ARK INVEST

Disruptive Innovation

Why Now?

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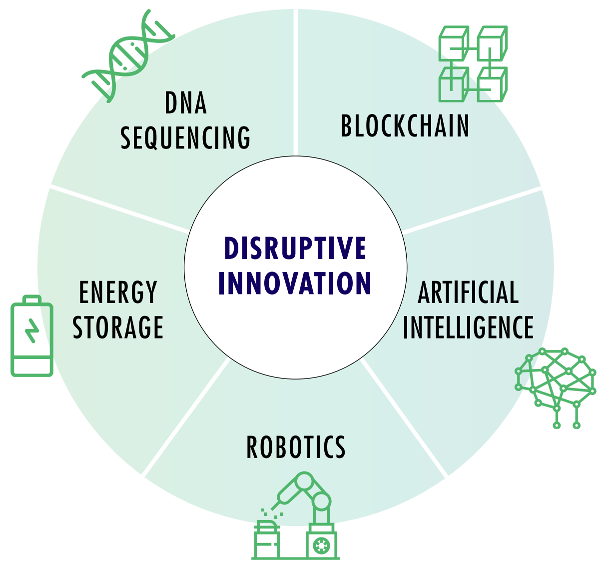
Investing in Disruptive Innovation: Why Now?

We believe that historians will look back on this era as one of unprecedented technological foment. They will see critical inflections in artificial intelligence and DNA sequencing and editing; they will recognize this as the 10 year stretch when robotics proliferation became inevitable and when the battery became the fundamental unit of energy delivery; and they will identify in blockchain and cryptocurrencies the roots of the structure that would grow to upturn the entire business and financial landscape.

They will identify five transformative innovation platforms **artificial intelligence, DNA sequencing, robotics, energy storage,** and **blockchain technology—**and they will say: from that point, everything changed.



They may compare this era to that of a century ago when the internal combustion engine (ICE), electrification and telephony swept through the economy. Those technologies transformed the way we travel, communicate, and transmit power. They may point also to the steam engine which transformed markets more than a century prior, ushering in the industrial revolution. We remember these technologies because they transformed the way the world worked, upending incumbent providers and creating fortunes as new businesses propelled the global economy forward.

Though perhaps presumptuous to identify technologies that historians will compare to electricity or the computer, the steam engine or the Internet, those advances do seem to share characteristics that apply today to several technologies hitting critical inflection points. Transformative technologies deliver dramatic cost declines, impact many industries and geographies, and serve as platforms for more innovation.[1] Academic institutions are replete with literature identifying and analyzing technologies that "interrupt and accelerate the normal march of economic progress".[2] While economic historians refer to them as General Purpose Technologies (GPTs),[3] we will refer to them interchangeably as transformative technologies, innovation platforms, or GPTs.

Identifying the Impact of Historical Transformative Technologies

To put today's technological moment into context, we compiled a list of past technologies generally accepted as transformative. Though academics may agree on the framework of a transformative technology platform, they do not agree on the technologies that qualify best as GPTs.[4] Surveying academic literature, we can quantify what percent of historians researching them agree that a technology qualifies as a GPT, as shown in the following table.

1 *These criteria are detailed in: Boyan Jovanovic and Peter L. Rousseau, "General Purpose Technologies," in Handbook of Economic Growth, ed. Philippe Aghion and Steven N. Durlauf, vol. 1, Part B (Amsterdam: Elsevier, 2005), 1181–1224.*
2 *Brynjolfsson, E., & McAfee, A. (2018). "The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies." Vancouver, B.C.: Langara College. 75.*
3 *The concept first appeared in: Bresnahan, T. and M. Trajtenberg. 1995. "General Purpose Technologies: 'Engines of Growth'?" Journal of Econometrics 65: 83-108.*
4 *Indeed, it seems that the only two technologies that can unequivocally be considered GPTs are the steam engine and electricity.*

Table 1: Historical General Purpose Technologies[5]

Technology	Year of Commercial Introduction	Consensus That the Technology Qualifies as a GPT (10 Highest – 1 Lowest)
Steam Engine	1780	10
Factory System	1800	3
Railways	1815	4
Iron Steamship	1821	1
Telegraph*	1840	3
Internal Combustion Engine (ICE)	1860	6
Telephone*	1880	5
Automobile	1890	3
Electricity	1894	10
Airplane	1908	1
Mass Production	1910	1
Chemical Engineering	1935	1
Lean Manufacturing	1960	1
Computers	1965	6
Internet	1984	6
Biotech	1994	1

