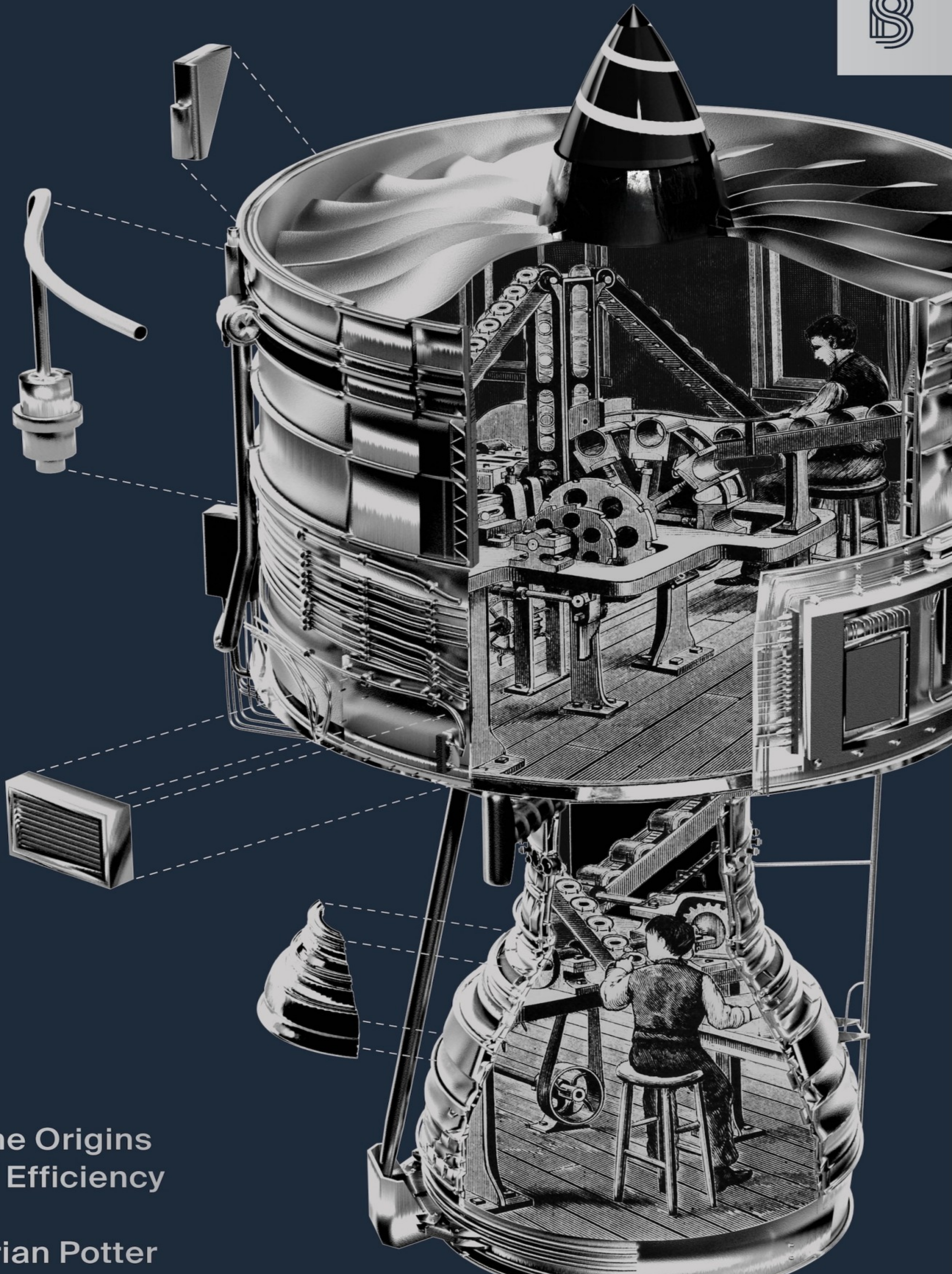
