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Innovation Insights

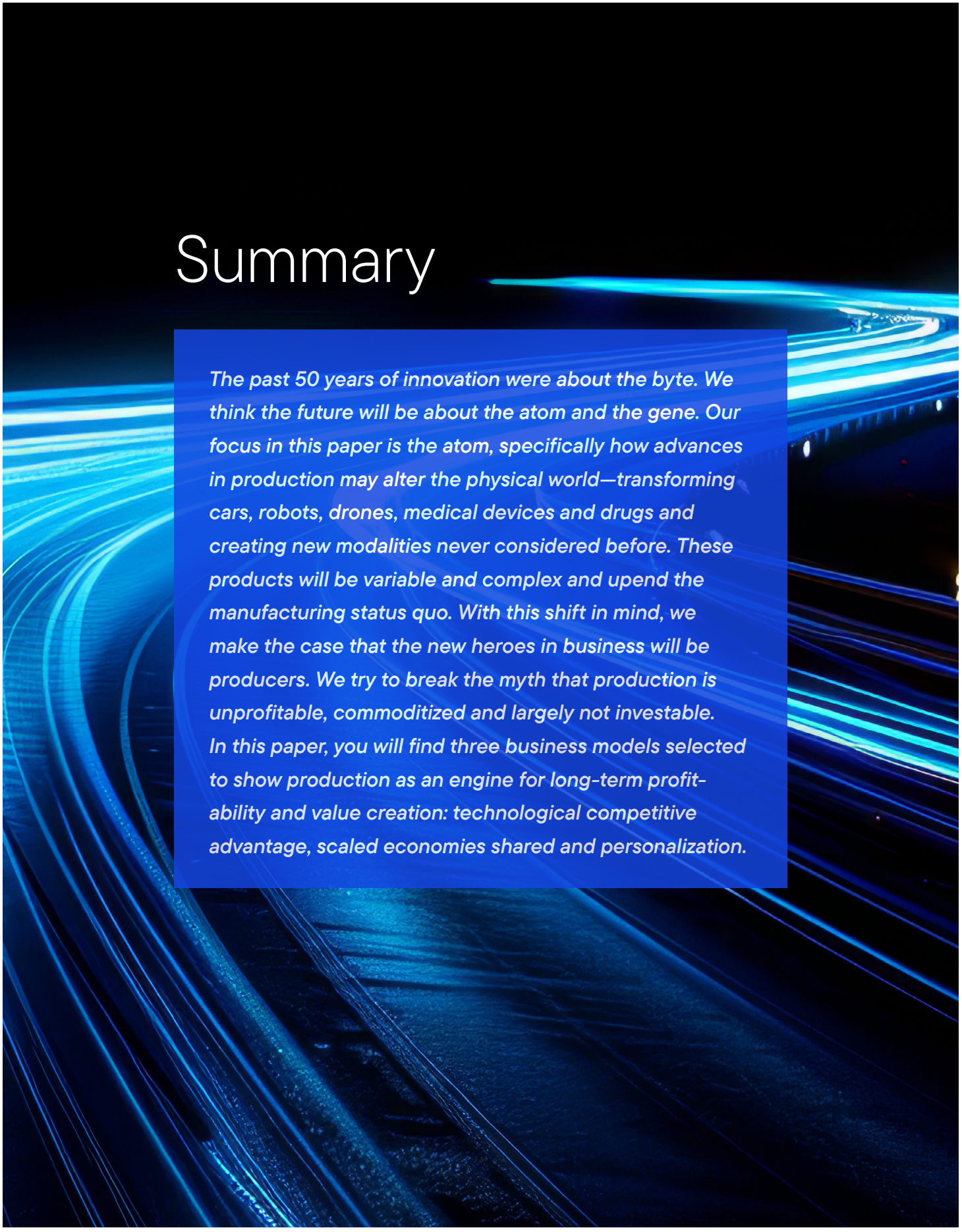
Franklin Equity Group

Production

Production in the Fourth Industrial Revolution doesn't have to be commoditized—three frameworks for how to invest



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Summary

The past 50 years of innovation were about the byte. We think the future will be about the atom and the gene. Our focus in this paper is the atom, specifically how advances in production may alter the physical world—transforming cars, robots, drones, medical devices and drugs and creating new modalities never considered before. These products will be variable and complex and upend the manufacturing status quo. With this shift in mind, we make the case that the new heroes in business will be producers. We try to break the myth that production is unprofitable, commoditized and largely not investable. In this paper, you will find three business models selected to show production as an engine for long-term profitability and value creation: technological competitive advantage, scaled economies shared and personalization.



Matthew Moberg
Portfolio Manager
Franklin Equity Group

Dear Investor,

This paper is both a journey and a story. Many people don't have time for either, so let me give you the outline and thesis up front: Production in the Fourth Industrial Revolution doesn't have to be commoditized. You can see this already in automated driving, robotics, military applications and many more products. We believe this change in what we produce and how we produce it will be profound, and we would not advise relying on legacy frameworks to invest in this environment. In just one small example, we are not confident legacy auto manufacturers will make the best electric vehicles. Even though the West—and particularly the United States—has reduced its reliance on making things, we think this disruption may cause the pendulum to swing in the opposite direction.

Is it possible, going forward, that the boring, organized and yet still inventive factory floor manager might displace the fascinating inventor as the economy's new hero? There are already examples: Tim Cook alongside Steve Jobs; Morris Chang alongside Jensen Huang; and, our favorite from history, Carl Bosch alongside Fritz Haber. Production matters.

In this paper, we outline three frameworks of production that avoid commoditization and instead have the potential to be tremendous generators of wealth. If you would like to learn of those immediately, skip to Section two of the paper. However, if you would like to be a part of something longer, please continue here.

Last year, we wrote a paper about blockchain. In it, we asserted that intermodal containerization was the second-greatest innovation of the 20th century. It was a fun and outlandish claim, but it did have merit. The simple shipping container allowed almost a billion people, particularly populations in East Asia, to pull themselves out of poverty. At the same time, another three quarters of a billion people in the relatively rich West enjoyed deflation in the cost of goods. About half the world's population experienced better living conditions, extended life expectancy and changed geopolitics. Change of this magnitude came from a reduction in shipping costs from between 15%–90% of the price of a good to less than 1%.

