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# THE CO-EVOLUTION OF TECHNOLOGIAL DESIGNS AND CATEGORIES DURING INDUSTRY EMERGENCE

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## Abstract

Technology scholars have long studied the evolution of technological designs during industry emergence. More recently, organizational theorists have highlighted the importance of categories for industry dynamics. Despite their common theme, the two literatures have largely evolved in parallel instead of converging to form a more comprehensive theory of industry evolution. In particular, the mechanisms by which categories and technological designs influence each other as the industry evolves have not been identified or explored. Our article addresses this void in the literature by proposing an integrative process model of industry emergence. The model adds to existing literature by bringing together two different but complementary perspectives of industry evolution, specifying the corresponding mechanisms, and placing special emphasis on the co-evolutionary nature of designs and categories.

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## ABSTRACT

Technology scholars have long studied the evolution of technological designs during industry emergence. More recently, organizational theorists have highlighted the importance of categories for industry dynamics. Despite their common theme, the two literatures have largely evolved in parallel instead of converging to form a more comprehensive theory of industry evolution. In particular, the mechanisms by which categories and technological designs influence each other as the industry evolves have not been identified or explored. Our article addresses this void in the literature by proposing an integrative process model of industry emergence. The model adds to existing literature by bringing together two different but complementary perspectives of industry evolution, specifying the corresponding mechanisms, and placing special emphasis on the co-evolutionary nature of designs and categories.

## INTRODUCTION

Understanding the dynamics of industry emergence and evolution is a core concern to scholars of the industry lifecycle and organizational theorists. Such dynamics have been associated with firm entry and exit rates (Gort & Klepper, 1982); entry timing advantages (Lieberman & Montgomery, 1988); and the creation of technological designs that compete with each other until one of them comes to dominate the industry (Abernathy & Utterback, 1978; Anderson & Tushman, 1990). Scholars have highlighted the fact that industries move from an era of ferment that is characterized by technological divergence and the creation of multiple designs, to a mature stage that sees convergence on a dominant design – that is, the design that is favored by most firms within the industry (Abernathy & Utterback, 1978; Anderson & Tushman, 1990).

Technology scholars have noted that, in order to fully understand the evolution of technological designs along the industry lifecycle it is necessary to look beyond technological dynamics to also take into consideration sociocognitive constructs such as the "hierarchy of consumer choices" (Clark 1985, p. 241), and "technological frames" (Orlikowski & Gash, 1994; Kaplan & Tripsas, 2008). Recently, a growing number of organizational theorists have highlighted the formation of categories as one of the fundamental social processes that shape the evolution of industries (Rosa et al. 1999; Bingham & Kahl, 2011). Such categorization dynamics are particularly important in shaping the early period of industry emergence, during which understandings about the new industry are still under construction (Kennedy, 2008; Navis & Glynn, 2010; Jones, Maoret, Massa, Svejenova, 2012).

While there is consensus about the importance of both categorical and technological processes in shaping industry evolution, the specific *mechanisms* through which each of these processes unfolds have not been fully identified. This is particularly true for the mechanisms that determine how categorical and technological processes influence each other over time – that is, how designs and categories co-evolve. The lack of such an integrative and granular theory about the processes and mechanisms that shape industry evolution hinders our efforts to fully understand some of the central dynamics in industry evolution, such as the locus of competition, the factors that affect the emergence of a dominant design and, ultimately, firm survival.

We address these shortcomings by detailing the mechanisms behind the creation of categories and technological designs, the mechanisms that drive their coevolution, and the influence of these dynamics on key milestones of the industry lifecycle, such as the emergence of a dominant design (Abernathy & Utterback, 1978) and a dominant category (i.e. the category that most stakeholders eventually adhere to when referencing the industry (Suarez, Grodal & Gotsopoulos, 2012)).

We deliberately choose to focus on categories as the key social constructs that co-evolve with technology over other social factors such as bandwagon effects and fads (Abrahamson & Rosenkopf, 1993; Fiol & O'Connor, 2003), alliance building (Garud et al., 2002), or technological frames (Orlikowski & Gash, 1994). We do so for two reasons. First, we aim at taking advantage of the rich body of literature on the topic that has been developed over the last decade (e.g. Zuckerman 1999, 2000; Hsu, 2006; Hannan et al. 2007; Kennedy 2008; Jones et al., 2012), and particularly of research that highlights the importance of categories during the gestational periods of industries (e.g. Navis & Glynn 2010; Kennedy 2008). These studies provide a natural starting point for our theorizing about the origins and the evolution of categories that emerge in new market spaces. Second, given that categorical evolution is also both dynamic and longitudinal, , the integration of categorization research with theories of technological evolution holds great promise for a more nuanced understanding of the complex dynamics of early industries.

Our main goal in this paper is to uncover the *processes* of technological and categorical evolution. To accomplish this, we focus on identifying and describing the *mechanisms* that underlie these processes. Although the mechanisms we outline below are active throughout the lifecycle of an industry, for the sake of clarity we associate each of them with the particular industry period in which they are most prominent. While an abstraction, this allows us to highlight their role more vividly, and provides additional insights into the temporal dynamics of industry emergence. We develop a set of propositions to explicate our theorizing. We end the paper with suggestions about how to empirically investigate the co-evolutionary process of categories and designs using both quantitative and qualitative approaches.

In the following sections, we detail the evolutionary mechanisms associated with each of four processes: technological evolution; categorical evolution; technological evolution's influence on categorical evolution; and categorical evolution's influence on technological evolution (see Table 1). While only the latter two address the co-evolutionary aspects that are the primary focus of this paper, we consider it important to begin by first reviewing our existing understanding of technological and categorical evolution. The specific *mechanisms* associated with these evolutionary processes have, indeed, not been explicated coherently in the prior literature, and their accurate identification is an important first step to developing our co-evolutionary model.

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Figure 1 provides an overview of our integrative model of the co-evolution of technological designs and categories. Mechanisms already described in existing literature are depicted in solid black font. We use these as steppingstones for proposing a number of additional mechanisms and developing several novel propositions that are numbered and depicted using grey font in the figure. Table 2 provides a more detailed summary and definitions of the mechanisms behind each process, which we proceed to explain in more detail in the following sections.

