Introduction

Arthur del Prado (1931-2016) resigned as chief executive officer of ASM International on March 1, 2008, to be succeeded by his eldest son. The Dutch entrepreneur left behind a company that accounted for net sales of almost one billion euros, employing almost 12,000 individuals at one American operation and various European and Asian operations.[1] Upon his retirement, Del Prado's career in the chip industry spanned as many as fifty years. In 1958, his career took off in the region now known as Silicon Valley in California, after which, from 1964 onward, he founded and developed Advanced Semiconductor Materials (ASM), a company located in Bilthoven, the Netherlands.

Through equipment manufacturer ASM, Del Prado became involved in virtually all technologies used in the fabrication of computer chips. He contributed to the rise of the chip industry and witnessed the technology's profound impact on our daily life. His perseverance, entrepreneurial instincts, and captivating cosmopolitism enabled major innovations in chip technology. The size and healthy condition of ASM at his resignation in 2008 testify to his achievements.

This study offers a glimpse into the tangled world of the chip industry through the untold history of a visionary entrepreneur and his little-known business. Companies active in competitive, volatile, and pricy high-tech industries depend on their innovative prowess for survival. Here, more than elsewhere, innovation is vital. By tracing and unraveling both innovation and business at ASM, it is possible to draw multiple lessons: about the dynamics of innovations, about the viability of business strategies, and, more in general, about the fate of high-tech firms in modern economies. After all, the realization of innovations depends on numerous influences, which always present themselves in unique ways throughout history.

For all those years, ASM was a major supplier of innovative technologies and this is an achievement that did not come about automatically. The company's long history is one of both failures and successes in innovation and business. Moreover, the wide variety of chip manufacturing technologies in which it engaged makes it a perfect case to study the various meanings and manifestations

1 The exact figure is 955.2 million euros. In 2008 the company had operations in the Netherlands, Belgium, Finland, the United States, Japan, Hong Kong, Singapore, China, South Korea, and Taiwan, with a total staff – in full time equivalents – of 11,832. – ASM International, *2007 Annual Report ASM International* (April 2008).

of innovation processes. The story of ASM allows us to explore and clarify the dynamics of high-tech innovation. Specifically, this study centers on the following research question:

> How to characterize and explain the innovation processes at ASM International from 1958 until 2008?

The timeframe covered by this study corresponds with Del Prado's presidency of ASM International, from his establishment of the company in 1964 until his resignation as CEO in 2008.

In this study I explore and reconstruct ASM's organizational and technological developments. I focus on specific innovations, and will also provide a general history of ASM – its struggles, failures, expansions, and successes. As such the study presents both a business history and a study of innovation. Various other aspects of ASM's business adventures will pass in review throughout the main story and its subplots as well. This includes the rather Machiavellian capers cut by Del Prado, detailing the wide-ranging entrepreneurial perils of operating in the chip industry. Also, the wizardry and ingenuity required to fabricate a computer chip will be explored, for ASM engaged in almost all major fabrication techniques. Moreover, because Del Prado's presidency of ASM basically concurred with the powerful rise of the chip industry, this study also offers various insights into the complex realities of the global computer chip industry. Overall, the study maps an industry and enterprise which, so far, hardly has been covered in academic historical analysis.

ASM International is a multidivisional company.[2] To be precise, the study takes the perspective of ASM International and subsequently its variety of subsidiaries. However, ASM International also encompasses the head office, which oversees and manages the various operations. For clarity sake, I will make the following distinction. Whenever I talk about the head-office, I speak of 'ASM International'. If I speak about ASM as the whole group of operations or 'companies' – including the headquarters – I will speak of 'ASM'. The various

2 The structure of multinational enterprises can be seen in various ways, like the functional, holding or multidivisional structure. Business historians Keetie Sluyterman, Gerarda Westerhuis and Abe de Jong defined the multidivisional structure as '(…) distinct and coherent operating units, a preference for substantial majority ownership of businesses, more or less standardized accounting and control systems, and the active integration of newly acquired operations.' - Abe de Jong, Keetie Sluyterman, and Gerarda Westerhuis, 'Strategic and structural responses to international dynamics in the open Dutch economy, 1963-2003', *Business History* 53:1 (2011) pp. 63-84, p. 69. The authors based their definition on: Richard Whittington and Michael Mayer, *The European Corporation: Strategy, Structure and Social Science* (Oxford University Press, Oxford, 2002).

subsidiaries are indicated through their respective names, – like ASM Japan, ASM Lithography, ASM Pacific Technology, etc.

From the 1990s onwards, the company itself distinguished its activities in 'front-end' and 'back-end'. Front-end being the businesses involving equipment that processes silicon wafers. Back-end concerned technologies for assembly and packaging of chips.

This study tends to focus upon the wafer processing activities. After an initial public offering of ASM Pacific Technology in 1989, back-end was managed by a distinct management team of this respective company, which merely gave account to its parent company ASM International on a quarterly basis. The head office did not interfere operationally within ASM Pacific Technology. Elaborating upon this distinction between front- and back-end, this study focusses upon the operations that were directly managed and overseen by ASM International. From the 1990s onwards, that is front-end.

The vibrant and innovative world of semiconductor manufacturing

The industry in which ASM has been operating is one of dazzling numbers. This includes the size of the chip industry, the different manufacturing processes, and the impact of chips on our daily life. Chips are everywhere. Throughout the day, we all rely on this particular technology numerous times, from our alarm clock waking us in the morning, our car driving us to work, and our payments made through our bank card to the seemingly endless possibilities of our smartphone. The list of applications involving computer chips is immense and continues to expand. The ordinary and overwhelming presence of computer chips in our lives overshadows the extraordinary world of innovation required to produce a chip.

In less than a lifetime – from the invention of the first solid state transistor in 1947 onward – the various skills and technologies required to make a chip were modified, improved, and transformed at an unprecedented rate. A basic constitutive element of the computer chip – and thus of the revolutionary development of information technologies – is a material that through minor alterations can either conduct or insulate electrical signals. This so-called semiconductor material is most often silicon.[3] Semiconductor materials proved to be more resilient and reliable than the preceding information technology of vacuum tubes. The centrality of the material and its properties is reflected in another term for the chip industry: *the semiconductor industry*. The key capability in the chip industry pertains to yielding and modulating semiconductor materials.

All the different treatments of semiconductor materials are primarily aimed at the large-scale and perfect production of a particular and vital component of

3 And other variations like germanium and gallium arsenide are used, though not in the volumes and applications like silicon.

a chip, the so-called transistor. It is an electrical switch, billions of which are packed into a single computer chip. In fact, the transistor as part of a computer chip is the most fabricated man-made object in the history of the world.[4] To get a sense of their sheer quantity, just imagine the few billion transistors on a chip multiplied by the millions of chips produced annually.

The semiconductor supply chain, from raw materials into application into an electrical device, is one of the most elaborated and globalized in the world. Advanced expertise resides and has been cultivated locally. As stated in *The Economist:*

> 'It may start in the Appalachian mountains, where deposits of silicon dioxide are the highest quality. The sand may then be shipped to Japan to be turned into pure ingots of silicon. These are then sliced into standardized wafers, 300mm across , and sent to a chip factory, or "fab", perhaps in Taiwan or South Korea. Here the slices will be imprinted with a particular pattern using photolithography equipment made in the Netherlands. That pattern will be determined by the overall design of the chip. This design might come from ARM, a company based in Britain. ... Once finished, it must be assembled into a package, in which the etched silicon is placed inside the familiar ceramic or plastic containers that are dotted across any circuit board, and then comes testing. That might take place in China, Vietnam, or Philippines.'[5]

Once tested, again, the chip is dragged multiple times across continents for integration in printed circuit boards, which are assembled into electrical products which on their turn are shipped to customers across the globe. This whole chain is a delicate balance, or as historian of technology David Brock put it, 'an orchestration of innovation'.[6]

By 2008, the wide presence of computer chips in our world resulted in a global annual revenue of about 250 billion dollars, a figure that grew to 469

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4 David Brock and Christophe Lécuyer, 'Digital Foundations: The Making of Silicon-Gate Manufacturing Technology', *Technology and Culture* 53:2 (2012) pp. 561-597, p. 561. Estimates of data service IC Insights were that in 2018 alone over 1,075 billion semiconductor products will be produced. In 1978 this number was just 32.6 billion. – Paul van Gerven, 'Halfgeleiderverkoop doorbreekt grens van een biljoen', *bits-chips.nl* (30-1-2018).

5 The Economist, 'The Chips are Down', *The Economist* (1-12-2018) pp. 20-22, 21.

6 'This in contrast to systems of innovation. 'In semiconductor manufacturing there exists an ecosystem of technologies. Within this ecology lithography exposure tools and photoresist are highly coupled: the performances and characteristics of each help define the fitness and success of the other.' - David C. Brock, 'Patterning the World: The rise of Chemically Amplified Photoresist', *Chemical Heritage Foundation, Center for Contemprorary History and Policy: Studies in Materials Innovation* (2009), pp. 17.

billion dollars in 2018.[7] These revenues were obtained by the sales of various kinds of computer chips. The majority of them are so-called memory chips that store information. In addition, there are chips that translate analog signals into digital ones – called linear chips – and those that process information, called microprocessors and controllers. Furthermore, some chips are designed in a general way, allowing users to program the chip for their own needs. And, finally, there are chips that are specifically designed and manufactured for a single application. Many chip manufacturers are specialized in one or a few of those different kinds of products.