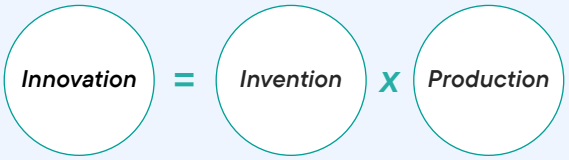
When I would discuss this story with clients, their first question often went in an unexpected direction, at least to me. They asked: "If containerization was the second greatest innovation of the 20th century, what was the first?" We like rankings. You can rank on so many metrics, and they are all so debatable. And, yes, we are investors first, so the most appropriate metric for us would probably be how much market capitalization an invention created. However, in this case, we chose to base our ranking on how many lives were affected. Containerization, for instance, may have improved the lives of billions, but it did not create a lot of direct and investable market cap.

The greatest innovation of the 20th century, in our view, is fertilizer. While containerization changed and improved lives, synthesized fertilizer created them. Close to two billion people on earth today may owe their lives to a secure food supply.[1] Food scarcity, historically speaking, has been a major catalyst for revolution, war and unrest.[2] It is fair to argue not only that synthesized fertilizer created lives but that it also created peace.

The story of fertilizer, which we will outline below, highlights the importance of production to the success of an innovation. It has been easy to miss this point over the past 50 years because the bulk of invention over this period has mainly made use of bits and bytes. One of my favorite formulas related to innovation is the following:



If the cost of goods is zero, as it is for most software and internet businesses, this formula is inclusive.[3] While the future is unknown, we anticipate that advances in the physical world—specifically robots, automated driving, genomic materials and personalized products—may begin to benefit from the wide availability of data. This means a more accurate formula related to innovation in the future may be:



In this paper, we argue for the importance of production through the story of synthesized fertilizer and go on to outline three clear frameworks to benefit from investing in production.

The success of everything digital, the engine of the Third Industrial Revolution, has overshadowed the profitability and competitive moats around production. Now, at the onset of the Fourth Industrial Revolution, we will see new innovations apply data to the real world. With this context in mind, we predict it is time for production to have its moment. As we move from manipulating data (the byte) to making physical (atom) and organic (gene) products, we believe there is meaningful opportunity ahead to profit from making things.

We hope you enjoy the paper.



Matt Moberg

Section One

The driest place on earth

This story begins at one of the driest places on earth: an archipelago off the West Coast of South America called the Chincha Islands. I know this piece of information because I have young children, and they are always asking about the extremes. Which is the tallest mountain? Where is the deepest sea? What is the longest road? The Chincha Islands, no wider than one square mile, receive less than an inch of rain a year.[4] That they are twice as dry as the Sahara Desert[5] isn't even the most interesting thing about them. Rather, it is that for hundreds if not thousands of years, millions of birds have lived on these islands and fed on anchovies in the deep, clear Pacific Ocean. The anchovies, for their part, eat the plankton that thrive on the area's cold, nutrient-rich waters. This is another wonderful example of nature's balance. Except, perhaps, for one thing. The islands are naturally only ~100 feet in elevation at their highest level, but, when the first Europeans learned of them in the middle of the 19th century, they measured over 300 feet high.[6]

At this point, the story may feel like a riddle. Millions of birds. Lots of feeding. Thousands of years. No rain. If you guessed the additional elevation was bird poop, or more politely, "guano," you would be correct. When the Europeans learned the island had so much guano, they quickly knew they had an economic winner on their hands. Guano, rich in phosphates, was some of the best fertilizer then available, and Europe needed more food for its exploding population. **Here was this "white gold" resting on the surface of the earth, ready to be shoveled onto the back of a ship and sent to faraway farmlands.** It was guano's surge in England that led to an agricultural revolution which then spurred the Second Industrial Revolution, urbanization and, ultimately, modern life. Hidden treasure on the high seas might have made a better story for the movies, but smelly guano was just as valuable.

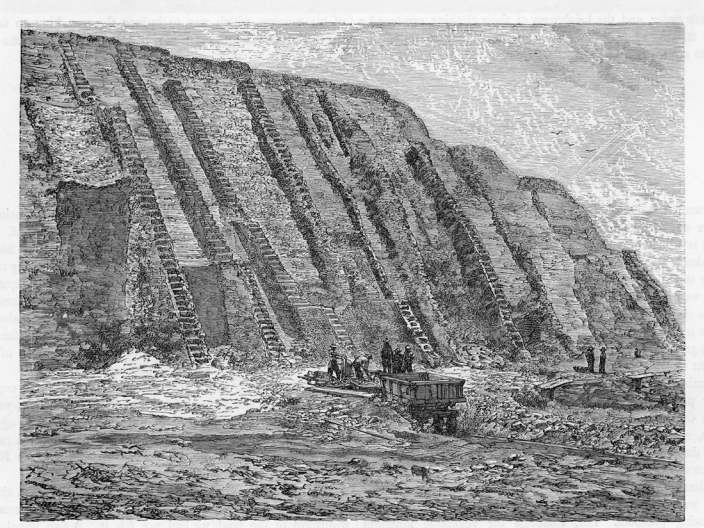
This story exists in a broader context. The political history of the world highly correlates to economic history, and economic history highlights the key role of food prices. As recently as the Arab Spring and as far back as Mesopotamia, this has been true. The Arab Spring, which occurred in 2010, coincided with a spike in bread prices.[7] For those caught in subsistence living, a near 50% increase in pita prices can spark bread riots that spiral into broader social unrest and upheaval.

Of particular importance to the story of guano is the year without a summer in 1847, which led to the uprisings and revolutions that swept across Europe in 1848. No ruler, particularly a monarch—whose hold on power is often tenuous—wants unrest. So, at the time, the Spanish did exactly what one might expect—they fought Peru to mine the guano, to keep food prices at home relatively low.[8]

Over 2,000 Chinese indentured servants came to the islands to harvest the guano after it was discovered.[9] The photos are simply amazing: Ten-foot ladders, piece after piece loaded onto a ship in hot, dry conditions. The risk of being buried alive under the guano was real.