**Though many papers explicitly exclude the telegraph and the telephone as GPTs since they are only used in a single economic sector we utilize the identification framework detailed in Bekar, C., Carlaw, K. & Lipsey, R. J Evol Econ (2018) 28: 1005. https://doi.org/10.1007/s00191-017-0546-0 which argues for inclusion of narrow technologies broadly deployed by all industries; we subjectively rate the telegraph and the telephone ourselves.*

As can be seen above, economic historians agree that the steam engine and electricity were transformative technologies, but they do not agree about much else. The internal combustion engine, computers, and the Internet are the only other technologies seemingly considered transformative by a majority of economic historians. One point on which they do agree is that technological breakthroughs do not happen very often. The historical cadence suggests that a breakthrough equivalent to the internal combustion engine occurs every two decades.[6]

Economic historians find these types of innovations fascinating in part because their macroeconomic effects can be confounding: instead of adding to economic momentum in their early years, transformative technology platforms often impede growth. While electrification did cause a discontinuous improvement in productivity across every manufacturing sub-sector in the 1920s, for example, it first placed a drag on the economy for more than a decade as businesses were forced to restructure to capitalize on the new paradigm. To access the promised productivity gains, they had to sunset or destroy old infrastructure and invest in the new world at a low-yield until the GPT reached critical mass.[7]

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5 *Data gathered from: Lipsey, Richard, Kenneth I. Carlaw and Clive Bekar. 2005. Economic Transformations: General Purpose Technologies and Long-term Economic Growth. Oxford: Oxford University Press, 2005. | Bresnahan, T. and M. Trajtenberg. 1995. "General Purpose Technologies: 'Engines of Growth'?" Journal of Econometrics 65: 83-108 | Caselli, F. (1999). "Technological revolutions." American Economic Review 89 (March): 79-102. | Wright, Gavin. 2000. Review of Helpman (1998) in Journal of Economic Literature 38 (March): 161-62. | Gordon, Robert J. 2004. "The 1920s and the 1990s in Mutual Reflection." Paper presented at Conference on Understanding the 1990s: The Economy in Long Run Perspective, Duke University, March 26-27, 2004. | Crafts, N.F.R. 2003. Was 19th century British Growth Steam-Powered: the Climacteric Revisited." Explorations in Economic History 41 (April): 156-171. | Jovanovic, Boyan and Peter L. Rousseau. 2005. "General Purpose Technologies" in Handbook of Economic Growth, Volume 1B, P. Aghion, and S. N. Durlauf, eds. Amsterdam: North Holland, pp. 1181 - 1224. | Rousseau, Peter L. 2008. "General Purpose Technologies." In Durlauf, S. N. and L. Blume, eds. The New Palgrave: A Dictionary of Economics, 2nd Edition. London: Macmillan. | Field, Alexander J., Does Economic History Need GPTs? (September 28, 2008).*

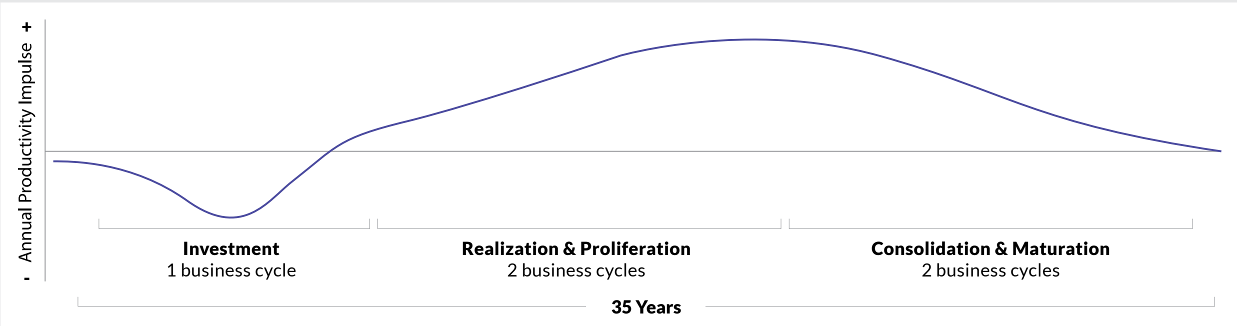
6 *Operating under the assumption that the degree of academic consensus is reflective of the relative momentousness of the innovation.*

7 *Electricity only provided dramatic productivity improvements in factories when the factories were built, from the ground up, to take advantage of the unique properties of electric power. Early attempts to electrify factories involved simply replacing a central steam-engine driving a crankshaft with an electric motor driving the same. All of the factory equipment remained belt-driven by that same central shaft, and so had to be clustered uncomfortably to minimize loss due to the mechanical transmission of power. Electricity can be transmitted nearly losslessly (on a relative basis); rather than being configured to minimize mechanical loss, ground-up electrically powered factories allowed machinery to spread out across the factory footprint to logically accommodate employee workspace and process through-flows.*

