The Mirroring Hypothesis: Theory, Evidence and Exceptions—Appendix A

Results within Each Group

This Appendix describes our detailed findings within each organizational group.

A.1 Industry Studies

Our sample contains ten studies that describe the relationship between technical architecture and organizational structure at the industry level. All but one were supportive of the mirroring hypothesis. Seven industries are represented in this group: computers (2 studies); banking (2 studies); bicycles (2 studies); building construction (2 studies); stereo equipment; semiconductors; and pen-and-paper role playing games. One study (Langlois and Robertson, 1992) dealt with two industries, computers and stereo equipment.

Industry Studies	Supportive	Weak support	Not supportive	Total
Descriptive	7	0	0	7
Normative				
Good Performance	2	0	0	2
Poor Performance	0	0	1	1
Total	9	0	1	10

All the descriptive studies in this group recount histories in which the introduction of a modular product architecture with codified design rules or standards was followed by industry fragmentation.

In two of the normative studies, the industry evolved in the other direction, towards consolidation. First, Fixson and Park (2008) describe how the introduction of Shimano's superior, integrated product triggered the consolidation of the bicycle drive train industry. Cacciatori and Jacobides (2005) describe how in the British construction industry, unresolved technical interdependencies across different steps in the building process led firms to merge, again leading to significant industry consolidation. In contrast, Sheffer and Levitt (2010) and Sheffer (2011) describe how the currently fragmented US construction industry (which mirrors current technology and building practice) is unable to implement system-level innovations that require coordination across firm boundaries. In the latter case, a mirrored industry structure is performing poorly with respect to new opportunities that require a different technical architecture.

Although we have stressed that causality between technical architecture and organizational ties flows both ways, industry studies can shed light on whether technology or industry structure is likely to change first. In all but one of the descriptive cases, a new, more modular technology arose first, and the industry subsequently broke apart. Typically, once the modular architecture was in place and standards widely disseminated, specialized firms would enter the industry by offering modules that competed with and eventually replaced the products of vertically integrated firms.

The case of semiconductors was slightly different although again technology came first: The researchers, Mead and Conway (1980) first provided a proof of concept for modularization in the form of a student project and a textbook. Subsequently technical standards and interfaces between design and manufacturing were worked out in contract negotiations between fabless design firms and foundries.[1] Technology was also the leading factor in the case of bicycle drive trains: Shimano introduced a superior integrated product, the demand for modular drive trains evaporated and specialist firms were forced to exit the industry.

Only in the case of UK building construction did organizational change come first as firms combined in order to invent new ways to address endemic technical interdependencies (Cacciatori and Jacobides, 2005). The US construction industry has not as yet experienced significant structural change, but may follow the path of the UK industry (Sheffer and Levitt, 2010; Sheffer, 2011).

Thus in eight out of ten instances, new technologies emerged whose optimal technical architectures were very different from the existing ways of doing business. The old industry structures proved to be inefficient with respect to the new technological value proposition, and competitive battles were decided in favor of organizations better aligned with the new technical architecture.

[1] The semiconductor industry is also different from the other industries that disintegrated in that vertically integrated firms continue to survive side-by-side with foundry-fabless combinations, although the two organizational forms have different capabilities and tend to focus on different parts of the market (Kapoor, 2013).

Summing up, the industry studies show how the balance of economic forces shaping industry structure can change under the impetus of architectural innovation (Henderson and Clark, 1990; Wolter and Veloso, 2008). Across a range of industries, the economics of mirroring combined with new technology can be strong enough to reshape an entire industry.

A.2 Within-firm Studies

Thirty-six studies fell into the within-firm category. Thirteen industries are represented: software (13 studies); semiconductors (5 studies); computers (3 studies); aircraft and defense (3 studies) telecommunications (2 studies); autos (2 studies); power tools; stereo equipment; food; pharmaceuticals; construction; and healthcare. The group is somewhat weighted towards software and information-based industries, but still has great diversity. Results are as shown below.

Within-firm Studies	Supportive	Weak support	Not supportive	Total
Descriptive	12	3	1	16
Normative				
Good Performance	8	2	4	14
Poor Performance	4	0	2	6
Total	24	5	7	36

The descriptive studies in this group generally sought to measure correlations between technical dependencies and interactions between people or teams. The correlations found were both high and significant. For example, based on *ex ante* knowledge of the technical interdependencies, Morelli et al. (1995) predicted 81% of the coordination-oriented communication among product development team members. Similarly, Sosa (2008) predicted 86% of interactions among developers based on component interdependencies identified by system architects.

