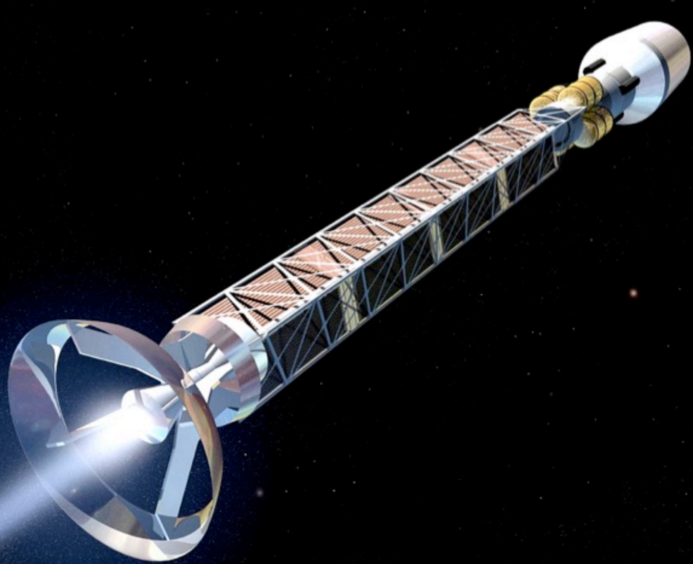


FUTURE CREATORS

How Young Scientists and Engineers Could Create Revolutionary Innovations That Would Change the World

Todd H. Rider






This is a work in progress. Please let me know if you have any suggestions for corrections, improvements, or additions.

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How Young Scientists and Engineers Could Create Revolutionary Innovations That Would Change the World

The process by which the boundaries of knowledge are advanced... corresponds fairly well with the exploitation of a difficult quarry for its building materials... There are those men of rare vision, who can grasp well in advance just the block that is needed for rapid advance on a section of the edifice to be possible, who can tell by some subtle sense where it will be found, and who have an uncanny skill in cleaning away dross and bringing it surely into the light. These are the master workmen.

Vannevar Bush, "The Builders" (1945)

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Executive Summary

> The end of our foundation is the knowledge of causes, and secret motions of things; and the enlarging of the bounds of human empire, to the effecting of all things possible.
>
> Senior scientist of Salomon's House, in Sir Francis Bacon's *New Atlantis* (1626)

Chapter 1: Remembering the Future. As shown by many historical examples in this chapter, one person who conceives a revolutionary scientific idea or creation—and can find the resources to properly demonstrate it—can change the world. This book is addressed to those who would like to become revolutionary innovators or creators, as well as to others who are in positions to help them. It offers advice and perspective for future creators, whether they are in elementary school, the middle of their scientific career, or somewhere in between.

Chapter 1 also explains powerful methods for finding and analyzing both the most important revolutionary scientific problems and the most suitable innovative solutions to those problems. In top-down systems analysis, one methodically considers all possible categories and subcategories of problems of interest, and then all possible categories and subcategories of solutions to specific ones of those problems, in order to identify and focus on the most promising solutions for the most important problems. Top-down systems analysis is strongly complemented by bottom-up brainstorming, in which one seeks inspiration for specific problems, solutions, principles, constraints, etc. that will test, correct, refine, and fill out the categories and subcategories.

To inspire and guide future creators, this book uses these methods to break down all currently foreseeable future creations into ten categories, and to further subdivide and analyze revolutionary innovations within each of those categories (with references to relevant previous research and suggestions for potential future work):

> **Chapter 2: Creations in Biology and Physiology** that are not immediately helpful or applied, yet may have later applications. Primarily, though, they would expand our knowledge regarding biochemistry, biological information flow (DNA, RNA, proteins, etc.), cell biology, organs and tissues, whole organisms, families and histories of organisms, and communities of interacting organisms.
>
> **Chapter 3: Creations in Chemistry and Materials** that are not inherently helpful or applied (though they may have later applications) but would expand our knowledge of atoms, molecular structures, collections of molecules, chemical reactions, and properties.
>
> **Chapter 4: Creations in Earth and Space Sciences** that are not directly helpful or applied but would expand our knowledge regarding terrestrial geology, the ocean and other water, the atmosphere, other astronomical bodies, and the space in between.
>
> **Chapter 5: Creations in Mathematics and Physics** that are not inherently helpful or applied but would expand our knowledge of phenomena, physical laws, and fundamental explanations ranging from microscopic particles and forces to macroscopic objects such as black holes and even the whole universe (or other universes).
>
> **Chapter 6: Creations That Improve Humans** with regard to their intrinsic properties, health, and/or lives, including physical performance and characteristics, mental performance, moral behavior, infectious diseases, noninfectious diseases and injuries, and aging and death.

Chapter 7: Creations That Improve Travel and Human Expansion in realms including land (and below), the ocean and other water, the atmosphere, space (including space stations, planets, and moons), time, and other dimensions or universes.

Chapter 8: Creations That Improve Resources for Humans, including food, water, air, the environment, housing, energy, materials, nonhuman labor, and communications.

Chapter 9: Creations That Aid Nonhumans should be considered for completeness, in addition to categories of creations that aid humans. Included in this category are creations that aid nonhumans on Earth, such as animals, plants, the microbiome, the non-living environment, and human-created entities such as genetically engineered organisms and artificial intelligence. Also included are creations that aid nonhumans elsewhere, such as alien life that we discover, possible alien life that we should not inconvenience with our current activities even before we discover them, and the non-living universe for which we should act as good custodians.

Chapter 10: Creations That Concern Revolutionary Innovation Itself can improve the process for producing creators and creations and thus improve the world, so they are themselves a category of revolutionary innovation. Much can be learned by studying the creators, creations, methods, and systems of revolutionary innovation throughout the past and around the world in the present. Much can also be accomplished by proposing and evaluating potential methods of improving revolutionary innovation in the future, based on ideas from the past and present, as well as new or modified ideas.

Chapter 11: Creations That Are Harmful include those intended to kill, hurt, restrict, control, manipulate, deceive, addict, spy, track, steal, damage, destroy, and/or have other harmful effects. Although many research sponsors would undoubtedly be interested in future creations in this category, for ethical reasons they are not discussed in detail in this book. However, precisely because the category is so interesting to many research sponsors, both the quantity and quality of previous revolutionary innovations in this category have been extraordinary. Even those scientists who choose not to pursue future creations in this category can learn much from previous creations in this category, in terms of the new science and non-harmful spinoff applications they have introduced, and also in terms of systems and methods of revolutionary innovation that were harnessed to arrive at those previous creations.

Chapter 12: The Road to Creation, from initially having a revolutionary idea to actually realizing that idea, is usually very long and filled with many obstacles. Whereas the other chapters deal with the scientific difficulties and some methods to overcome them, this chapter covers some of the common non-scientific obstacles (financial, political, cultural, personal, etc.) that one is likely to encounter along the way. In order to prepare future creators for such non-scientific obstacles, this chapter provides some advice from previous scientific and non-scientific innovators, as well as some potentially new advice.

The appendices cover a few small subsets of the above research areas in more detail, in hopes of providing useful pointers for future creators interested in those areas, and illustrative examples of brainstorming and analysis even for future creators who are interested in other areas:

Appendix A: Innovations to Improve Moral Behavior. One subcategory of methods to directly improve humans themselves is scientific innovations that could improve human moral behavior. Human society and human history are filled with examples of individual people and collective groups and populations that are governed by the darker side of human nature, causing great harm to themselves and to others. Even the most honorable people struggle with baser instincts and give in to them at least occasionally and briefly. Education, religion, law, and other disciplines have tried with only limited success to improve moral behavior. Just imagine what science might be able to tell us about the fundamental causes and potential solutions for human moral struggles, and consider how much difference that could make in the world. Of course, scientific experiments to understand and to improve moral behavior are themselves fraught with a large number of moral issues, as explained in this appendix.

Appendix B: Innovations to Address Infectious Diseases. Another subcategory aimed at directly improving the lives of humans encompasses methods of detecting, preventing, and treating infectious diseases, including diseases caused by prions, viruses, bacteria, fungi, protists, and helminths. This appendix analyzes subcategories in these areas and proposes some specific ideas that could be investigated further in the future.

Appendix C: Innovations in Advanced Space Propulsion. This appendix delineates and analyzes categories of propulsion suitable for interstellar space travel. In order to send a manned or unmanned spacecraft to other star systems within a sufficiently short transit duration (say several decades at most), the propulsion system must accelerate the spacecraft to an appreciable fraction of the speed of light. All foreseeable methods of onboard propulsion systems are analyzed, including chemical propellants, nuclear fission, nuclear fusion, and antimatter. All foreseeable methods using resources that are not onboard the spacecraft (ramjets, beamed power propulsion, etc.) are also discussed. The most promising areas for future research are identified.

Appendix D: Innovations in Unconventional Physics Applications. Unconventional physics applications include travel of objects or messages in time, into parallel universes or other dimensions, faster than light, via teleportation or wormholes, through solid or potential energy barriers, etc. It also includes unconventional physics methods of providing useful energy and/or force, such as “free” energy from the vacuum, reactionless propulsion, inertia control, antigravity, and artificial gravity. In many cases these effects are interrelated—for example, time travel could be turned into faster-than-light travel and vice versa. This appendix identifies categories of known and foreseeable physics that could potentially have such effects. It notes where previous research falls into those categories and points out many areas for future investigation.

Appendix E: Innovations in Nuclear Energy. Rearranging electrons in atoms releases chemical energy. From basic principles, rearranging protons and neutrons within the nuclei of atoms releases roughly a million times more energy—nuclear energy—because the protons and neutrons are much closer together than the electrons. This appendix identifies all foreseeable categories and sub-categories of approaches for extracting nuclear energy, evaluates which ones seem safest and most feasible, and suggests directions for future work.

The **Bibliography** lists key references for general knowledge in each field and for some important previous research on several specific topics.

Contents

To my students,
including those whom I have
not had the good fortune to meet.

Acknowledgments

> "But the Snark is at hand, let me tell you again!
> 'Tis your glorious duty to seek it!
>
> "To seek it with thimbles, to seek it with care;
> To pursue it with forks and hope;
> To threaten its life with a railway-share;
> To charm it with smiles and soap!
>
> "For the Snark's a peculiar creature, that wo'n't
> Be caught in a commonplace way.
> Do all that you know, and try all that you don't:
> Not a chance must be wasted to-day!"
>
> The Bellman, in Lewis Carroll's
> *The Hunting of the Snark* (1876)

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Chapter 1

Remembering the Future

> As a child I had not been content with the results promised by the modern professors of natural science. With a confusion of ideas only to be accounted for by my extreme youth and my want of a guide on such matters, I had retrod the steps of knowledge along the paths of time and exchanged the discoveries of recent enquirers for the dreams of forgotten alchemists. Besides, I had a contempt for the uses of modern natural philosophy. It was very different when the masters of the science sought immortality and power; such views, although futile, were grand; but now the scene was changed. The ambition of the enquirer seemed to limit itself to the annihilation of those visions on which my interest in science was chiefly founded. I was required to exchange chimeras of boundless grandeur for realities of little worth... [S]oon my mind was filled with one thought, one conception, one purpose. So much has been done, exclaimed the soul of Frankenstein—more, far more, will I achieve; treading in the steps already marked, I will pioneer a new way, explore unknown powers, and unfold to the world the deepest mysteries of creation.
>
> Victor Frankenstein, in Mary Shelley's *Frankenstein* (1818), Ch. III

This chapter offers general scientific advice to aspiring revolutionary innovators, or future creators, including:

1.1. Explaining the motivation for this book.

1.2. Covering key aspects of the training of future creators.

1.3. Surveying the entire range of potential revolutionary innovations, or future creations.

1.4. Discussing some disclaimers, caveats, and limitations of this book.

1.1 Motivation

1.1.1 Introduction

In the past, scientists dreamed of the future. They conceived grand, daring visions, and they realized them—semiconductors and submarines, miracle drugs and moon landings. Those revolutionary innovations changed the world.

In the present, scientists (if they are lucky enough to even find a job in science) are shackled to grant proposals, peer review committees, next year's popular product, tomorrow's stock price for the corporation. Those who still cling to the belief that innovations can and should change the world are regarded as naive, or useless, or deranged. As a result, there is much less innovation. Most of the innovation that does occur is not revolutionary, but rather evolutionary—very modest improvements of existing technologies and science.

Now only the children still remember the future. They remember vistas of endless exploration and progress; they remember the possibility of the impossible; they remember that the world can be far better than it is. At least until they grow up and are forced to recant those ideas.

If we as a society are again to remember the future, to be reminded of all the hopes and possibilities that we have forgotten, children must lead the way, and the rest of us must help them.

This book is addressed to those children, and to the adults that they become, and to the adults who can help them anywhere along their path.

If you are a young student, please skip to any section that sounds interesting, whether that may be science experiment kits, genetically engineered superhumans, faster-than-light spaceships, or something else. Do not get bogged down in the details presented here, and do not limit your ideas to only those given here. Dream as much as you can, as big as you can.

If you are an older student or already in a scientific career, I can offer some general advice, and point toward some promising directions that seem ripe for exploration. I hope that may be useful, but you will have to judge which of my details turned out to be correct or incorrect, or what I should have said but did not think to mention.

If you are a parent, teacher, professor, research manager, research sponsor, or other adult in a position to help young scientific innovators, please focus on whatever part of this book is most related to how you interact (or how you could interact) with young innovators. For their sakes, and for the sake of our world, please help them however you can.

1.1.2 Scientists' Ages at Their First Revolutionary Innovation

We can learn a great deal about how to inspire and support future revolutionary scientific innovators and innovations by studying the revolutionary innovators and innovations of the past. One of the most striking features of previous innovators is how many of them made their first revolutionary innovation by the time they were in their 20s, or in a few cases even in their teens. For example, Albert Einstein published his first important paper at age 23, and had published revolutionary papers on relativity, quantum physics, and statistical physics by age 26. Barbara McClintock was 23 when she began the genetics experiments that ultimately earned her a Nobel Prize. Manfred von Ardenne was 16 when he patented his first electronic invention. Mary Anning was 12 when she began to find and piece together the skeletons of extinct Mesozoic reptiles. Hermann Oberth was 14 when he built and launched his first rocket.

Table 1.1.2 lists hundreds of other examples of such innovators. Without getting bogged down in the details of the table (unless you are curious to look up more information on some of these innovators), notice their ages (in red) at the time of their first major discovery or invention. Then skim through the sorts of revolutionary innovations that those scientists created, and consider the impact they had on the world: biotechnology, vaccines, plastics, continental drift, quantum physics, transistors, computers, lasers, internal combustion engines and vehicles powered by them, nuclear energy, jet aircraft, rockets, etc.

Also bear in mind these points about the examples in the table:

- In the vast majority of cases, scientists do not make a brilliant discovery or invention just as soon as they begin conducting original research. If scientists published or patented a major innovation when they were in their 20s, generally they started many years earlier down the path of scientific education and research that led to that final result. Thus it is extremely important for future creators to begin their training and brainstorming as early as possible, ideally in elementary school or even preschool.

- For some scientists in the table, their first innovation was their most famous; in many other cases, they went on to create even greater innovations. Yet they began producing creative, important innovations by their 20s—their fount of revolutionary ideas had begun to flow.

- This table is far from being a comprehensive list of revolutionary scientific innovators who succeeded by their 20s. For those who are listed, one line in a table is hardly sufficient to properly explain their lives and their innovations. Despite those limitations, hopefully the examples in the table at least illustrate the enormous number and the great importance of the revolutionary innovations that were produced by such scientists.

- There are certainly a number of historical cases of scientists who did not produce their first revolutionary innovation until they were in their 30s or older. For example, Gregor Mendel did not begin his experiments with plant genetics until he was 34, and Wilhelm Herschel did not build his first telescope until he was 35; they both continued those studies for the rest of their lives. Aspiring future creators should not give up hope, even if they get a late start or have been unsuccessful so far at producing revolutionary innovations. Nonetheless, the earlier you begin, the better your chances of creating revolutionary innovations will be.

In stark contrast to this historical data on the revolutionary innovators who created so many different aspects of our modern world, nowadays most scientists in the United States and many other countries are not able to even begin working on their own new ideas until they are far older. First of all, having a Ph.D. or M.D. degree is usually a prerequisite for being allowed to do original research, and typically all of a student's work prior to that time (including the doctoral thesis research itself) is simply done at the direction of older scientists. In the United States in 2017, the median age at graduation with a doctorate was 31.6 [www.nsf.gov/statistics/srvydoctorates/]. Even most scientists who receive a doctorate still have to spend many more years closely following older supervisors' instructions in postdoctoral jobs, residencies, or entry-level positions at corporate or government laboratories before they finally have the freedom to conceive and to pursue their own original ideas. For example, in the United States in 2012, the average age at which Ph.D. scientists finally received their own first National Institutes of Health (NIH) research project grant was 41.9, and the average age at which M.D. scientists received their first NIH research grant was 43.8 [report.nih.gov/Workforce/PSW/].

Thus, whereas huge numbers of revolutionary innovations historically have come from scientists who created their first innovations in their early- to mid-20s, most (though not all) scientists now are not allowed to even begin conducting truly original research until their early- to mid-40s, if they are ever allowed at all.

Olympic gymnasts and concert pianists train from a very early age for their ultimate goal. It would be ludicrous to expect young people to simply watch Olympic gymnasts or concert pianists from the sidelines for decades, then finally step on stage for the first time in their 40s and be successful Olympic gymnasts or concert pianists themselves. It is equally ludicrous for the modern scientific system to hope to train revolutionary scientific innovators in that same fashion:

- The ability to create revolutionary innovations is a skill; like any other skill, it must be practiced as much as possible, from as early an age as possible, in order to optimize that skill.

- Even if the ability to create revolutionary innovations could be instantaneously and reliably switched on, doing so for the first time when scientists are in their 40s instead of their 20s gives them on average two decades less during which they can be productive.

- Not all decades of a scientist's life are equally productive in equal ways. Those lost two decades likely would have been the most productive time for creating revolutionary innovations. Those early years are often when people are at their peak energy and creativity in life, and also generally less weighed down by family and professional obligations.

This fundamental problem appears to be one of the major reasons why the modern system produces so few truly revolutionary innovations per scientist or per amount of funding, compared to the most productive scientific innovation systems of the past [Rider 2020].

This book is intended to teach students the best ways to work *through* and in many cases *around* the modern system to become future creators, in spite of the profound flaws of the modern system.

Table 1.1: Examples of revolutionary scientific innovators who produced their first major discovery or invention by their 20s. **See pp. 25–33.**

Revolutionary scientific innovator	**Years lived**	**First creation**	**Major discoveries or inventions**
Ernst Abbe	1840–1905	**26**	Diffraction-limited optics
Jakob Ackeret	1898–1981	**24**	Supersonic aerodynamics
Kurt Alder	1902–1958	**24**	Diels-Alder reaction
Luis Walter Alvarez	1911–1988	**25**	Particle detectors, meteorite killed dinosaurs
André-Marie Ampère	1775–1836	**27**	Electromagnetism
Mary Anning	1799–1847	**12**	Mesozoic skeletons, other fossils
Manfred von Ardenne	1907–1997	**15**	Television, electron microscope, nuclear weapons
Svante Arrhenius	1859–1927	**22**	Electrochemistry, biochemistry
Avicenna (Ibn Sina)	980–1037	**18**	Comprehensive medicine, etc.
Walter Baade	1893–1960	**27**	Asteroids, Cepheids, neutron stars, universe expansion
Charles Babbage	1791–1871	**28**	Computers
Karl von Baer	1792–1876	**25**	Developmental biology
Adolf von Baeyer	1835–1917	**12**	Organic chemistry, dyes, polymers, etc.
Róbert Bárány	1876–1936	**24**	Sense of balance
Werner Baum	1918–20??	**23**	Liquid propellant rocket engines
Eugen Baumann	1846–1896	**25**	Polyvinyl chloride, Schotten-Baumann reaction
Paul Baumgärtl	1920–2012	**20**	Backpack helicopters 1940
Zoltan Bay	1900–1992	**23**	Light emitting diode 1939, etc.
Otto Bayer	1902–1982	**21**	Polyurethane, etc.
Georg von Békésy	1899–1972	**27**	Sense of hearing
Max Bergmann	1886–1944	**25**	Protein synthesis and sequencing
Daniel Bernoulli	1700–1782	**24**	Fluid mechanics, flexible beams, mathematics
Jöns Jacob Berzelius	1779–1848	**27**	Si, Se, Th, Ce, catalysts, atomic weights
Friedrich Bessel	1784–1846	**20**	Parallax distances to stars, Bessel functions, etc.
Hans Bethe	1906–2005	**22**	Stellar physics, nuclear weapons, etc.
Joseph Black	1728–1799	**22**	Analytical balance, CO_2, Mg, latent/specific heat
Felix Bloch	1905–1983	**22**	Solid state physics, MRI, nuclear physics, radar
Nicolaas Bloembergen	1920–2017	**25**	MRI
Walter Bock	1895–1948	**26**	Synthetic rubber
Niels Bohr	1885–1962	**25**	Structure of atom, nuclear physics, etc.
Ludwig Boltzmann	1844–1906	**22**	Statistical and thermal physics
Max Born	1882–1970	**22**	Quantum physics, optics
Theodor Boveri	1862–1915	**26**	Cancer
Karl Ferdinand Braun	1850–1918	**24**	Diode 1874, CRT/oscilloscope, phased array antenna
Wernher von Braun	1912–1977	**18**	Liquid propellant rockets
Robert Bunsen	1811–1899	**22**	Cs, Rb, spectroscopy, electrochemistry
Adolf Busemann	1901–1986	**23**	Swept wings, supersonic/hypersonic aerodynamics
Adolf Butenandt	1903–1995	**24**	Hormones, gene mutations
Georg Cantor	1845–1918	**22**	Set theory, Fourier analysis, real analysis
Gerolamo Cardano	1501–1576	**23**	Algebra, paleontology, engineering, medicine
Sadi Carnot	1796–1832	**27**	Thermodynamics of engines
Alexis Carrel	1873–1944	**28**	Vascular sutures, transplantation, thoracic surgery
Augustin-Louis Cauchy	1789–1857	**20**	Complex analysis, continuum mechanics, etc.
Henry Cavendish	1731–1810	**28**	Hydrogen and other gases, Earth's density, electrostatics

Revolutionary scientific innovator	**Years lived**	**First creation**	**Major discoveries or inventions**
Subrahmanyan Chandrasekhar	1910–1995	**19**	Statistical physics, stellar physics
Rudolf Clausius	1822–1888	**26**	Thermodynamics
Arthur Compton	1892–1962	**24**	Photon-electron scattering
Charles-Augustin de Coulomb	1736–1806	**24**	Electrostatics
Richard Courant	1888–1972	**22**	Applied mathematics
Marie Curie	1867–1934	**25**	Radioactive elements
Pierre Curie	1859–1906	**21**	Piezoelectricity, radioactive elements
John Dalton	1766–1844	**26**	Meteorology, color blindness, gas laws, atomic masses
Charles Darwin	1809–1882	**22**	Evolution
Adolf Dassler	1900–1978	**17**	Sports shoes 1917
Humphry Davy	1778–1829	**20**	Electrolysis, Al, Na, K, Ca, Sr, Mg, Ba, B, Davy lamp
Peter Debye	1884–1966	**23**	Physical chemistry, solid state physics
Max Delbrück	1906–1981	**24**	Quantum electrodynamics, radiation, DNA
René Descartes	1596–1650	**22**	Mathematics, physics, engineering, optics
Rudolf Diesel	1858–1913	**22**	Diesel engines and vehicles
Paul Dirac	1902–1984	**23**	Quantum electrodynamics
Friedrich von Doblhoff	1916–2000	**26**	Jet helicopters 1942
Max Dohrn	1874–1943	**25**	Insulin, antibiotics, steroid hormones
Gerhard Domagk	1895–1964	**25**	Antibiotics 1932
Karl von Drais	1785–1851	**27**	Bicycle, typewriter, paper music recorder, etc.
Freeman Dyson	1923–2020	**23**	Quantum electrodynamics, nuclear rockets, etc.
Ernst Eckert	1904–2004	**26**	Heat transfer
Arthur Eddington	1882–1944	**24**	Stellar physics
Johanna "Tilly" Edinger	1897–1967	**23**	Paleoneurology
Paul Ehrenfest	1880–1933	**24**	Quantum physics
Krafft Ehricke	1917–1984	**22**	Rockets, nuclear engineering, solar system
Paul Ehrlich	1854–1915	**24**	Antibiotics, antibodies, microscope stains, etc.
Alfred Einhorn	1856–1917	**26**	Polycarbonate, procaine, etc.
Albert Einstein	1879–1955	**23**	Relativity, quantum, statistical physics, etc.
Willem Einthoven	1860–1927	**26**	Electrocardiogram 1895, etc.
Walter Elsasser	1904–1991	**22?**	Nuclear shell model, geomagnetism, systems biology
Leonhard Euler	1707–1783	**19**	Mathematics, fluids, astronomy, optics, etc.
Michael Faraday	1791–1867	**22**	Electromagnetism, benzene, electrochemistry, etc.
Pierre de Fermat	1607–1665	**21**	Number theory, analytic geometry, probability, etc.
Enrico Fermi	1901–1954	**19**	Statistical/quantum/nuclear physics, weak force
Richard Feynman	1918–1988	**24**	Quantum electrodynamics
Hermann Emil Fischer	1852–1919	**22**	Organic chem., enzymes, proteins, purines, barbiturates
Anton Flettner	1885–1961	**21**	Teleoperated robots, rotor ships, helicopters 1936
Siegfried Flügge	1912–1997	**21**	Nuclear weapons
Werner Forssmann	1904–1979	**25**	Cardiac catheter 1929
Joseph Fourier	1768–1830	**21**	Fourier transforms, heat conduction, greenhouse effect
James Franck	1882–1964	**24**	Photoelectric effect, nuclear physics, photosynthesis
Rosalind Franklin	1920–1958	**25**	Structure of DNA 1952
Joseph von Fraunhofer	1787–1826	**24**	Diffraction grating, spectroscope, achromatic lenses