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## MECHANISMS OF TECHNOLOGICAL EVOLUTION: UNPACKING THE THEORY OF THE INDUSTRY LIFE CYCLE

Most scholars agree that the process of industry emergence often begins with creative destruction (Schumpeter, 1934), as novel recombinations initiate an era of ferment that witnesses the entry of firms proposing alternative technological designs (Abernathy & Utterback, 1978; Anderson & Tushman, 1990). The era of ferment is characterized by an increasing divergence in the number of designs as "the rates of product and process changes are high and there is great product diversity among competitors. During this state, the [innovation] process is fluid, with loose and unsettled relationships" (Utterback & Abernathy, 1975: 641).

The period of fermentation and technological divergence culminates in the emergence of a *dominant design* (Abernathy & Utterback, 1978), "a single architecture that establishes dominance in a product class" (Anderson & Tushman, 1990: 13). The emergence of a dominant design leads to convergence on a few designs and to increased concentration (Klepper, 2002), thereby fundamentally altering the nature of competition and signaling the onset of the industry's maturity.

Scholars of the industry life cycle typically do not detail the specific *mechanisms* that underlie technology evolution (see Davis & Marquis, 2005; Hedstrom & Swedberg, 1996). A careful reading of their contributions, however, suggests three key mechanisms: *Technological recombination* is primarily responsible for the creation of new technological designs (divergence), whereas *design competition*, and *path dependence* contribute to the reduction in the number of designs (convergence). Acting together, these mechanisms fuel a complex process through which technological variations emerge and increase in numbers, before some of them are selected and retained over others that are abandoned (Anderson & Tushman, 1990).

**The Period of Divergence: Technological Recombination and the Creation of New Designs**

New industries generally emerge from innovations that spring from the creative recombination of technologies (Schumpeter, 1934; Abernathy & Utterback, 1978; Anderson & Tushman, 1990). *Technological recombination* is the creative synthesis of two or more previously separate technologies that results in the creation of a new technology to address an existing or potential need (Hargadon, 2003). Recombination with older ideas and technologies occurs even in the case of 'breakthrough' or 'paradigmatic' technologies that produce entire new industries (Basalla, 1988; Fleming, 2001). Mechanical typewriters, for instance, were created "as a synthesis of many existing elements. Clockwork suggested the idea of the escapement (to move the carriage one letter at a time). A telegraph sender provided parts for the first model for keys and arms. A sewing machine pedal was used for returning the carriage. The piano contributed the concept of the free and swinging arms and hammers for imprinting the letters" (Utterback & Suarez, 1993: 9). In a similar fashion, automobiles combined carriages previously propelled by horses with the internal combustion engine (Rao, 1994); and the biotechnology field was created by applying chemical knowledge to biological phenomena (Plein, 1991).

When the evolutionary path of a new industry is still undefined, and the understanding of customer needs and trends in the emerging market space is poor at best, the possibilities for recombination and experimentation are many. In their attempt to address still evolving customer needs, different organizations enter the emerging market space with different technological designs which correspond to their different ways of understanding the industry or to their different visions of its future (Kaplan & Tripsas, 2008; Benner & Tripsas, 2012). Essentially, potential recombinations can be as many as (or even more than) the organizations that enter the new market space. By constantly fueling the number of new designs that are introduced to the emergent market, technological recombination can lead to a plethora of technological designs that might differ from each other markedly, but still coexist temporarily in the young market space.

**The Period of Convergence: The Abandonment of Technological Designs**

As described in the industry lifecycle literature, the initial phase of technological design divergence is followed by a phase of design convergence that usually culminates in the emergence of one dominant design (Abernathy & Utterback, 1978). Despite the fact that this body of literature does acknowledge the importance of non-technology factors in the process that leads to the abandonment of some designs in favor of others, the emergence of a dominant design is ultimately seen as “the cumulative product of selection among technological variations” (Anderson & Tushman, 1990: 616). A careful revision of prior literature suggests that technological convergence is facilitated by two mechanisms: *design competition* and *path dependence*.

**Design competition.** Selection among alternative designs has long been viewed as the primary mechanism through which dominant designs emerge (Anderson & Tushman, 1990). *Design competition* is the process by which specific elements of a product design are retained over time in subsequent designs. This process leads to some designs to be retained and others to be abandoned as more and more producers converge on adopting a common set of product features. While this process does not preclude the introduction of still novel designs, it diminishes producers' incentives to do so, as consumers also increasingly converge on a set of design preferences (Clark, 1985). For instance, in describing the retention of key product design characteristics in the mechanical typewriter industry such as the single QWERTY keyboard, visible type, tab feature, shift-key, and carriage cylinder, Utterback (1994: 25) noted that "Any firm that wanted to offer a keyboard with an innovative arrangement of letters, or that wanted a circular type wheel (like the old Burt design), did so at its peril; it might capture some small niche… but it could abandon any hopes of being a mainstream producer with those sorts of designs".

**Path dependence.** In the course of their lifecycle, technologies and industries often come to crossroads or "technological guideposts" (Sahal, 1982), where one out of a number of design paths has to be chosen. Which of the alternative technological paths is selected largely determines the course of further development; investments and technological progression along the chosen path practically eliminate the other paths as options, as reverting to them becomes technically difficult or prohibitively costly. *Path* *dependence* is thus the mechanism through which prior technological choices determine subsequent technological possibilities. As Clark (1985: 241) pointed out, "the evolution of a complex product follows a hierarchy of design…there are choices in the development of a design that create precedents and are logically prior to other choices. These precedents create constraints...[that] may be inherent in the physical structure of the product or system, or they may arise because of interdependence between parts."

The impact of path dependence on technology evolution is more pronounced the further down the design hierarchy a technology is. Whereas at the early stages of a technology's evolution markedly different designs might be feasible, the choice of a specific path of technological evolution leads designs to converge and makes it increasingly difficult to return to a foregone technological guidepost. In the automobile industry, for example, the initial choice of internal combustion over electricity as the main source of power (Kirsch, 2000) largely determined the path of the industry's evolution. Even though the internal combustion engine was initially technologically inferior, continuous investment led to significant improvements in its performance, which were also accompanied by large investments in production capacity and complementary infrastructure. Recent attempts to return to an electric automobile design have had been hindered by the fact that undoing those years of technical decisions is both complex and costly.

