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Unbundling and Managing Uncertainty Surrounding Emerging Technologies

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Abstract. Emerging technologies, while offering enormous potential for economic growth, carry a high degree of uncertainty regarding whether and when that potential may be realized. How can firms evaluate the uncertainty surrounding an emerging technology? To address this question, we offer a structured approach that unbundles the uncertainty surrounding emerging technologies, incorporating both supply- and demand-side factors. These include the focal technology itself, the potential market applications, the users adopting the technology, the ecosystem of activities that support the technology's value creation, and the business model with which the technology is being commercialized. We further consider that the uncertainty surrounding each of these sources may not be resolved in a vacuum, but, rather, that it may interact with other sources of uncertainty in a pooled, sequential, or reciprocal way. Such a structured approach of evaluating uncertainty can help firms and managers in terms of the cognitive processes and the managerial practices and provide microfoundations for dynamic managerial capabilities. We illustrate the applicability of the framework for two emerging technologies—gene therapy and autonomous vehicles—and how the framework can be integrated with prominent managerial practices for managing uncertainty.

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Keywords: technological change • technology management • ecosystem • business model • dynamic managerial capabilities

1. Introduction

In this article, we view emerging technologies through the lens of innovating firms expending significant resources to develop and commercialize those technologies (e.g., 3D printing, artificial intelligence, autonomous vehicles, augmented reality, blockchain, and gene therapy). Although there is widespread recognition that emerging technologies are characterized by a high degree of uncertainty as to whether, when, and how they will evolve (e.g., Dosi 1982, Anderson and Tushman 1990, Christensen 1997, Adner and Levinthal 2002, and Rotolo et al. 2015), we lack a framework with which to characterize the sources of that uncertainty and their implications for firms and their strategies. Extant literature has generally considered uncertainty as an aggregate feature of the technological context. But, when simply treating uncertainty as high or characterized by many unknowns, we limit the role that managers can play with respect to sensing and responding to opportunities and threats and ensuring their firms' competitiveness in the face of technological change (Teece 2007, Helfat and Peteraf 2015).

We define uncertainty surrounding the emergence of a new technology as a general lack of knowledge regarding that technology`s value creation. This notion of uncertainty is consistent with the one articulated by Koopmans (1957) and Rosenberg (1996), in that it is difficult to foresee how new technology would contribute to economic growth through commercialization.[1] We unbundle the overall uncertainty surrounding an emerging technology into discrete sources that underlie a technology's value creation. These entail the *focal technology* itself (Kline and Rosenberg 1986, Freeman and Soete 1997); the *market applications* it can serve (Gruber et al. 2008); the *users adopting the technology* (Robertson and Gatignon 1998, Rogers 2003); the *ecosystem* of activities that support the technology's commercialization (Adner and Kapoor 2010, 2016); and the *business model* with which the emerging technology is being commercialized (Chesbrough and Rosenbloom 2002, Zott and Amit 2007).

Once we have unbundled uncertainty across each of these sources, we further consider interactions between them, which we argue can provide firms with an important basis to evaluate opportunities and allocate resources. We distinguish between pooled, sequential, or reciprocal interactions (Thompson 1967) and explain how an explicit consideration of such interactions can offer valuable insights about the resolution and the management of uncertainty surrounding an emerging technology.

We illustrate this framework on two different emerging technologies that have been prominent in recent times: fully autonomous vehicles (AVs) and gene therapy. These technologies differ, with gene therapy being a science-based discovery, whereas autonomous vehicles are an engineering-based technology, thus representing different ends of the knowledge spectrum. For both emerging technologies, extensive resources have been committed by large established firms, new start-ups, and public research organizations, but there remains significant uncertainty regarding when and how they will achieve mainstream adoption and if and when they can be successfully commercialized (Cavazzana-Calvo et al. 2004, Fagnant Kockelman 2015).

Finally, we consider the utility of the framework for scholars and managers. Scholars have emphasized that managing risks is fundamentally different from managing uncertainties (Teece et al. 2016, Packard 2017). When managing risk, firms are assumed to know about the alternatives and the probability distribution of the different outcomes. However, when it comes to managing uncertainties, firms face a "knowledge problem," which needs to be addressed by developing specific types of dynamic capabilities (Teece 2007). These include sensing capabilities that facilitate the identification of new opportunities, while recognizing the underlying challenges, and seizing capabilities that facilitate resource-allocation decisions and strategic commitments toward the emerging technology (e.g., Cooper and Schendel 1976 and Eggers Kaplan 2009). Unbundling the different sources of uncertainty surrounding an emerging technology and understanding the interactions among them can facilitate managerial cognitive processes that relate to attention, perception, reasoning, and problem solving, which ultimately helps firms to develop superior sensing and seizing capabilities (Helfat and Peteraf 2015). For example, we highlight how this approach can be deployed within several types of popular managerial practices, such as scenario planning, discovery-driven planning, real options, and experimentation, that are related to sensing and seizing activities and how it can increase the effectiveness of these practices.

Overall, our framework moves beyond the characterization of uncertainty surrounding an emerging technology being simply high to a structured approach based on identifying the specific sources of uncertainty and the interactions among them. Such an approach can help shed greater light on how emerging technologies might evolve and how firms might be able to innovate and take advantage of the opportunities presented by these technologies. The framework can also inform policymakers in terms of resource and coordination requirements necessary for ensuring technological progress.

2. Uncertainty Surrounding the Emergence of New Technologies

The emergence of new technologies has long been recognized as an important driver of economic growth (Dosi 1982, Freeman and Soete 1997). Researchers have studied the origins of such technologies (e.g., Vincenti 1984, Basalla 1988, and Levinthal 1998), the timeframe and trajectory of their emergence (e.g., Dosi 1982, Foster 1986, and Anderson and Tushman 1990), and how they ultimately impact industry participants (e.g., Christensen and Rosenbloom 1995 and Kapoor and Klueter 2015).