Since the early days of computer chip manufacturing, the machines to produce chips changed rapidly as well. A distinct industry has emerged to design, develop, and sell new semiconductor manufacturing techniques and equipment. Apart from semiconductor equipment manufacturers, like ASM, this industry consists of material suppliers and companies specialized in the construction of chip factories. The semiconductor equipment industry amounted to a value of around 30 billion dollars in 2008, a figure that increased to 65 billion dollars in 2018.[8] Despite the fairly small size of the manufacturing sector in comparison to the chip industry as a whole, this sector clearly plays a vital role.

There are numerous processes involved in altering the semiconductor material. The production of one computer chip involves tens of chemical and physical treatments, if not up to about one hundred. Three techniques are paramount and employed in different variations: the growth of a thin film through deposition techniques; the projection of a pattern through lithography; and the etching of materials through gasses and liquids. Next to these three predominant manufacturing processes, there are multiple metrology techniques and many steps in the assembly and packaging of chips.

Each step in the manufacturing process depends on highly specialized knowledge, forming a market of its own. For instance, the size of the market for lithography, a technology that involves highly specialized handling of optics, was 5.4 billion dollars in 2008.[9] The semiconductor production machines themselves

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7 Global sales of 2008 and 2017 based upon information of the Semiconductor Industry Association (SIA). – SIA, 'Global Semiconductor Sales Fell by 2.8 Percent in 2008', *semiconductors.org* (2-2-2009); and SIA, 'Global Semiconductor Sales Increase 13.7 Percent to $468.8 Billion', *semiconductors.org* (4-2-2019).

8 The number is relatively low in 2008 due to the global financial crisis. In 2007, the worldwide revenue for semiconductor manufacturing technology was 43 billion dollars. The chip industry's total revenue in 2007 was 255.6 billion dollars. Numbers derived from press releases of industry association for semiconductor equipment and materials, SEMI. - SEMI, 'SEMI Reports 2008 Global Semiconductor Equipment Sales', semi.org (25-3-2009); SEMI, '2018 Global Semiconductor Equipment Sales Jump to Record $64.5 Billion', *semi.org* (10-4-2019).

9 Dylan McGrath, 'Gartner sees tough year for litho stepper sales', *EETimes.com* (22-6-2009).

are costly, as equipment prices range from one hundred thousand euros up to as much as one hundred million euros. The semiconductor equipment industry, in which ASM is active, covers all these different segments.

The manipulation of semiconductor materials pertains in particular to miniaturization of transistors and other components of a computer chip. The industry's rule of thumb is: the smaller the transistor, the better. Smaller size improves a transistor's performance and decreases its cost. Furthermore, if a transistor is smaller, more transistors will fit on a single computer chip, and more transistors means more capabilities of the chip. For over half a century, the chip industry sought to shrink transistors to the smallest size possible, given the available technologies. As a consequence, innovation throughout the chip industry – and in particular in manufacturing techniques – has concentrated on the shrinkage of transistors.

The pace of the miniaturization by the chip manufacturers has been captured in the notable 'Moore's Law', which states that about every eighteen months the number of transistors on a chip is being doubled. Gordon Moore formulated this 'law' in 1965, and over the decades it turned out to be true.[10] Students of innovation have explained its veracity by detailing how it operates as a self-fulfilling prophecy in a strategic game.[11] Players in the semiconductor industry use the law as a yardstick to measure their own progress and to calibrate their strategy – in the knowledge that other players will do the same. Indeed, compliance with Moore's Law – regardless of the physical and organizational limits faced – has defined the competitiveness of chip manufacturers.

The endless race toward smaller chips forced suppliers of semiconductor equipment to run a parallel race. After all, the production of the newest chip that obeys Moore's Law requires, in its turn, new manufacturing technologies. In other words, the semiconductor equipment industry, in which ASM has been a player, had to follow the dictate of miniaturization. This task spurred continuous innovation for the equipment manufacturers. Besides miniaturization, the manufacturing techniques had to sustain or increase the production volumes, as well as improve the quality of the production processes. Every new and anticipated investment by chip manufacturers in their fabrication technology formed a new opportunity for equipment companies to distinguish themselves from their competitors.

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[10] Gordon Moore, 'Cramming More Components onto Integrated Circuits', in: David Brock (ed.), *Understanding Moore's Law* (Chemical Heritage Press, Philadelphia, 2006) pp.55-61.

[11] R.R. Schaller, 'Moore's Law: Past, Present and Future', *IEEE Spectrum* 34:6 (1997) pp. 522-59; Harro van Lente, 'Navigating foresight in a sea of expectations: lessons from the sociology of expectations', *Technology Analysis & Strategic Management* 24:8 (2012) pp. 769-782.

The semiconductor equipment industry has a cyclical market.[12] Commonly, its customer base – the chip manufacturers – will run ahead or stall their investments in new equipment simultaneously. The chip industry's investments are based on projected sales of their products, as well as on economic and industrial forecasts. Overcapacity in the production of memory chips or a financial crisis on the stock market may cause drastic cuts in capital expenditures by chip manufacturers.

Forecasting and anticipating needs and market developments are therefore central in managing and running a business in the semiconductor equipment industry. This involves balancing and assessing numerous aspects continuously, as well as justifying them in the quarterly and annual reports and at conference calls. It is all about securing one's share in potential growth markets. Equipment manufacturers have to navigate through these volatile and unpredictable waters of highs and lows in demand, while maintaining investments for the forthcoming generation of chips with yet again smaller transistors.

Exploring innovation processes

Navigating innovations in a complex and challenging environment like the semiconductor equipment industry hardly involves a straightforward task. The industry expresses a dialectic of order and capriciousness. On the one hand, markets are volatile and innovations bring major uncertainties.[13] On the other hand, notoriously strict and detailed procedures and processes guide the production of the tiniest transistors in massive volumes. Moreover, the industry makes a display of ambitious organizational and financial efforts in order to stay reliable and predictable for investors and customers.

Likewise, studying such a dynamic environment is not straightforward either and requires an appropriate conceptual framework. This study follows a rich tradition in social science and economic scholarship on innovation by regarding innovation as an evolutionary process of variation and selection that is shaped by numerous influences, forces, and dynamics.[14] In the remainder of this introduction I will draw from the evolutionary traditions in the history of technology, economics of innovation, and science and technology studies (STS)

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12 Clair Brown and Greg Linden, *Chips and Change: How Crisis Reshapes the Semiconductor Industry* (MIT Press Paperback Edition, Cambridge, 2011).

13 For instance, uncertainty about the acceptance of the innovation by the market, about the viability of established technologies, or about standards. – Clayton Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fall,* (Harvard Business Review Press, Cambridge, 1997).

14 Richard Nelson and Sidney Winter, *An Evolutionary Theory of Economic Change* (Harvard University Press, Cambridge, 1982) p. 97; Giovanni Dosi and Richard Nelson, 'An Introduction to evolutionary theories in economics' *Journal of Evolutionary Economics* 4:3 (1994) pp. 153-172.

to build a conceptual framework that allows me to trace the dynamics, as well as to explain and characterize the innovation processes at ASM between 1958 and 2008.

Three insights into studying high-tech innovation

While the historical, social, and economic scholarship on innovation as an evolutionary process is far too broad to summarize its findings in a few pages, I will highlight three basic insights that support the main tenets of these tradition: the discrepancy between contingency and the rule; the plea for symmetry in analysis; and the role of expectations in innovation.

The first insight is that any innovation is interspersed with contingency. While innovation processes definitively show some regularity and predictability, they are also notoriously uncertain and elusive. This contradistinction refers not only to the politics of running an innovative business – by means of procedures and rules versus contingency-bound entrepreneurship – but also to the academic perception of history. As such it relates to the traditional academic chasm between the need to narrate and the need to interpret historical events, or theorizing versus historicizing. Whereas socio-economic scholars tend to generalize technological change through concepts and theories, historians seem to feel most comfortable with presenting the unique events as they evolved.[15]

This in-depth historical study offers the opportunity to nurture new understanding about the dynamics of high-tech innovation, and it very much intends to do so. However, we have to be careful with generalizations and conceptualizations about this complex environment. For instance, the chip industry's ostensibly paramount Moore's Law did not become institutionalized by the whole industry until the late 1980s.[16] Throughout the history of the industry, none of the central actors managed to look beyond their immediate horizon, say, five or ten years ahead. Periodic premature proclamations about Moore's Law's imminent finality prove this point.[17] Moreover, this study of only one company should fully account for the case-specific conditions underlying it.

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15 John Tosh and Seán Lang, *The Pursuit of History: Aims, methods and new directions in the study of modern history* (Pearson Longman, Harlow, fourth edition; 2006), pp. 220-221.

16 Implicitly, however, miniaturization defined the course of innovation since the early 1970s already. – Robert Schaller, *Technological Innovation in the Semiconductor Industry: A Case Study of the International Technology Roadmap for Semiconductors* (George Mason University, 2004); and E. Mollick, 'Establishing Moore's Law', *IEEE Annals of the History of Computing* 28:3 (2006) pp. 62-75.

