Massive Modular Ecosystems: Identifying Socioeconomic Macrostructures in the Digital Age

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Abstract

The global economy has become rife with interdependencies, creating opportunities and tensions. For this reason, there is an urgent need for new tools to sort through industries that have become almost unfathomably complex. This paper combines insights from the business ecosystem and global value chain (GVC) literatures to develop a framework for identifying and characterizing "macrostructures" in the global economy. Socioeconomic macrostructures require methods for coordinating and aligning (i.e., governing) the activities of autonomous actors across multiple industries, ecosystems, and jurisdictions to innovate and create value. We test our approach through a case study of mobile handsets: an extremely complex and rapidly evolving class of products that combine subsystems and modules produced in multiple "sub-ecosystems." Because standards-based modular value chains and platforms can be identified as the prevailing governance structures, we characterize the mobile handset macrostructure as a *massive modular ecosystem* (MME). After reviewing the relevant literatures, all of which foreground modular governance as an enabler of distributed innovation, rapid scaling, and supply chain resilience, we offer an integrated analytical framework. We then deploy the framework to identify – according to function – the prevailing and alternative governance structures present in each of the main sub-ecosystems that comprise the mobile handset MME. We do this at three levels: system, subsystem, and retail. We then present the observed technical, market, and geographic outcomes for each sub-ecosystem, followed by a discussion section that summarizes the theoretical, strategic, and policy implications of our findings. We make two important observations. First, as the label suggests, modularity is the prevailing governance structure in an MME. But it is not the only one. Internalization and relational partnerships, for example, can create pockets of tacit activity unconstrained by modular interfaces, fostering cutting edge innovation and, potentially, the creation of new standards and platforms. On the other end of the spectrum, simple market linkages allow actors to easily round out products and services with well-defined, generic inputs. Our view is that economic megastructures cannot be perceived clearly without a framework that accommodates a full range governance structures. Our second observation is that business ecosystems in the mobile handset MME are hierarchically layered and also horizontally and diagonally linked with sub-ecosystems in adjacent industries. While many sub-ecosystems are highly concentrated (monopolies, duopolies, and oligopolies), others are more fragmented. However, the MME as a whole is effectively leaderless. This has profound implications for corporate strategy and public policy. Having defined the mobile handset MME as an important economic megastructure, we conclude by proposing an agenda in which our framework can be tested and refined through comparative research on ecosystem and value chain governance in additional complex global industries. It is our hope is that the concept of megastructures in general, and MMEs in particular, will help to provide a more comprehensive method for analyzing complex industries beyond relationships between specific firms or the governance of discrete ecosystems.

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1. Introduction

Digitization is transforming the organization and geography of industries. Once digitized, information can be generated, collected, stored, monitored, analyzed, and processed in ways not previously possible, and when common standards are used as modular interfaces, data can be transferred and put to use with greater ease across organizations and geographic space. Given that the technical structure of products has implications for industrial organization (Colfer and Baldwin 2016), an important effect of digitization on industrial organization is the emergence of global-scale modular business ecosystems associated with specific classes of products, applications, and technologies (i.e., industries). The modules and subsystems in these ecosystems can – albeit with significant engineering effort, because they are complex – be reused, connected, and layered to drive innovation and deliver products and services with immense complexity at scale.

These trends have been broadly recognized and great progress has been made on defining business ecosystems and global value chains in terms of actors and the roles they play, how activities are coordinated and interests aligned, boundary conditions (what should, and should not be included), and how innovation, value creation, and value capture tend to play out. There is broad agreement, for example, that modular governance supports distributed innovation and rapid scaling, and that the complementary efforts of actors within an ecosystem generate value above and beyond what firms might create on their own: a "complementary surplus" (Baldwin et al. 2024: 1). This, when combined with other work on the underpinnings and variety of governance structures extant in global industries (Gereffi et al. 2005, Ponte and Sturgeon 2013), create a platform for taking the next step of exploring how discrete business ecosystems and GVCs are interlinked to create "megastructures" in the global economy.

In this paper we begin this task by detailing one type of megastructure, the massive modular ecosystem (MME), based on a detailed case study of mobile phone handsets. We define an MME as an amalgam of sub-ecosystems primarily, but not exclusively, linked through standardized interfaces. Using this lens, we can conceive of loose coupling at the level of linked and layered sub-ecosystems rather than only between specific firms or functions in a technical system.

We make two important observations. First, as the label suggests, modularity is the prevailing governance structure in an MME. But it is not the only one. Internalization and relational partnerships, for example, can create pockets of tacit activity unconstrained by modular interfaces, fostering cutting edge innovation and, potentially, the creation of new standards and platforms. On the other end of the spectrum, simple market linkages allow actors to easily round out products and services with well-defined, generic inputs. Our view is that economic megastructures cannot be perceived clearly without a framework that accommodates a full range governance structures.

Our second observation is that business ecosystems in the mobile handset MME are hierarchically layered and also horizontally and diagonally linked with sub-ecosystems in adjacent industries. While many sub-ecosystems are highly concentrated (monopolies,

duopolies, and oligopolies), others are more fragmented. However, the MME as a whole is effectively leaderless. This has profound implications for corporate strategy and public policy.

The paper is organized as follows: In Section 2 we briefly review the relevant literature on modularity and standards, global value chains, and ecosystems and platforms. In Section 3 we present our framework. In Section 4 we turn to our case study. We assign governance types to each sub-ecosystem in the mobile handset MME, which is grouped into final systems, sub-systems, and retail. In Section 5 we present empirical evidence describing the technical, market, and geographic characteristics of the mobile handset MME. In Section 6 we discuss the theoretical implications of our approach and briefly highlight the strategic and policy implications of our findings. In the conclusion, we summarize our main arguments and discuss opportunities for future research.

The global economy has become rife with interdependencies, creating opportunities and tensions. For this reason, there is an urgent need for new tools to sort through industries that have become almost unfathomably complex, and our hope is that the concept of megastructures in general, and MMEs in particular, will help to provide a more comprehensive method for analyzing complex industries, beyond relationships between specific firms or the governance of discrete ecosystems. Having defined the mobile handset MME as an important economic megastructure, we conclude by proposing an agenda in which our framework can be tested and refined through comparative research on ecosystem and value chain governance in additional complex global industries. An MME is likely to be only one type of economic megastructure, and future research using the methodological tools developed in this paper will likely reveal others.

2. Literature review

The concept of an MME builds on three streams of literature: modularity and standards, global value chains, and ecosystems and platforms. In this section, we briefly review each.

2.1 Modularity and standards

A complex system, according to Simon (1962), almost always has a decomposable, hierarchical structure. Complex subsystems will have successively less complex subsystems nested within them, until, at the lowest layer we can observe simple, single-function inputs or discrete tasks.

Modularity in design

Although Simon did not use the term modularity, what he was describing was a modular system: "a special form of design which intentionally creates a high degree of independence or 'loose coupling' between component designs by standardizing component interface specifications (Sanchez and Mahoney 1996: 65)." The literature on modular design focuses on how modular systems can be intentionally created as a means of accelerating innovation (Ulrich 1995). Modularity conserves system design effort and spurs innovation at the system level, because modules can be used, re-used, re-combined,

and quickly adapted to alter the functionality of the overall system. At the same time, module designers can work (and innovate) with a large degree of independence from system designers (Meyer and Lehnerd 1997, Thomke and Reinertsen 1998).

Value chain modularity

In modular systems, interactions between complex subsystems will not be as strong as the interactions within them (Schilling 2000, Galvin and Morkel 2001, Takeishi and Fujimoto 2001, Brusoni 2005). The "mirroring hypothesis" promulgated by Colfer and Baldwin (2016) suggests that this has implications for industry organization. The designers of complex systems need to understand what each module can do, select the right modules, and use them to construct complex systems that perform to requirements. Sourcing modules externally provides them with more options, and allows them to incorporate functions about which they might have a limited understanding. The designers of complementary modules need to be deeply knowledgeable about their own domain and fully cognizant of the interface standard, but less knowledgeable of the inner workings of other modules or what the system as a whole is intended to do. Each participating firm can therefore focus on a narrower set of "core competencies" (Prahalad and Hamel 1999, Baldwin and Clark 2000, Baldwin 2007). This logic can repeat in a fractal pattern, creating increasingly refined and specialized sub-modules within modules, thus giving depth to the hierarchical dimension of an MME.

While the technical standards governing modularity can be closed — developed by a firm entirely for its own use — industry standards that are open for public use simplify the process of outsourcing because they offer "a pre-established way to resolve potential conflicts between interacting parts of a design" (Baldwin and Clark 2000: 73). At "thick crossing points" within modules, interactions between agents will tend to be complex, uncertain, and iterative, often involving the creation and exchange of tacit knowledge. Theories of industrial organization that engage the concept of modularity predict interactions that involve the creation and exchange of tacit knowledge will either be internalized or coordinated through "relational" ties between specific partners. By contrast, at "thin crossing points" governed by standardized interfaces, interactions can be simplified, lowering transaction costs and easing externalization (Baldwin and Clark 2000, Sturgeon 2002, Gereffi et al. 2005, Baldwin 2007).

Modularity can create challenges for firms. When an industry becomes highly modular, designers of complex systems can face a "modularity trap" where the system becomes too derivative of the sub-system modules it contains, losing distinctiveness in comparison to systems made by competitors using the same sub-systems (Chesbrough and Kusunoki 2001). Still, if modularity is managed wisely, it can conserve design effort, increase supply chain resiliency, and allow firms to focus innovation on what matters to its customers. For subsystem designers, producing modules with standard interfaces can expand their customer base, but also make it easy for system designers to substitute their products with the products made by competitors. This is part of the dynamic driving the 'smile curve' of profitability, where system designers close to end users are generally more profitable than subsystem suppliers and suppliers of relatively generic services (Mudambi 2008, Parker and Van Alstyne 2018).

Standards as modular interfaces

In the literature on modular governance, there has been surprisingly little attention paid to the multiplicity of standards that bind modular ecosystems together (Langlois 2006). Open, industry-level standards can emerge in a variety of ways, and for our purposes, the main differentiator is if an open industry standard is proprietary or non-proprietary. Proprietary industry standards may be sponsored by dominant firms that have prevailed in a standards war (Cusumano et al. 1992, Shapiro and Varian 1999), by aggressive protection of intellectual property by legal means, and by firms that have launched successful platforms (Gawer and Cusumano 2014). Non-proprietary industry standards may be sponsored by governments (Thun and Sturgeon 2019), formal standard setting organizations (Chiao et al. 2008), open source communities (West 2003), or alliances and consortia (Wiegmann et al. 2017). Closed standards sometimes evolve into industry standards over time, and eventually shift from proprietary to non-proprietary (Sturgeon 2019).

There is an active discussion about how firms can promulgate proprietary standards that allow them a place atop complex hierarchical systems with many suppliers (Teece 2018), and how "two-sided" platforms based on standard interfaces can draw in complementors to generate network effects (Van Alstyne et al. 2016). Either way, most attention is focused on how lead firms strategically cultivate proprietary industry standards at key interfaces to expand markets, erect barriers to entry, and earn rents (Leiponen 2008). This focus is understandable given the "winner-take-all" (or most) outcomes of recent competitive battles in the digital economy, and the rapid growth, extreme market power, disruptive effects, and vast rents (and personal fortunes) amassed by winners. In addition, successful proprietary standards can be very long-lived and typically come with licensing or other fees, and this can spur companies, groups of companies, open source communities, or governments to attempt to establish competing or alternative standards.

The role of standard-setters is to develop and promulgate the standards that underpin modular linkages in both technical systems and organizational structures. However, it is important to recognize that the vast majority of industry standards that govern MMEs are *non-proprietary*, created by voluntary and consensus-based processes such as formal standard setting organizations, consortia, alliances, and open-source communities.[1] Even the *de jure* standards set by states are largely pre-competitive, free to use, and rely on substantial input from industry actors. A view beyond proprietary industry standards is important since both proprietary and non-proprietary standards foster the interoperability that allows products, processes, and firms within and across industries to establish and maintain modular linkages. When modularity is thoroughgoing enough, it can connect ecosystem to ecosystem, thus enabling *massive* modularity.

[1] The ICT industry is rife with "mundane" standards (Langlois 2006). ICT-related industry standards comprise 43% of all standards issued by the twenty largest standard-setting organizations in the United States (Farrell and Simcoe 2012: 28). A personal computer alone is estimated to implement between 250-500 distinct standards (Biddle et al. 2010), though only a handful (Windows operating system and Intel CPUs, most prominently), are proprietary.

2.2 Global value chains

Increasing modularity, and the creation of industry standard interfaces, impact not just the organization of industries, but also their geography. In the 1990s and 2000s, the twin – and often entwined -– strategies of outsourcing and offshoring led to the disaggregation of value chains and the relocation of activities across the globe. The literature on global value chains (GVCs) provides a heuristic for mapping modes of coordination across global industries. Unlike much of the management literature, which typically is most interested in explaining relative firm performance, the GVC literature has roots in development studies. A core interest is how less-developed countries can leverage participation in GVCs to grow and "upgrade" their industrial bases, technological competencies, and human resources (Humphrey and Schmitz 2002, Kimura 2009, Brandt and Thun 2010, Gereffi and Sturgeon 2013, Brandt and Thun 2016).

A key observation of the GVC literature is that high value-added activities are often geographically separated from the low value-added activities. As a result of vertical specialization within GVCs, a firm in a developing economy that undertakes labor-intensive production activities that have been outsourced by a lead firm may never be exposed to R&D and product development, the suppliers of core technologies, or sales and marketing. For instance, Dedrick et al. (2009) use teardown analyses of a range of consumer electronic goods to show that the final assembly function performed by contract manufacturers in China consistently accounts for less than 2% of total value added. Whittaker et al. (2020) observe that this sort of narrow vertical specialization can lead to "thin industrialization" in countries that fail to develop the broad set of competencies and institutional supports that come when new industries emerge organically in one location over long periods of time. The GVC literature on industrial upgrading explores how industries in less developed countries might overcome such challenges.

To help guide research on knowledge transfer mechanisms and upgrading potential in GVCs, Gereffi et al. (2005) developed a conceptual model to help explain and predict the density of knowledge flows across organizational and geographic boundaries.
The methodology starts with the classic duality in theories of industrial organization: the decision by "lead" firms to make (within the corporate hierarchy) or buy (in the market) a specific input. As Williamson (1979, 1981) argued, incomplete contracts and co-specialization tend to generate shared (specific) assets, and risk (of opportunism), and therefore intensify motivations for internalization, while simpler transactions based on price are less costly to source in the market.

