approximately 29% per annum. But, if the rate of increase in functionality slows down for any reason (economic downturn, delays in introducing new technology), the industry nevertheless seeks to maintain the annual rate of cost reduction. The 2001 edition of the Roadmap illustrated (in condensed form) in Table 1 demonstrates this flexibility of Moore's Law – the doubling in the number of electronic elements per microprocessor is scheduled to

[2] Semiconductor Industry Association, International Technology Roadmap for Semiconductors (Austin, TX: SIA, 2001).

occur at slower (3 year) intervals out to 2016, but cost per element is scheduled to continue to reduce at its historic rate of 29% per annum. Maintaining this favourable relationship between functionality and price enabled semiconductor manufacturers to withstand market pressure, and continue to promote increases in demand in line with historical average, even when the rate of increase in functionality slows down.

Maintaining Technological and Financial Trajectories: the case of post-optical lithography

The Roadmap provides an instantiation of Moore's Law, and also a means of mediating between the strategies and investment programs of legally separate entities, dispersed geographically and across an extensive range of industries. It is a "market creation" device, allowing a shared opinion to be formed about the exact rate and timing of increases in product complexity, and the concomitant cost reductions required. But the Roadmap does more than offer participants a way of respecting Moore's Law, while adapting to the exigencies of current market conditions and any technological delays or difficulties. The Roadmap not only sets out "normal" rates of increase in device complexity and corresponding desired cost reductions, but it also indicates where less frequent innovations are required to allow such improvements to be maintained. For instance, and taking Table 1 as illustration, the Roadmap indicates that an increase in silicon wafer diameter (from 300 mm to 450 mm) is required around 2013. It indicates also that new lithographic technology is needed around 2010 to enable sufficiently small electronic elements to be patterned on silicon. The Roadmap thus highlights the cascade of innovations that are needed in all of the firms and industries that enable and complement the manufacturing of microprocessors. It allows existing and potential market participants to time their investments so as to adhere more or less to the injunctions of Moore's Law. The case of "post-optical lithography", and the apparent need (as indicated by the Roadmap) for this to be available around the year 2010, provides an illustration.[3]

For several decades, the patterning of electronic features on silicon had been achieved by beaming light through lenses. By continually reducing the wavelength of the

[3] See Miller and O'Leary (2007) for a more extended consideration of this example.

light source, while increasing the aperture of the lens, it was possible to pattern ever smaller elements. By the 1990s, however, it was suggested that optical lithography was entering its "twilight phase" (Geppert, 2004). Continued miniaturization would require a "post-optical" approach. The 1999 edition of the Roadmap stated that this "shift will drive major changes throughout the lithographic infrastructure and require significant resources to commercialize the system".[4] Five years later, Intel Corp had installed the world's first post-optical lithography tool, albeit not for high-volume manufacture. The following considers the series of steps that made this possible.

The early incorporation of Moore's Law in the semiconductor Roadmap was important here. For this demonstrated, as early as the first Roadmap of 1992, that there was a compelling need for immediate investment to devise post-optical lithography. Given the predictions of Moore's Law, the Roadmap indicated that the limits of existing optical lithography could be reached in ten or fifteen years. Around then, it was expected, continued miniaturization would result in electronic elements being too small to be formed by traditional optical methods. This prediction was coupled with the realisation that it could take a decade or more to produce a new lithographic system that would work at such levels of miniaturization and beyond. A two-pronged solution was suggested: first to seek ways to extend the life of 'conventional' optical lithography, and second to commence the investment needed on the part of suppliers, consortia and research agencies that would lead to post-optical solutions. As with other technological trajectories and competitions, it was clear early on that the world's major semiconductor firms would purchase only one system, meaning that the rewards for devising the successful system would be secured world-wide for many years and possibly several decades.