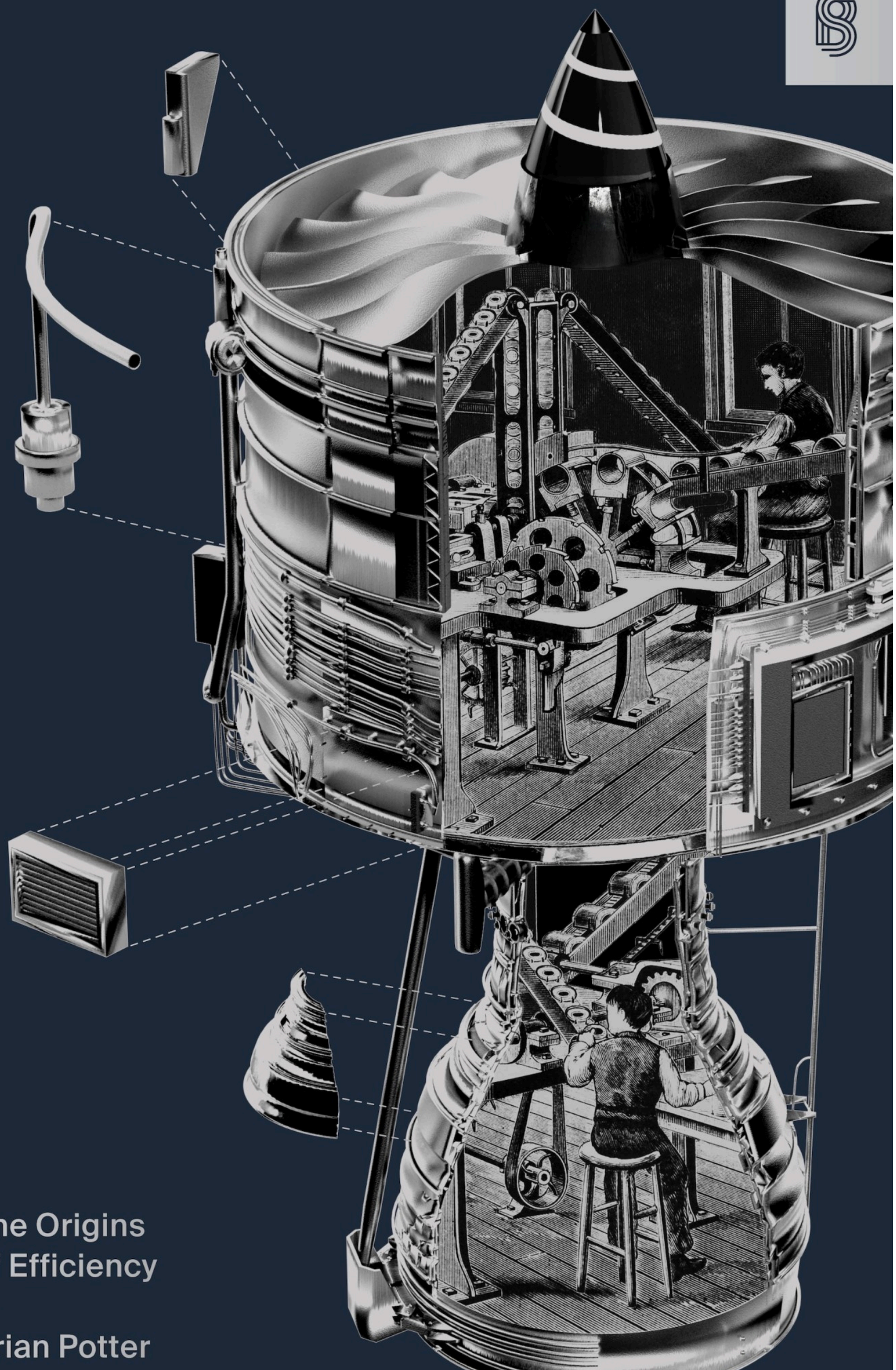