17 For instance in popular outlets about semiconductor engineering: Chris Mack, 'The Multiple Lives of Moore's Law', *spectrum.ieee.org* (30-3-2015; Or: The Economist, 'Technology Quarterly: After Moore's Law' (12-3-2016).

Either way, the argument in this dissertation aims to do both with regard to ASM's innovation processes, by uncovering the unique circumstances surrounding and affecting ASM's innovations and by reflecting on these results on the basis of the existing bodies of literature. This is why assessing innovation processes means reconstructing the possibilities, expectations, and assets as they were perceived and realized throughout the history at issue. The preservation or disregard of conventions in the chip industry will be revealed through a frame which seeks the appreciation of contingencies surrounding and defining innovation processes.

The second insight of evolutionary studies of innovation is that materiality matters. This insight concerns the ostensible discrepancy between the social and material domains. Renowned anthropologist Bruno Latour and sociologist Michel Callon attributed objects with social agency.[18] They convincingly argued that objects define social interactions and relations, and hence we should think more nuanced about the relationship between 'object' and 'subject' in technology studies. Latour and Callon plead for 'symmetry' in analyzing technological change, thus taking into account both human and material agency.

An innovation process involves specific dealing of humans and materials. This dealing is accompanied by power structures, molding humans and materials to their will. It is not a stretch to argue that an innovation process is a political process through which social, economic, and material elements are combined, negotiated, and aligned.[19] Michel Callon dubs this process 'translation'.[20] Through their realizations about the unnatural chasm between the social and material domains, Callon and Latour laid important foundations for Science & Technology Studies. Yet, this apprehension of the material world is hardly self-evident for most economic historians, which is why it requires explication.

The third insight is that all innovation processes are deeply future-oriented. In order to aptly reconstruct the development of ASM's innovation processes, the forward-looking aspect of the technology and the industry has to be recognized explicitly. The so-called 'sociology of expectations' in particular has examined this condition and its implications for the development of novel technologies. As sociologist of technology Harro van Lente has argued, expectations about

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18 Bruno Latour, 'How to write "The Prince" for machines as well as for machinations', in: Brian Elliott (ed.), *Technology and Social Change* (Edinburgh University Press, Edinburgh 1988), pp. 20-43; and Michel Callon, 'Some elements of a sociology of translation: domestication of the scallops and the fishermen of St Brieuc Bay', in: John Law (ed.), *Power, action and belief: a new sociology of knowledge?* (London, Routledge, 1986), pp. 196-223.

19 Bruno Latour, 'How to write "The Prince" for machines as well as for machinations'.

20 Michel Callon, 'Some elements of a sociology of translation'.

the future shape and define realities and actions in the present. Or as he put it: 'expectations are *performative:* they do something.'[21] Expectations legitimize, direct, and coordinate actions.[22]

In particular in the high-tech environment of the chip industry, expectations define the viability and operation of a company like ASM. This becomes unequivocal by looking at its public reporting and that of its competitors. In quarter and annual reports and conference calls, the executives justify their business decisions and primarily explain how they position themselves to reap the benefits of any future potential business effectively. Running the business of ASM is not so much about historical performances; it is about anticipating and effectuating new market developments. It is all about the future and its promises. This makes it relevant to consider the performative function of expectations and history.

Three elements to study innovation processes

With these three insights in mind I will now introduce three 'elements' that together shape innovation processes: fortuna, virtù, and path. These elements are shorthand for influences, forces, and dynamics studied by scholars in historical, social, and economic approaches of innovation.

The element of 'path' constitutes the strategic technological alternatives available to a firm.[23] It relates to the central concept of 'routine' put forward by evolutionary economists Richard Nelson and Sidney Winter: '[routines] may refer to a repetitive pattern of activity in an entire organization, to an individual skill, or, as an adjective, to the smooth uneventful effectiveness of such an organizational or individual performance.'[24] The element path helps to comprehend ASM's innovation processes beyond the ostensible random sequence of events, or fortuna.[25]

'Fortuna', then, is a contingency that disrupts order, and propels innovative actions.[26] It can manifest itself as luck, coincidence, crisis, or happenstance, which serves to delegitimize the beaten track or conventions. 'Virtù' is the creative will

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21 Harro van Lente, 'Navigating foresight in a sea of expectations: lessons from the sociology of expectations', *Technology Analysis & Strategic Management* 24:8 (2012) pp. 769-782, p. 772.

22 Ibid.

23 David Teece and Gary Pisano, 'The dynamic capabilities of firms: an introduction', *Industrial and Corporate Change* 3 (1994) pp. 537-556, pp. 541, 546, and 547.

24 Nelson and Winter, *An Evolutionary Theory of Economic Change,* p. 97.

25 Mark Blyth, 'Coping with the Black Swan: The Unsettling World of Nassim Taleb', *Critical Review* 21:4 (2009) pp. 447-465.

26 J.G.A. Pocock, *The Machiavellian Moment: Florentine Political Thought and the Atlantic Republican Tradition* (Princeton University Press, Princeton, 1975); and Teece and Pisano, 'The dynamic capabilities of firms'.

or improvisation in anticipation of or in response to fortuna. [27] Innovation does not materialize without this will to adapt conventions to new realities.

By building on these three elements – fortuna, virtù, and path – I will be able to study the innovation processes at ASM as part of an evolving semiconductor equipment industry. Together, these elements provide an adequate heuristic to trace the many actors and factors in the history I seek to reconstruct and understand. Moreover, they do justice to the three basic insights of historical, social, and economic studies of innovation listed above. Aside from acknowledging the importance of path dependence and expectations, these elements allow symmetry in analyzing the social and material domains, while also allowing us to reflect on history beyond its mere apprehension as a sequence of accidents and contingencies.

A historiography per element

The three elements to sustain this study – path, fortuna, and virtù – relate to and summarize wider bodies of literature about innovation and technological development. In particular, path aligns with a wide range of conceptualizations regarding innovation processes. Correspondingly, the discussion of path is more elaborate compared to those of fortuna and virtù.

Path

Basically, path is the opposite of fortuna and virtù. The element encompasses the 'rule', regularity and order in technological development. It encompasses the notion of 'routines', a key notion in the seminal work of Nelson & Winter:

> 'It is that most of what is *regular* and *predictable* about business behavior is plausibly subsumed under the heading "routine", especially if we understand that term to include the relatively constant dispositions and strategic heuristics that share the approach of a firm to the nonroutine problems it faces. ... At any time, a firm's routines define a list of functions that determine (perhaps stochastically) what a firm does as a function of various external variables (principally market conditions) and internal state variables (for example, the firm's prevailing stock of machinery, or the average profit rate it has earned in recent periods)' [28]

Various theories and concepts relate to the element of path, such as 'path dependency', 'opportunities', strategizing, and contextual logics affecting

[27] Pocock, *The Machiavellian Moment*.

[28] Nelson and Winter, *An Evolutionary Theory of Economic Change*, p. 15 and 16.

variation and selections in the innovation process.[29] Capabilities, capacity, knowledge, and experience accumulated in the past determine the alternatives available; combined with particular expectations about the future, a probable path in pursuit of an opportunity emerges. In this historiography of path, I reflect upon these key attributions of 'path'.

A representation of the future provides a sense of purpose, direction. Expectations about opportunities shape future realities for business, products, innovations, etc. The idea of an opportunity gives technological development a notion of directionality.[30] Opportunities are constantly present. Though in the literature some disagreement pertains about the level of articulation of the final opportunity at the start of an endeavor.[31] For instance, in the field of entrepreneurial history, the question is posed: Can an innovator, entrepreneur or company really foresee an opportunity in the way it comes about at the end of an innovation process or business development? Some pursuits of opportunities might be very causal.[32] Though in most cases, the appreciation of an opportunity

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29 Teece and Pisano, 'The dynamic capabilities of firms: an introduction', pp. 546 and 547. Others have made a similar point: 'This pattern of technical opportunity being exploited through a group of technological trajectories is a very robust feature of industrial dynamics. It is a reflection of the path-dependence, or directionality, of technical change, which exercises such a powerful influence on the evolution of the industry itself.' – Rod Coombs, 'Technological opportunities and industrial organization', in: Giovanni Dosi, Christopher Freeman, Richard Nelson, Gerald Silverberg, and Luc Soete, *Technical Change and Economic Theory* (Pinter Publishers, London, 1988) pp. 295-308, p. 298.

30 Coombs, 'Technological opportunities and industrial organization', p. 298. Two kinds of opportunities are to be distinguished – though this distinctions bears fairly little relevance for this study: '"Schumpeterian" opportunities created by disruptive changes in technology, politics, and regulation, society and demography, which alter the value of resources, and "Kirtzerian" opportunities which arise on account of errors and mistakes by prior market participants.' – Colin Mason and Charles Harvery, 'Entrepreneurship: Contexts, opportunities and processes', *Business History* 55:1 (2013) pp.1-8, p. 2.