Exhibit 1: Mountain of Guano at the Driest Place on Earth

This Is What 20 Stories of Bird Guano Looks Like. A Tough Way to Feed Your People.



WORKINGS AND GUANO DEPOSIT ON THE CHINCHA ISLANDS.

Europe's population was exploding, and they desperately needed to find reliable sources of fertilizer. Sending ships across the earth to look for guano probably felt—well—unsustainable.

The greatest invention of the 20th century

The scientific breakthrough came in the early 20th century from one of the greatest chemists of his day, Fritz Haber. He invented a way to combine nitrogen in the air with oxygen gas to make ammonia, a synthetic fertilizer. But, in his lifetime, he was better known for discovering that chlorine gas could be used as a chemical weapon during World War I.[10]

His involvement in chemical warfare plagued Haber for his entire life. And yet, as Benjamin Labatut imagines it, Haber, on his deathbed, when asked to name his greatest achievement, bypassed this creation entirely and instead said that it was his invention of ammonia fertilizer that would really change the world.

This was right. Although his contribution to chemical weapons was devastating in war, his work on synthesizing fertilizer ushered in a time of tremendous peace. At the time, the population was increasing dramatically, and there were no good alternatives to provide secure food sources. Artificial fertilizer helped ensure that people had plenty to eat and did not need to fight over resources.

That certainly qualifies artificial fertilizer, in our view, as one of the greatest inventions of all time.

But the process isn't named for Haber alone. It is the Haber-*Bosch* process.

We would tell you about Carl Bosch's background if there were much interesting to say. He was from a good family, married a nice woman and had children. He was meticulous, cost-conscious, mathematical and boring.

True to form, **Haber was the madcap inventor and Bosch the methodical engineer.** Yet it was Bosch who proved critical.

Haber's solution, until Bosch's involvement, produced only about a handful of fertilizer in one batch.[11]

Although Bosch was certainly less colorful, his achievements were no less amazing. He turned a converter the size of a cookie jar into an industrial plant capable of feeding an entire nation. His new device withstood pressure equivalent to 2,000 cars pressing on one square meter. In the early 1900s, this was not unlike trying to make transistors the width of atoms in difficulty.

In its first year, Bosch's factory produced enough nitrogen for agriculture to feed nearly one in 10 Germans.[12] The next year, capacity doubled. Six years later, capacity had grown tenfold and outpaced guano production.

It is hard to overstate just how important the Haber-Bosch process has been to our world. Artificial fertilizer replaced rapidly depleting organic nitrogen sources. Without it, population growth would have stagnated. Farmers in the late 20th century used 125x more fertilizer than their 19th century counterparts. That was enough to provide 47 grams of plant protein daily for each of the world's population at the time of six billion people. In the intervening years, we have added two billion more people. It is not too extreme to say that all these additional people may exist because of the Haber-Bosch process.[13]

The scientific breakthrough came in the early 20th century from one of the greatest chemists of his day, Fritz Haber. He invented a way to combine nitrogen in the air with oxygen gas to make ammonia, a synthetic fertilizer.



Section Two

A new era of production

As innovation investors, we have a lot to learn from the saga of Haber and Bosch. Their story, to us, is about one simple idea: **For an innovation to take off, invention is only part of the story.** You must be able to produce and commercialize the invention at scale. **Without production, there is no innovation.**

For every Fritz Haber, there must be a Carl Bosch. You can't have the iPhone with just Steve Jobs. You also need Tim Cook, the faithful operator. You can't have AI with just Jensen Huang, Nvidia's famed visionary. You also need Morris Chang, the founder of the only company in the world that can make the leading AI chips.

This dynamic is at work throughout the economy. The various technologies of the Fourth Industrial Revolution are only amplifying production's importance. Aging infrastructure, the push for renewable energy, space exploration, and advancements in genomics and medical devices all demand the construction of physical things in the real world.

This era of production can be highly profitable for investors. We have identified three models that may create tremendous value over the next decade and longer.

1. Technological competitive advantage

One way to make money in production is to have a technological competitive advantage that enables you to make something no one else can. If you have a sustainable technological edge, profits are likely to follow. One hundred years ago, successfully crushing two reactive gases into a space the size of a cookie jar qualified as one. We have come a long way since then. Today, the most advanced production in the world is in semiconductors. **At every step of the way, making a computer chip is, for lack of a better word, bonkers.**

If you want to build a house, your first step is to call an architect to draw you a blueprint. Similarly, if you want to build a chip, you need to call a designer.[14] But building a chip is on another level from a regular house. Instead of using lumber, your material is atoms, and those atoms must fit together perfectly. A chip is far more than an inert piece of silicon; it is a fusion of hardware and software exquisitely fine-tuned for a specific goal.

The chip "blueprint" is crafted by a team of engineers who program and design the chip for its specific use. It could be a CPU for computations, a GPU for graphics, DRAM for memory or analog to interact with the outside world.[15] On the software side, this involves writing millions of lines of code.[16] On the hardware side, the designers must be creative, solving puzzles of three-dimensional geometry on a microscopic scale.[17] In the past, it was enough to make things smaller.[18] Now, the electrons themselves pose a challenge, behaving in ways that defy classical rules, traversing barriers as if they were not there.[19] Today's semiconductor designers must contend with unseen forces that even the world's best physicists don't fully understand.[20]

Once you have a plan, you need to call a builder. Only a handful of companies in the world can take such a complex blueprint and make a chip from it. The specialized factories they use—called fabs—cost tens of billions of dollars to build, in part because of one essential machine that has a price tag in the hundreds of millions. This machine, a triumph of engineering, produces extreme ultraviolet (EUV) light, used to draw the transistors on the chip. Chris Miller, author of *Chip War*, describes how it works:

> The engineers realized the best approach was to shoot a tiny ball of tin measuring 30-millionths of a meter wide moving through a vacuum at a speed of around 200 miles per hour. The tin is then struck twice with a laser, the first pulse to warm it up, the second to blast it into a plasma with a temperature around half a million degrees, many times hotter than the surface of the sun. This process of blasting tin is then repeated 50,000 times per second to produce EUV light in the quantities necessary to fabricate chips.[21]

Making this machine is so difficult that only one company in the world can do it. But anyone who wants to make a leading-edge chip[22] will need one. That may be the most extreme example, but other parts of the process such as etching, packaging and deposition are almost as complex.

