GREAT INVENTIONS THAT CHANGED THE WORLD

JAMES WEI

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Foreword

The Earth is now 4.5 billion years old. Yet, virtually all the knowledge and inventions available toda appeared in the last century or so. Extrapolate that pace of change forward and accelerate it and or has an idea what life will be like a century, or millennium, in the future. Or perhaps more accurate one has *no* idea.

That is not to suggest that all previous times were Dark Ages of Innovation: On the contrary, ther was the lever, wheel, wedge, stirrup, long bow, telescope, and more, but nothing like the veritab flood of innovation that engulfs this fast-forward world in which we live today.

Various studies have shown that 50–85% of the growth in US GDP over the past half century ar two-thirds of the productivity increase (read standard of living gain) are due to advancements science and engineering. The US National Academies and many other organizations have conclude that the future quality of life in developed nations that have huge competitive disadvantages in th cost of labor will depend upon their ability to innovate; that is, to create knowledge throug extraordinary scientific research, to translate that knowledge into products and services throug engineering leadership, and through world-class entrepreneurship shepherd those products ar services across "the Valley of Death," where so many new innovations fail for economic reasons, ar into the marketplace.

This is not easy. Only about 1 patent application in 100 leads to a successful product. Thoma Edison, seeking a filament for an electric light bulb, once explained, "I have not failed. I have foun 10,000 ways that won't work." And 60% of new companies go out of business in less than 3 years.

Today, the populace of Earth must produce $1.5 million of goods and services each *second*, 24/ merely to preserve the existing standard of living on the planet—a standard under which half th population still survives on less than $2 per day. The Red Queen, speaking to Alice in Lewis Carroll *Through the Looking Glass*, offers sound advice: "*Here*, you see, it takes all the running *you* can do, keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!

Consider a snapshot of the lifetime of the author of this Foreword. He began his engineering trainin performing calculations using three sticks of wood and two pieces of glass; his youth include occasional summers of confinement to his yard due to the fear of polio; his early professional yea included helping put a dozen friends on the moon; and his business years ended with him workin with 82,000 engineering colleagues, along with experts in many other fields, to create $1000 of ne business every second, merely to keep the firm that employed them all afloat. Craig Barrett, th retired CEO of Intel, points out that 90% of the revenues that company receives on the last day of th firm's fiscal year are derived from products that did not even exist on January 1 of that same year. took 55 years for one-fourth of the US population to have an automobile, 35 years for the telephon 21 years for the radio, 13 years for the cell phone, and only 7 years for the World Wide Web.

In this book, Professor Jim Wei, a superbly qualified guide, conducts us—poets and physicists alik —through a fascinating and informative tour of what it means to invent. This is a tour punctuated wi risk-taking, failure, determination, insightfulness, luck, and, yes, even resounding success. We watc as scientists, engineers, and entrepreneurs collect a great deal of scar tissue—all without pain for us. seems that success in innovation is not always where one looks for it: penicillin was discovered wh Sir Alexander Fleming noticed that the bacteria he had been studying were not growing near the mo that had accumulated on a Petri dish that had been contaminated. A researcher of the Raytheo Corporation conceived the microwave oven when he noticed that a candy bar he was carrying in h pocket at the company's radar lab was melting. But, importantly, Louis Pasteur reminds us th "Chance favors only the prepared mind."

Margaret Thatcher notes that " . . . although basic science can have colossal economic rewards, the are totally unpredictable. Nevertheless, the value of Faraday's work today must be higher than th capitalization of all shares on the stock exchange . . . ." Indeed, it is doubtful that the early researche in quantum mechanics had iPods or GPS in mind as they labored in their laboratories.

Today, the character of innovation itself is changing. While there will always be room for th Edisons, Fultons, and Whitneys, innovation—in both the science and the engineering—is increasing becoming the province of teams—often of very large teams possessing very diverse backgrounds. Th is the era of Big Science. Astronaut Buzz Aldrin observes that "It's amazing what one person can d along with 10,000 friends." Inventions are now being found with increasing regularity at th intersection of disciplines. Plastics are made through the efforts of tiny bugs; and if one is dissatisfie with the output of these bugs, one need to only reengineer the bugs.

Science and engineering—which have brought us the Global Village by making distanc increasingly less relevant—are themselves leading the parade toward globalization. It is noteworthy this regard that America's innovation enterprise would barely function were it not for the foreign-bor individuals who came to America's shores for their education, stayed, started companies, and create millions of jobs. One such individual, Jerry Yang, has said that "Yahoo! would not be an America company today if the United States had not welcomed my family and me almost 30 years ago."

Unfortunately, Americans, in particular, have been inclined to take leadership in innovation fo granted. Dan Goldin tells of an incident that occurred when he was Administrator of NASA wherei the Agency was being criticized for investing so heavily in earth satellites. "Why do we nee meteorological satellites?" the critic asked. "We have the Weather Channel." If we expect to ge information from the Weather Channel, we need to support meteorological satellites. Of course, som innovations do seem rather humble—but that would be a dangerous generalization. A Nation Academy of Engineering panel led by astronaut Neal Armstrong concluded that the most importa engineering accomplishment of the twentieth century was the development of household appliances- which freed the time of half the population to contribute through more rewarding pursuits. It is als noteworthy that if one were born in America at the beginning of the twentieth century, one's li expectancy was 47 years. Much of the gain since that time has been realized through advances fields as diverse as food production and healthcare.

Unfortunately, as in so many pursuits, progress in innovation is not without its unintende consequences. It has, for example, been asserted that in spite of automotive advances, the averag speed of surface travel across London today is about what it was 200 years ago. Large-scale terroris has been made possible by developments in science and engineering that for the first time in histo enable individuals or small groups, acting alone, to profoundly impact the lives of large groups. A unscientific survey by the writer of this Foreword reveals that most people believe that an inventio that will inadvertently kill a quarter of a million people a year should be banned, until they hear th the invention is the automobile.

What of the future? The historical tendency has been to overestimate the near-term impact science, engineering, and entrepreneurship, that is, "innovation," and overestimate it in the long term A prime example of the former comes from Alexander Lewyt, founder and president of the applianc company by the same name, who in 1955 predicted, “Nuclear powered vacuum cleaners will be reality within ten years.” On the other hand, nowhere in the writings of Wilbur and Orville Wright the suggestion that passengers equivalent in number to the entire population of Houston would eac day hop aboard commercial aircraft somewhere in the United States.