31 In an article overviewing the debate about opportunities and posing different understandings, historians Daniel Wadhwani and Christina Lubinski aptly note: 'an uncritical retrospective point of view wipes away the uncertainty faced by entrepreneurs and the judgmental processes involved in opportunity identification because the actors' future has become revealed, the categories of events and developments are known and calculable and imply lie in a future waiting to be discovered.' – Daniel Wadhwani and Christina Lubinski, 'Reinventing Entrepreneurial History', Business History Review 91:4 (2017) pp. 767-799, p. 781. Another comprehensive overview about the literature of opportunities is John Park, 'Opportunity recognition and product innovation in entrepreneurial hi-tech start-ups: anew perspective and supporting case study', *Technovation* 25 (2005) pp. 739-752.

32 Mark Casson, *Entrepreneurship: Theory, Networks, History* (Cheltenham, 2010); The authors distinguish entrepreneurial opportunity (to create something new) from opportunity for optimization. – Scott Shane and Sankaran Venkataraman, 'The Promise of Entrepreneurship as a Field of Research', *The Academy of Management Review* 25:1 (2000) pp. 217-226; p. 220.

changes as more information is obtained.[33] Either way, the opportunity appears as very real for the innovator, entrepreneur or management.

To comprehend a rationalized opportunity for technological development, a concept suggested by historian of technology Thomas Hughes is helpful. In his marvelous discussion of Thomas Edison's systematic development and expansion of the electricity network, he made both the material and the social world part of the systematic analysis.[34] To conceptualize opportunities and directionality of actions in a system, he introduced the concept of a *reverse salient*, inspired by the battle lines of the First World War. [35] A reverse salient is an element that has fallen behind others and threatened the continued development of a technological system.[36] Thus understood, the reverse salient forms an alternate interpretation of an opportunity in a technological path. The system itself in which these reverse salients emerge is – similar to history itself – not static. It expands. Hughes shows the imperative nature of the innovation network in which ASM operated.

In the chip industry a reverse salient would be any failure to comply with Moore's Law. Such possibility is perceived to bear consequences for the competitiveness of respective chip manufacturers, the applicability of technology, or the state of the chip industry as a whole. Overcoming this imminent matter of obstruction constitutes an opportunity, a way to compete.[37] As will become

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[33] Among others, historians Andrew Popp and Robin Holt argued for the consideration of 'structural conditions containing and shaping the possibility for opportunity. Andrew Popp and Robin Holt, 'The presence of entrepreneurial opportunity', *Business History* 55:1 (2013) pp. 9-28, p.9.; Other authors: Wadhwani and Lubinski, 'Reinventing Entrepreneurial History', p. 780; Saras D. Sarasvathy, 'Causation and Effectuation: Toward a Theoretical Shift from Economic Inevitability to Entrepreneurial Contingency', *The Academy of Management Review* 26:2 (2001) pp. 243-263; Dimo Dimov, 'Grappling with the Unbearable Elusiveness of Entrepreneurial Opportunities', *Entrepreneurship: Theory and Practice* (January 2011) pp. 57-81.

[34] The literature on innovation systems is very expansive. Various perspectives exist, such as national, regional, sectoral and technological innovation systems: Charles Edquist , 'Systems of Innovation Approaches – Their Emergence and Characteristics', in: Charles Edquist (ed.), *Systems of Innovation: Technologies, Institutions and Organisations* (London 1997) pp. 1-34, pp.

[35] Hughes original explanation: 'The idea of reverse salient suggests the need for concentrated action (invention and development) if expansion is to proceed. A reverse salient appears in an expanding system when a component of the system does not march along harmoniously with other components. ... the reverse salient will not be seen, however, unless inventors, engineers, and others view the technology as a goal-seeking system.'- Thomas Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (John Hopkins University Press, Baltimore, 1983) pp. 79 and 90.

[36] See also Brock and Lécuyer, 'Digital Foundations' p. 564.

[37] Reverse salients do not bare the same consequences as fortuna. The reverse salient does not threaten the existence of the system, but only the pace of its expansion. Moreover, it is knowable, whereas fortuna is not.

apparent throughout the dissertation, reverse salients can be distinguished retrospectively, but they were also purported industry-wide during the innovation process as 'anticipatory reverse salients'.[38] Moreover, a reverse salient does not have to be commonplace. Its potency might differ for the participants in an industry.

The pursuit and realization of opportunities are influenced by numerous forces. Historians of technology, David Brock and Christophe Lécuyer claimed that technological development is influenced by the challenges posed by user, competitive and material 'logics'.[39]

> 'These material, [user], and competitive logics are not determinative, in the sense that they do not lead to necessary outcomes. But they are particularly stable over time and provide powerful resources and constraints to innovators and their patrons. When combined, they define chains of potential events that are actualized by the will, passions, and efforts of scientists and technologists – in other words, their emotional and professional commitments.'[40]

The logics point to forces that affected the pursuit of an opportunity – and the coming about of an innovative process.

Arguably, these three logics are not all, though. Depending on the interest of research other logics might be added as well. For instance, the organizational challenges might play a part – an organizational logic. Organizational processes define the ability to proceed into a direction and realize a potential. As such it offers sufficient leads for developing theories and concepts, ranging from study of the R&D department within an organization to reflection on roles and change

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38 Brock and Lécuyer, 'Digital Foundations'.

39 The exact denotations of the logics differ in the respective publications. – Christophe Lécuyer and David Brock, *Makers of the Microchip: A Documentary History of Fairchild Semiconductor* (MIT Press, Cambridge, 2010) pp. 2-3; Christophe Lécuyer, and Takahiro Ueyama, 'The logics of Materials Innovation: The Case of Gallium Nitride and Blue Light Emitting Diodes', *Historical Studies in the Natural Sciences* 43:3 (2013) pp. 243-280, p. 246. Brock and Lécuyer's user and material logic resemble a scheme by Bodewitz et al. but stems from Latour; Henk Bodewitz, Gerard de Vries, and Pieter Weeder, 'Towards a cognitive model for technology-oriented R&D processes', *Research Policy* 17 (1988) pp. 213-224.; Moreover, the line of thinking is traceable to the philosopher Martin Heidegger, in his essay 'The Question Concerning Technology'. To comprehend his idea, I quote from the article by Popp & Holt: '*causa materialis*, the material from which a thing is formed; … *causa formalis*, the form into which a thing enters; … *causa finalis,* the end to which it is formed …; and the *causa efficiens,* that [the actor] which brings about the effect [having agency]' –Popp and Holt, 'The presence of entrepreneurial opportunity', p. 19.

40 Lécuyer and Ueyama, 'The logics of Materials Innovation', p. 246.

in organizational processes, as well as on the organization's internal power and social dynamics. This social component hardly gets a place within the logics as formulated by Brock and Lécuyer, while the formulation and understanding of opportunities foremost is a social process.

A specific theory stressing the deeply social character of innovation is provided by Wiebe Bijker and Trevor Pinch.[41] Their 'social construction of technology' (SCOT) approach identifies, in the first place, the different meanings surrounding the development of a technology. The accompanying concept of 'interpretative flexibility' underscores that an artefact means different things for different social groups and that these interpretations decide the course of innovation. Moreover, an innovator might relate himself to more than one social group.[42] The SCOT approach follows the subsequent confrontations and negotiations, and the eventual 'closure' in which a particular meaning is stabilized.

While the SCOT approach is reluctant to specify in advance which social groups will be relevant, other approaches are more specific. For this study the concepts of *enactor* and *selector* are useful. Management scholars Raghu Garud and David Ahlstrom proposed the terms 'insiders' and 'outsiders', technology philosopher Arie Rip convincingly argued for 'enactors' and 'selectors' as useful terms[43] to distinguish different roles in the process of innovation.

Enactors present a technology as a solution to various perceived problems and are committed to make this particular technology successful.[44] Selectors operate just the other way around: they define the problem and consider various solutions. They are indifferent to the success of a particular technology, as they are committed to solve a problem. Garud & Ahlstrom call the phase during which the enactor and selectors assess each interests and arguments a 'bridging incident'.[45] Throughout an innovation process, moments of 'closure' exist, during

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41 Engineers – and especially experts – define their status of competence not only within their own organization, but also through their relative position among their peers. Trumping their competing engineers at other organizations might be one way to do so. – Trevor Pinch and Wiebe E. Bijker. 'The Social Construction of Facts and Artefacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other'. *Social Studies of Science* 14 (August 1984) pp. 399-441.

42 Edward Constant II, 'The Social Locus of Technological Practice: Community, System or Organization?', in: Wiebe Bijker and Thomas Hughes (ed.), *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (MIT Press, Cambridge, 1989) pp. 223-242.

43 . Raghu Garud and David Ahlstrom, 'Technology assessment: a socio-cognitive perspective', *Journal of Engineering and Technology Management* 14:1 (1997) pp. 25-48; and Arie Rip, 'Folk Theories of Nanotechnologists', *Science as Culture* 15:4 (2006) pp. 349-365, pp. 360 and 361.

44 A comprehensive definition is given by Sjoerd Bakker in his dissertation: Sjoerd Bakker, *Competing Expectations: The case of the hydrogen car* (BOXPRess, Oisterwijk, 2011), p. 8.