Emerging technologies represent novel technological innovations with the potential to become dominant in their respective industries (Rotolo et al. 2015). An important feature of emerging technologies is that there is significant uncertainty, which stems from a lack of knowledge regarding the economic potential of the new technology. For example, Rosenberg (1996) drew on historical cases of computers, lasers, and telephones to highlight the difficulty associated with foreseeing how new technologies would evolve and create value. Koopmans (1957) referred to such uncertainty as primary uncertainty, and Packard et al. (2017) referred to it as absolute uncertainty.[2]

As an illustration, gene therapy represents a novel therapeutic approach that emerged from scientific discoveries in laboratories as early as the late 1980s. The therapy entails inserting genetic material into the human body through a viral vector to permanently alter a defective gene. Thus, gene therapy offers one-off or significantly less frequent customized treatments for patients with genetic disorders, which are administered by specialized physicians. Such therapies promise superior biology-based therapeutic alternatives to traditional chemistry-based treatments and may address diseases for which no treatments previously existed (Kapoor and Klueter 2015).

Another example of an emerging technology is autonomous vehicles (AVs). An AV can drive itself from a starting point to a predetermined destination without human intervention, using various in-vehicle sensors, such as LiDAR (light detection and ranging), radar, and cameras, as well as mapping and communications software (Fagnant and Kockelman 2015). There has been increasing interest around AVs since 2004, when the US Defense Agency held its First Grand Challenge for AVs to travel a 142-mile course through the desert in less than 10 hours.

Both gene therapy and autonomous vehicles represent a substantial shift from the existing technological regimes, and, consequently, their emergence has been characterized as highly uncertain. In the 1990s, expectations concerning gene therapy were extremely high, with the approach being hailed as the "game changer" for the healthcare industry (Summers and Cooney 1994). New biotechnology firms such as Vical and Applied Immune Sciences, the larger pharmaceutical companies such as Bayer and Aventis, and many public research labs and universities pursued the technology in the hope of its successful commercialization (Kapoor et al. 2017). However, the emergence of the technology was punctuated by setbacks due to the efficacy and safety of the treatments, which has substantially prolonged the technology`s emergence and has increased doubts as to whether gene therapy could ever be commercialized (Cavazzana-Calvo et al. 2004, Kapoor and Klueter 2020b). In 2013, the first gene therapy (Glybera, to treat lipoprotein lipase deficiency, an inability to break down fats) was approved in Europe. Yet, gene therapies are only available for the treatment of rare genetic diseases, and the potential of the technology to treat more widespread conditions such as hemophilia has not yet come to fruition (Wilson 2012).

In a similar vein, the emergence of AV technology was accompanied by high expectations in terms of its commercialization potential and is being pursued by some of the biggest technology players, such as Google, Baidu, and Uber; the traditional automotive manufacturers, such as General Motors, Ford, and Volkswagen; and a number of automotive upstarts, including Tesla, Zoox, and Embark (Fagnant and Kockelman 2015, Monios and Bergqvist 2019). However, estimates regarding the commercialization of AVs have widely varied, ranging from less than three years to being at least a decade to several decades away from commercialization.[3] Thus, despite extensive resources being committed toward that technology, there is significant uncertainty regarding when and how it will achieve mainstream adoption.

These examples resonate with the literatures on emerging technologies and entrepreneurial opportunities, which consider the high uncertainty surrounding the emergence of a new technology as making it difficult for managers and entrepreneurs to foresee how the new technology would evolve and create economic impact (e.g., Casson 1982, Tushman and Anderson 1986, Eisenhardt 1989, and Townsend et al. 2018). However, this consideration of high uncertainty as an aggregate feature of the technological context has only limited utility for management research and practice. Consider the perspective of dynamic capabilities which is premised on managers having superior capabilities with respect to sensing the threats and opportunities, and seizing on the opportunities (Helfat et al. 2007, Teece 2007, Helfat and Peteraf 2015). If emerging technologies are characterized by a high degree of uncertainty, with many unknown unknowns, and managers are deemed boundedly rational, the role that managers can play with respect to sensemaking and acting on the opportunities is somewhat limited.

We suggest an alternative approach. It represents a shift from simply considering uncertainty surrounding the emergence of new technologies to be high to an explicit consideration of the different sources of uncertainty that may underlie the technology's emergence. To do so, we follow a structured approach of incorporating both the supply-side and the demand-side drivers of value creation underlying an emerging technology. This enables the identification of five distinct sources of uncertainty. Through such unbundling, we can identify "what" sources of uncertainty are actually relevant before we get to more aggregate questions as to "when" new technologies will successfully emerge. Further, we explain how these different sources might interact with respect to their focal uncertainties and how such interactions may shape the resolution of uncertainty surrounding an emerging technology.

We illustrate these different sources of uncertainty and their interactions with respect to the emerging technologies of autonomous vehicles and gene therapy. Finally, we illustrate how unbundling uncertainty can help firms with the management of emerging technologies through the development of superior sensing and seizing capabilities (Teece 2007, Helfat and Peteraf 2015).

3. Unbundling Sources of Uncertainty for Emerging Technologies

For an emerging technology, the value creation begins with the *technology* being deployed in a given *application domain* for a set of *users* by focal firms using a specific *business model*. In addition to focal firms, several actors in the *ecosystem* contribute to the technology's value creation. Each of these drivers of value creation can also represent an important source of uncertainty.