Beyond the cost of this and other machines, the manufacturer must keep the inside of the facility pristine. A single speck of dust in the wrong place can ruin a batch of chips. The air is cleaned constantly, and workers wear special gear called "bunny suits." It's a balance of precision and ingenuity, where every step

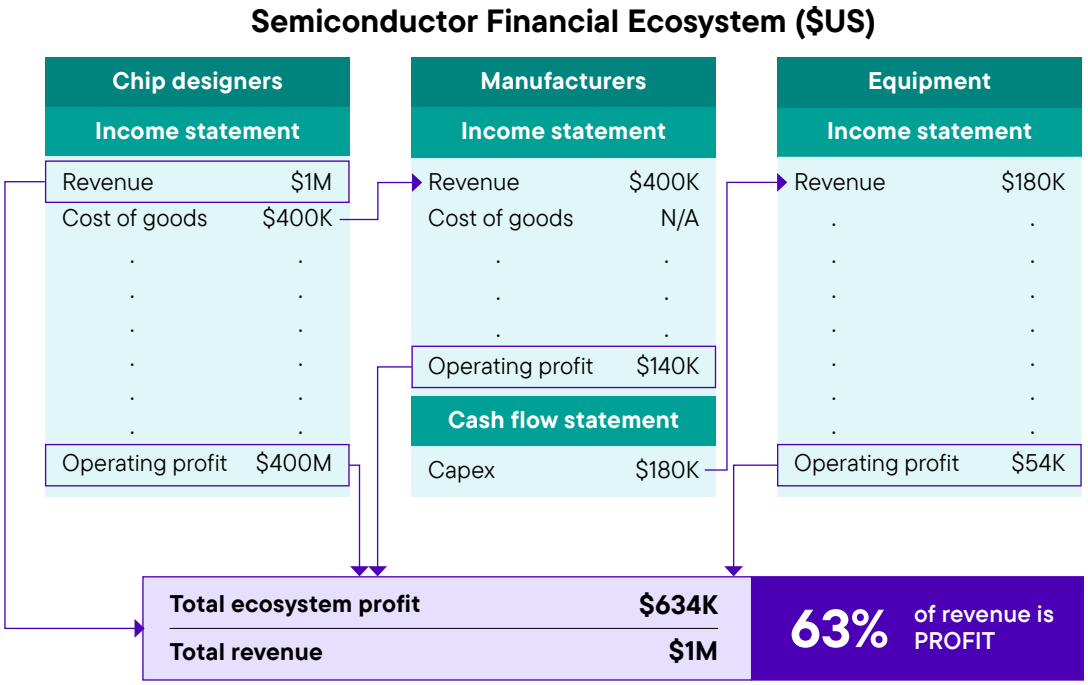
must be nearly perfect or the whole endeavor fails. Even with every precaution, at least when production on a new chip first starts, about one in every three chips being defective is considered a good yield for a leading-edge batch.[23]

We mention these details to highlight that each of the companies in this process, including the designers, the manufacturers and the equipment makers, benefits from the same competitive advantage: a technological edge. As Moore's law moves forward, they have not faltered. They continue to make leading-edge products for which we seem to have an insatiable demand.

Today's transistor nodes are approaching one nanometer. To put that in context, a nanometer is roughly how long a fingernail grows in one second. A human hair is 80,000 to 100,000 nanometers wide.[24]

The overall economy cannot function without chips. For example, China currently spends more on chips than it does on oil.[25] With that sort of demand backdrop, it follows somewhat predictably that those who enable the chip production process are indispensable. You can see this competitive advantage in the amazing profitability of the entire semiconductor ecosystem.[26]

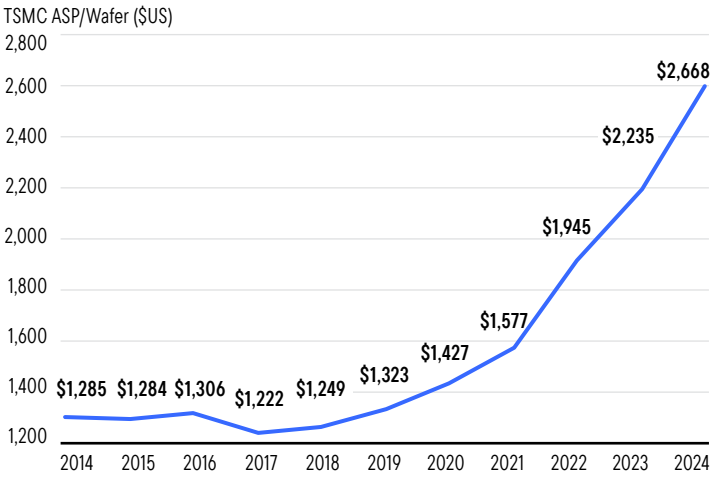
Exhibit 2: At Every Step of the Way, Firms in the Ecosystem Earn Healthy Profits



Source: Chart uses an index-weighted average for operating profit figures, calculated from the semiconductors section of the Vanguard Total World Stock Index Fund (VT). Capital expenditure for the manufacturing category is estimated as a historical % of revenue. Classifications of firms into designer, manufacturer, or equipment provider are our own. Chip software providers are excluded.

We roughly estimate that for every dollar spent on chips, the semiconductor ecosystem will earn nearly two-thirds of that dollar as profit. Of that, we estimate around 40% will go to the manufacturers and the producers of the physical equipment needed in the factories. This dynamic has lasted for years, and has resulted in pricing power for the industry, as this chart of average selling price (ASP) per wafer[27] shows:[28]

Exhibit 3: If We Are Making More and More Chips, Why Aren't Prices Going Lower? Answer: Technological Advancement



Source: Bernstein TSMC model.

The price of a wafer has steadily increased over the past decade. As long as semiconductor complexity continues to grow, we believe this trend will continue. This is no coincidence but instead a consequence of these companies' technical achievements, built up over decades of progress.

