Organizing Networks for Path Creation and Extension in Semiconductor Manufacturing Technologies

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Abstract

How do collectives of organizations create a new technological solution or extend an already existing technological path in networked organizational fields? This paper contributes, first, to a general understanding of the recursive interplay between technology development and the processes of organizing innovation in networks by highlighting the role of collectives of organizations (and not only entrepreneurs) coordinated through interorganizational networks and by using a praxis perspective informed by neo-institutional and structuration theory. Second, and more specifically, this paper adds to the action and network turn in neo-institutional theory by pointing to the importance of organizing collectives of actors through interorganizational networks in processes of field structuration as well as technology development. Third, it contributes to the literature on path dependency and path creation by developing the broader concept of path constitution that is based upon structuration and neo-institutional theory and unpacks the process of building commitment and generating momentum. To all three ends the paper presents the field of lithography as a (now) networked organizational field in which several, partly overlapping sets of organizations struggle and/or compete with each other over the creation of a new path and the extension of an existing technological path.

Key words: agency; innovation; path dependency; path creation; inter-organizational networks; organizational field; structuration theory; technology development

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Introduction

How is technology development organized? In the past, this question would have been answered for most industries with reference to the economic power and political influence of single large, centrally positioned and vertically integrated corporations. Nowadays, however, knowledge production and technological development are often much more distributed, particularly in science-based fields such as biotechnology, nanotechnology or photonics. Here, technology is developed by sets of organizations in more or less networked organizational fields (e.g. Garud et al. 2002; Powell and Grodal 2005; Hargrave and Van de Ven 2006). As we will show for the field of semiconductor manufacturing, interorganizational networks, in the form of R&D consortia in particular, are used to reach agreement about technological problems and possible technological solutions. Moreover, this collective form of organizing enables the organizations not only to create a new technological path but also to secure that a present path is actively extended.

Theoretically, we draw on and develop the notion of path dependency and path creation enhanced by key insights from structuration theory and recent advances in neo-institutional theory to understand technology development in the field of semiconductor manufacturing. While neo-institutionalists now conceptualize organizational fields also as an outcome of entrepreneurial agency and strategic action (DiMaggio 1988; see Delbridge and Edwards 2007 for a recent review), path dependence theory highlights, from a mainly evolutionary perspective, that processes of technology development may lead to a lock-in and become de-facto irreversible beyond the control of strategic actors (David 1985, 2001; Arthur 1989; Mahoney 2000; Pierson 2004). Combining these two approaches with the help of structuration theoretical thinking means to conceptualize, like Garud and Karnøe (2001), the notion of “path creation” as a form of *embedded* collective agency:

> “Path creation does not mean entrepreneurs can exercise unbounded strategic choice. Rather, entrepreneurs are embedded in structures that they jointly create (Granovetter 1985) and from which they mindfully depart. *Mindfulness* implies the ability to disembed from existing structures defining relevance and also an ability to mobilize a collective despite resistance and inertia that path creation efforts will likely encounter. Indeed, entrepreneurship is a collective effort where paths are continually and progressively modified as new technological fields emerge” (Garud and Karnøe 2001: 2).

Our central question in this paper is: How do collectives of organizations actively organize their activities in interorganizational networks to either strategically produce a mindful deviation for complex technology development or to continue an existing technological path?

In our field of analysis we observe activities that are related to both forms of strategic collective agency implied in this question – path creation and path continuation. A striking example for the continuation of a technology is the unexpected persistence of optical lithography as the dominant manufacturing technology for computer chips (Henderson 1995) since the late 1960s. The activities to produce an alternative technological solution since the late 1970s, in contrast, represent the strategy of mindful deviation with the aim of path creation. Anticipating the absolute limits for further developing the established technology, especially for the most demanding segment of high volume manufacturing in the mid 1990s (e.g. Linden et al. 2000), the industry actually started a globally coordinated effort to develop a completely novel technology for semiconductor mass manufacturing under the label “next generation lithography” (NGL).

The competition over the future technological basis for chip manufacturing has been and still is rather fierce. For, first, the players in this industry have always shared the view that, for economic reasons alone, ultimately there can and will be only one technology for mass manufacturing computer chips, i.e. that *only one* technological solution will prevail. Second, the fate of numerous organizations, including firms and research institutes, as well as the future structure of the semiconductor field depends much upon the question of whether the existing technological solution can and will be extended or another option finally be adopted by the field actors. Therefore, introducing NGL means nothing less than a change of the “technological regime” (Nelson and Winter 1977) or “technological paradigm” (Dosi 1982) of optical lithography that has characterized the field for so long.

Against this background of extreme competitiveness, the puzzle of how collectives of organizations actively organize processes of complex technology development in a networked field will be unpacked in this paper by referring not only to path dependency and path creation theory but also to new versions of neo-institutional theory. Since the development of technology is nowadays conceived as being actively institutionally embedded, we take up the more agency-oriented version of neo-institutional theory in general (e.g. Oliver 1991; Barley and Tolbert 1997; Fligstein 1997; Beckert 1999; Scott 2001) and the active structuration of organizational fields in particular (Leblebici et al. 1991; Hoffman 1999; Phillips et al. 2000; Garud et al. 2002; Greenwood et al. 2002; Hensmans 2003; Maguire et al. 2004; Dorado

2005; Van de Ven 2005; Greenwood and Suddaby 2006; Hargrave and Van de Ven 2006; Delbridge and Edwards 2007; Child et al. 2007; Lounsbury and Crumley 2007; Wijen and Ansari 2007). In particular, we will refer to the version of neo-institutional theory which considers the role of networks in organizational fields in order to cross-fertilize institutional theory with network research (Phillips et al. 2000; Kenis and Knoke 2002; Powell et al. 1996). In the field under study, the latter is relevant since inter-organizational networks, in the form of differentiated R&D consortia in particular (Doz et al. 2000; Sakakibara 2002), play an important role in forming collectives of organizational actors in order to develop and sustain technological solutions for NGL in the global chip industry today and shape the organizational field they are in. In addition to these new versions of neo-institutional theory we will explicitly use structuration theory that has been developed by Anthony Giddens (1984) as a social theory and that does not only match the action-turn in neo-institutional thinking but also informs much of the path creation literature.

The paper is organized as follows. Based upon a literature review, the next section introduces lithography as a crucial technology for modern societies which is being increasingly innovated in interorganizational networks. Then, we lay out our methodology for advancing the analysis of path constitution in networked organizational fields via a comparative in-depth case study approach based on theoretical concepts from neo-institutional, structuration and path theories. The section that follows tells the present NGL story and gives detailed empirical insights into the actual creation and extension of technological paths. The empirical insights are used for advancing a theory of path constitution that is based on neo-institutional and structurationist thought and helps to sensitize for the role networks can play in processes of complex technology development and for organizing for commitment and momentum in these very processes. The last section concludes with implications for future path research and for organizing collectives of organizations for constituting technological paths.

Overall, our paper contributes, first, to a general understanding of the recursive interplay between technology development and the processes of organizing innovation in networks (e.g. Freeman 1991; Ahuja 2000; Carlsson et al. 2002; Powell and Grodal 2005; Dhanaraj and Parkhe 2006) by highlighting the role of collectives of organizations (and not only entrepreneurs) coordinated by interorganizational networks (cf. Wijen and Ansari 2007 who, however, do not explicitly refer to networks) and by using a praxis perspective informed by neo-institutional and structuration theory. Second, and more specifically, this paper adds to the action and network turn in neo-institutional theory by pointing to the importance of organizing collectives of actors through interorganizational networks in processes of field structuration as well as technology development. Third, it contributes to the literature on path dependency and path creation by developing the broader concept of path constitution that is based upon structuration and neo-institutional theory and unpacks the process of building commitment and generating momentum (Garud and Karnøe 2001, 2003; Hargadorn and Douglas 2001; Garud et al. 2002; Windeler 2003; Stack and Gartland 2005). To all three ends the paper presents the field of lithography as a (now) networked organizational field in which several, partly overlapping sets of organizations struggle and/or compete with each other over the creation of a new path and the extension of an existing technological path.