## MECHANISMS OF CATEGORICAL EVOLUTION: UNPACKING THEORIES OF CATEGORICAL DYNAMICS

Even though the primary focus of literature in the industry life cycle tradition has been on evolution of technological designs per se, some authors have also highlighted the impact of social dynamics on technological evolution. Clark (1985), for example, notes the influence of consumers' conceptual frameworks on the introduction and evolution of technological designs. Kaplan and Tripsas (2008) theorize that technological frames (Gash & Orlikowski, 1991) influence the decisions made by product firms. Several technology scholars have emphasized the role of institutional actors in the success or failure of different designs (Garud & Kumaraswamy, 1993; Tushman & Rosenkopf, 1992; Garud & Rappa, 1994).

More recently, a growing body of literature on categorization has provided new impetus and powerful theoretical tools for the study of the socio-cognitive factors that influence industry emergence (Rosa et al., 1999; Negro, Kocak & Hsu, 2010; Jones et al., 2012; Pontikes, 2012). Categories are socially constructed partitions that divide the social space into groupings of objects that are perceived to be similar (Bowker & Star, 2000). Categories "have two basic properties: (1) constituent members, whose inclusion is defined by rules or boundaries pertaining to a common type of product or service, and (2) a concept, label, or identity that reflects the commonalities that link together the members of the category" (Navis & Glynn, 2010: 440).

A category label is a symbol (a word in most cases), which is used to reference a category and, consequently, a larger meaning structure (Peirce, 1931). When a person observes a label, she constructs the group of objects that she perceives as being associated with it. A category can thus be seen as the set of objects to which a particular label applies (Bowker & Star, 1999). Categories are important because they determine a set of characteristics that their members can be expected to possess and which distinguish them from or relate them to members of other categories.

Extant research has shown the importance of categorization processes in the evolution of new industries (Rosa et al., 1999; Weber, Heinze, & DeSoucey, 2010). However, prior literature in this stream has focused predominantly on how one particular category becomes legitimized in a nascent industry (Kennedy, 2008; Etzion & Ferraro, 2008; Weber et al., 2010; Navis & Glynn, 2010; Jones et al., 2012). In contrast, the dynamics through which categories are created and some of them are selected over alternative ones have been left relatively unexplored.

Below we detail the mechanisms involved in the evolution of categories. We posit that the categorical evolution process bears resemblance to technological design evolution in that it is also characterized by a period of divergence followed by a period of convergence. We propose that two main mechanisms contribute to the creation of new categories: *derivations* and *compounding*. Conversely, two mechanisms contribute to the reduction in the number of categories: *categorical selection* and *categorical envelopment*.

**Period of Categorical Divergence: The Creation of New Categories**

In early industries, stakeholders invent categories in an attempt to communicate and exchange information about a topic or product that is novel (Vygotsky, 1986; Pontikes, 2012). The creation of categories serves two primary purposes. First, a new category allows different stakeholders (i.e., consumers, producers, and analysts) to make sense of and discuss elements of the emerging industry and, over time, come to an understanding regarding its core traits. Second, novel categories function as markers of attention to which stakeholders can orient and come to understand that a new product category is emerging (Ocasio, 2011; Granqvist et al., forthcoming). However, when a novel industry is still unfamiliar, and its product's form and use are open to debate, stakeholders lack consensus regarding the category that is best suited to reference the industry.  Multiple categories are introduced by different stakeholders, reflecting the latter's different perceptions of the industry (Kaplan & Tripsas, 2008); in the case of producers, categorical introductions might also correspond to an attempt to promote a certain perception of the industry in order to gain a competitive advantage (Santos & Eisenhardt, 2009).

In the process of creating new categories, stakeholders have conflicting incentives regarding the positioning of the new category as similar to or distinct from existing categories. Distinctiveness can help set the category apart, highlighting the underlying product's or industry's novelty. In contrast, invoking similarity enhances information transfer by tapping into existing understandings and creating links to something already familiar (Bingham & Kahl, 2011).  Associations to other categories position each focal category in a web of meaning on a categorical map (Peirce, 1934).  A low (high) distance between a pair of categories on this map implies a high degree of conceptual similarity (dissimilarity) between them (Kennedy, Chok & Lui, 2011).

As noted earlier, categories are expressed through categorical labels (Navis & Glynn, 2010)..  Stakeholders' choice of a categorical label reflects their attempt to build links to existing categorical schemata by recombining existing elements or, alternatively, to stress the new category's novelty by generating a label anew.  Thus, new categories often emerge as "hybrids of previously unconnected categories, such as "electronic" book, "mini" van, or "personal" computer" (Navis & Glynn, 2010: 443). Categories that are created through recombinations of existing elements have informational advantages over categories that are created anew without any reference to pre-existing elements, and are thus likely to attract more attention and be more easily remembered (Berger & Heath, 2005).

We suggest that the two key mechanisms that lead to the creation of new categories are *compounding* and *derivations*.

**Compounds.** A compound is "the simple concatenation of any two or more nouns [or other words] functioning as a third nominal" (Downing, 1977: 810) [1]. Compounding allows category proponents to borrow meaning from existing categories in order to invoke familiarity with the novel product that they introduce or to communicate its defining characteristics (Lieber, 1983). Even the use of phonemes that are familiar can help stakeholders understand a new category and make them more prone to adopt and use it (Berger et al., 2012). Compounds are thus beneficial in managing the tension between familiarity and novelty as they elicit elements of existing categories, but simultaneously represent unique new recombinations.