Revolutionary scientific innovator	**Years lived**	**First creation**	**Major discoveries or inventions**
Augustin-Jean Fresnel	1788–1827	23	Fresnel lenses, polarization, diffraction, etc.
Hans Friedrich-Freksa	1906–1973	25	Double-stranded complementary DNA structure 1940
Leopold Freund	1868–1943	28	Radiation therapy 1896
Casimir (Kazimierz) Funk	1884–1967	27	Vitamins
Galileo Galilei	1564–1642	21	Classical mechanics, science instruments, astronomy
George Gamow	1904–1968	24	Nuclear physics, cosmology, genetic code
Richard Garwin	1928–	24	Nuclear weapons, spy satellites, etc.
Carl Friedrich Gauss	1777–1855	19	Math, astronomy, electromagnetism, telegraph 1833
Joseph Gay-Lussac	1778–1850	23	Properties of gases
Hans Geiger	1882–1945	24	Radiation detectors
Murray Gell-Mann	1929–2019	22	Quarks and quantum chromodynamics
Walther Gerlach	1889–1979	23	Particle spin, nuclear weapons
Edmund Germer	1901–1987	25	Fluorescent lights 1926
Walter Gilbert	1932–	25	Strong force, Lac repressor, DNA sequencing, introns
Sheldon Glashow	1932–	26	Electroweak theory
Heinrich Göbel	1818–1893	19	Incandescent light bulb 1854
Kurt Gödel	1906–1978	23	Incompleteness theorems, mathematical logic
Camillo Golgi	1843–1926	29	Golgi stain for neurons, Golgi apparatus in cells
Friedrich Goppelsröder	1837–1919	24	Chromatography 1861
Hermann Grassmann	1809–1877	22	Math, physics, linguistics
Helmut Gröttrup	1916–1981	23	Avionics, rockets, chip card
Bernhard Gudden	1892–1945	27	Photoelectric cells, proto-LEDs, transistors
Beno Gutenberg	1889–1960	22	Seismology
Erich Habann	1892–1968	??	Transistor 1942, radar, rockets, etc.
Fritz Haber	1868–1934	26	Ammonia synthesis, chemical weapons, etc.
Gottlieb Haberlandt	1854–1945	24	Plant tissue culture, stem cells
Ludwig Haberlandt	1885– 1932	28	Hormonal birth control 1921, etc.
Otto Hahn	1879–1968	25	Radioactive elements, nuclear fission, chemical weapons
George Ellery Hale	1868–1938	24	Spectroheliograph, magnetic fields in sunspots
Edmond Halley	1656–1742	19	Astronomy, geophysics, diving bell, etc.
Franjo Hanaman	1878–1941	24	Tungsten-filament incandescent light bulbs 1903
Albert Hanson	18??–19??	??	Printed circuits and multi-pin connectors 1902
Robert Havemann	1910–1982	26	Spectrophotometer 1936, colloids
Oskar Heil	1908–1994	25	Transistor 1934, etc.
Werner Heisenberg	1901–1976	22	Quantum physics, nuclear physics
Hermann von Helmholtz	1821–1894	22	Vision, hearing, electromagnetism, thermodynamics
Peter Henlein	1485–1542	20	Portable watch 1505
Gustav Hertz	1887–1975	24	Excited gases, gaseous diffusion, nuclear weapons
Heinrich Hertz	1857–1894	29	Electromagnetic waves, radio transmitter/receiver
David Hilbert	1862–1943	23	Algebraic theory/variational calculus/non-Eucl. geometry
Rudolf Hilsch	1903–1972	23	Transistor 1938, etc.
Johann Hittorf	1824–1914	23	Cathode rays
August Wilhelm von Hofmann	1818–1892	23	Polystyrene, aniline, sorbic acid, etc.
Franz Hofmeister	1850–1922	28	Amino acids and proteins

Revolutionary scientific innovator	Years lived	First creation	Major discoveries or inventions
Wilhelm Hofmeister	1824–1877	27	Alternation of generations in plants
Herman Hollerith	1860–1929	24	Calculating machines
Robert Hooke	1635–1703	20	Microscopy, astronomy, physics, paleontology, etc.
Fritz Houtermans	1903–1966	24	Nuclear physics, astrophysics, geophysics
Christian Hülsmeyer	1881–1957	20	Radar 1903
Alexander von Humboldt	1769–1859	20	Biogeography, geomagnetism, etc.
Friedrich Hund	1896–1997	26	Quantum physics
Christiaan Huygens	1629–1695	22	Pendulum clock, optics, astronomy, etc.
Werner Jacobi	1904–1985	25	Integrated circuits <1945, heavy ion beams, etc.
Max Jakob	1879–1955	24	Heat transfer
Frédéric Joliot-Curie	1900–1958	26	Artificial radioactivity
Irène Joliot-Curie	1897–1956	27	Artificial radioactivity
Pascual Jordan	1902–1980	22	Quantum physics
Brian Josephson	1940–	22	Superconductor tunneling
James Joule	1818–1889	22	Thermodynamics
Alexander Just	1874–1937	22	Tungsten-filament incandescent light bulbs 1903
Theodor Kaluza	1885–1954	24	Kaluza-Klein theory
Paul Karrer	1889–1971	22	Vitamins
August Kekulé	1829–1896	27	Benzene and other chemical structures
Athanasius Kircher	1602–1680	26	Geology, microbiology, archaeology, clocks, projectors
Gustav Kirchhoff	1824–1887	21	Circuits, Cs, Rb, spectroscopy, thermal radiation
Martin Klaproth	1743–1817	27	Ti, Sr, Zr, Te, Ce, U, etc.
Friedrich (Fritz) Klatte	1880–1934	27	Polyvinyl chloride, polyvinyl acetate
Oskar Klein	1894–1977	26	Kaluza-Klein theory, etc.
Robert Koch	1843–1910	22	Anthrax, staphylococcus, tuberculosis, cholera, etc.
Willem Kolff	1911–2009	27	Dialysis machines, improved heart-lung machines
Hans Kopfermann	1895–1963	28	Proto-laser 1928, etc.
Arthur Kornberg	1918–2007	24	DNA polymerase and other key enzymes
Albrecht Kossel	1853–1927	24	Structure/composition of DNA, RNA, proteins
Felix Kracht	1912–2002	25	Jet aircraft, rocket planes
Max Kramer	1903–1986	28	Guided missiles, smart bombs, submarines
Hans Adolf Krebs	1900–1981	22	Urea cycle, Krebs cycle, glyoxylate cycle
Herbert Kroemer	1928–	24	Drift transistor, semiconductor heterostructures
Ralph Kronig	1904–1995	20	Particle spin, solid state physics
Alfred Kühn	1885–1968	25	Genetics
Richard Kuhn	1900–1967	21	Vitamins, organophosphates, antibiotics
Gerard Kuiper	1905–1973	27	Kuiper belt, Mars/Titan atmospheres, Miranda, Nereid
Nicholas Kurti	1908–1998	23	Cryogenics
Rudolf Ladenburg	1882–1952	27	Proto-laser 1928, etc.
Paul Langerhans	1847–1888	22	Insulin-producing cells in pancreas 1869
Karl Landsteiner	1868–1943	23	Blood types 1900, polio virus 1909, etc.
Irving Langmuir	1881–1957	25	Surface chemistry, physical chemistry
Pierre-Simon Laplace	1749–1827	20	Orbits, probability, Laplace transforms, etc.
Max von Laue	1879–1960	23	X-ray crystallography, superconductivity

Revolutionary scientific innovator	**Years lived**	**First creation**	**Major discoveries or inventions**
Antoine Lavoisier	1743–1794	**20**	Chemistry of many elements
Joshua Lederberg	1925–2008	**20**	Plasmids
Adrien-Marie Legendre	1752–1833	**17**	Legendre polynomials/transformations, elliptic functions
Hermann Lehmann	1910–1985	**28**	Hemoglobin, pharmacokinetics
Kurt Lehovec	1918–2012	**22**	LEDs, transistors, integrated circuits
Gottfried Leibniz	1646–1716	**19**	Calc. machines, math, physics, engineering, geology, biology
Philipp Lenard	1862–1947	**24**	Electron, electromagnetism
Leonardo da Vinci	1452–1519	**20**	Aircraft designs, anatomical discoveries, etc.
Hilde Levi	1909–2003	**25**	Chlorophyll, isotope labelling of molecules
Willard Libby	1908–1980	**24**	Radiocarbon dating, gaseous diffusion enrichment
Robert von Lieben	1878–1913	**27**	Vacuum tubes
Justus von Liebig	1803–1873	**23**	Chemical radicals, analytical chemistry, biochemistry, etc.
Julius Edgar Lilienfeld	1882–1963	**23**	Transistor 1925, etc.
Otto Lilienthal	1848–1896	**19**	Gliders
Carl von Linde	1842–1934	**29**	Refrigeration
Fritz Lipmann	1899–1986	**27**	Coenzyme A
Peter Lobban	1945–	**24**	Recombinant DNA
Otto Loewi	1873–1961	**27**	Acetylcholine, other neurotransmitters and receptors
Fritz London	1900–1954	**27**	Superconductivy, London equations 1935
Heinz London	1907–1970	**23**	Superconductivy, London equations 1935
Hendrik Lorentz	1853–1928	**22**	Electromagnetism, special relativity, Zeeman effect
Konrad Lorenz	1903–1989	**29**	Animal behavior
Otto Lummer	1860–1925	**24**	Thermal radiation, mercury vapor lamp, etc.
Salvador Luria	1912–1991	**26**	Properties of bacteriophage
Charles Lyell	1797–1875	**20**	Geological processes
Feodor Lynen	1911–1979	**26**	Cholesterol, fats, vitamins
Ernst Mach	1838–1916	**22**	Aerodynamics, optics, relativity, hearing/balance
James Clerk Maxwell	1831–1879	**18**	Electromagnetism
Wilhelm Maybach	1846–1929	**23**	Automobiles, motorcycles, trucks, motorboats
Julius von Mayer	1814–1878	**26**	Thermodynamics
Maria Goeppert Mayer	1906–1972	**24**	2-photon absorption, nuclear shell model, etc.
Barbara McClintock	1902–1992	**23**	Chromosome structure
Alexander Meissner	1883–1958	**24**	Radio transmitters/receivers
Fritz Walther Meissner	1882–1974	**24**	Superconductivity, Meissner effect
Lise Meitner	1878–1968	**26**	Protactinium, nuclear fission
Kurt Mendelssohn	1906–1980	**24**	Superconductivity, cryogenics
Élie Metchnikoff	1845–1916	**20**	Macrophage cells
Franz Meyen	1804–1840	**24**	Cell biology, botany
Julius Lothar Meyer	1830–1895	**27**	Periodic table of the elements 1862, etc.
Wilhelm von Meyeren	1905–1983	**24**	Proto-laser 1944, etc.
Albert Michelson	1852–1931	**24**	Speed of light, binary stars
Johannes Friedrich Miescher	1844–1895	**25**	Purified DNA 1869
Thomas Hunt Morgan	1866–1945	**24**	Fruit fly genetics
Johannes Peter Müller	1801–1858	**24**	Comparative anatomy

Revolutionary scientific innovator	Years lived	First creation	Major discoveries or inventions
Paul Hermann Müller	1899–1965	26	DDT, etc.
Walther Müller	1905–1979	22	Geiger-Müller radiation detectors
Hans Multhopp	1913–1972	22	Jet aircraft, lifting body
Walther Nernst	1864–1941	22	Metal-filament lightbulbs, physical chemistry, acoustics
John von Neumann	1903–1957	20	Math, physics, computers, economics, etc.
Isaac Newton	1642–1727	23	Calculus, classical mechanics, gravitation, optics
Wilhelm Nusselt	1882–1957	24	Heat transfer
Hermann Oberth	1894–1989	14	Rockets, space stations
Hans von Ohain	1911–1998	23	Jet engines
Heinrich Olbers	1758–1840	20	Astronomy, mathematics, ophthalmology, vaccination
Karol Olszewski	1846–1915	27	Liquefied gases
Heike Kamerlingh Onnes	1853–1926	28	Cryogenics, liquid helium, superconductivity
J. Robert Oppenheimer	1904–1967	23	Stellar physics, nuclear weapons
Hans Christian Ørsted	1777–1851	29	Electromagnetism, aluminum
Wilhelm Ostwald	1853–1932	24	Physical chemistry
Nikolaus Otto	1832–1891	28	Internal combustion engine
Friedrich Paneth	1887–1958	23	Isotope labeling of chemical molecules, etc.
Denis Papin	1647–1713	25	Steam engine, steam-engine-powered vehicles, air pump
Paracelsus	1493–1541	23	Medicinal chemistry
Blaise Pascal	1623–1662	16	Math, calculating machine, fluid mechanics
Friedrich Paschen	1865–1947	23	Very early quantum physics experiments
Louis Pasteur	1822–1895	26	Crystallography, microbiology, vaccines
Wolfgang Paul	1913–1993	27	Ion traps, particle accelerators, nuclear weapons
Wolfgang Pauli	1900–1958	18	Particle spin statistics/exclusion principle
Linus Pauling	1901–1994	24	Quantum chemistry, protein structures
Hans von Pechmann	1850–1902	24	Polyethylene, diazomethane, etc.
Rudolf Peierls	1907–1995	22	Solid state physics, Manhattan Project
Max Perutz	1914–2002	24	Protein structures, hemoglobin, myoglobin
Auguste Piccard	1884–1962	29	Stratospheric balloon, cosmic rays, bathyscaphe
Max Planck	1858–1947	20	Quantum physics
Peter Plett	1766–1823	23	Vaccinia vaccine for smallpox 1790
Julius Plücker	1801–1868	27	Cathode rays, analytical geometry
Robert Pohl	1884–1976	21	Transistor 1938, etc.
Michael Polanyi	1891–1976	25	Physical chemistry, materials science, medicine, economics
Erwin Popper	1879–1955	23	Poliovirus
Ferdinand Porsche	1875–1951	22	Automobiles, tanks, gas/electric hybrids, etc.
Ludwig Prandtl	1875–1953	26	Fluid mechanics and aerodynamics, wind tunnels
Fritz Pregl	1869–1930	24	Quantitative chemical microanalysis
Vladimir Prelog	1906–1998	23	Stereochemistry
Ernst Pringsheim	1859–1917	23	Thermal radiation
Edward Purcell	1912–1997	25	NMR, radio astronomy, etc.
Karl Rabe	1895–1968	23	Automobiles
Isidor I. Rabi	1898–1988	27	NMR, radar, etc.
Santiago Ramon y Cajal	1852–1934	28	Connections among neurons

Revolutionary scientific innovator	Years lived	First creation	Major discoveries or inventions
William Ramsay	1852–1916	20	He, Ar, Ne, Kr, Xe, organic chemistry
Tadeusz Reichstein	1897–1996	23	Vitamin C, cortisone, etc.
Johann Philipp Reis	1834–1874	25	Telephone 1860
Alexander Rich	1924–2015	24	RNA structure
Nikolaus Riehl	1901–1990	26	Actinide chemistry, nuclear weapons
Bernhard Riemann	1826–1866	27	Differential geometry, mathematical analysis, number theory
Otto Röhm	1876–1939	25	Biotechnology 1901–
Heinrich Rohrer	1933–2013	22	Scanning tunneling electron microscope
Wilhelm Röntgen	1845–1923	24	X-rays and their applications
Marshall Rosenbluth	1927–2003	23	Nuclear weapons, plasma physics, computational physics
Wilhelm Roux	1850–1924	28	Tissue culture 1885, developmental biology
Heinrich Rubens	1865–1922	27	Thermal radiation
Ernst Ruhmer	1878–1913	23	Optical voice transmission, television, films with sound
Ernst Ruska	1906–1988	25	Electron microscope 1931
Helmut Ruska	1908–1973	23	Electron microscope, viruses, etc.
Ernest Rutherford	1871–1937	25	Nuclear physics
Leopold Ružička	1887–1976	22	Steroid hormones, pyrethrin insecticides, terpenes
Albert Sabin	1906–1993	28	Polio vaccine
Abdus Salam	1926–1996	25	Electroweak theory, grand unified theories, etc.
Jonas Salk	1914–1995	26	Polio vaccine
Eugen Sänger	1905–1964	20	Space shuttles, ramjets, antimatter propulsion
Frederick Sanger	1918–2013	24	Protein sequencing, insulin, DNA sequencing
Carl Wilhelm Scheele	1742–1786	24	H, N, O, F, P, Cl, Mn, Mo, Ba, W, etc.
Josef Schintlmeister	1908–1971	24	Superconductor electron pairs <1945, etc.
Paul Schlack	1897–1987	26	Polyamide
Heinz Schlicke	1912–2006	24	Radar, infrared sensors
Ernst Schmidt	1892–1975	27	Heat transfer
Christian Schönbein	1799–1868	28	Guncotton, electrophoresis, fuel cells, ozone
Rudolf Schoenheimer	1898–1941	24	Biomolecule isotope labels, cholesterol/atherosclerosis
Otto Schott	1851–1935	22	Borosilicate glass, optical glass, etc.
Walter Schottky	1886–1976	25	Solid state physics, semiconductors, transistors
Gerhard Schrader	1903–1990	25	Organophosphate insecticides/nerve agents 1936, etc.
Gerhard Schramm	1910–1969	26	Viral RNA, proteins, and mutations 1940
Erwin Schrödinger	1887–1961	26	Quantum physics, color vision, theoretical biology
Erich Schumann	1898–1985	24	Acoustics, shaped charges, rockets, nuc./bio/chem weapons
Theodor Schwann	1810–1882	23	Cell biology, proteases, fermentation
Julian Schwinger	1918–1994	21	Quantum electrodynamics, electroweak theory
Glenn Seaborg	1912–1999	25	Actinide chemistry, transuranic elements
Emilio Segrè	1905–1989	23	Antiproton, Tc, At, nuclear weapons, etc.
Ignaz Semmelweis	1818–1865	28	Antiseptics 1847
Werner von Siemens	1816–1892	26	Telegraph, dynamo, electric trains/elevators, speaker
Franz (Francis) Simon	1893–1956	27	Liquid helium, gaseous diffusion enrichment
William Smith	1769–1839	22	Geological strata
Arnold Sommerfeld	1868–1951	22	Quantum physics

Revolutionary scientific innovator	Years lived	First creation	Major discoveries or inventions
Hans Spemann	1869–1941	27	Developmental biology
Johannes Stark	1874–1957	25	Stark effect, quantum physics
Hermann Staudinger	1881–1965	26	Polymers, synthetic flavors, pyrethrin insecticides
Max Steenbeck	1904–1981	23	Particle accelerators 1927
Josef Stefan	1835–1893	23	Thermal radiation, thermodynamics
Jack Steinberger	1921–2020	28	Neutrinos, other areas of particle physics
Otto Stern	1888–1969	24	Particle spin, molecular beams
Georg Stetter	1895–1988	26	Nuclear physics, nuclear weapons
Fritz Strassmann	1902–1980	27	Fission reactions, etc.
John Strutt, Lord Rayleigh	1842–1919	25	Acoustics, optics, fluid flow, thermal radiation
Ernst Stückelberg	1905–1984	22	Quantum electrodynamics 1934
Ernst Stuhlinger	1913–2008	23	Electric rocket propulsion, etc.
Eduard Suess	1831–1914	24	Continental drift
Albert Szent-Györgyi	1893–1986	25	Vitamin C, Krebs cycle
Gÿorgy Szigeti	1905–1978	<29	Light emitting diode 1939, etc.
Leo Szilard	1898–1964	24	Nuclear physics, statistical physics, molecular biology
Kurt Tank	1898–1983	25	Aircraft design
Gustav Tauschek	1899–1945	23	Computers, magnetic memory, optical character recog.
Hermann Teichmann	1913–1976	<29	Modern solid rocket propellants <1942
Edward Teller	1908–2003	22	Nuclear weapons, physical chemistry, climate change
Nikola Tesla	1856–1943	27	AC electrical generators and equipment
William Thomson, Lord Kelvin	1824–1907	18	Thermodynamics, fluid flow
Nikolai Timoféeff-Ressovsky	1900–1981	25	DNA mutation, radiation effects
Nikolaas Tinbergen	1907–1988	25	Animal behavior
Charles Townes	1915–2015	24	Lasers, astrophysics
Eduard Tschunkur	1874–1946	??	Synthetic rubber
Alan Turing	1912–1954	24	Math, computers, cryptography
George Uhlenbeck	1900–1988	26	Particle spin
Stanislaw Ulam	1909–1984	20	Nuclear, computers, mathematics, bioinformatics
Simon van der Meer	1925–2011	28	Particle accelerators
Jacobus van 't Hoff	1852–1911	21	Physical chemistry, stereochemistry
Andreas Vesalius	1514–1564	23	Human anatomy
Rudolf Virchow	1821–1902	22	Cell biology, pathology, sanitation, archaeology
Herbert Wagner	1900–1982	23	Wings, jet engines, smart bombs, missiles, nuclear
Alfred Russel Wallace	1823–1913	25	Evolution
Otto Wallach	1847–1931	22	Alicyclic compounds
Hellmuth Walter	1900–1980	25	Rockets, aircraft, submarines
Otto Heinrich Warburg	1883–1970	24	Cellular respiration, cancer, etc.
James Watt	1736–1819	23	Steam engines
Wilhelm Weber	1804–1891	20	Telegraph 1833, electromagnetism
Alfred Wegener	1880–1930	24	Astronomy, meteorology, continental drift 1910
Steven Weinberg	1933–	24	Electroweak theory, quantum gravity
Gustav Weisskopf/Whitehead	1874–1927	19	Gliders, first powered flight 1901
Victor Weisskopf	1908–2002	22	Nuclear weapons, quantum electrodynamics

Revolutionary scientific innovator	**Years lived**	**First creation**	**Major discoveries or inventions**
Carl Friedrich von Weizsäcker	1912–2007	**24**	Stellar physics, nuclear physics, etc.
Carl Auer von Welsbach	1858–1929	**27**	Os filament, gaslight mantle, metal lighter, Pr/Nd/Yb/Lu
Abraham Gottlob Werner	1749–1817	**24**	Geology, stratigraphy, mineralogy
Alfred Werner	1866–1919	**23**	Coordination chemistry
Hermann Weyl	1885–1955	**22**	Number theory, quantum electrodynamics
John Wheeler	1911–2008	**22**	General relativity, nuclear weapons
Rolf Widerøe	1902–1996	**21**	Particle accelerators 1923
Emil Wiechert	1861–1928	**27**	Electron, electromagnetic fields, seismography, geophysics
Heinrich Wieland	1877–1957	**24**	Chemical weapons, bile acids
Wilhelm Wien	1864–1928	**22**	Thermal radiation, proton, mass spectrometry
Norbert Wiener	1894–1964	**19**	Math, cybernetics
Eugene Wigner	1902–1995	**22**	Physical chemistry, nuclear engineering, particle physics
Richard Willstätter	1872–1942	**22**	Chlorophyll, chromatography, gas mask filters, enzymes
Adolf Windaus	1876–1959	**26**	Cholesterol, vitamin D
Carl Wilhelm Wirtz	1876–1939	**28**	Measured expansion of universe 1918
Georg Wittig	1897–1987	**29**	Wittig reaction, other organic chemistry
Friedrich Wöhler	1800–1882	**27**	Be, B, Al, Si, Ti, Y, urea, chemical radicals
Thomas Young	1773–1829	**26**	Optics, solid mechanics, energy, physiology, archaeology
Hideki Yukawa	1907–1981	**26**	Strong nuclear force, nuclear weapons
Pieter Zeeman	1865–1943	**28**	Magneto-optics, Zeeman effect, mass spectrometry
Frits Zernike	1888–1966	**26**	Phase contrast microscope, etc.
Leonidas Zervas	1902–1980	**27**	Protein sequencing/synthesis
Karl Ziegler	1898–1973	**21**	Free radicals, organometallics, alicyclics, polymers
Karl Günter Zimmer	1911–1988	**24**	Nuclear physics, DNA mutation
Richard Zsigmondy	1865–1929	**24**	Colloids, ultramicroscope
Georg Ludwig Zülzer	1870–1949	**25?**	Insulin treatment for diabetes 1906, etc.
Konrad Zuse	1910–1995	**25**	Computers 1935
Fritz Zwicky	1898–1974	**27**	Jets/rockets, astrophysics, ionic crystals, electrolytes

1.2 Future Creators

This section covers key aspects of the training of future creators, including:

1.2.1. Career choices

1.2.2. Timeline

1.2.3. Things to read

1.2.4. Things to do

1.2.5. Sources of support

1.2.1 Career Choices

The world needs people in many different careers. Try to find a career that satisfies all of the following requirements, or at least as many of them as possible. An ideal career should be something that:

- You enjoy. Your work will occupy many hours of your days for the rest of your life, so your life will be much happier if your work is something that you like or ideally love to do. You will also do a much better job carrying out tasks if you enjoy them than if you find them boring or unpleasant.

- You are good at. Everyone has different talents; figure out what yours are, or work hard over several years to develop new talents that align better with the other criteria listed here.

- Helps people and the world, either directly or indirectly. Some jobs such as medicine and social work clearly and directly help people. Others such as music and art seem less directly helpful, yet nonetheless they can greatly enrich people's lives and our society. At the very least, make absolutely certain that your activities cause no harm, either directly or indirectly; sadly that rules out many high-paying and highly sought-after jobs, when you really think about their consequences for individuals or for society in general.