Success at innovation will have a major impact on the quality of life in the years ahead as wi failure. Perhaps a vaccine can be found to prevent cancer. Perhaps an effective means will be found o providing clean, inexhaustible, affordable energy for the entire planet. Perhaps there is a large astero hiding somewhere and intent upon destroying the Earth—a catastrophe that, through innovation, ca perhaps be prevented. The quality of life in developed countries today heavily depends upo advancements in science and technology—and this is increasingly becoming the case for all th world's nations. But the benefits of scientific advancements often accrue, not simply to the individu investor but to society at large, thus making it essential that the general public support both educatio and research in science and technology. Only in this manner can our children and grandchildren hop to enjoy a standard of living higher than that of the generations that have preceded them.

So just turn the page for a fascinating and illuminating adventure into the world of innovation- written by an author who knows.

Norman R. Augustin

Retired Chairman and CEO
Lockheed Martin Corporation and
Chairman, National Academies “Gathering Storm”
Committee on Competitiveness

Preface

We have made tremendous progress in the last two million years in comparison with the natur condition of mankind that is said to be "nasty, brutish, and short." We live much longer and healthie and we no longer need six children to ensure that two will survive to adulthood. We are no longe confined to live in tropical forests and savannas of East Africa; in fact, we can rather live almo anywhere on earth, from temperate farms to frigid cities. Inventions and technology are the mo dynamic forces of change and progress in the world today, altering our lives and work at increasin speed, as well as our societies and environment. Our grandparents toiled much longer and hard compared to our 40 hours a week, and yet we produce four times as much food per acre of farmlan We can travel thousands of miles to visit friends and family, hear their voices on the telephone, an connect to the world through computers and the Internet. Every citizen of the world would benef from knowing how inventions were made, how they have changed the world intentionally unintentionally, and how to use and manage inventions wisely.

This book is the outcome of a freshman course at Princeton University, intended for future citizen and leaders. This book highlights some of the most important inventions in history, from the fir stone axe 2 million years ago in East Africa to the current global connection through the computer an Internet. The inventions are from many geographical regions and civilizations of the earth, from Ea Africa to the Middle East, Europe, America, and Asia. My criteria for a great invention incluc satisfying a major need for many people over a long period of time, making a major advance technology, and having long-term consequences in changing our standard of living. This book organized around how we live and work rather than by time in history, by geographical regions an civilizations, or by types of technology. It is organized around tools and methods of production, foo and shelter, health and security, transportation and information, and pleasure and culture. Majo categories of inventions are listed and described, such as methods to grow food and make clothes. few featured cases are treated in greater depth, such as the invention of penicillin by Alexand Fleming and other contributors, and the 10 year development effort to bring sufficient supply penicillin for the D-Day invasion at Normandy and subsequently to the marketplace.

The inventors are described in their roles as creators and innovators, covering their backgrounds an preparations before their inventions, their motivations and methods, and their rewards, if any. Afte the invention, a few inventors remained actively involved in the entrepreneurial work of finance an development all the way to market success—like William Perkin and his invention of synthetic dye but most of them turned the tasks of development over to organizations with financial resources an staff with various needed talents, like Fleming with penicillin. When appropriate, the descriptions the inventions include the underlying scientific principles, the advancements in new technology, th creation of new markets, and the major changes in the world of our work and our lives.

Great inventions lead to new eras in human history. The stone axe released us from our dependenc on a few nature-given tools to solve a few problems into inventing many man-made tools to solv many problems. Fire enabled us to cook food and create ceramics and metals, as well as providin portable warmth to leave the tropics of Africa and move to the frozen north. Agriculture gave u abundant food, allowed us to abandon nomadic lives to settle in villages, improved nutrition an health, and increased life expectancy and birth rate. Writing and printing enabled us to record ou history, stories, wisdom, observations and technology, and to communicate with people far off i space and with future generations. The steam engine provided tireless energy and power industrialize mills and transportation. The computer and the Internet have connected the world an made globalization possible. The speed of the adoption of new inventions is uneven among wor populations, which gives the early adopters distinct advantages over the late adopters or nonadopter adding to the inequalities among people. The large-scale use of inventions can also lead to large-sca alterations in the natural ecology, favoring a few economically useful animal and plant species an suppressing others. The refuse and by-products of technology can also accumulate with time and cau damage to the environment.

Our expectations of a future with increasing prosperity and better quality of life depend on continued stream of new inventions. We are besieged by shortages of resources like water and energ by natural calamities of hurricanes and earthquakes, by epidemic diseases such as malaria and AID and by the threats of terrorists and nuclear wars. We clamor for new inventions to solve thes problems. However, a steady stream of great inventions is not an entitlement, but must be paid for b society with educational programs to train future scientists and engineers, by funding to suppo promising research, and by a reward system for successful inventors and innovative entrepreneur There are disturbing trends in recent years of decreasing support for inventions, so there a predictions that future rates of invention will not be adequate for our needs. This was eloquent pointed out by the National Academies report, “Rising Above the Gathering Storm,” and i subsequent sequel. We have a higher standard of living than our grandparents had, and we have muc to do to ensure that our grandchildren can continue that trend.

I wish to acknowledge the many contributors to the writing of this book, beginning with the class of students who took my freshman course and helped me to clarify which topics to include and how explain them more clearly. Norman Augustine joined me to teach at Princeton and taught m authoritative perspectives on inventions from the views of governments and high-technolog industries. Peter Bogucki gave me many ideas about the archaeology of early humans and brought m ancient stone axes that continue to inspire me. Tsering W. Shawa showed me how to mak geographical maps to illustrate the stories of human diaspora. My greatest thanks are to my famil My children Alexander, Christina, and Natasha edited and improved chapters of the book and als assisted with photo acquisitions. My wife Virginia gave me continued support and encouragemen and this book is dedicated to her.

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Chapter 1

Introduction

An invention is usually considered a delightful new device or method that would make life better. L us also look at some official definitions. The Oxford English Dictionary mentions that it could be discovery, a fabrication, introduction of a new instrument, a design or plan, a figment of imaginatio or a piece of music written by Bach.