Examples of new categories emerging through compounding abound. For instance, the category "laptop," first introduced in 1983 with the launch of Gavilan SC,

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[1] Linguists debate the extent to which compounds and noun phrases, where the modifier is a noun, are different (Giegerich 2004; Farnetani, Torsello and Cosi, 1988); that is, whether compounding into one word or two words are linguistically distinct. For example "power tool" is created through combining the two nouns "power" and "tool" into a noun phrase, where "power" is the modifier and "tool" is the head, whereas "air" and "plane" are combined into one word "airplane". The difficulty of distinguishing these two constructions (compounds and noun-noun phrases) made Bloomfield (1933) argue that "ice cream" is a noun phrase to some English speakers and a compound to others. For the sake of our exposition this differentiation is not important and we will, thus, refer to both noun-noun phrases, and compounds as simply "compounds".

compounded the words “lap” and “top” to communicate to potential users that the new computer allowed them to sit and work holding it on their lap, in marked contrast to prior products in that market space which were particularly heavy. Borrowing meaning from existing categories, proponents of the new category can also position a product vis-à-vis others and often signal its superiority. The category “smartphone,” for example, borrows meaning from the “phone” category to signal that the device’s primary purpose is communication with other people as with earlier mobile devices, and the “smart” category to signal the new device’s sophistication and superiority over earlier devices. By creating associations to preexisting, familiar categories, and by highlighting similarities to and differences from them, compounds immediately position novel products on the categorical map, thus capturing stakeholders’ attention and the enhancing information exchange among them.

**Derivations.** The second key mechanism through which new category labels are created is *derivation.* In the case of derivations, a new categorical label is created through the novel use or transformation of an existing word, most often by changing an existing word into a different word class, such as going from a verb to a noun. For example, the category “browsers” is derived from the verb “to browse,” while the category “computers” is derived from verb “to compute.” In contrast to compounds that simply invoke familiarity to established product classes, derivations also stress the activity for which the new product is to be used. Specifying the purpose of the new product allows new categories to be more rapidly understood. The extent of meaning transfer, however, is case-specific and time-variant. In the examples above, the purpose of a “browser” or “computer” is likely to be intuitively clear to most English speakers;

the exact domain in which they are to be used, however, is less so. Moreover, while the categorical label "computer" described well the primary function of early computers, the meaning of the label has evolved significantly since: currently, it refers to a machine that performs a rich array of functions most of which have little to do with computing as most users would understand the term (Bingham & Kahl, 2012).

> *Proposition 1: New categories introduced in nascent markets emerge predominantly through compounding and derivations*

**Period of Categorical Convergence: The Abandonment of Categories**

At the early stages of emerging industries, uncertainty and stakeholders' different perceptions about the industry lead to the introduction a multitude of novel categories. Such categories are often espoused and promoted by only a single stakeholder (e.g. a producer that coins a new category for their product offering). Lack of shared meaning and common use imply that the boundaries of such categories tend to be fuzzy and their position vis-à-vis other categories not well delineated, leading to overlap among coexisting categories (Pontikes, 2012). Similar objects might be grouped in different categories and dissimilar objects in the same category, leading to confusion. This stifles understanding and communication among stakeholders, and thus beats the very purpose of categories' existence. To resolve such confusion and facilitate better communication stakeholders gradually gravitate toward the use of only a few categories whose boundaries become better defined, whereas those categories that lose traction are gradually abandoned. As in the case of technological designs, which categories are retained and which ones falter depends on specific mechanisms that guide this selection process. We identify two such mechanisms that lead to categorical convergence, *categorical selection* and *categorical envelopment.*

**Categorical deepening.** When a new category is first introduced, it tends to be shallow in the sense that its meaning is not well defined and its connotations are limited (Pierce, 1934; Hannan et al. 2007). Over time, however, increasing use of and familiarity with the category, as well as negotiation among stakeholders expand the category's semantic connections and better define its meaning. We define this mechanism as *categorical deepening*.

When a category label is introduced it contains either none or only a few semantic connections to other labels and concepts (Pierce, 1934). Over time, however, as a label is used together with or in juxtaposition to other words and labels, connections between the new and existing labels begin to emerge. Such connections can invoke similarity or stress differences between the focal label and other labels. In either case, they help to clarify the label's meaning and position it "as a node in a network, with [its] properties […] represented as relational links from the node to other concept nodes" (Collins & Loftus, 1975: 408). For instance, the first time that a firm used the category 'e-commerce' to describe its product offering (late 1990s), the meaning of the category was rather unclear for the vast majority of consumers and other stakeholders (i.e., the semantic network associated with 'e-commerce' was sparse). Moreover, stakeholders found it difficult to distinguish similar categories that were emerging in the new market, such as 'online retailer" and 'dot-com'. As the familiarity and use of the Internet increased through the decade of 2000s, and online transactions became common, the meaning of the different categories used in this new space became increasingly well-defined and the semantic network associated with the different categories became denser.

Categorical deepening thus leads to stakeholders' deeper understanding of what a category means; this, in turn, allows them to compare categories and choose which among them are best suited to describe the emerging industry (Rosa et al. 1999). Categories that perform well at this task are retained; others that are not picked up or that develop negative connotations are gradually abandoned and disappear (e.g., the category of "dot-coms" to describe firms, after the burst of the bubble in 2000). Categorical deepening is thus a key driver of the categorical selection and categorical convergence that takes place in a new industry.

Categorical deepening also implies that categorical boundaries become gradually clearer. A denser meaning structure encourages the emergence of categorical membership rules as stakeholders form concrete expectations about the traits that products belonging to any focal category can be expected to possess. Categories thus become increasingly crisp (Pontikes, 2012) and clearly defined vis-à-vis other categories. Stakeholders' convergence on the use of only a few, well-defined categories not only leads other categories to be abandoned, but also leaves less room for new categories to be introduced.

Rosa et al. (1999) demonstrate vividly this dynamics in the "minivan" industry. During the early phases of the industry, a multitude of categories such as "minivan," "compact van," and "people mover" were used to reference products in the industry. As stakeholders converged towards the use of the "minivan" category, the competing categories gradually disappeared to the books of history.

**Categorical envelopment**. A second mechanism of categorical convergence is what we term *categorical envelopment*. In contrast to categorical deepening which leads one category to be selected over competing alternatives, categorical envelopment involves the broadening of one category's meaning to the point that it fully encompasses the meaning of another. In this case, the narrower category's defining characteristics become taken-for-granted elements of the larger category, causing the narrower category to cease to exist independently (Colyvas & Powell, 2006).