- Would not be accomplished at all/accomplished as well/accomplished as soon without you. Find places where you can really make a difference by your presence and your activities. If others would do something just as well or better in your absence, let them, and seek a different project or career where you can have a greater impact.

- Earn enough money for you (and your family or future family) to live on. Unfortunately this can be the most challenging requirement in the modern world, which often assigns much higher financial merit to jobs that are pointless or that harm society than to jobs that actually help society.

Hopefully you can find one career that satisfies all of the above requirements. It not, you might consider some combination of jobs (either simultaneously in parallel or in series over time) that would collectively fulfill all of these requirements. It is also quite possible to have one or more paying jobs along with one or more unpaid passion projects or hobbies.

The world needs some small fraction of people to conduct revolutionary research. Unfortunately, currently a career in revolutionary scientific research is likely to bring you many more struggles and much less money than many alternative careers (see Section 1.2.5.5). Therefore, even though revolutionary scientific research is desperately needed, you should only pursue a career in revolutionary scientific research if you feel personally compelled to do so.

You can switch to an alternative career anywhere along the path, or at any later time. There are several "off ramps" on the path toward a career in revolutionary scientific research, as shown in Fig. 1.1 and discussed on the following pages.

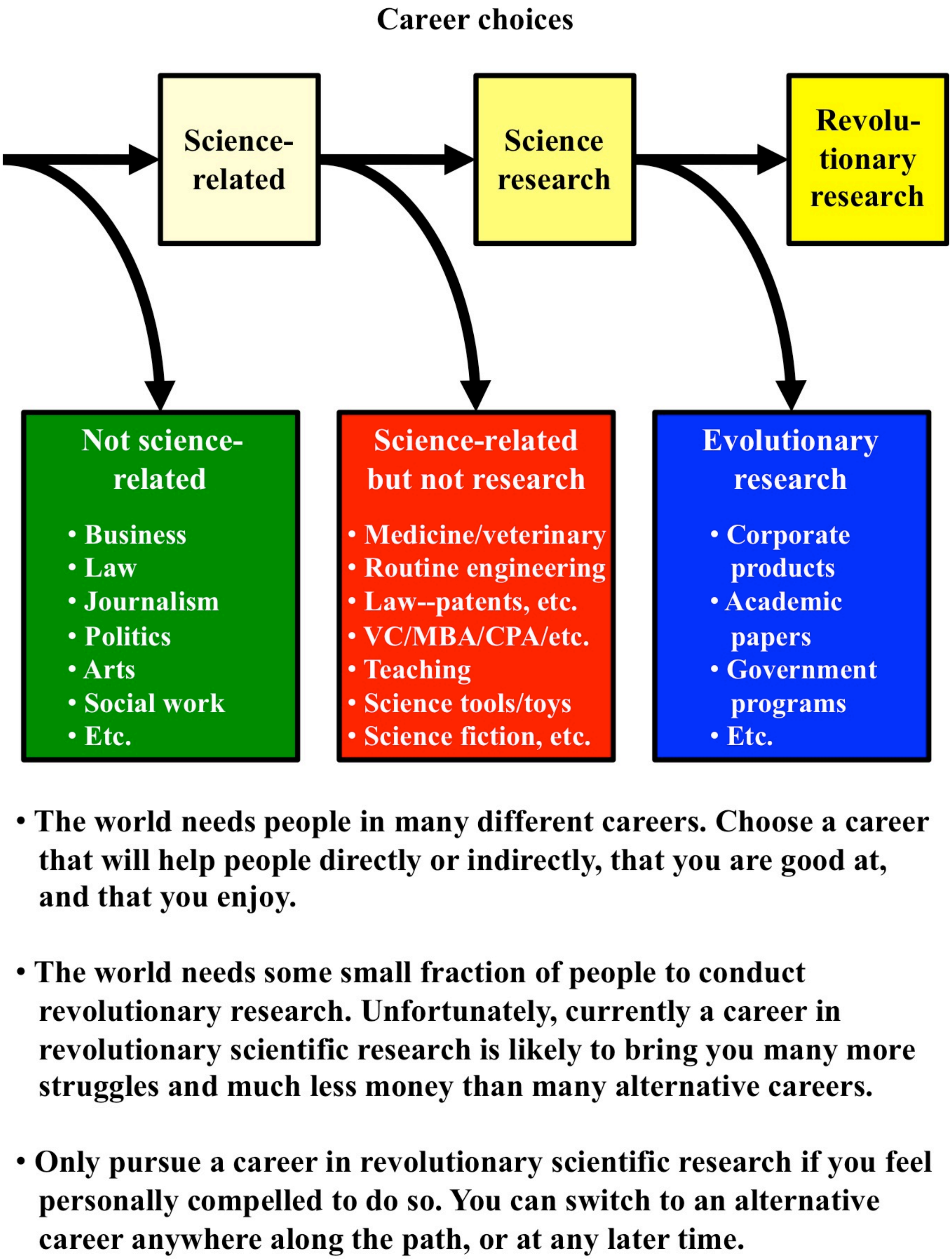

Figure 1.1: Some of the choices involved in choosing a career in revolutionary scientific innovation or opting for a different career somewhere along the way.

First of all, you can choose a career that is either science-related or not science-related. Most fields and careers, both science-related and non-science-related, can be used either to harm society or to help society. Whatever career you pursue, make sure you spend your life using it to help society in general and the people you interact with in particular. There are many worthy careers that are not science-related and through which you can help society, such as:

- Business
- Law
- Journalism
- Politics
- Writing, art, music, theatre, etc.
- Teaching non-science-related subjects
- Social work, clergy, etc.

If you decide to pursue a science-related career, you can choose to do research or something else. Some examples of science-related careers that do not involve research include:

- Serving as a medical doctor, nurse, veterinarian, or other healthcare worker.
- Becoming an engineer, architect, software developer, technician, mechanic, or other professional helping to design, produce, or maintain useful but relatively routine products.
- Practicing law in science-related areas such as writing patent applications or negotiating technology licensing agreements.
- Pursuing a business or finance career in science-related areas, for example by evaluating scientific ideas for venture capital firms, or by earning business or finance degrees to work in corresponding positions in science-related companies.
- Teaching science or math subjects at K–12 grade levels or at a community college.
- Producing and/or selling scientific or medical tools, equipment, or supplies, or even educational scientific kits and toys that could inspire future creators (see Section 1.2.4.1).
- Writing or offering science advice for science fiction films, television shows, novels, comics, etc. At its best, science fiction can inspire future creators and creations (e.g., Jules Verne, *Frau im Mond*, and the *Tom Swift Jr.* novels), and/or challenge the general public to think more deeply about societal problems and solutions (e.g., H. G. Wells, *Brave New World*, *Star Trek*, and *Black Mirror*). For more information, see Section 1.2.3.4.

If you decide to pursue a career in science research, you can choose to do either revolutionary research or evolutionary research. Generally it requires far more people and far more time to take an already-existing revolutionary approach and develop that all the way to a final product than were needed to originally conceive that revolutionary approach. Thus an ideal world should have some revolutionary innovators to produce the initial ideas and prototypes, yet many more evolutionary innovators who can carry those to a final practical product.

In our current real world, almost all research is evolutionary, and unfortunately even most of that suffers from significant limitations. At present, the most common categories of evolutionary research include:

- Corporate products, usually very near-term, low risk, easily marketable products such as improved electronic devices, new or updated software or online services, slightly improved pharmaceuticals, etc.

- Academic papers, generally produced in vast numbers by only doing quick experiments that are virtually certain to work, and then reporting the results in as many papers as possible (see Section 1.2.3.2).

- Government programs, often limited to maintaining previously developed technologies, managing the vast bureaucracies that have grown up around them over the past many decades, and outsourcing most new development to corporate or academic laboratories.

Goodness knows the world could really use new revolutionary innovators and revolutionary innovations, even though nowadays it usually does not support and reward them as it should. If you really feel called to be a future creator, or would like to consider becoming a future creator, please continue on in the next sections. If at any point you decide that that path is too difficult or not to your interest, you can always backtrack and reconsider the above options, or other options that you may discover.

1.2.2 Timeline

Figure 1.2 shows an idealized timeline for the education, training, and support of young people who could become revolutionary scientific innovators. Many aspects of this timeline are also applicable to those who opt for other careers at some point, so it can be fruitful for young people to start down the path shown in Fig. 1.2 even if they are not positive that they want to be future creators.

The development of future creators as illustrated in Fig. 1.2 is divided into different periods of time from preschool to grad school and beyond, as is discussed in this section. It also covers different major categories of activities all along the way:

Things to read (Section 1.2.3)

Things to do (Section 1.2.4)

Sources of support (Section 1.2.5)

It must be emphasized that the timeline shown in Fig. 1.2 is only a notional generalization. A student may want to begin a given activity earlier or later than shown here, or may not have the interest or opportunity to pursue some activities, or may find additional activities that contribute to their education, training, and support.

If you are a parent, teacher, or other adult in a position to aid future creators, do everything you can to provide opportunities for as many of these activities as possible, and to provide as much encouragement and support as possible. However, please do not push students to do activities that they really do not want to do, or to go down an educational and career path that they really are not interested in pursuing. The desire to become a successful future creator—or any other type of successful professional—must ultimately come from within, from the student's own personal interests and drive. Einstein developed the theory of relativity because he was passionate about pursuing it, not because his mother told him he had to.

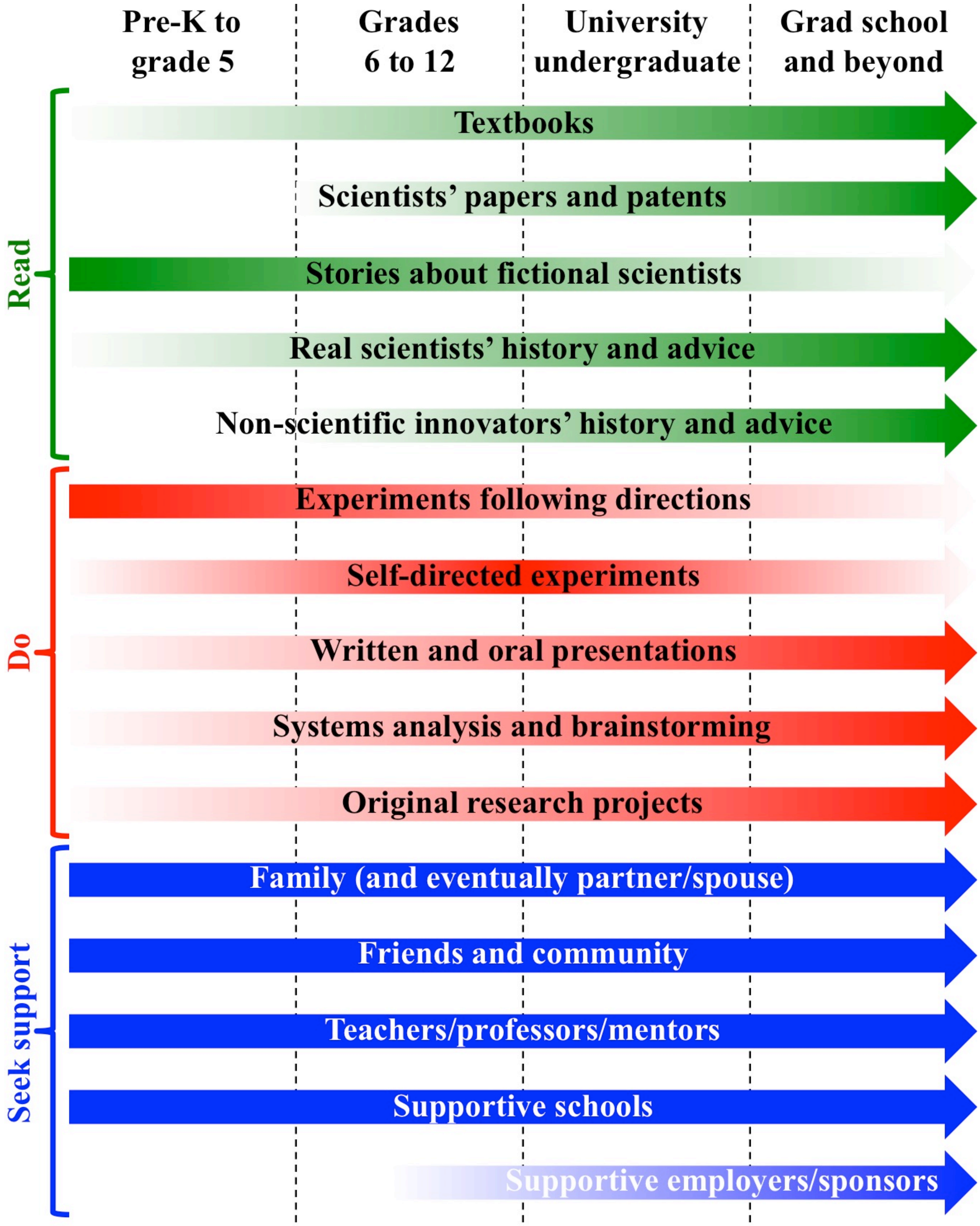

Figure 1.2: The major aspects of the education, training, and support of young people who become revolutionary scientific innovators. Many of these aspects are also applicable to those who opt for other careers at some point.

1.2.2.1 Pre-K to Grade 5

Many (though not all) people who are really passionate about their careers—everything from scientists to race car drivers—developed that passion in elementary school (grades K through 5), or sometimes even in preschool. Preschool and elementary school are the ideal time for students to learn about different possible careers, including science, and to see what direction or directions seem most appealing. For some students, stimuli such as films or books about fictional scientists, videos or stories about real scientists, an awe-inspiring visit to a science museum, or a science experiment kit (with adult supervision) can trigger a lifelong obsession with science. Other students may simply not find such things of interest, or may initially enjoy them but then move on to other interests, and that is certainly okay too. Someone has to grow up to be an accountant.

Elementary students usually have short attention spans. If elementary students show a real interest in science, they should be encouraged to try scientific activities (everything from conducting simple experiments to watching science videos) that are short, varied, and intermixed with other non-scientific activities. In this age range, the most important thing is to cultivate students' general interest in science, not their detailed knowledge of science or prolonged concentration on scientific tasks. If and when the students want more science, feed them more, but do not force-feed them, or else the students may begin to feel that science is a chore and not a passion (and thus ultimately choose a different career path). In upper elementary school, as students' attention spans grow longer and their personal passion for science becomes stronger, scientific activities can become longer and more numerous if that is what the students want.

1.2.2.2 Grades 6 to 12

Middle school (grades 6–8) and high school (grades 9–12) are the ideal time for students who have become interested in scientific careers to learn much more about science from classroom teachers, from independent study outside the classroom, or both. That process involves learning as much as possible about the facts, methods, theoretical explanations, and practical applications of the major scientific fields. It also involves learning how to safely and accurately conduct laboratory experiments in each of the scientific fields.

If students are considering careers in scientific research, they should be strongly encouraged to carry out independent scientific research projects in middle school and high school. That will help them to assess whether they truly enjoy what is involved in doing research, and also to develop and refine the skills that are involved in successfully carrying out independent research projects from beginning to end.

As with any skill, conducting independent, revolutionary research generally requires years of practice to become truly adept. Yet if students begin early enough and work hard enough at it (from their own motivation, not driven by others), they can potentially make their own revolutionary discoveries or inventions while they are still teenagers. In fact, if enough scientific resources and supportive adults are available, high school can be an especially fertile time to come up with groundbreaking new ideas and innovations. In some cases, students may have more free time in high school than they ever will again, they may have already gained a sufficient understanding of the prerequisite scientific theories and experimental methods, and yet they can still view scientific fields with fresh eyes looking for new possibilities and overlooked ideas, instead of simply accepting everything as it has been passed down.

Future creators also need more than just knowledge, skill, and research resources. They are human beings, and to be maximally productive and happy, they need the same sort of supportive relationships that all humans need. School years can be a time in which to build lifelong supportive relationships with family members, friends, teachers, mentors, and perhaps even a future spouse.

1.2.2.3 University Undergraduate

During their time as university undergraduates, one of the most important objectives of students should be to master the detailed scientific knowledge and methods in their chosen field of interest, and ideally even in multiple scientific fields. That task can consume an enormous amount of time and energy, and students should be prepared (and encouraged and aided) to spend fully as much time and energy as is required. If the professor of a given course is not a good teacher (many are not) and does not assign a textbook that explains things well, students should find and fully exploit a good textbook on that subject for themselves (Section 1.2.3.1).

If students really want to be revolutionary innovators, they should also continue to think of and seriously investigate potential revolutionary innovations even while taking undergraduate courses. Without interfering with their courses, they can conduct brainstorming sessions, literature searches, theoretical research, or experimental research in the summers, during holidays, on weekends, or during downtime from coursework each day. As already mentioned, innovative research is a skill that needs to be practiced as long and as much as possible, in order to be most effective at it. The undergraduate years can be a great time for research, since universities generally have many scientific resources, and yet undergrads are usually deemed "unimportant" enough that sufficiently determined undergrads can fly under the radar and work on a research project of their own choosing without having to justify to a department head or financial sponsor why they are investing so much time in a particular project.

Note that many undergraduate students do participate in research projects, yet very few of them actually conduct their own innovative research. University laboratories are always looking for undergrads who will work for low wages or even for free, usually just following orders from a grad student, who follows orders from a postdoc, who follows orders from a professor, who follows orders from the department head or financial sponsors. That is an excellent way to learn how to be a trained monkey; it is not a good way to learn how to do innovative, independent research. (See p. 173.) I have personally witnessed cases such as an absolutely brilliant theoretical physics undergrad being assigned to spend summers stacking lead shielding bricks at a particle accelerator, and a promising young electrical engineering student ordered to spend summers peering through microscopes and counting how many damaged transistors could be seen on integrated circuit chips. Undergraduates should be extremely careful about agreeing to a job in a laboratory, unless they really need the money or the hands-on lab experience that job can offer, or they can reach an agreement with whoever runs the lab that they can pursue sufficiently independent and creative work.

As with high school, the years spent in university can be an ideal time to find and build lifelong relationships that can continue to be supportive of the future creators and their creations even long after graduation.

If you are headed for university, you should know that undergraduate life is probably where you will make the closest friends you will have for life. For 24 hours a day for four years, you and the people around you will go through extreme stress and sleep deprivation from homework, papers, exams, research, romantic relationships, job searches, grad school applications, etc. It is an incredible bonding experience, perhaps not unlike going through a war together. Some of those closest friends you will probably meet in your dormatory or other housing. Others may live in other housing units, but you may meet them in classes and spend time with them studying outside of classes. Still other friends you may meet in special interest groups you join. There are all kinds of those (science clubs, music and theatre groups, sports groups, volunteer service groups, cultural groups, religious groups, etc.) where you can bond with people who have similar interests, or learn a whole new skill or hobby.

Decide what sort of university culture you would most like to experience, and then seek that out from the outset, both by which university you choose and by which part of that university's academic/cultural/housing system you aim for.

1.2.2.4 Grad School and Beyond

Having a doctoral degree is often necessary (but still not sufficient by itself) in order to find institutional and financial support for your revolutionary projects. Depending on your field and your intended sources of institutional support, that could be a Ph.D. or an M.D.; a few people obtain both. My comments in this section mainly pertain to Ph.D. graduate school programs in science and engineering. Medical school is a somewhat different beast, with numerous courses, laboratory activities, and clinical practice

Your mileage may vary, but in general there tends to be a drastic change in culture between undergraduate life and grad school life. In grad school, friends are often much fewer and further between, and you are more on your own. Whereas undergraduate students commonly live in large groups on or immediately adjacent to campus, most grad students live in more isolated, off-campus apartments with whatever roommates they can find on short notice to share housing costs. Undergrads usually spend most of their time taking courses, interacting with many other students in the process; grad students may only take a few courses in their first years, and otherwise spend most of their time working on research by themselves or in small groups, at the direction of a Ph.D. advisor. Most students go to different schools for undergraduate and graduate education, so unfortunately most of the friends you make as an undergrad will end up far from wherever you end up.

Although the specific arrangements may vary, often Ph.D. advisors pay all or part of the annual tuition for grad students, provided that the grad students spend as much time as possible working for the advisor, doing exactly what the advisor tells them to do. (Those projects are usually designed primarily to enrich the advisor with more grant applications and grant funding, more contracts with companies, more money from wealthy donors, more publications listing the advisor as an author, more patents listing the advisor as an inventor, etc., while paying lip service to "training" the student in the process.) As a result, most grad school students have far less time and opportunity to pursue their own innovative research projects than high school or undergraduate students do.

Sometimes you can find fellowships or scholarships that pay for all or part or your grad school education, which can free up much of your time to pursue your own ideas without being financially dependent on a particular Ph.D. advisor. Of course, you would still need an official Ph.D. advisor, but you can probably find one who is willing to offer advice and sign off on whatever you want to do for your thesis research (within reason, of course), as long as the advisor does not have to pay for you. If you cannot obtain fellowships or scholarships, at least try to find a Ph.D. advisor whose research interests overlap as much as possible with your own, and who will allow you to be as independent and as creative as possible in pursuing problems and solutions for your Ph.D. thesis.

After you obtain your Ph.D., it becomes even more difficult to fly under the radar and choose your own innovative research. You are at the mercy of what your employer is willing to pay for you to do, or what financial sponsors are willing to pay you or your employer to do. If you have made revolutionary discoveries or inventions by the time you obtain your doctoral degree, you will be more likely (though still far from certain) to find employers/sponsors who are willing to support you to continue that revolutionary research or to aim for new revolutionary discoveries or inventions.

Therefore, if you would like to pursue a career in revolutionary innovation, it is imperative that you produce some revolutionary innovations by the time you get your doctoral degree, if at all possible. In fact, in view of the difficulty of finding truly supportive advisors and doing truly independent research in grad school, I strongly recommend that you produce revolutionary innovations during your high school and undergraduate years if you can. Even having a very early track record of revolutionary innovation is no guarantee that you will be able to find opportunities to continue to pursue revolutionary innovation, but it greatly improves your chances.

1.2.3 Things to Read

Scientists and engineers typically read a large quantity of information. If you would like to become a scientist or engineer, you should read a lot too. Categories of material that I strongly recommend you read include:

1. Textbooks
2. Scientific papers
3. Patents
4. Stories about fictional scientists
5. Real scientists' history and advice
6. Non-scientific innovators' history and advice

1.2.3.1 Textbooks

In this section, I would like to offer:

A. Advice to students on how to find (and afford) the best currently available textbooks under the present system.

B. Advice for textbook authors and responsible institutions on how to produce better and certainly much more affordable textbooks in the future.

A. Reading textbooks

Different people learn things better in different ways. Some people naturally prefer to learn new material by reading about it. Other people learn better from watching lectures or videos explaining those same concepts. Still other people learn best by actively doing things—solving problems and doing experiments on their own. To pursue education and a career in science or engineering, you need to be able to absorb information in all of those ways.

Yet in science and engineering, almost all of the material is available in writing, and much of it is *only* available in writing, including everything from classic old textbooks to the very latest published research papers. Thus even if reading is not your preferred mode for absorbing new material, you need to practice it and become good at it anyway. And if you pursue a scientific education, you will get a huge amount of practice reading new material.

Textbooks are the best way to learn virtually all fields of science and engineering. Textbooks can carry you from initially having no knowledge about the methods and information of a field, or from the historical origin of a scientific field, all the way through all aspects of that field and its research history, up to the time that the textbook was published. Some fields have not advanced much in decades, so even older textbooks can bring you fully up-to-date. Other fields (especially computers and some areas of biology and medicine) have been advancing rapidly in recent years, though with a good textbook published within the last couple of years, you can come up to speed on everything except the most recent years of research results.

If you are a student, hopefully your teacher or professor will assign a good textbook for your course. If your teacher or professor does not assign a textbook, or if they assign a textbook that seems confusing or incomplete, you should seek out a better textbook on that subject.

In this section and in the Bibliography, I recommend the best textbooks I have seen on each subject, with a few caveats:

- These textbooks are in English. Some of these have been translated into other languages, or were translated into English from other languages. There may be better textbooks available in other languages.

- I have not seen every English textbook on these subjects, and other people might prefer a different textbook than what I recommend. Please consider my suggestions, but also listen to other opinions and use your own judgment glancing through several textbooks before you invest a lot of money and time in a particular book.

- Any list of textbooks such as this will rapidly become out of date, as some books go out of print, others are updated to new editions, and entirely new books are written. I will try to update this list in the future. If I stop updating it, hopefully others can update it or produce similar lists. In any event, this list represents the quality of textbooks that students and teachers should seek out (or write themselves in the future), in my opinion.

- I have tried to select what I believe is the single best book on each subject, but it can be hard to balance the requirements of being as readable as possible for new students and being as complete as possible for more experienced students and professionals. If you would like to consult several different, complementary books on a subject, please see the other books listed in the Bibliography. If you have sufficient interest, money, and time, you may decide to buy multiple books on a given subject, or even multiple books for each of several subjects.

Aspiring future creators can begin reading science textbooks sometime in elementary school (grades K–5), and certainly by middle school (grades 6–8). By the end of high school (grades 9–12) and before entering university, I strongly recommend that future creators should have learned all of the textbooks in Table 1.3 (or their equivalents) from cover to cover. If you plan to work in one of these fields, the corresponding book will give you an excellent overview of the field and the most important information in that field. Even if you plan to work in some other field, these textbooks represent the general knowledge that every good scientist should know about other scientific fields, just in case they happen to need it.