But, as the history of the industry had already demonstrated, simply calling for capital spending would not necessarily result in that spending taking place. Nor would it necessarily produce the breadth of investments that would allow the range of candidate technologies to be developed sufficiently and assessed adequately. Of the three key technologies that were being discussed in the 1990s (X-ray, electron-beam projection and

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[4] Semiconductor Industry Association, International Technology Roadmap for Semiconductors (San Jose, CA.: SIA, 1999, pp.152-3).

extreme-ultraviolet), different levels of investment were occurring in each. The X-ray system, long supported by IBM, had received the most resources devoted to it, while the other two had received significantly less. Lucent Technologies (formerly part of Bell Laboratories) was a key proponent of the electron-beam projection system, but extreme-ultraviolet technology lacked a key corporate sponsor. This was of concern to the executives of Intel, AMD and Motorola, and they took steps to promote renewed investment in it by establishing the "Virtual National Laboratory", a collaborative partnership formed between the private and public sectors. A consortium funded by Intel, AMD and Motorola, and termed the EUV LLC (EUV Limited Liability Company), would fund the Virtual National Laboratory to serve as an expert systems integrator for the unique components comprising extreme-ultraviolet lithography. The components would be devised by an extensive set of supplier firms, research agencies and industries, but tested and integrated as an operable system in collaboration with the Virtual National Laboratory.

Between October 1997 and December 2005, the consortium responsible for the Roadmap organised at least eight conferences devoted to post-optical lithography. There were deep-seated disagreements there, and elsewhere, as to which system could be made operable for mass use. Just as Intel, AMD, and Motorola were committing to the development of extreme-ultraviolet, Lucent Technologies was abandoning that approach, and planning to set up a rival consortium to that of EUV LLC. While this was viewed as highly desirable in so far as it encouraged the development of competing systems, the scale of the investment needed meant, according to the Roadmap designers, that at some stage it was important to narrow the range of options through coordinated global interactions among government, industry and universities.[5] The international conferences allowed for such assessments to be conducted openly and robustly. At the end of each conference, a survey of attendees provided a ranking of the approaches that had been demonstrated. Each method was argued for by a "champion", and delegates assessed these presentations in relation to criteria that included whether the technology would be available world-wide when needed, whether it would meet all core operational

[5] Semiconductor Industry Association, *International Technology Roadmap for Semiconductors* (San Jose, CA.:SIA, 1999, pp. 152-3)

requirements for multiple product generations, and whether the capital outlay to purchase the technology would be justified by throughput rate and life-cycle operational costs. At the fourth such conference, held in Reston, Virginia, in September 2000, delegates reacted in overwhelmingly negative terms to X-ray lithography, answering "never" when asked to specify when it was likely to be available for high-volume production. This reinforced views expressed less strongly at previous conferences in 1998 and 1999. As a consequence, X-ray lithography was eliminated from further consideration at future conferences and from listing in the International Roadmap. While this did not, of course, preclude firms such as IBM from continuing to invest in X-ray lithography, it increased the risks and also narrowed the range of firms that might share the development costs. IBM announced during 2000 that it would join the EUV LLC, thus indicating an important shift in its investment priorities towards post-optical lithography.

But technological choices and their concomitant economic evaluations tend not to follow a neat path. An "immersion" system – which held out the promise of significantly extending the life of existing optical forms of lithography – was entered on the International Roadmap in 2003. At the time of writing, key firms are continuing to extend this by using various techniques, while doubts are being expressed as to whether EUV lithography will be ready for volume production in 2011, with major technical challenges remaining, including EUV masks, mirrors and "resists". This, notwithstanding over a decade of development work on EUV lithography supported strongly by many of the leading microprocessor companies. Since 2001, industry conferences have been made aware of potential "showstoppers", intractable design or engineering sisues that could prevent the system from working effectively in the factory (Semiconductor Industry Association, 2001, p. 13). For instance, while commercializing aspheric-mirrors was considered to pose low levels of technical risk, in so far as these components were unique to the extreme-ultraviolet system, optics firms might not make them production-ready if major doubts attended the perfectibility of other components, such as the illuminator. Yet again, the Roadmap conferences played a role here, seeking to delineate a programme and time-line for convincing the industry that a particular technological "showstopper" could be resolved, while also seeking to ensure that cost-of-ownership calculations would meet key benchmarks. At issue was not only to