At the early stages of the smartphone industry, for example, categories such as "camera phone" and "PDA phone" had gained traction describing different segments of the industry and products with different capabilities. Eventually, however, both categories were enveloped by an expanding "smartphone" category. As technology and consumer preferences continued to evolve, the defining elements of camera phones (i.e. optics and software to take and store photos) and PDA phones (i.e. software to keep track of daily events) became *sine qua non* elements of all devices belonging to the "smartphone" category, rendering the categories of "camera phones" and "PDA phones" redundant.

Categorical deepening and categorical envelopment are both indicative of how categories are largely defined in terms of similarity to or difference from other categories (Pierce, 1934; Weber, Heinze, & DeSoucey, 2010. If two or more categories overlap fully on the dimensions that stakeholders deem important or if one or more categories are subsets of a larger category, envelopment is likely to occur and lead to the abandonment of the narrower categories. In contrast, if two categories are very distant, the markedly different perceptions of the industry that they incarnate might not be able to coexist within the same industry. In this cases, stakeholders' convergence toward one dominant perception leads to categorical selection and the abandonment of categories that stakeholders do not favor. As categories that are created through compounding and derivations inherently invoke both familiarity (through the recombination of existing categories) and novelty (being a new-to-the-world category label) we propose that they are more likely to survive than categories that are created anew:

> *Proposition 2: Categorical deepening and categorical envelopment are the basic mechanisms associated with the abandonment of categories*

## THE INFLUENCE OF TECHNOLOGICAL EVOLUTION ON CATEGORICAL EVOLUTION

In the preceding sections we detailed the mechanisms of categorical and technological evolution, examining them independently of each other. However, categories and technological designs do not develop in vacuum, but rather bear direct influence on each other's evolution. In the following sections we detail the mechanisms through which technological evolution shapes categorical evolution and vice versa. Beginning with the influence of technological designs on categories, we propose that it occurs through two main mechanisms: *technological echoing* and *feature-based clustering*.

**Technological echoing.** In the section on categorical evolution, we described how new category labels are created through derivations and compounding, but remained agnostic with regards to the mechanisms that drive the choice of the original labels that are used in compounds or derivations. This choice, however, is not random; derivations and compounds are often formed to reflect technological developments. We define *technological echoing* as the mechanism through which technological designs influence the creation and evolution of categorical labels.

In an emerging industry where technologies, categories, products, and even user needs are in flux and poorly understood, compounds and derivations often reflect the actual or aspired technical characteristics of the product. As understanding of the new product is poor, referencing its defining technological characteristics helps stakeholders to better grasp its function and to position it vis-a-vis preexisting products. In the early stages of what is now called the automobile industry, for example, early compounds such as "auto-mobile" and "horseless carriage" directly referenced the new vehicle's main characteristic, the fact that it was self-propelled. This set the new product clearly apart from previous products and technologies that all relied on horses as their driving power. Similarly, categories such as "electric car" or "power tools" make direct reference to the products main technological characteristics. We, thus, propose an inherent relationship between technological recombinations and the new categories created in early industries:

> *Proposition 3a (technological echoing): Most of the words or word stems recombined or altered in compounding and derivations reflect core traits of the underlying technology*
>
> *Proposition 3b: The higher the number of technological designs, the higher the number of categories created through compounds and derivations.*
>
> *Proposition 3c: The larger the variety of technological designs, the higher the number of categories created through compounds and derivations.*

**Feature-based clustering**. We define *feature-based clustering* as the mechanism through which the stakeholders' awareness of specific technological features influences the mechanisms of categorical deepening and categorical envelopment. Feature-based clustering generally strengthens the forces of categorical convergence.

As noted earlier, the existence of ill-defined and overlapping categories in early industries creates much confusion among stakeholders. Information that allows stakeholders to better define and compare the competing categories helps them in their process of selecting some categories over others and making sense of the whole evolving market space.  Design- or technology-specific characteristics provide information that aids stakeholders' sense making and decision processes. As stakeholders gain experience with the new industry, their ability to judge the similarities or differences among different products and technological design increases. Products that are judged to be similar in terms of technological features are considered to be "close" and are often clustered together in one category.  In contrast, products deemed to differ on these same features will be categorized differently (Murphy, 2000; Hannan et al., 2007).  By sharpening categorical boundaries and allowing for meaningful groupings, technological clustering influences the mechanisms that drive categorical convergence --categorical deepening and envelopment. Sharper category boundaries reduce confusion and facilitate the selection between categories by the different stakeholders. Similarly, sensible groupings of different designs based on specific technological features, bring the original categories associated to those different designs closer together in a categorical map (Peirce, 1934), thus facilitating the process of categorical envelopment.

For example, during the early development of technologies at the nano-scale in the 1980s, these technologies initially carried different labels across different disciplines. Materials scientists would refer to such technologies at "single-layer depositionings" or "advanced materials;" physicists would refer to them as "mezzo-science;" chemists used the term "molecular control;" government officials would call it "nano-science;" and some service providers would refer to this work as "nanotechnology" (Grodal, 2007). Over time, however, stakeholders from different disciplines began to realize that the technologies labeled differently by different stakeholders actually had a high degree of similarity in terms of technological properties as they were all on the nano-scale. As stakeholders started clustering together technologies at the nano-scale they also began using a common label, referring to these technologies collectively as "nanotechnology". The label nanotechnology, thus, came to envelop the other existing labels, which all but disappeared. This process was to a large degree dependent upon stakeholders creating clusters of similar technologies. We, therefore propose that technology clustering affects how categories are selected upon and which categories are enveloped:

*Proposition 4 (technology clustering): The faster stakeholders begin to agree upon key similarities and differences in the different technological designs in the industry, the faster the process of categorical convergence.*

## THE INFLUENCE OF CATEGORICAL EVOLUTION ON TECHNOLOGICAL EVOLUTION

Theories of technological design evolution are often characterized by implicit assumptions of technological determinism. In reality, however, the process of technological design evolution has strong socio-cognitive underpinnings (Shane, 2000; Abrahamson & Rosenkopf, 1993; Garud et al., 1992). Categories in particular, as embodiments of different perceptions of an underlying technology and its envisioned use, can play a significant role by influencing design decisions and thus a technology's evolutionary path. We identify two mechanisms through which categorical evolution shapes the process of technological evolution: *categorical echoing*, and *categorical inclusion and exclusion.*

**Categorical echoing.** The extensive literature on the role of recombinations in the evolution of technological designs has focused primarily on the technological aspects of the process (Abernathy & Utterback, 1978; Utterback & Suarez, 1991). Technological recombination, however, does not occur in a vacuum. While technological capabilities determine which recombinations are deemed feasible, which of them are actually pursued depends on perceptions about their relevance and desirability (Clark, 1985). Such perceptions, in turn, are socially constructed and expressed in categories. We term *categorical echoing* the process through which categories influence technological recombination.