The Organizational Field of Lithography:
Towards Developing Technology in R&D Networks

Optical lithography has been and continues to be an extremely important technology, since it guarantees the advancement of manufacturing semiconductors that are nowadays needed for a broad range of products and services – as, for example, illustrated by the report *Harnessing Light* sponsored by the National Research Council (1998) of the U.S.. To secure the further development of the industry and modern societies, key actors in the global chip industry have considered more than one candidate for NGL. Actually, only a few years ago at least five technological alternatives were still envisaged that were promoted either in Europe, in Japan or in the U.S.. Two of these, namely synchroton lithography and extreme ultraviolet lithography (EUVL), are typically considered post-*optical* technologies because they are still based on photons used in optical technology but nevertheless would constitute a radically new system technology. The other three alternatives are proximity electron lithography (PEL), electron projection lithography (EPL), and ion projection lithography (IPL). They are based on particles and thus constitute an entirely different technological paradigm (cf. Linden et al. 2000: 97-99).

Almost like the field of semiconductor manufacturing itself, the field of research on and development of tools for manufacturing has become increasingly networked (Langlois 2000). According to neo-institutionalists, an organizational field comprises “those organizations that, in the aggregate, constitute a recognized area of institutional life: key suppliers, resource and product consumers, regulatory agencies, and other organizations that produce similar services or products“ (DiMaggio and Powell 1983: 143). In the case of optical and post-optical lithography the key organizations of the field are chip manufactures like Intel, AMD, Motorola, Infineon and Samsung, tool producers or system integrators like ASML, Canon and Nikon, a broad range of component suppliers, corporate R&D consortia, industry associations, global testing facilities, university research centres, and government funding agencies. Deviating to some extent from DiMaggio and Powell's definition, we conceive of *networked organizational fields* as social systems in which interactions and relations among more or less independent organizations are coordinated in time-space in and around interorganizational networks, consortia in particular.

Today, the organizational players in the field of semiconductor manufacturing recognize each other as members of the same organizational field. In addition, they see themselves as members of a networked organizational field not least because of their intensive network-like interaction and coordination of activities that have arisen in and across a broad range of R&D consortia as well as along the different supply chains. Despite many variations in detail and a never ending struggle over forms of coordination, the overall structure of the organizational field of semiconductor tool manufacturing in general and of research on tools for manufacturing in particular has changed rather radically in the two decades from in-house development and the neoclassical ideal of a free market (Browning et al. 1995; Mowery and Rosenberg 1998: 124-135) towards distributed developments coordinated in interorganizational networks, especially in the U.S. (e.g. Ham et al. 1998; Carayannis and Alexander 2004). That is to say, the R&D activities in this industry are mostly coordinated today by a distinct network mode of governance (Grabher and Powell 2004), in which rather independent organizations collaborate and coordinate their interactions and relations in time-space predominantly through their enduring relations with each other (Windeler 2006). The chip manufacturers like Intel and Texas Instruments and, more recently, Samsung take the leading role in such coordinating activities but are supplemented in this role by similar efforts of system integrators like Canon and Nikon in Japan and ASML in Europe.[1]

Today, R&D networks are increasingly interrelated with tool manufacturing and supply networks. Not only are the members of the R&D networks mostly recruited from the organizations who are engaged in tool manufacturing, but the infrastructure of the manufacturing networks is intentionally mapped onto the R&D networks, since developing a

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[1] Such a *networked* organizational field differs from an "organizational field network" (Kenis and Knoke 2002). Instead of considering any relationship between organizations as amounting to a "field-net" on the macro level, the former focuses on those ties that – due to intensive interaction and cooperation (rather then competition) – can be ascribed a network *governance*.

system technology requires that all the components have to exhibit the highest technical standards possible and, at the same time, have to be mutually aligned with great precision. This very tight technical interdependency of components has been uncommon even in the lithography industry until very recently. For the development of optical lithography it has been stated:

> “The individual manufacturing steps are often mastered at an experimental rather than a scientific level and are difficult to replicate on different tools or in different facilities. Such complexity has historically required manufacturers to work closely with equipment suppliers to improve the performance of each tool” (Ham et al. 1998: 139).

This is even more true for the development of NGL, in which the three separate supply chains for the wafer stepper (including compelx sub-components like the light source and optics), the resist, and the mask have to be mutually coordinated in such a precise way that they are quite likely to merge into one supply chain for the production of steppers.[2] This trend is caused by the fact that the technical specifications of all NGL options are so demanding that the performances of the individual components are directly interrelated and the production of one component, in turn, becomes increasingly dependent on the development of the other components needed to produce this system technology. For instance, a delay in resist development may require additional efforts from the light source manufacturers, thus closely intertwining the supply chains of stepper and resist. The questions, yet unanswered in the literature, are how R&D is coordinated in this complex process of technology development and how far individual or collectives of mighty players like end-producers and system integrators are capable of coordinating the R&D process and undertaking the complex, risky and economically demanding process on their own.

What the literature does tell us is that the powerful industry players use consortia to coordinate the distributed innovation activities in time-space to some extent. Most studies to date have concentrated on the most prominent consortium SEMATECH which focuses on basic research and standard setting (and which is thus figuring out the common ground for developing all technological solutions) in the global industry (e.g. Browning et al. 1995; Ham et al. 1998; Browning and Shetler 2000; Carayannis and Alexander 2004). SEMATECH was

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[2] The stepper is a large machine in which the patterns of the microchips are “printed” onto the silicon wafer using laser light. The supply chain for the stepper consists of numerous companies producing stepper components, e.g. the laser light source or the focusing optics, and extends down to the material suppliers for these components. The supply chain for the resist produces a light sensitive lacquer, the so called photo resist, which coats the wafer and in which the patterns are actually printed. Last but not least, the mask carries the template of the chip’s pattern, which is then projected through the focusing optics onto the resist. The mask supply chain typically includes suppliers of mask blanks and the mask shops, where the patterns coming from the chip manufacturers are transferred onto the mask blank.

founded in 1987 by 14 high-tech companies (Intel, AMD, Motorola and IBM among them) representing at the time 85% of the U.S. national capacity for semiconductor manufacturing with funding from the U.S. Defense Department matching the member firms' annual contributions. The consortium today not only organizes the construction of the International Technology Roadmap for Semiconductors (ITRS) but also basic research for precarious aspects of the technological infrastructure in particular for extending the optical path as well as for developing an NGL solution. To this end, SEMATECH engages in "funding the development of new equipment by suppliers, improving the reliability of manufacturing equipment, qualifying new and improved manufacturing equipment for plan application, developing roadmaps for microelectronics technology and its manufacturing equipment, developing standards for equipment interfaces, and improving communications between semiconductor manufacturers and equipment makers" (Carayannis and Alexander 2004: 227-228; see also Grindley et al. 1994). Over the years, the network structure of the consortium has shifted not only from U.S. to a more global[3] but also from mainly horizontal to also vertical collaboration, i.e. it started to coordinate joint research projects with suppliers for the much needed equipment for manufacturing semiconductors (Carayannis and Alexander 2004). Today the SEMATECH consortium constitutes a particularly large and global interorganizational network in the field.

SEMATECH is the most encompassing and best-studied consortium. The prominent role it plays is legitimated by its assumed neutrality. Other consortia active in R&D in the field of lithography have not received so much attention in the literature till today. This is mainly because they are much younger. However, they are also far less neutral than SEMATECH because they are organized in order to promote one technological option only. The most prominent consortium of a collective actor network pushing one technological option was the Intel-led Extreme Ultraviolet Limited Liability Company (EUV LLC), a consortium which, as its name tells, was dedicated to push the EUVL alternative (Linden et al. 2000). Other cooperative R&D efforts like PREVAIL (IBM and Nikon) were dedicated to promote the EPL option. In the shadow of these dedicated consortia there have been other R&D activities which more or less have also focused on one single technological option but are far more

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[3] Ten years after the formation of the consortium it was renamed International SEMATECH for including five Asian and European firms (Philips Semiconductors, STMicroelectronics, Infineon, Hyundai and Taiwan Semiconductor Manufacturing Company) "making the organization a truly global consortium" (Carayannis and Alexander 2004: 229). This impression was strengthened even further when SEMATECH, at about the same time, announced a broad agreement with SELETE, a Japanese consortium for leading edge semiconductor technologies, and started working with it on developing and standardizing manufacturing equipment.

loosely coordinated within government funded research programs like MEDEA+ in Europe or the industry consortium SELETE in Japan (Ham et al. 1998; Sigurdson 2004).