In between hierarchy and markets, Gereffi et al. draw on diverse literatures to identify three additional forms of governance. First, the economic sociology, economic geography, and competency and resource view literatures provide various explanations for the persistence of relational ties, formed when the risk from co-specialization and the demands of transmitting complex information can be mitigated by repeat transactions (), socially and/or geographically embedded trust networks (Granovetter 1985, Scott 1988, Powell 1990, Storper 1995, Adler 2001), or onerous time and cost constraints related to the needed capital expenditures and capability development in lead firms (Barney 1991,

Prahalad and Hamel 1999). Similarly, Williamson argues that buyers will resist internalization when transactions are infrequent. These concepts form the basis of a *relational* form of governance in industrial organization (and by extension in GVCs industrial organization). It has been argued by economic geographers (Saxenian 1996) that the relational form is especially relevant in the context of high performing industrial clusters, such as those focused on innovation (e.g., Silicon Valley) and/or responsive supply chains (e.g., Northern Italy and Southern China).

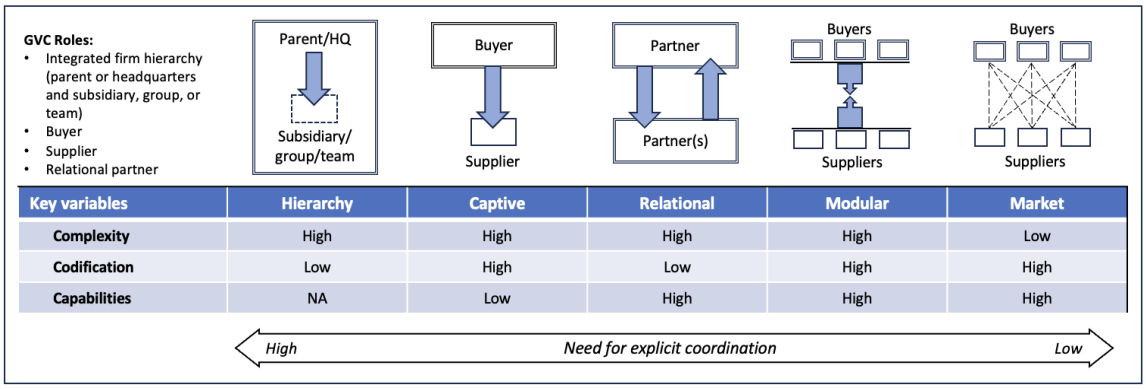
Second, and based on the literature on modularity detailed in the previous section, Gereffi et al. predict that a *modular* form of inter-firm governance is to be expected when complex requirements can be codified, usually with the assistance of information technology, and deployed as a standardized technical interface between value added stages, tasks, or firms. The modular form is closer to price-based market governance than other governance forms, but because the information being codified is complex, issues, or "exceptions" to what might be expected across a thin crossing point are bound to arise with regularity, forcing personnel on each side of the modular linkage to temporarily, yet regularly, engage in closer coordination to remedy problems. This means that supplier capabilities must be high in terms of the technical and business aspects of their module, the standard interface, and the ability to jointly solve problems with buyers. True "plug and play" coordination cannot be expected even in modular value chain governance.[2]

Finally, a *captive* form of governance is expected to occur when lead firms find it practical to provide detailed instructions, heavy monitoring, and even machinery to less capable suppliers, even when information requirements are relatively complex.[3] In such cases, suppliers are treated in some ways as an internal division of the lead firm, and risk is mitigated by the strong position of the lead firm, which often dominates the suppliers' sales.

As this summary suggests, Gereffi et al. operationalize their model using three independent variables: the complexity of the transaction (density of information flow), the potential for codifying the information required for the transaction, and the supplier's competency relative to the transaction's requirement. The predicted (binary) values for the three independent variables associated with each of the five governance forms are shown in Figure 1, with the forms arranged in order of the need for explicit coordination and stylized diagrams above each column.[4]

[2] This has been a misconception of the self-identified "critics of modularity" (sites), who point to case studies where modular linkages are not perfectly smooth as evidence that modular value chains do not exist, or always revert to the relational form. Value chain governance with no relational elements will fall squarely into the market category.
[3] For example, in the context of GVCs, foreign lead firms are often required by law to use local suppliers.
[4] Empirical work using proxies for the three variables and five governance forms has supported the model's predictions (Schmitt and Van Biesebroeck 2017).

Figure 1. Five governance structures posited by global value chain theory with key variables and roles



Key variables	Hierarchy	Captive	Relational	Modular	Market
Complexity	High	High	High	High	Low
Codification	Low	High	Low	High	High
Capabilities	NA	Low	High	High	High

High ← *Need for explicit coordination* → *Low*

Source: Inomata 2017, based on Gereffi et al, 2005.

2.3 Business ecosystems and platforms

The concept of business ecosystems encompasses a wider set of relationships than a value chain, although there is disagreement over exactly how broad this scope should be. The most general definition of a business ecosystem is "an interdependent network of self-interested actors jointly creating value" (Bogers et al. 2019), with the common qualifications that ecosystem actors must be "autonomous" and provide "complementary" inputs (Baldwin et al. 2024). As Jacobides et al. (2018: 2260) note, an ecosystem involves the coordination of "interrelated organizations that have significant autonomy." There is no common ownership binding together actors (as is the case in an internal firm hierarchy) and there will sometimes be no contractual relationship (as there is in the case in a formal sourcing relationship). Self-interested actors specialize within the ecosystem at the same time they coordinate and cooperate with complementary actors in pursuit of a common goal.

The concept emerged from work on value networks, with the focus on an expansion of a linear value chain to include the complementary inputs required to create value (Normann and Ramirez 1993, Rosenbloom and Christensen 1994), focal innovations and the complementary products and services that allow it to create value (Adner and Kapoor 2010), the geography of entrepreneurship, examining regional entrepreneurial networks and technology clusters (Saxenian 1996, Finegold 1999), platform business models based in a platform and its complements (Gawer and Cusumano 2014, Parker and Van Alstyne 2018).

Adner (2017: 42) emphasizes that an ecosystem is inherently multilateral, meaning "not only a multiplicity of partners, but also a set of relationships that are not decomposable to an aggregation of bilateral interactions." For example, when Airbus introduced the double-decker A380 airplane in 2007, its success partially depended on airports investing in complementary facilities that could handle the larger aircraft (Forsyth 2005). In other words, the relationship between two firms does not take place in isolation, but may be impacted by a third firm's actions or the actions of institutional actors such as standard setting bodies or government agencies. As a result, Adner argues our traditional tools for

understanding bilateral ties (e.g. transaction cost economics, property rights, relational ties, etc.) are inadequate.

With so many actors and influencing outcomes, ecosystems are generally perceived to be highly dynamic. Stability in ecosystems, according to Baldwin (2020), comes at a fragile balance point between interdependence, the force that binds the members of an ecosystem together, and the autonomy that allows them to act independently. If interdependence is too powerful, the system collapses into a hierarchy; if independence is too dominant, there is no incentive to interact at all (Baldwin 2020: 22).

Complementarity and platforms in business ecosystems

Several scholars have placed the concept of complementarity at the center of business ecosystems (e.g., Jacobides et al. 2018; Baldwin 2020): the idea that actors working together create more value than they would create working independently. This "complementarity surplus" comes from the advantages of specialization, and especially from distributed innovation, where specialized actors can innovate independently, allowing system integrators to incorporate cutting edge components, modules, and subsystems into higher level systems. This "plug and play" approach to system design is greatly facilitated by modularity (Baldwin et al. 2014).

Two key dimensions of complementarity in business ecosystems are strength and symmetry. When complementarity is strong between system elements or the actors that provide them, the high level of interdependence means that system elements will be useless and actors unproductive in the absence of co-specialized inputs.[5] In the business ecosystem literature, strong complementarity (associated with high asset specificity in transaction cost theory or co-specialized assets in the dynamic capabilities literature) will incentivize internalization, or hierarchical governance. When complementarity is weak market governance will suffice because there will be many substitutes for each system element (or actor that provides it).

Complementarity can also be asymmetrical when some inputs and actors are co-specialized and highly dependent on others, but dependence is not mutual. Asymmetrical complementarity forms the basis of a particular form of ecosystem: the platform. A platform ecosystem is defined by Baldwin (2020: 11) as "a technical system comprising a core set of essential functional elements (the platform) plus a set of optional complements"[6] In terms of actors, platforms have a *sponsor* that specifies the requirements for accessing the platform (the interface standards), *complementors* that provide goods and services that can be accessed via the platform, and the platform's *users*, who access goods and services over the platform and, in some cases, enrich the platform with user-supplied content, usage data, or personal information, and peer-to-

[5] Where Baldwin uses the terms strong/weak complements, Jacobides et al. use unique/general complements.

[6] Adner and Kapoor (2010) and Jacobides et al. (2018), in their focus on innovation and business ecosystems respectively, equate the ecosystem with a platform. Baldwin, by contrast, acknowledges the possibility of multiple forms of ecosystem coordination.

peer networking, all of which increase the value of the platform.[7] Because complements are optional, and not co-designed with the platform, and interoperability is ensured by means of a standard interface, a platform ecosystem always depends on modular governance. A modular platform differs from a modular value chain (in GVC terms) in that the platform's user is able to select from available complements rather than buying a product or service from one supplier at a time (e.g., the user of an Android platform can choose which firm to buy the handset from and which apps to download, while a handset firm choosing a contract manufacturer is buying services only from the contract manufacturer). A platform differs from market-based relations because the complements that are chosen have significant interdependencies, such as adherence to a particular standard (Adner and Kapoor 2010, Jacobides et al. 2018).

A remarkable feature of modular platforms is the potential for very powerful network and scaling effects. This is captured by the concept of supermodularity, the idea that more of one good will make another good more valuable in a positive feedback loop which results in a growing pool of complementors (Jacobides et al. 2018, Baldwin 2020). As Jacobides et al. note (2018: 2263), supermodular network effects can occur both in production and consumption, but there is greater potential for strong network effects and rapid scaling on the consumption side because the vast number of potential users relative to industrial buyers (Van Alstyne et al. 2016, Cusumano et al. 2019). In addition, innovation is accelerated by expanding access to novel ideas and complementary resources.

3. Toward a method for understanding complex global industries in the digital era

In this section we combine insights from the three literatures just discussed to construct a single framework. The framework enables analysis of two under-emphasized features of complex industries where modularity is a prevailing feature: the *variety* of governance structures present, and the *layering* of sub-ecosystems. The result of this broader analysis is an identifiable socioeconomic macrostructure.

3.1 An integrated governance framework

Following the literature on complex systems and modularity in the design of technical systems (Simon 1962, Ulrich 1995, Sanchez and Mahoney 1996, Baldwin and Clark 2000, Murmann and Frenken 2006), we define an MME as a layered and nested hierarchy of business ecosystems – groups of autonomous yet interdependent organizations that set standards and offer final products, subsystems, components, and other inputs within identifiable sub-ecosystems. While both vertical slices and horizontal layers in an MME can be, and often are, viewed, studied, and theorized as tightly defined business ecosystems unto themselves, a looser definition of what constitutes an ecosystem reveals that they are almost always linked to adjacent ecosystems, not only vertically across value chain stages, but laterally and diagonally, since sub-systems and components commonly flow into multiple industries.

[7] However, not all platform users are *end*-users. Because platforms exist in at multiple levels of MMEs, users do as well. A lower levels, users take up a position similar to buyers in modular value chains.

We begin by mapping the *functions* associated with a generic *technical system* in an industry, such as a car, airplane, completed software system, or mobile handset. As Holgersson et al. (2022) explain, value within a complex system is created by specific functions. Functions that have no practical use on their own (a jet engine, for example) can be conceptualized as subsystems that need to be linked together to create a finished technical system with practical uses (e.g., an airplane). When mapped to the actors that produce them, we can see that subsystems in complex industries are typically produced in *sub-ecosystems*. Internally, each functional sub-ecosystem can have a different prevailing governance structure, but when modularity prevails at the level of the overall technical system (final product design and component sourcing), then the benefits of loose coupling, such as distributed innovation and risk reduction, can be realized industry-wide. Because the concept of an MME views complex industries as an amalgam of linked sub-ecosystems, we can conceive of loose coupling at the level of sub-ecosystems rather than only between specific firms or functions in a technical system.

The distinction between these two levels of analysis, *technical system*, consisting of subsystems (defined by function), and *sub-ecosystem*, populated by actors playing one or more roles, is crucial for our analytical method. In the former we examine the nature of interdependencies and linkages between various intermediate inputs within a final system (parts, components, modules and subsystems), and in the latter we examine the roles played by the firm and non-firm actors contributing to the production of specific technical systems and subsystems. Since complex systems are rife with interdependencies, complementarity is present in both levels of analysis, but technical and organizational systems do not "mirror" one another perfectly. For example, it is much easier to replicate (and therefore substitute) even a complex subsystem (e.g., by reverse engineering) than it is to replace powerful actors that may have their positions in the MME locked in though path dependence and network effects, intellectual property ownership, or spatial embeddedness in supportive national or regional institutions and production systems. In addition, actors have agency to choose governance structures that suit their strategic aims. To understand a complex industry, it is necessary to map both technical and organizational systems.

The second step is to identify *roles* in each sub-ecosystem. Any understanding of "who does what" within an ecosystem by identifying which actors and sets of actors provide which functions is inherently provisional. Technological, managerial, and regulatory conditions are not static, and as they change, so do options for innovation, relationship-building, deal-making, deployment of resources, external sourcing, and geographic relocation. But is it possible to look for general patterns and take a "snapshot" of those patterns. Firms and other actors have agency to decide what roles to play, and often play multiple different roles in various systems and subsystems, and change their roles over time. Despite this dynamism, a focus on roles is crucial because in many cases "interdependencies tend to be standardized within each role" (Jacobides et al. 2018: 2265). In an app store, for example, all apps have the same role in the ecosystem – complements to an app store specific platform – and it is this role that defines the interdependencies within the ecosystem rather than the traits of any individual actor, since again, actors may play multiple roles (Jacobides et al. 2018: 2265).

The third step is to identify the characteristics of *linkages*. Autonomous actors in business ecosystems play different roles, but do not align their activities uniformly. In our framework, industrial organization is shaped in important ways by five independent variables, three of which are derived from the GVC literature (complexity, codifiability, supplier competency) and two from the ecosystem literature (complementarity strength and symmetry). It is important to note that these variables can be interrelated: for example, complexity heightens interdependencies (and hence the strength of complementarity) while codifiability relaxes interdependencies.