Categories constitute the lenses through which an evolving market space is understood (Rosa et al., 1999). Invoking a larger meaning structure, they can have a marked influence on which technological features are deemed desirable and thus on the specific technological evolution path that will be pursued (Garud & Rappa, 1994). The creation of novel categories can spur recombinations which producers otherwise would not have considered. This happens because the specific alternatives that are pursued depend on both their technical feasibility and how prominently they figure in an actor's cognitive repertoire (Clemens & Cook, 1999). Moreover, even when a certain recombination is currently not feasible, categories can direct technological search in its direction and influence which technological features will eventually be available. For instance, the "camera phone" category used by several producers to position their devices in the early phase of the smartphone industry, may have directed companies to work on including additional features associated with cameras to their new devices, such as zooming capabilities and flash. Similarly, the “gaming device” category adopted by other early smartphones to position their products, led to the introduction of larger screens and research on improved graphics.

The multitude of compounds and derivations that stakeholders create in early industries, thus, not only function to attract the attention of stakeholders and to transfer information about the underlying product, but they ultimately also shape the path of technological creation by stimulating new technological recombinations. Therefore, we propose the following:

> *Proposition 5 (categorical echoing): The specific paths and extent of design activity in an early industry will be influenced by the type and number of categorical compounds and derivations created by stakeholders.*

**Categorical inclusion-exclusion**. Another way in which categories can guide technological evolution is by setting boundaries for which design features are accepted as belonging to a product category. As the industry evolves toward maturity, categorical boundaries gradually sharpen, solidify the meaning, and create clearer rules of categorical membership regarding the characteristics of products or technologies that belong to a focal category. We define *categorical inclusion-exclusion* as the mechanism through which categories implicitly dictate which features a product design needs to posses in order to be a valid member (inclusion), and which traits products cannot posses in order to claim membership to the category (exclusion).

The rules of membership imposed by categories can be quite detailed (Hannan et al., 2007). For example, Meyer (1995: 46) describes that the defining characteristic of the now obsolete “pen computing” category was “the use of a pen or pencil as the primary means of interaction between a user and a machine“. A product that did not use a pen for writing directly onto a computer screen, yet claimed membership to the “pen computing” category, would see its claims questioned.

Conversely, even if a product possesses all the traits dictated by a category, the introduction of features that are seen as incompatible with it might put the product’s membership claims to question. In the motorcycle industry, for example, stakeholders’ categorical understandings emphasize that motorbikes are not supposed to have more than 2 wheels. Having 3 or 4 wheels creates confusion, as it blurs the boundaries between the “motorcycle” and the “automobile” categories, and violates notions of the larger meaning associated with motorcycles such as “freedom” and “risk-taking”. Seidel and O’Mahony (2012: 23), for example, describe how the idea of adding a calculator to the capabilities of an “eBook” was abandoned, as they did not perceive a calculator as part of the “book” category. In contrast having an address book was deemed an acceptable part of the category:

> Someone had a long discussion about why we would need a calculator in it [the eBook]. At the end, [the project manager] would go, ‘But it's a book!’…….” The manager’s implication was that books did not have calculators and, to be consistent with that metaphor, neither should the eBook. In another instance, the question of whether to allow a list of contacts on the eBook was addressed differently. The executive manager explained that “someone can have a little black book of names [which] is a book also. So it fits the paradigm.

Categorical inclusion and exclusion reinforce the effects of technological competition and path dependence. As categories and stakeholders’ corresponding understandings of the industry solidify, any product or technology that strays too far from them is likely to be penalized (Zuckerman, 1999). Variations or advancements of a technology are thus constrained not only by the limits set by technological path dependence, but also by the expectations set by the rules of membership to a category. Categorical inclusion-exclusion limits product differentiation based on technological features, intensifying the process of technological convergence. Therefore, we propose the following:

> *Proposition 6 (categorical inclusion and exclusion): The stronger (weaker) the rules of categorical membership, the lower (higher) the number of technological designs.*

## A PROCESS MODEL OF THE CO-EVOLUTION OF TECHNOLOGICAL DESIGNS AND CATEGORIES

We set out in this paper to integrate industry lifecycle theory with organizational theories of categorization in order to reach a more nuanced understanding of industry evolution. Our theory and the proposed mechanisms are summarized in the temporal process model depicted in Figure 1, introduced at the outset of this paper.

The mechanisms through which categorical and technological evolution occur unfold horizontally on each side of the figure. Both technological and categorical evolution first undergo a period of divergence: the number of technological designs and categories increase during this period, fueled respectively by technological recombinations, and compounding and derivations. The initial period of divergence is followed by a period of convergence: the number of categories and technological designs in use decreases significantly, fueled respectively by design competition and path dependence, and categorical deepening and envelopment. For simplicity, we have depicted in Figure 1 the transition from the phase of divergence to the phase of convergence as roughly co-occurring for technological designs and categories; this is not necessarily always the case in reality. Yet, given that technological designs and categories coevolve, the two points of transitions are unlikely to be very far apart.

Indeed, as the figure also makes apparent, categories and designs do not evolve independently, but directly influence each other. These co-evolutionary processes are present during both the early period of divergence and the later period of convergence. During the period of divergence, technological recombinations are influenced by categorical echoing, as categorical structures directly affect which technological designs producers choose to explore. At the same time, the new categories created are influenced by technological echoing, as derivations and compounds directly reflect the technological designs that they reference.