The US Patent Office requires that for an invention to receive a patent, it should be new, inventiv and useful or industrially applicable. It is possible to be new without being inventive, such as scientific discovery that may have no immediate practical application. The Patent Office defined fo general categories of inventions: (a) a process or a method, (b) a machine, (c) a manufacture, and (d) composition of matter. A significant improvement can be patentable, but an idea or suggestion mu be accompanied with a complete description of the actual machine, and reduction to practice is ofte required. The patent gives the owner the exclusive right to use the invention for a number of year such as 20 years, and can license the right to another party for considerations. The owner can also su anyone infringing on the patent without a contract and payments. In practice, it is very easy to dete infringement on a patented product when it is sold in the market to many customers, and somewh more difficult to detect the presence of a patented matter in a manufactured product. The mo difficult to enforce is a patented machine or method that is installed in a factory not open to the publ without a search warrant.

We usually think of inventions as providing the means to satisfy our material needs, such as fo food, clothing, and shelter. For these purposes, we have invented the tools of agriculture, of spinnin and weaving, and of beams and roofs. Our spiritual needs such as knowledge, beauty, truth, and justic are also supported by inventions and technology—including the ability to record and print words an pictures, and to communicate to people far away and to future generations. There are very fe revolutionary breakthrough inventions on brand new technologies, such as penicillin and transistor Most inventions are based on making improvements on an existing technology to make it mo effective or efficient such as vulcanized rubber, or finding a new use for an old material such as usin ether for painless surgery and childbirth.

What is a great invention? An invention adds to the store and power of technology, which bestow benefits (and sometimes harm) on our work, lives, society, and the environment. We value a invention according to a number of criteria including: (a) the audacity of the technology over th existing technologies, (b) the expansion of our capabilities to perform tasks that were consider impossible, and to open doors to exciting new possibilities, and (c) the valuable and long lastin benefits that it brings to many people.

The greatest inventions make dramatic breakthroughs, and open new eras in human histor Consider the lives of early men in East Africa about 4 million years ago without the sharp teeth o lions to tear meat. The stone axe was the first great invention that allowed our ancestors to eat th food of lions, and set us on the path of independence from our meager tools of teeth and clav bestowed by nature, as we could invent a whole arsenal of new and powerful tools. Fire led to th invention of cooking and softened tough meat and cereal as food, to ceramics and metallurgy, and t the colonization of the frozen north. Agriculture led to much greater and more secure food productio and allowed people to settle in villages and cities. The steam engine led to tireless power f manufacturing and transportation and to a burst of productivity increase and the Industrial Revolutio Modern sanitation and the germ theory lowered the rate of infant mortality, so that it is no long necessary to have six children to ensure that two would survive to adulthood. Each generation human society inherited a much bigger toolbox of technology from the previous generations, and ca enrich it by the constant addition of ever more new inventions to benefit the next generation.

A drug that cures lung cancer would benefit millions of people, and would be considered mo important than a drug for a rare disease that affects only thousands, according to the Jeremy Bentha principle of greatest happiness for the greatest numbers. Bentham also specified that happiness shou be ranked by intensity, duration, and certainty. An invention that keeps us alive is more valued than a invention that improves our vanity; an invention that remains in use for many years is valued mo than inventions that are quickly replaced; and a drug that always works is better than one that work only some of the time.

The direct benefits of an invention can be obvious, such as fire providing warmth and light. Th unintended indirect benefits (or harm) are often slower in coming but can be far more important, suc as fire leading to cooking which softened tough grains, and made possible pottery, bronze, and iro The synthetic dye mauve was invented by William Perkin in 1856 and was used for only a short perio of time before it was replaced by newer and better dyes, but its success inspired many chemists an entrepreneurs, and subsequently gave rise to many new synthetic dyes and synthetic drugs, such sulfonamide. These new drugs became the foundation of the modern pharmaceutical industry, an saved millions of lives. Freon was a refrigerant introduced in 1920 that made possible safe hom refrigerators without the hazards of fire and toxic leaks, but it accumulated in the atmosphere f many decades and led to the ozone hole and global warming, which made it no longer suitable.

1.1 Inventors and Inventions

Consider where and when great inventions were made, who made these inventions, what motivate them, what were their methods, and how revolutionary were their inventions?

1.1.1 Cradles of Inventions

In the past several hundred years, the most inventive places on earth were in Western Europe and late in North America as well. Is there an association between climate and inventions? Let us use th Köppen Climate Classification scheme, which is based on the distribution of temperatures and rainfa of each month in the year. Mellinger, Sachs, and Gallup observed that the temperate zones within 10 km of the ocean or a sea-navigable waterway accounts for only 8% of the world land area, but h 23% of the population, and 53% of the GDP of the world. It is also the most inventive area in th modern world, with the highest standard of living.

The most inventive places in the ancient world were in the dry climate (Mesopotamia, Egypt) an located at large rivers. The more recent inventive and economically successful places tend to be in th humid temperate zone (Athens, Rome, London, Xi'an, Philadelphia), and less often in the humid co zone (Beijing, Boston, Berlin). The tropical humid equatorial climate of the Amazon and Cong supports a large population, but is not very inventive; the cold polar and the highland climates suppo little population, and are not inventive.

However, the ancient cradles of the most important inventions came from the tropics, and gradual migrated to warm subtropical climates, and later to cool temperate zones. Let us look at this migratio for six great inventions: the stone axe was from Olduvai Gorge in Tanzania (latitude 5°S) 2 millio years ago; fire was first mastered at Zhoukoudian in China (40°N) 500,000 years ago; agricultu began in the Fertile Crescent (33°N) 10,000 years ago; writing began in Mesopotamia (33°N) 3,50 years ago; the steam engine was established in Scotland (56°N) in 1750; and the electronic digit computer began in the United Kingdom (51°N) and the United States (41°N) around 1950–2000. The exhibit a steady northward movement with time.

The climates of Eurasia and North America were not always the same throughout human histor The world climate turned distinctly colder from Pliocene to Pleistocene 2 million years ago, perhap by as much as 2–6°C in comparison with the year 1950, and much of Northern Europe and Americ were under sheets of ice. The ice age ended at the beginning of Holocene 10,000 years ago, and th world began to warm up significantly.