Looking with Leblebici et al. (1991) at the organizational field of researching and developing tools for chip manufacturing today one, *first*, has to emphasize that the field is now a networked field constituted by a set of collectives of organizations formed around consortia which reflect several stages of different supply chains and which compete with each other or mutually sustain each other. *Second*, the collectives do not only organize for the creation of the know-how necessary for technology development but also refine the technologies, i.e. the tools, knowledge and methods used for organizing their activities with each other. *Third*, state regulations play a major role for the formation of the field. The constitution of SEMATECH, for example, was only possible, because the anti-trust laws were relaxed and models of private-public partnerships in R&D were introduced in the U.S. in the mid 1980s (Browning et al. 1995; Ham et al. 1998; Carayannis and Alexander 2004). *Fourth*, most obviously, the practices of doing R&D have dramatically changed in the field. For instance, they now show more collaborative properties despite the continuously fierce competition between the industry actors.

Looking at the existing literature on the semiconductor tool manufacturing industry many questions with regard to our central question on the role of collectives of organizations in processes of complex technology development remain unanswered. A *first* one is: Are there other consortia of interest in the field beside the basic research and standard setting consortium (SEMATECH) and the different single-technology-pushing consortia (like EUV LLC) that should be considered? How, for instance, is the provision of facilities for prototype testing coordinated, which is of elementary importance for technology development? Since the efforts of the consortia are technologically tightly interrelated a *second* question arises: How exactly do the actors in these technologically interrelated processes coordinate across organizations, beside the fact that the field is constituted by different, partly overlapping networks that offer actors basic experiences to work in this networked organizational field? This question becomes particularly interesting in face of the fact that competition remains between the organizational actors, similar to Garud et al.’s (2002) finding for other technological fields, shaped by standards. Possible answers to these two questions give rise to a *third* one: How do actors in these consortia use the networks for creating and extending a technological path respectively? Since the consortia as locales for networking organizations, of chip and tool manufacturers and research institutes in particular, are supposed to have enhanced communication and understanding, supported coordination, and reduced technological and timing uncertainties (Linden et al. 2000) a *fourth* question is: How do organizational actors actually use these networks in order to reach common understanding, to develop norms and standards, and to exercise power and influence in order to create or sustain a technological path in time-space? Not only organizational researchers observing the field but the actors themselves continue to look for answers to this question. This is crucial and even if some preliminary answers and solutions are found, the question always remains open, because collaborative networks are more or less fragmented arenas of specialized interests (Sydow and Windeler 1998; Garud et al. 2002) and, as such, keep on creating new uncertainties. Related to the networked organizational field of semiconductor tool manufacturing and R&D and due to the time frame of over nearly 15 years of technology development a *fifth* question is: How can a collective of actors, some of them competitors, generate and sustain commitment or momentum over this long period of time?

Methodology

Path Constitution Analysis

In order to answer these questions and to gain empirical insights into how these networks are organized in detail for the creation of a new or the extension of an existing technological path, we have developed a ‘Path Constitution Analysis’ methodology (PCA). The PCA is based upon four principles derived from a combination of path dependency and path creation theory on the one hand and from the agency- and network-oriented contributions to neo-institutional theory on the other.

First, technological paths are constituted in organizational fields by sets of organizational actors who are able to coordinate their activities in order to act collectively. Therefore, the PCA has to be a *multi-actor analysis* which looks at how actors coordinate their activities in processes of path constitution and a *multi-level analysis* including at the very least the field and the organization or the interorganizational network as relevant levels of analysis. Until today only few studies have looked at processes of path creation in technological fields such as Post-it® notes (Garud and Karnøe 2001), automobiles (Porac et al. 2001), internet software (Garud et al. 2002), and wind turbines (Kemp et al. 2001; Garud and Karnøe 2003). However, these studies, in spite of the increased acknowledgement of agency, even collective agency, in such fields, are quite silent about exactly how actors go about establishing and using their networks for selecting the most promising alternatives from the pool of visible solutions, for developing shared views and understandings, for mobilizing resources in order to secure commitment and generate momentum and so forth – and how the individual and collective actors in this competitive and collaborative process refer to prevailing structures of signification and legitimation as well as resources of domination and reproduce these in their organizing practices (Giddens 1984), therefore adding *multi-dimensionality* to PCA.

Second, since technological paths are characterised by a kind of irreversibility, initiated by small or bigger events and sustained by a momentum or even by a lock-in, the PCA has to be a *process analysis* that has to be carried out over time with respect to several dimensions, including those suggested by structuration theory: signification, legitimation, and domination. The research design for such PCA lends itself very well to the *comparative and longitudinal* analysis of at least two competing technological (or institutional or organizational) alternatives. Because of the focus on agency, the extreme complexity, and the unclear nature of the causality involved, an “inquiry from the inside” (Evered and Louis 1981) or “naturalistic inquiry” (Lincoln and Guba 1985) is needed which is only possible in very detailed comparative case studies using mainly qualitative methods but using quantitative data for “triangulation” (Jick 1979) wherever possible.

Third, we propose that any PCA needs to differentiate betwe*en different forms and phases of path constitution* (Figure 1). Looking at *forms* of path constitution, technological paths can be either more mindfully produced or of a more emergent quality. This implies that PCA should be based on a gradualist concept of paths, whereby the degree of reflexivity may be used to discriminate to which extent paths are constituted intentionally (Windeler 2003). The resulting taxonomy not only provides a frame for classifying technological paths it also points to the fact that PCA is basically a *gradual* analysis, taking both emergent as well as deliberate elements of organizing for path creation and extension into account. A comparative and longitudinal study of alternatives is also helpful in dealing with this reflexivity dimension.

– INSERT FIGURE 1 ABOUT HERE –

Fourth, looking now at phases of path constitution (Figure 1) we distinguish between path generation, path continuation and path termination. In the phase of path generation, the development of a path may be constituted by more or less emergent phenomena and chance events like in the case of QWERTY (David 1985) or the active shaping of the path like in the case of the Post-it® notes (Garud and Karnøe 2001). In the phase of path continuation we can distinguish between emergent path persistence (a case which comes close to the classic understanding of path dependency) and deliberate path extension (as in the case with optical lithography). Last, paths may also terminate, which may be unintentional or deliberately brought about in which case we speak of path dissolution and path breaking respectively. In our empirical analysis, we find that the development of NGL is currently torn between path creation and path extension, as highlighted in Figure 1.

Triangulation in data collection and analysis

For analysing the constitution of technological paths in the field of lithography we have combined different methods and forms of data. Following the approach of a naturalistic inquiry from the inside in order to understand complex historical and actual process (see also Garud et al. 2002; Greenwood and Suddaby 2006) and to advance a theory of path constitution in general and of organizing networks for path creation and extension in particular, the main source of information are 40 semi-structured interviews we have conducted so far with development engineers, strategic technology executives and CEOs from chip manufacturers, system integrators and component suppliers as well as executives from leading R&D consortia and government funding programs. Last but not least we interviewed industry experts and selected academic scholars. The interviews were mainly conducted in Europe and the U.S.. The first round started in 2003 and was followed by two more in 2005 and 2006 respectively (see Table 1 for details). These interviews each took about 90 minutes on average with specific sets of questions tailored to the respective field of practice/expertise.

The questions aimed at three levels of analysis, first the organizations, second the consortia as interorganizational networks in the field, and third the organizational/technological field itself. More macro aspects (e.g. national or supra-national policies) were considered only as they have an influence on the organization, the consortium or the field. In terms of content, the questions focused on structures as well as on practices, emphasizing those that are related to organizing networks for path creation or extension. In addition to obtaining general insights into the empirical field, this allowed the interviewees to elaborate their perspective on the particularities of the state-of-the-art technology development in the semiconductor industry as well pointing out relevant issues to be addressed by our own research. These in-depth interviews were supplemented by a yearly expert panel with five representatives from chip manufacturers, suppliers and R&D consortia in order to keep up to date with the real time developments in the field (marked with an asterisk in Table 1).

– INSERT TABLE 1 ABOUT HERE –

A second source of information has been the a content analysis of field documents, especially of the trade press, company reports, and conference proceedings. Also, information about company mergers, shifts in strategic orientation and the industries comments on “critical events” in the development of NGL since the mid 1990s was collected, coded and related to each technological option. Thereby, we were also able to trace the industry’s discourse on the networked R&D structure over the last ten to fifteen years.[4]

This triangulation of data and methods enables us to compare the specific perspectives on the technological options and the development of the field by relevant actors which differ significantly not only according to their position in the supply chain but also to their interests in and views about technological alternatives. This triangulation in the collection of data makes our analysis more robust and grounded in the data, especially since we had the opportunity to cross check our findings in subsequent interviews with practitioners and industry experts.