During the phase of convergence, categorical echoing operates through the mechanism of categorical inclusion and exclusion to influence technological evolution. Those technological designs that better fit the emerging categorical structure are better understood and enjoy an advantage over competing technologies. Moreover, as categories gradually solidify, categorical inclusion and exclusion further reinforce technological path dependence by creating specific rules regarding which technological extensions fit with the existing categorical structures and which would fall outside it. Likewise, technology influences the evolution of categories during convergence through the mechanism of technology clustering. As the differences and similarities between technological designs begin to be better understood, and as the number of designs remaining in the market decreases significantly, stakeholders can more easily make sense and compare existing categories by contrasting the technological characteristics of the products they contain. Thus, technology evolution during convergence strengthens the mechanisms of categorical deepening and categorical envelopment.

The outcome of the coevolution between technological designs and categories eventually leads to the establishment of one dominant technological design (Abernathy & Utterback, 1978) and one dominant category (Suarez et al., 2012). While a dominant design is the product architecture that achieves dominance in a product class (Anderson & Tushman, 1990), a dominant category is the category that most stakeholders use when referring to the emerging industry (Suarez et al., 2012; see also Kaplan & Tripsas, 2008).

## DISCUSSION

We began this paper with the question of whether and how technological designs and categories influence each other during industry emergence resulting in the model described above. Our model expands current theories of technological evolution by highlighting the importance of categories during industry emergence and, in particular, by proposing an integrated model of industry evolution that takes into account the coevolution of technological designs and categories. While scholars of the industry lifecycle have long pointed to the role of socio-cognitive factors (see Clark, 1985; Sahal, 1985; Kaplan & Tripsas, 2008), they have not identified the specific mechanisms through which these factors shape industry evolution. Leveraging the rich literature on categorical dynamics (Kennedy, 2008; Navis & Glynn, 2010; Rosa et al., 1999), we delve into more depth to describe in detail the mechanisms that drive the evolution of designs and categories, as well as their coevolution.

We also contribute to existing theories of categorization by theorizing the dynamics of categorical evolution. Prior studies have focused primarily on the processes through which a single category becomes legitimized (Weber et al., 2008; Navis & Glynn, 2010; Jones et al. 2012). An emphasis on legitimation, however, overlooks the fact that the creation, evolution, and dominance of one particular category is intrinsically related to the creation, evolution and survival of competing categories. Our focus on the origins of categories and the selection processes that eventually lead to the dominance of one single category brings greater granularity and new insights to understand these dynamics.

We add new insights by extending existing research on categories back in time since existing studies have primarily focused on documenting what happens after a category has been created (Weber et al. 2008; Navis & Glynn, 2010; Jones et al., 2012). Extant literature has emphasized that the analogies employed in relationship to a category after it is created are important for creating legitimacy and familiarity around that particular category (Etzion & Ferraro, 2009; Bingham & Kahl, 2012). We suggest that the process itself of creating and labeling a category needs to be taken into account, even when evaluating categorical familiarity and novelty. For instance, the degree to which category labels created through compounding and derivations recombine existing categories influences its familiarity among stakeholders.

We also extend categorization research by explicitly considering the dynamics between categories and the process that leads to the selection of ones over others. Existing literature has focused primarily on the category that eventually becomes dominant and has paid little attention to the process through which that category comes to dominate over others (Weber et al. 2008; Navis & Glynn, 2010; Jones et al., 2012 Etzion & Ferraro, 2009; Bingham & Kahl, 2012; for an exception see Pontikes, 2012). We complement extant research by identifying the mechanisms (deepening and envelopment) that drive categorical competition and dominance.

**Industry Boundaries**

An important aspect of industry evolution is the construction of industry boundaries (Santos & Eisenhardt, 2009). The existing theory of the industry life cycle has not paid much attention to defining what an "industry" is. For instance, Anderson and Tushman (1990: 606) use "standard industry boundaries" in their study, as defined by 4-digit Standard Industrial Classification (SIC) codes. SIC codes are defined by similarities in the production processes or consumer demand (Department of Revenue website, October 2012). More generally, product similarity comes from the standard economics insight that an industry is composed by a group of products that are good substitutes for each other as evidenced by high cross-elasticities of demand[2]. However, scholars in both economics and industry life cycle research have rarely focused on how stakeholders come to perceive products as similar, which is a key antecedent of cross-elasticity and thus the formation and delineation of industries. Tellingly, Tirole (1989: 13) in one of the most widely used textbooks in industrial economics states upfront that:

> For the purpose of the present book, this empirical difficulty of defining a market will be ignored. It will be assumed that the market is well defined, and that it involves either a homogeneous good or a group of differentiated products that are fairly good substitutes.

It is fair to say, therefore, that the important issue of defining the boundaries of an industry is still unresolved. In this paper we have stressed the importance of the construction of categories during industry emergence, given that categories are socially constructed partitions that divide the social space into groupings of objects that are perceived to be similar (Bowker & Star, 2000). It follows that the evolution of categories within an industry is intrinsically related to the construction of industry boundaries and thereby to the competitive dynamics that unfold within the industry. As products are placed within the same category they become perceived as more similar, which strengthens competition and substitutability between them. Categorical selection and envelopment help to define the set of products that are seen as similar. As some categories are chosen over others, the meaning and membership of the remaining categories becomes clearer and, in turn, the boundaries of the industry become increasingly sharper. The emergence of a dominant category espoused by most stakeholders is the culmination of this boundary-definition process and denotes a marked reduction in the cognitive uncertainty that characterized the earlier stages of the industry.

Our model of the co-evolution between categories and technological designs highlights that industry boundaries are socially constructed. The social constructivism in this process implies that it is the interaction among industry stakeholders that leads to judgments of similarity and that determine the dimensions or traits on which such judgments are based. Far from being stable at the beginning, these judgments are dynamic, which makes categorical and industry boundaries vary across different points in time (or across locales). The evolution of categories in a new market space leads to the gradual sharpening of the boundaries of the competing categories and the eventual emergence of a dominant category. It is this process of categorical evolution that ultimately determine the extent to which stakeholders will consider two products substitutes of each other, and thus determines the boundaries of the new industry.