3.1. Focal Technology

A key source of uncertainty for an emerging technology is rooted in the process of scientific discovery and technological problem solving under conditions of incomplete knowledge (Vincenti 1984, Day et al. 2004, Nelson 2015). During the emergence of a technology, it is often challenging to understand how the technology will perform and to accurately assess the effort and time necessary to achieve a technological advance (Dosi 1982, Freeman and Soete 1997, Oriani and Sobrero 2008). For example, the pattern of technological advance is often complex and somewhat disorderly (Kline and Rosenberg 1986, Sood and Tellis 2005). Moreover, the technological advance in a given emerging technology does not take place in a vacuum. Multiple alternative technologies (e.g., Anderson and Tushman 1990) and the industry's prevailing technologies (e.g., Adner and Kapoor 2016) may evolve at the same time. This makes it very difficult to predict how the technology would improve over time as a function of the effort expended and whether those improvements would be adequate to generate performance superiority over prevailing technologies.

3.2. Application

Another important source of uncertainty underlying a technology's emergence is associated with a lack of information about possible applications where the new technology can be successfully deployed (Freeman and Soete 1997, Gruber et al. 2008). Emerging technologies often have properties whose utility may not be immediately obvious, making it difficult to determine in which application a technology will create the most value. For example, general purpose technologies (GPTs) are an important example of emerging technologies, which have the potential to serve multiple applications in a wide range of market sectors (Bresnahan and Trajtenberg 1995). Scholars have also used the terms "enabling technologies" or "general technologies" to highlight technologies that may not have as wide an economic impact as GPTs, but can still be used across several applications (Teece 2018). For such technologies, the value-creation potential within an application is typically not established ex ante, but requires substantial efforts over time (Chesbrough and Rosenbloom 2002, Maine and Garnsey 2006).

3.3. User

Within a given market application, user uncertainty results from a lack of information regarding users' preferences and the way users will adopt an emerging technology (Robertson and Gatignon 1998). It is often unclear how potential users perceive the benefits associated with emerging technologies and if they are willing to incur the cost of adopting that technology and when they will decide to adopt the technology. A pattern observed for new technologies is that when the number of cumulative users of a new technology is plotted versus time, the curve typically resembles an S-shape, with a slow initial rate of adoption by a small set of users, which could then accelerate to entail a large set of users before gradually slowing as the market becomes saturated (Hall 2004). However, this adoption process is highly uncertain. In many cases, adoption stops at the initial set of small users (Moore 1999). Moreover, even when adoption takes off, there is substantial variation in the rate of that adoption across the different emerging technologies (Rosenberg 1972, Hall 2004). Although we know that specific factors like social networks or geographic proximity among users can help facilitate a technology's commercial adoption, how such factors would impact the rate of adoption are difficult to assess ex ante (Hall and Khan 2003, Rogers 2003).

3.4. Ecosystem

Beyond the industry participants originating and developing an emerging technology, a range of actors in the ecosystem contribute to an emerging technology's value creation (Kapoor 2018). Ecosystem uncertainty is rooted in whether and how the set of actors and the associated activities in the ecosystem can contribute to the technology's value proposition. In many cases, the commercialization of an emerging technology is dependent on innovation by other actors in the ecosystem (Adner and Kapoor 2010). These may be suppliers, whose components need to be integrated in a focal offer underlying an emerging technology, or complementors, who provide additional products and services to increase the focal offer's value creation. Suppliers and complementors may need to innovate with respect to the technologies (e.g., improving the performance of batteries for electric cars) or the business model (e.g., developing a service plan for charging infrastructure). Further, policymakers and regulators may also have to innovate by introducing new policies and regulations to enable the emerging technology's value proposition (e.g., subsidies for electric cars or safety-testing standards for autonomous vehicles). Finally, ecosystem participants may also need to agree on new technological standards to bring about the emerging technology's value proposition. In the absence of these innovations, bottlenecks may arise, constraining the commercial viability of an emerging technology.

3.5. Business Model

Business model uncertainty stems from the question of how firms appropriate value for their products, or the "profit equation," which will be used to commercialize an emerging technology (Casadesus-Masanell and Ricart 2010). The business model specifies the logic of how the business surrounding the emerging technology creates and delivers value to customers and outlines the breakdown of revenues, costs, and profits associated with delivering that value (Teece 2010). Firms may have a wide range of business models to choose from, but may lack clarity as to which model ultimately holds the most value for the commercialization of an emerging technology in both the short- and the long-run (Chesbrough and Rosenbloom 2002, Zott and Amit 2013). In many cases, the prevailing business model within an industry may not be viable, and new business models may have to be developed that may entail changes to who performs the underlying activities or how and when users pay for the products and services associated with the emerging technology (Amit and Zott 2012, Snihur et al. 2018).

3.5.1. Illustrative Cases of Gene Therapy and Autonomous Vehicles. Gene therapy and autonomous vehicles provide useful illustrations through which we can examine these sources of uncertainty. The emergence of gene therapy over the last three decades has been characterized by significant technological uncertainty around the therapeutic approach. Initial attempts at the development of gene therapy in scientific laboratories and clinical trials showed promise, but also revealed many challenges, such as severe side effects for patients. In the early 2000s, serious doubts about gene therapy's safety emerged, with scientists attempting to resolve these technological uncertainties by furthering their scientific understanding of the treatment (Kapoor and Klueter 2020b). Application uncertainty for gene therapy stemmed from many possibilities the technology has in commercial markets, including agricultural, human, and animal health (Ledford 2015). However, with each potential market having different requirements and constraints, it is unclear in which of these applications gene therapy has the largest potential for value creation.

There is also significant uncertainty with respect to the adoption of gene therapy by users. For example, in human healthcare, it is hard to predict the adoption by patients due to their serious concerns regarding treatments that will permanently alter their genetic code (Addison and Taylor-Alexander 2015). With respect to the ecosystem, gene-therapy treatments, unlike the traditional treatments, cannot be administered at home, but, rather, by trained physicians in specialized treatment centers. This creates ecosystem uncertainty regarding the establishment and availability of such centers. Additionally, ecosystem uncertainty stems from regulators, who may need to create new rules for regulating the development of personalized medicine.