We posit that the combined values of these five variables generate predictable organization patterns that we refer to as *governance structures*. While it is beyond the scope of this paper to provide proxies for each of these variables, Figure 1 provides some key questions that can be asked to help identify the value of governance variables across a technical system.[8]

Table 1. Governance variables with research questions[9]

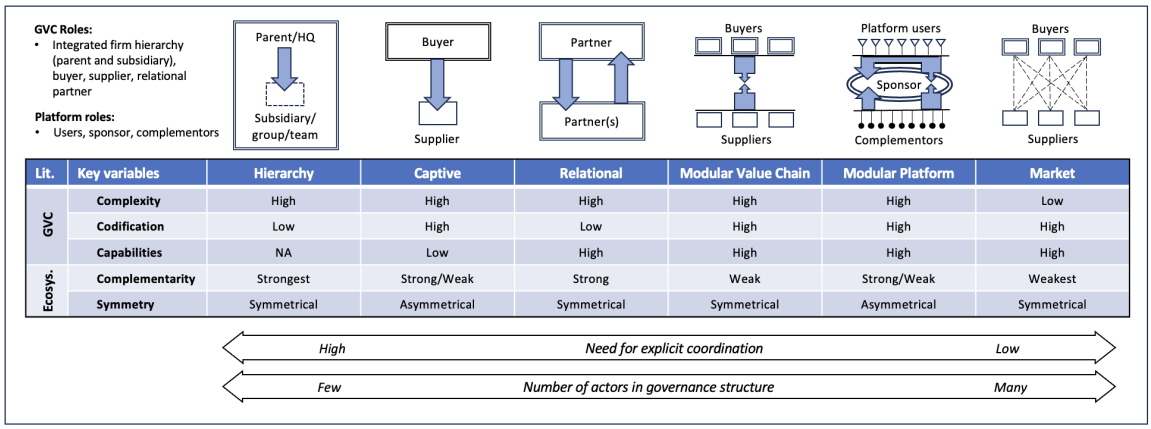
Governance variable	Research question
Complexity	How complex is the information and knowledge required to sustain a particular function, particularly with respect to product and process specifications?
Codifiability	To what extent can a function's requirements be codified and, therefore, transmitted efficiently and without transaction-specific investment between parties?
Capabilities	Are the capabilities of actual and potential actors in an ecosystem adequate in relation to the requirements of transactions?
Strength of complementarity	Strong complements: are inputs to a final system "unproductive unless used together" (Baldwin 2020: 13)? Are complements *specific and unique* inputs that are inseparable from the system they are part of? Weak complements: Are there substitutes for all inputs in a group of complements? Does withdrawal of one component not destroy the value of the others?
Symmetry of complementarity	Symmetric complements: are all complementary functions equally strong or equally weak? Asymmetric complements: Are both strong and weak complements present in a technical system? Do non-unique components *depend on* the unique ones for their value, but not the reverse?

Figure 2 depicts an integrated framework with the predicted value of the three independent variables from GVC governance theory mapped to complementarity strength and symmetry from the business ecosystems literature. The variables are presented

[8] Values for the five governance variables can be assigned using proxies, and these will differ by function.
[9] The questions for strength and symmetry of complementarity are inspired in particular by Baldwin 2020, Section 5.3.

mainly in binary terms (high/low, strong/weak), but there are also several spectra inherent in the framework: for example the need for explicit coordination (high/low) and the number of actors in the governance structure (few/many). These variable combinations yield six governance structures.[10] Block arrows within the diagrams depict the direction and extent of explicit coordination within each.

Figure 2. Conceptual framework: six governance structures in global value chains and business ecosystems



Lit.	Key variables	Hierarchy	Captive	Relational	Modular Value Chain	Modular Platform	Market
GVC	**Complexity**	High	High	High	High	High	Low
GVC	**Codification**	Low	High	Low	High	High	High
GVC	**Capabilities**	NA	Low	High	High	High	High
Ecosys.	**Complementarity**	Strongest	Strong/Weak	Strong	Weak	Strong/Weak	Weakest
Ecosys.	**Symmetry**	Symmetrical	Asymmetrical	Symmetrical	Symmetrical	Asymmetrical	Symmetrical

This framework can be used to identify the roles that firms and other organizations play in complex industries, and how these roles align in specific governance structures. The roles, listed in the upper left corner of Figure 2, include parents and subsidiaries in internal corporate hierarchies, buyers and captive suppliers, partners with relational ties, buyers and suppliers in modular value chains, platform sponsors along with the platform's users and complementors, and buyers and suppliers with arms-length market linkages that do not require explicit coordination. Again, actors have agency, within limits, to select the roles and types of linkages they form, and these choices are non-exclusive, in that actors can exercise different options with different business partners.

Beginning on the left side of Figure 2 with *hierarchical governance*, managers orchestrate activities among subsidiaries and teams. Complex interactions can be supported even when complexity is high, either because management can (theoretically) control the property rights generated from tacit knowledge and dictate who participates in projects, or because closed (and proprietary) standards have been developed to codify the exchange of complex information for exclusive use inside the firm. With bureaucratic control, the strength of complementarity can reach its zenith and co-specialized inputs can be symmetrically dependent on others produced within the firm.

Similar dynamics are possible with *captive governance*, with power asymmetry between buyers and smaller suppliers (again, theoretically) standing in for direct managerial control. Complex, uncodified information exchanges are possible, but because of relatively low supplier capabilities, most important supplier activities need to be strictly codified according to instructions (and often, financing, machinery, software, and parts lists) provided by buyers. Inputs can have strong complementarity with systems (co-

[10] In the ecosystem literature, these are sometimes referred to as "alignment structures." (Adner 2017)

specialization), but because buyer and supplier capabilities are asymmetric, substitutability is high, with supplier inputs strongly tied to buyer requirements, but not vice-versa. High risk of losing business from a dominant buyer mitigates opportunism by the supplier, but the supplier's weak position provides little protection from unilateral decision-making by buyers. As a rule of thumb, a supplier's relationship to a buyer can be considered captive when the buyer represents a high enough proportion of sales (say, 50% or more) that the supplier would face an existential crisis if the buyer were to suddenly withdraw from the relationship.

With *relational governance* interacting firms are on more equal footing, acting as partners over the course of one or more projects. The complexity of interactions can be high to the point where routines are novel, allowing for the development of entirely new products, inputs, technologies, and processes for which codification schemes (emergent standards) have yet to be worked out. The deep co-specialization (strong complementarity) needed for this type of alignment requires high capabilities on both sides (symmetry of complements), giving both actors motivation to protect joint IP flowing from the creation of new knowledge and novel products. Co-specialization creates risk, but this can be mitigated through contractual agreements, long-term relationships and the perceived importance of future collaborations.

The framework includes two categories of modular governance where complexity of interactions are high, yet standards are both well-established and open for use, and capabilities are high relative to requirements. *Modular value chains* are expected when complements are weak and symmetrical. Such arrangements can be conceptualized in binary, buyer-supplier terms, but can also extend to buyer and supplier groupings. Indeed, because of low switching costs for both buyers and suppliers, because of well-developed technical standards, industry-level effects can be observed, such as when modularity not only eases supplier switching and also the ability of suppliers to scale, learn, and reduce risk by serving multiple customers (potentially in multiple end markets). The aspect of modular governance that makes it more common in the digital era is that computerization raises the potential for codification despite high complexity. (An account of how modularity emerged in the mobile handset MME can be found in Appendix 2.)

The second type of modular governance is the *modular platform*, which combines high levels of codification and complexity with asymmetric complementarity. With platform governance, we expand the field of actors beyond buyer-supplier and partner-to-partner governance arrangements of the captive and relational types, and beyond the linear value added concept of the modular value chain, to include the roles of platform sponsor, platform user, and platform complementor. Platform sponsors can be a firm or consortium of firms with a proprietary standard, a government agency or private sector led standard setting organization, or an open source community promulgating a non-proprietary standard. A platform's users can be consumers or industrial users. The stylized modular platform diagram in Figure 2 includes modular linkage options for user-created content, as when users post their own content on social media or ecommerce sites according to the rules of the platform, and a link between users and third-party complementors, as when users access apps via an app store. The diagram also depicts the possibility that complementors might contribute tools and other technical inputs that

improve the value of the platform – again, according to the rules set by the platform sponsor. Platforms may include "native" complements developed and maintained by the sponsor, as well as optional complements supplied by 3rd parties. All three of these dynamics can increase the value of the platform via network effects, and, because modular linkages make it easy for users and complementors to come onto the platform, allow the ecosystem to scale. For users and complementors the strength of the platform's complementarity is high, since the usefulness of their complements is greatly enhanced by or even entirely dependent on the platform.[11] However, it is asymmetric, since no single user or 3rd party complementor is necessary for the platform to function. Asymmetric complementarity in the context of modular governance (high complexity, codifiability, and capabilities) comprise a set of governance variables unique to modular platforms.

Finally, *market governance* is characterized by simple, price-based transactions. The complexity of firm-to-firm interactions can be very low, but the competencies needed to produce products for sale will vary. Therefore, the strength of complementarity is low and the symmetry between buyers and sellers is high.

As with roles, firms have agency in choosing governance forms, and different choices can be made even within the same function. Relational ties can be formed between any partners or set of partners for any reason. Hierarchical and relational governance are especially suitable for radical innovation. Captive ties are suitable for situations where supplier activities need to be tightly controlled. Relational ties sometimes form between groups of firms working in an alliance with the intention of promulgating a new industry standard or platform ecosystem. As long as complex information flows can be codified according to industry standards, modularity is an attractive organizational strategy from both a technological and managerial perspective since it decreases business risks from tight interdependence, reduces the cost of experimentation, derisks and accelerates incremental innovation, and in the case of modular platforms, creates potential for powerful network effects (Holgersson et al. 2022: 6).

4. The mobile handset industry as a massive modular ecosystem

Because they are extremely complex, produced in high volumes, and contain many complex subsystems and governance forms, mobile handsets provide an ideal case study for examining how multilayered ecosystems emerge, impact competition, and shape organization and geography in complex industries. To navigate through this complexity, we examine mobile phone MME governance at three levels: the system level, which covers how handset companies design phones, source key subsystems, and manufacture end products; the subsystem level, focusing on the prevailing governance structures present in the production of key inputs to system-level products; and the retail level, covering the governance of end user purchasing of phones and apps.

[11] In the digital economy, tools exist to automatically convert, or "port" a complement from the platform it was designed for to a similar platform, but "native" complements are known to have superior functionality. Given the complexity of the design rules for modular platforms, significant engineering effort is needed to create equivalent complements.

The technical functions in the MME are roughly "mirrored" by sub-ecosystems responsible for supplying the subsystems in question (cite mirroring hypothesis). These sub-ecosystems are populated by actors playing one or more specific roles, and in the case of modular governance, adhering to specific design rules and/or technical requirements governing the format of information exchange (linkages).

4.1 Handset-level governance

Table 2 shows governance at the system-, or product-level, of the mobile handset MME. For each sub-ecosystem depicted, the prevailing governance structure linking the subsystem to the system is indicated,[12] the main actors and their roles identified, and a few key industry standards listed. When our research detected them, alternative governance structures are also noted.

The first row of Table 2 represents governance of the handset design function. Due to their immense complexity, all mobile handsets are designed on sophisticated software platforms. Handset designers (the platform users), utilize computer aided design (CAD) software for system-level industrial and mechanical design, and electronic design automation (EDA) software for the design of electronic circuitry. Outputs are generally in industry-standard formats so they can be easily received and acted upon by suppliers, regulators, and manufacturers. Handset designers can access a variety of optional platform-specific complements, which have evolved over time to comprise vast libraries of complementary functionality, features, and specific components, available either when the software subscriptions are purchased or as add-ons after the fact. Linkages between the design platforms and their complementors is asymmetric in that the platforms are essential for compatible complements but the complements are optional for users and non-essential for the platform's sponsor.

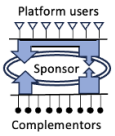
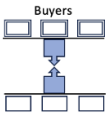
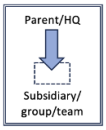
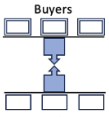
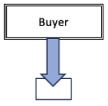
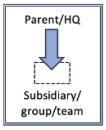
The second row of Table 2 depicts four subsystems that provide a handset's core functionality: application processors (APs) – the "brains" of mobile phones that run applications and perform processing and control functions; core memory modules that provide long-term information storage and retrieval; display modules that provide the touchscreen user interface; and radio frequency modules that manage connections to mobile phone cellular infrastructure for voice and data communications.[13] As the second column of this row shows, the sourcing of the most complex components and subsystems is primarily governed via modular value chains, where the interface is codified by a myriad of proprietary and non-proprietary standards (see examples in the fourth column of Table 2). Although modular linkages reduce transaction costs and facilitate scaling,

[12]The answer to the question of which governance structure in a sub-ecosystem can be considered "prevailing" can depend on how dominance is measured, according to revenues, profits, or number of users and complementors. For example, Apple iPhones have higher profits than most Android-based phones but many more Android phones are sold. Here we used market share as a measure.

[13] Mobile handsets typically include between 500 and 1,500 individual components, modules, and sub-assemblies. Simple components can be purchased from component manufacturers or distributors through simple market linkages, since the standards and specifications are well-known and features and functionality do not vary.

high complexity typically requires some interactions between buyer and supplier engineers, especially for higher-end phones, either as a routine part of the design process or later on if problems arise that require joint attention. There are also important examples of handset companies opting for non-modular governance, despite the potential for modularity created by clear standards. Prominent examples of alternative governance structures are provided in the fifth and six columns of Table 2, showing that multiple governance structures can be expected to coexist in an MME.