Why did most great inventions arise in these temperate places, and why at that moment in time? Th most frequently cited requirements to support inventions include the following:

1. *Environment*. The hunter–gatherers need a healthy and agreeable climate with warmth, rainfall and soil, suitable for the growth of plants and animals for food. The farmers need to find loca plants and animals that can be domesticated, stone and clay for construction, trees for fuel, and ores for metallurgy. The temperate climate provides the stimulus of a change of seasons and cyclonic storms, and gives the residents challenges to keep them alert with problems to solve Arnold Toynbee proposed the Golden Means theory on the genesis of a civilization. A group of people can live in comfortable torpor for a long time, and would need a stimulus or a challenge in order to respond and move into a dynamic creative state. There are various stimuli, such as living in a hard country and environment, moving to a new habitat, external blows from enemies internal pressures, and penalty in comparison with other groups. If the stimulus is necessary to wake one from contented torpor then would more stimuli always lead to better responses? He proposed that challenges should be large enough to be stimulating, but not too large to be overwhelming. He gave the following examples as illustration:

- The Vikings living in Scandinavia had a mild climate during the Viking Age, and were not sufficiently challenged to produce much literature; but the Vikings in Iceland were exposed to a bleak and barren environment and made greater achievements in literature; and the Vikings living in Greenland had an even more bleak and barren settlement, and were barely able to survive and had no time for literature.
- The Europeans that settled in North America at Virginia and the Carolinas had a comfortable life, and made few contributions to literature; the settlers in Massachusetts had a more harsh climate and stony soil, and were sufficiently challenged to achieve leadership in intellect and commerce; the settlers in Maine and Nova Scotia had scanty livelihoods and no time for literature.

If we rank the climate zones according to the degree of challenge, we may obtain the following from the least challenging to the most challenging, and the optimum is presumably somewhere in the middle: humid equator < humid temperate < humid cold < dry < highland < polar. Environment alone is insufficient to explain why North America was dormant before Columbus, and became a world leader after 1950.

2. *Contacts and Heritage.* Inventors build on the stimulus of previous technologies, which they ~~inherited from their ancestors; they also learn from neighbors and visitors that they meet.~~ They need access to transportation in order to trade and to communicate with other people, and to learn new ideas and technology. Jared Diamond argued that the various people of temperate Eurasia can travel 13,000 km from Western Europe to East Asia without a change in climate, and can learn and adopt inventions and ideas from other people. On the other hand, the peoples of North and South America became a series of isolated communities as a similar trip of 13,000 km from the Bering Strait to Tierra del Fuego would involve crossing numerous climate zones, with the need to adapt to new food sources and enemies, and to stay warm or cool. The people of Oceania were likewise isolated from the Eurasian inventive communities. This requirement of heritage and contact does not explain why Africa did not continue to be inventive after a glorious start, or the long sleep of Rome between Justinian and the Renaissance, the sudden birth of the Islamic civilization with Mohammed, and the long silence of Mongolia after Genghis and Kublai Khan.

3. *Soul and Leadership.* The creativity and dynamism of a civilization, as well as subsequent stagnation and decline, have many causes that are difficult to analyze and explain. One can put together a long list of influences: internal tradition, philosophy, religion, external challenges, optimism, stability and security, openness to new ideas, and willingness to adopt progressive ideas and to reward innovators. Charismatic leaders are possibly the most important requirement. Oswald Spengler believed that each great civilization has a soul, which runs through the course of a thousand years from the awakening of barbarism to growth of a new civilization, from expansion to the zenith of empire, to decline and eventual decadence. His Apollonian soul is the Greco-Roman civilization, and his Faustian soul is the Western civilization from Merovingian to now. This explanation can be viewed as an inspired oracle instead of a scientific method, as it gives no principles to predict the arrival of the future souls.

1.1.2 Creativity

We have very little knowledge of the inventors of the first stone axe, who lived in East Africa some 2 3 million years ago. After the invention of writing, we begin to have written documents and som information on the inventors. Who were the inventors, and what were their backgrounds an education; why did they become interested in inventions, and what were their methods; and ho revolutionary were their inventions?

In ancient times most people toil for immediate needs, and only a few had the leisure to pursu interests that did not produce short-term benefits. Perhaps the earliest inventors known by name history were Imhotep and Yu the Great. Imhotep dated from 2600 BCE in Egypt, and was chancello to the pharaoh Djoser and high priest to the sun god Ra. He was also the first engineer, architect, an physician of Egypt; was credited with the invention of the papyrus scroll and the architectu columns; and was declared to be a god after his death. Yu the Great lived around 2060 BCE in Chin and was the founder and first emperor of the Xia Dynasty. China was suffering from great floods, an the king Yao assigned the task of taming the flood to his minister Gun. Gun erected numerous dike that failed, and he was executed by Yao, who turned around and assigned the same job to Gun's so Yu. Instead of erecting dikes, Yu dredged new river channels to serve as outlets to the flood, and fo irrigation. Yu labored for 13 years as an inventive hydraulics engineer, tamed the flood, and wa reward with the kingship by Yao. For these two inventors, the process of invention took little time in schedule crowded with numerous important duties. No inventor since Imhotep and Yu has received a much recognition and honor as these two.

The occupations of the inventors at the time of invention can generally be divided into part-tim amateurs who dabbled in inventions as a hobby or side interest, and dedicated professionals wl received support to invent for wealth and fame.

Inventions require time and patience, as well as optimism from the inventors, who often must hav other means of livelihood. The part-time inventors had other occupations or inherited wealth, ar occasionally took time out to invent something. Archimedes (287–212 BCE) was a wealthy aristocra and a relative and advisor to the king of Syracuse. He was freed from the concerns of making livelihood, and had the time to make scientific discoveries and inventions such as a method determine the density of metals by immersion in a bath, and the Archimedes screw to raise water fro a river. Other examples of amateurs as inventors include Alexander Fleming and Wilhelm Roentge who were professors engaged in teaching students and making scientific investigations. They als made accidental discoveries that led to great commercial success.