45 Garud and Ahlstrom, 'Technology assessment: a socio-cognitive perspective', p. 44.

which one of the roles persists.[46] This could be one of multiple enactors, or the viewpoints of one of multiple selectors. Closure can occur through new insights or results, a redefinition of the problem at hand, or rhetorically.

The positions of enactor and selector cut across conventional roles within an organization, such as the role of engineer, marketing manager, CEO, and equipment supplier. Categorizing individuals, groups, and/or organizations into either enactors or selectors highlights their intentions and their posture within the innovation process beyond their formal position. Without dwelling into, for instance, typical CEO-behavior or sales management personalities, the notions of enactor and selector focus on the agencies within the formation of a technological path.

Another important body of literature addressing the direction and speed of a technological path focuses on 'strategy'. A famous definition is to regard strategy as a pattern in a stream of decisions.[47] This definition holds both for business as for the innovation process. The appreciation for and articulation of strategy for business and innovation differed over time. New understanding of business and innovation strategies succeeded each other. In case of business management, for instance, this involved the introduction of new management theories applicable for multi-divisional firms.[48] Prominent contributors to this part of strategy involve management gurus like Peter Drucker, P.H. Prahalad, Michael Porter, Gary Hamel and Clayton Christensen.[49]

In case of innovation management, scholarship on 'strategy' relates to innovation as being part of a wider system or ecosystem, or the distinction of 'Research & Development (R&D) generations'.[50] This general conception reflects

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46 In their original paper, Pinch and Bijker distinguished closure through rhetoric and closure by redefinition of the problem. The authors emphasize that closure involves foremost that the key social groups see a controversy as being solved. - Pinch and Bijker, 'The Social Construction of Facts and Artefacts'.

47 Henry Mintzberg and James Waters, 'Of Strategies, Deliberate and Emergent', *Strategic Management Journal* 6:3 (1985) pp. 257-272, p. 257.

48 Keetie Sluyterman, *Dutch Enterprise in the Twentieth Century: Business strategies in a small open economy* (Routledge, Abingdon 2005), part of: Geoffrey Jones and Mary Rose (ed.), Routledge international studies in business history, p. 3; and Pankaj Ghemawat, 'Competition and Business Strategy in Historical Perspective', *Business History Review* 76 (2002) pp. 37-74.

49 Peter Drucker, 'The Effective Decision', *Harvard Business Review* 45:1 (1967; C.K. Prahalad and Gary Hamel, 'The Core Competence of the Corporation' *Harvard Business Review* (May 1990) pp. 79-91; Michael Porter, 'From Competitive Advantage to Corporate Strategy', *Harvard Business Review* (May 1987) pp. 43-59; and Clayton Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Harvard Business Review Press, Boston, 1997).

50 De Jong, Sluyterman, and Westerhuis, 'Strategic and structural responses'; Johan Schot and

that the management of R&D within an organization over time improved, matured and adapted to the changing context and demands for an innovative firm.[51] So far, at least six generations have been distinguished by various authors. The first generation can be seen as technology-push, where basic research determines the course of technological and subsequently product development of a firm. This generation prevailed until the early 1970s. The second generation, until the mid-1980s, involved market-pull, with business units determining the requirements for R&D . The third generation involved an integrated and parallel approach across divisions, balancing the corporate and business units' R&D interests; it emerged in the early-1980s and lasted until the mid-1990s. The distinctions between generations are not often that clear, foremost since authors tend to distinguish their 'generation' in order to spotlight their own contribution. Yet, the distinctions and their temporal embedment do indicate changing understanding of how R&D should be managed and deployed within an organization.

Fitting with our notion of 'path', strategy is both progressive and retrospective, it relates to the future but is situated in the past. [52] For the actor involved in an innovation process or business development, a strategy can be conscious or it can be revealed after a series of decisions.[53] Management scholars Henry Mintzberg and James Waters defined strategy as a deliberate or emergent pattern in a stream of decisions.[54] Deliberate strategy involves a realization of a strategy as originally intended, and the emergent strategy entails the realization of patterns or consistencies regardless of the original intention. Mintzberg and Waters' distinction is pivotal.

At any point of time, an innovator can reassess or reinterpret this pattern of decisions. Through such an exercise, the innovator might turn a hitherto emergent

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Edward Steinmueller, 'Three frames of innovation policy: R&D, systems of innovation and transformative change', *Research Policy* 47 (2018) pp. 1554-1567, p. 1558; Philip Roussel, Kamal Saad, and Tamara Erickson, *Third Generation R&D* (Harvard Business School Press, Cambridge, 1991)

51 Roussel, Saad, and Erickson, *Third Generation R&D*; William Miller, and Lagndon Morris, *Fourth Generation R&D: Managing Knowledge, Technology and Innovaiton* (John Wiley & Sons, New York 1999); Roy Rothwell, 'Towards the Fifth-Generation Innovation Process', *International Marketing Review* 11:1 (1994) pp. 7-31; and Dennis Nobelius, 'Towards the Sixth Generation of R&D Management', *International Journal of Project Management* 22:5 (2004) pp. 369-375.

52 Business historian Alfred Chandler famously stated that structure followed strategy. However, the stipulation of a strategy does not always precede action. - Alfred Chandler, *Strategy and Structure: Chapters in the History of the American Industrial Enterprise* (MIT Press, Cambridge, 1962).

53 Sluyterman, *Dutch Enterprise in the Twentieth Century*, p. 2 and 3

54 Mintzberg and Waters, 'Of Strategies, Deliberate and Emergent', p. 257.

strategy into a new deliberate one. If a strategy is reinterpreted, a company's structure is already in place and subsequently defines the maneuverability of the manager. Then, strategy follows structure. The reciprocal relation between strategy and structure makes the corporate (innovation) strategy both constant and variable.

After a while, as time progresses, the strategic pursuit of opportunities – deliberate or emergent – creates a path that, in its turn, constrains and informs further decisions. Based on the sequence of actions, contingencies, and innovations, it is possible to distill a rule through the first interpretation of opportunities present already. This rule serves as a handle on the hurtling pace of history.[55] These conventions about one's path also define the perception of future possibilities.

Path dependency implies that the innovator is constrained by assets, experience, capabilities, and reputation. As economists Richard Nelson and Sidney Winter argued, technological development in complex industries like the chip industry is cumulative.[56] It is very hard to innovate from scratch. Chip production relies on experience and the capacity to absorb any new bit of relevant information – or 'absorptive capacity'.[57] It is not easy to change one's business within the industry, as it depends on very specific skills and knowledge.[58] The perseverance of the past – the path dependency – defines the anticipation of opportunities ahead.

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55 Over time, a strategy gets embedded in the organization. Utterback characterizes the organizational development as 'from entrepreneurial organic firm to hierarchical mechanistic firm with defined tasks and procedures and few rewards for radical innovation.' - James Utterback, *Mastering the Dynamics of Innovation* (Harvard Business School Press, Boston, 1994), p. 91. Theorizing about entrepreneurship, Joseph Schumpeter distinguished two phases, dubbed Schumpeter Mark I and II. Mark I consists of pioneering entrepreneurs and *Unternehmergeist*, while Mark II rather involves routinized entrepreneurship embedded in clear procedures. - Roberto Fontana, Franco Malerba, and Astrid Marinoni, 'Knowledge intensive entrepreneurship in different sectoral systems', in: Franco Malerba, Yannis Caloghirou, Marueen McKelvey, and Slavo Radosevic (Ed.), *Dynamics of Knowledge Intensive Entrepreneurship: Business strategy and public policy*. Part of series: Routledge Studies in Innovation, Organization and technology (Routledge 2015) pp. unknown.

56 Nelson and Winter, *An Evolutionary Theory of Economic Change*, p. 97.

57 Franco Malerba, *The Semiconductor Business: The Economics of Rapid Growth and Decline* (University of Wisconsin Press, Madison, 1985); Wesley Cohen and Daniel Levinthal, 'Absorptive Capacity: A New Perspective on Learning and Innovation', *Administrative Science Quarterly* 35:1 (1990) pp. 128-152.

58 Giovanni Dosi, 'Technological Paradigms and technological trajectories. A suggested interpretation of the determination and directions of technical change', *Research Policy* 11 (1982) pp. 147-162.

Efforts have been made to characterize this path, also dubbed 'regime' by economists.[59] This involves characterizations of the technological path as well as the industrial path. In the case of technology, Keith Pavitt's taxonomy of sectoral patterns is most notable, involving the supplier-dominated, scale-intensive, science-based, information-intensive, and specialized-supplier patterns of technological change.[60] Pavitt's taxonomy of 'paths' was altered, repealed, complemented, and renewed various times.[61]

Economists James Utterback and William Abernathy offered another characterization of technological and industrial path.[62] They distinguish two waves of innovation during the development of an industry, which typically takes several decades. The first wave consists of a rise and fall of *product innovations*, like, say, a diode, the DRAM memory chip, or the CMOS transistor. A second, subsequent wave entails the rise and fall of innovations of techniques to produce the products – to which we might refer as manufacturing technology. The authors label these *process innovations*. Examples in the semiconductor industry are the invention of a manufacturing procedure, packaging techniques, and the

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59 Nelson and Winter, *An Evolutionary Theory of Economic Change*; Stefano Breschi and Franco Malerba, 'Sectoral Innovation Systems: Technological Regimes, Schumpeterian Dynamics, and Spatial Boundaries', in: Charles Edquist (ed.), *Systems of Innovation: Technologies, Institutions and Organisations* (London 1997) pp. 130-15, p. 133.