A highly motivated elementary or middle school student with very supportive and insightful adult assistance from teachers or parents could begin learning directly from the high-school-level textbooks in Table 1.3. Alternatively, a student may find it easier or more enjoyable to begin learning each subject with the middle-school-level textbooks in Table 1.2. In that case, first learn as much as you can from the middle school textbook, and then go back over all the material in much more detail by working your way through the corresponding high school textbook.

The whole point of reading a textbook is to really absorb the material—to understand it, to remember it, and to be able to use it to solve scientific problems. Instead of simply reading through the pages and feeling that you are finished, make sure you do these things for each textbook you study:

- Work your way through at least a representative selection, and ideally all, of the problems that are usually found at the end of each chapter in the textbook. Many textbooks list the answers to every other problem in the back of the book so you can check your work, or you can buy a separate book with all the answers for that textbook.

- After you have learned part of a subject, figure out how you would explain that same material to someone else. You do not really understand something unless you know how to clearly, concisely, and correctly explain it in your own words.

- As you go through the textbook, while everything is as fresh as possible in your mind, create a very brief handwritten or typed summary of the key points and equations you have learned. Save that written summary. It may help you in studying for exams in that subject, or years later you may want to refer to it to refresh your memory about the subject. It may even ultimately become the basis for a new textbook you could write that would be better than the existing textbook.

Subject	**Best Single Textbook**
Math	Richard Brown, McDougal Littell math series
Physics and engineering	Hewitt, *Conceptual Physics*
Earth/space science	Glencoe, *Earth Science*
Chemistry and materials science	Wilbraham et al., *Pearson Chemistry*
Biology and medicine	Miller & Levine, *Biology*

Table 1.2: Recommended middle-school-level textbooks.

Subject	**Best Single Textbook**
Precalculus	Blitzer, *Precalculus* *or* Stewart, *Precalculus*
Calculus	Stewart, *Calculus*
Physics and engineering	Young & Freedman, *University Physics with Modern Physics*
Earth/space science	Tarbuck & Lutgens, *Earth Science*
Chemistry and materials science	Brown & LeMay, *Chemistry: The Central Science*
Biology and medicine	Urry et al., *Campbell Biology*

Table 1.3: Recommended high-school-level textbooks.

If you are able to finish all of the textbooks in Table 1.3 (or their equivalents) in high school with time to spare, please consider picking one or more of the university textbooks in Tables 1.4–1.5 (or their equivalents) and getting a head start on your university studies. Select any subject that interests you and learn as much as you can. The more subjects you can master before you enter the university, the better.

Tables 1.4–1.5 list recommended textbooks for the major subjects of the major fields of science and engineering. Please see the Bibliography for additional recommendations. To avoid redundancy, I have only listed each subject and textbook under one field, although it may be required for other fields as well.

Tables 1.4–1.5 list roughly 100 textbooks on different subjects, depending on how you count. A typical modern science or engineering graduate might cover the equivalent of around 15 or so of these textbooks or their equivalents. I strongly recommend that future creators study as many of these subjects as possible, so they can work in multiple fields or use ideas from one field in another field in creative ways. If you get a head start on the subjects before university, find a university environment that is supportive of your studying as many subjects as possible, and continue to study any remaining subjects on your own after university, it is quite feasible to work your way through all or almost all of the listed subjects and textbooks. Even if you do not have the interest, time, or energy to go that far, learning at least half of these subjects would be a very worthy goal that could greatly enhance your research career.

Textbooks are ridiculously overpriced, and in many cases publishers try to maximize their sales by cranking out relatively unnecessary new editions of a book every few years. To save money:

- Instead of a new copy, you can buy a used copy in good condition from a reputable seller.
- Except for a few rapidly moving subjects (especially computers and some topics in biology and medicine), usually you can also buy an edition that is recent but not the very latest without losing any important content (unless you are taking a class that uses problems only contained in the latest edition).
- You can also consider "international editions" that are generally much cheaper than the publisher's official version for your country; some international editions are virtually the same as the official version, and some are greatly altered or very poorly printed, so always check before you buy.
- Some useful books may also be available at wikibooks.org, archive.org, or elsewhere online.

Even after you have learned thoroughly from a textbook, the book can remain a useful reference for the rest of your career, in case you need to look up details or refresh your memory. A collection of suitably chosen textbooks that you can keep for life can serve as your large "hard drive" of useful scientific information and methods, whereas your brain is your much smaller working memory that accesses whatever it needs from the "hard drive" textbook collection, whenever it needs it.

If a textbook is good, buy it and keep it permanently, preferably as a physical copy, or at least as an electronic copy (e.g., pdf file with no digital rights management) that will not expire or fail to transfer to your future devices and accounts. Only rent a physical or electronic textbook if it is required for a course but you are certain you will never need it again in your life. Limited-time, online access to supplemental materials is another gimmick from greedy publishers; only do it if it is required for a course, but otherwise just focus on learning from and keeping the real textbook.

Subject	**Best Single Textbook**
Math	Riley
Calculus	Stewart *Calculus*
Differential equations	Edwards/Penney *or* Nagle
Complex analysis	Jeffrey *or* Saff/Snider
Probability	Bertsekas/Tsitsiklis *or* Walpole
Statistics	Bevington/Robinson *or* Navidi
Linear algebra	Savov *or* Singh
Group theory	Hamermesh
Physics	Benenson *or* Young/Freedman
Experimental physics	Dunlap *or* Melissinos/Napolitano *or* Moore
Classical mechanics	Morin
Electromagnetism	Griffiths
Statistical physics	Kittel/Kroemer *or* Schroeder
Nonrelativistic quantum physics	Griffiths/Schroeter *or* Liboff
Relativistic quantum physics	Griffiths
General relativity	Hartle *or* Ohanian/Ruffini
Nuclear engineering	Shultis/Faw
Nuclear physics	Krane
Nuclear fuel	Benedict **or more recent book?**
Fission reactors	Lamarsh/Baratta
Plasma physics and fusion	Chen
Nuclear weapons	Sublette
Particle accelerators	Chao
Nuclear medicine	Wagner/Szabo/Buchanan **or more recent book?**
Mechanical engineering	Sadegh/Worek
Statics and dynamics	Beer
Mechanics of materials	Beer *or* Hibbeler
Fluid mechanics	White
Acoustics and shock waves	Blackstock *or* Kinsler *or* Pierce
Thermodynamics	Cengal/Boles
Heat transfer	Mills
Aerospace engineering	Agrawal/Platzer
Aerodynamics	Anderson
Helicopters	Leishman
Aircraft propulsion/gas turbines	Farokhi
Rocket propulsion	Sutton
Astrodynamics	Wiesel
Control systems	Kabamba/Girard
Electrical engineering	Santoso/Beaty
Applied electromagnetism	Bradley *and* Staelin
Optics and lasers	Meschede
Solid state physics	Kittel *or* Simon
Semiconductor devices	Pierret *or* Sze
Circuits	Agarwal/Lang *or* Horowitz/Hill
Signal processing	Haykin/Van Veen *or* Oppenheim
Computer architecture	Patterson/Hennessy

Table 1.4: Recommended university-level textbooks.

Subject	**Best Single Textbook**
Earth science	Tarbuck/Lutgens
Geophysics	Fowler
Physical geology	Plummer
Rocks and minerals	Klein/Philpotts
Paleontology	Benton/Harper
Marine science	Garrison *or* Townsend *or* Trujillo/Thurman
Atmospheric science	Ahrens/Henson *or* Wallace
Space science	Bennett *or* Chaisson/McMillan
Astronomical tools and methods	Birney *or* Chromey
Solar system and planetary science	Encrenaz *or* Lissauer/de Pater
Stellar physics	Kippenhahn
Interstellar space and galaxies	*or*
Cosmology	Dodelson/Schmidt *or* Liddle
Chemistry	Brown/LeMay
Chemistry laboratory methods	Zubrick
Organic chemistry	Carey *or* Clayden *or* Klein
Inorganic chemistry	Housecroft/Sharpe *or* Greenwood/Earnshaw
Physical chemistry	Atkins *or* McQuarrie/Simon
Analytical chemistry	Harris/Lucy *or* Skoog
Chemical engineering	Green/Southard
Materials science	Callister
Strength of materials	Dowling
Polymers	Coleman/Painter
Metals	Abbaschian
Ceramics	Carter/Norton
Glass	Shelby
Composite materials	Clyne/Hull
Biology	Urry
Biology laboratory methods	Barker *or* Gallagher/Wiley
Biochemistry	Ferrier
Molecular biology	Cox *or* Krebs *or* Watson
Genetics	Griffiths *or* Klug
Cell biology	Alberts *or* Lodish
Microbiology	Engleberg *or* Madigan
Botany	Buchanan *or* Jones
Zoology	Kardong
Medicine	Harrison
Physiology	Guyton/Hall
Anatomy	Moore *or* Netter
Surgery	Brunicardi *or* Townsend
Developmental biology	Barresi/Gilbert *or* Carlson
Neuroscience	Kandel
Immunology	Abbas
Cancer	Pecorino *or* Weinberg
Pharmacology	Katzung

Table 1.5: Recommended university-level textbooks (continued).

B. Writing and publishing textbooks

Over the last several decades, there has been an overwhelming trend in the United States, and to a lesser degree in some other countries, for powerful groups to corner the market on products and services that are considered essential by most of the population, then raise the prices of those products and services far faster than inflation, as high as the population can possibly bear to pay (or even beyond). In the United States, that has been true for medical care, prescription drugs, housing, university tuition, phone/television/internet service, and other commodities.

Unfortunately it has been true for textbooks as well. In the United States, currently a new textbook might cost roughly ten times as much as a non-textbook of comparable size. Textbook prices have been increasing far faster than the general inflation rate or other book prices, and that trend shows no sign of stopping in the foreseeable future.

The enormous difference in cost between textbooks and non-textbooks does not appear to be justified by any legitimate factors. Textbook authors may earn nothing, or a smaller percentage than non-textbook authors. Often the textbook authors and their associates do all the typesetting and editing, so textbook production costs can be low. Many modern textbooks are consumed in an electronic format instead of a printed format, so in those cases there are no costs for physical materials. In any event, even most printed textbooks do not have inherently higher materials costs than non-textbooks; some recent textbooks even have noticeably inferior physical quality. With the widespread modern use of automation, color printers, and print-on-demand technology, it is equally cost effective to produce either textbooks or non-textbooks with color illustrations, small production runs, periodic updates, etc. The fact that publishers often market a very expensive textbook within the United States and yet simultaneously and profitably produce and sell an identical or nearly identical, far less expensive, "international edition" in other countries demonstrates that the high prices are purely artificial.

In fact, the exorbitant prices of textbooks are created by powerful monopolies ranging from the local classroom to the international level. A professor can require a particular edition of a particular textbook, and every student in that professor's course has no choice but to acquire that book, instead of some earlier edition of that book, or some other comparable textbook on the same subject. Some specific textbooks are (usually quite justifiably) regarded as the best choice for a given subject, and therefore most professors and students involved in courses on that subject, in many universities and many countries, all buy the same textbook instead of alternatives. Moreover, whereas there was previously a very large number of textbook publishers, in recent decades those have consolidated into a remarkably small number (e.g., Cengage, Elsevier, Pearson, McGraw-Hill, Springer, and Wiley), each of which can control most of the major textbooks within a certain academic field or subfield. Finally, in contrast to the wide range of independent textbook sellers that used to compete with each other, nowadays Amazon (through the many branches it owns, including amazon.com, abebooks.com, ZVAB.com, bookfinder.com, bibliofind.com, etc., as well as countless online storefronts that must sell via those Amazon branches) has a near monopoly in selling both new and used textbooks from all publishers.

Vastly overpriced textbooks harm students in several ways:

- Having to buy so many overpriced textbooks for so many courses during a complete university education financially harms students and their families, who often take on a lifetime of debt to try to pay for a university education, while the publishing company executives and stockholders rake in millions of dollars on top of all the millions of dollars they already possess. In other words, the wealthy publishing executives and stockholders are engorging themselves on enormous sums of money that have been borrowed by deeply indebted students and families who have been given no other choice.

- Similarly, having to buy such overpriced textbooks for so many students for so many courses, and update them periodically, sucks a large amount of financial resources out of K–12 schools, and thus out of the taxpayers and families who pay for them.

- Because textbooks are so expensive, it becomes prohibitive for students to acquire more than one book for a given class or subject. Often it is extremely helpful to have multiple textbooks for a given subject or class, if they explain different parts of the subject or explain it in different ways.

- Overpriced textbooks make it far more difficult for scientists and engineers to build up a personal library of reference books that they can keep and use for their entire careers. They create a strong incentive for students to only temporarily rent access to a physical or electronic copy of the textbook (or to the accompanying website, which often has supplementary material), or to buy a book but resell it later to try to recoup some of the expense.

By directly harming students, their families, and the lifetime careers of future scientists, engineers, and medical doctors, the publishing companies are actively harming whole organizations, societies, and countries. Therefore, it is in the best interests of those organizations, societies, and countries to take strong measures to permanently eliminate this problem.

In order to make textbooks much lower cost or free, I would suggest these strategies for consideration:

- If you are teaching a course on a subject, try to find a free, online textbook that is as good as the commercially published textbooks listed in Tables 1.4–1.5. If you cannot find a suitable free textbook and must use one of the commercial textbooks, allow your students to use older editions of the book—do not require them to find specific problems or pages that are only available in the most recent edition of the book, or only available in the restricted-access online material for the book.

- If you write a new textbook, preferably make it available for free on the internet. At the very least, choose a publisher such as Dover that has a long track record of holding textbook prices as low as absolutely possible and of keeping textbooks in print for many decades. Make sure your book will remain available online or in print for long after you retire or die, and give permission for others to update it if necessary.

- If you are a textbook publishing company, please voluntarily take steps to make all of the books you publish as inexpensive as possible, to allow students to keep them permanently (not just to rent a physical book or rent online access to the book or supplementary materials), and to keep the books in print for many decades. If you decide to stop producing a book, put it online for free, or hand it off to a low-cost, long-haul publisher like Dover. If you do not take such steps voluntarily, other people, organizations, and governments may solve the problem without your voluntary participation, in ways that your publishing company may find less pleasant.

- If you are a government with jurisdiction over publishing companies or their sales in your region of the world, take measures to greatly reduce the price of textbooks—regulate textbook publishers and their sales, break up the small number of huge publishers into a large number of competing companies so that no one publishing company has a large share of the market, revoke or limit their copyright protection on textbooks, etc. Furthermore, governments should actively investigate and prosecute both the companies and the specific individual executives involved in violating any relevant laws, including antitrust violations, price fixing, collusion, kickbacks, etc.

- If you are a government with jurisdiction, also break up Amazon, which through amazon.com, abebooks.com, ZVAB.com, bookfinder.com, bibliofind.com, and countless storefronts it hosts has a near monopoly in selling both new and used textbooks from all publishers.

- Let students permanently own their textbooks as printed copies and/or in a very stable digital format that will easily transfer to their future devices and accounts (such as a pdf file with no digital rights management).

While high prices are the most urgent problem with textbooks, a second important problem is quality. Many textbooks do a poor job covering everything they should and explaining everything they should, or at least they do not do as good a job as they could. Even when there is an excellent textbook on a subject, professors often assign their students to read greatly inferior textbooks. Furthermore, many professors or aspiring professors feel social, institutional, and/or financial pressure to write a new textbook on a subject, even if their new book is of lower quality or not as useful as books that are already available, and then they commonly compel their students to buy it.

In order to improve the quality of textbooks, I would suggest:

- If you teach a subject and decide to use an existing commercially published textbook, choose the one that mostly clearly explains that subject, such as those listed in Tables 1.4–1.5.

- Do **not** write another textbook unless you can truly create a better one or address an unfilled niche, not just pad your CV with additional publications. If you do write a textbook, make sure it will be available for much less money than existing similar textbooks, and ideally make it free. Also make sure it will remain available indefinitely (such as on the internet or reprinted by Dover), not go out of print within a few years.

- Rather than writing a new textbook, seriously consider obtaining rights to and updating an already existing (if possibly dated) excellent textbook from retired or dead authors.

- If you write a new textbook, make sure you incorporate as many insights as possible from existing textbooks. Make sure your new textbook incorporates the best explanations and best types of examples/problems and covers all the important topics that existing textbooks on that subject cover. Also read some of the best-written textbooks on other subjects (see Tables 1.4–1.5), note the general teaching methods that make them so good, and employ those same methods as much as possible in your book.

- At the same time, if you write a new textbook on a subject, rethink the content and approach that has traditionally been used for that subject. Maybe some topics should be added, removed, or taught differently now. View the subject with fresh eyes, and help provide your students a fresh and improved view of the subject.

- It is highly advantageous for future creators to learn as many subjects as possible, so they can make new discoveries and inventions by combining those subjects in new ways or by applying insights from one subject to another. Yet due to the growth of scientific knowledge, each subject is larger than it used to be, and there are more subjects than there used to be. Therefore, if you write a new textbook, look for any possible ways you can make your book easier/faster to read and to learn from than previous textbooks, without losing anything important. Also look for ways you can cover several overlapping topics or fields with one book or one chapter, in order to minimize redundancy. Just as an example, the same fluid equations govern parts of fluid mechanics, aerodynamics, acoustics, plasma physics, stellar physics, marine science, and atmospheric science, so students need not start from scratch in learning all of those subjects individually.

- For mathematically-oriented scientific subjects, it is not terribly helpful to show that something happens just because several pages of mathematical calculations indicate that it happens, as many previous textbooks have done. Make absolutely certain that you also provide a clear, physically intuitive explanation in words for exactly why and how something happens. Make the mathematical calculations as short and as clear as possible. If necessary, provide two mathematical derivations—one derivation that is very short and intuitive, even if it is approximate or takes some liberties, and the other derivation that is longer and more precise.

1.2.3.2 Scientific Papers

It is absolutely vital to seek out and read relevant scientific papers before you begin to do research and produce your own papers. This section offers advice on (A) reading scientific papers and (B) writing scientific papers.

A. Reading scientific papers

If you are interested in potentially doing research in a particular scientific area, you should read everything you can about that area first. That will help you to understand what has already been discovered or invented in that area, what tools and methods are used in that area, and what work remains to be done. While you can learn some basic information from textbooks (Section 1.2.3.1), news articles, and trustworthy websites, to get the most detailed and most up-to-date understanding, you need to read scientific papers.

Unfortunately there are many factors that make it difficult to read scientific papers. Some of the main problems, and the best solutions that are available at the moment, are briefly discussed below.

1. The large number of papers. There are an enormous number of science, engineering, and medical journals, and a mind-boggling amount of papers published in them, from many decades ago to the current moment. Papers relevant to your topic of interest may have been published in many different places and times. Use websites such as the following to search for relevant papers:

https://scholar.google.com

https://www.worldcat.org

https://pubmed.ncbi.nlm.nih.gov (primarily biology, medicine, and chemistry)

https://arxiv.org (primarily physics and astronomy preprints that have
not yet been peer-reviewed, so they may contain large or small mistakes)

https://www.biorxiv.org (primarily biology preprints)

https://chemrxiv.org (primarily chemistry preprints)

https://eartharxiv.org (primarily earth science preprints)

https://engrxiv.org (primarily engineering preprints)

https://www.medrxiv.org (primarily medical preprints)

https://www.sciencedirect.com (some services are free and some require payment)

https://clarivate.com/webofsciencegroup/solutions/web-of-science/
(only available if you or your institution will pay for it!)

https://www.scopus.com/home.uri (only available if you or your institution will pay!)

2. The expense of searching for papers. Even just to search for scientific articles, without even reading the articles, some websites (such as some of those mentioned above) require you to pay. Only use those if your school or institution pays for them. Otherwise try to get as far as you can with the search websites that are free. Use many different search terms, and several different search websites, or else you may miss some important papers that are directly relevant for your topic.

3. The expense of papers. Most scientific papers are not available for free. Although scientists may be paid by employers or sponsors to do research, they submit papers on that research to journals for free—they do not receive some percentage of the journal's income or otherwise make money from the papers they write. Other scientists who are asked by the journals to review and approve the papers do not receive any money from the journals. The papers are formatted by the scientists themselves, and any final polishing of the formatting is generally done by low-ranking, poorly paid people working for the journals. Most journals are electronic now so there are no printing costs. Yet despite all of these factors that should minimize costs, most journals charge high annual rates for subscriptions to access all of their articles, and absolutely staggering amounts of money for a non-subscriber to access individual articles. Those fees have been increasing much faster than inflation or actual scientific research budgets for decades. They only serve to enrich the top management and investors of the publishing companies that own the journals, to prevent most people on the planet from ever being able to read or use those scientific results, and to greatly harm scientific progress and modern human societies. For the good of science and humanity, organizations and governments with the power to solve this problem must do so, and do it as soon as possible. As noted previously for the case of textbook publishers (some of which are also journal publishers), ideally the people and organizations that have caused this problem and profited so greatly from it should be prosecuted and penalized to the maximum extent of the law, to ensure that this or similar problems do not happen again in the future.

In the meantime, individual scientists must try to deal with this problem as well as they can. If your school or institution subscribes to journals or whole collections of journals, make as much use of that as possible. If you do not belong to an organization with such resources, public libraries may have or be able to obtain some papers you need. Otherwise you must make do with whatever information is available for free. Some journal articles are indeed available for free online. Even for those that are not, an earlier draft version of the article (perhaps not the final version, and perhaps containing uncorrected mistakes) may be available from preprint search websites such as those listed above. If nothing else, you can almost always find the abstract and sometimes the first page of a paper online for free, so you can judge if you are missing much by not having the paper.

4. The language of papers. Researchers in each scientific subfield are constantly developing more and more unnecessarily specialized vocabulary, which they then use in all the scientific papers that they write. This "tower of Babel" effect makes it much more difficult for (a) students to learn a given field, (b) researchers in different fields to communicate, use, or spread ideas, (c) the public to understand and appreciate the work, and (d) the work to have any impact in the real world beyond the virtually inaccessible specialized literature. Without using significantly more space or energy, the authors of scientific papers could and should describe their ideas, work, and conclusions in terms that as many other people as possible can understand.

If you are new to a field, start with textbooks in that field (Section 1.2.3.1) to learn some of the most common specialized language of that field. From there, try to find the papers that seem most readable or do the best job explaining their terms. If all else fails, ask an expert in that field or search online to see if you can learn the meaning of specific bits of cryptic terminology from papers.

5. The large fraction of bad or useless papers. Even narrowing down the papers to those that are potentially related to your topic of interest, you are likely to find a huge number, and the vast majority are probably junk. Some might actually be useful for something else but not your particular project, some may not be useful from any perspective, some might simply repeat earlier papers without adding anything truly new, and some may be partially or completely incorrect (regardless of where they came from, where they were published, or how much they were peer reviewed).

To avoid wasting your time, read a paper's title first. If that sounds potentially interesting, read the abstract. If that still seems interesting, quickly glance through the paper or its figures. Only read the paper in depth if it passes all of those tests; even then you should read the paper critically to see if you spot any flaws in the methods and reasoning that led to its results and conclusions. Otherwise the sooner you can dismiss a paper while being confident that you are probably not missing anything, the sooner you can move on to look at another paper. Look especially for papers that really address the major issues of a topic head-on, rather than simply nibbling around the edges of the topic. Of course, when you do finally find a paper that is very relevant and well done, take the time to study it in detail, and gain as much from it as you can. All of that advice may sound incredibly mercenary, yet it is the only realistic way to wade through the huge percentage of scientific sludge to find what is really important.

Read as many scientific papers as you can. As you are learning to be a scientist, and learning about a particular scientific field, papers can be highly educational. As you are considering what original research you should do, papers can show you what has already been done, and how it was done. As you continue to work on your own research, papers can inform you of new developments that might aid your research, cause you to alter your research, or even indicate that you should switch to a different research project. The more widely you read in various scientific fields not directly related to your current project, the more ideas you can gather that might help with that project or future projects.

B. Writing scientific papers

If you conduct serious science fair projects in high school, publishing one or more scientific papers based on them can look very good when you are applying for colleges, scholarships, etc.

Probably the biggest step in publishing a paper is deciding which journal to send it to. People obsess over the relative "impact factors" of journals way too much. Ideally you would like to publish in the most "prestigious" journal that has a real chance of accepting your paper. In my opinion, impact factors and prestige are overrated, but you do want your paper to appear someplace that already has a regular readership of people who will properly understand and appreciate your work. If the journal will make your paper readily available online for free, not hidden behind a pay-per-view firewall or paid journal subscription, that will also get you a lot of future readers on the internet. If your research/safety advisor works in that same scientific field, he or she can probably advise you on the best journal to target. If that journal ultimately refuses to publish the paper, you can always send it someplace else.

Once you decide which journal you would like to submit to, read their style guide very carefully, and study the format of other papers in that journal. Different journals have very different and very particular preferences for how the entire paper should be written and formatted.

For general advice on writing scientific documents, see Section 1.2.4.3.

After you submit your paper to a particular journal, an editor from that journal will decide if they think your paper is worthy of being peer-reviewed. If they do not, they will immediately reject your paper with some brief explanation. You can either offer counter-arguments to their objections and try to persuade them to send it out for peer review, or you can accept their decision and send the paper to another journal.

If the editor sends the paper to reviewers, after a month or two you will probably receive around 1–3 paragraphs of comments from approximately 2–3 anonymous reviewers. The reviewers will comment on (1) whether they think your paper should be published in the journal and (2) whether you should change anything in the paper. The editor may also offer more comments of their own at this point.

If the reviews are mostly positive, you should do your best to comply with all the requested changes. Even if the reviews are largely negative, don't give up immediately. Make as many changes and improvements as you can, summarize your improvements and your counter-arguments to any criticisms you feel were unfair, and send the revised paper and your summary back to the editor. That quite often works, but not always.

Scientists generally publish a number of papers over the course of their careers, and hopefully you will too. Unfortunately, any attempt to cover this area requires the honest discussion of some unpleasant issues.