The stages of macroeconomic adjustment to disruptive innovation are illustrated in the chart below. The productivity associated with transformative technologies shifts from a promise to a drag during the heavy investment phase, accelerates rapidly as the GPT scales and proliferates, and then diminishes with competition and consolidation as the technology matures. The process typically evolves over four decades as each phase - investment, realization, proliferation, consolidation and maturation – takes roughly seven years, or a full business cycle.[8]

FIGURE 1

Stylized Productivity Curve for Technology Platforms

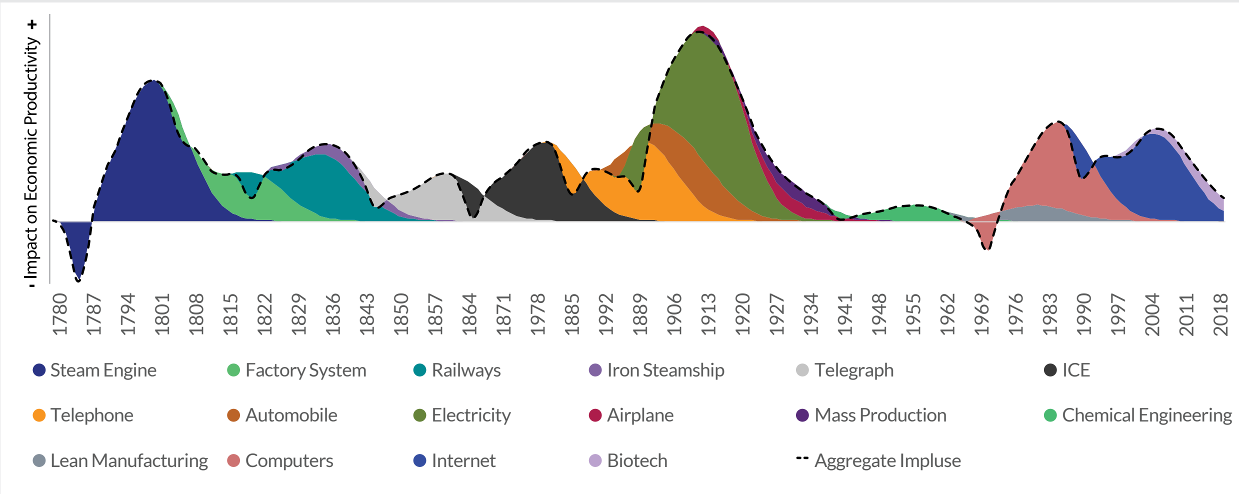


Source: ARK Investment Management LLC, 2019

During the last few centuries, disruptive innovation has waxed and waned in its impact on economic activity. By taking the productivity curve represented in Figure 1 and scaling it by the "consensus" scores tabulated in Table 1 we can produce an estimate for the aggregate relative macroeconomic productivity impact of innovation platforms over time—leading up to the introduction of the biotech platform several years ago.[9] The time series appears in the graph below. The dotted black line sums the estimated economic productivity impact, including the initial negative impacts of the investment phase.

FIGURE 2

Estimated Impact of Historical Innovation Platforms on Economic Productivity



Source: ARK Investment Management LLC, 2019

8 *As should be obvious this approximation is intentionally rough. If you accept our approximation for the date of commercial introduction of the Internet at 1984 then the investment phase extended through to 1991, realization and proliferation to early 2005 and consolidation and maturation to 2019. This timeline "feels" right, so long as the ongoing upheaval in mobile connected devices is a separate GPT platform.*