Finally, there remains considerable uncertainty as to the way in which gene-therapy treatments would be priced and reimbursed, given that a treatment may represent a permanent cure (Wilson 2012). Industry participants have discussed several business models, including a pay-per-treatment model, an annuity payment model with payments spread over a set timeline, or a pay-for-performance model, in which payments are halted if the treatments stop working. For example, Glybera entered the market with a price tag of one million dollars per treatment, but was withdrawn from the market in 2017, as it proved to be not commercially viable (Morrison 2015). Thus, the business model in terms of how firms will commercialize gene therapy and appropriate value remains unclear.

As another illustration, there are different sources of uncertainty surrounding the emergence of autonomous vehicle technology. In terms of the focal technology, the Society of Automotive Engineers has defined several distinct levels of automation, going from level 0 (no automation—driver in complete control) to partial and conditional automation (levels 2 and 3) to high and full automation (levels 4 and 5), where, at the most advanced level, the vehicle is capable of performing all driving functions.[4] Higher levels of automation (4 and 5) require improvements in sensing arrays and software. However, the cost and effort, as well as the time necessary to achieve these autonomy levels, are still unclear. The emergence of the AV technology is also characterized by application uncertainty, as the technology can be deployed in a range of applications. These include defense, logistics (e.g., trucking), and personal mobility. However, which of these applications may be more viable, as well as when, is uncertain.

Substantial uncertainty for autonomous vehicles also stems from users within a given market application. For example, in the application of personal mobility, the value proposition of autonomous vehicles for commuters might not be attractive relative to other alternatives (i.e., driving a vehicle or riding in public transport), and it is unclear how AVs may change the patterns of travel behavior by commuters in general (Harb et al. 2018). Ecosystem uncertainty is also highly prevalent for AV technology. Suppliers need to innovate in their lidar sensors and artificial intelligence software, which must be integrated within AVs. A severe bottleneck may arise if insurers are not yet ready for such technology, as algorithms and software will assume the driver's responsibilities, or if industry participants cannot agree on connectivity standards for AV technology (Fagnant and Kockelman 2015). Further, regulators would need to agree on standards and testing procedures to ensure the safety of the AVs.

Finally, there is uncertainty with respect to the business model for AV technology (Teece and Munoz 2018). Traditional auto manufacturers follow a manufacturing-based vehicle-sales business model. With the emergence of AV technology, alternative models may become more attractive, but there is a lack of information as to whether licensing AV technology, vehicle sales, operating fleets, or offering AV-related services will be the most viable. It is possible that a completely new business model may need to be developed for successful commercialization. Table 1 summarizes these distinct sources of uncertainty for both gene therapy and AV technology.

Table 1. Unbundling Sources of Uncertainty in Gene Therapy and Autonomous Vehicles

	Sources of uncertainty				
	Technology	Application	User	Ecosystem	Business model
Uncertainty surrounding gene therapy	Safety Efficacy	Agriculture Animal health Human health	Resistance to receive permanent genetic modifications	Local treatment centers Insurance	One-time payment Outcome based payment Annuity
Uncertainty surrounding autonomous vehicles	Level of automation cost	Defense Trucking Passenger vehicles	Resistance to driverless Willingness to pay for convenience	Supply of sensors Insurance Infrastructure	Vehicle sales Operating a fleet Mobility as a service (MaaS)
Representative literature[a]	Dosi (1982), Foster (1986), Anderson and Tushman (1990), Henderson (1995), Kapoor and Klueter (2020b)	Freeman and Soete (1997), Maine and Garnsey (2006), Gruber et al. (2008)	Mahajan et al. (2000), Hall and Khan (2003), Rogers (2003), Hall (2004)	Adner and Kapoor (2010, 2016), Adner (2017), Kapoor (2018)	Chesbrough and Rosenbloom, (2002), Zott and Amit (2007), Kapoor and Klueter (2015)

[a]The literature cited here identifies the different sources of uncertainty that we illustrate using the cases of gene therapy and autonomous vehicles.

Unbundling uncertainties allows us to move from the notion of uncertainty being high to systematically investigating the different sources of uncertainty that are pertinent to the emerging technology's value creation. At the same time, we not only identify the different sources of uncertainty, but also gain insights into the distribution of uncertainty across the different sources.

This analysis is important because, for an emerging technology, not all sources of uncertainty necessarily need to be high. For example, monoclonal antibodies, another emerging biotechnology in healthcare, faced substantial and similar challenges to gene therapy with respect to resolving technological uncertainty (Marks 2012). However, unlike gene therapy, monoclonal antibodies treatments did not require new treatment centers or revisions to insurance plans in the ecosystem. Perhaps more importantly, the business model for monoclonal antibodies—prescribed as long-term treatments, resulting in recurring costs for patients and insurers—sustained the prevailing pharmaceutical model. Thus, uncertainty with respect to the business model was low and relatively easy to manage (Kapoor and Klueter 2015). In a similar vein, uncertainty related to electric vehicles was predominantly centered on the ecosystem (i.e., battery cost and charging infrastructure), but technological uncertainty with respect to the design and manufacturing of the vehicle was rather low, and the business model conformed to a large part with the prevailing sales model of internal-combustion-engine vehicles (Bohnsack et al. 2014).

4. Interactions Among Different Sources of Uncertainty

The uncertainty associated with each source underlying the emerging technology may not exist in an isolated manner. Sources of uncertainty may interact. Accordingly, unbundling the different sources of uncertainty may not be sufficient, unless the interactions between the different sources of uncertainties are explicitly recognized (Rosenberg 1996). Motivated by Thompson's (1967) typology of interdependence of organizational tasks (pooled, sequential, and reciprocal), we suggest that a similar typology could be useful to understand how one source of uncertainty may interact with another source.