The Origins of Efficiency

—

Brian Potter



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For Mercy

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Introduction

This is a book about efficiency—about figuring out ways to produce goods and services in less time, with less labor, using fewer resources. It's an attempt to understand why certain production processes become more efficient, and to identify the mechanisms responsible. In other words, it's about how things get cheaper to produce over time.

Why care about efficiency? It is not, admittedly, a sexy concept. Efficiency typically doesn't inspire passion or capture the imagination. Children don't dream of growing up to be efficiency experts. Increasing efficiency might help a company earn greater profits, but it seems like the purview of factory supervisors, middle managers, or accountants, not something of pressing concern to our day-to-day lives. In some cases, pursuing efficiency can even appear socially destructive, with cost reductions creating higher profits for big corporations at the expense of lost jobs, lower quality, and worse service. Who among us doesn't pine for the (real or imagined) days when products were made in the US and built to last, instead of being made in China out of cheap plastic?

This perspective, while perhaps not entirely mistaken, misses the larger picture. Finding ways to produce goods and services with fewer resources—improving what we'll call *production efficiency*—is the force behind some of the largest and most consequential changes in human history. Efficiency is the engine that powers human civilization.

This is a bold claim. To explain, let's start with the story of a modern miracle made possible by increased efficiency: penicillin.

The story of penicillin

In the 1930s, Oxford University scientists Howard Florey, Ernst Chain, and Norman Heatley were searching for substances that might be used to resist infection. This was no mere academic exercise: War in Europe was looking increasingly likely, and infection had historically almost always killed more soldiers on the battlefield than opposing forces. During the American Civil War, more than two-thirds of the 660,000 deaths were attributed to infection, and infection killed between 12 and 15 percent of wounded soldiers treated in frontline hospitals in World War I.[1]

When searching through the scientific literature on the subject, the researchers came across the work of bacteriologist Alexander Fleming. In 1928, Fleming had returned from vacation to discover that some of his petri dishes had been contaminated, which had halted the growth of the staphylococcus bacteria he was working with.[2] Reasoning that there must be some agent present that was killing the bacteria, Fleming isolated the contaminant, which was later found to be a mold particle of the species *Penicillium notatum*. Fleming named the antibacterial substance penicillin, published several papers about his discovery, and preserved the mold culture. However, due to the fragile nature of the substance, he was unable to isolate it.[3] Further attempts by British scientists in the 1930s fared no better.[4]

Building on this earlier work, Florey, Chain, and Heatley were able to successfully isolate penicillin. Chain found that by carefully controlling the pH and temperature of the solution it was in, the penicillin would remain stable until it could be crystallized via freeze-drying.[5] By 1940, tests in mice showed that the substance was capable of treating what could otherwise be lethal bacterial infections.[6] During the first human trial of penicillin, it was given to an Oxford police officer with a severe staphylococcus infection, and his condition greatly improved. By 1945, penicillin was being hailed as a miracle drug, and Fleming, Florey, and Chain would be awarded the Nobel Prize in Medicine for their research.

This is how the story is often told—as a tale of scientific discovery, in which some combination of serendipity and persistence resulted in an important breakthrough that changed the world. But that story is radically incomplete.

In actuality, *Penicillium notatum*, the species of fungus the scientists used to produce penicillin, only generated the substance in miniscule amounts. In fact, over the course of an entire year, the researchers had gathered such a small amount of penicillin that they exhausted their supply during the initial trial, and the police officer they had treated relapsed and died.[7] Yes, penicillin was a miracle drug—but without a way to produce it in large quantities, it was of little use.