Linking empirical data and our conceptual approach was achieved by generating sets of questions for each interview on the basis of our theoretical framework informed by ideas taken from the path dependency/creation, neo-institutional and field structuration literature as well as our expanding knowledge about the field, while, at the same time, allowing the interviewees to express their own views. The latter aspect is indispensable for gathering data on the different relevance structures within the field, e.g. the contrasting assessments of the current situation seen either from the side of the chip manufacturer or system supplier, which

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[4] We also used methods of social network analysis on the co-authorship of conference presentations at the most important industry conference (SPIE) between 1996 and 2006. We will not present and discuss the results in this paper, though.

are necessary to judge how the relevant actors mindfully deviate from existing structures and how they reflexively monitor their own deviation as well as that of others. The interviews were transcribed and then coded both with analytical as well as empirical categories by different researchers. Sets of interviews were discussed in research group meetings. The documents from the field were also discussed group meetings. In this way, we generated a rich interpretation of the practices of networked R&D in the semiconductor industry and we were able to "ground" (Glaser and Strauss 1967) our analytical approach to path creation and extension in a rich set of data, lending empirical relevance to concepts like lock-in or organizational field. Because of the iterative process in which we derived constructs from data and aligned them with theory we stayed sensitive to emerging phenomena from the data, while at the same time allowing for a grounded theorizing on networked path constitution.

Important concepts like reflexivity and mindfulness are reconstructed from interview data and content analysis of the business press. However, both are not a question of individual opinion or strategic marketing. Following the structurationist approach we only speak of mindfulness when sets of actors in the field signify the activities for the advancement of a particular technology by actors as mindful, when this is accompanied by related recurrent activities and when mindfulness, or related codes of signification, are sanctioned as an adequate signification in the field. In sum, mindfulness must be a structural property of the practices of technology development in the eyes of actors in the field as well as in the eyes of the observer conducting a PCA.

Analyzing path constitution via networks

As mentioned before, a PCA that focuses, as in our case, on the creation or extension of a technological path requires a *multi-actor, multi-level, multi-dimensional* analysis. Although the R&D consortia constitute most of the networked organizational field and thus the most immediate level of analysis where actors reproduce structures and, in this very process, are guided by these very structures, more micro as well as more macro levels should not be disregarded. For instance, important corporate actors like Intel but also ASML may mobilize organizational rules and resources when they enter a sub-field or network, and they actually did when developing a second supplier of a certain testing technology in order to decrease the dependence of the industry on the one and only in the market place, as the representative of a supplier company pointed out (I-24). However, these actors may also be subject to rules and resources on more macro levels such as the global economy, the national innovation system or the regional organizational field they are embedded in and, thereby, reproduce or transform the structural properties of these social systems. Striking examples here are national and transnational research programs and the funds they provide for developing modern technologies.

Especially if the *multi-dimensional* analysis is to be grounded in structuration theory three dimensions of actions and structures should be distinguished analytically. Actors refer in their path-related activities to the rules of *signification* that dominate the organizational field of action. For instance, they use the common vocabulary and interpretative schemes or utilize roadmaps as accepted ways of expressing the requirements for the further development of a particular technology or a particular mode of organization. As far as the *dimension of legitimation* is concerned, actors qualify, for example, activities or roadmaps as viable or not viable, fair or unfair, right or wrong and use practical as well as contextually proven and accepted procedures and techniques like roadmaps, conference talks and so on to express their views or to sanction others. Last but not least the *dimension of domination* needs attention, since this dimension is particularly relevant in an “economic field” (Giddens 1984) like NGL. This dimension highlights that actors utilize immaterial and material means e.g. to influence the processes of producing a technological artefact and the organizing of the activities and relations as well as economic prospects of the actors involved. They, thereby, recursively constitute the domination aspects of social practices. For example, firms use money and machines as well as knowledge and refer to sets of actor relations in order to collectively produce a particular technology like the stepper. In other words, they use material as well as immaterial means as allocative resources. However, they often and at the same time utilize material as well as immaterial means to coordinate R&D activities and relations in time-space, for example by creating a consortium or by producing updates of roadmaps for technology development and, thereby, influencing the constitution of actors and their relations on future markets (see Windeler and Schubert 2007).

In the case of path constitution usually both allocative as well as authoritative resources have to be mobilized in order to generate momentum or try to exercise control over the development of a technological or organizational path. Both kinds of resources, and their enactment, have always to be considered in combination with rules of signification and legitimation. For by referring to these rules *and* resources actors can augment or diminish resources, contribute to the development and strengthening of a path, trigger its dissolution or promote its breaking.

Findings: Organizing Networks for Creating or Extending a Path?

Innovating chip manufacturing technology has been pursued mainly in R&D consortia that have helped to adjust divergent views, pool technical expertise, coordinate financial investments and share risks between the consortia members for some time (Browning et al. 1995). So it comes as no surprise that, in our interviews, the experts from the field of NGL have all referred to consortia as *the* institution for conducting R&D and stressed the need for collaborative R&D in the semiconductor tool industry. At the same time, they admit that, at least for a radical change in technology like the shift from optical lithography to NGL, this type of R&D is by no means a routine procedure, but an extremely complex and delicate process requiring constant collective organizing efforts that are superimposed with coordination needs along the different supply chains. In addition, the interviewees point to other types of interorganizational networks that add to the networked character of the field.

First, there are countless mostly *bilateral* and *highly reflexively coordinated projects,* some of which are either an offspring of the collaboration within R&D consortia or, at a later stage, may develop in such multi-lateral network forms of collaboration. Second, several *equity joint ventures* have been created for administering R&D in the field of lithography. Take for example the Advanced Mask Technology Center (AMTC), created by AMD, Infineon and Toppan, or Xtreme Technology, a joint venture of Philips and Fraunhofer. Third, there are two other ‘consortia’ or *platforms of collaboration* which have been overlooked in the research on the chip manufacturing industry so far and are committed to prototyping the lithographic technology, especially testing alpha and even beta tools. These platforms are not placed in the centre of the struggle about alternative solutions, even if they help to demonstrate in the end if a solution works or not. One is a university-affiliated but independently operating international research centre in Belgium called IMEC. The second is Albany Nano Tech, which is built in line with the successful IMEC platform in affiliation with the State University of New York in Albany, New York. Right from their founding, both count not only chip but also tool and component manufacturers as formal members in their technology programs (test facility engineer, I-7: 3) and, thus, contribute to the fact that the field has become more vertically networked and more reflexively coordinated.

In consequence, tool manufactures such as ASML, Canon and Nikon have started to collaborate with their suppliers in order to set industry standards (supply company CEO, I-13:

5). Moreover, both sites offer early access to advanced NGL prototype production tools, so called alpha tools, to chip manufacturers and their suppliers. Both sites are thus not only an important functional means for developing and testing NGL – for developing and adopting masks and resists, a process that takes up to two years (I-13: 6) – but also locales for networking organizations, tool manufacturers in particular and, as such, contribute significantly to the fact that collaboration has become a common practice in the field where – similar to biotechnology – networks are now *the* locus of innovation (Powell et al. 1996). Finally, *industry associations* such as the Semiconductor Equipment and Materials International (SEMI) contribute significantly to the networked multi-layered character of the field.

In this networked organizational field, other technological solutions, as already mentioned, have been dismissed for technical and, especially, economic reasons (e.g. EPL and IPL) because "it meant leaving behind 20 or 30 years of knowledge" (chip manufacturer representative, I-33) or "cannot deliver the necessary throughput" (supply company CEO, I-13). The organizing efforts continue to focus on two alternatives: EUVL as a case of creating a new technological path, and enhanced immersion technology as a case of extending the old path of optical technology – as we will show soon. Since SEMATECH has extended its activities also to the established alternative (SEMATECH representative, I-31: 35), once again, the old has become the most vivid challenger of the new. Nevertheless, the field remains characterized by high technological and economic uncertainties that lead some major actors like Intel or IBM to engage in several consortia supporting different technological paths at the same time and also to change membership over time, signalling shifting commitments as well as betting on different horses (Van de Ven and Garud 1993; Windeler 2003). For instance, IBM used to develop an EPL option with Nikon up to 2000 and then became a member of EUV LLC. Even though IBM officially continued the EPL development, the strategic manoeuvre of joining the EUV consortium was marked as a great success for EUVL. A similar decision was made by Infineon, which also joined the EUV LLC and thereby may have hampered its own development of the IPL option.