demonstrate the viability of a particular technological solution, but also to shape expectations regarding cost and price of the various components comprising the system. By estimating capital cost per machine, the cost per "mask" containing the image of the integrated circuit, and an output measure of throughput of silicon wafers per hour, an Intel manager sought to demonstrate to delegates that the capital cost of an EUV machine should, at high volume, be comparable to that of an "immersion" system (Silverman, 2005, pp. 4-5).

The ongoing development work on post-optical lithography demonstrates the key role that Moore's Law and Roadmaps play in the shaping of the industry and the decision-processes that comprise it at the pre-competitive stage. With major technological innovations signalled ten or fifteen years ahead of their needed introduction, technological and financial risks are given visibility and linked firmly together. While Moore's Law sets out the basic contours of the landscape for years ahead, Roadmaps and their associated conferences spell out in more detail and assess the multiple conditions that have to be met to satisfy the continued viability of Moore's Law. Spanning the entire industry, they mediate between the scientific and the financial domains, and allow the market-creating attributes of Moore's Law to continue, at least for the present.

Conclusions

The simplest conclusion that follows from the above is the proposition that there is an important class of calculative practices – which we can call information exchanges, instruments, technologies, models, or rationalized processes – that social scientists have to date largely neglected. The defining characteristic of these practices empirically is that they span entire industries or sets of industries, and that they provide an infrastructure that helps to link up or mediate among firms and a wide range of research agencies. It is argued that these practices have a market-defining or market-creating capacity, and that they mediate between science (or technology) and the economy. An imagined technological future is linked to and made feasible through an imagined economic future. We have taken as our example in this paper the phenomenon that has come to be called Moore's Law, together with 'roadmaps' that we have argued are an essential complement

to the market-making and mediating capacities of Moore's Law. Through Moore's Law, Roadmaps, and their associated conferences, an imagined future of increasing technological complexity is linked to and made feasible through an imagined future of reduced cost.

It is of course the case that a wide range of social scientists have drawn attention for several decades now to a range of boundary-spanning activities that form networks between firms and other organizations. But this large and diverse literature has tended to focus primarily on organizational and inter-organizational forms, and networks of personal connections, rather than attending to the practices and instruments that provide the pre-competitive calculative infrastructures that enable markets to operate. The recent literature that can be designated by the term 'science studies' has offered a useful complement to this existing focus, yet this too has its shortcomings. In focusing more or less exclusively on technological infrastructures and devices, it has tended to neglect or downplay the roles that ideas, programmes or myths play in articulating and mobilising such devices. Drawing on arguments concerning the governing of economic life and the roles of accounting in making that possible (Hopwood and Miller, 1994; Miller and Rose, 2008; Power, 1997), this paper has argued that we should attend to *both* ideas and instruments, and the interplay between them. For it is, we suggest, through that interplay that each dimension finds its conditions of operation.

The potential implications of attending to these calculative infrastructures are of significance for a wide range of researchers. First, it implies a broadening of the domain of sociological and organisational analysis to include more centrally the models or practices which provide an infrastructure through which the governing of economic life occurs. It places science as an institution and set of practices at the core of sociological and organisational analysis, while enjoining researchers to consider what we have termed the "modes of mediation" between and the economy. Second, it suggests that the modelling of these practices, the benefits of which may extend beyond inter-firm complementarities, could be worthwhile. Third, there are potential implications for "event studies", to test whether non-financial disclosures impact on analysts' forecasts. Fourth, and finally, it has significant implications for investment appraisal and the management of risk.

Note

This paper draws extensively on work conducted jointly with Ted O'Leary. See, in particular, Miller and O'Leary (2007), and Miller, Kurunmäki and O'Leary (2007).

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