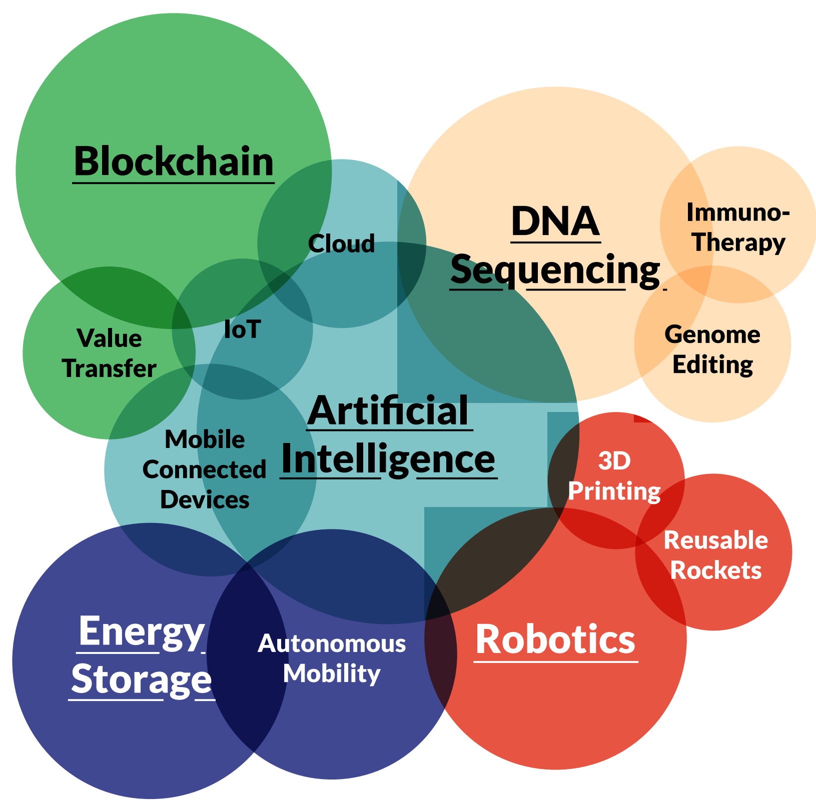
9 *For a critical discussion of this methodology see page 7.*

The early 1900s were technologically momentous, thanks to the concurrent evolution of the internal combustion engine and car, electrification, and the telephone. In contrast, after The Great Depression and World War II, innovation was fallow, perhaps setting the global economy up for a period of economic stagnation and inflation in the 1970s. Because transformative technologies are characterized by steep learning curves and rapid cost declines, the lack of innovation may have left the economy more prone to inflation while, in recent times, the computer and the Internet combined to offer strong innovation tailwinds and low inflation.

Identifying the Impact of Today's Transformative Technologies

This history helps put into perspective the impact of innovation on the economy both now and in the future. ARK Invest has identified 14 transformative technologies that are approaching tipping points as costs drop, unleashing demand across sectors and geographies and spawning more innovation. These transformative technologies could become the critical productivity signposts that future historians might identify. Because the lines between and among different platforms sometimes blur, particularly in this age of convergence, we have bucketed the candidate technologies into five major platforms: artificial intelligence, DNA sequencing, robotics, energy storage, and blockchain technology, as shown by the five largest circles in the graph.

FIGURE 3
ARK's Cluster of Major Innovation Platforms



Source: ARK Investment Management LLC, 2019

For each of these transformative technologies or innovation platforms, we model cost declines, addressable markets, price elasticity of demand, and adoption rates. From these forecasts we can estimate cash flows and ultimately the potential equity market value of each. In the table below, we delineate the timing of commercial introduction for the technologies, our expectation of the value that each should create in the equity market, and the consensus score that future historians likely will accord to each as a General Purpose Technology.

Table 2: Today's General Purpose Technologies Identified by ARK

Technology	Platform	Year of Commercial Introduction	Market Opportunity+	Estimated GPT Consensus Level
Blockchain	Blockchain	2009	Mega	7
Frictionless Value Transfer	Blockchain	2007	Mid	2
Autonomous Mobility	Energy Storage	2007	Large	5
Battery Systems	Energy Storage	2009	Mid	3
Sequencing Technology	DNA Sequencing	2004	Large	5
Gene Editing	DNA Sequencing	2012	Mid	4
Immunotherapy	DNA Sequencing	1998	Mid	2
Adaptive Robotics	Robotics	2005	Mega	6
3D Printing	Robotics	1986	Lower	1
Reusable Rockets	Robotics	2015	Lower	1
Neural Networks	Artificial Intelligence	2012	Mega	6
Mobile Connected Devices	Artificial Intelligence	2007	Mid	3
Cloud Computing	Artificial Intelligence	2007	Mid	2
Internet of Things	Artificial Intelligence	2011	Mid	1