The weakly supportive studies indicated that a need for knowledge integration could override strict mirroring in some cases. For example, in a study of an aircraft engine development at Pratt and Whitney, Sosa et al. (2004) showed that, although technical dependencies predicted team interactions to a large degree, independent teams sometimes met to resolve system-wide issues. And in a large-scale study of acquisitions, Puranam et al. (2009) showed that overlapping knowledge indicated by patents increased the probability of integration of an acquisition into the acquirer's organization (vs. remaining a stand-alone business).

One descriptive study did not support the mirroring hypothesis. Looking at 22 within-firm software projects at multiple locations, Srikanth and Puranam (2011) found that 19 of them had high levels of technical interdependency even though there was sparse communication between locations. In section 7 of the paper, we argued that with the right digital technologies and tools in place, stigmergic coordination can occur without ongoing communication between developers. (This is not to say that communication is not helpful, only that it is not always necessary.)

The normative studies showed that mirroring is desirable, but usually difficult to achieve and maintain (Amrit and van Hillegersberg, 2008; Baldwin and Clark, 2000: Ch. 7; Colwell, 2006; Mead and Conway, 1980). Other studies measured the performance benefits of mirroring, showing that mirrored tasks took less time to complete (Cataldo, et al. 2008), resulted in fewer defects (Gokpinar et al. 2007) or led to lower stockout rates and inventory levels (Zhou and Wan, 2014).

Four studies supported the hypothesis by providing evidence of poor performance in unmirrored organizations. Each was a case of premature modularization. In each case, the plan was to create a loosely coupled organization mirroring a new modular technical architecture. However latent technical interdependencies persisted and the organizations struggled to deal with them (Ovaska et al. 2003; Herbsleb and Grinter, 1999 a, b; Herbsleb and Mockus, 2003; Bailey et al. 2012).

Six normative studies failed to support the mirroring hypothesis. In four, a collocated, highly interactive team within a single firm designed a modular system made up of independent components. For example, Lehnerd (1987) described how, through an intense collaborative effort across functional units, Black and Decker redesigned its product line as a family of modular products assembled from standardized components. These studies, all with good outcomes, indicate that it is possible to succeed by "breaking the mirror" in a deliberate way.

Finally, two studies documented poor performance in mirrored organizations. In the photolithographic industry, Henderson and Clark (1990) described how successive waves of new entrants introduced new technical architectures, while the incumbents were not able to keep up. The authors suggest that relying on the organizational ties that arose endogenously within a given technical architecture prevented engineers and managers from seeing possibilities inherent in architectural innovations. Dougherty and Dunne (2012) described the advent of digital technology in pharmaceutical R&D and showed that natural knowledge boundaries exist between digital and therapy scientists, resulting in little communication between the two groups. However, this natural division of tasks and knowledge results in missed opportunities to combine knowledge in innovative ways. Faced with ongoing external innovation, passively mirrored organizations may find themselves in a trap.

Summing up, from the descriptive within-firm studies we learn that the mirroring of technical interdependencies and communication linkages is an extremely common pattern within firms. The normative studies indicate that systems architects and managers are conscious of the benefits of placing organizational ties where technical interdependencies are present. However there are two important caveats to the normative recommendation. First, premature modularization of a technical system will cause unforeseen technical interdependencies to be revealed: dealing with these is expensive as they must be addressed on an ad hoc basis. Second, the optimal bounds of knowledge are not as tight as strict mirroring would imply. Organizations that build knowledge only in response to current technical problems, may be taken unawares by architectural innovations. Finally, contradicting Conway's Law, the normative studies present clear evidence that in some cases, tight-knit teams can 'break the mirror' and create modular technical architectures that do not reflect their own communication patterns.

A.3 Studies of Buyer-Supplier Relations

Fifty-two studies focused on mirroring in buyer-supplier relations. Nineteen industries are represented including autos (16 studies); software (6 studies); aircraft (5 studies); semiconductors (4 studies); manufacturing equipment (3 studies); chemicals (2 studies); diverse manufacturing (2 studies); computers (2 studies); IT support (2 studies); steel; metals; air conditioning; home appliances; cameras; bicycle drive trains; clothing; banking; construction; and professional services. The auto industry, software and aircraft are over-represented in this group. Results were as follows.