Today, semiconductors offer the best example of an industry where a technological edge drives exceptionally profitable production. The technology is advancing at a rapid pace, and demand for chips is continuing to increase, leaving a great backdrop for industry leaders. As we look forward, **we think there could be more manufacturers with large excess profit pools flowing from a technological edge.** For instance, some segments of clean energy, robotics, health care, and even space exploration have the potential to enjoy material excess profits for an extended duration. If these new technologies continue to develop in this manner, we believe their respective industries could also experience excellent profits from production.

2. Scaled economies shared

A durable technological edge is a powerful way to earn a good profit in production. However, if the edge is not sustainable, the company runs the risk of earning excess profits, which will draw increased competition. When this happens, building sustainable moats based on scale and pricing is an effective way to maintain profitable production.

"The critical ingredient isn't just to have scale in production, but to share that scale with consumers, thereby preventing new competitors entering the market."

Our favorite framework for this model is called "scaled economies shared," coined by two investors we admire, Nick Sleep and Qais Zakaria. They first identified it at work in retail. We see it in production. The concept is simple: pass the cost advantage of enormous scale back to your customers in the form of lower prices. In return, those customers will become increasingly loyal and drive ever more scale.

You can see this model at work for the largest three retailers in the United States. To start, each of these three companies has enormous scale—together, they capture around one of every three dollars that the American consumer spends.[29] But scale is just one half of the model. The other half is pricing. These companies only make about a nickel for every dollar spent. They forego some profits to deliver the lowest possible price to their customers. This is the "shared" part, and it is the key to the model.

When you share the scale with customers, they are happy and do more business with you. This drives further scale, earns more profits and ultimately results in a stable competitive advantage over the long term.

Scaled economies shared also works in production, particularly when innovation progresses, new industries emerge, and being the first to scale profitably matters. You can observe this with the rise of electric vehicles (EVs).

At the start of the EV trend, we were sold environmentalism, electrification, modernity, design and automation. Now, the next selling point could be the simplest for any consumer to understand: price.

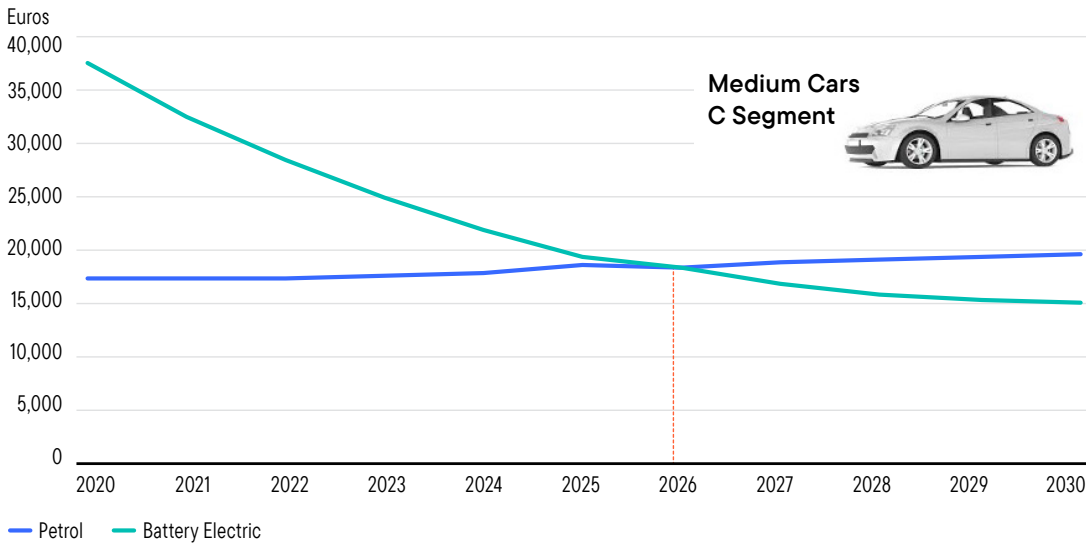
The earliest EV makers likely believed from the very beginning that, over time, EVs would cost less than internal combustion engine (ICE) vehicles. The reason: an ICE car requires thousands more parts than an EV.[30] And less complicated production is cheaper production. As Elon Musk described it in a recent Tesla earnings call, much of the reason for their success comes from their relentless focus on cost containment. As he put it, they worked first to "delete a lot of parts" entirely and then to "get US$0.50 on average out of the 10,000 items" in an ICE vehicle.[31]

The fruits of these ideas are now taking shape. The cost curve for EVs continues to come down, sliding toward parity with ICE vehicles. The EV manufacturers are now putting scaled economies shared in motion. They are choosing not to capture those excess profits today and instead to return the cost savings to customers through lower prices, stifling the competition in the process.

The numbers tell the story. The world leaders in EVs from the United States and China sell millions of cars a year and make billions of dollars in operating profit.[33] As the below chart suggests, the largest EV manufacturers are increasingly choosing to share the benefits of their scale, with eyes on cars cheaper than their ICE counterparts.[34] On the other side, legacy automakers sell EV cars on the scale of thousands, not millions, and, more often than not, operate at a loss on EVs.[35]

Scaled economies shared in production is not exclusive to electric vehicles. We see it in other places in hardware, like smartphones. iPhones today, on an inflation-adjusted basis, are more than 20% cheaper than in 2017.[36] In a world where inflation peaked at around 9%, this reflects a marked pivot in strategy for Apple.