60 The supplier-dominated pattern concerns companies dependent on innovations of their suppliers. The scale-intensive pattern pertains to companies that competed through economies of scale. Innovation occurred at the mass-producing companies themselves. The science-based pattern concerns ventures that innovated through intensive R&D efforts, whether internal or in cooperation with research institutes. The last one, specialized-supplier pattern, relates to suppliers who concentrate on product innovations intended for other industries. Later, Pavitt added the 'information-intensive' trajectory, which involves firms in the service sectors relying upon complex information processes. – Keith Pavitt, 'Sectoral patterns of technical change: Towards a taxonomy and a theory', *Research Policy* 13:6 (1984) pp.343-373; Joe Tidd, John Bessant, Keith Pavitt, *Managing Innovation: Integrating Technological, Market, and Organizational Change* (2nd edition; Wiley, Chichester, 2001), p. 115.

61 A very useful overview of the efforts in this regard is offered by: Fontana, Malerba, and Marinoni, 'Knowledge intensive entrepreneurship in different sectoral systems',. Other examples are the patterns formulated by historians Mila Davids, Harry Lintsen, and Arjen van Rooij as part of the extensive project on Business in the Netherlands during the Twentieth Century (BINT) – Mila Davids, Harry Lintsen, Arjen van Rooij, *Innovatie en kennisinfrastructuur: vele wegen naar vernieuwing.* Bedrijfsleven in Nederland in de Twintigste Eeuw (Boom Amsterdam, 2013), pp. 213 and 214. Or the alternatives offered by. - Stefano Breschi, Franco Malerba and Luigi Orsenigo, 'Technological Regimes and Schumpeterian Patterns of Innovation', *The Economic Journal* 110 (2000) pp. 388-410.

62 James M. Utterback and William J. Abernathy, 'A Dynamic Model of Product and Process Innovation', *Omega* 3:6 (1975), pp. 639-656; Utterback, *Mastering the Dynamics of Innovation,* p. xviii.

introduction of new lithography stepper machines. These are in fact the products developed and sold by ASM.

Utterback and Abernathy claim that both waves will always be there throughout the development of an industry. The predominance of one will never imply the annulment of the other.[63] Typically, product innovations are more prominent in the first phase of an industry, and process innovations at a later stage; when the two waves intersect, a *dominant design* emerges in the industry. In a later work, Utterback defines a dominant design as a – I would say, rather Platonic – template of how a product is 'supposed to look and operate'.[64] From that moment on, competitiveness in the industry tends to depend predominantly on the efficient production of the dominant design. Hence, the rise of process innovations.

As we will see in this study, Utterback & Abernathy's waves of innovation help to explain the demand for ASM's products. The wave of process innovation in the chip industry created a strong demand for new manufacturing technologies, which ASM managed to provide. The waves of innovation appoint to the dynamism in the chip industry, as well as to the subsequent position of ASM's technological development in it.[65]

To conclude, the element 'path' opens the door to theories about opportunities and innovation, but also to characterizations of the technological and industrial patterns. Bearing in mind the contrast between contingency and the rule – as discussed above– the element of path offers a hold on the interminable sequence of contingencies, acts, and innovations constituting and affecting the course of ASM's history. Path constitutes regularity, order.

Fortuna

The element fortuna challenges the rule and disrupts the element path. In his magnum opus *The Machiavellian Moment,* Pocock explores Machiavellian thought about political innovators dealing with uncertainty and contingencies, or *fortuna*. According to Machiavelli, fortuna involves an event that moves beyond

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63 This was suggested by Malerba, for instance: 'At a general level, Abernathy and Utterback (1975 and 1978) claimed that product innovations are more frequent in the early stages of an industry, while process innovations characterize the later stages. The early stages of the semiconductor industry, on the other hand, have been characterized by both product and process innovations.' –Malerba, *The Semiconductor Business,* p.57.

64 Utterback, *Mastering the Dynamics of Innovation,* p. 25.

65 The rise and fall of innovations touches on Hughes's notion of momentum, during which a system displays velocity. – Thomas Hughes, 'The evolution of large technological systems', in: Wiebe Beijker, Thomas Hughes and Trevor Pinch (ed.), *The Social Construction of Technological Systems* (MIT Press, Massachusetts, 1987), pp. 51-82, p. 76.

conventionality and expectations, and this urges a reaction of the political leader.[66] The significance of unexpected events, fortuna, for our political world was also recognized by philosopher and historian Van Middelaar. In a striking passage, he stresses the significance of events for the unfolding of history:

> 'The word "contingency" – *Ereignis* as Heidegger called it – ... refers to the substantial openness of human affairs. This concept leaves room within the unforeseen. It forces an opening in the closed view of history of Hegelians and Marxists, who see humanity progressing towards a defined destination; an opening in the deterministic worldview of scientists who ban chance, will-power, and choice from their causal schemes; an opening in the extrapolations and scenarios of economic planning offices and futurologists, who get a kick out of their jaunty dotted lines leading toward tomorrow. Who knows, contingency tells all of them, things might turn out differently.'[67]

In terms of the evolutionary thinking in which this study is situated, fortuna can be seen as mutations – spontaneous or affected by wider developments – that alter the course of technological development, or business.

Pocock also labels some events as 'Machiavellian Moments'. During such event, an entity is confronted with its 'own temporal finitude', while it tries to 'remain morally and politically stable in a stream of irrational events conceived as essentially destructive of all systems of secular stability.'[68] In response to this contingency and subsequent uncertainty, the entity might move ahead beyond conventions, and thus innovate. Pocock indeed calls the entity or political leader confronted by Machiavellian Moments an 'innovator'.[69]

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66 Nassim Nicholas Taleb would call *fortuna* a Black Swan. After years of getting the apparent truism of 'All swans are white' reconfirmed at every encounter with a white swan, the confrontation with a 'Black Swan' urges one to revise one's point of view or conventions. This notion is drawn from philosopher Karl Popper's famous critique on falsifiability. – Nassim Nicholas Taleb, *The Black Roman: The Impact of the Highly Improbable* (Penguin Books, 2nd edition, London, 2010). In the terminology of former US Secretary of Defense Donald Rumsfeld, fortuna can be seen as the 'unknown-unknown': that which cannot be known and yet be very consequential.

67 Original quote in Dutch. – Luuk van Middelaar, *De nieuwe politiek van Europa (Historische Uitgeverij, n.p., 2017)*, p. 198.

68 Pocock, *The Machiavellian Moment,* p. viii.

69 For instance: '*Il Principe* is a study of the "new prince" – we know this from Machiavelli's correspondence as well as from internal evidence – or rather of that class of political innovators to which he belongs. The newness of his rule means that he has performed an innovation, overthrowing or replacing some form of government which preceded him.' – Pocock, *The Machiavellian Moment,* p. 160.

Current economic and technological competition quite resembles the political domain – pervaded by uncertainty, strive and also rules – as studied and characterized by Machiavelli and Pocock.[70] The challenges faced by political leaders during such Machiavellian Moments of blind contingencies bear a striking resemblance with those confronted by techno-industrial innovators such as ASM as a company, or Arthur del Prado as ASM's chief executive officer. This resemblance was propagated by anthropologist Latour, who applied the Machiavellian apprehension of politics to the process of innovation.[71] Embedded in a socio-technical environment, the innovation process can be seen as a politics – as negotiating, aligning, and dealing with human and non-human agencies.[72] In other words, the political accounts for both the social and the technological domain. Likewise, fortuna itself manifests in both these domains, for instance as competition between companies or a disappointing result of research. Whether material or social, fortuna provokes innovation beyond conventionality.

In some instances, fortuna will originate in the immediate environment or in broader historical shifts, such as the Cold War, the rise of transnational capitalism, or the cumulative digitalization of society, which propelled further technological development in semiconductor and interrelated industries.[73] The conceptualization of fortuna allows us to appreciate the contingencies and uncertainties underlying technological and social change. By tracing manifestations of fortuna and its effects throughout the history of ASM, it becomes possible to integrate the unforeseen yet defining contingencies into the analysis.

Virtù

The disruption of path by fortuna requires an answer. After all, as business historian Keetie Sluyterman stated:

> '[C]hanging economic or political circumstances invariably forces [business leaders] to react and reconsider their strategies. This pattern of action and reaction is central to the development of businesses.'[74]

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70 Latour, 'How to write "The Prince" for machines as well as for machinations'.

71 Ibid.

72 His understanding elaborated upon his and Callon's plea for symmetry in analysis. Latour, 'How to write "The Prince" for machines as well as for machinations'; Callon, 'Some elements of a sociology of translation'.

73 Brock and Lecuyer, 'Digital Foundations', p. 564.

74 Sluyterman, *Dutch Enterprise in the Twentieth Century*, p. 2.

And, as we should add, central to innovation as well. The disturbance of regularity poses the innovator – or business leader – in a situation surrounded with uncertainty in which the old order does not offer consolation.