Source: ARK Investment Management LLC, 2019

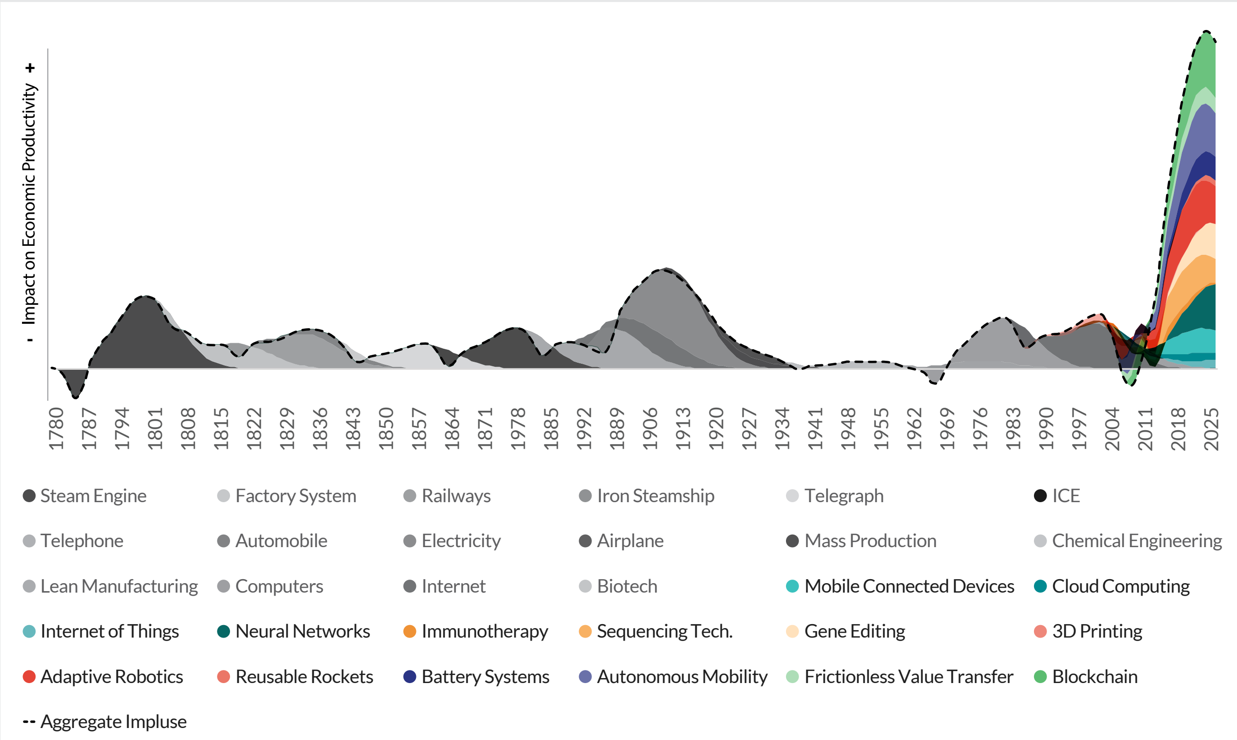
*+ Market opportunity provides an indication of ARK Invest's estimate of ultimate equity market capitalization attributable to the technology:
Mega = >$10 trillion; Large = ~$10 trillion; Mid = <$10 trillion; Lower = ~$1 trillion; Blockchain attributable market cap expected to be realized in cryptoasset network values.*

As shown, we assume that historians will not accord any current transformative technology a score as meaningful as that for electrification or the steam engine. Instead we assume that neural networks and adaptive robotics will be perceived to be on par with the introduction of the Internet itself, which could be too conservative. Neural networks probably will transform every sector while the Internet was more limited in scope. Similarly, adaptive robots are likely to enhance the productivity of physical labor throughout the global economy. Indeed, our modeling suggests that neural networks and adaptive robotics will create equity market appreciation exceeding $50 trillion, each having an impact more than double that attributable to the Internet to date. In this scoring system, only blockchain technology provides an upheaval more momentous than the introduction of computation, the automobile, or the Internet.

When combined with the Investment, Realization & Proliferation, and Consolidation & Maturation cycles, these scores extend the innovation impact time series another 15 years. As shown in Figure 4, this scoring system confirms the view that during the next 15 to 20 years, the five innovation platforms will combine to transform the global economy extraordinarily, in ways little understood today.

FIGURE 4

Estimated Impact of Technology Platforms on Economic Productivity



Source: ARK Investment Management LLC, 2019 | Forecasts are inherently limited and cannot be relied upon.

Specifically, this methodology suggests that the world has yet to feel the full force of the rogue technology wave that is likely to crest at three times the amplitude of any technology cycle in history. As for time frame, the five platforms are approximately nine years from peak productivity: think 1975 for computers or 1994 for the Internet to get a sense of all of the excitement to come.

We are aware that this analysis has a number of shortcomings. First, economists have had difficulty measuring the impact of General Purpose Technologies on productivity, perhaps because of the cyclical and secular cross-currents inherent in macroeconomic data, but also because of disagreements about which technologies qualify as GPTs. Second, we assign the same investment, realization and consolidation curve to each transformative technology, an obvious weakness because different technologies have different adoption cycles and submit to different diffusion curves. That said, while we model adoption curves for each technology and have found that they are changing at accelerated rates relative to past cycles of innovation, the assumption that adoption cycles are uniform enables a conservative comparison of today's advances against others in history. Finally, some historians even question the validity of General Purpose Technology theory because of screening criteria that seem too ambiguous to provide information value.[10] That said, we must try. Though we agree that the screening criteria present challenges, perhaps the problem is a function of the scarcity of historical examples rather than a weakness in the theory itself.