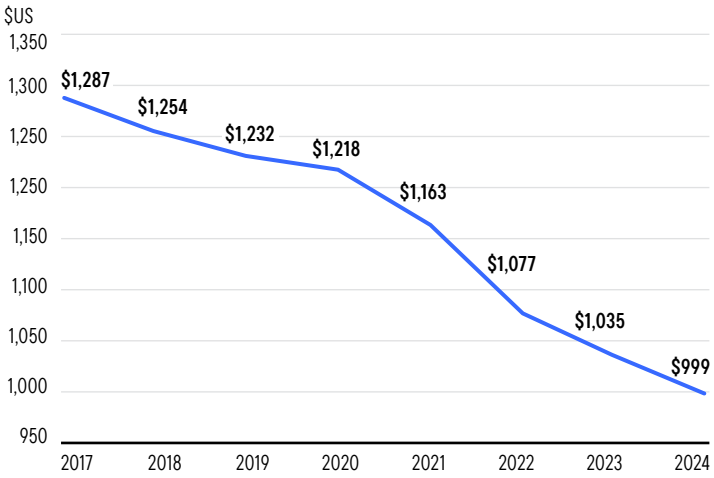
Exhibit 4: At Price Parity, EVs Are about 9%[32] of All New Cars Sold. What Happens if EVs Are Materially Cheaper than ICE Cars?



Source: "Explained: Are we ready to switch to emissions-free cars?" Transport & Environment. July 15, 2021.

Exhibit 5: Even if It Might Not Feel Like It, Today's iPhones[37] Are Cheaper

Inflation-Adjusted iPhone Prices



Source: Khan, Zak. "iPhone price history: How Apple's pricing changes (inflation included)." Android Authority. November 18, 2024.

This may be reflective of a broader shift in strategy for smartphone makers, where the phone is now the platform upon which other things are sold. Once you own the phone, you're in the ecosystem, and there is a whole host of other ways companies can earn revenue, like cloud storage, television, music and games. So, by sharing the benefits of scale through a cheaper phone, these smartphone companies may increase their revenues over the long-term.

Scaled economies shared is also happening elsewhere. In media, ~US$15 a month gets you access to ~US$16 billion in content spend from a streamer.[38] And in the military: Spending on cost-efficient drones can build a defense against older, more expensive technologies.

These are just a few examples of how scaled economies shared works in production. We expect that, as the Fourth Industrial Revolution leads to more innovation, this model will become more and more common—and fruitful, for those managers who can resist the tug of avarice and instant gratification and instead share the value with their customers.

3. Personalization and new manufacturing methods

Scaled economies shared was made possible through the rise of mass production, itself only a recent phenomenon. Starting with the invention of the assembly line in the early 20th century, it became clear that standardizing goods and producing them in bulk was a more efficient and cost-effective way of doing business. The consequences have been far-reaching. Today, we live in a world of standardization, of no more than three sizes—small, medium and large.

> **"Our final model of profitable production, personalization, imagines a different sort of world where difference is the norm, and there is a unique product for each person at an affordable price."**

We think personalization will likely take hold first in areas of the economy with pricing power, like health care and, to some extent, fashion. Later, as the underlying technology improves, it will spread throughout the economy.

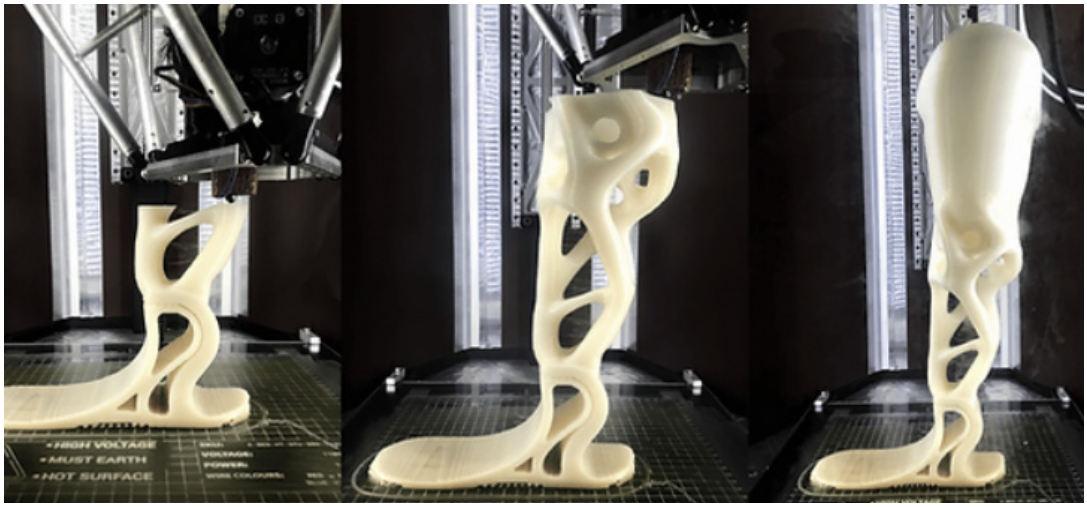
Of our three models, personalization is the most nascent, taking shape out of advancements in equipment, technology and manufacturing. However, finding efficient but flexible ways to make things is still the main bottleneck, and so use cases today are idiosyncratic and experimental. But progress is accelerating.

From today's vantage point, we don't know how profitable personalization will be for the producers. It may be that the profits in the ecosystem accrue to those who make the equipment and the factories, rather than the goods. But we can envision a future where a personalized product is table stakes, rather than optional enhancement, for most companies.

Health care companies are the earliest adopters of personalization. Take, for example, the smile aligner, a popular alternative to traditional braces. Before aligners, orthodontists relied on their judgment to place standard brackets and bend the wire by hand with pliers. Then came the 3D printer. 3D-printed aligners and scanning technology take the guesswork out of orthodontia and make the whole process more efficient.[39]

Exhibit 6: A Prosthetic Leg 3D-Printed by a Start-Up in San Diego

Is It Better Than the Real Thing? Five Minutes to Print or 25 Years to Grow



Source: DeVivo, Luca. "UniLeg Spotlight: The World's First Complete 3D Printed Below-Knee Prosthesis Solution." Limber. June 19, 2024.

Aligners have transformed an industry that was once local and sub-scale into profitable mass manufacturing of personalized products. Millions of people can now hold in their hands an object so detailed that it captures the exact topography of their unique smile.

This sort of personalization is also starting to gain ground in surgery, especially for routine procedures, like knee replacement. The old method was not unlike putting a broken vase back together with super glue. Doctors would use their judgment to find the right spot on the knee, adhere a piece of metal to the bone, and scrape out the damaged tissue.[40] It was better than nothing, but, for what matters, like longevity and recovery time, it wasn't fantastic.