Struggling for radical change:
Creating a path for Next Generation Lithography

The story of innovating EUVL, the NGL option that is seen as the most likely successor technology of optical lithography today, is, first and foremost, one of collectively organizing networks, and we will now look in more detail at how these have actually been organized and then used for the creation of a new technological path. Setting and keeping the course for EUVL requires significantly more than just technical feasibility which is a highly complex achievement on its own. In addition, each technological option for NGL has to be cost effective for volume production and the doubts in the industry regarding these two factors are magnified by the escalating development costs (hundreds of millions of dollars) and the long duration (about ten to fifteen years) of R&D processes. Achieving a sustained industry-wide support for a NGL option like EUVL in the light of high technical uncertainty and economic risk was one of the main aims of networked R&D. However, the networked form of innovating EUVL can not be understood as the simple result of technical or economic determination.

One of the first networked strategic actions in order to set the course for EUVL happened when in 1996, Intel invited all six tool manufacturers (ASML, Nikon and Canon plus the at this time still existing U.S. firms SVGL, Ultratech and GCA) to discuss with them how to innovate EUVL, as an Intel representative pointed out:

> "We showed them what we had in the internal lab that we want to commercialize down the road and we asked what they wanted to do with it. So we initiated this process essentially in 1996 that we had kept at a very low level of investment until then" (I-33).

One year later, Intel initiated the $ 250 million public/private EUV LLC consortium with Motorola and AMD as a Cooperative Research and Development Agreement (CRADA) with three leading U.S. laboratories: Sandia National Laboratories, Lawrence Livermore, and E. O. Lawrence Berkeley National Laboratories. The consortium was dedicated to push EUVL (Linden et al. 2000) *first*, by reaching an important "milestone", i.e. delivering a proof of principle for EUVL's technical feasibility within three years, and *second* by establishing early R&D relations with relevant suppliers, like ASML, Nikon and Canon. *Third*, EUVL was pushed further by announcing the leading chip manufacturers' interest in this option to the organizational field. As a component supplier pointed out:

> "It was the aim of this consortium to demonstrate the feasibility of EUVL. This was particularly important because of the complexity of the technology. But it gave evidence not only of the technical feasibility but also the enthusiasm, which was its aim, too" (supply company representative, I-6).

We can see here that the formation of the consortium goes well past mere economic and technical concerns. It is the locus for mobilising collective efforts that mindfully deviate from the established technological path. In addition, actors like Intel reflexively used material and immaterial means to establish the consortium and, thereby, coordinate activities and relations among a defined set of actors in the consortium. However, the importance of the EUV LLC goes much further. The consortium acted as a collective and tried to strategically position and frame their activities and announcements at conferences, in the press etc. within the industry-wide recognized set of rules and resources. Thereby, the NGL option EUVL was not only actively coined as the successor technology to optical lithography. It was, in addition, signified as the solution favoured by the members of the consortium. This, in turn, legitimized the use of resources to sustain the endeavour to deliver the proof of principle for EUVL's technical feasibility first of all for the members of the consortium. The resource character especially of the material means invested was enhanced by the rules of signification and legitimation established in this very process. In addition, the suppliers in the field monitored this closely and reflexively. They adjusted their activities strategically to the endeavours of the EUV LLC in particular. This has its rationale in the fact that the members of the EUV LLC represent most important industry players in the field. Together these activities of the EUV LLC member organizations inside and outside of the consortium and the activities of key suppliers in the field opened up a trajectory for a highly promising technology development and triggered a process of a recursive development in which sets of rules and resources augmented each other. As we will show now, the sets of rules and resources used by the members of the consortium and by allied suppliers were embedded viably into the established field structures in time-space, which made the collective efforts more effective.

Engaging in strategic networking activities has, of course, a history in this field. First of all, actor constellations like the EUV LLC were only possible in the U.S. after regulations changed, i.e. the anti-trust laws were relaxed. In addition, the establishment of the EUV LLC was influenced by previous successful cooperative ventures like the I300I, an international initiative to introduce 300mm wafers, established as a subsidiary of and modelled after the likewise successful SEMATECH consortium (Ham et al. 1998). Also, it goes without saying that these networked activities were not restricted to the U.S., since networking established itself as a form of modern and highly efficient coordination globally in the mid 1980s (e.g. Piore and Sabel 1984; Amin and Thrift 1992). For instance, in Europe the EUCLIDES program initiated by the tool manufacturer ASML, component suppliers Carl Zeiss and Oxford Instruments started in 1998. In Japan an EUV program was started under the framework of the government funded ASET consortium. Moreover, networked activities were not confined to EUVL technology with different constellations of actors pursuing different options, like the IBM and Nikon PREVAIL program for EPL. These networks were mindfully embedded in the respective funding regulations and practices with, for instance, the EUV

LLC's operational budget being exclusively paid by the industry, EUCLIDES having a public/private funding structure and ASET being completely financed by the Japanese government.

Initiating strategic alliances for technological development entails multiple strategic considerations for the participating companies. Today, it is a commonplace within the industry that alliances are supposed to reduce the uncertainties of technological feasibility and economic viability, as all our industry sources confirm. Apart from being a legitimate form of state-of-the-art R&D, the membership in consortia helps the companies to time their investments with regard to others companies' investments and expected return of investment. In addition, convincing smaller companies with a limited budget to partake in a specific line of research may tie those companies irreversibly to one technological option, thereby creating durable commitment structures. Last but not least, with the initiation of the EUV LLC, Intel sought to generate technology related intellectual property, so that no company outside the consortium would be able to lead or block R&D for EUVL once the technology became more mature:

> "If this technology doesn't work, we're going to be out on the order of $250 million. On the other hand, if it works, what we want to do is recover our investment. But more importantly, what we want is access to the tools prior to our competitors who didn't take that risk" (Sander H. Wilson of Intel, cited in Linden et al. 2000: 103).

From this perspective, path creation – especially in an already networked field like semiconductor manufacturing – is essentially linked to the creation of new networks within the field, while at the same time reflexively drawing on the successful experience from former networks. Especially in the very early phase of R&D, networks are strategic means of convincing the relevant actors all along the supply chain to join in on the mindful deviation from the established technological solution. The initiation of EUV LLC as the first big scale EUVL R&D consortium can thus be seen not as a random small event which may become significant only in hindsight, but as a purposeful big event in the organizational field. It was supposed to align the multiple expectations and counter the warranted doubts towards EUVL as the most promising successor technology to optical lithography. Moreover, EUV LLC constituted an interorganisational network of powerful end-producers and influential suppliers which not only reflexively coordinated their activities and relations in the light mainly of their enduring relationships but reflexively pursued a fine-grained mutually coordinated process of technology development with additional strategic forms of signalling to the field.

For successful path creation in the case of complex and strategically important technologies like chip manufacturing tools it is not enough to simply create one single network which proves the technical feasibility of a technological option under laboratory conditions like the EUV LLC did in 2001. As a response to EUV LLC's technological poof of principle, the successful members of the EUV LLC consortium, together with other members in the industry, then strategically retransferred the further process of EUVL R&D to SEMATECH as the accepted, neutral locale for collaborative technology development. The success of the EUV LLC, in turn, legitimized SEMATECH to reflexively set up a larger collaborative EUV program for developing the required infrastructure for high volume manufacturing:

> "In cooperation with universities, national laboratories, suppliers, integrated device manufacturers, and other industry consortia, SEMATECH has been spearheading the worldwide effort to develop this EUV infrastructure in the source, mask, optics, and resist areas" (Wurm et al. 2007: 1).

Moreover, developing EUVL through SEMATECH has two additional aspects and fulfils two strategic ambitions especially for the members of the EUV LLC consortium. *First*, SEMATECH was able to address a broader range of technological issues and open the participation on EUVL to all the companies in the various supply chains interested in its development, thus increasing the number of mobilized actors. *Second*, by hosting a series of workshops and conferences it created public visibility for those yet undecided or unconvinced on EUVL. This can be seen as a reflection of the industry's consensus that it will only be possible to commercialize one NGL option. The goal of continuing EUVL development within an established R&D consortium thus lends credibility to the option while at the same time it counters the scepticism and resistance that highly secretive, instead of relatively open and participative, R&D can trigger.

Focussing the industry's attention on EUVL by strategically initiating cooperative R&D like in case of EUV LLC and then reflexively generating a broader acceptance by setting up an EUVL program within SETAMTECH were two major steps for successful path creation. However, setting the course and mobilizing allies needs to be supplemented by continuous activities and is aimed at monitoring the global process and firmly staying on course. A networked form of global monitoring was initiated when "in autumn 2003, the International EUV Initiative (IEUVI) was launched to further the coordination of collaborative efforts among leading EUVL R&D consortia and to address infrastructural issues for commercialization. It built on an earlier coordination effort between Japan's only EUVL R&D entity ASET and the U.S. organization EUV LLC by expanding membership to CEA/LETI of France, SEMATECH of the U.S. and several others who joined as members since then. The IEUVI coordinates R&D activities by identifying opportunities for inter-regional benchmarking and collaboration" (Gargini et al. 2006).