Table 2. Handset level governance: functions, governance structures, actors and roles, and key standards

Sub-ecosystems by function	Prevailing governance structure	Actors and roles	Key industry standards	Alternative governance structures with examples	
Handset and circuit board-level electronic design • Computer aided design (CAD) software for system-level design and electronic design automation (EDA) for circuit board level sub-system and module design	**Modular Platforms** (asymmetrical complementarity) 	**Users:** • Phone system firms internal system design groups and external design services firms (weak complementors) **Platform sponsors:** • CAD and EDA platforms (strong complementors) **Complementors:** • 3rd party IP blocks & platform-specific design tools (weak complementors)	• Non-proprietary standard file formats for both inputs and outputs (e.g., DXF, GerberX2, BOM) • Proprietary IP blocks and tools offered on each CAD and EDA software platform • Optional proprietary 3rd party IP blocks and tools • Non-proprietary open-source IP blocks and tools	**None** • Phones system firm design groups have no viable alternatives to externally sourcing CAD and EDA software	
Key component and sub-system sourcing • Application processor • Core memory • Display • Radio frequency module	**Modular value chains** (symmetrical complementarity) 	**Buyers:** • Phone system firms unless sourcing internally (weak complementors) **Suppliers (weak, symmetrical complements):** • Sub-system suppliers (weak complementors)	• Proprietary reference designs and tools from application processor vendors • Non-proprietary industry standards (examples) ○ Memory: Joint Electron Device Engineering Council (JEDEC) standards ○ Display: Digital Visual Interface (DVI) standards ○ Radio frequency: 3GPP implementations – 1G, 2G, 3G, 4G, 5G	**Relational** (symmetrical complementarity)  • Major Chinese phone companies when sourcing application processors from Qualcomm for higher-end phones (strong complementors)	**Hierarchy** (symmetrical complementarity)  • Apple, Samsung, and Huawei when sourcing application processors internally (strong complementors)
Final system assembly • Sub- and final assembly of final systems, circuit boards, sub-systems, and modules	**Modular value chains** (symmetrical complementarity) 	**Buyers:** • Phone system firms when not sourcing from an internal manufacturing division (weak complementors) **Suppliers:** • Contract manufacturers (weak complementors)	• Non-proprietary standard file formats for computer aided manufacturing (CAM) machinery (e.g., DXF, GerberX2, BOM)	**Captive** (asymmetrical complementarity)  • Apple's (strong complementor) to Foxconn (weak complementor)	**Hierarchy** (symmetrical complementarity)  • Samsung's phone system design division to Samsung's internal manufacturing subsidiaries (strong complementors)

The third row of Table 2 focuses on the assembly of the mobile handset. The prevailing governance structure for this function is also a modular value chain, enabled by industry-standard formats for design outputs and the global supply base of contract manufacturers that emerged in the 1990s and 2000s in the ICT industry to provide manufacturing as a service (Sturgeon 2002, Raj-Reichert 2018). However, just as with sourcing key subsystems, some firms make different choices. For example, to maintain the utmost control over quality, cost, and component purchasing, Apple has developed a captive governance structure with its largest contract manufacturer, Foxconn of Taiwan, which makes nearly all iPhones, while Samsung has chosen to assemble nearly all of its mobile handsets in-house for similar reasons (Zylberberg 2017).

4.2 Subsystem level governance

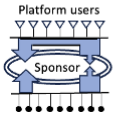
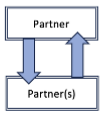
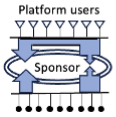
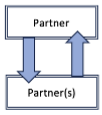
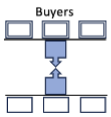
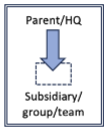
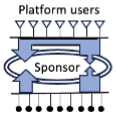
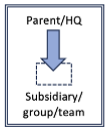
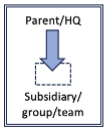
In this section we examine the governance structures *within* sub-ecosystems, which is a matter, not of how the sub-systems are specified and sourced by handset system designers, but how the subsystem itself is produced. The method of analysis is the same as at the system level. Each subsystem corresponds to a function within the finished handset system, and within the sub-ecosystem that produces it there are actors playing one or more roles and adhering to standards that, to a greater or lesser degree, structure design rules and linkages within and between actors in the sub-ecosystem. For brevity's sake Table 3 summarizes governance in just three subsystems: the phone's application processor (which actually consists of three sub-ecosystems: AP design, AP architecture, and AP manufacturing), operating systems, and core memory modules. We choose these for their importance but also to demonstrate the diversity of governance structures that coexist within the mobile handset MME. However, in the text we discuss all of the sub-ecosystems shown in Table 3 and mentioned in the handset-level analysis.

Application processors are designed using EDA software platforms in a manner similar to what was described previously in Section 4.1 (with the same software vendors dominating). As shown in the first row of Table 3, AP design firms in turn sponsor their own modular platforms. Qualcomm (U.S.), for example, offers products with a range of customizability, from highly modular reference design system-on-chips (SOCs) to more flexible products with optional characteristics.[14] MediaTek, a fabless AP design firm based in Taiwan, has historically focused on highly modular SOCs for medium and lower end handsets.[15] In the highest end handset segment, where performance is most critical, the most successful phone companies – Apple, Samsung, and Huawei – design APs internally. In addition, AP design firms have set up programs for 3rd parties to provide compatible complements.

[14] Even after an AP is fabricated, firms can pay Qualcomm for a digital key to unlock "fused" circuitry within the AP.

[15] Qualcomm and MediaTEK are fiercely competitive and are constantly trying to capture the market segments dominated by the other, in a classic "fight for the middle" dynamic (Brandt and Thun 2010, 2016).

Table 3. Subsystem level governance: functions, governance structures, actors and roles, and key standards

Sub-ecosystems by function	Prevailing governance structure	Actors and roles	Key industry standards	Alternative governance structures with examples
Application processor design Design of semiconductors and chips sets for application processing, central processing, and control of sub-functions including inputs and outputs	**Modular Platform** (asymmetrical complementarity) 	**Users:** • Application processor design firms (weak complementors) **Platform sponsor:** • CAD and board-level EDA, and semiconductor EDA software platforms (strong complementors) **Complementors:** • 3rd party providers of IP blocks and platform-specific design tools for semiconductor logic design (weak complementors)	• Non-proprietary standard file formats for both inputs and outputs (e.g., GDSII and the Open Artwork System Interchange Standard) • Proprietary IP blocks for each EDA software platform • Proprietary 3rd party IP blocks, including ARM reduced instruction sets • Open-source IP blocks	**Relational** (symmetrical complementarity)  • EDA platforms have strong complementary links with leading actors in a variety of sub-ecosystems including APs (e.g., Qualcomm), semiconductor manufacturing (e.g., TSMC)
Application processor instruction set architecture for mobile devices Industry standard application processor architecture and IP blocks for efficient power consumption in mobile electronics	**Modular Platform** (asymmetrical complementarity) 	**Users:** • Application processor designers (weak complementors) **Platform sponsor:** • ARM RISC platform (strong complementor) **Complementors:** • 3rd party providers of IP blocks and platform-specific design tools (weak complementors)	• ARM proprietary IP and licensing programs • ARM partner programs and APIs	**Relational** (symmetrical complementarity)  • ARM "Total Access" and "Flexible Access" licenses that, according to the company, "turn the relationship from a sales engagement to a design partnership"
Application processor manufacturing Manufacturing of application processor semiconductors, including fabrication and test of chip designs	**Modular value chains** (symmetrical complementarity) 	**Buyers:** • Application processor designers (weak complementors) **Suppliers:** • Semiconductor foundries (weak complementors)	• Non-proprietary standards that ease the transfer of design information such as the GDS2 circuit layout standard and hardware description languages (HDL) such as Verilog that are used to model electronic systems • Proprietary requirements specific to each foundry	**Hierarchy** (symmetrical complementarity)  • Samsung's internal application processor design groups when using internal manufacturing subsidiaries (strong, symmetrical complements) **Relational** (symmetrical complementarity)  • TSMC's Open Innovation Platform, composed of 5 "sub-alliances" to work with leading companies in EDA, design, value chain, cloud computing and IP
Operating system software Provides end-user experience and controls mobile handset sub-functions	**Modular Platform** (Android: asymmetrical complementarity) 	**Users:** • Phone system firms without internal OS designs (weak complementors) **Platform sponsor:** • Google's Android Open Source Project (AOSP) (strong complementor) **Complementors:** • Several tiers of 3rd party contributors to pre-distribution versions of Android (weak complementors)	• Proprietary Google licenses for Android • Proprietary Google APIs for AOSP	**Hierarchy** (symmetrical complementarity)  • Apple iPhone to iOS, Google Pixel phone to Android, and Huawei handsets to Harmony OS Next (strong, symmetrical complements)
Memory module design and manufacturing Design and manufacturing of core memory semiconductors	**Hierarchy** (symmetrical complementarity) 	**Parents:** • Internal semiconductor memory design group (strong complementors) **Subsidiaries:** • Internal semiconductor memory manufacturing group (strong complementors)	• Non-proprietary standard file formats for both inputs and outputs (e.g., GDSII), Joint Electron Device Engineering Council (JEDEC) standards • Internally developed (proprietary) IP blocks for use in 3rd party EDA software platforms • Proprietary 3rd party IP blocks • Open-source IP blocks	**None** • All memory semiconductors are designed and produced within vertically integrated device manufacturers (IDMs)

In AP design, one complementor stands out: ARM Technologies, a UK-based company that provides reduced instruction set architecture (ISA) for mobile device processors that, among other things, helps AP designers reduce power consumption to increase battery life, a critical success factor for mobile handsets. As shown in the second row of Table 3, ARM has been able to achieve this, and to lock in users through powerful network effects, by sponsoring its own modular platform based on proprietary standards that define flow of data within the processor, how data are formatted, and how the processor interacts with other subsystems. ARM's platform significantly speeds time to market and

lowers the cost of chip design for AP designers (users). ARM's technology licenses range from fully functional systems-on-a-chip core designs to *ala carte* licenses that allow more customization.[16]

Application processor design, architecture, and manufacturing

The third row of Table 3 depicts the governance structures present in the chip manufacturing sub-ecosystem. Once the AP is designed, the circuit geometry (layout of what goes where inside the AP) is defined according to industry standards such as GDSII, process design kits, and hardware description languages (HDL) such as Verolog, industry standard software used to model electronic systems. These evolving standards, many of which emerged as proprietary standards, are now managed in the public domain by industry associations such as the IEEE. They enable modular linkages between semiconductor designs and manufacturing processes. Samsung uses internal semiconductor manufacturing divisions to produce a subset of the APs used in its mobile handsets, but the design process and adherence to industry standards is similar. Except for Samsung's Exynos AP, all APs are produced by "foundries" (essentially, contract manufacturers of semiconductors) mostly according to modular value chain governance, though a few "lead users," such as Apple and Qualcomm, have relational ties with foundries to produce cutting edge mobile handset APs.

Operating systems

The fourth row of Table 3 depicts governance in the OS sub-ecosystem. The function of an OS is to provide the interface with the handset user and signal the AP to coordinate subsystem functions. Apple and Google take different approaches to coordinating OS development. Android is the prevailing OS, present in about 80% of mobile handsets. Google's distributions (i.e., versions) of the Android OS are also based on a Linux kernel and co-evolve with ARM, but the company sponsors a modular platform sub-ecosystem to develop successive versions, while keeping tight control over final versions. This makes the ecosystem a hybrid: partially open-source and non-proprietary, and partially proprietary.[17] Complementors are invited to contribute code to upcoming versions of the

[16] ARM has four ways of licensing its technology: a "core license" which includes most of the AP's design, a "Built on ARM Cortex Technology license," which allows uses to modify cores, an "architectural license" with which users can design their own ARM-compatible processors, and a "flexible access license," which provides users with access to the full range of ARM technologies and tools *al la carte*. Some of these tools (such as debuggers, interconnect protocols, peripheral controllers, etc.) are provided by ARM, while others are from third party firms that take advantage of open access to ARM's protocols and interfaces to develop complementary services for users.

[17] AOSP contains the core source code (including an open-source Linux kernel, which itself was a hybrid of many ad hoc de facto software standards), along with open-source apps (e.g., maps, calendars, etc.), security and testing functions, extensive documentation, and a wide variety of design and development tools. AOSP drew from a creative and freewheeling open-source community to create a vast codebase and toolkit from which different versions ('skins') of Android could be customized and innovated upon by handset firms, subsystems companies and Google itself. Apple loosely couples successive versions of the iPhone and iOS, allowing older phones to run newer operating systems (to a point). However, Apple's design activities are not fully independent from the broader mobile handset MME. In fact, elements of the iOS kernel and other software components are based on free, open-source software.#, and both the A-series AP and iOS are based in important ways on ARM's reduced instruction set architecture (See

OS in very specific ways through the Android Open Source Platform (AOSP), but the company contributes its own code and retains control over which complementor contributions are accepted in the final distribution of each version, as depicted in the second and third column of the fourth row of Table 3. From its inception in 2008 through 2020, more than 10 million contributions of code were made to AOSP, with about three quarters apparently coming from engineers at companies other than Google (Thun et al. 2022: 30). However, not all users or complementors have the same relationship with Google. For example, less sophisticated phone system firms are granted access only to new, finalized versions of Android, while Google experiments on next-generation versions with a select group of sophisticated handset firms with which the company has developed closer relational ties, as shown in the fifth column of the fourth row of Table 3.[18]

Memory, display, and radio frequency modules

While only core memory is included in Table 3 in the interest of space (in the fifth row), we touch on the governance of the other two complex sub-ecosystems here as well. In contrast to the sub-ecosystems highlighted in this section so far, the design and production of core memory, and similarly, display modules, are always governed internally, within corporate hierarchies. The design tools and modular interface with manufacturing is similar to APs, but manufacturing is carried out within the corporate hierarchy to optimize production processes and resources. The design content of memory is low, relative to APs, mainly consisting of three dimensional grids and stacks of cells that can record data by changing their value to a 1 or 0. With displays, the tiny cells change color. With both subsystems, design content is relatively minimal. However, there is a premium placed on process excellence – to drive miniaturization in the context of high volume production. The lack of co-specialization in handset design commodifies these subsystems. However, even in this case "lead" buyers such as Apple are reported to have relational ties with key memory and display suppliers, including rival Samsung (Adamu 2024). The governance of the radio frequency module sub-ecosystem is primarily a mix of hierarchical and relational, in terms of both design and manufacturing, due to some extreme design and manufacturing challenges arising from embedding analog circuitry on exotic substrates (see Appendix 3 for more detail).

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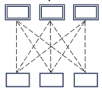
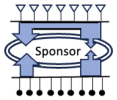
https://github.com/writeups/iOS/blob/master/About%20iOS/Mach_and_BSD.md. More broadly, see https://opensource.apple.com/).