Buyer-Supplier Relations	Supportive	Weak support	Not supportive	Total
Descriptive	13	1	3	17
Normative				
Good Performance	11	12	3	26
Poor Performance	6	0	3	9
Total	30	13	9	52

The descriptive studies all sought to correlate measures of technical interdependency with insourcing or outsourcing of components. In this context, the mirroring hypothesis suggests that components with many complex linkages to the buyer's technical system will be insourced, while modular components with few technical interdependencies will be outsourced. Thirteen studies provided strong support for the hypothesis, one provided partial support, and three did not support the hypothesis.

The partially supportive study established limits to mirroring associated with technical change. Consistent with mirroring, Cabigiosu and Camuffo (2012) found that higher component modularity was associated with lower levels of information sharing between buyer and suppliers. Furlan et al. (2013) then showed that the negative association held for only components subject to low levels of technical change.

Of the three non-supportive studies, one (Helper et al. 2000) is an anomaly, because it essentially contradicts six other studies of the auto industry, all of which offered strong support for the hypothesis. The lack of correlation between technical interdependency and insourcing in this study is the result of pooling data from two very different systems, one of which (the U.S.) displays strong mirroring but poor performance, while the other (Japan) is able to 'break the mirror' by building long-term relational contracts between buyers and suppliers. Relational contracts are discussed in section 6 of the paper.

The other two contradictory studies involved software which, we have said, constitutes a special case for which the economics of mirroring can sometimes be suspended (Herbsleb et al. 2005; Srikanth and Puranam, 2011).

The normative studies present a different picture. While seventeen were fully supportive of the hypothesis, twelve provided partial support, and six were not supportive. The normative studies supportive of the hypothesis showed that (1) a mirrored system performed better than an unmirrored one (11 studies); or (2) the quality of outsourcing relationships was positively correlated with the components' modularity (5 studies). In four cases, an initially unmirrored system was perceived to be unsatisfactory and redesigned to be mirrored (Garud and Munir, 2008; Ro et al. 2007; Shibata et al. 2005; Mikkola, 2003). In six cases, firms inadvertently created unmirrored relationships via premature modularization and their performance suffered as a result (McIvor et al. 2006; Mikkola, 2003; Tang and Zimmerman, 2009; MacDuffie (Ford), 2013; Jacobides et al. 2015; D'Adderio and Pollock, 2014).

Twelve studies indicated that partial mirroring can achieve good performance. Nine of the twelve indicated that while modularity was a desirable property of outsourced components, the system integrator's knowledge and/or communication linkages between buyers and suppliers needed to be broader than the task boundaries. In this group, four stressed the extensive knowledge of the system integrator (Brusoni et al. 2001; Brusoni, 2005; Prencipe, 2000; Takeishi, 2001, 2002), two stressed communication and trust between buyers and suppliers (Howard and Squire, 2007; Langner and Seidel, 2009), and three stressed both knowledge and communication (Dibiaggio, 2007; Miozzo and Grimshaw, 2005; Cabigiosu et al. 2013).

One partially supportive study described in detail the difficulties of managing a partially mirrored system. Looking at the early stages of development of a new commercial jet aircraft, O'Sullivan (2006) documented the tensions arising from incompatible incentives and late-stage design changes. Despite these manifold problems, however, the resulting product still met or exceeded all project goals.

Six normative studies were not supportive of the mirroring hypothesis. In three cases, suppliers were actively involved with customers in product and process designs and the organizations performed very well (Anderson, 1999; Bonacorsi and Lippinari, 1994; Sako, 2004). All of these cases involved the construction of long-term relational contracts between buyers and suppliers (Baker, Gibbons and Murphy, 2002; Gibbons and Henderson, 2012). One study by Clark (1989) showed that US auto firms that insourced interdependent parts suffered from longer lead times that Japanese firms that outsourced such parts. Again, effective relational contracts, such as are typical of Japanese buyer-supplier relations*,* can provide effective coordination across the boundaries of otherwise separate firms.

Finally, two studies suggested the possibility of a mirroring 'trap.' At Sumitomo Chemical and Nippon Steel, Collinson and Wilson (2006) found that the knowledge and communication patterns that responded to the needs of existing customers impeded the firms' ability to design innovative products for new customers. In the aircraft industry, Brusoni and Prencipe (2011) found that two of three aircraft engine manufacturers had their fleets grounded because they clung to knowledge sharing and communication practices developed in conjunction with earlier, more modular technical architectures.