Pooled interactions are present when any two sources of uncertainty are relatively independent of each other—that is, the resolution of uncertainty in one source has little or no effect on the resolution of uncertainty in another source. Although the sources of uncertainty are independent of each other, they have an aggregate effect on the overall likelihood that an emerging technology gets commercialized, as each source of uncertainty may independently limit commercialization (Adner 2012). For example, in the context of gene therapy for humans, health-related concerns by patients with respect to the adoption of treatments which permanently alter ones' genes (user uncertainty) is independent from the uncertainty surrounding a viable gene-therapy business model. Although the two sources of uncertainties do not interact directly, they both need to be addressed to achieve the commercialization of gene therapy.

In a similar vein, the successful commercialization of AV technology requires actors (such as sensor makers, vehicle manufacturers, and regulators) in the ecosystem to agree on standards regarding the connectivity among vehicles and the surrounding infrastructure. However, the resolution of uncertainty with respect to such standards has little effect on the resolution of uncertainty with respect to the business model of automotive firms commercializing AV technology.

Sequential interactions point to interdependence between two tasks, in which one is an input for the other—that is, one task must be completed before the other can be undertaken. Applying this lens to sources of uncertainty underlying an emerging technology suggests that, for sequential interactions, one uncertainty needs to be resolved prior to the resolution of another (Cooper 2000, Adner 2012). For example, linear models of technology emergence from research to development to commercialization and cases of "technology push" emphasize that technological uncertainty needs to be resolved before products can be brought to market (Kline and Rosenberg 1986). In the case of gene therapy, sequential interaction is present between uncertainty with respect to the technology and the user. First, sufficient technological improvements had to be made to establish the efficacy and safety of a treatment before uncertainty stemming from a user's safety concerns for a gene therapy could be resolved. The relationship between application uncertainty and the user uncertainty for AV technology can also be characterized as following a sequential interaction. It is only when uncertainty around a viable application is resolved (e.g., trucking versus passenger) that the uncertainty around users can be addressed, such as that related to safety concerns and adoption cost.

When the resolution of one source of uncertainty impacts the resolution of another source and vice versa, we consider this to be a *reciprocal interaction.* Reciprocal interactions create feedback loops. Addressing one source of uncertainty shapes the resolution of another source of uncertainty, which then feeds back to the original source of uncertainty.

In the context of AV technology, technological uncertainty and ecosystem uncertainty can interact in a reciprocal way. As firms try to improve the technology with respect to the level of automation and achieve mainstream adoption, regulators may need to develop new testing procedures to ensure the safety of the AVs, and these tests would then have to be incorporated within the development of the technology itself. Similarly, uncertainty with respect to the coverage of gene-therapy treatment by insurers in the ecosystem will have a reciprocal interaction with the business-model uncertainty around gene-therapy treatments (one-time versus annuity-based versus outcome-based). Both of the uncertainties cannot be resolved independently—the resolution of one has a direct impact on the other, with significant feedback between the two sources. Table 2 summarizes the different types of interactions and provides illustrative examples from gene therapy and autonomous-vehicle technology.

Explicating the interactions among different sources of uncertainties can help shed light on how and when the overall uncertainty surrounding the emerging technology may be resolved. For pooled uncertainty, the sources of uncertainty are independent of one another, so each can be addressed individually.

Table 2. Interactions Among the Different Sources of Uncertainty: Gene Therapy and Autonomous Vehicles

	Pooled interaction	Sequential interaction	Reciprocal interaction
Uncertainty surrounding gene therapy	User uncertainty (safety concerns) = Business model uncertainty (one-time vs. annuity-based vs. outcome-based)	Technological uncertainty (efficacy and safety) → User uncertainty (safety concerns)	Business model uncertainty (one-time vs. annuity-based vs. outcome-based) ↔ Ecosystem uncertainty (coverage by insurers)
Uncertainty surrounding autonomous vehicles	Ecosystem uncertainty (connectivity standards) = Business model uncertainty (vehicle sales vs. fleet operation vs. mobility service)	Application uncertainty (defense vs. trucking vs. passenger) → User uncertainty (cost to integrate autonomous vehicles, safety concerns)	Technological uncertainty (level of autonomy) ↔ Ecosystem uncertainty (regulation)

However, the challenge of pooled uncertainty is that all sources of uncertainty may matter for value creation for the emerging technology. Using a probabilistic notion, pooled interactions result in a multiplicative effect, wherein each source of uncertainty can affect the likelihood of emerging technology's commercialization (e.g., Adner 2012).

Identifying that sources of uncertainty interact sequentially can also be useful, as it clarifies which source of uncertainty needs to be addressed prior to another source of uncertainty. In the case of sequential interaction, reducing uncertainty in one source can directly impact the subsequent resolution of another source of uncertainty. In probabilistic terms, there is conditional dependence between the two sources of uncertainty that corresponds to a Bayesian updating process (Cooper 2000).

When sources of uncertainties interact in a reciprocal way, it is challenging to know and anticipate when one source of uncertainty has sufficiently been resolved. There is no easy calculus that allows for incorporating such dynamic models of feedback cycles, and, accordingly, such interactions may be most difficult to manage (Cooper 2000, Nielsen and Jensen 2009).[5]

5. Management of Uncertainties

Managing uncertainties is fundamentally different from managing risks. When it comes to managing risks, it is implied that managers know about the alternatives and the probabilities associated with their respective outcomes (Packard et al. 2017). In terms of managing uncertainties, however, there is little information available regarding alternatives and outcomes, and the strategic-planning process is much less reliable. Accordingly, superior capabilities with respect to sensing and seizing of opportunities are of fundamental importance (Casson 1982, Teece 2007, Helfat and Peteraf 2015).