10 *See for example: Field, Alexander J., "Does Economic History Need GPTs?" (September 28, 2008).*

The criteria for transformative technologies are apparent in the five technology platforms that we have identified, allowing for comparisons with other innovation platforms throughout history. Electricity provided a discontinuous reduction in the cost to generate, transmit, and deploy automated power. Adoption was widespread across sectors, with applications at both the business and the consumer levels that inspired many other innovations to be built on top of them. Similarly, spurred by advances in neural nets, artificial intelligence is accelerating computational capabilities much more rapidly than expected, with ramifications for every industry, including multi-trillion dollars worth of innovations beyond what we can imagine now.

Every one of the five innovation platforms that we have identified shares traits common to the fundamental innovations throughout history. Robots are transforming from an automotive-centric technology to ubiquitous devices that most bits-based businesses will deploy. Lithium-ion batteries will power these and other devices, from flying personal vehicles to augmented reality glasses. DNA sequencing costs have fallen more than a million-fold during the past 15 years and will continue to unlock the codes to life and death, while the next class of multi-trillion-dollar global technology networks will be built on top of blockchain technologies.

That these technology waves all could crest concurrently presents business leaders and investors with both tremendous opportunity and tremendous peril during the next 10-15 years. The hallmarks of these technologies—rapidly declining unit-costs and -prices impacting many industries and geographies and spawning countless other innovations—stack in such a way that forecasters may underestimate their impact over meaningful time horizons.

A steep cost decline means that relative competitiveness will change radically during the next 10-15 years. Just because an electric vehicle is more expensive than its gas-powered counterpart today does not mean it will remain so. Financial participants and business heads probably will underestimate the breadth of addressable markets over the medium term.

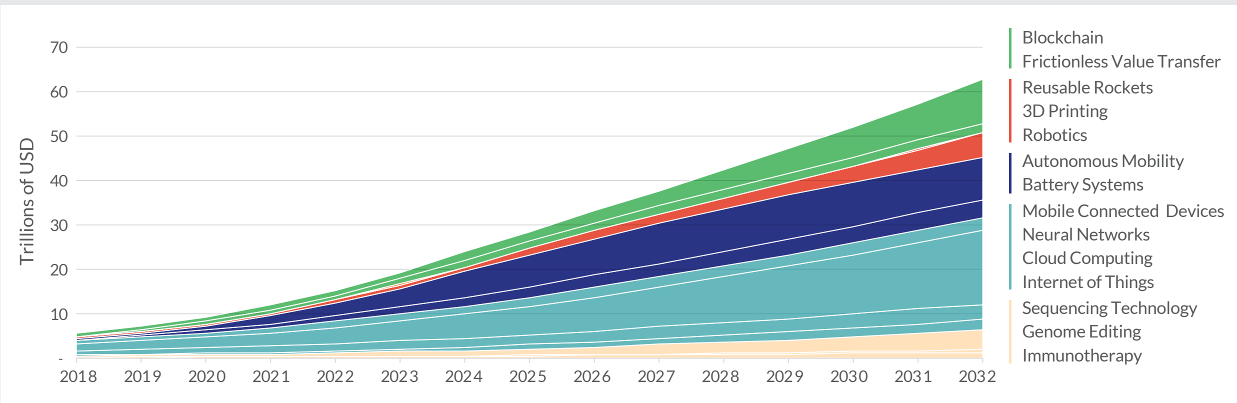
Technologies that cut across sectors are not only more likely to push down cost curves more rapidly than expected thanks to scaling benefits but also to be overlooked by industry-specific experts, who often are informed by and contribute to a status-quo-biased echo chamber of like-minded leaders. The fundamental economics of food production, delivery and consumption are likely to be transformed comprehensively by robotics, a concern that seems to be at the bottom of the list for grocery store CEOs and food retail analysts but, given the degree of disruption on the horizon, should be at the top. Often technologies that impact many economic sectors are derided as too uncertain in their ramifications for business leaders to evaluate.

And, innovation platforms that spawn more innovation often are underestimated because analysts and experts can't imagine the breadth and scope of applications that they will inspire. What if consumers could detect E. Coli before consuming it? What if geneticists could detect early-stage cancer with a blood test? What if experts could accelerate the domestication of wild animals? Innovation platforms frequently are assessed on the basis of the applications that already have been built or are obvious, but the unexpected application often unlocks the most value. The Chairman of IBM once stated famously that his team expected global demand for computers to increase to five, a classic failure of the imagination.