**Boundary Conditions**

In this paper, we have detailed the processes of technological and categorical evolution that culminate in the emergence of one dominant design and one dominant category that characterize mature industries. However, there are boundary conditions to this process.

We noted earlier that categories often expand to envelop narrower ones and include increasingly diverse elements (Pontikes, 2010; Grodal, 2007). Stakeholders' increasing degree of sophistication and technologies' further evolution might render such broadening categories unfit to accurately describe the dimensions that stakeholders consider to be important. In such cases, categories might partition into several subcategories that better capture differences between continuously evolving products, thus forming a hierarchy of categories (Lakoff, 1987). For example, categories like "minivan", "SUV", and "convertible", are all subcategories of the higher-in-hierarchy “automobile” category that emerged to capture specific characteristics on which members of the automobile category differed and which were deemed important by stakeholders.

Furthermore, subcategorization is likely to occur in two cases. First, as Suarez et al. (2013) note, sometimes the convergence on a dominant category happens too quickly. In such cases, the schema used to determine inclusion and exclusion remain unclear, and the dominant category might thus become too broad to be meaningful. Narrower and more meaningful sub-categories might thus subsequently emerge to replace the dominant category. For example in the case of artificial intelligence (AI) the category became too broad to be meaningful, which later led the category to break up into subcategories such as “neural networks”, “intelligent control” and “natural language processing”. In the second case, while the dominant category might be highly appropriate at the time of its emergence, it might be rendered obsolete by further technological development. As technology evolves and new recombinations become feasible, the dominant category might lose its ability to accurately capture the increased degree of differentiation among products in the industry. As in the automobile example above, new and narrower categories might emerge to reference in more detail the underlying products. Over time, these different subcategories can develop into independent new industries that undergo their own cycles of further categorical and technological evolution.

**Empirical Testing**

In this paper we have theorized the processes of technological and categorical evolution and developed a process model that integrates the mechanisms of the coevolution of categories and designs. These mechanisms need to be empirically tested in future empirical research. We suggest below several methods, both qualitative and quantitative, that could be used to further examine the dynamics of technological and categorical coevolution.

An important obstacle in testing our model is the need for longitudinal data on both categories and technologies starting from an industry's inception. As done in prior studies on technological evolution, archival data can be used to track the introduction and evolution of various technological designs. Collecting data on categories poses more challenges given that, as abstract sociocognitive constructs, categories leave no paper trail. Prior literature has tackled this issue by studying categorical labels (Granqvist et al. 2012) which do leave a paper trail as they are used in various documents such as firms' press releases, annual reports, industry reports, newspaper articles, etc. Following this methodology in her study of the software industry, Pontikes (2012) extracted category labels from press releases in order to track the introduction of new categories to the industry and the positioning chosen by various producers for their products. The construction of an exhaustive dataset of categories used in an industry also facilitates the study of how categories come about and shape up over time. For instance, it would allow examining what preexisting categories are combined, and how, to give rise to new categorical compounds or derivations. Such data would allow us to investigate the characteristics of compounds and derivations that might influence their chances of retention, survival, and dominance.

Press releases and product descriptions can also be used to study how categories and technologies coevolve over time. Specific categories become associated with specific technological traits that might change or evolve over time. By studying the overlap of technological characteristics between products that might belong to different categories, as well as the co-occurrence of different categorical labels in the same press release, researchers could construct a categorical map to show which categories are more proximate or more distant to others.

The theory we have build in this paper points to exciting and fruitful new research opportunities.  While progress has been made separately in the understanding of technological and categorical evolution during industry emergence, more research is needed to understand how these two related processes interact. We believe our paper is a serious and important effort in that direction.

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**TABLE 1 Mechanisms Shaping the Co-evolution of Technological Designs and Categories**

| From \ To | Technological | Categorical |
|---|---|---|
| **Technological** | **1. Technological → Technological**<br>Technological recombination<br>Design competition<br>Path dependence | **3. Technological → Categorical**<br>Technological echoing<br>Technological clustering |
| **Categorical** | **4. Categorical → Technological**<br>Categorical echoing<br>Categorical inclusion and exclusion | **2. Categorical → Categorical**<br>Compounding<br>Derivations<br>Categorical deepening<br>Envelopment |

**TABLE 2 Mechanisms Shaping the Co-evolution of Technological Designs and Categories: Definitions**

| Process | Mechanism | Definition |
|---|---|---|
| **Technological → Technological** | Technological recombinations | Technological recombination is the creative synthesis of two or more previously separate technologies that results in the creation of a new technology to address an existing or potential need (Hargadon, 2003) |
| | Design competition | Design competition is the process by which specific elements of a product design are retained over time in subsequent designs |
| | Path dependence | Path dependence is thus the mechanism through which prior technological choices determine subsequent technological possibilities |
| **Categorical → Categorical** | Compounding | A compound is "the simple concatenation of any two or more nouns [or other words] functioning as a third nominal" (Downing, 1977: 810) |
| | Derivations | The process of creating a new label based on an existing label or word. Often this is the process through which words are changed into a new syntactical category. |
| | Categorical Deepening | Categorical deepening is the process through which with increasing use of and familiarity with the category, as well as negotiation among stakeholders the category's semantic connections expand and its meaning become better defined. |
| | Categorical envelopment | Categorical envelopment involves the broadening of one category's meaning to the point that it fully encompasses the meaning of another. |
| **Technological → Categorical** | Technological echoing | Technological echoing is the mechanism through which technological designs influence the creation and evolution of categorical labels. |
| | Feature-based clustering | Feature-based clustering is the the mechanism through which the stakeholders' awareness of specific technological features influences the mechanisms of categorical deepening and categorical envelopment |
| **Categorical → Technological** | Category echoing | Categorical echoing is the process through which categories influence technological recombination. |
| | Categorical inclusion-exclusion | Categorical inclusion-exclusion is the mechanism through which categories implicitly dictate which features a product design needs to posses in order to be a valid member (inclusion), and which traits products cannot posses in order to claim membership to the category (exclusion). |

**FIGURE 1 Technological and Categorical Evolution during Industry Emergence**