[18] To allow handset-makers the flexibility to customize the look of Android while maintaining control and the integrity of the OS, Google requires that all devices be approved through Google's Android Compatibility Program. This process ensures that modifications to the OS do not result in a non-compatible "forked" variant that would splinter the ecosystem and undermine network effects. If handset companies are approved, they gain access to Google's proprietary apps and design IP that are not technically part of open-source versions Android, including Google Mobile Services, GooglePlay (the gateway to millions of third-party apps), and Google's proprietary apps (e.g., YouTube, GoogleMaps, Chrome) and other features (e.g., voice commands, GooglePay). This leverage allows Google to maintain coherence and uniformity across Android devices, as well as benefit by directing Android users onto Google's licensed apps and services (e.g., search), where Google earns revenue from advertising placement. In short, the Android sub-ecosystem controlled by Google combines contrary elements – a proprietary platform that is at the same time supported by multiple open-source communities and 3rd party complementors.

4.3 Retail level governance

Table 4 shows governance structures at the retail level of the mobile handset MME. The first row depicts how end users (buyers) can purchase phones from suppliers (in this case, retailers and resellers such as mobile service providers) over simple, arms-length, price-based market channels. As they choose, end users can judge the quality of phones through a set of industry-standard specifications and conventions having to do with sub-system performance metrics such application processor speed, display pixel density, battery life, and memory capacity. Like most of the retail sector, mobile handset retailing is extremely fragmented.

Table 4. Retail level governance: governance structures, actors and roles, and key standards

Sub-ecosystems by function	Prevailing governance structure	Actors and roles	Key industry standards	Alternative governance structures with examples
Mobile phones • Provides end users with access to mobile handsets and vice versa	**Markets** (symmetrical complementarity) Buyers  Suppliers	**Buyers:** • Smart phone end users (weak complementors) **Suppliers:** • Various on-line and physical store channels (weak complementors)	• Phone specification conventions used in retail settings • Retail pricing • Carrier plans that include phones, phone financing, or discounts	**None** • All end users obtain smart phones via simple markets
Application stores • Provides end users with access to applications and vice versa	**Modular Platforms** (asymmetrical complementarity) Platform users  Complementors	**Users:** • Smart phone end users (weak complementors) **Platform sponsors:** • GooglePlay and Apple App Stores (strong complementors) **Complementors:** • 3rd party developers of Android and iOS compatible apps (weak complementors)	• Non-proprietary APIs for open-source versions of Android • Proprietary APIs for Android and Apple iOS published by Google and Apple	**None** • End users currently have no viable alternatives to obtaining smart phone apps via Google and Apple app stores, although the European Union is trying to force Apple to allow alternative access pints for IOS compatible apps.

As shown in the second row of Table 4, app stores are modular platforms, sponsored by either Apple or Google, that connect handset users with applications that are produced by 3rd party app developers (complementors). The modular linkage between the platform and the complements is called an application programming interface (APIs), an extensive set of proprietary design rules set by the platform's sponsor.[19] Modular linkages also commonly exist between users and platform sponsors as well as users and app makers, for example for the collection of usage data or user-provided content.[20] In-app payments also flow between users and complementors over the platform.[21] The complementarity between the platform and app developers is asymmetric in both cases: the apps will not function without the platform, but the platform is not dependent on any single app or user.

[19] In this way, app developers retain their ability to innovate freely at the level of user experience and promote their app on the relevant on-line store, which represent huge potential user bases. App makers are required to abide by the platform's rules governing participation and pay the platform sponsor a share of revenue. It is possible to convert, or "port" an iOS app for use on an Android phone, but there is inevitably a loss of functionality and reliability relative to apps that are designed from the ground up to run on one or the other platform. Only the largest app makers have the internal resources to develop native apps for both platforms.

[20] Social media platforms such as Facebook, LinkedIn, and YouTube make much heavier use of user-created content than mobile handset apps, but the concept is the same.

[21] The division of revenue from these purchases has proven to be extremely controversial, triggering lawsuits between the platform sponsors and the most popular app developers.

5. Technology, market structure, and geographic outcomes in the mobile handset MME

How does variation in sub-ecosystem governance matter? In this section, we document the technology, market, and geographic outcomes of the mobile handset MME. Details about our data sources can be found in Appendix 1.

5.1 Technology

Table 5 shows that across all mobile handset subsystems, technological performance has grown rapidly. Processing speed increased nearly threefold between 2009 and 2020, supported by denser semiconductor circuitry and additional AP cores for multitasking.[22] In order to cache working data and speed processing, some volatile memory (DRAM) has been encapsulated in the AP. Encapsulation of one or more graphics processing (GPU) cores (for photo and video processing, now for AI), grew from only a quarter of handsets in the dataset to nearly all handsets over the period.[23] The capacity of core memory grew by an astonishing average rate of 39% per year, and display quality, camera capabilities, and battery life also improved dramatically.

There have also been regular additions of new functions and features, including WIFI for internet access, GPS for navigation, and nearfield wireless for mobile payment and other applications requiring secure proximate connectivity. To support multifarious wireless data formats and standards, handset designers need to pack in multiple antenna systems, all while filtering multiple radio signals to avoid interference. All of this performance and functional improvement has taken place with little change in the physical size of the handset.

The technical complexity of the OS has grown along with the increase in handset performance and functionality. iOS and Android have upwards of 12-15 million lines of code, making them some of the world's largest pieces of software (Fernández 2024), and the documentation for app developers is voluminous as well. To sum up, the technical challenges of mobile handset system and subsystem design and manufacturing are extreme and, in many cases, leads the way in the consumer electronics sector.

Growing technical complexity in mobile handsets has been accompanied by increasing scale. Between 2009 and 2015, by which time Android had become the dominant operating system along with iOS, sales of mobile handsets increased at a compound annual rate of 33.7%, peaking at 1.46 billion units shipped in 2016 (Thun et al, 2022).

[22] For example, the 2023 iPhone 15 Pro's A17 Bionic AP had 19 billion transistors, up from 8.5 billion in the AP powering the 2019 iPhone 11 series handset (Friedman, 2024).
[23] In general, encapsulating functions into the AP speeds processing, lowers costs, and shifts complexity and capability requirements from system-level design to sub-system design.

Table 5. Mobile handset performance and functional improvements by subsystem (2009 and 2020)

Subsystem	Measure	2009	2020	% Change	CAGR
Core subsystems					
Application processing					
- Clockspeed	Avg. MHz	615	2,406	291%	13%
- Processing cores	Avg. # of cores	1.0	7.9	686%	21%
- Cache memory	Avg. # gigabytes	0.2	6.8	3,114%	37%
- GPU	Phones w GPU	26%	99%	281%	13%
Core memory	Avg. # gigabytes	4.0	146.8	3,579%	39%
Display					
- Resolution	Avg. # pixels	189,686	2,478,871	1,207%	26%
- Pixel density	Avg. # of pixels per sq. inch	188	387	106%	7%
- Colors	Avg. # of colors supported	2,315,489	265,413,043	11,363%	54%
Radio frequency module					
- Frequency bands	Avg # of bands supported	5.2	25.7	393%	16%
- Cellular data links	Avg. # of links supported	6.9	19.0	177%	10%
Other important subsystems					
Other wireless functions					
- WIFI standards	Avg. # supported	2.1	5.2	150%	9%
- GPS	Avg. # of systems supported	1.8	4.8	162%	9%
- Nearfield communications	Share of phones	0%	62%	NA	NA
- Wireless charging	Share of phones	1%	24%	2,300%	33%
Camera					
- Video resolution	Avg. # pixels	237,492	10,997,856	4531%	42%
- Optical zoom	Avg zoom (x -times)	1.0	1.7	68%	5%
- Primary camera	Avg. # camera functions	1.4	14.9	964%	24%
- Secondary camera	Avg. # camera functions	2.0 (2013)	9.5	375%	22%
Battery					
- Capacity	Avg. watt-hours	4.7	17.0	262%	12%
- Talk time (2010-20)	Avg. hours	7.5	30.4	305%	15%

Note: Bluetooth wireless connectivity is not included in the "other wireless functions category because it was already ubiquitous prior to 2009.[24]
Source: Authors calculations using data from PhoneDB (https://phonedb.net/), a mobile phone specifications database. N=15,544 phone models

5.2 Market structure

As Table 6 shows, increasing modularity across the mobile handset MME correlates with significant changes in market structure. While these changes vary by sub-ecosystem, there has been a general drift toward higher market concentration, with the top firm in each sub-ecosystem capturing a higher market share with increased modularity.[25]

[24] Introduced in the early 2000s, Bluetooth began to see widespread adoption in mobile handsets by 2004 as the technology improved significantly with the release of Bluetooth 2.0, which introduced Enhanced Data Rate (EDR) capabilities. The Bluetooth Special Interest Group (SIG) was formed in 1998 to oversee the standard's development, licensing and trademarking. The SIG was originally composed of five companies — Ericsson, IBM, Nokia, Toshiba and Intel — but almost immediately grew to 400 members and had 30,000 member companies as of 2023 (Jaycon, 2023).

[25] The data in Table 6 should only be considered indicative since time series data is not generally available from consistent sources using robust methods. As the source references below the table show, data was collected from a variety of sources, most with opaque methodology and inconsistent or unknown denominator definitions (some share estimates are calculated from the top 5 of 10 firms, some from larger lists). Estimates for the four key subsystems (APs, core memory, displays, and RF modules) are derived from a dataset obtained from IHS Markit containing a complete list of components found in 456 handsets produced between 2006 and 2020 (average 38 reports per year). This dataset is biased toward higher priced handsets.

Table 6: Sub-ecosystem market and geographic outcomes correlated with rising modularity in mobile handset technical architecture

Sub-ecosystem	Prevailing system-level governance structure	Less modular technical architecture (2002-11)		More modular technical architecture (2017-23)	
		Top Firm mkt. shares	Top country mkt. shares	Top Firm mkt. shares	Top country mkt. shares
Handset level					
Computer aided design (2006 and 2020)	Modular platform	AutoDesk (US): 31% Dassault (FR): 21% Siemens (DE): 15%	US: 57% EU: 38%	AutoDesk (US): 55% Dassault (FR): 19%	US: 61% EU: 23%
Mobile handset shipments (2007-09 and 2017-19 averages)	Modular value chain	Nokia (EU): 47% Blackberry (CA):17% Apple (US):10% Other brands: 29%	EU:47% CA:17% US:10%	Samsung (KR): 25% OPPO (CN): 19% Apple (US): 17% Huawei (CN: 17% Other brands: 40%	Top 3 CN: 35% KR: 25% US: 17%
Contract manufacturing (2002 and 2018)	Modular value chain	Flextronics (US): 20% Solectron (US): 18% SanminaSCI (US): 15%	US: 58% TW: 30% CA: 12%	Foxconn (TW): 46% Pegatron (TW): 12% Quanta (TW): 9%	TW: 90% US: 10%
Subsystem level					
Operating system (2009 and 2017-2020 average)	Modular platform	Symbian (FL): 36% Apple iOS (US): 35% Blackberry (CA): 7%	EU: 36% US: 35% CA: 7%)	Android (US): 74% Apple iOS (US): 24% Windows (US): .4%	US: 98.4%
Application processor (2004-07 and 2017-22 averages)	Modular platform	Qualcomm (US): 27% Texas Inst. (US): 20% Motorola (US): 8%	US: 55%	Qualcomm (US): 67% Huawei (CN): 15% Samsung (KR): 9%	US: 67% CN: 15% KR: 9%
- Electronic design automation (EDA) software (2005 and 2021)	Modular platform	Cadence (US): 34% Synopsys (US): 26% Mentor (US):18%	US: 78%	Synopsys (US): 42% Cadence (US): 32% Mentor* (US*): 18%	US: 92%
- Instruction set architecture (2011 and 2023)	Modular platform	ARM (UK): 92%	UK: 92%	ARM (UK): 99%	UK: 99%
- IC manufacturing (2004-07 and 2016/2022 averages)	Modular value chain	TSMC (TW): 48% UMC (TW): 19% Chartered (SG): 7%	TW: 71% KR: 9%	TSMC (TW): 58% Samsung (KR) 13% Global Foundries (US): 8%	TW: 69% KR: 13% US: 8% CN: 8%
Core memory module (2004-07 and 2017-20 averages)	Hierarchy	Samsung (KR): 30% Intel (US): 28% AMD (US): 7% STMicro (DE): 7%	US: 35% KR: 30% EU: 7%	Samsung (KR): 73% SK Hynix (KR): 14% Micron (US): 6%	KR: 87% US: 6%
Display module 2004-07 and 2017-20 averages)	Hierarchy	Samsung (KR): 33% Wintek (TW): 14% ATI (CN): 13%	KR: 33% TW: 14% CN: 13%	Samsung (KR): 73% Japan Disp. (JP): 8% LG (KR): 8%	KR: 81% JP: 8%
Radio frequency module 2004-07 and 2017-20 averages)	Hierarchy	RF Micro (US): 12% Skyworks (US): 11% Murata (JP): 7% Qualcomm (US): 7%	US: 30% JP: 7%	Qualcomm (US): 39% Skyworks (US): 11% Qorvo (US): 11%	US: 61%
Retail level					
Phone retail outlets	Market	Fragmented	Everywhere	Fragmented	Everywhere
App distribution platform revenue (2023)	Modular platform	Nascent and fragmented	Small scale	AppStore (US): 67% GooglePlay (US): 23%	US: 100%

Notes: * Mentor Graphics was acquired by Siemens of Germany in 2016, but the subsidiary is still mainly headquartered in Wilsonville, Oregon, USA, (south of Portland).
Sources: CAD-CAM software 2006: Jon Peddie Research; Autodesk 2024:. Phone System: Gartner (2004-07), IDC (2017-20) via Statista. Contract Manufacturers 2002, Sturgeon and Lee (2005), 2018, In4ma, 2019,. AP, core memory, display, and FR module subsystems: IHS Markit Teardowns. ISA, Fitzpatrick, J. (2011). ARM 2009, Yarrow (2010), "An interview with Steve Furber." Communications of the ACM, 54(5), 34-39 (2011); ARM IPO Prospectus F-1 (2023). OS: StatCounter, from Statista. EDA Design Software, EDACafe ; IC Manufacturing: 2005, IC Insights, and 2022, TrendForce: IC Insights ad Gartner from Statista. App distribution platforms 2023, Bigabid.

In EDA software, three other West Coast firms have long dominated, Cadence, Synopsis, and Mentor Graphics[26], with Synopsys taking over the top spot from Cadence in the latter period to gain a 42% market share in 2021. Within APs, the ARM instruction set architecture is essentially a monopoly in mobile handsets. The company's market share in mobile handsets increased from 92% in 2011 to 99% in 2021.[27] At the retail level, the distribution of mobile apps (outside of China) was a duopoly between Apple and Google, with Apple's App Store accounting for 67% of revenues and GooglePlay accounting for 23% in 2023.