The opportunity associated with transformational innovation platforms starts by identifying the enabling tools that will allow the technologies to grow, the companies with direct financial leverage to the platforms themselves, and the entities well-positioned to deploy these technologies. The risks associated with disruption lie in the traditional indices upon which many investors have relied increasingly to guide their equity investments. By their nature, indices are backward looking, often based on tangible assets—that bank branch and this railroad line—that have generated predictable cash flows historically. An index cannot incorporate the threat of autonomous electric trucks to railroads, or the menace that mobile digital wallets—in-pocket bank branches— pose to banks saddled with bricks and mortar.

According to our estimates, the five technology platforms should generate more than $50 trillion in business value and wealth creation over the next 10-15 years. Today, they are in their infancy and account for less than $6 trillion in global equity market capitalization, giving investors an opportunity to capitalize by almost 10-fold if they have positioned their portfolios on the right side of innovation. As shown below, artificial intelligence should account for more than a third of this incremental value but each of the five transformative technology platforms should contribute meaningfully. By 2030, we expect that each will account for multiple trillions of dollars in equity value, as shown below.

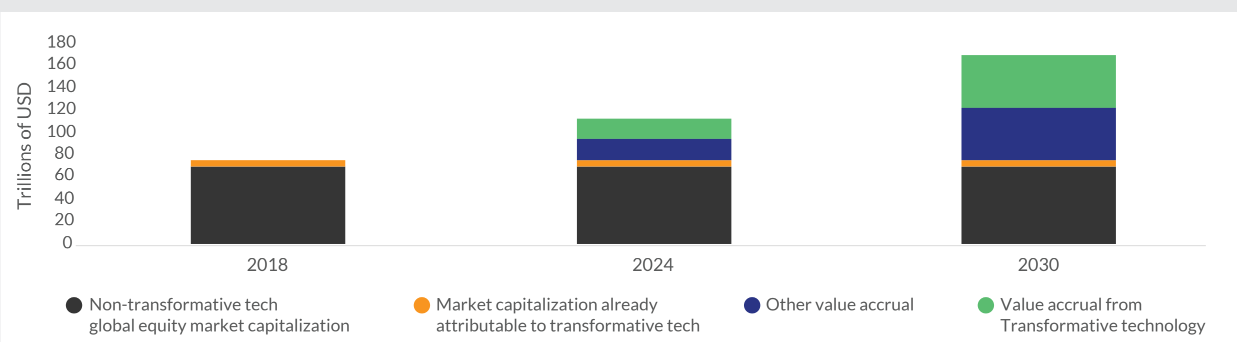
FIGURE 5
Projections For Total Equity Market Capitalization Attributable



Source: ARK Investment Management LLC, 2019 | Forecasts are inherently limited and cannot be relied upon.

Though this forecast does not anticipate that the incremental market capitalization will accrue solely to those companies already listed publicly, the implications for publicly listed companies are obvious and profound. Globally, the public equity market capitalization totals approximately $80 trillion.[11] Historically, equity markets have appreciated at roughly 7% at a compound annual rate, suggesting that roughly $90 trillion of market capitalization will be created by 2030 if past is prologue.[12] According to our research, transformative technologies like those we have referenced above could garner

FIGURE 6
Equity Market Capitalization Potential Growth Composition



Source: ARK Investment Management LLC, 2019 | Forecasts are inherently limited and cannot be relied upon.

11 *Equity market capitalization globally totaled $83 trillion as of end of March 2019 according to the World Federation of Exchanges monthly report.*

12 *Compounded annual price appreciation of the S&P 500 measured from 1940 through 1Q19 equals just over 7%.*

more than half of the incremental $90 trillion during the next 11 years, implying that the majority of the growth in global equity markets across every geography, every sector and every style will be influenced by innovation platforms which, ultimately, will account for roughly a third of the total value of global equity markets, as shown in Figure 6.[13]

Given the magnitude of the technological impulse we are anticipating, aggregate equity market capitalizations could appreciate at a more rapid rate than historically has been the case, as the exponential growth associated with innovation increases average returns. That said, the sagging returns from traditional businesses being disrupted or destroyed by transformative technologies could be a significant drag on portfolios exposed to broad-based benchmarks.

Though the information, forecasts, and comparisons presented in this paper are crude—intentionally so given the time horizon—the conclusions are difficult to ignore. Ours is a technological moment without historical analogue. The threat to existing businesses is grave and the opportunities for companies participating in new technological ecosystems probably will be measured in the trillions. We believe that historians will look back upon these years with wonder—that the world delivered so much innovation in such a short period of time. Life and business are changing now. That change—roiling, disruptive, tumultuous, productive—could prove to be more profound than any other in history.