So the researchers' focus shifted to devising high-volume manufacturing methods for penicillin. Because such operations were difficult to carry out in Britain due to the war, Florey and Heatley traveled to the United States, where a joint effort between government (in the form of the US Department of Agriculture's research labs), industry (in the form of pharmaceutical giants such as Pfizer and Merck), and academia gradually developed mass production techniques.[8]

One of the first improvements was to the growth medium. USDA researchers discovered early on that corn steep liquor, a nutrient-rich and inexpensive by-product of cornstarch manufacturing, provided an ideal growing medium for the mold.[9] This advance enabled a thirtyfold increase in penicillin production, making large-scale production possible for the first time.[10]

A second area of improvement involved developing techniques that would allow for submerged fermentation—growing the mold within a solution, rather than just on the surface of the growth medium.[11] Initial US manufacturing operations grew mold cultures in milk bottles, but the process was time-consuming and labor-intensive, requiring thousands of bottles to be emptied and cleaned by hand.[12] And because the mold only grew on the surface, each bottle produced a comparatively small amount of penicillin. It was estimated that using the bottle method to grow enough penicillin for the war effort would require "a row of bottles that stretched from New York to San Francisco."[13] If researchers could figure out how to grow the mold within the solution, this would allow for vastly higher production volumes.[14]

Alexander Fleming's original mold strain and its descendants proved unsuitable for submerged fermentation, so US researchers began to search for other strains that might work. They soon discovered that strains of mold that produced penicillin at all were quite rare. In one researcher's sample of 1,000 strains of penicillium molds, only one other was found to produce penicillin.[15] After looking through tens of thousands of strains, scientists eventually identified the ideal candidate on a moldy cantaloupe. This strain was not only capable of growing while submerged in fermentation tanks that could hold thousands of gallons of solution, but it also produced much more penicillin than earlier strains.[16]

Scientists were able to further improve the cantaloupe strain by cultivating naturally occurring mutants of it and deliberately inducing mutations via X-ray and radiation bombardment. This process ultimately resulted in the Wisconsin Q-176 strain, which produced up to 100 times more penicillin than Fleming's original and became the antecedent to all major industrial strains.[17]

The overall increase in the volume of penicillin produced through these improvements was staggering. According to Emory School of Medicine professor Robert Gaynes, "In 1941, the United States did not have sufficient stock of penicillin to treat a single patient. At the end of 1942, enough penicillin was available to treat fewer than 100 patients. By September 1943, however, the stock was sufficient to satisfy the demands of the Allied Armed Forces."[18]

Penicillin production reached 80 million units per month in 1943. By early 1944, it had risen by a factor of 200 to over 18 billion units per month. By 1945, manufacturers around the world were producing 5 tons of penicillin annually.[19] And as production volumes rose, the price of penicillin fell. In 1943, a 600-milligram vial of penicillin cost $200; by 1952, the same vial cost just $1.30.[20]

As a result of the widespread availability of penicillin, Allied forces eliminated an estimated 75 to 80 percent of battlefield infection deaths.[21] And the production advancements didn't stop after the war. Between 1950 and 1980, better manufacturing technology boosted productivity by a factor of three, while additional strain enhancement increased productivity by a factor of 16. By 1982, penicillin production had reached 12,000 tons annually—2,400 times the amount produced in 1945. Over that same period, the inflation-adjusted price of penicillin dropped by a factor of 1,000.[22]

These gains in efficiency, along with the subsequent development of other antibiotics, brought about widespread reduction in death and suffering from infection. Prior to the emergence of antibiotics, bacterial illnesses were responsible for approximately 20 percent of all deaths in the US.[23] Between 1936 and 1952, deaths from bacterial illnesses in the US dropped by nearly 70 percent.[24] By some estimates, antibiotics have extended the average human lifespan by 23 years.[25]

The initial discovery of penicillin was, of course, necessary to these later achievements. But it was only by making antibiotics cheap and widely available—that is, by producing them efficiently—that this miracle medicine was able to save millions of lives.

Efficiency and abundance

The story of penicillin is in one sense an outlier: Rarely in human history have such dramatic efficiency gains arrived so quickly. But in another sense, the story of penicillin is simply the story of civilization. For most of human history, producing almost *anything* required an enormous amount of time, effort, and resources. But, as with penicillin, we have over time figured out ways to produce many things much more efficiently, using less labor and fewer materials.