Not included in Table 6 is the market and geographic structure of platform complements, which, because of clear rules for participation and low barriers to entry, tend to be highly fragmented. However, the number of platform complementors, and their geographic dispersal, while generally greater than in other parts of the mobile handset MME, appears to vary by the size of the user pool and level of competency required. According to Thun et al. (Thun et al. 2022: 21 and 30) the number of mobile apps peaked in 2017 at 1.3 million, with countries with large user populations accounting for a significant share of releases (China accounted for 16%, India for 5%, and Brazil for 3% in 2017). By contrast, the number and locations of complementors for more technically demanding contributions to platforms appear to be more constrained. According to company documents, Qualcomm's invitation-only Qualcomm Advantage Network includes just 453 members of which 112 firms offer about 600 complementary hardware, software and services products optimized for specific Qualcomm chipsets. Similarly, in 2023, only 175 firms were listed in company documents as being approved in ARM's Partner Ecosystem, with another thousand offering complementary products, some of which compete with aspects of ARM IP. Of the more than 10 million contributions of code made to Google's AOSP between 2008 and 2020, 55% came from email addresses associated with U.S.-based companies, with 23% coming from Google itself (Thun et al. 2022: 30).

In subsystems where hierarchical governance prevails – core memory, displays, and RF modules – there is also a high level of market concentration. Samsung increased its share of core memory and displays found in the teardown dataset referenced in the table from 30% and 33% in the earlier period to 73% for both in the later period. RF modules also show increased concentration, with the top firm controlling 12% share in the teardown dataset in the earlier period and a 39% in the later period, and Qualcomm moved into the top position based on its decade-long struggle to offer a complete RF-AP solution (see

[26] Mentor Graphics was purchased by Germany's Siemens in 2017 and renamed Siemens EDA.

[27] By licensing its IP at relatively low prices and entering the mobile computing market early on the company gained a monopoly on AP architecture for mobile phones as early as 2005 (Krazit, 2006). With a 99% market share in mobile AP instruction sets, and high shares in industrial networks (IoT), automotive, and consumer electronics processors, the company claims that 15 million engineers trained to use its platform, and that more than one thousand 3rd party complementors providing tools and services, with 175 admitted to the company's more relational "Partner Ecosystem." By licensing its IP at relatively low prices and entering the mobile computing market early on the company gained a monopoly on AP architecture for mobile phones as early as 2005 (Krazit, 2006).

Appendix 3 for details). IC contract manufacturing (foundries) also show increasing concentration, with TSMC's market share growing from 48% on average in the 2004-2007 period to 58% when shares in 2016 and 2022 were averaged.

The most prominent exception to the trend towards greater concentration is mobile handsets at the system level, where modular governance led to a divergence of outcomes according to segment. The early market leader (Nokia) held a 47% market share on average in the 2007-2009 period, but disappeared from the market in the mid-2010s, replaced by a few dominant firms at the high end (Apple, Samsung, and Huawei), while in more price sensitive segments, modular governance allowed firms with lower capabilities (led by China-based Oppo, Vivo, Xiaomi, and Lenovo, but also including scores of small and private label brands) to enter the market, driving the "other brands" category from 29% of the market in 2007-2009 on average, to 40% in the 2017-2019 period. However, these figures may vastly understate the fragmentation of the mobile handset market. One on-line database of handsets lists no fewer than 5,166 handset brands worldwide.[28]

Of course, the highest degree of fragmentation in Table 6 is seen in the subsystem organized by markets – the final sale of mobile handsets to consumers.

5.3 Geography

The right-hand columns in each of the two periods shown in Table 6 depict the geographic outcomes in the mobile handset MME. These data use the headquarters to denote location. While global firms locate their operations in many countries, and this has important operational and policy implications, the location of the primary strategic headquarters determines the nature of political and regulatory vulnerabilities, which will be a topic covered in the subsequent discussion section.

Given the high market concentration of the largest firms in most sub-ecosystems, geographic concentration is partly a function of their global dominance. However, due to agglomeration forces, it is often the case that top firms in a given ecosystem are headquartered in the same country, leading to higher geographic concentration than market concentration. The table also shows a remarkable degree of stability over time in terms of country dominance, and a marked increase in geographic concentration (from an already high base), especially in sub-ecosystems governed by modular platforms and hierarchies. Thus, platform sponsors may jockey for position, but country dominance changes only rarely.

However, changes over time in the geographic center of gravity for sub-ecosystems can occur, as illustrated in memory, handsets and contract manufacturing, where ownership consolidates in one country over time as laggard countries and regions fade in importance or drop out entirely.

[28] https://deviceatlas.com/device-data/devices

6. Discussion

In this section we discuss the theoretical, strategic, and public policy implications of our work.

6.1 Implications for theory and research design

As we explain in Section 2, the concept of modularity plays a key role in both the GVC and business ecosystem literatures, but the emphasis differs and each approach has strengths and shortcomings. GVC governance theory approach highlights the *variety* of governance structures linking activities across various geographies — hierarchical, captive, relational, modular, market — but its conception of modular governance lacks the broader view of modularity that emerges when asymmetric complementarity[29] is taken into account. As a result, GVC governance theory cannot account for modular platforms.[30]

For example, a handset firm's relationship with a contract manufacturer and a platform sponsor's relationship with app developers may both be based on modular linkages according to GVC governance theory – given high complexity, codifiability, and capabilities relative to requirements – and each actor will contribute a complementary function or set of functions, the nature of complementarity is different. When lead firms source from contract manufacturers, complementarity is symmetrical in that each is dependent on the other to fulfill the specific value proposition: the lead firm will contribute the product's design, and the contractor will manufacture it. By contrast, an app store platform sponsor and an app developer also perform complementary roles, but complementarity is asymmetric in that the app developer is dependent on the platform to create something of value for the end user, but not the reverse. The failure of one app developer will not affect the success of the platform nor of other app developers.[31] As indicated by our framework (Figure 2), modular platforms have looser ties (requiring less explicit coordination), lowering entry barriers for complementary actors and therefore allowing a larger number to participate.

While the ecosystem literature provides the language of complementarity needed to expand the concept of modularity, it has two weaknesses. First, the ecosystem literature fails to seriously engage the range of coordination forms present in complex industries.

[29] However, complementarity is a very general concept. Joint contributions to a value proposition are made when two or more autonomous actors align their activities, however they are governed. However, the business ecosystem literature makes useful distinctions between the strength and symmetry of these complementary contributions, and we have built these into our conceptual framework.

[30] While the focus on value chain modularity may have been appropriate when the GVC governance framework was being developed in the early 2000s, the digital revolution has continued apace, increasing the potential for codifiability in complex industries, therefore expanding the possibilities for modular governance to encompass a wider range of activities and business models.

[31] Asset specificity (co-specialization) is a key indicator of complementarity. While Gereffi et al. (2005) acknowledge the importance of asset specificity in shaping governance choices, their focus is on how different forms of governance can deal with the problems created by co-specialization rather than how the form of asset specificity itself may vary. Theories of complementarity in the management literature focus on variability in asset specificity.

The fact that modular value chains, hierarchical and captive governance, relational ties and even markets all remain present and viable options for actors in complex industries is barely present in the analysis. Baldwin (2020) points to multiple forms of ecosystem coordination, including hierarchical governance and relational ties, but as the ecosystem literature has converged with the platform literature, the dominant focus is on modular platform governance and the strategic opportunities and challenges it creates. Baldwin et al. (2024: 2) even include modular governance as a necessary criteria for ecosystems, as do Jacobides et al. (2018).[32] While modular platforms are an appropriate focus, since they are a relatively novel and an increasingly prevalent – and even dominant – characteristic within economically and socially important business ecosystems in the digital age, companies commonly exercise a range of governance choices for different inputs, with different partners, for various time periods, either for pragmatic or strategic reasons. Even in industries where modularity prevails, firms will choose to simultaneously or sequentially internalize some business functions, tightly control supplier operations with captive ties, collaborate with strategic partners via relational linkages, all while purchasing a range of inputs through simple markets. However, in such industries these choices are shaped, and often constrained, by prior actions and the modular governance structures that prevail. While modularity is not the only governance structure that can be observed in an MME, non-modular governance options are often exercised within a sea of modular linkages. In complex industries, it is usually unfeasible to even contemplate building new ecosystems divorced from a modular backbone that has co-evolved over many decades. It can become impossible to introduce even radical innovations without compliance with key prevailing standards.

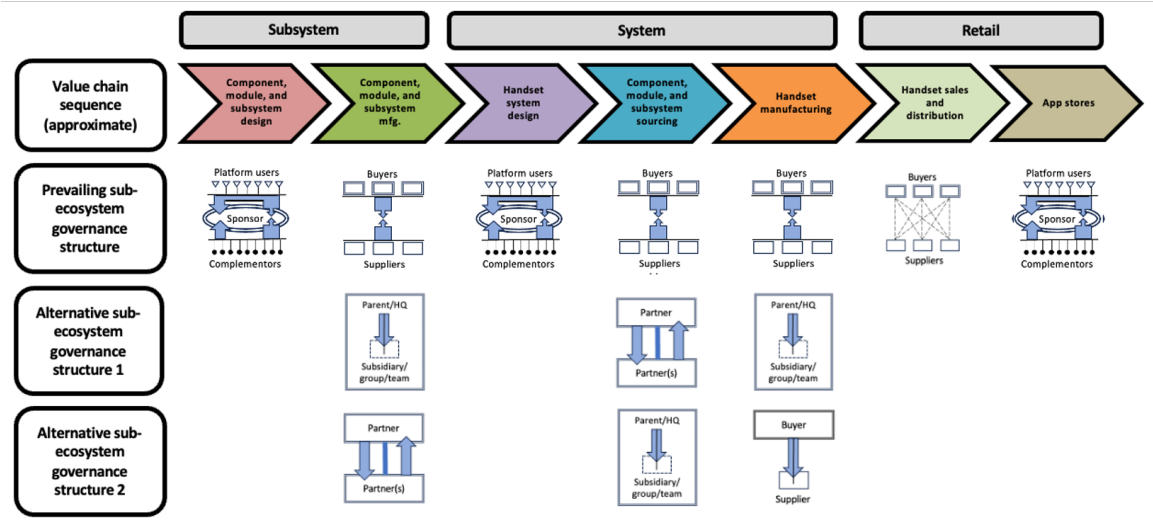
Second, in seeking to highlight the role of complementarity, and to demonstrate how modular platforms, in particular, are different from linear value chains, or "pipelines", the literature on business ecosystems makes scant use of the analytical heft offered by the concept of value added chains (see for example, Van Alstyne et al, 2016). Vertical, hierarchical, and nested patterns across multiple distinct ecosystems are obviously present even in complex industries characterized by "two-, or multi-sided" platforms, since platform ecosystems can provide specific intermediate functions that need to be linked in a rough sequence to arrive at a final product. In our case study, ecosystem nesting abounds, for example in the case of ARM's instruction set architecture and its complementors, an in the EDA platforms and their vast libraries of complementary design elements. To help make this point, Figure 3 reintroduces the governance structures present in the mobile handset MME, as detailed in Section 4, according to a stylized value chain, showing the prevailing and alternative governance forms for each stage.[33]

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[32] Jacobides et al. (2018: 2260) state, "modularity…creates the conditions for an ecosystem to emerge" because it allows for coordination between interrelated actors that have significant autonomy.

[33] As is typically the case, the value chain sequence shown in value chain mapping diagrams such as Figure 3 is only an approximation. For example, some component, module, and subsystem design may take place *after* system design, not before, as when handset designers provide specifications for customized items. The Figure may be especially useful as a first approximation for researchers comfortable with value chain logic. An additional tool for GVC researchers, a stylized decision tree for predicting governance forms in an MME, is provided in Appendix 4.

Figure 3. The mobile handset MME as a value chain, with prevailing and alternative governance forms



The inclusivity of our approach raises the important issue of boundary conditions. What is included and excluded in our definition of a business ecosystem, how are they linked together, and for what purposes? We have already pointed out that there is some disagreement in the literature on the boundaries of business ecosystems, and that we have an expansive view that includes all six governance structures in our framework. This roughly concords with the relatively loose boundary conditions for ecosystems as developed by Adner (2017) and others, most concisely stated by Baldwin et al. (2024) as: "a network of autonomous economic actors interacting to create value" (p.1). This loose definition allows us to avoid some of the strictures placed on the concept as follows.

First, we do not believe that ecosystems must include modular governance, as Baldwin et al. (2024) do. The alignment of activities and interests between Toyota and its bevy of affiliated suppliers in Japan is not primarily accomplished through modular linkages, since most have been described as being captive, relational, or somewhere in between. Nevertheless, it is hard to conceive of Toyota's production network as anything but a distinct ecosystem consisting autonomous economic actors interacting to create value. The interface standards that enable modular governance can emerge from non-modular activities and actors, for example as internal processes based on proprietary standards become codified and migrate out to become either proprietary or nonproprietary industry standards (Sturgeon 2021; Baldwin et al. 2024), or be intentionally developed by government policy (Kuan and West 2024), but this does not mean that other forms of governance disappear from the broader ecosystem. Firms routinely internalize specific business functions or processes to advance their strategic goals around specific "kernals" of IP, and develop relational ties within or across sub-ecosystems to foster cutting edge innovation or competing platforms. But in an ecosystem where modularity prevails, these discrete kernels and innovations can only offer a value proposition to end users if they are deployed in the context of modular complements.

Second, generic inputs are almost always needed to achieve a specific value proposition, and while they might be easy to substitute for in theory, they may be hard to come by in

practice, for example when geographically concentrated sources of supply are interrupted by *force majeure* events or the intervention of trade or industrial policies.

There is broader agreement that the purpose of ecosystems is to coordinate complementary contributions that generate a focal value proposition in the form of a product or service. However, some clarification is needed in regard to the unit of analysis. As we discussed in Section 3, our goal is to examine contributions across ecosystem layers, which requires value propositions to be defined at the level of industries (classes of related products and services that share common actors, technologies, standards, and end uses). For example, the purpose of the mobile handset MME is to coordinate the value proposition of mobile handsets in general, not for a specific model. We include only sub-ecosystems that make contributions that are embodied in, or co-specialized with, the products within an industry.[34] However, shared standards and actors mean that linkages in an MME can extend to the sector level and even across sectors, as evidenced, for example, by growing electronic content across the transportation sector, which come with established and emergent modular value chain and platform governance structures.[35]

We believe that centering the analysis of ecosystems on a specific value proposition led by a focal, or lead firm creates a myopia that obfuscates the presence of megastructures such as MMEs. Many of the actors in ecosystems (lead firm buyers, suppliers, complementors, and non-proprietary standard setting organizations) work on multiple value propositions at the same time, both within and across what we have historically defined as industries. In an MME, specific sub-ecosystems are not only focused on a specific value proposition (a product or service delivered to end users); their focus is on a specific technical function. A sub-ecosystem may have many or very few focal firms. Suppliers to these focal firms are most often shared across focal firms within their sub-ecosystem.