Given the opportunities and threats that each of these technology platforms poses, we will discuss each in a bit more detail. If our research is correct, then each of these platforms will create multiple trillion dollars in equity capitalization over the next decade.

Artificial Intelligence

Computational systems and software that evolve when fed with data should solve heretofore insoluble problems while automating knowledge work and accelerating the permeation of technology into all industries globally. These learning systems will require different computational hardware than historically has been the case and will provide insurmountable competitive advantages to those companies whose business models are centered on data. They will transform not only retail, media and telecom, as did the Internet, but all sectors in the economy, even those impervious to disruption, notably health care and financial services.

Energy Storage

Declining battery costs should cause a Cambrian explosion in mobile form factors and push the supply of electricity to the edge of networks. According to our research, electric vehicles will become price competitive with traditional cars within three years, enabling micro-mobility and aerial systems - including flying taxis - that will transform city landscapes. These innovations will increase the demand for electrical energy, displacing fossil fuels and provisioning electrical energy more efficiently while reducing not only the vulnerability of grids but also operating expenses and the capital intensity of transmission and distribution. As traditional automotive manufacturers and suppliers unravel, the energy sector will face peak oil demand while infrastructure evolves to accommodate high electricity-consuming mobility business models.

13 *In the embedded forecast roughly a fifth of the value accrual to transformative technology platforms would accrue in the form of cryptoasset network values, a category of asset that is unlikely to be considered comparable to traditional equity.*

DNA Sequencing

As the cost to sequence a whole human genome falls precipitously, DNA Sequencing, a test once limited to the research lab, should see widespread clinical adoption and volume growth crossing two orders of magnitude.[14] Cancer care will transform from treatments to cures, as will that of complex disorders, as the efficiency of research and development in the biotech space soars and scientists crack the code of life and death. Gene-editing should transform chronic diseases into curable conditions, changing the economics of therapy and destroying legacy pharmaceutical franchises and traditional diagnostic testing businesses. The advances will extend into agriculture and materials science.

Robotics

Advances in software, sensors and actuators should enable robots to operate alongside humans in all sorts of environments. If their unit costs decline by more than 50% while their capabilities increase, as we anticipate will be the case, robots should transform every business that depends upon physical processes and workflows.[15] Fears about their impact on employment should prove unfounded as robots will boost productivity and lower unit costs enough to transform non-market activities—such as food preparation and grocery shopping—into services, creating demand that overwhelms the productivity improvements.

In the mobility space, robots that can move people and parcels from place to place, operating on top of legacy transportation infrastructure and integrating with legacy systems, should change the economics of physical movement, reducing the cost of taxi delivery and surveillance by an order of magnitude. Autonomous taxi travel will become the norm and personal car ownership the exception, enabling new business models and increasing the velocity of ecommerce. Data generated by autonomous systems will provide real-time insights into decision making. Companies in the automotive, logistics, retail and insurance sectors that do not or cannot adapt to the new world order should become severely impaired.

Blockchain Technology

We believe all money and contracts are likely to migrate onto open source protocols that enable and verify digital scarcity and proof of ownership. The financial ecosystem will be forced to reconfigure and take advantage of more transparency, fewer capital and regulatory controls, and a collapse in contract execution costs. More of everything in the world will become money-like: fungible, liquid, and quantified. Every corporation and consumer will have to adapt, calling into question the very structure of a corporation.

We believe that no sector, industry, or company in the world will escape the throes of change now underway.

14 *ARK Investment Management LLC, Big Ideas 2019, page 63.*
15 *ARK Investment Management LLC, Big Ideas 2019, page 80.*

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Brett joined ARK in February 2014. Brett has worked alongside Catherine Wood, ARK's CEO and CIO, for almost ten years since their time at AllianceBernstein. As Director of Research, Brett directs the proprietary research of ARK's investment team. Initially, Brett directed research for ARK as principal and founder of iamB Consulting, a firm that specializes in dimensioning the ramifications of innovation and disruption for investors and high-growth ventures. From 2007 to 2012, he conducted thematic research and advised portfolio managers as a member of AllianceBernstein's Research on Strategic Change team. His research topics included "Global Energy in the Face of Carbon Dioxide Regulation", "Social Media and the Rise of Facebook", the "Reformation of the Financial Services Landscape", and the "Emergence of Electric Vehicles". Prior 2007, Brett worked in business development in the Radio-Frequency Identification industry. Brett earned his Bachelor of Science in mechanical engineering at MIT.

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