Prior to the past several hundred years, for example, most human effort went into producing enough food to eat. As late as 1500 CE, roughly 75 percent of the populations of England, France, Germany, and Austria worked in agriculture.[26] The continent was perpetually one crop failure away from devastating famine. Europe's Great Famine of 1315 to 1317, brought on by severe summer rains and low temperatures, is estimated to have killed between 10 and 15 percent of the population, depending on the country. And while the Great Famine was extreme, it was by no means unique: Between 1300 and 1400 CE, Italy experienced an estimated 11 years of famine, while Spain experienced 25.[27]

Contrast this meager state with that of the present-day United States. The US began as an agrarian nation, and as late as 1880, 50 percent of the labor force worked in agriculture, a state of affairs not so different from medieval Europe.[28] Today, however, farm employment comprises just 1.2 percent of the workforce, and the US has fewer people working on farms today than it did in 1820.[29] Yet the US produces vastly more food than it did in the 19th century. Between 1866 and 2018, potato production in the US increased by a factor of 6.8, wheat production increased by a factor of 11, and corn production increased by a factor of nearly 20.[30] And modern farming requires not only less labor but also less land: Producing a bushel of wheat requires just 20 percent of the land today that it did in 1866, while a bushel of corn requires just 10 percent of the land. This increase in production has been accompanied by a steep decrease in price. Depending on the crop in question, between 1866 and today, the price has fallen by as much as 50 to 85 percent.[31]