Sensing involves the "filtering of technological, market, and competitive information from both inside and outside the enterprise, making sense of it, and figuring out implications for action" (Teece 2007, p. 1326). Once sensed, firms need to seize the opportunities presented by emerging technologies and make strategic commitments under uncertainty. *Seizing* requires taking actions such as the commitment and allocation of resources and organizational efforts toward emerging opportunities and the timing of such actions. Prior literature has highlighted the significant challenges for firms in perceiving the threats and the opportunities surrounding emerging technologies and undertaking strategic commitments (Eggers and Park 2018). Underlying these challenges are managerial cognitive processes that relate to attention, perception, reasoning, and problem solving (Helfat and Peteraf 2015). Managers are constrained in terms of attention, and their perception, reasoning, and problem solving tend to be biased by prior experiences and prevailing business models.

Our proposed framework can facilitate these cognitive processes by offering a structured approach to evaluating an emerging technology's value creation. It considers a holistic set of factors that underlie an emerging technology's commercialization (i.e., technology, application, user, ecosystem, and business model), which can be easily communicated within an organization. Sensing each of the factors and the interactions among them may facilitate the identification of new opportunities, while recognizing the underlying challenges and threats that may accompany their emergence. The framework also makes explicit that the same technology can be subject to very different levels of uncertainty, depending on the application, the user, the ecosystem, and the business model, and that these sources could themselves vary in terms of the degree of the uncertainty. This perspective underscores an important role for managerial innovations stemming from new business models and new market applications, in which the emerging technology can be deployed, which is separate from technological innovations. The process of unbundling can also reveal where the uncertainty lies, how it might be resolved, and which source may be the primary bottleneck for the technology's commercialization, helping managers focus and mitigate the constraints around attention and cognitive capacity (e.g., Adner and Feiler 2019).

The proposed framework can also guide the resource-allocation process. For example, if an emerging technology is characterized by two different main sources of uncertainty, the resource-allocation process can be very different, depending on the type of interaction between the two sources. In the case of a pooled interaction, the resource-allocation process can be treated as independent across the two sources, but resources would have to be expended simultaneously to minimize the likelihood of a bottleneck. In the case of sequential interaction, the resource-allocation process follows a coordinated approach, such that a firm expends resources toward first resolving uncertainty in one source and, conditional on the resolution, expends resources on the second source. Finally, in the case of reciprocal interaction, there is a greater need to maintain both simultaneity and coordination, which will make the resource-allocation process much more demanding. In such cases, a dedicated organizational unit may be essential to managing such complex coordination.

The proposed structured approach to unbundling the different sources of uncertainty and recognizing the interactions among them can also be integrated with prominent managerial practices for managing uncertainty and provide firms with a basis for improving their sensing and seizing capabilities. Scenario planning is a popular practice, in which managers identify the most relevant uncertainties in contexts when predicting the future is not possible (Schoemaker et al. 2013). Rather than describe all possibilities, the scenario-planning approach translates the relevant uncertainties into a small number of possible scenarios, which serve as the basis for evaluating strategic action. This qualitative approach requires reasoning and judgement when building the scenarios. Our framework could offer a valuable means by which managers can systematically take into consideration the key sources of uncertainties and their interactions to envision possible future scenarios and evaluate their plausibility. Additionally, incorporating our framework into the scenario-planning process can help offset biases that individuals might have as they make sense of an uncertain technological context through preexisting mental models (e.g., preference for certain application domains, or cognitive representations that do not incorporate interactions among different sources of uncertainties).

Discovery-driven planning (DDP) is another popular approach that is premised on explicitly quantifying outcomes to understand and manage the uncertainties around emerging opportunities (Christensen et al. 2008, McGrath and MacMillan 2009). The approach requires the translation of uncertainty into specific assumptions that need to hold to achieve the expected outcome and then narrowing these assumptions down to the ones that are most relevant and need to be tested early for assessing the viability of the emerging opportunity through specific milestones (e.g., first prototype or production).

Unbundling of uncertainties can help with the implementation of the discovery-driven planning process as it relates to emerging technologies. For example, one of the key exercises within the DDP is to create a "reverse-income statement," which starts with the intended future return from the emerging opportunity and then imputes the required revenues and the underlying costs that would generate that return. Our approach provides a systematic method to translate different sources of uncertainty into specific assumptions. Additionally, by explicating interactions, our framework also offers a structure in which the assumptions are interdependent in a sequential, pooled, and reciprocal manner. This structure can inform planning with respect to the different milestones and the testing of assumptions.

Our framework can also inform management practices associated with resource allocation toward emerging technologies. Consider, for example, real options as a popular management practice in which small initial resource commitments (i.e., options) are made in the face of uncertainty (McGrath 1997). Based on the real-options reasoning, managing uncertainty entails generating multiple alternative paths within a decision tree and relying on intermediate investments and outcomes as means of pursuing opportunities surrounding emerging technologies (McGrath and MacMillan 2000). Accordingly, a real-options approach provides firms the choice to both explore and abandon opportunities related to the emerging technologies. A challenge in the real-options approach is how uncertainty is incorporated in the analysis because it is difficult to understand the underlying factors behind the option. Our approach can help decision makers consider the underlying sources of uncertainty and, in the process, improve their subjective probability assessments when engaging in real-options analysis. Further, by highlighting the different types of interactions, our approach suggests that there are some boundary conditions to the effectiveness of using real options to allocate resources. When sources of uncertainty interact sequentially, real options would be well suited. However, under conditions of pooled uncertainty, firms may need to make independent smaller investments at the same time, raising the cost of real options. When sources of uncertainty interact in a reciprocal manner, a single real option addressing one source of uncertainty may not be enough, and one needs to place, at a minimum, two options to address both interacting sources of uncertainty.