Independent entrepreneurs are people without the sponsorship of a government or a company, b who gave up regular occupations to dedicate themselves to inventions, hoping to gain fame ar fortune. James Watt invented several much improved steam engines, and went into partnership wi Matthew Bolton. Charles Goodyear gave up all other work to concentrate on finding a way to impro rubber. Alexander Graham Bell invented the telephone. Thomas Edison was among the first to take u inventions as his main occupation and source of income, when he set up his independent industri research laboratory in Menlo Park, New Jersey in 1876 with funds from his previous inventions. Tl Silicon Valley is full of such independent entrepreneurs, and some of them became very wealthy at a early age.

The corporate employees are engaged by firms or governments to do research and inventions, ar may be required to sign over future patent rights and profits to the employers. Leonardo da Vin (1452–1519) was paid by the Duke of Milan and by Francis I as a painter and military engineer, whe he invented methods of fortifications and siege engines, as well as flying machines. After the dy discovery of Perkin, the German companies such as Hoechst, Bayer, and BASF poured resources in research, hired highly educated graduates from universities to discover new dyes at lower cost higher quality, and later branched out into pharmaceuticals with the discovery of the sulfa drugs. Tl DuPont Company set up a research laboratory in 1902 to diversify from their traditional business making gunpowder, and hired Wallace Carothers who went on to invent nylon in that laborator Thomas Midgley invented the tetraethyl lead and the refrigerant chlorofluorocarbons (CFC) in tl General Motors laboratory. The Bell Laboratory was set up in 1925 by the parent company AT&T, an one of their most famous inventions was the transistor by the team of Bardeen–Brattain–Shockle Corporate funding has become the dominant support of inventors, where teams of specially train scientists and engineers are housed in special buildings and laboratories, equipped with mode equipment and instruments, and are paid to do full-time discoveries and related activities.

The successes of inventors owe a great deal to the encouragement of society, for support before tl inventions, and for rewards after the inventions. Public support includes education in science ar technology, research grants, and patent protection, which gives the inventors a monopoly o exploiting their inventions for 17–20 years. Another form of encouragement is public honors in tl form of prizes and recognitions, such as the Nobel Prize and the Inventors Hall of Fame.

Why was the inventor motivated to invent something? It is often said that necessity is the mother inventions. This would imply that many inventions began with needy and dissatisfied custome followed by deliberate searches to find solutions to important problems. There are many examples these *Market-Pull* inventions, when the investigators were motivated by market applications. Ra rubber was used to make raincoats and balls, but they were brittle in cold weather and sticky in h weather. Charles Goodyear searched for a method to improve the qualities, and to turn unsatisfactor raw rubber into a useful product. He spent 5 years doing trial-and-error experiments before h discovered that sulfur and heat could be used to vulcanize rubber. The Newcomen steam engine wa used to remove water from flooded mines, but it was very inefficient and wasted a great deal of coa James Watt made many improvements so that the steam engine became much more efficient, and th tireless and inexpensive engine started the Industrial Revolution. Home refrigerators original operated with a number of refrigerants that have toxic and flammable properties, such as sulf dioxide and ammonia, and posed real threats. Thomas Midgley was asked to find a nontoxic an nonflammable refrigerant, and he invented the chlorofluorocarbons. In a modern company government agency, the quest for an invention may begin at the marketing department, reporting customers with needs who are not satisfied, and demanding a better product.

Another mode of invention is to start from a technology, and then search for customers. Th investigator may have created an improved or new technology, either by accident or while looking fo something else. The investigator may also start from a "platform" technology that has prove successful in serving one market, and search for other markets that can be served by the same slightly modified technology. These are sometimes called the *Technology-Push* inventions, since th investigators had the technical capability first. The Watt steam engine was so successful in pumpin water from mines that Robert Fulton modified it to operate steamships, then George Stephenso modified it to drive trains, and even the textile industry adopted it to power textile mills. CFC effective in refrigerators and air conditioners, due to its nonflammable and nontoxic properties, whic also makes it suitable for other applications such as propelling aerosols and blowing dust o computers.

The most innovative event is created when an invention creates a new demand that did not exi before, and thus a brand new market. The vegetable and mineral dyes available in 1850 were few an drab, but since the public was not aware of the possibility for a greater and more vibrant variety dyes, they did not clamor for them. Perkin was an 18 year old schoolboy on vacation at home, wh started out looking for a way to synthesize quinine to treat malaria, but his oxidation of coal t resulted in a brilliant dye. It led to a series of more brilliant dyes, as well as the modern chemic industry. From the beginning of history, humanity suffered, and died of infectious diseases, but th suffering public did not know that it was possible to invent miracle drugs. Alexander Fleming wa working with staphylococcus bacteria in a London hospital when he found colonies in the Petri dish in his musty and dusty laboratory. He observed that bacterial colonies do not grow in rings aroun areas that have been accidentally contaminated by a green mold, and he found the substance that h named penicillin. This led to its widespread use in medicine, and created the new market antibiotics. In the same way, there were no market demands before the launching of the person computer, the cellular telephone, or the Internet. Steven Jobs was famous for inventions th anticipated public demand: the public could not imagine such miraculous machinery as the iPad an iPhone before they were introduced, and could not live without them after they were introduced.

For the inventors of the stone axe 2 million years ago, a stone with a naturally broken sharp cleava was found to be effective in cutting meat, and became used regularly. Probably the long process improvements over the next 2 million years was guided by random tinkering, trial-and-err experiments, and remembering which methods produce better products. This process of empiric inventions had no scientific theory and systematic data for guidance. This method survives today areas with insufficient scientific understanding.

Paul Ehrlich was a medical doctor searching for a drug to cure syphilis without severe side effect and was convinced that arsenic held the answer. He reacted arsenic with other chemicals to form mar new compounds, and hoped that one of them would not be overly toxic to humans but still effective c syphilis. He synthesized 606 arsenic compounds, and found the compound Salvarsan to have th desired properties. The random search of thousands of objects is a very slow and expensiv undertaking, but is worthwhile when the goal is very important and no knowledge or theory exists help. This method is sometimes called "Edisonian" as it was used by Thomas Edison in his search f a carbon filament in the incandescent lamp. It was also the method used to discover taxol, the rece drug for uterine and mammary cancer.