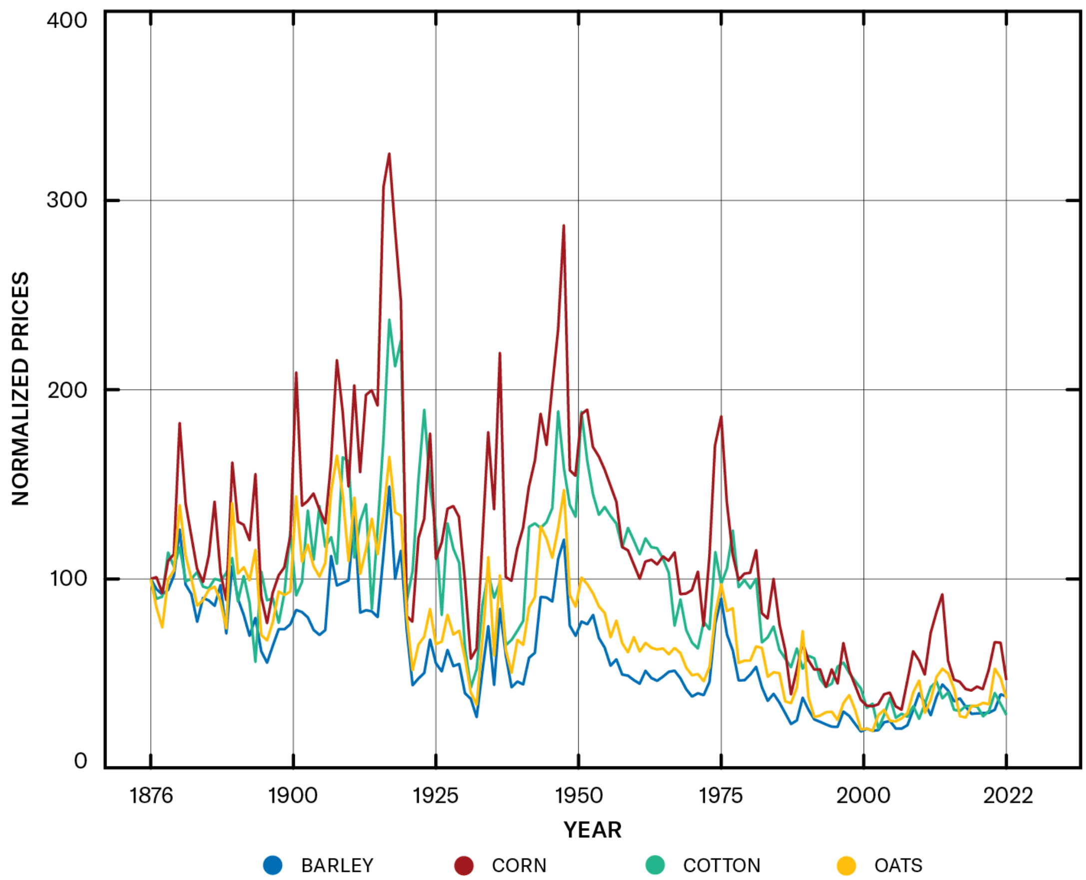

Figure 1. Real (inflation-adjusted) price of US crops over time, normalized to 1876 = 100. Data from USDA, *Crop Production Historical Track Records*.

If we look at the rest of the world, we see a similar trend. The massive increase in worldwide agricultural productivity during the 1960s to the 1980s, often called the Green Revolution, is credited with reducing food prices by 35 to 65 percent, increasing food supply by 12 to 13 percent, and increasing caloric intake by 11 to 13 percent in developing countries.[32] If we compare the period after 1990 to the century from 1870 to 1970, worldwide deaths from famine declined by roughly 96 percent.[33]

We can see the same story outside of agriculture. Fabrics and textiles, for example, have been used by humans since before recorded history.

Archaeologists have discovered linen fabrics dated as early as 7000 BCE, and farmers began to breed sheep for their wool as early as 3000 BCE.[34] Textiles were an important technology, used for everything from clothing and bedding to containers and sails for ships.

Textiles are made by weaving thread. Thread, in turn, is made by spinning—twisting together numerous short fibers of cotton, wool, flax, or hemp into a single continuous length of fiber. Prior to the Industrial Revolution, textiles were incredibly time-consuming and labor-intensive to produce, largely because they required an enormous amount of thread, which itself was tedious and laborious to make. A 100-square-meter Viking sail, for instance, took about 60 miles of thread, while a Roman toga used about 25 miles.[35] Before the late 1700s, this thread would have been made by hand, using either a drop spindle or, later, a spinning wheel. Even the fastest spinners were only able to spin about 90 to 100 meters of thread an hour on a spinning wheel, while drop spindles produced closer to half that rate. At these production speeds, a Roman toga required roughly 900 hours of labor simply to spin the thread for it and another 200 hours to weave it.[36] To produce the sail for a Viking ship, 385 days of labor were needed to spin the thread, and another 600 days were needed to shear the sheep and prepare the wool.[37]

Preindustrial societies, therefore, devoted an enormous amount of time and effort to spinning thread, with anywhere from eight to 20 spinners supplying thread for a single weaver.[38] As Virginia Postrel notes in her book *The Fabric of Civilization*, "Whether Aztec mothers, orphans in the Florentine Ospedale degli Innocenti, widows in South India, or country wives in Georgian England, women through the centuries spent their lives spinning."[39] In 1770, on the eve of the Industrial Revolution, England had on the order of 1 to 1.5 million spinners, out of a total workforce of around 4 million.[40]

When the Industrial Revolution arrived, textile manufacturing was one of the first industries to be mechanized, resulting in an enormous rise in textile production. Between 1770 and 1841, Britain's output of linen and wool cloth more than doubled, and the output of cotton cloth increased by a factor of over 100.[41] Between 1784 and 1832, the costs of manufacturing cotton thread in Britain dropped by over 90 percent. By 1850, it was cheaper to produce cotton fabric in Britain than almost anywhere else in the world—which enabled the country, which had just 1.8 percent of the global population, to supply half of the world's cotton.[42]