Now, doctors, with the help of robots and 3D scans, can place a new type of "cementless" prosthetic to match the unique architecture of the patient's knee. The existing bone then grows around the prosthetic and holds it there permanently—no glue involved, and no future surgeries needed.[41] Fewer repeat surgeries could save the medical system thousands of dollars.

Aligners and knee replacement are two instances where the enabling technology is reasonably advanced. In other pockets of medicine, we need further technical advancement for personalization to take hold at scale. An example of this is immunotherapy, a promising new cancer treatment which may prove to be among the most consequential discoveries in health care.[42]

Immunotherapy modifies the unique immune system of the patient to cure her cancer.[43] Once a patient's blood is removed, her unique immune cells are edited, grown artificially in a lab, and then returned to the patient equipped to find and destroy the cancer.

But today there are obstacles related not to science but to manufacturing. Cells outside the body are fragile. It is not their natural habitat, and so it takes great effort and attention to craft an environment where they can thrive and grow. It can take weeks and hundreds of thousands of dollars to manufacture just one dose.[44] In this way, immunotherapy is emblematic of the challenges facing the personalization model. The demand is there, the idea is there, but the manufacturing technology needs to advance.

And there is no shortage of talent working on these hard problems. Multiple startups are trying to automate cellular therapy production. AI is transforming what robots can do. Someone just invented a 4D printer, which builds objects that unfold or change shape. And thinkers in materials science are sparking paradigm shifts in industries as diverse as home construction and retail.[45]

Yes, personalization is at the earliest stage of our three examples. Yet this means much possibility lies ahead. Innovation, not merely imagination, can run wild. **People may be able to design their own custom sneakers, printed car seats may morph to match our bodies, and our old, rigid factories may come to seem quaint.**

It is those firms that find efficient ways to make these ideas reality that will likely make great investments.

Conclusion

Our three models—technological competitive advantage, scaled economies shared and personalization—represent very different ways to earn sustainable profits in production. Yet they are also examples of something else, something more sweeping. The global economy is at the precipice of change, and the way forward for innovation is through production, not around it.

Innovation often allows winners to disrupt the incumbents. Today, the United States has allowed its manufacturing dominance to fade. These fresh technologies and frameworks are opening an opportunity to change the global supply chain. The way forward is rarely the way back. In this case, it will not be through antiquated assembly lines. Rather, it will be through new products made with new methods of production, resulting in new winners. We believe those who build the factories of the future, factories that are smart, flexible and technologically advanced, appear poised to win the era of economic development that is upon us.

You can see this transformation at work today. **Even the beneficiaries of the digital revolution, the big tech companies, are investing in production.** The Magnificent Seven,[46] once vaunted as asset- and capital-light, illustrates this phenomenon. This diverse set of companies increasingly resembles the industrial giants of the late 19th century. They have capital expenditure (capex) budgets that exceed all other industries, and those budgets continue to climb.

This is an optimistic time—that technological progress compounds on itself has never been more apparent. Yet, if the digital revolution was a disappearing act, where the world dissolved into the computer, the wonders of this next era will spill back out of the machine, coming to transform our physical world. We have always needed both dreamers and producers, but the stories of innovation have tended to favor the former. Now, the pendulum of history is shifting toward the Boschs, Cooks and Changs—those talented individuals who take inventions out of the lab and into the world.

Key takeaways

- In the Fourth Industrial Revolution, production will play a key role. New technologies will disrupt current ones, creating new winners. The general-purpose technologies we have identified so far include electric vehicles, clean energy, artificial intelligence, robotics and genomics.
- We are already seeing production gain in importance in the case of the big tech companies, who were once asset-light and are now spending heavily on capital expenditures.
- The skillsets are different for inventors and producers. A successful innovation requires both.