The modern scientific method arose in the Renaissance, and became the new source of the mo productive inventions. Francis Bacon described the scientific method in 1620 as an endless cycle the following steps:

i. Make observations of a phenomenon, note the regularity and reproducibility of the observations and confirm by more measurements.

ii. Make hypothesis of an explanation about the cause of this phenomenon.

iii. Based on this hypothesis, make predictions of other phenomena that can be observed anc measured.

iv. Perform experiments designed to test the predictions, and compare to the results to confirm o deny the validity of the hypothesis.

v. If the experiments confirm the predictions, the hypothesis receives one more vote o confidence; if the experiments deny the predictions then the hypothesis needs to be revised and we return to (iii) to repeat the cycle.

The scientific method led to a set of fundamental theories that govern the physical world, such the Newton's law of motion, the Maxwell law of electromagnetism, and the second law thermodynamics. Systematic experiments for many years led to a body of knowledge and databases the properties of matter. In modern times, there is a very large body of scientific knowledge ar understanding, which became the foundation of many inventions. The public support of education science and engineering creates a larger pool of workers who have the necessary background f inventions based on science.

The modern inventors who have studied the physical and biological laws can make reliab predictions on many consequences when an action is taken. For instance when you climb a peak 20,000 ft, what would be the boiling point of water, and how long would it take to make a hard-boile egg? Another challenge is how you would operate a pressure cooker to control the pressure so that yo can hard boil an egg in 2 min instead of 5 min. Most technology today is based on reliable science ar supplemented by the less reliable intuition and hunches, based on the skill and the inspiration of th artist. The rate of inventions based solely on empiricism was painfully slow for millions of years, ar became dormant in the west during the middle ages; but since the scientific method, the rate science-based inventions has been phenomenal.

Most inventions are embedded in a long evolutionary sequence of many closely related invention and can be studied as a continuum over time. Each invention in such a sequence can be considered b e *incremental*, as they made small and more or less obvious improvements in the technology, c adapted a product to a slightly different market application. After many years of improvements, suc technologies often become mature and do not offer further opportunities for developmer Revolutionary improvements come with inventions that merit the designation of *breakthrough*, as the involve unexpected and novel ideas that spawn many applications and improvements in the future.

The following table is a matrix of inventions with rows from current technology to improve technology, and finally to revolutionary technology. The columns range from serving the currer market to serving additional markets, and finally to creating brand new markets. In an increment invention, an investigator starts from a current market served by a current technology, and looks fo incremental changes that would lower costs or improve quality, or serves to find a new market. For th inventor, this is a relatively safe path that poses small challenges in getting the technology ready and receptive market. However, the rewards in fame and fortune are likely to be modest. There are thre forms of this incremental invention, which are listed as:

i. Keeping the same market and searching for an improved technology. Salicylic acid from willow bark will cure headaches, but it is very harsh on the stomach. Felix Hoffman chemically added an acetyl group to salicylic acid, and the result was aspirin, which has the same effectiveness but is less harsh on the stomach.

ii. The term "platform" technology is sometimes used when one takes a proven technology successfully used in one application, and looks for other applications. Botox is the deadly poison from the botulism bacteria that causes paralysis of the muscle. Many years later, it was found to be effective in removing facial wrinkles.

iii. The steam engine was successful in pumping water from flooded mines. Robert Fulton modified the Watt engine to propel the steamboats he was operating on the Hudson River, and George Stephenson modified the engine to propel railroads.

	Serve current market	Serve additional markets	Create brand new markets
Current technology	Business as usual	(ii) Botox to remove skin wrinkles	(vi) Morton, ether for anesthesia
Improved technology	(i) Hoffman modify aspirin	(iii) Fulton and Stephenson used steam engines for trains and ships	(vii) Cellular telephone
Revolutionary technology	(iv) Midgley, CFC for refrigerators	(v) Midgley, CFC for air conditioning and aerosol	(viii) Perkin, synthetic dye for textile Fleming, penicillin as antibiotics

Occasionally, we witness the excitement of an invention that takes a revolutionary leap forward in creating a *breakthrough* technology. This is more risky, as it may be difficult to make this technology effective, safe, and economical.

iv. Thomas Midgley was asked to come up with a refrigerant that is not flammable and not toxic thus suitable for home refrigerators. Instead of studying the currently available refrigerants, such as sulfur dioxide and ammonia, and finding ways to improve their properties by additives or substitutions, he used the periodic table of Mendeleev to discover a new class of compounds, the CFC.

v. Since CFC became successful in refrigerators, the same nontoxic and nonflammable properties make them useful in air conditioning and aerosols.

Sometimes we create a brand new market that did not exist before. This is also risky as customers may not embrace this unfamiliar new technology, and may refuse to use it.

vi. Ether is a chemical used for solvent and paint removal. Morton introduced diethyl ether into surgery as an anesthetic, which reduced pain and suffering. Before ether was introduced for anesthetics, there was not a market for an effective and safe anesthetic.

vii. Many changes were made to the traditional telephone to make the cellular phone, which is portable and not tied to the wall by a cord. It created the new market of cellular telephone.

Undoubtedly the most exciting inventions involve the simultaneous creation of a revolutionary technology and a brand new market. These inventors take a doubly risky path, as the technology may not work, and the public may not embrace this new product.

viii. Perkin's synthesis of mauve from coal tar was a brand new technology, and created colors so brilliant and enchanting beyond what occurred in nature, which started the new field of synthetic dyes. Fleming's discovery of penicillin enabled us to save millions of lives from bacterial infections, and created the new field of antibiotics. Before Perkin and Fleming, dyes and drugs were found in plants and the earth, but these two inventions awakened the world to the realization that there is unlimited potential in synthetic chemistry. The doors that they opened are even more valuable than those two original inventions of mauve and penicillin.

1.2 Innovation, Development, Diffusion

Joseph Schumpeter once said that an invention that is not widely used is irrelevant to human affair There are thousands of ingenious and admirable inventions that were neither carried out in large sca nor were they used by millions of people to change the world. Hero of Alexandria in the first centur produced a steam engine by jet action, but it was treated as a curiosity and did not lead to benefits f society. Leonardo da Vinci invented a number of flying machines, but there is no record that they we ever built to change transportation or warfare. Crawford Long of Georgia actually used ether f anesthesia in surgery a few years before William Morton in Massachusetts, but Long did not publis his results and had no influence in subsequent medical history. Out of the many thousands o inventions in history, only a few were able to travel the long and difficult path from discovery t development, to be manufactured on a large scale, and to be sold widely in the marketplace, and effe significant change in the world.