If we fast-forward to the present day, these efficiency gains, and their accompanying abundance, are almost impossible to fathom. As of 2018, the US consumed roughly 35 kilograms of textiles per person each year.[43] Assuming a preindustrial spinner could produce on the order of 100 pounds of fiber a year, supplying enough thread for US consumption using preindustrial methods would require on the order of 230 million people just to spin the thread.[44] Of course, modern thread is not spun by hand but made in highly automated spinning mills staffed by a small number of employees. These mills can manufacture upward of 75,000 pounds of fiber per person per year—750 times what a preindustrial spinner could produce.[45]

Finally, consider a subject dear to both author and reader: the production of books and text. Prior to the mid-1400s, the primary "technology" used to copy a page of text in Europe was manual reproduction. A scribe (often a monk, though later paid copyists became popular) would carefully copy the text from an existing manuscript into a new manuscript by hand. Although there had been some efforts to improve this method, such as the *pecia* system, which broke a manuscript into chunks that many scribes could work on at once, the production and reproduction of text remained time- and labor-intensive.[46] Copying a single page could take a day or more, and increased output could only be achieved by devoting more and more scribes to the task. As a result, books and manuscripts were rare. In Western Europe in the 14th century, manuscripts were produced at an estimated rate of about 20,000 to 30,000 per year, and there were likely fewer than half a million books in all of England—less than a single large bookstore might have today.[47] They were also expensive: For the amount it cost to produce a single volume in 1450, a person could buy two cows, a dozen sheep, or 10 weeks of labor from a farmhand.[48]

As with agriculture and textiles, book production would experience incredible gains in efficiency in the coming centuries. The first dramatic leap occurred sometime around the 1440s, when a goldsmith named Johannes Gutenberg developed a new system for copying text: the printing press. The printer would coat metal blocks shaped like individual letters (cast using a special alloy of lead, tin, and antimony that Gutenberg developed) in an ink made from lampblack and varnish (also developed by Gutenberg), then arrange them on a screw press, a then-common mechanism used for things like producing wine or paper.[49] As the printer turned the screw, the ink-coated letters would press the ink down upon the page.[50]

This system was still slow compared to modern methods: It took Gutenberg nearly five years to make just 180 copies of his first book, the eponymous Gutenberg bible.[51] But even this sluggish rate of production —around 200 to 250 sheets per hour—represented a vast improvement over what had previously been possible.[52] And with the development of powered presses in the early 18th century, that figure climbed to over 1,000 sheets per hour—10,000 times as fast as hand-copying.[53]

The immediate impact of the printing press was a dramatic reduction in the cost of creating a page of text, and a corresponding increase in the number of books produced. By 1500, the rate of book production had increased fiftyfold from the 1300s, to one to two million books per year. By 1600, roughly as many books were printed in Western Europe every five years as had been produced in the entire thousand-year period between 450 and 1450.[54]

The cost of text also dropped precipitously. Though it's hard to get reliable data prior to 1450, it's estimated that by the 1500s the cost of a book was one-eighth of what it had been in the 1300s.[55] By the 1700s, the price of a page of text in England was one-fiftieth of the prevailing price in the Middle Ages.[56] What had previously been a luxury item limited to a small number of universities, monasteries, and the very wealthy became a good a merchant or craftsman might own. And as books and manuscripts became cheaper and more available, literacy rates improved. Across the continent, literacy gradually rose from an average of 12 percent in the late 1400s to 31 percent in the 1700s. In Great Britain, literacy rates increased from 5 percent in the late 1400s to more than 50 percent by the 1600s.[57]

Regardless of where we look, we see the same story—not just in agriculture, textiles, and books but also in steel, watches, shipping, and shoes.[58] For most of history, it took an enormous amount of time, effort, and resources to produce just about everything. In his book on daily life in medieval Europe, Jeffrey Forgeng notes that "it is hard to envision how much effort it takes to produce even the simplest of goods when each piece must be transformed by hand from raw materials to finished product… In all cases the amount of human labor involved was enormous."[59]