Summing up, as in the within-firm studies, the descriptive studies of buyer-supplier relations showed that mirroring is a prevalent, but not universal pattern across a range of industries. The normative studies qualified this finding by showing that firms often combine modular technical interfaces with rich communication linkages and/or relational contracts, thus on the whole, there is less information hiding across modules than Parnas (1972, 1978) would have considered ideal. There are also ways to 'break the mirror' via long-lasting relational contracts that build trust and encourage knowledge transfers across firm boundaries. Finally, there is again evidence of a mirroring 'trap,' where an exclusive focus on problem-solving within an existing technical architecture can lead to failure or missed opportunities.

A.4 Across-firm Studies of the Management of Knowledge

As indicated above, several studies of buyer-supplier relations indicated that partial mirroring is both a common pattern and desirable way for firms to manage knowledge. This finding is borne out in ten studies of the management of knowledge. This group is weighted towards semiconductors (4 studies) with autos (2 studies), computers, metal manufacturing, clothing and diverse manufacturing also represented. Results were as follows.

Management of Knowledge	Supportive	Weak support	Not supportive	Total
Descriptive	2	4	0	6
Normative				
Good Performance	0	4	0	4
Poor Performance	0	0	0	0
Total	2	8	0	10

Only two studies were fully supportive of the mirroring hypothesis. Almeida et al. (2002) found that foreign multinationals were most likely to cite their own patents, and were more likely to cite patents of their U.S. alliance partners than those of other firms in the market. Lee and Berente (2012) showed that over time, patenting by OEMs and suppliers in the auto emissions industry tended to mirror the technical architecture of the dominant design.

However, three other studies involving patents indicate that partial mirroring may achieve better performance than strict mirroring. For example, in the semiconductor industry, Tokumaru (2006) found that, even as the industry split apart and firms became more specialized, the average patent portfolio became more diversified. Similarly, patent data suggests that Rolls Royce continued to invest in R&D related to components it outsourced (Prencipe, 1997). Relatedly, Kapoor and Adner (2012) showed that while integrated semiconductor firms brought next-generation products to market faster than non-integrated firms, this effect was weaker when the non-integrated firms had internal knowledge (reflected in patents) that was relevant to the components they outsourced.

For some firms, developing knowledge through R&D and patents may not be enough to sustain the capabilities they need. Jacobides and Billinger (2006) and Parmigiani and Mitchell (2009) both describe firms that concurrently make and buy the same components. In these cases, the benefits of maintaining an internal and external view of the component apparently outweighed the economies of scale that would accrue to either pure insourcing or pure outsourcing strategies.

Atalay et al. (2014) further show that the vast majority of vertically integrated firms in the US do not ship products internally between their own plants. Thus the observed vertical integration (in terms of ownership) was not a response to technical interdependencies related to transfers of physical goods. Instead, the authors argue, vertical integration may facilitate transfers of intangible goods, such as management ability and/or knowledge.

A.5 Across-firm Studies of Alliances and Consortia

Twelve studies dealt with strategic alliances and consortia. The range of industries included software (3 studies); computers (2 studies); scientific instruments (2 studies); information technology; semiconductors; aircraft; and construction, thus the group was slightly weighted towards information-based industries. Results were as follows.

Alliances and Consortia	Supportive	Weak support	Not supportive	Total
Descriptive	1	3	0	4
Normative				
Good Performance	0	2	6	8
Poor Performance	0	0	0	0
Total	1	5	6	12

This group as a whole is largely unsupportive of the mirroring hypothesis. The descriptive studies indicate that partial mirroring is most common pattern. Two large-sample studies found that the use of alliances was correlated with product modularity measured by industry standards and heterogeneity of inputs and outputs (Schilling and Steensma, 2005; Sahaym et al. 2007). A case study of software alliances showed that while product modularization decreased the need for cross-firm communication, digital artifacts and repositories and routine testing served the same function (Grunwald and Kieser, 2007). Another case study of two multi-institution scientific projects indicated that technical interdependence was weakly correlated with communication linkage, but while the technical interdependencies shifted over time, communication patterns remained stable (Kratzer et al. 2008).

The normative studies all described cases where multiple firms collaborated successfully to build technically interdependent products or systems. Some cases involved a non-decomposable technological problem. In the case of the B-2 "Stealth" Bomber, no one firm had all the capabilities and resources needed to develop the aircraft independently, and thus the US Air Force awarded separate contracts to five different firms. However, the technical requirements associated with achieving "stealth" demanded rich communication linkages between design teams at the separate firms. The companies developed shared information systems to make their ongoing efforts more transparent to one another (Argyres, 1999). Staudenmeyer et al. (2005) similarly found that, in inter-firm product development projects across seven firms, inter-firm dependencies were ubiquitous and were resolved by direct person-to-person contact rather than the adoption of formal standards or interfaces. Corresponding levels of knowledge sharing were observed in cases involving flight simulation software, an offshore drilling platform, and a particle detector (Miller et al., 1995; Barlow, 2000; Tuertscher et al. 2014).