A discovery does not become a widely used technology until it has been shaped to suit the factor where it will be manufactured, to suit the customers in the marketplace, and to find sufficie financial backing to pay the bills till revenue begins to roll in. Some argue that there are two separa acts to a successful innovation: (a) the invention, which is an original act of discovery with or witho an economic motive and (b) the innovation, which is driven by entrepreneurs for econom development. In the case of the atomic bomb and radar, the innovations were driven by th government for political and military reasons.

1.2.1 Development

After a discovery, the concept needs to be shaped into one or more products to suit specific needs o the marketplace, so that it can be sold at sufficient volume and price to compete with other product It must be possible to make the product in a factory, with a suitable manufacturing process, ra material supply, equipments and plants, and at an affordable cost. The entire innovation effort must b organized under some leadership, with access to sources of finance to pay the bills till the produc can be sold in volume. This sequence of events involves many people with different talents, and mu be coordinated successfully.

Wallace Carothers of DuPont discovered that he could make polymer fibers by reacting a 16-carbo diacid with a 3-carbon dialcohol, which has a melting point of below 100°C. What products cou DuPont make with this technology that would earn a profit for the stockholders? DuPont decided make nylon as a luxury stocking for women, as they already had experience making the semisynthet rayon fiber for the textile industry, and a pair of nylon stocking requires only a few grams of polyme and can be sold for a high price. This decision set up a number of development problems of productio and marketing. Nylon stockings were offered to displace silk stockings from the market, so there ha to be advantages to women to wear nylon instead of silk, and the price of nylon could not be too hig in comparison to silk prices. A pair of silk stockings had to be ironed, so it required a sufficiently hig melting point; DuPont found a solution by replacing the dialcohol with the diamine, which resulted a higher melting product. How could DuPont acquire enough raw materials of diacids and diamin from plentiful and cheap coal tar or petroleum? After a great deal of investigation, they decided switch to the 6-carbon diacid and the 6-carbon diamine, which could be made from the abunda supply of 6-carbon benzene, and was named nylon 66. The polymer also had to be pulled in the molte form through diamond dies and twisted into fibers of the appropriate thickness and elasticity. Th DuPont Company had enough confidence in this decision to finance the development from pa earnings. Ten years passed before the first satisfactory product emerged dating from the origin Carothers discovery.

When Alexander Fleming of St. Mary's Hospital discovered penicillin in a Petri dish, more than decade elapsed before it became a lifesaver for millions. Fleming was a bacteriologist, and had n idea how to manufacture and market a novel drug. Penicillin was produced in his Petri dish with concentration of 30 ppm, and he did not have the knowledge and skill to extract and purify the dru for clinical tests with animals and humans. He could make a few milligrams in one Petri dish, but h could not manage a million Petri dishes to make 1 kg of penicillin. Some of the purification an testing were solved a decade later by the chemists Howard Florey and Ernst Chain of Oxfo University. They lacked the industrial capability to produce penicillin in wartime England, and Flore sailed to the United States to seek help. Penicillin is a very unstable liquid, and decomposes in about h, and he did not know how to store it and have it ready for clinical use. After these problems we solved, a big source of financing was needed to pay for the costly steps of building plants, buyin machinery and raw material, recruiting and training labor, and developing a storage and distributio organization. The US Scientific Research Board became the entrepreneur to manage the developments and assigned different tasks to different organizations and investigators, and persuade the US President and Defense Department to take the risk and finance this unproven venture.

Perhaps more than 99% of all the discoveries do not make it to the marketplace, either because the fail to find an entrepreneur with sufficient resources to undertake the expensive developmen manufacturing–marketing processes, or because they run into obstacles in the process. There is a illness called “kala-azar” or black fever, which is spread by sand flies, and kills half a million peop per year, making it the second largest parasitic killer in the world after malaria. It occurs main among the poor people in India, Bangladesh, Nepal, Sudan, and Brazil. The drug paromomycin w discovered in the 1960s and seemed very promising, but was abandoned due to the high cost of Pha III clinical trials and the low probability of making sufficient profit to recover the development cost

A number of private foundations, such as the Bill and Melinda Gates Foundation, are beginning t finance the development of such neglected drugs. Even after the drug has been tested and found to b effective with negligible side effects, distribution looms as the next hurdle as getting the drug remote villages at the end of pothole-pocked roads will be difficult.

In the last two centuries, there have been several very successful models of managing developme from discovery to the marketplace:

- *The Discoverer–Entrepreneur Model*. Synthetic mauve was accidentally discovered in 1856 by William Perkin when he was a schoolboy of 18, who realized that its rich purple color could be used to dye textiles. He dropped out of school, formed a partnership with his father and brothers, developed the process for manufacturing, procured the necessary raw material, visited textile manufacturers to persuade them to use his dye, built the factory, and supervised the manufacturing and shipment of dyes. Besides doing the discovery and development, he was also the entrepreneur who found financial support and managed the entire enterprise from the beginning to the end. Thomas Edison also followed his discoveries with entrepreneurial work, participated in forming companies and kept much of the profit. Alfred Nobel, the inventor of dynamite, was also a discoverer–entrepreneur. The modern equivalents of this super solo model are some of the Silicon Valley information technology start-up entrepreneurs, especially those in software who do not require large capital investments in plants and equipment.
- *The Company Acquisition Model*. Fritz Haber informed the BASF Company that he had found a way to synthesize ammonia from air and water, but Haber did not have the means or the knowledge to turn it into a process. The company purchased the rights to Haber's patents, and retained him as a consultant. Then the company proceeded to develop the process under the direction of Carl Bosch, built the plants, sold the product to the German government, and finance the effort. Many start-up companies in the Silicon Valley sold their companies to large corporations, instead of remaining independent and taking more risks for more control and a chance to make bigger profits.
- *The Central Command Model*. The DuPont Company hired Wallace Carothers to do research. After the discovery of nylon in 1935, the company decided that it should be developed for stockings. DuPont assigned many talented researchers to solve problems of manufacturing and marketing as well as financing the entire project. This model can be appropriate for a company with a strong staff and deep pockets.
- *The Consortium Model*. The development of Fleming's penicillin was first carried out by Florey and Chain, and later by numerous American industrial organizations with the chemical engineering skills to make large-scale production, purification, concentration, and stabilization o the product for storage and shipment. This process was financed by the US government as part o the efforts of fighting the World War.