Complementing this initiative, international testing programs were started at the university affiliated facilities of IMEC and Albany Nanotech which would offer early access to prototypes of high volume steppers, so called alpha and beta tools. Like SEMATECH, these platforms are not placed in the centre of the struggle about alternative solutions, like EUV LLC or IEUVI, but they help to assess whether an alternative will be economically viable in addition to technical feasibility. In their respective EUVL programs, the chip makers, the tool manufactures and component suppliers jointly engage in broad testing under near production conditions, which is supposed to tackle or even clear the last remaining uncertainties before eventual production.

All the networked efforts we have listed so far in the development of EUVL have to be seen as the medium and result of the practices surrounding the creation of a new technological path. Reflexively drawing on already existing experiences and structures of signification, legitimation and domination in the field the relevant collectives of actors formed new networks and used existing ones in order to prove the technical feasibility, asses the economic viability and last but not least create a broad acceptance and sustain continuous commitment for EUVL. As a result, these networks become the central locus for innovating the technology, tying what seems to be the major part of the whole industry very closely to the success or failure of the technological option. Even though these networks are, in the meantime at least, seen as the taken for granted legitimate form of state-of-the-art R&D in the industry, coordinating the fierce competitors in collaborative ventures is a matter of delicately tailoring each consortium and program to the needs of its participants, first against the background of previous experience and second according legal requirements as well as technical specifications. Creating a technological path by means of different consortia and programs means to skilfully manoeuvre within the legitimate boundaries of the field, adapting to existing as well as emerging organisational constraints while at the same time creating durable relations between the future producers and customers of this technology. In this way, creating the path of EUVL not only consists of technological feasibility and economic viability, but of embedding the radical techno-economic bundle within the regulations and practices of the field.

Continuously winning the struggle for the moment:
Extending the path of optical lithography

Whereas the revolutionary advent of EUVL can only be explained by referring to an unprecedented effort of networked mindful deviation as organized disembedding from the established technologies and reference structures by mighty players in the field, the incremental evolution of optical lithography is in no way self-evident nor completely path-dependent. True, the experience the companies and their engineers have gained in pushing the limits of optical lithography ever further (Henderson 1995) have constituted a technological paradigm within semiconductor manufacturing technology which, given the risks of NGL, led to “a natural desire to extend the existing technology as long as possible” (Golda and Philippi 2007: 95). For this reason, as confirmed by all our interviewees, the industry somehow fosters a conservative stance towards novel technologies along the lines of Tushman and Anderson’s (1986) preference for “competence-enhancing” rather than “competence-destroying” technological breakthroughs. However, extension does not come naturally but “this dominance of optical lithography in production is the result of a worldwide effort to improve optical exposure tools and resists” (Chiu and Shaw 1997: 3), an effort which – as we will show now – not only involves the use of material resources but, in addition, of rules of signification and legitimation which only by their subtle interplay renders extending the path possible. This is in particular obvious in our case of the extension of an existing established technological solution since, interestingly, these incremental enhancements have become so complicated in recent years that they are also considered to be quite radical, while at the same time EUVL has been established as a kind of “natural successor” to optical lithography within the industry.

We will only look at one particular incremental enhancement of the established lithography, liquid immersion lithography (LIL), in more detail. Since all other NGL options have been discontinued except EUVL, the continuous enhancements of optical lithography are now its most serious competitor. The principle of immersion has been known in optics for over a hundred years. Put simply, a drop of fluid (water or oil) is placed between the optical lens and the target. Compared to air, the higher refractive index of fluids leads to a better image resolution. Originally used in microscopy to enlarge the image of the specimen immersion is used in lithography to print miniaturized features onto silicon wafers. Introducing water as an immersion fluid into high volume manufacturing did, however, not come naturally to the industry. Like the introduction of copper into the manufacturing process before, a taboo needed to be broken for allowing path extension. The incremental enhancement of the existing lithographic technology using deep ultraviolet light at a wavelength of 193nm thus consists of continuing to use most of the established components like source, masks and optics, but to introduce a drop of water between the last lens and the wafer, which required only minor adjustments compared to EUVL. Similar to path creation, we can see here that some sort of mindful deviation with respect to the present technology and dominant reference structures is also necessary for extending a path, but in contrast these incremental enhancements have the benefit of requiring only little adaptation within the supply chain infrastructure and – especially in the short run – they are cheaper than radical changes (test facility engineer, I-15).

The proof of principle research for LIL was conducted at the Rochester Institute of Technology with some capital investment from chip manufacturers around the year 2001. Before, a different extension of the established lithographic technology was favoured within the industry and had already received substantial funding within several research programs. This technology based on 157nm radiation was supposed to fill the gap between the established 193nm technology and NGL. The intention was to reduce the feature size on the chip by reducing the exposure wavelength, which is the standard model of incremental innovation in the industry. Even though 157nm lithography was well on its way, some technical and economic difficulties were still discussed in the industry, leading to a two-year delay in development. And after Intel publicly announced not to continue with 157nm lithography early in 2003, the industry’s support ceased within the year while at the same time 193nm immersion lithography rapidly gained support. The competition between 157nm and 193nm lithography enhanced with immersion vividly shows that the extension of a path need not be the story of straight-forward incremental enhancements even if the process is supported by mighty and strategically acting players, but is also the story of competing technological solutions and shifting constellations of actors supporting them. Especially major players like Intel, “champions” as they are called in the industry, are able to strategically influence this competition by increasing or decreasing their support for a technological option, thus influencing the support of other companies and steering the process of technological developments within certain limits.

For the development of LIL we can see from the network perspective that, as soon as the proof of principle was delivered, supplier companies started bilateral projects for commercialising LIL. As our interviewees point out, the technology was so close to market introduction that they did not bother with setting up government funding programs but rather ventured for a swift market introduction under their own control. However, these bilateral endeavours were backed up by a fine-grained adjustment of the overall technical, economic and social requirements to be complied with by the suppliers along the networked value chain for this established process of technology development for optical lithography. The firms and other actors involved in the development of LIL, therefore, coordinated their activities highly reflexively in bilateral projects not only with reference to the projects they are engaged in themselves but to requirements along the value chain, too. SEMATECH itself reflexively supplemented this process by organising LIL workshops around the globe, the first one in December 2002. SEMATECH subsequently organized follow up workshops in July 2003 and January 2004. These workshops served to focus and coordinate the globally distributed R&D efforts by first identifying the then most critical issues in the first workshop, reviewing these issues in the second and listing ten new critical issues to be discussed in the third. For six out of those ten issues identified, SEMATECH organized task forces, three of which worked out a research agenda which was to be carried out in research centres and universities with SEMATECH funding. The remaining four issues were left to the tool suppliers. In addition, SEAMTECH (so far) held a yearly series of four International Symposia on Immersion Lithography in cooperation with IMEC and SELETE, starting in 2004. Last but not least, SEMATECH launched a biannual conference called the Litho Forum in 2004, where all technological options (optical and NGL) are discussed and compared by industry experts with a survey about the development status of each technology at the end of the conference. In the 2004 survey, LIL was seen as the most likely candidate for leading edge production in 2007. Even companies which were long known for their strength in in-house developments publicly praised the collaborative innovation of LIL, like George Gomba from IBM at the plenary session of the SPIE Advanced Microlithography conference in February 2007: “IBM addresses this challenge using a collaborative innovation strategy that incorporates our internal R&D and manufacturing teams along with our technology development partners and strategic relationships with lithography-component suppliers.” (Gomba 2007: 7).

In the case of LIL development it is interesting to note that apart from the established practices of organizing conferences and holding workshops, the technique of surveys is now introduced as an additional instrument of technology development into the process, which reflexively draws on previous positive experience with organizing expectations, most notably the International Technology Roadmap for Semiconductors (ITRS). However, the value of organizing expectation does not lie in a valid forecast of future technology development, but in reflexively coordinating the current R&D efforts (see Schubert 2007).