Most of the alliances involved new—and thus uncertain and poorly understood—technologies. For example, to develop "next-generation lithography" (NGL) technology in the semiconductor industry, firms such as Lucent, IBM, and Intel, formed multiple, firm-spanning consortia that advanced novel technologies by coordinating "an unprecedented level of interorganizational cooperation" (Appleyard et al., 2008, p. 419). Such industry-level consortia were also found in disk drives, "blade" computers, and flight simulation software (Scott, 2000; Snow et al. 2011; Miller et al. 1995).

5.6 Studies of Open Collaborative Projects

Our sample contains 22 studies of open collaborative projects. Of these 19 dealt with open source software, one with digital media, and two with physical artifacts (semiconductors and rodeo kayaks). Thus the distribution of industries in this group is highly skewed. Results were as follows.

Open Collaborative Studies	Supportive	Weak support	Not supportive	Total
Descriptive	5	3	10	18
Normative				
Good Performance	3	0	0	3
Poor Performance	1	0	0	1
Total	9	3	10	22

In the open collaborative setting, most developers lack the organizational ties of firm co-membership and collocation. Their opportunities for face-to-face communication are highly restricted. They do, however, have many communication channels and the system under development is often digital (or has a digital representation) thus can be easily viewed, transferred, and otherwise manipulated.

The descriptive form of the mirroring hypothesis predicts that a distributed organization such as this will (1) create a modular technical system with low cognitive complexity and few interdependencies; (2) have a high division of labor, with individuals and (small) teams focusing on specific modules; (3) have high levels of information hiding between individuals and/or groups working in different parts of the system. The normative form of the hypothesis predicts that mirrored systems with these characteristics will have higher performance than unmirrored systems.

Five descriptive studies were supportive of the mirroring hypothesis. Three found that open source codebases were more modular than codebases created within firms (MacCormack et al. 2006; 2012;

Baldwin et al. 2014). One found that an increase in technical dependencies (interfaces) between files was correlated with the formation of new communication links between people working on the files (Le and Panchal, 2012). Another found that an open source codebase was highly accessible, consistent with low cognitive complexity (Herraiz et al. 2006). One study contradicted these findings, but it was flawed in that it did not control for the functionality of different codebases (Paulson et al., 2004).

Three studies were partially supportive of the hypothesis. Consistent with mirroring, they found that most code components in open source systems were small and most tasks were performed by single individuals, not teams. However, contra mirroring, two also found that larger files were the responsibility of a cadre of core contributors, who ranged throughout the system, did not respect module boundaries, and generally acted as systems integrators (Koch and Schneider, 2002; von Krogh et al. 2003). The third found that most tasks involving multiple people were completed without any apparent communication between the developers (Bolici et al. 2009).

Nine descriptive studies found that open collaborative groups do not as a general rule divide labor and knowledge along the lines defined by the technical system's modular architecture. Instead using multiple communication channels, large ad hoc groups may convene to work intensely on specific problems (Elliott and Scacchi, 2003; Spinellis, 2006). In this process, individuals often directly observed the work of others and built upon it in a rapid, iterative fashion (Baldwin et al. 2006; Gulley, 2001, 2004; Kokshagina, Boxenbaum and Cartel, 2015). Module boundaries were not strictly defined or enforced and usually a core set of developers made contributions to many different parts of the system (Bird et al. 2008; Bowman and Holt, 1998; Gutwin et al. 2004; Mockus et al. 2000, 2002).

In contrast, the normative studies found, consistent with mirroring, that the formal organizational structure of one large open source project (Mozilla) provided a one-to-one mapping from code components to individuals ("committers") (Mockus et al. 2002). Developers also brought in modules from other systems (Haefliger et al. 2008). In performance comparisons, articles involving interdependent tasks had higher quality when authored by smaller teams (Kittur et al. 2009). And one study found poor performance associated with lack of mirroring: a multi-authored component with critical system impact in the Linux codebase was not well-structured or well-documented (Rusovan, et al. 2005).

Summing up, the studies of open collaborative projects suggest that it is possible for a group of individuals with few organizational ties to collaborate to create a technical system that is modular in design but not mirrored by a matching division of labor. We discuss this conundrum in Section 7 of the paper.