Given increasing complexity in the organization of industries and the rise of novel forms of coordination, scholars of industrial organization have felt the need to scale their unit of analysis up from the level of firms and vertically structured industries to the level of

[34] The inclusion of co-specialized contributions raises the question of why we have not included mobile communications infrastructure in our analysis of the mobile handset MME. Like many of the sub-ecosystems included (e.g., memory, displays, semiconductor foundries, and ARM's instruction set architecture), mobile infrastructure contributes value to many products in many industries ("internet of things" devices, for example). While mobile telecom equipment is not embodied in mobile handsets, it is co-specialized with radio frequency modules via standards promulgated by the 3GPP consortium, and includes semiconductors made by many of the same suppliers to mobile handset firms. We can only say that infrastructure has been omitted, along with countless other standards-based inputs (e.g., digital imaging modules, AI cores, etc.) in the interest of space and simplicity. A full map of the mobile handset MME would, in fact, reach deep into the architecture of the information and communications technology (ICT) sector.

[35] Adner (2017) uses the concept of value proposition to demarcate the boundaries of a system. It is worth noting that unlike Jacobides et al. we include generic complements and market linkages in our definition of an MME (i.e. those that can be governed by market relations) because while these might be generic from a technical perspective, they may be unique from a geographic perspective, or become so with shifts in industrial, trade, or national security policies, a topic we will return to in the paper's conclusion.

ecosystems. We applaud this work, but seek to increase the level of analysis further: to socio-economic *megastructures* composed of many interlinked ecosystems.

6.2 Technology: innovation with complexity and scale

Complexity and scale are characteristics that are usually in tension with each other. Production in very large numbers is often limited to relatively simple and standardized products while extremely complex products such as subway systems and aircraft carriers require more customization and small-batch production (Hobday 1998). Complex systems are necessarily structured in a set of layered and overlapping systems, subsystems, and key components, and the challenge of innovation is distributed across subsystem suppliers that are able to innovate and operate with a measure of independence (Simon 1962, Tushman and Murmann 1998, Murmann and Frenken 2006). Because the range of capabilities required are vast and often interdependent, and the level of specialized knowledge that is required to perform each task is deep, industries producing complex systems typically feature "systems integrators" to oversee the design of the overall system and coordinate the activities of specialized suppliers (Prencipe et al. 2003, Brusoni 2005). Complex products can be very innovative, but without modularity, they are difficult to produce at scale. In an MME, design and coordination tasks are simplified by codification embedded in standardized technical and organizational interfaces between subsystems, tasks, and firms.

The mobile handset MME is very innovative, as suggested by Table 5, but in keeping with the literature on modular ecosystems, innovation has several sources and characteristics. First, modularity allows innovation to be distributed across subsystems, and because actors in each sub-ecosystem has to be deeply knowledgeable about their own domain (and the codified interface) but only loosely knowledgeable of others (Baldwin and Clark 2000, Baldwin 2020), they do not have to be overly concerned about interdependencies between modules. This not only allows the MME to scale, but specialization allows for the subsystem-specific investments in physical and human resources that help to drive innovation at the subsystem level.

Second, because governance can include modular platforms with optional complements, MMEs are highly resilient. New functions can be added (and removed) in response to changes on both the demand- and the supply-side–often at great scale (e.g. the hundreds of thousands of complements to the app store referred to in Table 4) without severely impacting or putting at risk the other elements of the system (Sanchez and Mahoney 1996). An example of modular scaling in a platform sub-ecosystem is mobile apps. From 2009, the year after the Android OS was introduced through 2017, the number of compatible apps available on GooglePlay increased at an average rate of 96% per year (Thun et al, 2023). However, modularity is often combined with other forms of governance – hierarchical, captive, and relational – often used to speed novel features and functions to make and pursue cutting edge innovation. Apple, for instance, has often brought in-house sub-systems that it deems to be sources of core competitive advantage (e.g. design of APs) and has deeply relational ties with key subsystem providers (e.g. chip fabricators such as TSMC). Relational linkages are in fact common *across* sub-ecosystems, for example between leading EDA firms, semiconductor equipment firms, and semiconductor foundries (Kuan and West 2024). Since none of these firms provide

inputs that are prima facie co-specialized with any handset or handset brands (final systems), innovations can "travel" across the MME (Ponte and Sturgeon 2013). At the same time, we have to refer back to Baldwin's (2020) balance point in ecosystems between interdependence and independence. With too much interdependence, not only between specific actors but across the broader MME, products can become overly derivative and innovation can stall. By introducing non-modular governance forms into an MME, which by definition is governed primarily by modularity, the balance can be kept and innovation can proceed apace.

6.3 Market structure: ecosystem governance and barriers to entry

The data presented in Section 5 shows a complex mix of concentration and fragmentation. Most of the subsystems are oligopolies that are dominated by a few powerful firms, but because these firms are quite specialized, none of them is able to extend their dominance across the entire MME. The choice of governance form, both within subsystems and between subsystems, plays an important role in shaping the market power of firms.

As Table 6 showed, the general pattern is for markets at the system level to be fragmented, because modularity lowers barriers to entry at the low end of the market, but concentrated at the subsystem level for various non-exclusive reasons, including high capability and capital spending requirements, lock-in from network effects on successful platforms, tight control over important IP via legal means, and/or regulations that favor specific firms from specific jurisdictions. In subsystems governed by modular platforms, Table 6 shows the rates of concentration (e.g. the OS, app processors, and app distribution platforms). Network effects are accentuated when a user must invest in highly specific skills in order to use a complement, and hence is reluctant to switch, (e.g., Android and ARM design tools) and when a need for backward compatibility creates path dependence (e.g., ARM's ISA, 3GPP's telecom interconnect standards, Gerber and GDSII circuit layout standards). While the platforms are concentrated, the market for complements is typically highly fragmented. This is because of the defining feature of modular platforms: asymmetric complementarity with clear design rules for complementors; in these cases entry barriers are low for any complementor with enough competence to learn the rules and act upon them.

In subsystems in which hierarchy is the dominant form of governance, the barriers to entry are usually created by huge and ongoing capital requirements and demanding process technologies. As has been explained in Section 4.2, memory modules require huge capital expenditures and have extreme requirements for precision in manufacturing. Displays, while not hugely complex from a circuit design point of view, are also very technically exacting and capital-intensive to produce, and the small size and rising functionality of mobile handsets created a demand for very high-quality displays that could only be produced by industry leaders such as Samsung and Japan Display.

Perhaps less obvious are the cases where the pattern of concentration and fragmentation is shaped by the interaction between actors residing in different parts of the MME. High concentration may not be the result of an individual firm's core capabilities or powerful network effects within a subsystem, but rather how a firm leverages relationships with

firms in adjacent subsystems. In some cases, deep relational ties can create a "club" of firms able to resist the participation of new entrants. TSMC, for example, has strong core capabilities and maintains an enormous rate of capital investment, but also works very closely with the leading players in adjacent subsystems (e.g. EDA software, ARM, key equipment suppliers such as ASML). Because a firm can maintain only so many deep relational linkages, this web of ties within the MME can support only limited membership. Multilateral relational ties of this sort involve the cutting edge of innovation.

In a similar manner, captive ties may allow a dominant supplier to "ride the coattails" of a powerful buyer. In contract manufacturing, standard interfaces and the rise of (global) modular value chains in the 1990s (Sturgeon 2002) eventually led to the entry of a large number of East Asia-based firms and increasing fragmentation until Foxconn's nearly exclusive, captive relationship with Apple allowed it to establish a dominant position. While Foxconn had strong internal capabilities from the start, and these capabilities made it a viable partner for Apple, the firm's 46% global market share in 2018 was based almost entirely on the success of the iPhone. The crucial barrier to competition was the captive linkage rather than internal capabilities alone.

6.4 Bringing geography in

The importance of geography is underemphasized in the business ecosystem literature. The dominant conception of modular ecosystems in the technology management and innovation literature is that they consist purely of information flows, and with this comes the implicit – and mistaken -– assumption that interfirm information can be transferred unimpeded by factors external to firm decisions, such as international trade frictions or geopolitical rivalry. While disregarding the enabling and limiting roles played by nation-states in the development of business ecosystems may have been a reasonable analytical choice in an earlier era, barriers to trade and investment have risen quite suddenly as governments have been willing to aggressively deploy national security and industrial policies to incentivize domestic production and innovation, block perceived bad actors' access to crucial inputs, and exclude specific companies from "critical" infrastructure such as telecom, high performance computing, and data services.

The geography of an MME, and the interdependencies that are inherent in the system, create an unavoidable tension: the clusters that are crucial for the critical activities and key subsystems within an MME are by definition spatial units that reside within the jurisdictions of nation-states, but even the most dominant nations within the MME will find that not all the required clusters are within their own borders. Geography must thus be a central concern for both firms and nation-states because both can suddenly find themselves cut off from crucial markets, inputs, and arenas for collaboration.

From the perspective of nation-states, the tension that results from participating in an MME creates several key policy challenges. The first is the problem of replication or substitution. The scale and complexity of MMEs means that any country or firm that seeks to control or capture an entire complex, geographically distributed industry within its borders is likely to fail. Self-sufficiency would require extraordinary levels of capability development and capital investment and likely entail significant additional

costs from efficiency losses (SIA and BCG report). The capital and knowledge resources in an MME simply outstrip what can be expected to reside in any one country. Furthermore, the specificity of industrial clusters means that the capabilities in place-specific sub-ecosystems emerge only after long periods of time, and are therefore difficult to replicate, especially over the short term. Indeed, the market concentration discussed in the previous section and demonstrated is accentuated when viewed according to the geography of ownership, as suggested by the difference between the top firm market share and the top country market shares in Table 6. Because excellence in any specific technological or operational aspect of a sub-ecosystem tends to be geographically and historically rooted, reinforced by specialized labor markets, infrastructure, supporting firms, and institutions, the dominant firms responsible for key subsystems are typically concentrated in specific countries and specialized industrial clusters that are difficult to replicate or substitute (Scott 1988, Storper 1995, Saxenian 1996, Thun 2006). However, similar to market structure, geographic specializations exist across the broad MME, making even the most dominant industrial clusters highly dependent on clusters elsewhere. In addition, the voluntary private-sector standard-setting processes that underpin much of the MME are typically global in scope. Contributors to consortia, industry associations, formal standard-setting organizations, and open-source communities hail from the world over. Because of low barriers to entry, complementors to proprietary modular platforms also hail from diverse locations.

The second is the problem of innovation. Withdrawing from the distributed and specialized capabilities that buoy innovation in an MME will almost certainly result in products and services that are several generations behind the frontier, not least because of the time it would take to build up anything close to a self-sufficient industry. If national firms become isolated from MMEs, they risk being partitioned away from the intricate dance of innovation that takes place independently in each node, and then connected up via modular linkages to create extraordinarily complex and highly functional products and services such as mobile handsets. Even more profoundly, the entire sectoral innovation system could be disrupted and degraded if key actors and institutions are excluded or choose to withdraw.

The third is the problem of unpredictable and rapid change. The immense geographic and functional complexity of MMEs – as compared to more discrete structures in the global economy such as MNEs and GVCs – means that supply disruptions can arise suddenly and from surprising places and ripple more broadly across industries, triggered by strategic trade prohibitions and other geopolitical or environmental shocks. Additional challenges can also originate from the encapsulation of functions by adjacent sub-systems, which may or may not have a geographical dimension. If a dominant firm successfully incorporates functionality (encapsulates) controlled by one or a few adjacent, downstream, or upstream players in its own products, markets can disappear with breathtaking rapidity, as we have seen with the rise of Google's Android OS and the incorporation of graphic processing and various wireless functions into highly integrated APs. Furthermore, even complete dominance in a subsystem is always precarious, as new ecosystems can be built on top of an MME, well-evidenced by the sudden threat of AI to Google's 95% global search dominance. Policymakers may find it difficult to react with the required wisdom and speed, since the outcomes of these competitive battles can

only be observed in hindsight. Even if states opt for a more targeted approach, focusing on a few "strategic nodes," "chokepoints," or "bottlenecks," the multi-layered character of MMEs, rife with inter-dependencies, means that policymakers will be hard pressed to know where, exactly, to focus their attention.

Given the intense policy focus on resolving the political tensions (geo- and otherwise) arising from MMEs, analysis of the geographic and ownership features of MMEs in a range of "critical" industries is urgently needed. Will the shift to an outcomes-based global system lead to a decline, fragmentation, or re-alignment of MMEs, or will the dispersed yet concentrated organizational and geographic structures we see today prove to be more durable? It is too early to tell, but in any case, industrial and national security policymakers will need to grapple with the entirety of MMEs to avoid the unintended consequences that might come from narrow interventions based on incomplete conceptions of how complex global industries function (Gereffi et al. 2021). Industrial and trade policy solutions – import substitution, re-shoring, near-shoring, or friend-shoring – ignore the reality of MMEs at their peril.

Summary conclusion

Our central observation is this: when modularity (in both value chains and platforms) is the prevailing form of governance in an industry, distinct ecosystems and sub-ecosystem will coevolve into a complex, layered socioeconomic megastructure that we are calling a *massive modular ecosystem* (MME). In this way, we expand the definition of an ecosystem from an organizational structure composed of partially independent and autonomous *actors* that interact in complementary ways to create *something* of value,[36] to an organizational structure composed of *ecosystems and sub-ecosystems* that are complementary in that their interaction creates additional value in *classes of related products and services*. An MME is, therefore, an ecosystem of ecosystems where modularity and the standards that underpin it play a key role in aligning the interests of actors within and across sub-ecosystems. Each sub-ecosystem is based on a multiplicity of evolving standards, some industry-specific and some shared across sectors.