In addition to real-options reasoning, experimentation through the deliberate testing of hypotheses is another way that managers can allocate resources under uncertainty. The idea is that experiments can facilitate the search for information and learning, which can reduce uncertainty (Casson 1982). Because experimentation can be costly and time-consuming, knowing where to allocate resources initially for experiments, and the amount of resources to commit, is important. Our approach can help in both the design of experiments and the drawing of inferences from the experiments. With respect to the design, if uncertainty only stems from one source, such as the technology, the design of an experiment is relatively straightforward. In the case of multiple sources, designing the experiment and drawing inferences are much more challenging. In the case of sequential interdependence, the learning from an experiment can inform the design of the next experiment. However, when interactions are pooled or sequential, the design and the inferences are much more problematic. The framework also cautions managers when drawing inferences from simple experiments within one source of uncertainty. If the source of uncertainty interacts with another source of uncertainty, and such an interaction is not taken into account as part of the experimental design, inferences may be problematic.

Figure 1 illustrates how the structured approach of evaluating uncertainty surrounding an emerging technology can support firms and managers in terms of the cognitive processes and the managerial practices and, as a result, help provide microfoundations for dynamic managerial capabilities with respect to sensing and seizing (Helfat and Peteraf 2015). For example, by specifying the different sources of uncertainty and analyzing how they interact, managers can focus their attention and apply practices like scenario planning to sense and respond to opportunities and threats.

6. Discussion and Conclusion

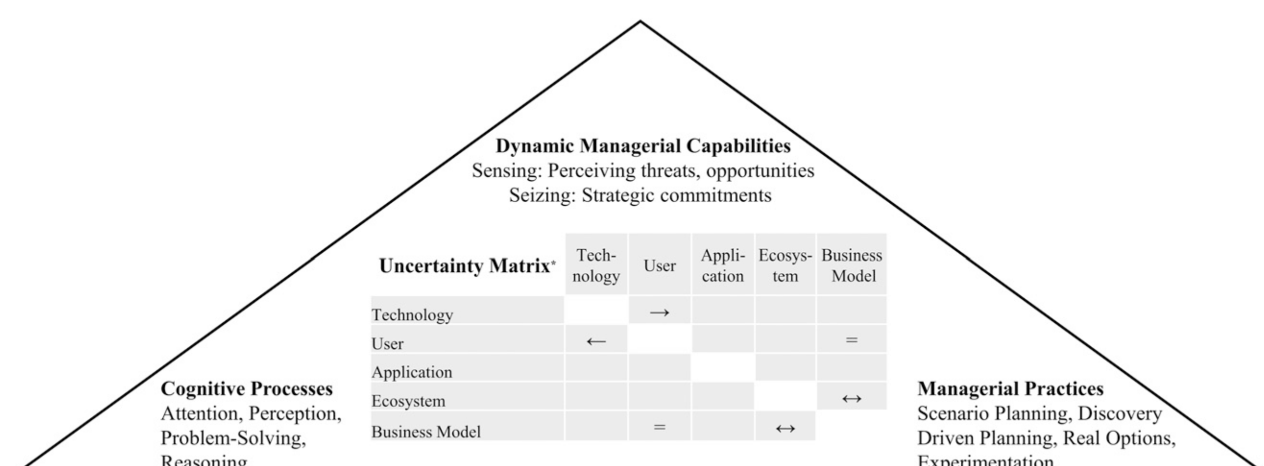
Emerging technologies, although offering enormous potential for economic growth, carry a high degree of uncertainty as to whether and when that potential may be realized (e.g., Foster 1986, Anderson and Tushman 1990, Rosenberg 1996, and Rotolo et al. 2015). In this article, we have outlined a framework for evaluating the uncertainty surrounding an emerging technology. The framework proposes a structured approach to identifying the different sources of uncertainty that underlie a technology's value creation–the focal technology itself, the market applications that it can serve, the users adopting the technology, the ecosystem of activities that support the technology's value creation, and the business model with which the emerging technology is being commercialized. Beyond unbundling the different sources of uncertainty, the framework explicitly takes into account that uncertainty with respect to each of the sources may interact in a pooled, sequential, or reciprocal manner, impacting how and when the overall uncertainty surrounding the emerging technology may be resolved.

Unbundling the sources of uncertainty surrounding an emerging technology allows us to identify what sources are actually relevant before we get to the more aggregate questions of if and when the technology will be successfully commercialized. In so doing, the framework offers specific guidance as to where the critical sources of uncertainty lie and how the process of resolution might take place across the different sources. Such an approach also helps to elevate the role that managers can play in sensing opportunities and making strategic commitments during periods of rapid technological change (Cooper and Schendel 1976, Eggers and Kaplan 2009, Adner and Kapoor 2016).

By explicating the interactions among the different sources of uncertainties, we offer an understanding of whether sources are independent (as with pooled interactions) or if uncertainty with respect to one source is conditional upon that of another source. This can have important implications with respect to which sources of uncertainty one needs to address first and how to allocate resources across the different sources over time. For example, when interactions are reciprocal (i.e., a dynamic relationship in which one source of uncertainty affects the other, and vice versa), there may be a need to simultaneously consider two sources of uncertainty and allocate resources to resolve that uncertainty in a highly coordinated manner. In contrast, when interactions are pooled, the resource-allocation process can be treated as independent across the two sources, but resources would have to be expended simultaneously. Through the cases of gene therapy and autonomous vehicles, we illustrate both the relevance and the application of our framework for analyzing emerging technologies.