1.2.2 Factory Production and Market Penetration

No invention can be manufactured in large enough quantity at reasonable cost unless a number production factors are available. For instance, the Sahara and Greenland cannot adopt agriculture as way of production because their climate and soil are not suitable. Diamonds are mined in Sou Africa, which lacks skilled diamond workers or the right marketing outlets. Consequently, the ra diamonds are shipped to the Netherlands and to Israel, to be polished into gems and sold at luxu showrooms. The principles of the atomic chain reaction was demonstrated by Enrico Fermi

Chicago, but the atomic bomb could not be manufactured till sufficient uranium-235 had bee separated and enriched, and plutonium had been created by neutron bombardment.

The economists often list the "factors of production" as land, labor, capital, and technology.

- The term "land" includes the natural resources that come with the land—the bounties or paucity of climate, temperature, rainfall, animals, plants, soil, and minerals.
- The term "labor" includes considerations of the total number of workers, their age distribution, the states of health and vigor, the education and skill, and the intangible aspects of diligence and creativity. Another indispensable factor is "entrepreneurship," which is the leadership with an overall vision of the enterprise, the ability to find financial resources, and the courage to take charge and make risk decisions.
- The term "capital" includes capital investments into the technology of production machinery, tools, buildings, inventions, patents, and methods of production. It also includes society's investment in the public infrastructure for transport, so that raw material can be efficiently brought in and products brought out; for information infrastructure such as telephone and Internet; and for utilities such as dependable electric power and water.
- The term "technical knowledge" is not one of the classical factors of production, but must be available in the education and previous experience of the staff, and as patents and trade secrets.

When a product is bought steadily by a group of customers over a period of time, it must be due the needs that are met by the product. The customer must be satisfied by the benefits from th products, and have sufficient purchasing power to cover the costs of the product at posted prices. customer usually has a choice of other products on the market, and will do a cost/benefit analysis determine that this product is worth buying either because it costs less or has better benefits than ar other competing products. The needs and constraints of buyers are different for consumer produc such as nylon stockings, for business products such as oil tankers, and for government products suc as nuclear submarines. The entrepreneur tries to understand the needs, the budget, and the competitio of each group of customers, and tailor the products and prices to suit these realities.

Throughout history, the global reach of an invention often followed trade, migration, an colonization. The traders were often the first visitors to an isolated community, and the first to expos the natives to new goods and methods. Marco Polo was credited with bringing back a number inventions from China to the Western world, such as noodles. Peaceful migration and militar conquests bring a larger influx of exposure, such as the appearance of horses and firearms in the Ne World. There are a number of consumer barriers to the diffusion of new technology, thus the proces can take many years before a new technology is adopted. Besides cost/benefit and competition, the can be many social barriers to the market acceptance of new products, such as inertia, xenophobia, an religious and cultural taboos. The rate of adoption of a new technology such as the mp3 player can b compared to a parade led by the innovators for their own uses, followed closely by a few intrepid ear adopters. There is a tendency for the innovators and early adopters to be risk takers who are younge better educated, of higher socioeconomic status, and who take pride in being the trendsetters for the generation. They are followed by the majority, who join when they are encouraged by the satisfactio and recommendations of the early adopters. The trailing groups are the late adopters, who are mo conservative, more inflexible, and suspicious. Finally there are the laggards who do not join th parade at all. The late adopters and laggards can be older skeptics who have an aversion to change, a less educated, and are socioeconomically lower.

The US Census Bureau provided data for 2007 on the relatively new technology of the Interne which is used by more than 4/5 of the wealthier users with more than $100,000 in annual income ar by the younger users less than 44 years old. On the opposite end, the Internet was used by less than 1 of the lower-income population who earn less than $20,000 and users older than 65.

The World Bank publication of World Development Indicators gave the following data on popula use of information technologies as an international comparison per 1000 population. The high-incon nations use the television 10 times more often than low-income nations, and use personal compute 100 times more often. In this instance, wide usage is not simply a matter of need, but is driven b purchasing power and education as well.

Nation	Radio set	TV set	Personal computer	Internet
Low income	139	91	7.5	10
Lower middle	360	326	37.7	46
Upper middle	466	326	100.5	149
High income	1266	735	466.9	364
United States	2117	938	658.9	551

1.3 Changing the World

Inventions lead to technological developments and effects on society that can be either beneficial harmful. Many people feel that new technology is basically beneficial and gives society more choice even if it is sometimes hazardous, and people should be willing to adapt to the inevitable march progress. Others view many technological developments as basically harmful, because they may fa into the hands of unscrupulous individuals and institutions who would misuse them. The steam engi and penicillin are generally viewed as beneficial inventions with a few unfavorable consequences, b weapons of mass destruction are more often viewed as primarily harmful. In the free marke inventors respond mostly to demands from people with strong purchasing power, and ignore th weaker signals from people with ethical concerns or weak purchasing power. Inventors can serve th needs of the poor and powerless only if there is a market demand created by governments ar nongovernment organizations.

1.3.1 Transforming Work

When Adam and Eve were banished from the Garden of Eden, they were told that “By the sweat o your face you shall eat bread.” Since the beginning of time, mankind has had to labor to produce th necessities of life. Human history took great leaps forward when outstanding inventions appeared expand our capabilities so we could produce results previously thought to be impossible. Howeve most inventions have the more modest goal of making our work more efficient and productive. Th productivity of our work largely determines how well we live, and how easy it is to produce th necessary and luxury goods and services for ourselves and our families. Our employment also affec our self-esteem, sense of accomplishment, purpose in life, and ability to help others.

There were a few truly outstanding inventions that so greatly expanded human capabilities that w could accomplish work that could never be done before. Several times in history, a new inventio changed the way we work to make a living, and ushered in a new age in our history.

The *stone axe* was the first human invention that put us on the evolutionary path. To be huma means that, simply by our ingenuity, we can supplement the gifts of nature. The first human inventio