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Endnotes

1. Source: Smil, Vaclav. *Enriching the Earth*. 2001.
2. Source: "Excerpt from: What I learned this week." 13D. January 20, 2011.
3. To expand on the point: The cost of an additional search, piece of software, or social media post is de minimis compared to, say, that of another washing machine.
4. Source: "Climate and Average Weather Year-Round in Chincha Alta." Weather Spark. November 25, 2024.
5. Source: Peel, R. Francis and Gritzner, Jeffrey Allman. "Sahara." Encyclopedia Britannica, November 13, 2024.
6. Source: "PERU. Chincha Islands. Guano Wo Kings, North Island, antique print, 1863." Antique Maps and Prints. Source: Johnston, Paul. "The Smithsonian and the 19th century guano trade: this poop is crap." National Museum of American History. May 31, 2017.
7. Source: "Use your loaf: why food prices were crucial in the Arab spring." *The Guardian.* July 16, 2011.
8. As an aside, and well beyond the scope of this paper, Spain did not suffer from the 1848 uprisings that swept through Europe. However, this is a multi-faceted story that we do not explore in this text.
9. Source: Cushman, Gregory. *Guano and the Opening of the Pacific World: A Global Ecological History.* 2013.
10. Another infamous chemical weapon, mustard gas, is a derivative of Haber's chlorine gas. Although initially used in WWI to devastating effect, mustard gas would later form the basis for cancer chemotherapy. In a surprising twist of events, the chemical used for a weapon that killed so many soldiers has subsequently helped save millions of people from cancer. Source: "Statistics and Graphs." National Cancer Institute. August 1, 2024.
11. In fact, scientists had been working on artificial synthesis for over a hundred years prior to 1905 and managed to make a very small amount of ammonia several times. The amounts were de minimis and the methods impossible to scale. Haber's attempt produced 100 grams, equivalent to the weight of a stick of butter.
12. Some rough math: demand for nitrogen from guano, the next best alternative, was upwards of 760,000 *tons*/year in the United States alone. Assuming that the guano was ~10% nitrogen on average, that meant the US wanted 76,000 tons/year of nitrogen. In its first year, the Oppau plant produced 5,500 tons of nitrogen, or 7% of all needed nitrogen for the entire United States. Germany had 2/3 the population of the United States at the time, so 10% of Germany's population is a reasonable estimate. Source: Smil, *Enriching the Earth,* 102.
13. In the 21st century, it is fair to say that our modern problem is not too little fertilizer but too much. Ammonia drains from cropland into our oceans, where algae feast on the nutrient, die and, in decomposition, suck all the oxygen from the water. This creates zones of hypoxia, also referred to as 'dead zones,' where no marine life can survive.
14. Chip designers have become increasingly important to the entire technology ecosystem. The designers are key to Moore's Law continuing because they work within the confines of physics to pack ever more transistors into the same space. Moore's Law is an axiom of microprocessor development holding that processing power doubles about every 18 months especially relative to cost or size. It is named for Gordon Moore, co-founder of Intel.
15. Source: Miller, Chris. *Chip War: The Fight for the World's Most Critical Technology.* 2022.
16. Qualcomm's chips for cell phones, for example, are built on tens of millions of lines of code.
17. Introduced in 1999 but not used in a working chip until 2011, FinFet is a nanometer-scale 3D circuit that "sets two ends of the circuit and the channel of semiconductor material that connects them on top of a block, looking like a fin protruding from a whale's back" (Miller 2022, 217).
18. Source: Fried, Ina. "Nvidia's latest AI chip packs more than 200 billion transistors." Axios. March 19, 2024. There are 200 billion transistors on Nvidia's latest chip, delivering 20 petaflops of compute (10^15 calculations per second).
19. This phenomenon is called quantum tunneling.
20. Source: Gleiser, Marcelo. "Quantum mystery: Do things only exist once we interact with them?" Big Think. January 18, 2023.
21. Source: Miller, Chris. *Chip War: The Fight for the World's Most Critical Technology.* 2022.
22. "Leading edge" refers to the most advanced chips available on the market. Usually, this is tied to length in nanometers.
23. Source: Shilov, Anton. "Analysts estimate TSMC's 3nm yields between 60% and 80%." Tom's Hardware. December 31, 2022.
24. Source: Hough, Jack. "ASML is the chip-equipment leader. Its stock is poised to bounce back." *Barron's*. January 10, 2025.
25. Source: Gros, Daniel. "Western chip subsidies will benefit China." Project Syndicate. January 9, 2024.
26. Source: VT Index. Capital expenditures estimated as a % of revenue.
27. A wafer is a term for a unit that contains multiple chips. Chips per wafer is highly variable and can be in the tens or even the thousands.
28. Source: Bernstein. Graph shows blended wafer price (US$8"-eq wafer).
29. Source: Escobar, Sabrina. "A strong economy bodes well for retail stocks. Here's where to shop in 2025." *Barron's*. January 23, 2025.
30. Source: "EV vs. ICE: Fewer Moving Parts, Less Maintenance." Alpha Motor Inc. September 17, 2024. A traditional combustion engine car has more than 2,000 moving parts. For an electric vehicle, it is only 20.
31. Source: Tesla Earnings Call. Third quarter 2024.
32. Source for 9% EV figure: Tucker, Sean. "America set EV sales record in 2024." Kelley Blue Book. January 14, 2025.
33. Tesla sold over two million cars in 2023. BYD Auto of China sold over three million. Tesla made US$2 billion that year, and BYD made US$4 billion. Source: Company filings.
34. BYD's cheapest vehicle is $10,000 in China. Source: Johnson, Peter. "BYD would still have the cheapest EV in the US with a 100% tariff." Electrek. September 17, 2024.
35. Source: Industry reports. In 2023, Ford sold fewer than 50,000 Mach-E vehicles and lost money on every vehicle. GM sold a few more than 75,000 EVs in 2023. BMW sold around 376,000. Selling nearly two million vehicles a year amortizes the fixed costs of production over a wider base, thus also reducing the fixed cost per vehicle sold. High volumes then improve asset utilization. Tesla's inventory turnover ratio is 20x. This strong asset utilization further drives operating leverage for Tesla, and, in turn, enables them to lower the prices on their vehicles.
36. Source: Khan, Zak. "iPhone price history: How Apple's pricing changes (inflation included)." Android Authority. November 18, 2024.
37. We chose iPhones rather than smartphones broadly because they created the category.
38. Source: Spangler, Todd. "Six biggest companies to spend record US$126 billion on content in 2024, up 9%, led by Disney." Variety. October 29, 2024.
39. Source: Schwaar, Carolyn. "The 3D printing behind the billion-dollar smile business." Forbes. August 13, 2023.
40. This is called a "cemented" knee. It is a metal prosthetic applied with bone cement as the type of glue to hold it in place. The prosthetic comes in limited sizes.
41. Source: Frank, Christina. "How robots are helping personalize knee replacement surgery." Johnson & Johnson. May 8, 2024. Source: Kayani, Babar, et al. "Robotic-arm assisted total knee arthroplasty is associated with improved early functional recovery and reduced time to hospital discharge compared with conventional jig-based total knee arthroplasty: a prospective cohort study. National Library of Medicine." July 2018.
42. Emily Whitehead, a young girl with treatment-resistant leukemia, was the first person in the world to undergo what is called "CAR-T cell therapy." In Emily's case, her CAR-T cells were removed from her body and then genetically modified to recognize a protein on the surface of her leukemia cells. Once they could recognize the protein, the cancer cells no longer lived in "disguise." Her immune system attacked and destroyed the cancer. She has been cancer-free for 10 years. Source: Mukerhjee, *Song of the Cell.* 4-5.
43. This is also being used to optimize organ transplants. The immune system will often perceive organ transplants as "foreign" and attack them, which causes the transplant to fail. This problem has led to the rise of "anti-rejection genomics," which, like immunotherapy, modifies immune cells. In this case, the goal is to prevent, not encourage, an immune response. Currently, the Mayo Clinic is conducting a clinical trial with patients who have received kidney transplants to see if this works.
44. Source: Shah-Neville, Willow. "Cell and gene therapy manufacturing: trends, advancements and challenges." Labiotech. July 27, 2023.
45. Source: Gibbs, Anna. "This designer looks for magic in everyday materials." *MIT Technology Review.* October 2024.
46. The "Magnificent Seven" are Alphabet, Amazon, Apple, Meta, Microsoft, Nvidia and Tesla.

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