In order to extend the established path in a networked form the relevant constellations of actors did not need to initiate a costly consortium like the EUV LLC, rather they used the resources at hand, mainly through SEMATECH, to coordinate a series of conferences and workshops which served as focal points for the reflexive binding together of the distributed research efforts and as a locale for mutually monitoring the progress of competitors as well as allies. Such gatherings link the networked R&D which, in sharp contrast to EUVL, is not conducted under the framework of consortia or research programs, thereby increasing the importance of both, the networked R&D as well as that of the conferences and workshops themselves. The fact that the optical lenses for LIL are currently developed in a consortium with all three system integrators, suppliers and other firms represents the exception from the rule and nicely illustrates that bottlenecks in this technology also require the multi-lateral collaboration among competitors (supplier company representative, I-40: 4).[5]

Discussion: Towards a Theory of Path Constitution in Networks

Our study of the NGL field has shown that new technological paths are currently either dominantly mindfully created or extended in an organizational field that is characterized by extreme technological challenges, almost unmanageable uncertainties and powerful economic forces that, again and again, seem to drive chip as well as tool manufacturers to extend the present technological path. Moreover, it has demonstrated that different types of networks are an important means as well as an outcome of organizing for path creation and path extension. While in the case of path creation (i.e. EUVL) consortia and other types of multi-lateral networks seem to be of utmost importance, the extension of the technological path (i.e. LIL) is by and large put forward by bilateral projects that, however, are at least to some extent embedded and supported by a networked infrastructure. Despite this important difference, it seems justified to speak in both cases of a constitution of technological paths in a networked organizational field – and organizing being at the heart of path constitution.

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[5] With Canon and Nikon two Japanese tool manufacturers belong to the consortium that, for this very reason, is not eligible to receive funding from MEDEA+. This is quite a typical constellation in this globally networked industry, which causes severe problems since private investors are often not ready to provide resources to a field that is characterized by high technological uncertainty.

Organizing networks for field structuration:
Towards a networked organizational field

The notion of *organizing* seems to be most appropriate for delineating this process because of the rather high degree of reflexivity involved. While organizations are always assumed to have a high degree of reflexivity (cf. Giddens 1990: 302-303), this is not at all that obvious in the case of interorganizational networks. However, R&D consortia and the other types of networks identified in the field of lithography seem not only to support organizing processes but – as social systems – are themselves outcomes of organizing conceived here as reflexive structuration. By and large, they seem to have been intentionally “engineered” (Doz et al. 2000). This comes as no surprise in an industry where the organizational field itself it subject to strategic influencing and reflexive structuration (e.g. Leblebici et al. 1991; Hoffman 1999) by only a small set of globally relevant end producers and system suppliers. Networks of relationships in such fields, whose role so far has remained rather opaque in the research on field development and path constitution (see, however, Garud et al. 2002 for an exception), are not only an outcome but also a means of these structuration processes. For individual and corporate actors, like individual firms, research institutes, joint ventures, or consortia and other types of interorganizational networks rely on these relationships for influencing the field in general and the constellations of actors, the development of the technology, the regulations, and the practices in particular. In turn, these field properties support agency in a way that makes it easier for organizations to form these very networks of relationships. In this regard, any path constitution analysis should identify the practices by which knowledgeable actors use the network structures in their activities. These practices of using networks should be at the centre of relational approaches to agency and organizing (Emirbayer and Goodwin 1994) and should be incorporated more into neo-institutional theories that have opened more to agency and networks (Delbridge and Edwards 2007).

With respect to the creation of a technological path such as EUVL this implies that networks are organized against a history of an at first only horizontally and later also vertically networked field which the underlying complex and highly differentiated supply chains are mapped into. While in the beginning there was only SEMATECH supported by only 14 chip manufacturers this consortium is now only one among several that contribute to the networked character of the NGL field (even though it remains the most important). The relationships that have emerged in the course of the development of the field are now of a more diverse nature and, what is more important from a neo-institutional and path perspective that is informed by structuration theory, increasingly reflexively produced and reproduced by organizational actors in order to create a new technology or even a technological path. The same is true with respect to the mode of path extension. In the case of LIL, however, newly set-up dyadic relationships among manufacturers, system integrators and components suppliers from the different value chains are embedded in the overall network structure of the field. This comes as no surprise, since the LIL technology requires significantly less basic research and has already been developed closer towards marketability.

Organizing networks for path constitution:
Generating momentum to stay on course

Organizing networks is exceptionally important for the creation of new technological paths like EUVL, especially for generating momentum in terms of shared expectations and mobilizing resources in order to collectively develop the technology. However, as we have seen, it is also important for the mindful extension of the present path of optical technology. Building on the seminal contributions by David (1985) and Arthur (1989) as well as on more recent accounts by Garud and Karnøe (e.g. 2001) and the insights gained from the field of lithography, we define a *technological path* as a socially embedded process of developing a certain technological solution (incl. artefacts) from a set of (competing) technological alternatives; a process that is recursively constituted by actors' social practices in an organizational field. This process is triggered by coordinated activities of powerful actors and is governed by a positive self-reinforcing mechanism, setting a specific pattern of action into motion that generates momentum, which, at least potentially, leads into a lock-in. However, 'momentum' as an outcome of positive self-reinforcing mechanisms does not necessarily emerge all by itself, but may well – as both our case studies demonstrated – be mindfully constituted, i.e. created or extended, as the respective technological alternatives are intentionally selected from the pool of thinkable solutions and promoted. Classic path dependency theory offers history-dependent emergence of a self-reinforcing lock-in as an explanation, whereas the – originally contrasting – concept of path creation seeks to account for the mindful activities of collectives of actors by invoking DiMaggio's "notion of institutional entrepreneurs as actors who have an interest in specific institutional structures and who command resources which can be applied to influence institutional rules" (Beckert 1999: 781).

To integrate both path dependency and path creation (and path extension) we have called for a more gradualist understanding of path processes and for a PCA that accounts not only for emergent paths but also for mindful contributions of (collectives of) actors, specifically through the organizing practices of such actors (see Figure 1 in our methodology section). EUVL development is a case of (still ongoing) *path creation* while LIL is a case of (equally not yet fully accomplished) *path extension*.

Regardless of how a path has been generated, whether by emergence or creation, a certain form of "irreversibility" must exist for the path to continue (Bassanini and Dosi 2001). Following David and Arthur, the irreversibility is stabilised by the mechanism of ever increasing returns or other types of positive feedback that lead, eventually, to a lock-in. The consumer market, especially in the case of technologies with high "network externalities" (Katz and Shapiro 1985), is a very good example of how momentum builds up and is reinforced until a technological possibility is institutionalised as a standard – like the dominance of the VHS video recording system (Cusumano et al. 1992). Irreversibility, however, does not necessarily emerge, but may well – as the case of LIL demonstrates – be mindfully created, too. In path extension, actors make use of path dependency in that they seek positive feedback and a definable momentum to support the process of path extension. The relative degree of path persistence and path extension is obviously variable in specific empirical cases.

Our understanding of technological paths, which is informed by structuration theory as much as our understanding of field structuration, departs rather radically from the classic model of path constitution as originally proposed by David and Arthur and reflected in evolutionary economic theory (Dosi 1982; Nelson and Winter 1982; Witt 1997). Like David and Arthur as well as Dosi et al., we reject the idea of an omniscient, a-historical actor as imagined in neo-classical economic theory, who always chooses the optimal solution in situ, and we also acknowledge the possibility of producing sub-optimal results in technology development. However, we criticise the evolutionary perspective of classical path dependency, because it de-emphasises the active role that actors might play – and in the cases under scrutiny actually have played – in creating technological innovations as well as the possible links between, for example, technologies and/or institutions. Especially for an understanding of the processes of change and the massive coordinated activities of manifold actors in development processes, the agency of actors – and the agency of collectives of actors in particular – deserves a closer look (see also Pierson 2000; Garud and Karnøe 2001). This will enable us to understand better whether path processes, as quite obvious in the case of NGL studied, are mainly created by actors through path-creating or path-extending networks, for example, or whether they emerge primarily behind the actors' backs.

From a perspective informed by agency- and network-oriented version of neo-institutional theory and by structuration theory in particular, the constitution of paths is the medium and result of social practices brought about by knowledgeable actors (Windeler 2003). As our interviews have shown, the actors in the NGL field have at the very least a practical knowledge and understanding of the networked contexts they act in. This knowledge goes well beyond individual insights; rather it seems to have amounted to an industry-wide understanding of the actors in the field which itself is embedded in a more general meaning attributed to networks in the development of the reflexive modernity in the last twenty years or so. These actors reflexively and recursively take up social practices in acting, whereas social systems (like organizations and interorganizational networks) and institutions (like professions and networked forms of R&D governance) regulate the practices they refer to (Greenwood et al. 2002). Social systems, organizations in particular but also some interorganizational networks like the R&D consortia studied in detail here, also regulate the reproduction processes with a high degree of reflexivity, especially by monitoring and rationalising their actions in time-space. As collective actors they can augment their power by intervening into social praxis by organizing the coordination of activities and relations – for example by setting up and maintaining networks of research laboratories and firms by coordinating resource expenditures, by naming and sanctioning processes. They can never control these processes fully, though.