Currently, the scientific research system in the United States (and perhaps some other countries) is highly dysfunctional. Most researchers are rewarded primarily for the sheer number of their published papers, which provides a strong incentive:

- To neglect learning new things, teaching students, helping others, or doing anything else that does not directly and immediately lead to a published paper.
- To avoid investigating hard problems or big ideas that are too risky or would take too long to reach the point of publication.
- To immediately begin doing whatever experiments are close at hand without first spending time brainstorming or planning.
- To only try something that you feel certain in advance will work.
- To immediately bury any negative results that you do happen to get without publishing them or further investigating them.

- To do as little new work as possible before writing a paper about it.
- To write as many other papers about the same thing as possible, with few if any significant differences among them (especially if they are published in several different journals).
- To skip any further tests to check if your initial results might be incorrect before publishing.
- To avoid testing results that others have already published to see if they are repeatable.
- To choose research topics for papers that are more likely to create a splash (e.g., "Cat Owners Are Slightly Less Likely to Die of Cancer Than Dog Owners"), even if they are scientifically highly dubious or have no real importance or use.
- To avoid taking very basic research all the way to practical products, since that would be too hard and time-consuming.
- To become increasingly micro-specialized, cranking out papers only within one very narrow sub-field.
- To develop increasingly specialized vocabulary to sound more impressive in your papers.
- To publish in journals that are increasingly inaccessible (in terms of language, cost, interest, access, and readership) to anyone else outside your area of micro-specialization.

These perverse incentives have led directly to the five problems noted in Part A above.

If you hope to continue to publish scientific papers during your career, bear in mind all of these problems, and do your very best not to participate in or contribute to these problems. In fact, being truly effective as a revolutionary innovator generally involves doing essentially the opposite of all the trends just described (see for example the revolutionary innovators on pp. 25–33), and thereby running the very serious risk of being judged a failure by the current system. Ideas for exactly how to do that are discussed elsewhere in this chapter and in Chapter 12.

Whether you choose to try to follow the conventional system and its rules, or to try to be a revolutionary innovator, you should at least have a very clear and sober idea of what you are getting into before you begin your career.

1.2.3.3 Patents

Patents are a highly specialized yet quite useful form of scientific literature. This section offers advice on (A) reading patents and (B) writing patents.

A. Reading patents

As part of any good search of the scientific literature, you should also search patents. Some science and engineering ideas or results are only published in the form of patents, not journal articles or books. In other cases, the information in an author's patents greatly supplements what that author has published in other forms.

Some good websites for doing free patent searches include:

https://worldwide.espacenet.com

https://patents.google.com

https://www.uspto.gov/patents/search

It can be tricky to find patents on the topic you are interested in, even if they are out there. Try all of the above websites—one of them may find patents that the others do not. Use many different search terms, since you cannot be certain what specific words might have been used in patents relevant to your topic. If your searches return too many irrelevant patents, try searching for combinations of terms to narrow it down, or only search for patents within a specified time period or country. Some or all of the above websites should translate patents, if you find a patent that seems relevant but is in a language you cannot read.

Let your search branch out until you are satisfied that you have found everything important that there is to find. Most patents reference other patents, and sometimes journal articles or books, so look those up too if they seem to be of interest.

Patents are notoriously difficult to read and understand, since they tend to combine the very worst literary practices of both scientists and lawyers. If one section of the text seems too difficult to understand at first, start with a different section. If all of the text is too confusing, see if you can figure out the diagrams. If the patent is related to other patents or journal articles, read those to see if they shed more light on the content.

Do not be awed when reading patents, no matter how impressive and official they may sound. Just because something is covered or stated in a patent does not mean it will work as described, is truly advantageous over alternatives, or is even feasible. I have seen government-approved patents for "inventions" that clearly violated well-known laws of physics and completely failed to work when tested in a laboratory. Always evaluate patents—and any other sources—critically, taking into account everything you already know and information from other relevant sources.

If you find specific scientists who have patents and/or papers on a particular research topic of interest to you, learn as much online as you can about those scientists and their work. Consider contacting them if you have questions about their research or want to find out if they might be willing to help you or hire you. They may not respond or may not help, but there is usually no harm in asking.

B. Writing patents

Existing patents are collectively known as the “prior art”—who has already invented what. Before you file or even begin to write a new patent application, you should thoroughly search the prior art for any related or partially-related patents, gain a detailed understanding of them, and be prepared to explain exactly how your new invention and new patent application differ from everything else that came before.

In addition to containing lots of scientific and engineering details, patent applications must be written in a high specialized legalese language in order to have a realistic chance of (1) being approved by the government patent office and (2) being upheld by courts in any lawsuits necessary to enforce one’s patent rights. While there are books that try to teach you how to write your own patent [Pressman and Blau 2020], the only truly reliable approach is to hire a professional patent lawyer, which is expensive. The legal and government fees involved in filing a patent application, responding to any objections from the patent office, and maintaining patent rights for as long as possible after a patent is issued are also expensive. Moreover, patents are most useful if you have paid to write, file, and maintain patents not just in your own country, but in all countries that might manufacture, sell, or buy your invention, and that is even more expensive. Finally, if there is a lawsuit over who actually invented something, generally whichever side can afford the best and the most lawyers will win, or at least can postpone losing for so long that it does not matter anymore.

For all of these reasons, in most cases I would recommend that individuals do not file patents. If you are an individual who has invented something, just put your invention out there, make sure the public hears loud and clear that you were the inventor, and hope that your invention is actually used somewhere and does some good. Individuals do not have a realistic chance of making money by patenting their inventions, apart from astronomically lucky circumstances or cases from long ago when it was much easier to do. The only really good reason for an individual to file a patent is if you are a high school or university student and would like to file a no-frills patent in one country for as little money as possible, just to add to your resume.

If you are doing research at a university, company, government laboratory, or other organization, that organization may choose to file patents based on anything you invent there. The organization will bear all the costs of filing, maintaining, and (if necessary) litigating the patents, although they will also reap all or virtually all of any financial reward that the patents ultimately bring from sales, licensing, or legal settlements. Some organizations might promise you otherwise, but realistically what I have described is just the way things work. If your organization does want to file a patent application, you will likely be asked to write a draft of the scientific or engineering details of the application. A patent lawyer will then take whatever you write and translate it into 24-carat gibberish. You should at least be paid for your time to write up your scientific input, and you might even eventually get a free wall plaque or a small one-time financial bonus from the organization. If nothing else, patents are always good for your resume.

If you do help to write a patent application and want it to be as effective as possible, use systems analysis (Section 1.2.4.4) to ensure that your patent descriptions and claims cover as many categories as possible, describe them in terms that are as general as possible, and cover all possible contents of the categories as thoroughly as possible. Provide as many specific examples as possible (including experimental data if you have it), but state that they are just examples, not the only cases to which the patent application is limited.

Note that some people and organizations are “patent trolls.” They try to think up as many ideas as possible, file as many patent applications on those as they can, and word the patent applications in as general and as vague a fashion as possible. Then they sit back and do nothing; they do not even try to conduct research on an invention, develop it, build it, test it, publicize it, market it, or license it to someone else. Rather, they wait for someone else to later invent the same thing or something similar enough and to do the hard and expensive work of actually developing it. At that point, the patent troll threatens to sue the new inventor/developer for patent infringement unless they pay the patent troll hefty fees for the invention that they had independently conceived and developed without the patent troll, during the time that the patent troll was refusing to do anything to develop the invention. Some patent trolls also buy up as many patents from others as possible, for as little money as possible, in order to add them to their arsenal. Beware of trolls. Do your best to avoid them and to avoid feeding them either money or patents. Certainly do not become a patent troll or go to work helping a patent troll, even though that may be lucrative in a dysfunctional system.

1.2.3.4 Stories About Fictional Scientists

This section offers advice for both (A) future creators who would enjoy reading about fictional scientists and (B) anyone who would like to write inspirational stories about fictional scientists.

A. Reading about fictional scientists

Future creators from preschool through the end of their careers can enjoy science fiction stories, books, comics, films, and television series. Reading or watching science fiction is an excellent way to stumble across new ideas that might actually be investigated in the real world. Sometimes a science fiction idea can be tried directly (though usually on a much smaller scale) in the real world. In other cases, a science fiction idea may inspire a real-world scientist to think of a new idea that is only partially or tangentially related to the fictional idea.

In addition to inspiring particular future creations in the real world, science fiction can also encourage the general career path and self-motivation of real-world future creators. Since real-life role models and mentors may be scarce, and real-world obstacles can seem discouragingly numerous and immense, this sort of inspirational or motivational role for science fiction may be even more important than its role in introducing specific new scientific ideas.

Some of the most effective motivational science fiction of this type possesses some or all of the following properties:

1. A scientist or engineer is the main character, or at least one of the main characters, of the story. That sends a message that future creators are important.

2. The fictional scientist/engineer is trying to accomplish some good, and indeed does ultimately accomplish some good. That shows that future creators should focus on creations that are helpful, not creations that are harmful or that simply bring money, fame, or power to the creators and their sponsors.

3. One or more discoveries/inventions by the scientist/engineer are the primary plot of the story or the key to resolving the primary plot; if they are not the primary plot, they should at least play a major role in the story. That conveys a message that the discoveries and inventions of future creators are important.

4. The scientist/engineer arrives at useful solutions or results by long and hard work (which may also in part include sudden flashes of insight), not by a lucky coincidence/magic rock/alien gift/fairy godmother/etc. That shows that future creators should plan to work very hard and for a long period of time to arrive at their discoveries or inventions; if they sit back and wait for a lucky creation to fall into their lap, that probably will not happen.

5. The scientist/engineer arrives at useful solutions or results primarily by employing their knowledge, intelligence, and creativity, not primarily by brute force, running and jumping, punching, gunfights, explosions, etc. That communicates that intelligent thought is usually

much more useful for solving problems than unintelligent action (although there may be fictional or real-life situations in which both thought and action are required).

6. The scientist/engineer lives in the present time, in a world that is as realistic and as similar to our own world as possible. That allows future creators to better identify with the story, rather than feeling that a prerequisite for making discoveries/inventions is living in a world very different than where they actually are.

7. The fictional discoveries/inventions feel grounded in real science, even though they will obviously be things that do not currently exist, and that may or may not prove feasible in the real world. If the characteristics of a fictional discovery/invention are too far-out and magical, or if the story's explanation for the discovery/invention relies upon obviously incorrect scientific details or meaningless gibberish, that makes it much harder for future creators to identify with the story.

8. While it is not required, the younger the fictional scientist/engineer is, the easier it will be for students to view that character as a role model. In order to maintain an air of plausibility, though, the lower the age of the fictional scientist is, the more limited their fictional scientific contributions and breakthroughs should be in scale. (Young fictional scientists could be shown to be working with or assisting one or more older scientists, to help maintain plausibility.)

9. The fictional scientist/engineer and their fictional discoveries/inventions confront and ultimately overcome serious obstacles, ideally both scientific obstacles (struggling to make something work) and non-scientific obstacles (facing villains, disasters, or other hardships). That prepares future creators to deal with both scientific and non-scientific obstacles during their careers.

10. As a result of their hard work, discoveries/inventions, and overcoming of obstacles, the fictional scientist/engineer has a rewarding and happy ending (or at the very least, their work allows a happy ending for others and is gratefully remembered). That sends a positive message that the work of future creators is worthwhile and will be rewarded and remembered.

Jules Verne's stories—such as *Twenty Thousand Leagues Under the Sea*, *Journey to the Center of the Earth*, *From the Earth to the Moon*, and *Around the Moon*—are some of the earliest and most influential examples of this type of literature. (Although H. G. Wells is sometimes considered in the same category, Wells primarily just used a highly implausible and poorly explained science fiction idea as a quick plot device in each book to then conduct a detailed literary exploration of social themes that he found much more interesting, rather like some later television series such as *The Twilight Zone*.)

These sorts of science fiction stories were wildly popular and avidly consumed by children and adults throughout the German-speaking world in the early twentieth century. They emphasized individualism and presented fictional role models for how a young engineer or scientist could invent or discover something so important that it would change the fate of the country or of the entire world. Some of the major authors included Hans Dominik, Otto Willi Gail, Otfrid von Hanstein, Fritz Mardicke, and Paul Thieme [Fisher 1991]. Likewise, early German films depicted similar stories about creating a life-like robot (Fritz Lang and Thea von Harbou's *Metropolis*, 1927), building a moon rocket (Lang and von Harbou's *Frau im Mond*, 1929), and accomplishing other technological feats.

Otherwise, most of the stories I am aware of that best match the above criteria were written in the United States between the 1940s and the early 1970s, which seems to have been quite a golden age for inspiring, supporting, and rewarding revolutionary innovators and innovations. Some of the best examples include:

- Robert A. Heinlein's juvenile novels. Heinlein was a retired U.S. Navy lieutenant and former engineering student, and was married to a retired Navy lieutenant commander and chemist, Virginia Heinlein [Dick 2008, pp. 341–352]. Heinlein's first novel, *Rocket Ship Galileo* (1947), described how three teenage budding engineers and their adult mentor from the Manhattan Project built a nuclear-powered rocket and traveled to the moon. (Ironically they found that German rocket engineers had secretly already gotten there.) Heinlein wrote a total of 12 juvenile novels through 1958's *Have Space Suit—Will Travel*, each depicting how young people assisted with a further step in space exploration. The popularity of his books prompted other authors such as those listed below to write juvenile science fiction novels [Clute 2017].

- Lester del Rey's juvenile novels. Del Rey was a longtime author, editor, and publisher of science fiction. From 1952 to 1968, he wrote over 20 juvenile novels in which young people created or assisted with projects on space flight (e.g., *Marooned on Mars*, 1952, and *Mission to the Moon*, 1956), submarines (*Attack from Atlantis*, 1953), robotics (*Runaway Robot*, 1965), time travel (*Tunnel Through Time*, 1966), and other innovations [Clute 2017].

- The *Tom Swift Jr.* series, published 1954–1971 by the Stratemeyer Syndicate (which also produced the *Hardy Boys* and *Nancy Drew* novels). Most of the 33 books in this series were written by James Duncan Lawrence, a former mechanical engineer and teacher. As depicted in these books, Tom Swift Jr. was a young inventor who used the resources of his father's large engineering company to build a series of increasingly sophisticated aircraft, spacecraft, submarines, robots, atomic devices, and other creations [Jonathan Cooper 2007; Open Library 2010].

- Bertrand Brinley's *Mad Scientists' Club* stories. Brinley was a retired Army captain, whose Army duties had included (among other things) advising children on how to safely experiment with rockets in the 1950s. Based on that work, he published the detailed nonfiction *Rocket Manual for Amateurs* in 1960, followed by a series of 1960–1974 fictional stories about students who formed the Mad Scientists' Club to create and test their own inventions [Brinley 2010].

- The *Danny Dunn* series, published between 1956 and 1977 by Raymond Abrashkin and Jay Williams. The books focused on discoveries and inventions that were made by young students and adult scientists usually working together. The discoveries and inventions combined some real-world scientific ideas and approaches with very fanciful science fiction adventures designed to appeal to young readers [Clute 2017].

Like their earlier French and German counterparts, these books from American authors presented children with fictional role models who through their scientific knowledge, hard work, and individualism created revolutionary innovations, despite both scientific obstacles and human opponents.

These books were extremely popular, became fixtures in public and school libraries in the United States, and inspired countless children to pursue careers in science and engineering. However, by the early 1970s, most books like these ceased to be produced in the United States, as shifts in children's interests made such books less marketable. More recent juvenile fiction tends to focus on children (e.g., Harry Potter), superheroes (e.g., Marvel and DC characters), or animals (e.g., cats, dragons, etc.) who are magically granted special powers, instead of having to achieve things using scientific knowledge and hard work.

There are examples of similar inspirational fiction in other media. The various *Star Trek* and *Stargate* series (and some other science fiction television series along those same lines) often featured an engineer, scientist, or medical doctor racing against time to solve some problem, albeit usually in a world very unlike our own.

In films, *Contact* (1997) is perhaps the supreme example of this genre, and it owes its success to Carl Sagan's deep insights and profound message. The struggles by the main character in *Phenomenon* (1996) to find research support and human understanding may also resonate with many future creators.

Unfortunately in recent films, the vast majority of heroes receive their abilities by sheer luck and overcome adversity by witless action. One of the few big heroes that bucked that trend and exemplified most of the qualities enumerated above was Tony Stark, especially in the first couple of *Iron Man* movies before the Marvel films increasingly diverged from a real-world setting.

If any readers know of any other major, recent fictional scientists/engineers that could be recommended here as inspirational role models, please let me know. If there truly is a shortage of recent examples, young future creators might still enjoy and benefit from reading some of the older books mentioned above, if they can make allowances for the fictional and much older versions of the "modern" world in which those stories are set.

Although most of this discussion has focused on the importance of fictional role models for young future creators, positive fictional depictions can also give an important boost to older creators who feel weighed down by their real-world struggles to overcome scientific and non-scientific obstacles. They can serve as "Chicken Soup for the Mad Scientist's Soul."

B. Writing about fictional scientists

Because fictional scientists and engineers can be so motivational for future creators (and demonstrably were motivational for many earlier creators), and because they seem to be far less numerous than they were in previous decades, there is a great need for writers and publishers/production studies to create brand new stories about such scientific role models. If any readers have suitable talents and interests, please consider developing a new book series, comic book, television series, films, online stories or videos, or other media about fictional but realistic scientific heroes. If you do that, please take into consideration the above enumerated list of characteristics, and also spend some preparatory time studying what worked (and what did not work) in some of the earlier books, television series, and films mentioned above.

1.2.3.5 Real Scientists' History and Advice

This section offers advice for both (A) future creators who would like to read about real scientists and (B) anyone who would like to write about real scientists.

A. Reading about real scientists

Creators of any age, from elementary school through the end of their careers, should read books by and about other revolutionary scientific innovators. From such books, you can gain many insights and ideas for how to deal with various types of scientific and non-scientific obstacles to research. More generally, the books can be quite inspirational and motivational.

Some of the very best books that really analyze what made previous scientific innovators tick were written by István Hargittai and his colleagues.[1] I highly recommend that you read as many of those as possible.

You can also seek out books by or about revolutionary innovators such as those listed on pp. 25–33.

For many additional books by or about previous scientific innovators, see the Bibliography of this book and also that of *Forgotten Creators* [Rider 2020].

For further suggestions, see Section 12.2.

No human being is perfect, so you should not expect to find any role models who were perfect. In fact, many of them had flaws that were as profound as their accomplishments. The same Einstein who worked out the theory of relativity from start to finish refused to fully embrace quantum theory, despite all of its evidence and applications. The same Vannevar Bush who founded the modern U.S. research system and promoted revolutionary programs such as the Manhattan Project refused to believe in the possibility of long-range rockets, even when confronted with German examples. The same Thomas Jefferson who helped to codify the ideals of human rights kept people enslaved to serve him. The same Martin Luther King Jr. who literally sacrificed his own life to improve the lives of African Americans is reported to have treated many women rather poorly. Such people still make excellent role models if you learn as much as you can from their weaknesses as well as their strengths, their mistakes as well as their successes. (Likewise you will always be imperfect and make mistakes, but at least do everything in your power to try to minimize their number and their consequences.)

As you are reading any book by or about a revolutionary scientific innovator (scientist, engineer, doctor, etc.), always be watching for anything you can you learn that you or others might be able to apply. For example, watch for any answers to questions such as the following, and learn as much from them as you can:

- What factors inspired the person to become a scientist?

- How did the person learn science, and what helped?

[1] Balazs Hargittai and István Hargittai 2015; Balazs Hargittai et al. 2014; István Hargittai 2000–2006, 2002, 2006, 2010, 2011, 2013, 2016.

- How did the person begin doing original research, and what helped?
- What was the person's first revolutionary discovery or invention? How was it made?
- What were the person's other revolutionary innovations, and how were they accomplished?
- How did the person identify which scientific problems to work on?
- How did the person figure out the best approaches/solutions to those problems to pursue?
- What scientific obstacles did the person encounter, and what methods did they use to overcome them?
- What non-scientific obstacles did the person encounter, and what methods did they use to overcome them?
- Which people were most supportive or helpful for the scientist, and how?
- What were the person's scientific and personal strengths, and how did they become so good in those areas?
- What were the person's scientific and personal weaknesses or failings, and what should they have done differently?
- What things, if any, could the person have done to be even more successful at revolutionary innovation than they were?
- How did the person help others around them (family members, friends, teachers, students, research collaborators, etc.), or how could they have treated them better than they did?
- How and what did the person teach their students and those whose research they supervised?
- How did the person divide their time among science research, science education, work tasks not directly part of productive research or education (bureaucratic requirements, committee/managerial/administrative work, or work just to pay the bills), family and friends, etc.? (Note that the division of time will probably be different at different points in a person's life.)
- When did the person cease to produce new revolutionary innovations? Why did they cease? What did they do after that?

B. Writing about real scientists

If you are a scientific innovator, please consider writing a book to share your thoughts and experiences regarding the above sorts of questions. If you are someone else who has the ability, interest, and opportunity, please consider writing insightful biographies of scientific innovators, or helpful analyses of groups of non-scientific innovators.

1.2.3.6 Non-Scientific Innovators' History and Advice

There have also been countless innovators who were not scientists. Even though they were not trying to solve scientific problems, they did have to develop very creative solutions to the types of problems that they did focus on. In addition, along the way, they had to face and overcome many of the same sorts of non-scientific obstacles that scientists also encounter: difficulties in finding financial and political support, personal struggles, attacks from people and organizations that opposed them, etc. Thus scientists may find inspiration or at least consolation by reading books by or about non-scientific innovators. The most helpful books concern people who were both (a) highly innovative and (b) deeply committed to helping others through their innovations, not just using their innovations to gain fame, fortune, or power for themselves. (Of course, it may also prove useful to learn about the approaches taken by people who were highly innovative but not philanthropic, or deeply committed to helping people but not especially innovative.)

Just to provide a few examples of this genre as a starting point, scientists might consider reading about:

- Innovators in literature, music, and the arts such as:
  - Jane Austen
  - Johann Sebastian Bach
  - Samuel Clemens (Mark Twain)
  - Johann Wolfgang von Goethe
  - Franz Joseph Haydn
  - J. R. R. Tolkien
- Political and social innovators such as:
  - Susan B. Anthony
  - Marcus Aurelius
  - Dietrich Bonhoeffer
  - Jimmy Carter
  - Benjamin Franklin
  - Betty Friedan
  - Mohandas Gandhi
  - Thomas Jefferson
  - Martin Luther King, Jr.

  - Abraham Lincoln
  - Niccolò Machiavelli
  - Fred Rogers
  - Franklin D. Roosevelt
  - Harriet Tubman

- Religious innovators such as:
  - Confucius
  - Lao Tzu
  - C. S. Lewis
  - Mencius
  - Siddhārtha Gautama (the Buddha)
  - Menno Simons
  - John Wesley
  - Zoroaster/Zarathustra
  - Jesus, Moses, and numerous other biblical figures

For further suggestions, see Section 12.3.

As you read a book by or about a non-scientific innovator, keep watch for answers to questions such as those in Section 1.2.3.5.A.

If you are a non-scientific innovator, please consider writing a book to share your thoughts and experiences regarding those sorts of questions. If you are someone else who has the ability, interest, and opportunity, please consider writing insightful biographies of non-scientific innovators, or helpful analyses of groups of non-scientific innovators, that address those sorts of questions.

1.2.4 Things to Do

Categories of activities that future creators should do, and should become good at doing, include:

1. Experiments following directions
2. Self-directed experiments
3. Written and oral presentations
4. Systems analysis and brainstorming
5. Original research projects

With all student activities, there should always be proper adult supervision!

1.2.4.1 Experiments Following Directions

Many scientists and engineers were first inspired by educational science kits that they experimented with as children. Good science kits or sets generally include detailed directions for specific experiments, as well as all or at least most of the supplies needed to conduct those experiments.

The early to mid-twentieth century, and especially the 1940s–1960s, were a golden age for such kits in the United States:

- A. C. Gilbert, an M.D. from Yale University, founded the A. C. Gilbert Company in 1909 in New Haven, Connecticut to produce science- and engineering-related kits for children. His sales steadily increased until World War II but really boomed after the war from the late 1940s until the 1960s. Gilbert's kits included Erector Set engineering construction kits for building everything from robots to locomotives; chemistry sets with dozens of chemicals; high-quality compound microscopes with slide-making accessories; and even the "U-238 Atomic Energy Lab" that provided children with several real uranium ore samples, other radioactive sources, a Geiger counter, a cloud chamber, an electroscope, and other nuclear physics supplies. However, Gilbert died in 1961, his company merged with the rival Porter company in 1967, and the combined company (Gabriel Industries) slowly petered out during the 1970s [Gilbert and McClintock 1954; Jitterbuzz 2017; Bruce Watson 2002].

- Harold Porter founded the Porter Chemical Company (Chemcraft) in 1914 in Hagerstown, Maryland to also produce science and engineering kits. The company's history very much paralleled that of the rival Gilbert company: sales increased until the wartime shortages of World War II, but then blossomed into a golden age from the late 1940s to the 1960s. Porter's products included lavishly equipped chemistry sets but also mineralogy kits, biology dissection sets, and a variety of microscopes. Porter died in 1963, and in 1967 Gabriel Industries bought and merged the Porter and Gilbert companies. The combined Gabriel company operated with declining sales and declining kit quality through the 1970s, changed hands in 1978, and finally ceased operations entirely in 1984 [Tyler 2003].