In sum, our conceptual framework specifies the full range of governance options and invites analysis of nested and layered ecosystems in complex global industries. Our intent is to provide a framework that will allow researchers, policymakers, civil society actors, and managers to map these structures as a first step in crafting more effective and nuanced strategy, policy, and social action. MMEs are important because, as Holgresson et al. (2022: 6) observe, digitization is driving the organizational forms and business

[36] This definition draws on elements of Baldwin's (2020) definition of a business ecosystem: ("a group of autonomous firms and individuals whose actions, decisions, and investments are complementary in the sense that their value as a system is greater than the sum of the values of the separate parts";) and Adner's (2017) definition of an ecosystem: "the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize"). Our contribution is to pull back the lens to include a view of how distinct sub-ecosystems can be aligned within and across ecosystems, industries, sectors, and geographies.

models born in the information and communications technology (ICT) sector across broad swaths of the global economy.[37]

In this paper we have defined the mobile handset MME as an important socioeconomic megastructure. Our hope is that our framework will be tested and refined through comparative research on ecosystem and value chain governance in additional complex global industries. An MME is likely to be only one type of economic megastructure, and it is our expectation that future research will reveal others.

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[37] Holgresson et al. 2022: 12, citing Moore 2006, also "locate the origins" of modular ecosystems in standards and managerial practices from in the computer industry

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Appendix 1 – Data sources

The IHS Markit product portfolio includes assessments of all electronic, electro-mechanical and mechanical components inside each mobile device, i.e. the teardowns. IHS purposively samples for flagship brands or product families (for e.g., Apple iPhones) as well as handsets produced by new or market gaining manufacturers, and handsets requested by clients. This data includes the BOM and a pricing model developed by IHS industry experts used to calculate component unit costs as well as the total manufacturing costs (hand assembly, auto insertion, test costs) of each device. Components are categorized by function (e.g. analog baseband, apps processing, battery and power management, etc.), by which sub-assembly it appears (e.g. printed circuit board, camera module, display module), and by component family and type (accessory, assembly, battery, electro-mechanical component, acoustics, etc). For each component, IHS reports the dimensions of the the package and - whenever possible - the name of component vendor. On average, vendor information is available for 21% of the components in each model, including all but a few makers of higher-value components. The list of 1108 unique vendors was enriched with the country of vendor headquarters and - when relevant - the headquarters country of the parent company. To truly capture the time dimension and evolution of manufacturer-supplier relationships, a better understanding of joint ventures and of mergers and acquisitions over time is needed.

PhoneDB is an online data source that contains information on individual phone model specifications and contains 15,544 phone models with information on the (approximate, since price can vary by geography and time of sale) retail price, release date of the model, network technology and many other features not exploited in the current analysis. We were able to match 516 devices in the IHS teardown dataset to this data set.

The Android Open-Source Project contains every open-source commit (software contribution) submitted and approved to be included into AOSP, which serves as the foundation of the Android operating system. Our dataset includes important metadata on every commit (e.g. commit date, email and organization of contributor, Android release) and the 'location' of the commit within the nested folders of AOSP, which indicates the purpose of the commit. Additional information also indicates some details about the substance of the commit itself. Our dataset included 11,432,275 commits, mostly from 2008 to 2020, of which we were able to identify the headquarter firm for 86% of the commits.

3GPP is the primary standard-setting organization for the creation and finalization of technical specifications for the mobile telecommunications industry. After finalization, technical specifications are turned into formal standards by the major telecom business associations in China, Europe, India, Japan, Republic of Korea and North America. For transparency, 3GPP publishes a wide range of information on conference meetings, personnel, and each stage of development of the specification, from initial proposal to final publication, including the individuals and organizations involved. Our dataset contained 16,189 work items between 2001 and 2020, which contributed to the finalization of nearly 2,500 3GPP technical specifications.

Thus, the descriptive statistics presented in this paper cover a wide range of phone models. A dataset complete with all collected variables is available for a subset of 602 models released between 2002 and 2020. This baseline dataset includes the bill of materials, with data on the various components used in each device and their unit costs, total direct material costs, manufacturing costs and labor wage assumptions - as well as device-level specifications like the Operating System (OS), the retail price, and the headquarter location of the producer of each smartphone and of each branded component.

The time dimension in the dataset is constructed by using information on the release date of individual handsets. This choice is informed by how the industry works. Handset makers cannot swap out complex parts in a handset without major redesign work. There are too many interdependencies. A redesign to swap out a CPU would take about 6 months. Given this, it is unlikely that a phone model will be redesigned to use different components over the lifespan of the product. It is more likely that a company would simply design a new handset, which is often done once a year for most major brands. It is not only design engineering that makes it hard to swap components; testing is also a costly and time-consuming activity that generate stickiness to the initial choice of design and inputs of both phones and individual complex components.[38]

[38] Test engineers throw every imaginable use case at a device/system to make sure it works under all conditions and rarely occurring scenarios ("corner cases") might take a long time to track down and adjust for. This includes connections to various external devices and systems, as well as various hardware and software "calls" on the device to do this or that. This is especially true for high-value brands like Apple that do not want to have their flagship phones fail in the field for any reason.

Appendix 2 – How modularity emerged in the mobile handset MME

As Table 2 shows, modular governance currently prevails at the system level: modular platforms are used for system design without exception, and key subsystems and manufacturing services sourced in modular value chains, with exceptions. How did such thoroughgoing modularity come about? One reason is the transition to digital technology. Before 1990, mobile telephony was expensive, short-range, and relegated to first responders and other closed commercial networks. Large-scale installation of longer range "cellular" networks that could be used by consumers ramped up in the 1990s.[39] Levels of vertical integration in phones was much higher than it is today, and when components and subsystems were outsourced, semiconductor firms and other key suppliers typically had either relational or captive ties to lead firms (Park and Ogawa 2009: 792).

During this period, an underlying shift from analog to digital processing inside handsets began, with analog (radio) processing shunted from core processing components to a new "radio frequency" module responsible (along with the handset's antenna) for communicating with cell towers. To summarize a very complex set of technical problems, analog signals (radio waves) are much more difficult to codify than the 1s and 0s of digital signals. As a result, early cellular phones had integrated product architectures, more or less unique to each device. With digitization, it became easier to codify more elements of the handset's technical system, and externally sourced components and software that were less co-specialized with handset designs became more common. Because the market was growing, and more componentry could be used across many handset designs and brands, more suppliers entered and grew along with the industry.

As modularity increased, specialized semiconductor firms such as Texas Instruments (TI), Analog Devices, Lucent (all USA-headquartered), and Philips (the Netherlands) began bundling the complete stack of interconnect and analog-to-digital conversion protocols into highly functional technology platforms, or "chip sets," making it easier for a broader range of handset brands to enter the market with basic, low-cost handsets for mass markets. MediaTEK, a "fabless" semiconductor design firm based in Taiwan, went a step further when it began offering an integrated system-on-a-chip (SOC) APs for mobile handsets in the mid 2000s, along with software and detailed instructions on how to implement them in a handset design. These chip sets and associated "reference designs" covered not only how phones connected to the network, but also included many of the new functions that were being added at the time, such as address books, audio playback, and image processing for basic cameras, as well as interfaces with higher capacity memory chips needed to accommodate burgeoning information storage needs. These highly integrated modular solutions expanded the market for mobile handsets, especially in the price-sensitive Chinese market, but resulted in very similar phones, since they allowed phone designers little leeway for customization. Industry leaders such as

[39] These collected analog radio signals from local areas, converted them to digital signals that could be carried long distance between central offices handling wired telephony, and then converted back to analog radio signals that were routed to recipients.

Nokia and Motorola responded, on one hand, by deepening relational ties with key suppliers (TI in particular) to develop cutting-edge handsets closely aligned to the newest generation of telecom infrastructure, and on the other hand offering their own low-cost handsets (Imai and Shiu 2010; Thun and Sturgeon 2017). Chinese firms responded by trying to move up-market, setting off a classic "competing for the middle" dynamic as described by Brandt and Thun (2011).

In the late 2000s, a less gradual and more dramatic shift toward modularity in mobile handsets was led, not by an incumbent from the telecom industry, but by two companies from the world of personal computing and internet search applications: Apple and Google. The industry had struggled to introduce more modularity in software for several years. For example, the market leader, Finland's Nokia introduced the Symbian OS software in 1998. It was efficient and reliable, but lacked a standardized modular interface between the OS and applications – what is referred to as an application programming interface (API) today. This created a barrier for third party app developers, truncating the network effects of the platform and therefore its scalability. Even within Nokia, almost every handset was coupled with a different version of Symbian, and because there were dozens of versions that were not entirely compatible with each other, third-party app developers were frustrated by constant delays and uncertainty (Lamberg et al. 2021). Perhaps not surprisingly, given its origins as a telecom equipment company, Nokia's focus was on matching software designs with appropriate AP features so as to optimize network performance (e.g., improved voice clarity and fewer dropped calls) rather than focusing on making it easier for 3rd parties to offer new handset applications. As a result, telecom operators were often relied upon to work with app developers to bundle applications with handsets – and in fact, the features available on mobile handsets at the time were largely under the control of network operators. The lack of scaling motivated Nokia to develop a consortia including several other handset producers (Samsung, Motorola, and Sony-Ericsson) in the Symbian ecosystem, but the challenge of assuring the compatibility of platforms and complements in an increasingly cost-competitive consumer-oriented market continued to be daunting, especially when spread across several handset brands using different processors and product architectures. Furthermore, there was no centralized marketplace for Symbian applications where users could discover and purchase software. If the app was not bundled with the handset, users had to purchase the software directly from each developer. With the introduction of Apple's first iPhone in 2007, the operating system (OS) was delinked from applications, following a pattern set as it had been with the Macintosh and IBM-compatible PCs. This introduced a modular platform to the mobile handset for the first time. Google's proprietary distribution of the open source Android OS was released the following year. Apple's iOS and Google's distribution of Android were designed to work on a new class of touch screen handsets without fixed keypads. This offered both internal and 3rd party app developers a flexible palette where users could run a myriad of applications. As millions of apps became available and functionality skyrocketed, sales of touchscreen smartphones boomed, which in turn motivated more developers to create more apps, creating powerful network effects. By 2015 iOS and Android became a near duopoly and incumbent handset firms and their proprietary OSs essentially disappeared from the market (except for Samsung, which managed to make the transition to Android).

Appendix 3 – How the radio frequency (RF) sub-ecosystem works

The radio frequency (RF) subsystem in mobile handsets is composed of dozens of components packaged into one or more discrete modules.[40] The most basic function is to convert analog radio signals, emitted by cell towers and captured by the phone's antennae, into digital data used by other subsystems, and vice-versa. RF modules contain many different types of components (e.g. tuners, filters, amplifiers) and also link to other components in the handset, such as antennae.

Given that the RF spectrum is scarce , national agencies (such as the USA's Federal Communications Commission) possess ultimate jurisdiction over which entities can use specific RF bands for what purpose (e.g., private sector vs. the military, wireless communication vs television broadcasting) but since there is a strong motivation for wireless devices to work – and for telecom infrastructure companies to sell equipment – in multiple geographies, many industry standards and spectrum allocations are negotiated through global standard setting organizations (SSOs) with the consent of national agencies. Since the 3G era (starting in 2001), the International Telecommunications Union (a United Nations body) has set the basic parameters and requirements of next generation standards through a collective standard setting process. These requirements are then implemented by 3GPP, a voluntary private sector SSO that sets technical standards via a substantially collective process. Finally, these technical standards are converted into national standards and published by national regulatory agencies.

Components are fabricated on different substrate materials, such as gallium arsenide, ceramics, silicon-on-insulate. Each of these has its own material science challenges and distinct knowledge domains, as does combining them in a single physical package. As mobile handsets have become more complex and capable, for example gaining the ability to transmit more data across multiple telecom networks and network standards, the competency requirements have increased dramatically, especially with 4G and even more so with 5G.

The evolution RF works differently than with fully digital subsystems, which have a relatively smooth evolutionary path from generation to generation, partly because they has historically been dominated by one material (CMOS silicon) and improvement roadmap: reducing feature size according to Moore's Law every 16-18 months years. By contrast, RF technology comes in huge step changes that happen roughly once a decade and there with no persistent roadmap. New standards are implemented gradually once they are established, but the process is dominated by sharply defined "generations." For instance, a 3G frequency band of 2.1 GHz allowed handsets to transmit data at 2 Mbps, fast enough to browse the internet. A 4G frequency band of 2.6GHz, allows 40 Mbps speeds, fast enough to stream video. 5G signals represent an even larger leap, to a frequency bands ranging from 24 to 100 GHz, supporting speeds up to 10 Gbps, enough for demanding low latency applications like self-driving cars. Because of this, not every firm is able to make these leaps.

[40] Because they serve as the radio interface with the outside world, RF modules are typically referred to as "front end" modules in the industry.

The effect is that there are only a few companies remaining this space and moreover, most rely on each other for specific components and processes. During the 2G era (starting in 1991), there were several dozen major suppliers. By the start of the 2020s, there were only five major firms left – each with some capabilities across all domains, but usually a leader only in one component or even sub-component.[41] As such, to make a complete RF subsystem, several, if not all of the five major companies must exchange information in order to utilize their competitors' components and advanced design and manufacturing capabilities. This is coordinated, in significant ways, through open and non-proprietary standards.

For the makers of RF components and modules in the RF sub-ecosystem, the collective and public nature of RF standard-setting creates the conditions for modular interfirm ties in which complementarities are weak and symmetrical (two-way). But there are contrary forces at work. On the one hand, the diversity of knowledge domains within each RF subsystem deepens firm specialization and solidifies niche domination by each of the majors – a trend that normally would demand relational ties with strong complementarity with phone system designers. However, public industry standards allow RF sub-system suppliers and phone system designers to comply with stringent public standards by combining and packaging RF componentry in different ways, often using inputs from different companies. Presently, all of the five major players provide necessary inputs somewhere in all] RF subsystems, and no single firm dominates the market. This is the nature of MMEs: there is often development and exchange of tacit knowledge within each sub-ecosystem, but exchange of codified information between sub-ecosystems in service of hugely complex, fast-moving, and innovative final systems.

Most recently, and after a long struggle, Qualcomm has been able to gain traction with its RF products by integrating them with their "Snapdragon" application processors. Of course, mobile handsets utilize many other wireless RF subsystems, such as WIFI, Bluetooth, nearfield communication, in addition to satellite connectivity, among others, each utilizing their own spectrum that is usually governed through other global SDOs. However, while the standard-setting processes persist, these subsystems have gradually been digitized and encapsulated into the application processor.

[41] For example, Japan's Murata specializes in low frequency SAW filters, while the USA's Broadcom specializes in higher frequency BAW filters.

Appendix 4 – Decision tree for determining governance forms in value chains and ecosystems