Both the creation and the extension of a technological path rely on agency or, more precisely, on how organizational actors refer to structures of social systems in order to mindfully deviate either from an existing path – or to extend or even defend this very path. They do this in an organizational field that is shaped by institutions and nevertheless is an arena of power dependencies and strategic interactions and characterized by tensions and contradictions (Brint and Karabel 1991; Hensmans 2003). Even more importantly, this field is not only context but text and as such, at least potentially, an object of active and reflexive institutional structuration. It has been shown in the analysis of NGL/EUVL and optical lithography/LIL, that networks of relationships are both an important means and an outcome of such field organizing activities. For instance, they help produce a common understanding about the probabilities that a certain technological path will prevail and to establish legitimacy to attract sufficient resources (see also Hughes 1983; Garud et al. 2002).

Networks, at least from a structuration perspective, are also important for coordinating or even combining allocative and authoritative resources. However, the role of networks goes well beyond that. R&D consortia and other kinds of interorganizational networks have an important role for generating (and sustaining) momentum in order to create a path or to stay on course. Generating momentum is particularly important in these two cases of (mindful) path creation and path extension but may also be relevant in the case of path breaking (see Karim and Mitchell 2000, for an example). Momentum is understood here as a critical mass of directed energy displaying a rate of growth suggesting velocity (Hughes 1983). From a structuration perspective, this momentum binds, attracts or pulls actors onto a technological path, but does so not all by itself. Rather, the actors often choose strategically to join a certain technological path because it is in their interest. While, as stated before, they could always act otherwise, they are attracted to join the path that promises increasing returns; even despite the fact that the same increasing returns or other types of positive feedback may lead into a lock-in with potentially undesirable consequences for the single organization or even the network of organizations.

The detailed analysis of two cases leads to a rather long list of indicators or even drivers of momentum that, at least at first sight, is not any different for path creation and extension. The list ranges from common beliefs about technological and economic feasibilities over conference attendance and voting behaviour to purchase orders creating cash-flows to suppliers. The decisive point we would like to make is that all these indicators are structural properties of social practices that are coordinated by interorganisational networks. In turn, this means that these indicators are bound together via their recursive interrelatedness in networked social practices. As in the two cases presented, the sets of indicators are thereby interrelated in a way that the resulting force can be seen as a momentum which generates a kind of self-sustaining irreversibility.[6] However, the failed development of the 157nm option for optical lithography illustrates also that the degree of self-sustained irreversibility reached is never absolute.

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[6] This momentum may either – as in the case of EUVL – be change-based or – as in the case of LIL – stasis-based. However, both types of momentum that Jansen (2004) nicely differentiates require energy on the part of the individual or organizational actors.

Since the momentum and the associated degree of self-sustained irreversibility is constituted in and through the networked practices of the actors that are involved in the process of technology development, it rests on the actions coordinated by the organizations in their interrelated networks. The continuation of the momentum remains a medium and result of embedded strategic activities of collectives of actors. Similar to Garud et al.'s (2002) insight that sponsors of technological standards face "mobilization challenges" as well as "maintenance challenges", we conclude also for the field of NGL that dilemmas arise between the two when, for instance, "too little control may lead to fragmentation or loss of ownership, whereas too much control may stifle the very emergence of a standard" (Garud et al. 2002: 208).

Conclusions and Implications

The empirical insights from the research reported here enhance our practical understanding of momentous current developments in the semiconductor industry which will ultimately affect, more or less directly, how people as consumers, employees and citizens will communicate, interact and pursue their interests in the future. Above and beyond such valuable practical insights, however, we have suggested and explored a number of novel theoretical avenues related to theories of path dependence and path creation, technology development, and neo-institutionalism.

First, without denying the characteristic features of paths such as irreversibility and positive feedback, we are able to show through a gradualist method of path constitution analysis that both the generation of a new path and the continuation of an existing path may happen at the same time and depend on mindful, coordinated activities by the actors concerned who seek to create or extend paths respectively. At the same time, the very fact that immense efforts are required by the actors shows that their agency is always limited, facing given rules and resources that predetermine options at the same time that they are mobilized to promote options. For future research, this basic finding implies that the continuation of a path in itself is no evidence for the absence of agency while the constitution of a new path cannot immediately be attributed to agency either. In both cases it is an empirical question and matter of detailed analysis to establish how emergence and mindfulness contribute to the explanation together. We suggest that this understanding of path constitution can be supported by structuration theory, but further conceptual and empirical research ins required to spell this out. Conceptually, the three structuration-theoretical dimensions of signification, legitimation and domination still need to be brought into the analysis more explicitly. Empirically, our cases of rather mindful, highly reflexive and agency-infused path constitution need to be contrasted with more emergent cases. Nevertheless, further studies on paths can already build on the concepts and findings presented here.

Second, our research contributes to research on technology and innovation management by demonstrating quite strongly that technology development, at least in the cases we studied, depends on the capability of actors to organize various kinds of networks through which the momentum to create or extend a path can be generated. We have presented an exceptionally complex case of distributed innovation in a highly networked organizational field and were thus able to identify not only a large variety of relevant networks but also the ways in which they are related to each other. Like path constitution, network governance, especially at this level of complexity and sophistication, can be characterized by the structuration-theoretical interplay of the network members' agency and the network and field structures whereby, with a high degree of reflexivity, networks can be actively shaped but not fully controlled. Further research on technology development and innovation in networks can be inspired by our results to take a closer look at practices of organizing collective action in the formation of new networks or strategic use of existing networks for all forms of path constitution.

Third, by looking at networked organizational fields and the institutionalization of certain network forms and practices such as consortia, we also contribute to neo-institutional theory and in particular to recent debates on institutional entrepreneurship (Dacin et al. 2002; Garud et al. 2007). From the structuration theoretical perspective we have adopted, there is no paradox of embedded agency, because instead of a static dualism of structure *vs.* agency we assume a dynamic duality of structure and agency (Giddens 1984; Sewell 1992; Barley and Tolbert 1997). Through our empirical investigations, we have been able to demonstrate that it will be instructive in further research to analyse organizational practices at various levels and in various forms in order to capture the interplay of structure and agency and how it allows for the parallel development of (a limited number of) competing technological options and the organizational forms required to support them within the larger networked organizational field. With our emphasis on collective action through networks, we support the notion of "collective institutional entrepreneurship" (Möllering 2007) and the organizational challenges it implies.

Although this paper is based on rich observations over many years of active field research, it remains exploratory in terms of the intended contributions to future conceptual and empirical research. The findings from the semiconductor field are instructive, but until further results from other technological fields are included in the analysis, we cannot claim a very high degree of generalizability or theoretical saturation. We do claim to have shown, however, that in comparing different fields it will be meaningful in further research to apply our gradualist method of path constitution analysis, which is geared towards both emergence and mindfulness and can capture different phases of path constitution, and to analyse the practices of organizing in a given field.

The findings presented here are also selective in that we have not discussed our data in terms of more structured, quantitative methods such as social network analysis which, with some serious practical difficulties, might give some additional insights that complement our qualitative analysis. We have also underplayed practices such a road-mapping and project-based forms of cooperation for lack of space. Moreover, the method of path constitution analysis that we have adopted warrants a detailed methodological discussion in itself. Setting these limitations aside as suggestions for further research, this study offers rich and meaningful insights on how organizing networks and collectives is an important part of technology development, innovation and path constitution (Dhanaraj and Parkhe 2005).

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Tables and Figures

Type of Organization	**Region**	**Number of Interviews**
Supplier	GER	12*
	EU	2
	US	1
Consortium	US	9**
	EU	3
	J	1
Chip Manufacturer	GER	5*
	US	2*
Project Executing Organization	GER	2
	EU	1
Research Laboratory	GER	1
Ministry	GER	1
	TOTAL	**40**

Table 1: Field interviews (* panel member).

Form of path constitution Phases of path constitution	*Emergent*	*Mindful*
Path generation	path emergence	path creation*
Path continuation	path persistence	path extension*
Path termination	path dissolution	path breaking

Figure 1: Phases and forms of path constitution (* cases identified in this paper).