Because it took so much time and effort to produce things, most people had very little. In his examination of preindustrial everyday life in Europe, Fernand Braudel observes that prior to the 18th century, the numerous poor "lived in a state of almost complete deprivation." Inventories of French peasants described the sum total of their worldly possessions as "only a few old clothes, a stool, a table, a bench, the planks of a bed, sacks filled with straw."[60]

As the time, effort, and resources required to produce goods and services have fallen, they've become cheaper and more widely available, giving rise to a world of incredible abundance. And it is this abundance that makes modern life possible. Abundant food has improved health, reduced hunger, and nearly abolished famine. Abundant books have enabled mass literacy and education. Abundant steel has made nearly all modern technology possible. More generally, this abundance has freed us from a life of near-constant toil, affording us more time for entertainment, leisure, and creative endeavors. Over the past 150 years, annual hours worked per person has declined by nearly 50 percent in most Western countries.[61] Without this enormous increase in production efficiency, modern life would be impossible to sustain.

Where does efficiency come from?

The dramatic rise in production efficiency is partly a story of societies accumulating wealth over time. A business might start out by adopting production processes that are cheap yet labor-intensive, but as it earns profits, it can use those profits to purchase machines and equipment, reducing the amount of labor required. A modern farm in the US, for instance, uses one quarter of the labor of a farm in 1948 but twice as much farming equipment.[62]

But this isn't the entire story. Even if we adjust for changes in inputs—machines, buildings, and so on—there have still been significant reductions in terms of what's required to produce a given amount of output over time. Economists call this measure total factor productivity—the amount of output that can be produced from a given quantity of inputs, where inputs include both labor and capital (such as machines and equipment), as well as materials, energy, and other purchased services. Between 1800 and 2000, US total factor productivity in agriculture is estimated to have increased more than sevenfold, and in manufacturing it has increased more than ninefold.[63] Modern production methods might use more machinery or energy than historical methods, but on balance the input requirements have still fallen massively.

What explains these gains in total factor productivity? Part of the answer involves the development of new and improved technology. Gutenberg's printing press gave us cheap books; the spinning mule gave us cheap thread. More generally, novel inventions make it possible to produce goods with fewer resources than before. But as we'll see in the chapters ahead, while technology advances are a crucial part of how increased efficiency happens, this explanation is at once too broad and too narrow.

It's too broad because it fails to tell us what specific conditions allow technology to improve efficiency and make things cheaper. In other words, to understand how technology increases efficiency, we need to be able to differentiate between the types of technologies that successfully reduce production costs and those that don't. The world is full of technologies that, despite predictions, failed to make things cheaper. Nuclear power, for instance, was widely expected to greatly lower the costs of generating electricity due to its enormous fuel density.[64] A 1,000-megawatt coal plant burns over 7,000 tons of coal a day; a 1,000-megawatt nuclear plant, on the other hand, uses just 0.07 tons of nuclear fuel (uranium pellets) a day.[65] By essentially eliminating the cost of fuel, nuclear power was expected to produce electricity that was "too cheap to meter."[66] But more than 60 years after the construction of the first civilian nuclear reactor, this hasn't happened. Nuclear power plant construction projects routinely go massively over budget, and since the 1970s, the cost of nuclear power in the United States has gone up nearly tenfold.[67] This is due in part to burdensome regulations that have prevented nuclear power from reaching its potential. But even setting those obstacles aside, nuclear power has trouble producing electricity for less than the coal-fired plants it was predicted to replace.[68]

Another example of a technology that has failed to improve efficiency is factory-built housing. Unlike most industries, construction remains a largely craft-based field, where skilled craftspeople build houses on-site using methods that have changed relatively little in 100 years. For decades, builders have attempted to improve this process by moving construction into the factory, to do for homes what Henry Ford did for cars. But while it's possible to build houses in factories, factory-based construction has consistently failed to yield significant reductions in cost. (We'll look at factory-built housing more closely in Chapter 10.).

Space travel is yet another example. In the 1970s, experts predicted that the development of the space shuttle would reduce the cost of space travel, potentially making space colonization, lunar mining, and space