Machiavelli sees virtù as a vital ability for survival in the face of happenstances or fortuna.[75] Virtù is the art of dealing with uncertainty.[76] It involves both reactive and anticipative serendipity. Inspired by both Machiavelli and Pocock, Van Middelaar – once again – defines the notion of virtù aptly:

> 'For him [Machiavelli], it is strictly a political notion: a combination of intelligence, courage, and perseverance, stripped of any moral and theological connotations. It is about taking action, taking initiative, anticipation, and playing along with a given situation. ... All human institutions are susceptible to erosion through time. ... *virtù* is vital to counter *fortuna's* disruptive power.'[77]

In particular in the competitive environment of the chip industry, dealing with contingencies is a matter of life and death. This pertains to both the entrepreneur in pursuit of new business opportunities and the engineer engaging in technological development. Their success in dealing with uncertainty defines their competitiveness. There is always a competitor who will be happy to take over your share of the market or rob you of your customers. A company like ASM constantly has to prove its relevance. Moreover, as claimed by Pocock, innovation is the mere consequence of virtù:

> 'Since by his own act the innovator inhabits a delegitimized context, where *fortuna* rules and human behavior is not to be relied on, he is obliged to take the short view and continue to act – and in that sense, to innovate. In a very precise sense, then, action is *virtù;* when the world is unstabilized and the unexpected a constant threat, to act – to do things not contained within the structures of legitimacy – was to impose form upon *fortuna*.'[78]

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75 The notion of virtù as used rather implicitly by Machiavelli has been subjected to intense study. The meaning of virtù can be traced back to Greek, Roman and early Christian uses. – Pocock, *The Machiavellian Moment,*; and see also: John Geerken, 'Machiavelli Studies since 1969', *Journal of the History of Ideas* 37:2 (1976) pp. 351-368.

76 Pocock defines virtù also as: '...the skill and courage by which men are enabled to dominate events and fortune." – Pocock, *The Machiavellian Moment,* p. 92.

77 Original quote in Dutch. – Van Middelaar, *De nieuwe politiek van Europa,* p. 29.

78 Pocock, *The Machiavellian Moment,* pp. 177-178.

In contrast to the deliberate and strategic pursuit of opportunities – as expounded in the element of path – action as virtù is more impromptu. It is an act swaying the innovator into terra incognita, impelling innovation. Without virtù there is no innovation.

Pocock also recognizes that deeds bear consequences:

> 'On the one hand *virtù* is that by which we innovate, and so let loose sequences of contingency beyond our prediction or control so that we become prey to *fortuna;* on the other hand, *virtù* is that internal to ourselves by which we resist *fortuna* and impose upon her patterns of order, which may even become patterns of moral order.'[79]

To show virtù, and thus to innovate, paves the way for new conventions and rules. As such, innovation is central to human behavior and changes in our world. It changes the course of history and creates new opportunities beyond our expectations. To paraphrase another scholar in Machiavellian thought, John Geerken, virtù is to keep laws and reality into equilibrium, to prevent their excessive separation.[80]

Though, very much like path, virtù is defined by path dependency and expectations about the future. Perceptions about prevailing certainties determine the direction of action in response to fortuna.[81] Opportunities as defined within path – such as the reverse salients – are evanescent when facing fortuna. The perception of opportunities becomes more intuitive, foremost relying upon experience, trust, or a gut feeling. As stated by management scholar Dimo Dimov:

> '[B]ecause the ultimate results of entrepreneurial actions cannot be reliably anticipated, but are revealed only when the uncertainty about the future is resolved, for opportunity (...) to be presented as a rational mean-ends choice, one needs to assume complete foreknowledge of future states and payoffs, thereby standing outside the realm of uncertainty. Without such axiomatic specification, people cannot be deemed to have acted rationally on the expectations that they would

79 Pocock, *The Machiavellian Moment*, pp. 167 and 169.

80 Geerken, 'Machiavelli Studies since 1969', p. 363.

81 This is what management scholar Saras Sarasvathy dubs effectuation. She defines it as '(...) processes [that] take a set of means as given and focus on selecting between possible effects that can be created with that set of means'. In other words, what can we do with what we have, instead of what do we need to get where we want to be. - Sarasvathy, 'Causation and Effectuation: p. 245.

> gain what cannot yet be fully or reliably defined before the action takes place'[82]

In this way, virtù is the temporal adaption of a strategy or a path, and is rooted in a bounded rationality. It is an indispensable attribute for running a business. Without adaptation to unforeseen events – virtù – business flounder.[83] Rather than emanating from thin air, innovation follows from the human willingness to engage and adjust to an uncertain future packed with contingencies.

Historical resources

This study relies on three kinds of resources. The first source is the personal archive of Arthur del Prado. This archive consists of roughly one hundred moving boxes containing documentation covering the period from Del Prado's initial start in 1958 to his resignation as chief executive officer of ASM International in 2008. The archive reflects Del Prado's position within the company, which resembled that of a spider in a web. Technical reports came in frequently, and numerous boxes contained drafts or negotiations surrounding stock options, public listings, merger and acquisition negotiations, legal disputes, and changes to the articles of association.

Remarkably, most of the archive contains information sent to Del Prado. Relatively few files contain his own writings, reports, or correspondence. His personal writings are in abundance only during his years as European Marketing Manager for Knapic Electro-Physics from 1958-1964. As president of ASM, Del Prado rarely committed his thoughts and decisions to paper. As such, the archive seldomly offers direct insight into his perspective, yet it helps to chronologize and detail events and streams of information. At the time of writing, the future of this personal archive is yet unknown. Presently it is in the possession of ASM International.

The second source comprises interviews I conducted with various individuals involved with ASM in the past or up to the present. For this study, I interviewed eighty-five individuals at various locations around the globe, including executives, engineers, and management assistants (cf. list of interviewees in the bibliography).

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[82] Dimov, 'Grappling with the Unbearable Elusiveness of Entrepreneurial Opportunities', p. 61

[83] Mind the apt quote of Popp and Holt: 'Creative, inceptive, imaginative decision-making, the conjuring of entrepreneurial opportunity, is firmly located in time as an unending flow in a world where there is action and not merely the illusion of action: a world where history *comes into* being. The entrepreneurial decision-maker becomes an active rather than a passive figure.' - Popp and Holt, 'The presence of entrepreneurial opportunity', p.9

The purpose of these interviews was twofold: to gain a better understanding of the technology sold or produced by ASM and to get a better grasp of the history of ASM and its activities beyond the written sources and through the perspectives of the interviewees. In context of the former, some individuals I interviewed multiple times. The interviews were important in particular for re-imagining decisions, emotions, and expectations beyond or in line with those expressed on paper in the archive.

In addition, this study concerns secondary sources, including academic publications, industry reports, and personal recollections. The majority of the academic literature focuses on chip manufacturers, while rarely covering equipment suppliers as well. At a technological level, the period after the early 1970s appears to be a blind spot. Historians David Brock and Christophe Lécuyer covered individually and together some major elements of innovations in the semiconductor industry.[84] Another particularly relevant study is Franco Malerba's *The Semiconductor Business*, on the decline of European competitiveness in semiconductor manufacturing until the early 1980s.[85] As such it is an indispensable resource on the European semiconductor industry's state of affairs from the early 1950s to the 1980s.

The wider context of development in Dutch business and technology is extensively covered by two distinct, multi-volume projects written in Dutch: 'Business in the Netherlands during the Twentieth Century' and 'Technology in the Netherlands in the Twentieth Century'.[86] Although these projects address

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84 David Brock, *Understanding Moore's Law: Four Decades of Innovation*. (Philadelphia: Chemical Heritage Press, 2006); David Brock and David Laws, 'The Early History of Microcircuitry: An Overview', *IEEE Annals of the History of Computing* (2012) pp 7-19; David Brock, 'From automation to Silicon Valley: the automation movement of the 1950s, Arnold Beckman, and William Shockley', *History and Technology* 28:4 (2012) pp. 375-401; David Brock and Christophe Lécuyer, 'Digital Foundations'; Brock and Lécuyer, *Makers of the Microchip*; Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970* (MIT Press, Cambridge, 2005); Christophe Lécuyer, 'Silicon for Industry: Component Design, Mass Production, and the Move to Commercial Markets at Fairchild Semiconductor, 1960-1967', *History and Technology* 16:2 (1999) pp. 179-216; Christophe Lécuyer and David C. Brock, "The Materiality of Microelectronics," *History and Technology* 22:3 (2006) pp. 301-325; Christophe Lécuyer and David C. Brock, "High Tech Manufacturing," *History and Technology* 25:3 (2009) pp. 165-171; Christophe Lécuyer and David C. Brock, "From Nuclear Physics to Semiconductor Manufacturing: The Making of Ion Implantation," *History and Technology* 25:3 (2009) pp. 193-217.

85 Malerba, *The Semiconductor Business*.

86 The project on 'Business in the Netherlands during the Twentieth Century' (Bedrijfsleven in Nederland in the Twintigste Eeuw) consists of seven volumes about the following topics: entrepreneurs, multinationals, competition, governmental policies, innovation, human capital, and corporate governance. The project is led by Joost Dankers, Keetie Sluyterman, and Jan Luiten van Zanden. The project 'Technology in the Netherlands in the Twentieth Century'

various themes like innovation, entrepreneurship, corporate governance, and several technological domains, they do not specifically deal with ASM or the semiconductor equipment industry.