- The Skil-Craft company started up in the 1950s in Chicago to compete with the Gilbert and Porter companies in the postwar boom of demand for science and engineering kits. During the 1950s and 1960s, Skil-Craft produced high-quality kits in chemistry, microscopy, and other scientific fields. In 1968 they were bought out by Western Publishing/Golden Books, resulting in several 1970 sets in chemistry, biology, microscopy, and geology that combined Skil-Craft's well-thought-out experiments and Golden Books's beautiful illustrations [Fichter 1970a, 1970b; Parker and Martin 1970a, 1970b, 1970c]. Unfortunately, sales declined in the 1970s, the company changed hands in 1979, and operations ended in 1984.

This section lists some of the best modern resources I have found for science experiments for students. As with all student activities, there should always be proper adult supervision.

If at all possible, I recommend setting up a dedicated workspace where you can conduct your experiments and store your scientific supplies, preferably in a place where other children and any pets cannot get into them. That might be anything from a desk in your bedroom to a workbench in your basement.

For convenience, I have divided up the activities into:

A. General resources for science experiments

B. Biology experiments

C. Chemistry experiments

D. Physics experiments

E. Earth and space science experiments

F. Engineering experiments

A. General resources for science experiments

Some of my own educational materials are available at: https://riderinstitute.org/education/

The Annotated Build-It-Yourself Science Laboratory, by Raymond E. Barrett and Windell H. Oskay, is a book that explains MacGyver-like methods to create your own laboratory equipment for biology, chemistry, physics, and earth science using commonly available items. It is available from various booksellers. (*MacGyver* was a television series in which the fictional hero used common items to solve scientific problems during emergencies.)

Janice VanCleave wrote lots of science experiment books for all grade levels and scientific fields. They are available from https://scienceprojectideasforkids.com and various booksellers.

Home Science Tools (www.homesciencetools.com) sells supplies for individuals, families, and home schools. They do a much better job of maximizing selection, maintaining high quality, and minimizing prices than any other science education supply company I have seen. They are very nice folks with excellent customer service. (Danger Will Robinson! Avoid the fairly small number of non-scientific creationist books and creationist curriculum packages that they also sell!)

Thames & Kosmos features a wide variety of science kits that are made in Germany and available worldwide from various online dealers. They are extremely well designed, educational, and easy to use, though they do seem overpriced for what they actually contain.

American Science & Surplus (www.sciplus.com) has an ever-changing stock of interesting stuff; they are an especially good for optical and electrical parts.

Educational Innovations (www.teachersource.com) sells a wide variety of supplies.

Scientifics Direct (www.scientificsonline.com) was formerly known as Edmund Scientific. It has gone downhill but is still worth checking out.

Carolina Biological Supply (www.carolina.com) is a major supplier for schools. They tend to be expensive and may or may not sell to individuals, depending on what you want to order.

Ward's Science (www.wardsci.com) is another major supplier for schools. They also tend to be rather expensive and may not sell to individuals.

The *Magic School Bus* series of books, written by Joanna Cole and Bruce Degen, does a wonderful job of explaining several scientific topics to young children.

There are many high-quality educational videos, fictional films, or older DVDs about scientific topics. For whatever reasons, many of them seem to involve space exploration or dinosaurs. Examples include (parents, always screen for suitability first!):

- *The Bomb* (2015, PBS)
- *Cosmos* (1980, hosted by Carl Sagan)
- *Cosmos* (2014, hosted by Neil deGrasse Tyson)
- *Nova* (long-running PBS series)
- *Space, Time and the Universe with Brian Greene* (*Elegant Universe/Fabric of the Cosmos*)
- *The Universe* (series, 2007 onward)

- *Apollo 11* (2019, restored archival footage from 1969)
- *Apollo 13* (1995)
- *From the Earth to the Moon* (miniseries, 1998)
- *The Dish* (2000)
- *Contact* (1997)
- *Gravity* (2013)
- *The Martian* (2015, extended edition)
- *Voyage to the Planets and Beyond* (2004)

- *Walking with Monsters/Dinosaurs/Allosaurus/Beasts/Cavemen* (1999–2005)
- *Chased by Dinosaurs* (2003)
- *Sea Monsters* (2003)
- *Prehistoric Park* (2006)

B. Biology experiments

For good biology books, see especially:

Kenneth R. Miller and Joseph S. Levine, *Biology*

Lisa A. Urry et al., *Campbell Biology*

David P. Clark and Lonnie D. Russell, *Molecular Biology Made Simple and Fun*

For more detailed books on different topics within biology and medicine, see pp. 989–995.

You will be amazed what you can see with a good microscope (both for biological and non-biological specimens)! Do make sure you buy a good one, however, even though that is more expensive, since cheaper, poorly made, more widely available children's microscopes will only frustrate you and make you rapidly lose interest in trying to see anything. The single best source of high-quality yet reasonably priced microscopes I have seen is Home Science Tools (homesciencetools.com). Certainly some other dealers offer good microscopes too, but always check very carefully before you buy. I especially recommend acquiring some or ideally all of the following:

- An inexpensive, battery-powered, handheld plastic microscope (sciplus.com or other online dealers) for very young students or for use in the field.
- A high-quality, low-power microscope, especially one with binocular (two) eyepieces, dual-power 10x and 30x magnification, and both top and bottom lighting (homesciencetools.com). This type is perfect for viewing insects, leaves, rocks, fossils, ancient coins, and similar items.
- A high-quality, high-power microscope, especially one with four magnifications (40x, 100x, 400x, and 1000x), separate coarse and fine focus knobs, a mechanical stage to move the slide, a bright LED light, and binocular eyepieces to minimize eyestrain (homesciencetools.com). This type can only use very small, flat samples on microscope slides, but it can show anything from the compound eye of an insect to individual bacterial cells.
- Several sets of already prepared microscope slides with samples from humans, animals, plants, bacteria, etc. (homesciencetools.com).
- Kits with blank glass slides, glass coverslips, several colors of stains, balsam sealer, and instructions to make your own microscope slides (homesciencetools.com).

Home Science Tools (homesciencetools.com) and other suppliers sell dissection tools, preserved whole animals from many species, preserved organs of several types, and sets of several animals or several organs. Some of the sets also come with an excellent guidebook for dissection [Berman].

MiniPCR (minipcr.com) produces and sells very high-quality biotechnology equipment, reagents, and educational lessons. Unfortunately their high prices tend to be better suited for schools than for parents.

The National Centre for Biotechnology Education (www.ncbe.reading.ac.uk) sells worldwide through direct orders to their website; some of their supplies are also resold at higher cost by Carolina Biological Supply. NCBE produces and sells very innovative supplies for battery-powered gel electrophoresis, centrifugation, micropipetting, lyophilized DNA and restriction enzymes, DNA extraction/electrophoresis, protein extraction/electrophoresis, polymerase chain reaction, bacterial transformation with a plasmid, photosynthesis, microbial fuel cells, and assorted other enzymes.

C. Chemistry experiments

The best introductory chemistry textbooks are:

Antony C. Wilbraham et al., *Pearson Chemistry*

Theodore L. Brown and H. Eugene LeMay, Jr., *Chemistry: The Central Science*

Theodore Gray wrote several books that are also fun and inspiring to read: *The Elements*, *Molecules*, *Reactions*, and *Theodore Gray's Completely Mad Science Experiments.*

For more detailed books on different topics within chemistry and materials science, see pp. 986–990.

The Thames & Kosmos Chem C3000 (sold by numerous dealers online) may well be the best chemistry set that is currently available. Thames & Kosmos also makes some smaller chemistry sets, as well as sets covering several other scientific fields.

Robert Bruce Thompson designed wonderful kits and corresponding instruction books for chemistry, forensic science, and biology. Although he died, his family still produces and sells his kits (www.thehomescientist.com), and his books are still sold by amazon.com or other booksellers.

Home Science Tools (homesciencetools.com) sells several chemistry kits of various sizes. They also sell a wide range of individual chemicals and pieces of equipment.

Molymod produces plastic ball and stick components that can be used to assemble models of inorganic, organic, and biochemical molecules. Their kits are sold by several online dealers. For general purposes, I especially recommend the Molymod MMS-004 Inorganic/Organic Teacher Set.

D. Physics experiments

The best general textbooks on physics are:

Paul G. Hewitt, *Conceptual Physics*

Hugh D. Young and Roger A. Freedman, *University Physics with Modern Physics*

For more detailed books on different topics within applied math and physics, see pp. 964–976.

These books can teach you how to build some amazing (though very challenging) physics projects:

David Prutchi and Shanni Prutchi, *Exploring Quantum Physics Through Hands-On Projects*

Robert Iannini, *Electronic Gadgets for the Evil Genius*, 2nd ed.

Robert Iannini, *More Electronic Gadgets for the Evil Genius*

United Nuclear (unitednuclear.com) sells antique uranium-glazed Fiestaware, spinthariscopes, Geiger counters, uranium ore, Trinitite, and other nuclear-related materials and instruments.

Thames & Kosmos makes several physics-related kits that are sold by various online dealers.

Home Science Tools (homesciencetools.com) sells many physics-related kits and individual components.

Other sources for physics-related supplies include American Science & Surplus (www.sciplus.com), Educational Innovations (www.teachersource.com), and Scientifics Direct (www.scientificsonline.com).

E. Earth and space science experiments

The beautifully illustrated *Golden Guide* series from St. Martin's Press covers most topics in earth and space science on a level suitable for elementary, middle, and high school students.

For good general textbooks on earth science, see:

Glencoe, *Earth Science*

Edward J. Tarbuck and Frederick K. Lutgens, *Earth Science*

For more detailed books on different topics within earth and space science, see pp. 983–986.

If you would like to buy rocks, minerals, or fossils online, see www.geoed1.com, www.djminerals.com, www.rocksandminerals.com, www.twoguysfossils2.com, and www.homesciencetools.com.

There are several good books that can help you collect and identify rocks and minerals. The *Roadside Geology* book series from Mountain Press describes what types of rocks, minerals, and fossils you can find in different locations within U.S. states, with a book available for almost every state. Two excellent identification guides for rocks and minerals are Pellant and Prinz et al.

For an excellent guide for identifying common fossils, see Walker/Ward.

Paleontologists must reassemble prehistoric skeletons from jumbles of bones. To build your own dinosaur-like skeletons out of chicken bones, see two wonderful books by Chris McGowan: *Make Your Own Dinosaur Out of Chicken Bones* and *T-Rex to Go.*

Whereas paleontologists dig up the fossils of ancient animals and plants, archaeologists dig up human remains and artifacts. An easy way to try your hand at archaeology is to clean some ancient Roman coins and try to read their inscriptions and identify the rulers they depict. Look for entire lots composed of relatively inexpensive, uncleaned Roman coins from reputable dealers on VCoins (www.vcoins.com/ancient/) or elsewhere online.

To learn more about Roman coins, other ancient inscriptions, and other aspects of archaeology, see:

Zander H. Klawans, *Handbook of Ancient Greek & Roman Coins*

Mark Collier and Bill Manley, *How to Read Egyptian Hieroglyphs*, 2nd ed.

Michael D. Coe and Mark Van Stone, *Reading the Maya Glyphs*, 2nd ed.

Jane McIntosh, *The Practical Archaeologist*, 2nd ed.

Supplies for meteorology activities are sold by Home Science Tools (homesciencetools.com). Some good books showing how to do meteorology experiments are:

Storm Dunlop, *Guide to Weather Forecasting*

Mary Kay Carson, *Weather Projects for Young Scientists*

Brian Cosgrove, *DK Eyewitness Weather*

Meteorite Market (www.meteoritemarket.com) sells genuine and affordable fragments of meteorites that have been found worldwide.

For practical guides to astronomy activities with binoculars or a telescope, see:

Robert Bruce Thompson, *Illustrated Guide to Astronomical Wonders*

Terence Dickinson, *NightWatch* and *Backyard Astronomer's Guide*

Guy Consolmagno and Dan M. Davis, *Turn Left at Orion*

If you want to stargaze, it is easiest to start with binoculars. The larger the diameter of the objective lenses (the lenses on the opposite end of the binoculars from your eyes) is, the more light they will gather and the easier it is to see dim stars. A magnification of 8–10x is good—less is disappointing and more is too difficult to hold steady with your hands. Buy a round rotating star map (available from homesciencetools.com, telescope.com, or other dealers) and learn your way around the sky. Countless dealers sell cheap, poor-quality binoculars. You can buy binoculars of good quality from reputable dealers such as telescope.com (Orion), celestron.com, homesciencetools.com, and opticsplanet.com.

If you love stargazing with binoculars and still want more magnification, *then* buy a telescope. If you would like to buy a telescope, here are some of the most important considerations:

- Telescopes that are designed to be used for astronomy have an eyepiece that comes out at an angle of 90^o relative to the main tube of the telescope, making is possible to look into the eyepiece even when the telescope is pointed straight up. Telescopes designed for non-astronomical applications like bird watching usually have an eyepiece that is parallel or at a 45^o angle relative to the telescope tube, which makes it much more difficult to aim them upward at the stars.

- In selecting a telescope, get the largest tube (objective lens/mirror) diameter you can afford; the actual magnification is less important (and is often overhyped by sellers).

- Refractor telescopes use glass lenses, making them rather heavy and long but rugged. Reflector telescopes use curved mirrors, so they are lighter yet easier to get out of optical alignment. There are several types of hybrid (catadioptric) mirror/lens telescope designs that are the best of both worlds but tend to be rather expensive.

- A telescope tripod with an altazimuth mount is much easier to aim in general, yet is not straightforward to adjust for the Earth's rotation as stars steadily shift across the sky as the minutes go by. An equatorial mount is harder to set up and aim initially each night, but then can be easily adjusted for the Earth's rotation.

- Lots of dealers sell cheap, poor-quality telescopes. You can buy telescopes of good quality from reputable dealers such as telescope.com (Orion), celestron.com, homesciencetools.com, and opticsplanet.com.

F. Engineering experiments

For detailed books on different topics within engineering and applied physics, see pp. 972–983.

Model rockets can be a highly entertaining way to learn engineering, physics, and math skills. Model rocket kits and launching supplies are available from Estes (estesrockets.com) and other companies online. Some good books that offer advice on rocket construction and also discuss some of the relevant science and math are:

G. Harry Stine and Bill Stine, *Handbook of Model Rocketry*

Mike Westerfield, *Make: Rockets: Down to Earth Rocket Science*

Elenco (www.elenco.com) makes and sells a wide variety of very educational and fun electronics and robotics kits. Their kits are also available from many other online dealers.

With kits featuring either Arduino or Raspberry Pi computer chips (available from various online dealers), you can build and program your own computer, and even use it to control anything from your room lights to a custom-built robot.

K'NEX sets can be used to build everything from simple supported bridges to surprisingly large and sophisticated machines. Especially look for the Big Ball Factory or other large advanced sets.

Lego Technic kits are a great way to build and learn about mechanical engineering systems with complex gear trains and other features.

Similarly, Lego Mindstorms kits are a fun way to explore robotics and computer programming.

The engineering construction sets marketed under the names or either Meccano or Erector Set (sold by various online dealers) are also a great way to learn engineering skills by building systems of increasing size and mechanical complexity.

Some good books on simple engineering experiments are:

Rudolf F. Graf, *Safe and Simple Electrical Experiments*

Mario Salvadori, *The Art of Construction*

1.2.4.2 Self-Directed Experiments

After you have gained experience doing science experiments by following specific directions, you can start to get more creative with your experiments. This is a great intermediate step between first doing prepackaged experiments exactly as directed and later conducting completely independent, novel research. As with any student activities, always make sure you have adult supervision, use proper personal protective equipment, and stay safe.

A good way to start doing more creative experiments is to think up and try variations on experiments that were described in a science kit's directions. What happens if you make one change but do everything else the same? What happens if you make a different change instead of that one, or a further change in addition to that one? What happens if you combine methods or materials from two or more different experiments from the directions?

Always think before you try something, in order to stay safe and to make the best use of your science supplies and money. For example, connecting a 1.5-volt lightbulb to a 9-volt battery is an interesting experiment, yet perhaps not sufficiently interesting to justify the cost of buying a replacement bulb. Similarly, dumping all of your chemicals together may be not only quite dangerous, but also a waste of chemicals that you could have used in much more enlightening ways for many future experiments.

Also think before you try something, in terms of trying to predict what will happen. Making predictions, or scientific hypotheses, helps to guide your work toward experiments that are more likely to have interesting results. If your prediction or hypothesis proves correct when you compare it with the actual experimental results, that can show that you correctly understood the scientific principles involved. If your hypothesis does not prove correct, the surprising results can help you to rethink your ideas and develop a better understanding of the relevant scientific principles.

Professional scientists keep notes about their experiments in a lab notebook and/or in computer files. You should start to keep notes too. Write down or type up the date you tried something, what you tried (at least enough information for you to reconstruct it in the future), and what happened. Make your notes while you are doing your experiment or immediately after; if you wait several days before making notes, you may not remember all the details, or you may entirely forget to make the notes. Make and save photographs of your experimental setup and/or results if that helps to simplify or supplement your notes. Keep your notes from different experiments all in the same place—the same notebook, the same three-ring binder, or the same computer.

Your lab notes are for your own benefit, so you can remember what you have tried previously when you are planning future experiments. You should choose whatever method of making notes, and whatever level of detail of the notes, you are most comfortable with. Your notes do not have to be a meticulous diary, unless that is what you really want. Your note-taking methods and level of detail will also depend very much on your age, interests, and other factors.

Above all, science experiments should be fun! Make hypotheses and take notes as much as is consistent with having fun. However, do not let yourself feel so burdened by hypotheses and notes that you cease to have much fun, or else you may give up on science and opt for non-scientific activities and careers that seem more interesting. Having skimpy notes and hypotheses is better than charging through experiments without any notes or hypotheses at all, or giving up doing any experiments because making detailed notes and hypotheses feels like an unpleasant burden.

Whether they are young or old, scientists should not be reckless, yet they also should not be perfectionists, or else they may never begin something, and certainly may never complete it. Science is all about plunging ahead and having fun, while always using your brain along the way.

1.2.4.3 Written and Oral Presentations

Future creators should become very proficient at both (A) written presentations and (B) oral presentations. In a scientific career, presentations of both types can be very important for obtaining financial or political support for your planned research, and also for reporting and publicizing the interim or final results of your research. Ideally future creators should learn and practice their skills at written and oral presentations from elementary school onward, with progressively more challenging and more sophisticated presentations.

Throughout your career, present your research in such a way that it will be comprehensible to scientists outside that particular field and also to non-scientists. Along the way, actively maximize your interactions with scientists in other fields in a variety of environments, in order to cross-pollinate ideas.

If at all possible, include photos of experimental equipment, results, prototypes, etc. in your written and oral presentations, or perhaps even bring them to show alongside your written and oral presentations.

A. Written presentations

If you pursue a scientific career (or any of many non-scientific careers), it is very important to be able to write well. You should always do your best to make sure the final version of what you write does not contain any misspelled words; do not rely on the autocorrect or spellcheck functions of your computer to do that for you, since the computer may autocorrect to a different word than you intended or miss instances where you used the wrong word but spelled it correctly. Likewise, always do your best to ensure that your sentences are grammatically correct and that they flow smoothly for the reader, and do not trust the computer to take care of that for you. Finally, make sure your writing is well organized, with a clear topic for each paragraph, and clear and logically ordered roles for the paragraphs in explaining the main point of your paper. For more detailed advice, see Strunk and White's *The Elements of Style* [Strunk and White 2000].

Most scientific documents must be written according to a very specific format and length limit, and the details of those requirements vary greatly depending on the type of document and the intended recipient of the document. Make certain you fully understand those formatting requirements before you start writing, and be sure you obey all of the requirements in your final document. Some major categories of scientific documents that you will probably need to write—anywhere from middle school science fairs to the end of your professional career—include:

- An abstract, which must fit within a specified, very limited number of words or characters yet must summarize the essential points you need to convey.

- A proposal to a research sponsor or organization, generally within a very rigid format specified by that sponsor or organization, which should explain your proposed research topic and the specific experiments you would like to conduct as clearly and as persuasively as possible.

- Specialized paperwork, with content and format specifically requested by an organization or a sponsor, for approval of safety, financial details, or other aspects of a research project.

- An interim or progress report on a research project for an organization or sponsor, conforming to length and format standards requested by that organization or sponsor. The interim report should clearly explain what you have accomplished so far, and how you plan to complete the rest of the project.

- A final report or university thesis, which usually does not have a length limit, and often does have considerable flexibility in just how you format it, yet should be as complete, detailed, rigorous, and flawless as possible.

- A journal article, which must be written within the length limit and particular formatting requirements of the journal to which you will submit it. Different journals have very different length and format requirements, so make sure you study them very closely. (For more information, see Section 1.2.3.2.)

- A patent application, which requires your scientific knowledge to describe your new invention, yet also requires detailed legal knowledge to write it in such a way as to maximize its chances of being accepted and providing as much legal protection as possible. Therefore most patent applications are written by specialized patent lawyers and filled with lots of legalese language, but are based on draft scientific sections that were written earlier by the inventor. (For more information, see Section 1.2.3.3.)

Whatever type of scientific document you are writing, you should be as clear, as concise, and as accurate as possible. Always keep in mind the specific audience that will be reading your document. Do not skip over anything relevant they would not know without explaining it, yet also try not to bore them with things they would already know, if that can be skipped or simply cited as a reference.

Unless otherwise specified, almost any type of scientific document from a brief abstract to a huge final report should cover all aspects of your research project, with an appropriate fraction of the document devoted to each major aspect such as:

1. The main objective of your project.

2. Why accomplishing that main objective would be useful or important.

3. Any major relevant work has been done by you or others previously, and how your current project differs from that earlier work.

4. The experiments, calculations, or other specific work that you plan to do, are doing, or have done for your project. If possible, include lots of diagrams, tables, graphs, photographs, etc.

5. What you expect or expected the results of that work would be.

6. The results you actually got from that work, if it partially or fully complete.

7. What you have learned from your results, and how they impact your main objective and its broader implications.

8. Any further related work that you would like to do, are doing, or recommend that others do.

9. Major references you used during your project, including books, articles, online information, interviews with experts, etc.

10. Acknowledgments for people or organizations that helped, hosted, or funded your work.

Get several people to read over your scientific document before you submit it. Wherever possible, try to get people who are native speakers of the language used in the document, and who have some knowledge of the scientific area covered in the document. They may catch typos or scientific errors you missed, or they may have suggestions about portions that need to be organized differently or explained more clearly. Even if you have pored over your own writing many times, it is easy for your mind to think you are seeing what you intended to write on the page, not some typo or other error that may actually be on the page.

B. Oral presentations

Oral scientific presentations almost always have visual aids, since any verbal description must usually be accompanied by diagrams, photos, equations, graphs, or other information that is easier to see than to hear. Oral presentations may be categorized by the format in which the visual information is shown:

- Slide presentations, generally given once, at a scheduled time, to anything from a small conference room or classroom to a large ballroom of people. Many school and work presentations, and some conference presentations, are given in this format.

- Poster presentations, usually given repeatedly, upon demand, to individual or small groups of people who come by within a specified time window. The visual aid may be one large poster or a group of several smaller posters (sometimes matted to enhance their visual appeal). Most science fair projects and many conference presentations are displayed in this format.

- Whiteboard, blackboard, or "chalk talks," generally a much more informal and far more interactive way for scientists to collaborate in real-time brainstorming, or for teachers to see how well students can think on their feet in solving problems.

There are some general good practices to follow regardless of which oral presentation format you are using.

Prepare your slides, poster, or notes for your "chalk talk" well in advance, and do your best to make them flawless.

Rehearse your presentation many times, both privately and with any friends, family members, or scientific colleagues you can round up.

If you use slides or a poster, make sure their contents are sufficiently clearly explained and self-contained that someone could understand their major points even if you were not there. Include lots of diagrams, tables, graphs, photos, etc.

Know who your audience will be and design your presentation accordingly; do not bore them with things they already know, or omit things they will want to hear about or have you explain.

Do your best to anticipate the sorts of questions that your audience is most likely to ask, and plan and practice how you can best answer those questions.

Most presentations have an assigned time limit. Make sure you stay well within that, including allowing plenty of time to answer questions. Practicing your presentation repeatedly in advance should guarantee that you know how long it will take. If a slide presentation does not have an assigned time limit, bear in mind that many audience members will start to zone out after 20 minutes or so, and plan to say everything you really want to say within than 20 minutes. The duration of a poster presentation will be highly dependent on the level of interest and background knowledge of the people who come up to your poster. In your advance preparations, plan and practice a few-minute talk you could use to give the most important points to someone who is less interested, and a longer version you could give to someone who wants to hear more of the details.

It can be difficult to remember all the details you want to include in your oral presentation. Make sure those details, or at least specific cues to help you remember them, are written down in your slides or your poster; use the slides or poster as a guide or an outline to help you through the presentation. Bring notes you can refer to during a "chalk talk," but try not to bring notes to a slide or poster presentation.

Be sure you periodically make eye contact with various members of your audience throughout the talk, and make certain they can hear you throughout the talk (do not turn your back to your audience or turn your head away from your microphone, if you are using a microphone). In order to better connect with your audience and to keep them awake, I highly recommend sprinkling a few planned jokes throughout the presentation, provided you feel comfortable doing that and they are not forced, corny, or tasteless.

It is quite common to have stage fright or other fears about giving oral presentations. Part of the solution for that is to prepare as thoroughly as possible in advance. The other part of the solution is to completely change how you view the presentation—it is not a painful experience to be endured, but rather quite the opposite. Rock stars love performing in front of all of their fans who understand and appreciate their music. Most science nerds do not encounter many fans or much adulation in everyday life. Giving an oral presentation is a rare opportunity to bask in the glow of an audience that finally truly understands and appreciates both you and your work, even if most of the world does not. Enjoy your few minutes as a rock star as much as you possibly can!