We also show how this framework contributes to the theoretical perspective of dynamic capabilities,

Figure 1. Management of Uncertainty Surrounding an Emerging Technology



*Depicted uncertainty matrix corresponds to gene therapy, as discussed in the paper and illustrated in Table 2.

which are critical to firm performance during periods of rapid technological change (Teece 2007, Helfat and Peteraf 2015, Teece 2017). According to this perspective, firms need to develop specific types of dynamic capabilities—those that help them sense new opportunities, while recognizing the underlying challenges, and those that help them seize the opportunities through resource allocation and making strategic commitments. The structured approach to unbundling the different sources of uncertainty and recognizing the interactions among them can provide a basis for firms to develop superior sensing and seizing capabilities. One potential way such superiority may be achieved is by integrating our proposed approach into several managerial practices that make up a firm's sensing and seizing activities, such as those of scenario planning, discovery-driven planning, real options, and experimentation.

Further, extant management literature has often characterized uncertainty as a unidimensional construct–for example, distinguishing low versus high (Dess and Beard 1984, Tushman and Anderson 1986), stable versus variable (Lawrence and Lorsch 1967), low velocity versus high velocity (Eisenhardt 1989), and smooth versus abrupt (Suarez and Lanzolla 2007). Such constructs surrounding uncertainty have yielded important insights with respect to the challenges and the effect of uncertainty on firms. In the context of emerging technologies, however, uncertainty is always high, and, accordingly, these constructs lack the variance to help managers understand and deal with environments characterized by rapid technological change. Our proposed approach moves beyond the aggregate characterization of uncertainty surrounding an emerging technology as high with many unknown unknowns to one of different sources of uncertainty and the potential interactions among them.

Finally, unbundling sources of uncertainty surrounding an emerging technology can also help generate new insights for policymakers. An important challenge for policymakers with respect to emerging technologies is to ensure that resources are expended toward technological progress at a time in which there may be multiple technological paths toward realizing that progress. Our approach can guide policymaking in terms of which technological paths may be more viable, which sources of uncertainty may be more critical in enabling progress, and when coordination of resources may require a more centralized policy-level initiative involving many different types of actors.

There are several avenues for our framework to be extended. First, we focused on uncertainty as it relates to an emerging technology's value creation across all industry participants. Future research could incorporate how the different sources of uncertainties and the interactions among them may affect established incumbents, startups, or diversifying entrants (Kapoor and Klueter 2020a, b). For example, it would be important to examine which types of firms might be better positioned to manage the different types of uncertainties and take advantage of the emerging opportunities. Relatedly, uncertainty with respect to the ecosystem, business model, and application domain may require established firms to reconfigure their existing knowledge base or routines, and firms may vary in terms of their ability to reconfigure (Eklund and Kapoor 2019).

Second, we have focused on uncertainty due to a general lack of knowledge regarding an emerging technology`s value creation during the nascent period of emergence. In so doing, we have not considered uncertainty with respect to the potential for opportunistic behavior by actors in the ecosystem. Such behavioral uncertainty may be particularly relevant during later stages of a technology's evolution and have important implications for value appropriation by focal firms (Adner and Kapoor 2010). It might be useful to explore how uncertainty with respect to emerging technology's value creation that we focus on in this article and behavioral uncertainty with respect to value capture may impact firm strategies and the overall evolution of the industry.

The process of unbundling uncertainty is intended to facilitate the evaluation and strategic decision making around emerging technologies. Although we expect the process to aid managers and uncover differences across firms, not all of the uncertainty around emerging technologies would necessarily have to be resolved for value creation to take place. Some uncertainty may always be present, or the locus of uncertainty may change over time. Future research could explore how firms make strategic commitments in the face of evolving uncertainty and how those commitments impact firm performance.

Endnotes

[1] We note that there is significant debate around the concept of uncertainty in terms of how it is being conceptualized across a variety of fields (e.g., decision making, entrepreneurship, finance, operations, and organization theory). For example, Townsend et al. (2018) offered a useful observation—that is, that treatments of uncertainty in the entrepreneurship literature have focused on the problem of unknowingness, but have confounded issues of uncertainty with those of ignorance. Our focus here is about universal lack of knowledge regarding how an emerging technology might create value, and we do not consider issues of ignorance.

[2] Koopmans (1957) drew an important distinction between primary and secondary uncertainty. Although primary uncertainty stems from a lack of knowledge about states of nature, secondary uncertainty stems from a lack of knowledge about the actions of other actors. Williamson (1984) built on Koopmans' notion of secondary uncertainty to distinguish between secondary uncertainty arising from a lack of communication of an "innocent" type and that stemming

from willful nondisclosure, disguise, or distortion of information by actors behaving strategically. Although secondary uncertainty plays an important role in terms of the interactions among actors, our focus in this article is on primary uncertainty. We expect that issues surrounding secondary uncertainty become much more relevant at later stages of a technology's evolution (Adner and Kapoor 2010).

[3] A selective list of predictions for AV commercialization, based on public announcements, can be found at http://www.driverless-future.com/?page_id=384. These predictions suggest AVs being commercialized over the next two to five years. However, according to Gartner's well-known hype cycle (https://www.gartner.com/smarterwithgartner/top-trends-in-the-gartner-hype-cycle-for-emerging-technologies-2017/), AVs were at the peak of hype (inflated expectations) in 2017, and it will take more than 10 years for the hype to subside and commercialization to take place. According to McKinsey's analysis (https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/self-driving-car-technology-when-will-the-robots-hit-the-road), the commercial availability of AVs is at least a decade away. Several industry analysts (http://bestride.com/news/shocker-googles-autonomous-car-is-years-away), regulators (https://www.wsj.com/articles/autonomous-car-proliferation-decades-away-u-s-regulator-says-1479233888), and policymakers (https://scipol.duke.edu/content/australian-government-fully-self-driving-cars-decades-away) have recently stated that proliferation of AVs is several decades away (websites were last accessed November 17, 2020).

[4] Society of Automotive Engineers (https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles; website last accessed November 17, 2020).

[5] We note that even if interactions between the sources of uncertainty may be modelled in a probabilistic sense initially, there can be new sources of uncertainty and potentially, new interactions that may emerge over time, and for which other modelling approaches may be more relevant.

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