The industry reports I used for this study were published by industry data service companies like VLSI Research, Dataquest and Gartner. VLSI Research published some of its industry reports at its own chipshistory.org website. The Dataquest reports were made available by Gartner, after the latter acquired the former. The reports are accessible via the online archives of Computer History Museum. The reports involve monthly newsletters and data reports of chips and equipment manufacturers from 1979 until 1998.

Finally, I relied on personal recollections as found in articles on websites, in academic journals, and in biographical works. Three former ASM managers have published a book about their work for the company: Richard Fierkens, Patrick Lam, and Ray Friant.[87] These books are more akin to management books, however, as the authors try to sum up the origins of success in business. In addition, a few business histories are available, such as one on Applied Materials and one on Kulicke & Soffa.[88] In both cases, their writing seems motivated by marketing interests of the company rather than by scholarly objectives.

Outline of the book

This book tells the story of ASM and its innovations in two types of chapters. The *Innovation chapters* explain and characterize various innovations and innovation processes at ASM, while the *Business chapters* discuss the organizational and entrepreneurial developments at ASM. Both storylines, of innovation and of business, are closely interwoven. Furthermore, the first segment of Business chapters is interrupted by an *intermezzo*, in order to detail an emerging standard outline of a chip and its fabrication process in the late 1960s. This intermezzo also contributes to my analysis by providing a clear and historically correct picture of the complex – and for many readers, unknown – manufacturing process of computer chips and its evolvement.

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consists of six volumes, discussing 'public works, the office and information technology', 'minerals, energy and chemicals', 'agriculture and nutrition', 'household technologies and medical technology', 'transport and communication', and 'cities, construction, and industrial production'. The series was edited by Johan Schot, Harry Lintsen, and Arie Rip.

87 Richard Fierkens, *Hightech in een boerendorp. De biografie van Fico-ondernemer Richard Fierkens* (Herwen 2014); Patrick Lam and Edmund Lam, *Soaring like Eagles: ASM's High-Tech Journey in Asia* (John Wiley & Sons, Singapore, 2006); Ray Friant, *Beyond Buzzwords*: *The New Agenda for Directors, CEOs & Executives* (Advanced Management Press, Convent Station, 2006).

88 Eric Nee, *Information for Everyone: The Applied Materials Story, 1967-2002* (Applied Materials, Santa Clara, 2003); Jeffrey Rodengen, *50 Years of Innovation: Kulicke & Soffa, 1951-2001* (Write Stuff Enterprises, Fort Lauderdale, 2002).

The *Innovation chapters* deal with a selection of ASM's innovations in semiconductor deposition technologies in order to explain and characterize innovation processes at ASM. After the establishment of ASM's general innovation processes in the first innovation chapter, the successive innovation chapters detail anomalies and their effect to this practice. Moreover, each chapter highlights a theme of innovation, like innovating in a start-up or governmental influence on innovation. In the Innovation chapters only wafer processing equipment and processes are studied, and to be even more precise, only chemical vapor deposition techniques. This fabrication process – in all its varieties – constituted the prime competence of ASM Front-end throughout the company's history.

The innovations covered by the Innovation chapters are told in chronological order. In each case the development of one technology is reconstructed, and the technologies at hand elaborate upon the one discussed in the preceding one. These respective accounts are followed by a reflection through the above-discussed three elements path, fortuna and virtù. These three scoop nets, so to speak, pass in review, depending on the structure of the story. Together, the innovation chapters offer a unique peek into the heart of the company: there where it innovates semiconductor technology.

Innovation I focuses on the establishment of ASM's innovation pattern as the firm transformed from representative into equipment manufacturer. This is done by following ASM's innovations in chemical vapor deposition (CVD) technology, from 1971 until 1985. Through mapping the change in innovation methods and habits, the reader obtains insight into the dynamics and regime of innovation at a high-tech start-up venture.

Innovation II describes in detail how a new product – the Epsilon single wafer epitaxy reactor – was developed from the first sketches in 1982, until its introduction to the market in 1988. Through the example of the epitaxy reactor, developed by American and Dutch engineers in Tempe, Arizona, I will study social factors affecting the variation and selection process resulting in an innovative product.

Innovation III explores how ASM and the respective European and Dutch authorities collaborated in altering ASM's innovation strategy from 1979 until 1995. In this chapter, the analysis centers on the development of cluster technology at ASM through governmentally supported research projects. I will investigate the changing governmental means and ASM's needs.

Innovation IV discusses the protracted effort to innovate a major anticipated obstacle for the continuation of Moore's Law, from 1996 until 2007. It concerned the introduction of a so-called 'high-k gate dielectric'. Through intense cooperation with customers and research institutes, ASM engaged this challenge, while pioneering the innovative atomic layer deposition technique in semiconductor manufacturing. This chapter provides an analysis of the close involvement of envisaged customers throughout the development of the high-k technology.

The *Business chapters* study the organizational development of ASM as a whole. These chapters investigate where, why, and what happened during Arthur del Prado's presidency. Whereas the innovation chapters zoom in on separate segments of the company, these business chapters investigate the importance of all the other activities of ASM as a whole. As such, they substantiate the organizational context in which ASM's innovation processes occurred. They also explain the entrepreneurial and strategic maneuvers made by Del Prado to steer his company through the industry, adapting to its constantly changing environment.

Each set of Business chapters centers around a successive phase in the company's history. Moreover, as ASM as a multidivisional enterprise evolved, so did its organizational trials. At the start of each segment of Business chapters, these challenges are related to temporal insights from leading management scholars, like Peter Drucker in the 1960s, Michael Porter in the 1980s and Clayton Christensen in the 21st century. The chapters themselves consistently start with a characterization of the industrial developments ('Industrial context'), a short indication of the affairs at hand within ASM ('Corporate course'), followed by a more in-depth discussion of events ('Elaboration of affairs'). I analyze these organizational perils, developments and strategic changes from the angle of the concepts of path, fortuna and virtù.

This set of chapters starts with Del Prado's entrance in the industry in 1958, the establishment of ASM in 1964, and its transformation into a multinational original equipment manufacturer until 1979 (*Business I*). Accordingly, this chapter describes the maturation of ASM's business strategy, tracing it back to Del Prado's early career as salesman.

Business II zooms in on the early 1980s, ASM's golden years. Through a series of cunning acquisitions of operations and technologies, the company expanded into new markets and engaged new technological opportunities in the period between 1979 and 1985.

This was followed by a period in which the company struggled for survival, from 1985 until 1993, discussed in *Business III*. These chapters reveal that ASM's business strategies and operations, which had been a source of impressive growth earlier, were contested. As important innovations and new activities were leveraged with external funds, a deterioration of the market and subsequent anxious investors caused ASM to hit rock bottom.

After the turmoil of the late eighties and early nineties, ASM had to make drastic choices to reach calmer waters in the period between 1993 and 1999. *Business IV* describes these years as a time when ASM recovered financially and refocused its operations. Throughout these years, however, ASM's financial resources remained scarce and some of its internal weaknesses were still very much present.

Business V discusses the years 1999 until 2008, in which the company engaged technological expansions and implemented operational consolidations simultaneously. The account in these chapters show that Del Prado's entrepreneurial spirit was far from extinguished yet, even though temporal expectations with regard to corporate governance and shareholder value limited his ability to engage new opportunities. Eventually, these events culminated in Del Prado's resignation as CEO in 2008.

Together, the nine blocks of Innovation and Business chapters bring a detailed account of the history of ASM and the fortunes of high-tech. Still, the structure of the book allows readers to be selective. Some readers will be happy to read the introduction and conclusion of each block only. This will bring them an overview of the highlights and an indication of finer details of the story. Others might be solely interested in the organizational developments and stick to the Business chapters, which are attuned to each other. The same accounts for the Innovation chapters. Moreover, the distinction of industrial, organizational and in-depth analysis of the Business chapters helps the reader navigate this elaborate history.

The book ends with a discussion about what, in the end, shaped the innovations at ASM and how this allowed the company to navigate the stormy waters of the semiconductor industry. In this final chapter, I will return to the research question posed at the beginning of this introduction. Based on reflection on the findings from the innovation and business chapters, I will offer a general characterization of ASM's history. I will also draw lessons about the dynamics of innovation, about the direction of business strategies, and, in general, about the fate of high-tech firms in modern economies.

Given the prominence of ASM in the semiconductor industry, in particular in the Netherlands, some readers will be curious about what happened after 2008, when Del Prado resigned. In the Epilogue, therefore, I will concisely discuss the current state of affairs at ASM. This concerns the industrial developments, organizational developments and Arthur del Prado's entrepreneurial activities from 2008 until 2018, which I will address merely on the basis of publicly available sources.

In a personal afterword I will account for my adventure of studying these histories. I briefly recall what it meant to meet and interview engineers, business people, scholars, and secretaries, as well as what it was like to travel to Japan, Singapore, and Silicon Valley and to digest dozens of meters of archives. I will consider what guided me through questions and fascinations, through puzzles, mysteries, and the magical sense of understanding and appreciation. Here I will reflect, as I should, on my own path, fortuna and virtù.