If people ask questions or make comments about your presentation, always be very polite in how you respond, and alway try to answer as carefully and as accurately as you can. Your goal is to win over as many people as possible. If someone believes they have spotted an error in your work or suggests a better way to do the same thing, consider what they say very carefully. Perhaps you are right and can easily demonstrate that your project is entirely correct. However, it is always possible that someone could find something important that you overlooked. If that happens, make sure you thank the person, graciously acknowledge the error, and use that information to improve your project and your presentation in the future.

1.2.4.4 Systems Analysis and Brainstorming

The most critical aspect of revolutionary innovation is finding the best problem, and the best potential solution for that problem, on which to work. Perhaps you are eager to find a good problem but cannot think of one, or maybe you know of a good problem but cannot think of a possible solution for it. Or perhaps a particular problem or a particular solution may catch your fancy, or may be urged upon you by a mentor, employer, or sponsor. Yet before you (and your mentor/employer/sponsor) devote all of your time, energy, and resources to a specific project, potentially for many years, you should ensure that you are choosing the most promising path.

Systems analysis is a rigorous, top-down method of finding the best problems and solutions. It was widely taught and utilized in the greater German-speaking scientific world ∼1800–1945[2] and practiced in certain U.S. military scientific circles ∼1940–1970[3], yet unfortunately it does not seem to be well known or exploited nowadays. Top-down systems analysis can be directly complemented by bottom-up brainstorming.

This section explains the basic steps that are involved in:

A. Top-down systems analysis for problems

B. Top-down systems analysis for solutions

C. Bottom-up brainstorming for problems and solutions

Figure 1.3 shows a simplified graphical representation of systems analysis and brainstorming.

[2] The general practice of systems analysis from the German-speaking world was later most clearly articulated in English by Theodore von Kármán [Daso 1997] and Fritz Zwicky [Zwicky 1969].

[3] For example by government-funded think tanks such as the Institute for Defense Analyses [IDA, Finkbeiner 2006], JASON advisory group [Finkbeiner 2006], MIT Lincoln Laboratory [Grometstein 2011], MITRE Corporation [Shearman 2008], RAND Corporation [Jardini 2013; Kaplan 1991], and The Analytic Sciences Corporation [TASC, www.fundinguniverse.com/company-histories/analytic-sciences-corporation-history].

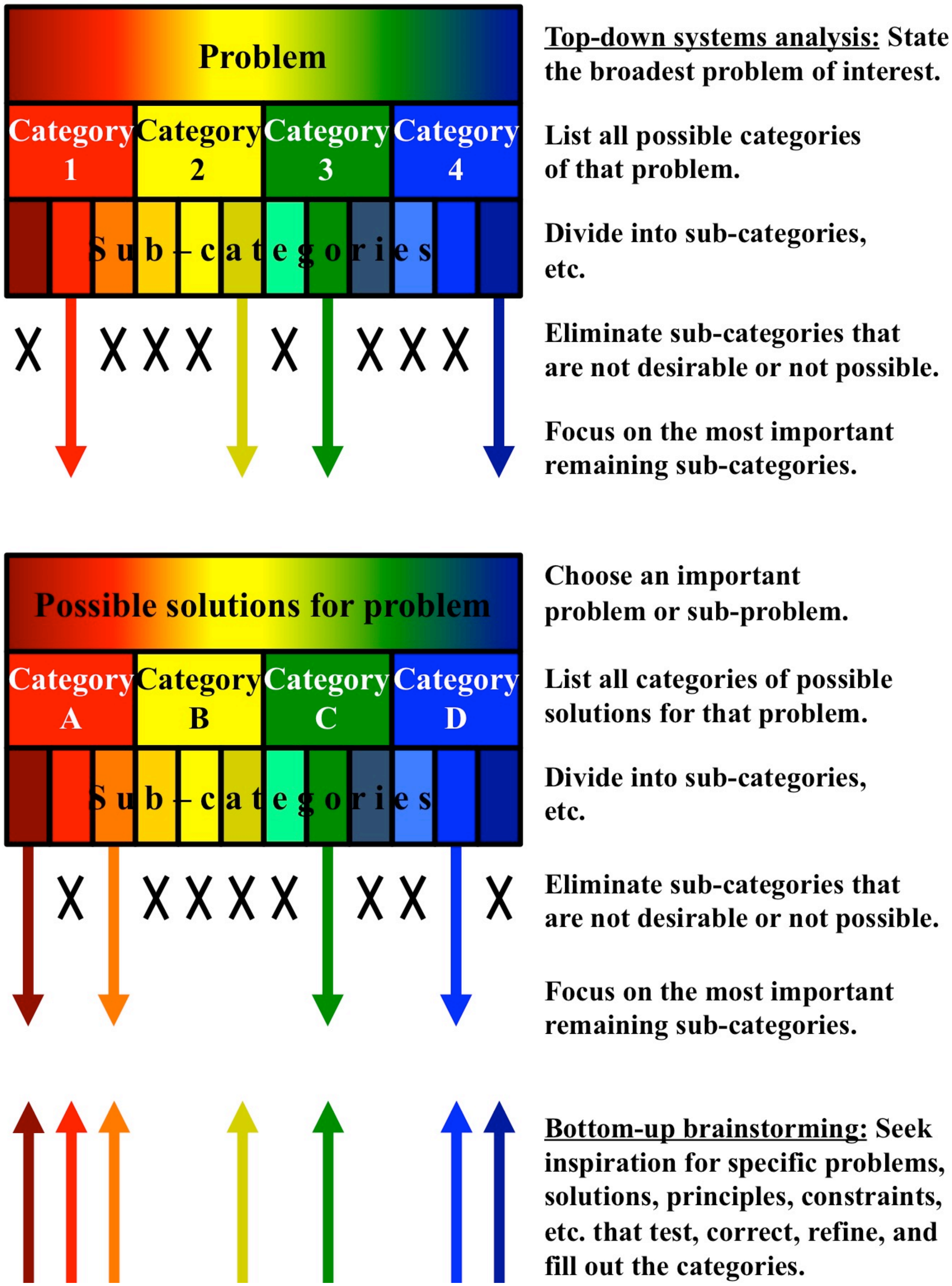

Figure 1.3: In top-down systems analysis, one methodically considers all possible categories of problems of interest, and all possible categories of solutions to those problems, in order to identify and focus on the most promising solutions for the most important problems. That is complemented by bottom-up brainstorming, in which one seeks inspiration for specific problems, solutions, principles, constraints, etc. that will test, correct, refine, and fill out the categories.

A. Top-down systems analysis for problems

The first half of system analysis involves methodically searching for the best specific problem(s) to try to solve:

- The first step is to state the broadest possible problem of interest to you, and to define it as clearly and succinctly as possible. Just as examples, that problem might be solving global warming, or curing cancer, or winning next year's science fair, or launching your career, or addressing a specific area requested by your mentor/employer/sponsor.

- For the specific problem you just stated, list all possible categories of the problem. To continue with the examples above, those might be different general causes and/or effects of global warming, or different general causes or types of cancer, or different general categories of possible science fair projects of interest to you, or different general categories of research problems for which you have suitable abilities and resources, or different general categories of problems that would interest your mentor/employer/sponsor. Try to make the categories:

  - As general as possible.

  - As non-overlapping as possible. If some overlap is unavoidable, at least clearly define the ways in which multiple categories can overlap or combine.

  - As complete as possible, such that any possible problem satisfying the broad statement of the first step would fall within one (or more) of these general categories.

  - Without regard to any theoretical or practical constraints, at least at first. At this stage, do not rule out any categories, no matter how impossible, impractical, or even undesirable they may seem. Consider everything and list everything to be as exhaustive as possible.

  - As insightful as possible, with regard to how they subdivide the overarching problem. For example, for categories under global warming, would it be more useful to define the problem in terms of different categories of causes of global warming, different categories of effects of global warming, or some completely different set of categories? Imagine that the general problem is an apartment building that you must search visually from the outside. It might be more fruitful to peer into the building from the windows on one side (divide the problem into "apartments" as they appear from that side), or to peer in from the windows on a different side of the building, or to look down at the apartments from above, or to look up from below, or even to employ multiple views or methods of categorization (creating an array of categories in two, three, or even more dimensions).

- After you choose a set of categories and work on the problem for a while, you should be prepared to revisit your categories if necessary to find a different set of categories that better help to analyze the problem. In quantum physics, that is called "re-diagonalizing the matrix"—choosing a different set of orthogonal coordinates or solutions if your initial choices turn out to be too distorted to solve the problem.

- For each of those categories, list all possible sub-categories of problems. Again, try to be as general, as non-overlapping, and as complete as possible. As before, choose the most helpful way to divide up the sub-categories, and be prepared to revisit that decision later if necessary.

- For each sub-category, list all possible sub-sub-categories, and continue to break the problem down into smaller and smaller pieces until you have gotten down to the lowest level that is still meaningful to you. Depending on your problem, your interest, and your resources, that may be only one layer of broad categories, or ten layers deep of sub-sub-sub-categories.

- The objective of this whole approach is not to be bewildered by a zillion possibilities, but rather to search them methodically and narrow your focus to the best ones. Once you have defined as many categories and sub-categories as you can or as you want, eliminate all of those that are not desirable or are not possible:

  - Some categories of problems may be topics that you or your mentor/employer/sponsor are simply unwilling to pursue.

  - Some categories of problems may cause more harm than good if investigated.

  - Some categories of problems may not be possible to address with your skills and resources.

  - Some categories may violate fundamental scientific principles (e.g., conservation laws, the second law of thermodynamics, quantum uncertainly principles, etc.).

  - By doing background research, you may find that some categories already have been tried unsuccessfully in the past.

  - From background research, you may find that some categories already have so many good scientists working on so many good ideas within that category that you could make a more important contribution to some other category or some other problem.

- Try to find irrefutable reasons to rule out whole categories first. Then for those categories that cannot be ruled out, try to find compelling reasons to rule out some of their sub-categories. If necessary, next consider sub-sub-categories and then even further down.

- Hopefully the preceding analysis has identified several categories or sub-categories of problems that are worth pursuing. If it identified too many for you to pursue them all, prioritize them based on your interests or resources and then focus on the highest priority problem categories or sub-categories.

- If possible, do not narrow your final focus to just one category or sub-category of problems, but rather try to choose two or more. If you have the resources to pursue multiple problems in parallel, you may ultimately succeed with one problem even if you encounter unforeseen obstacles with another problem. Even if you only have the resources to actively pursue one problem, keep the runners-up in the back of your mind, in case circumstances force you to switch to a different problem later. Make sure you have carefully considered the possible problems before committing to focusing on the one or the few problems that you think are best. Revisit your decision from time to time to verify that you are still on the best path.

B. Top-down systems analysis for solutions

The second half of system analysis involves methodically searching for the best solution(s) to the identified problem. The process parallels that of the first half:

- The first step is to state the particular problem or category/sub-category of problems to which you would like to find solutions.

- For that problem, list all possible categories of solutions. As with the earlier analysis, try to be as general, as non-overlapping, and as complete as possible. As before, choose the most helpful way to divide up the categories, and be prepared to revisit that decision later if necessary. At this stage, do not rule out any categories, no matter how impossible, impractical, or even undesirable they may seem. Consider everything and list everything to be as exhaustive as possible.

- For each of those categories, list all possible sub-categories of solutions, then all possible sub-sub-categories, and continue to break the problem down into smaller and smaller pieces until you have gotten down to the lowest level that is still meaningful to you. Depending on your problem, your interest, and your resources, that may be only one layer of broad categories, or ten layers deep of sub-sub-sub-categories.

- As before, once you have defined as many categories and sub-categories as you can or as you want, eliminate those that are not desirable or are not possible. Some categories of possible solutions may violate fundamental scientific principles, exceed the available resources, do more harm than good, etc. Try to find irrefutable reasons to rule out whole categories first. Then for those categories that cannot be ruled out, try to find compelling reasons to rule out some of their sub-categories. If necessary, next consider sub-sub-categories and then even further down.

- Hopefully this analysis identifies several categories or sub-categories of solutions that are worth pursuing. If it identified too many, prioritize them based on the probability of success and other considerations, and focus on the most important solutions.

- As before, if at all possible, do not narrow your final focus to just one category or sub-category of solutions, but try to choose two or more. If you have the resources to pursue multiple solutions in parallel, you may ultimately succeed with one solution even if you encounter unforeseen obstacles with another. Even if you only have the resources to actively pursue one solution, keep the runners-up in the back of your mind, in case circumstances force you to switch to a different solution later. Make sure you have carefully considered the possible solutions before committing to focusing on the one or the few solutions that you think are best. Revisit your decision from time to time to verify that you are still on the best path.

- Systems analysis can yield very different results for different problems:

  - For some problems and solutions, the system analysis may quickly branch out to many viable alternatives, and it may not be necessary or possible to consider many levels of subcategories.

  - For other problems, so many categories of solutions may be completely ruled out (as impossible, impractical, or undesirable) that you may decide it would be a more productive use of your time to choose an entirely different problem and start over.

  - For some problems and solutions, there may be relatively few categories, sub-categories, and branches, and it may be possible to follow a fairly linear, logical trail from the initial problem to the final solution, with only a few caveats about alternate paths not taken along the way.

C. Bottom-up brainstorming for problems and solutions

In contrast to top-down systems analysis, another approach is bottom-up brainstorming. A spontaneous thought, a random connection of two ideas, or something you see or hear may give you a specific new problem, or a specific new potential solution for a problem, without any rigorous analysis or derivation—like the alleged bathtub "eureka" moment of Archimedes.

Some scientists only rely on bottom-up brainstorming, and some only rely on top-down systems analysis. In practice, the best approach is probably to do both; the two approaches are nicely complementary.

To do bottom-up brainstorming, you should keep a careful lookout for new ideas at all times and in all places. As soon as you see them or think of them, write them down on paper or in an electronic device that you carry with you at all times. Do not worry about evaluating or screening out ideas initially—that can come later. Just write down absolutely everything. You might find new ideas from your daydreams, or from dreams at night, or from something you happen to hear, read, or see. Sometimes the ideas come to you unbidden, yet you can also actively seek them out. Borrow ideas from other fields, from nature, from history, from what has worked before, from science fiction, or elsewhere. Combine different ideas or different fields, or closely examine how different ideas or fields intersect, to find novel problems and/or novel solutions.

Sometimes you might find a useful new idea that is relevant not for the problem you were actually trying to solve, but rather for some other unrelated problem. Pursue those extra ideas to see where they might lead, if you happen to have them.

If you try very hard yet still cannot find suitable new ideas, do not push yourself or berate yourself. Just let the general topic percolate in the back of your mind for days, months, or even years, and see what may eventually pop up.

Whereas top-down systems analysis leads to general categories of problems or solutions, bottom-up brainstorming usually leads to very specific examples of problems or solutions. Sometimes it provides flashes of insight about ways to prove or disprove certain ideas or categories. Thus systems analysis and brainstorming can be highly complementary, for example in the following ways:

- If you have an initial bottom-up brainstorming idea, top-down systems analysis can then broaden that individual initial idea into a whole category of related ideas, some of which might be even better than the initial idea.

- Conducting a systems analysis first can suggest categories in which it would be profitable to then brainstorm for specific ideas.

- Similarly, systems analysis can rule out categories in which it is not worth brainstorming for ideas, if you can prove on fundamental principles that any ideas falling within that category would automatically be impossible, impractical, or undesirable.

- If you take a general systems analysis category and then brainstorm, you can fill out that category with very specific ideas that can be implemented.

- Brainstorming may yield an idea that turns out to be in a category that had been previously overlooked by systems analysis, or incorrectly ruled out by systems analysis, showing that the initial systems analysis needs to be revised and improved.

- Brainstorming may result in specific ideas for how to test or disprove the fundamental scientific feasibility of a general category.

- Brainstorming may show that it would be more fruitful for systems analysis to divide up the problems or solutions using some other set of categories (as with the earlier analogy of searching an apartment building from different sides, or "re-diagonalizing the matrix").

The above methods of top-down systems analysis and bottom-up brainstorming are applied to a wide range of scientific areas in Chapters 2–11 and Appendices A–E. Those chapters and appendices should serve to further illustrate these general methods.

1.2.4.5 Original Research Projects

Original research projects may be conducted for anything from a middle school or high school science fair, to an independent research project or thesis at a university, to a short- or long-term project during your professional career. Ideally, future creators should do all of those things, gaining more experience, proficiency, and success with each project from youth to adulthood. Even if you ultimately choose a different career path, such projects teach many useful skills (planning projects and schedules, working independently and collaboratively, giving written and oral presentations, etc.) that are useful in many careers.

A well-conducted original research project should draw upon virtually all of the skills you have learned up to that point, as covered in other sections of this chapter. This section offers some advice on:

A. Selecting your research project

B. Conducting your research project

C. Presenting your research project

A. Selecting your research project

The most critical step of an original research project is coming up with a good problem and good potential solution for that problem that you can pursue. You should use both top-down systems analysis and bottom-up brainstorming (Section 1.2.4.4) to find the best topic. Search as long and as broadly for ideas as you can before you have to decide. You may find inspiration from the chapters and appendices of this book, science news stories, science fiction, real life experiences you have, people you talk to, or other sources.

Also consider your own unique interests and hobbies as you search for a good topic. They may lead you to a project that no one else would discover, or at the very least you may find a research project even more enjoyable if it overlaps with some of your other interests. For instance, I once met a student who loved to sew, decided to do an independent research project on which types of stitches are best for applications such as parachutes and automobile air bags, and ended up winning the top prize at a national science fair. As another example, I saw another student who loved to volunteer at an animal shelter and was inspired by that to develop a DNA test to determine how allergenic certain animals were, so that more animals could be adopted even by people who had allergies.

Make a list of project ideas as you think of them, don't rule anything out initially, and then finally evaluate all of your ideas to choose the best one to pursue. The project that you ultimately choose should be:

- Original. Make sure you are not knowingly or unknowingly simply rehashing a project that someone has already done before. Conduct background research in the scientific literature (see part B below and also Sections 1.2.3.1 1.2.3.2, and 1.2.3.3) to verify that no one has previously accomplished what you are proposing to do, and just as importantly that no one has proven that what you are proposing is impossible for sound scientific reasons, or has found a much better alternative way to do. It is certainly acceptable to try variations, extensions, or new combinations of what others have done previously, but try to be as creative as possible, both in your new spin on the ideas and in how far you advance the state of the research field.

- Yours. Closely related to the first point, the project should be your own idea, not a ready-made project given to you by a parent, teacher, professor, employer, or other person. It is certainly okay and even highly recommended to seek advice from other people on various scientific areas or on specific possible projects you are considering, but ultimately the project should be your idea and your choice. (At some points during your education and your career, you may have no choice but to take on a specific project. Whenever possible, though, try to propose a project of your own choosing that will satisfy your school or employer, or at least try to find ways to put your own creative spin on a project that someone else assigns to you.)

- Doable. *You* should be able to carry out the necessary designs, experiments, calculations, tests, construction, or demonstrations with the resources, skills, and time you have available. If you cannot, pick a different project that you can do.

- Approvable. You should also be able to get any necessary approvals from The Powers That Be (parents, school, employer, sponsor, safety committee, etc.) to pursue the project. Again, if you cannot, choose a different project.

- Important or useful. Before you sink a great deal of your time, energy, and resources into a project, make sure it is something that will have as much impact as possible if you are successful.

- Enjoyable. Choose a project topic that you truly like, because you will be spending a great deal of time and energy on the project. If you find the topic uninteresting or unenjoyable before you even start, you will be absolutely miserable during the project, and you will probably not do a good job either.

- Not over-crowded. Choose a problem and/or solution that does not already have a lot of talented people hard at work on the case. If they are already working on it, they will probably succeed before you do, or they would probably do just fine without you. Find a neglected but promising topic where your ideas and your hard work will make much more of a difference.

Boil your project idea down to a specific objective that you can clearly state. For a pure science project, that will generally be a hypothesis; the goal of the project will be to prove or disprove that something happens or why it happens. For an applied science or engineering project, the goal will usually be to see if you can create something that will successfully perform a specific task, or at least make major, measurable progress toward creating something suitable. It is okay if your project idea is nebulous at first, but do not let it remain that way, or else you will have difficulty making concrete progress toward it, determining that you cannot make concrete progress toward it, or convincing others that your results are real and meaningful.

In an attempt to follow this scientific method in the most literal and simple-minded way possible, far too many science fair projects and even academic research projects are reduced to the level of simply testing the effect of X (light, water, antibiotics, music, a fancy chemical, etc.) on Y (plants, insects, bacteria, worms, an exotic cell line, etc.). Yes, science does involve measuring reproducible effects, yet it is much richer than that. Albert Einstein's research was not simply "the effect of speed on time," and Rosalind Franklin's research was not just "the effect of DNA on X-rays"—their research had so much more meaning than that, and other truly productive science research, including your research, should as well. Do *not* do a research project that is simply "the effect of X on Y"; you will be bored out of your mind by the project, and everyone else will be too. "The effect of X on Y" is frequently a necessary part, but almost never a sufficient whole, of a good research project.

B. Conducting your research project

If you are doing a middle school or high school science fair project, make sure that you the student are the one coming up with the ideas and doing all the work from the beginning of the project to the end. You should certainly have proper adult supervision from parents and teachers to make sure what you are doing is safe and is not a scientific wild goose chase, and you can seek out advice from adults on your ideas or other aspects of the project. However, parents, teachers, or other adults should not propose the main ideas, make the decisions, or do the work for you, no matter how eager they may be to do so. One cannot train a young aspiring Olympic ice skater by doing their ice skating for them—that would be counterproductive.

Also avoid doing science fair project research in a university or company laboratory where you are handed a particular experiment and told exactly what to do. The resulting science fair projects can sound very impressive and unfortunately often win awards, but that experience may only teach you how to be a trained monkey. You will gain far greater skill at being a revolutionary scientific innovator, and you will create far more revolutionary scientific innovations, if you develop and carry out your own project and experiments from scratch. (For more information, see Sections 1.2.4.1 and 1.2.4.2.) Your equipment may be much less sophisticated, but it will all be yours, and you will know your scientific topic inside out and back again. Don't just take my word for it though—see p. 173.

In one state high school science fair that I helped to judge, the largest and most detailed display came from a student who had tested some obscure, complicated chemical on some specialized type of cultured animal cells in a professor's university lab. Obviously that is not the sort of thing that would ever even occur to a student working independently; it demonstrated zero creativity and initiative, and it did not even have much meaning or use. I was far more impressed by another, smaller, simpler display at that science fair. That student had independently conceived, implemented, and demonstrated an idea to coat small adhesive bandages with a chemical that changed color in the presence of glucose, so that people who were diabetic but did not realize that could find out just from treating common scratches in daily life. She was the real scientist.

As you are considering which project to choose from your list of possible ideas, and even after you have begun work on a particular project, conduct as much background research in the scientific literature as possible. As already noted, you do not want to waste time pursuing a project if someone else has already done it, proven that it cannot be done, or found a much better alternative approach. Even if no one has done your specific research project, information from related research can help you plan how best to conduct your own project. Search for and obtain information from relevant books, encyclopedias, journal articles, other periodicals, patents, the internet (be careful to distinguish reliable vs. unreliable sources and information), and people with suitable expertise. For more detailed advice on scientific references, see Sections 1.2.3.1, 1.2.3.2, and 1.2.3.3. Keep detailed files, notes, or copies of all references, all in one place (either electronic or on paper). You will need to be able to quickly refer back to that information when you write your research proposals, reports, and papers.

If your project builds directly or indirectly on someone else's work, check that work very thoroughly before you begin your project. That policy not only will help you fully understand the research, but may also lead to your discovering important flaws in their previous work that could greatly harm your work if not corrected first. (I have encountered this problem numerous times in my own research career. It pays to be paranoid!) Even—or especially—if someone else assigns a specific project to you for a thesis or a job, check all of their work and assumptions first before you begin.

Find out what safety, financial, institutional, or other legal approvals you need to obtain *before* you begin any work. Make sure you do all of them, as well as any further paperwork or future renewals of the approvals. You do not want to do a great deal of work and then later find that all of it is rejected by a science fair or a journal because you did not submit the right form earlier.

Keep notes from the very beginning of your project (or even earlier, when you are considering various projects) to the very end. Those notes may be in the form of one bound notebook, a three-ring binder that you put handwritten sheets and printouts into as you generate them, or a computer folder with organized files on your ideas and experiments. Sometimes a science fair, school, or employer may have very specific requirements for the format in which you make and store your notes, but if not, choose whatever method feels most comfortable and helpful for you. Record your ideas, calculations, plans for experiments, results of experiments, and other work. Include copies of any diagrams, photos, graphs, printouts, or other materials that are produced along the way. Do not feel obligated to go into so much detail that the lab notes become a chore that you neglect, yet do record enough information that you can later reconstruct exactly what you did when you write a final report, journal article, patent, etc. In some cases, other people may need to be able to read your lab notes later—especially in situations such as science fair competitions, patent disputes, or reviews of your work by your teachers or employers.

Also at the very beginning of your project (or even before you commit to that particular project), use top-down systems analysis and bottom-up brainstorming (Section 1.2.4.4) to list as many as possible of the different aspects of your project or idea that you could investigate. For each of those, list as many as possible of the specific methods you could use to investigate that aspect of the project or idea. Depending on your particular topic, methods might include doing theoretical calculations, creating and running computer simulations, conducting experiments, making measurements, building prototypes, trying certain things to see if they work or to see what happens, etc.

Out of all possible aspects and methods of investigation that you have listed, focus on those that are most critical for demonstrating whether or not the fundamental project topic is truly feasible and worthwhile. If your project is to create a faster-than-light spaceship, you should be focusing most of your effort on determining whether or not its faster-than-light propulsion method will actually work, not on determining what is the best color to paint the spaceship. While that principle seems obvious, far too many real research projects expend their resources focusing on peripheral issues and not the most important issues that will make or break the success of that project or approach. Of course, your available resources may limit which aspects of the project you can investigate, which methods you can use to investigate them, or how far you can carry your investigation. Within the constraints of your resources, focus on the most important aspects, and investigate those in as many ways as possible, advancing them as far as possible. If that work leads you to prove that the overall project goal (faster-than-light travel, etc.) is impossible, let the rest of the scientific world know that so they do not waste their time on it, and then move on to a different project. If your work instead proves that the overall project goal is feasible and removes the most important obstacle to that goal, you can then select the next most important issue and investigate that.

Along the way, generate and collect as many types of measurements and as much data as you can. Repeat each measurement several times, average the measurements, and think about sources of errors or variations. Make sure you include as many relevant positive and negative controls as possible. Analyze your results as many ways as you can. Make tables and graphs in whatever formats seem most enlightening for you and for those to whom you will be explaining your research. Always bear in mind the limitations that are imposed by experimental error and by any assumptions you have made. Show and discuss error bars and the scientific and mathematical details behind them.

Work as hard on your project as you can, as much as you can, for as long as you can. It can take up to a year to do a good science fair project. A university thesis project could require anywhere from one to several years. Some research projects are lifelong endeavors.

If possible, even work on multiple projects. Work on as many problems in parallel as you can without slowing down the projects. If you run into a roadblock or get tired of working on one problem, you can switch to another, and then come back.

For each problem, work on as many solutions in parallel as possible without slowing down the solutions. Pursuing several approaches in parallel greatly reduces the overall risk of failure. It also minimizes the time to get to a final working solution, instead of having to try several things in series before something finally works.

Finish up and leave a particular project, problem, or solution and move on to something else if:

- You run out of time, money, political support, ideas, supplies, or other essential resources.
- You encounter completely insurmountable scientific or non-scientific obstacles.
- You reach a point at which you have done most of what you can do (diminishing returns or apple polishing).
- Enough other talented people begin to work on it.

C. Presenting your research project

Periodically during your project, and certainly at the end of the project, stop to think about the the bottom line, the most important results and meaning, of everything you have done so far. Use the results of that introspection to convey the main points of your project to others, or to alter the course of your project if necessary.

Most science projects, including those done for science fairs, university theses, and work careers, usually involve giving both written and oral presentations. See Section 1.2.4.3 for advice on such presentations. Written and oral presentations are a vital opportunity to demonstrate to your teachers, professors, sponsors, employer, or scientific colleagues just how much you know and just how much you did, but always honestly and graciously acknowledge the contributions and assistance of anyone else who was involved in the project.

Some of the major science competitions for middle and/or high school students include:

- Broadcom MASTERS and lower-level science fairs that feed into it (grades 6–8, www.societyforscience.org/broadcom-masters/)
- International Science and Engineering Fair (ISEF) and lower-level science fairs that feed into it (grades 9–12, www.societyforscience.org/isef/)
- Science Talent Search (STS, submit the application in grade 12 but do your project in 11th grade!, www.societyforscience.org/regeneron-sts/)
- Lemelson InvenTeams (lemelson.mit.edu/inventeams)
- Junior Science and Humanities Symposia (www.jshs.org)
- Science Olympiad (www.soinc.org)
- Science Bowl (science.osti.gov/wdts/nsb)
- FIRST robotics competitions (www.usfirst.org)

If you are interested in entering student science competitions, read those websites in detail to find out which competitions you are eligible for, and exactly what rules you must obey in choosing, conducting, and submitting your project.

There are few if any science fair competitions for university-age students or older researchers. Submitting research to journals and conferences may be viewed in a similar fashion, yet it is not quite the same thing. If a person or organization were in a position to create a science fair competition for university-age students or older researchers to promote truly revolutionary scientific innovators and innovations, I would strongly encourage that.

1.2.5 Sources of Support

Future creators are not simply machines for producing new discoveries and inventions. They are human beings, and as such they need heathy relationships with other human beings, and proper support from other human beings, in order to be as happy and as productive as possible. Some of the most important sources of support for future creators are:

1. Family and partner/spouse
2. Friends and community
3. Teachers, professors, and mentors
4. Supportive schools
5. Supportive employers and sponsors

1.2.5.1 Family and Partner/Spouse

Family is the first and frequently the most important source of support for future creators. If you are raising a child who may be a future creator, please give them as much love and encouragement as possible. Help them have access to as many of the activities and resources mentioned elsewhere in this chapter as possible. However, please do not push a child toward becoming a future creator, or any other particular career. Ultimately people must choose for themselves what career they feel is best, and their drive to prepare for that career and to succeed in that career must come from within themselves.

If you are a future creator, never take for granted what your parents, grandparents, or other family members probably have done, are doing, and will do to help you succeed. Most parents and older family members sacrifice a great deal in order to help the children of the family as much as possible. Always let them know how much you appreciate how much they have done for you, and always do as much as you can to help them too.

As you grow older, the supportive family around you generally shifts from the family of your birth, about which you had no choice, to the family of your own creation—your spouse/partner, children if any, and so forth—about which you have every choice.

Most people, including most future creators, choose to find a spouse or partner rather than going through life alone. Some creators go through several spouses or partners, which is usually detrimental for the spouses/partners, the creator, and the creator's work. For the good of everyone involved, and for a future creator's maximum scientific productivity, I highly recommend:

- Choose your spouse/partner very wisely. Find someone with whom you are very compatible intellectually, emotionally, in terms of your interests, and in other ways; you should be able to share your soul with this person, and share their soul, and do it for life. Whatever other friends or family you have, your spouse should be someone who can and will always be your closest friend. Make sure they are truly good, mature, and wise deep down, and not just on their best behavior while you are getting to know them. Let them get to truly know you, your weaknesses as well as your strengths. Do not be in a rush to find a spouse/partner, and do not unnecessarily limit your selection in terms of geography, background, or other parameters. Jane Austen's wonderfully perceptive novels are great parables about the importance of marrying wisely—I highly recommend reading and learning from them.

- From before you select a spouse/partner until you die, know that your spouse/partner's career and desires are at least as important as your own, and act accordingly throughout your entire life. Discovering some new secret of the universe may be important, but it is less important than taking good care of this other piece of the universe that has completely entrusted itself to you. And remember that love is not a feeling; saying that you love someone means that you are committed to always taking care of them to the best of your ability—the feelings will take care of themselves.

That advice may sound old-fashioned or corny, and it may almost seem irrelevant if you see many people putting their careers first and treating other people poorly, yet if you follow this advice, things are much more likely to work out better in the long run than the alternatives would have.

If you are the spouse of a revolutionary innovator, certainly do help them however you can. Be very patient and understanding with what almost anyone else would probably consider a highly eccentric person who feels compelled to pursue esoteric interests with as much time and energy as possible. Make sure your creator spouse never forgets that they cannot help humanity with their creations if they are not part of humanity themselves, and help the creator stay connected through you, other family members, and friends. A sympathetic ear can mean everything to a creator, listening to the scientific and non-scientific obstacles that your spouse faces every day, even if you cannot offer specific advice. Perhaps this book might give you a better understanding of how your creator spouse may think and feel. Yet no matter how revolutionary your spouse's creations may be, your own needs, desires, and life are just as important as your spouse's; make sure your spouse always remembers that and does everything possible to help you even as you help your spouse.

If you have children, always bear in mind that they are just as important too. Give them all the time, love, and attention they need, grant them the freedom to choose whatever careers they feel are best for themselves, and support them however you can.

Some siblings or even cousins can be close confidants or supporters for part or all of your life. Take good care of the people who are around you, and in turn rely on their support if they are willing and able to offer it.

1.2.5.2 Friends and Community

It can be invaluable to have one or more close friends, someone other than a spouse or family member with whom you can very openly and comfortably discuss your struggles and triumphs. Due to the investment of time, energy, and trust required to build and maintain such friendships, it is generally practical only to have a very small number of such friends, at least at any given point in your life. Yet that is far more valuable than having large numbers of more casual friends whom you simply greet in the hallway or "like" online.

Becoming close friends usually requires a sufficient overlap in major interests, core beliefs, and in many cases experiences. It would be unrealistic to expect total unanimity unless you clone yourself, but good friends can focus on the areas that do overlap, and learn and be respectful in the areas that do not.

Because close friendships involve deep knowledge and trust about each other, they are often forged when people are together in close proximity for extended periods of time, especially going through the same or similar stressful experiences, such as school, military service, or a challenging work environment.

It also tends to be easier to create strong friendships earlier in life, when many people are likely to feel alone, vulnerable, and in need of new supportive relationships. Later in life, people are more likely to already have as many close friends as they need or have time for, or to have enough emotional support from their spouse or other family members, or simply to be too busy or too jaded to easily form new close friendships.

Close friendships should involve mutual need and support. Make sure you spend at least as much time asking about and listening to your friend's struggles and thoughts as you spend sharing your own with your friend. And do not do that merely as a formality—make certain that you truly care about what your friend is going through, and make sure your friend knows that. Ask questions about the things that matter most, and really listen to the answers, and then ask follow-up questions to probe more deeply, and listen some more. In some cases you might have similar experiences you can describe, or advice you can offer, but the most important service you can offer is always to be ready to really listen.

Some relationships may not involve equally bidirectional support. There may be some people whose sympathetic ear, advice, or support you need on occasion, but who do not need much equivalent support from you, if they already have enough support from others. Similarly, there may be people who sometimes need you to offer a sympathetic ear or advice or support, yet who are unable or unwilling to offer you much in return. Those types of relationships are perfectly normal and healthy as long as they are not abused, although I would not count them among your close friendships.

Healthy friendships should generally make you feel better about yourself, and feel as if you have more energy (other than justifiable occasions when a friend may need to point out an error you have made, or may require an especially large amount of support from you). If what you consider to be a close friendship seems to consistently leave you feeling worse about yourself or drained of energy, closely scrutinize that relationship and either try to fix it or reclassify it as something other than a true friendship.

Due to the common need to change location for reasons of education, career, family, or otherwise, it is relatively unlikely that close friends will remain geographically close for a lifetime. Yet as already noted, there may be far fewer opportunities to cultivate new close friendships as one grows older. Work very diligently to keep your close friendships healthy and to remain connected despite years, distance, and changes in your own and your friends' lives and interests. And remember that close friendship involves having truly meaningful conversations, ideally in person or via the phone or video chats, or at least by long heartfelt emails sent both ways. Never let superficial online comments or clicks, or mailed cards or newsletters, become a substitute for that deep interaction.

More broadly than individual close friendships, it is helpful to be a member of a community of people (some of whom you may be closer to and know better, and others whom you may not) who will support you, and whom you can support in turn. As with individual friendships, a community is usually routed in some shared interests, beliefs, or experiences. It could be anything from a religious group to a hobby club to a set of neighbors or officemates. If you cannot find such a community, perhaps you can help to build a community from scratch, especially if you have a friend to help.

Close friends are rare, and a truly supportive community is also rare. Find them if you can, consider yourself fortunate if you do, and take good care of them.

1.2.5.3 Teachers, Professors, and Mentors

There are various helpful roles that a teacher, professor, or mentor can perform. In some cases, you may be looking for the best person for one of those roles. In other cases, you may find one person who performs all of those roles admirably.

If you would like to learn a particular science-related subject, try to find a teacher or professor who helps you to learn that subject as easily and as thoroughly as possible. Different students learn better from different methods—hearing oral explanations by the teacher, reading written explanations in a textbook, watching experimental demonstrations, solving theoretical problems themselves, doing hands-on experiments themselves, etc. Different teachers tend to focus more on one or more of those methods. Try to find a teacher who very effectively utilizes the same method by which you find it easiest to learn, or who uses multiple methods and helps you to see the same subject from many different angles to understand it better.

Ideally education is an interactive, two-way process. Try to find a teacher who has plenty of time and eagerness to answer students' questions, and whose answers are very helpful and very patient. Ask any questions you need to, and as many as you need to, to fully understand the material. If you are trying to learn, there are no "dumb questions" or questions you should be ashamed to ask. Find a teacher who believes that too.

A good teacher should be able to adapt the level and style of their teaching to their current students, using knowledge about the students and feedback from the students. Likewise, a good teacher should know from students' questions, facial expressions, or performance in solving problems which topics need to be covered further and which topics the students have already mastered, and then spend the instructional time accordingly.

Whereas most teachers and professors impart education via pre-planned curricula and regularly scheduled lessons, most mentors provide useful information and advice about various scientific or non-scientific issues as they happen to arise, on an as-needed basis. Some mentors are regular teachers or professors; other mentors are work managers, older students, older employees, or other people you may meet along the way.

Just as you should try to find a teacher whose educational style best matches your own, look for mentors whose style fits well with yours. Seek out mentors who truly want to help you, not simply use you for their own purposes. (It is certainly okay if the mentoring relationship is mutually beneficial, for example if the mentor teaches you how to do something new and useful, and by doing it you help the mentor.) A good mentor can teach you all the things you might have eventually learned on your own by trial and error, but in a much faster and painless fashion. A good mentor can also teach you some things you might never have discovered on your own. Ideally a mentor should be a sympathetic ear, always ready to listen to your difficulties and to offer advice or assistance wherever possible. A good mentor should be patient with your mistakes, as long as you learn from your mistakes and keep trying your best.

If you cannot find a good teacher for a given subject, a well-written textbook on that subject that matches your own level and style can fully take the place of a teacher (Section 1.2.3.1). Sadly, it can often be difficult to find a good teacher in the specific subject, location, and time in which you need one, so do plan on resorting to textbooks as your primary teachers for at least some fraction of your education. Even if you have an excellent teacher, a good textbook can greatly supplement what you learn from that teacher, and help you to use your interaction time with the teacher in the most efficient manner.

Unfortunately, good mentors are even rarer than good teachers. While nothing can fully substitute for an ideal mentor, there are alternative solutions that are at least much better than nothing. See Sections 1.2.3.5 and 1.2.3.6, as well as the entirety of Chapter 12, for more information.

1.2.5.4 Supportive Schools

Students and their parents may not have any choice about which elementary, middle, and high schools the students will attend. If you do have a choice, try to find a school that caters to the particular educational mode or style by which you learn best, or that uses several educational modes including your preferred style. Also try to find a school in which the teachers, administrators, and other students are genuinely interested in the well-being of the students and in creating a positive, supportive environment for learning. If you do not have any choice in what school to attend, try to find the most supportive teachers within the school, and do not be bashful about asking the school administration for accommodations to help with your learning experience (the worst they can do is say no, and they may agree to all or at least some of your requests).

If the best or only school available to you is inadequate, supplement it with your own reading (Section 1.2.3) and your own activities (Section 1.2.4). Even if your school is amazing, you can still gain a great deal from outside reading and activities.

Students and their families generally have vastly more options in selecting universities for undergraduate/graduate education. Gross societal dysfunction in the United States and in some other countries has led to costs for a university education that are astronomical and still rising much faster than inflation. In general, select the best university you can for your particular interests and personality style without bankrupting yourself or your family. Having a famous university on your resume can be an advantage later in life, but it is only one factor among many that will be weighed. Having a good education is much more important. If one makes certain choices, it is entirely possible to obtain an excellent education at a university that is not at all famous, just as it is possible to obtain a poor education at a highly famous university.

There are several factors to consider in weighing which university can provide you with the best education in your preferred area. Obviously one huge factor is the quality of the actual teaching. Look for professors who truly care about their teaching and are rewarded for it by the university, as opposed to professors who only do it as a hurried afterthought because the university demands that they focus on other things. Consider the quality and culture of the other students. Even if a professor is a poor teacher, the students in a course may learn the subject thoroughly if they spend a great deal of time studying the material together and helping each other. On the other hand, it can be difficult to learn properly even from a stellar teacher if the other students are highly distracting or have a culture that mocks anyone who tries to study. Finally, evaluate the research environment at the university. Ideally students should be encouraged to learn how to be very independent and competent scientists by conducting experiments and pursuing projects in the university's laboratories. All too commonly, though, students are just used as slave labor to perform uncreative, repetitive tasks that will simply bring more fame and fortune to the professor who runs the laboratory. Before you decide which university to attend, find out as much as you can about all of these factors, especially by delving into online comments by current and former students at that university, and by contacting some of the students for additional candid information.

Excellent grades and recommendation letters from teachers/professors at each school and university you attend are absolutely vital for the next step in your career, or even for many future steps of your career. Regardless of the quality of your school and what you think of it, for the entire time you are at that school, work as hard in all of your classes as you possibly can in order to secure both top grades and glowing letters of recommendation. Do not take more courses at one time than you can comfortably handle, and do not let other activities divert your time and energy away from giving all of those courses your very best. If you work hard in a course and are still struggling, seek additional help as soon as possible from the teacher/professor, a tutor, other students who understand the material better than you do, or the best textbook(s) on that subject (Section 1.2.3.1).

Do not only receive, but also give. When you find good teachers or professors, let them know how much you appreciate their teaching, and what specifically you find most helpful about it. Encourage and help other students in your classes however you can, just as you may need their encouragement and assistance. If you discovered a good school, a good course, or a good teacher, let potential future students know that. Likewise, do whatever you can to warn potential future students away from bad choices.

1.2.5.5 Supportive Employers and Sponsors

Employers generally provide you a place to work—a lab, an office, equipment, co-workers, etc. Sponsors provide funding for specific research projects. One way or another, you need both. Some employers hire you and provide you with research funding. Other employers give you a place to work as long as you can bring in enough funding from outside sponsors, and give you the boot if you cannot. Some sponsors will provide you with enough money to create your own company or lab from scratch in order to do the work the sponsor would like to fund.

Clearly revolutionary innovators can accomplish far more during their lives if they can find supportive employers and sponsors than if they cannot. Unfortunately finding supportive employers/sponsors is often the greatest challenge that revolutionary innovators face, and in many cases it may be impossible.

The research system in the United States and many other countries is divided into three sectors of employment: (1) universities, (2) corporate research, and (3) government-run or government-funded laboratories. As explained in more detail in *Forgotten Creators*, over the last several decades, each of those sectors has become increasingly dysfunctional in its own ways, contributing to the overall decline in revolutionary scientific innovation [Rider 2020]:

1. While universities have produced innovators, discoveries, and inventions for centuries, there are serious problems with the modern academic system:

(a) Professors at many universities are generally evaluated primarily or exclusively for research, so they tend to neglect teaching. Professors who are deemed to invest too much effort in teaching may even be denied tenure or otherwise punished, while other professors often delegate teaching to poorly paid adjunct professors or graduate students.

(b) The modern academic system seems to be extremely focused on publishing as many papers as possible, even if they are highly repetitive of previous papers by the same researchers, do little to actually advance their field, and often are of dubious quality (or even plagiarized or faked entirely). Researchers openly talk about maximizing the number of "minimum publishable units." Academics are so judged by their continuous high production rate of papers that they cannot really afford to get negative results. For that reason, they tend to pursue experiments (1) with a readily predictable and immediate payoff, (2) with insufficient optimization for repeatability, (3) with very little risk or innovation, and (4) preferably without focusing on truly practical applications that would take much longer to perfect. Likewise, academics usually cannot afford the time to publish any negative results if they do happen to get them (which would be very helpful to warn others of dead ends or misconceptions). The result appears to be an exponentially increasing deluge of repetitious, minimally innovative, or even spurious papers.

(c) Although it is considered to be by far the most important product of the system, this output of papers seems to end up largely unread and unutilized because (1) the number of papers is so incomprehensibly vast, (2) the papers are inaccessible to most of the world due to exorbitant online journal paywalls or the cost or obscurity of the printed volumes in which they appear, and (3) most academic researchers are too busy frantically writing their own papers to spend much time reading, trying to replicate, or applying other researchers' papers.

(d) Instead of multidisciplinary cross-pollination or even proper perspective within a given field, modern academia seems to demand extreme microspecialization. To compound the problem, researchers in each subfield appear to continually develop more and more unnecessarily specialized vocabulary, and this "tower of Babel" effect makes it much more difficult for (1) students to learn a given field, (2) researchers in different fields to communicate or spread ideas, (3) the public to understand and appreciate the work, and (4) the work to have any impact in the real world beyond the virtually inaccessible specialized literature.

(e) Universities now seem to be bottomless pits for tuition, research grants, donations, university-hosted conference fees, and other funding, with tuition rising far faster than inflation for many decades, university faculty and staff endlessly pursuing wealthy donors and sponsor grants full-time, untapped university endowments mounting ever higher, and an explosion of administrators, extravagant campus architectural projects, ever more expensive athletic programs and facilities, and other costs with at best a tenuous connection to actual research and education.

(f) For decades there has been an exponential multiplication of professors and postdocs who want to be professors. Although this process began as a way to build up an academic system from minimal roots, in the modern environment in which the number of positions for professors has been relatively constant for years, it now functions for all practical purposes as a pyramid or Ponzi scheme that primarily benefits those who got in earlier. Those entering the system more recently tend to work very long hours to make the whole system function, are paid quite poorly, and have very dim career prospects.

2. Decades ago, corporate research programs made sizeable investments in very innovative, longer-term research and development projects, ultimately leading to products ranging from revolutionary microelectronics to whole new classes of pharmaceuticals. Unfortunately, corporate research (even including start-up companies and venture capitalists) now appears to be hobbled by several widespread problems, such as:

(a) With top management and investors seemingly focused only on tomorrow's stock prices and next year's products, companies are generally only interested in developing very near-term, very low-risk (non-innovative) products.

(b) There appears to be a strong financial incentive for companies to take whatever amount of innovation does exist in their R&D pipeline and spread that innovation out for as many years as possible over a long succession of slightly improved products, in order to ensure planned obsolescence of each product and profitable sales of the next version of the product. There seems to be a strong disincentive to release as much innovation as possible as quickly as possible, which would spur the need for much more extensive and accelerated innovative research programs to refill the pipeline with future products.

(c) Research and development for any period of time is apparently viewed as an immediate financial loss for the company, not an investment in the company's future, and scaled back or entirely replaced with the hope of finding some other company's research that can be bought out or simply imitated. It is presumably much more lucrative to wait for someone else to invest in developing an innovative product, then just copy that product and try to capture as much of the market share as possible.

(d) Companies tend to be very unstable, with an endless series of mergers, acquisitions, or internal reorganizations that can completely redirect any research and development priorities on an almost annual basis.

(e) Profits for top management and investors seem to grow ever larger while rewards and working conditions for the actual research and development employees have stagnated at low levels or even worsened in recent years. Upper management tends to view the workers as disposable, interchangeable cogs in the machine that can be frequently and easily replaced, not skilled experts whose abilities should be cultivated, allowed to reach their maximum potential, and rewarded with and for longtime service.

3. Although government-run or government-funded laboratories played major roles in developing revolutionary innovations (nuclear technology, radar, space flight, guidance systems, etc.), especially 75+ years ago, they now seem to be mired in a number of problems, including:

(a) Each lab appears to be strongly focused on some core technology that was very innovative roughly three-quarters of a century ago when the lab was founded, but that is now very mature and for which government funding is steadily declining.

(b) Because of their previously reliable government funding and potentially dangerous core technologies, government labs tended to develop very risk-averse management cultures in which it is generally much safer politically to do nothing than to support any progress or change.

(c) Any new work at government labs seems to be highly constrained by a wide variety of internal and external regulations that have greatly increased in number and severity over the last 75+ years.

(d) As funding for government labs has declined in recent years, not only have their research staff sizes decreased, but the surviving staff members have had to devote larger and larger fractions of their time to pursuing outside resources instead of actually conducting research. In many cases, the staff members spend much of their time writing proposals to try to obtain funding from outside sponsors. In other cases, the surviving staff are no longer allowed to conduct their own research, but rather must spend their time selecting and managing outside contractors to do the research.

(e) In cases where government labs have attempted to reform their structures and their areas of research, those reforms often mimic some of the worst practices of modern industry, for example either by focusing on very short-term, non-innovative, low-risk work or else by investing in a rapid succession of poorly thought-out "get rich quick" schemes.

(f) For all of the preceding reasons, government labs often have great difficulty attracting and retaining talented scientific professionals, and may instead accumulate mediocre personnel to fill out available positions, with some of those mediocre personnel ultimately rising to management positions at all levels as managerial openings become available over time.

I certainly do not mean to suggest that there are currently no revolutionary scientific innovators or innovations, or no places in which revolutionary innovators and innovations can find support. Some do still exist, and those that do should be greatly commended. Yet they are much rarer than they used to be, and much rarer than they should be.

I also do not intend to discourage future creators by painting such a bleak picture of the present research environment. Quite the opposite—I hope to explain why there is such a shortage and great need for new revolutionary innovators, and I hope to give them a better understanding of some of the challenges they must face in order to succeed in developing their revolutionary innovations.

Of course, no one should enter such a troubled career path unless they personally feel strongly compelled to do so. For alternative career paths in fields that are potentially much more lucrative and more supportive than revolutionary innovation, see Section 1.2.1.

After having studied the above problems in the academic, corporate, and government research sectors, if someone finds one of those sectors preferable to the other two and is willing to endure its known difficulties for the duration of a career, that can be a clear and well-informed choice.

One possibility for intrepid young innovators is to seek areas where R&D funding for new projects might be more readily available than is the case in the mainstream system:

- Some corner of the existing research system may still be conducive to revolutionary innovation, especially if it is nurtured and protected by a scientific "enlightened despot" like those that were common in prewar Germany and the 1940s–1960s United States—perhaps a particularly farsighted corporate CEO/owner/investor/senior manager, a philanthropist, a university administrator, or a defense or intelligence sponsor.

- Some field that is so incredibly old, so new, such a novel combination of existing fields, or so offbeat that it is not filled to overflowing with peer-reviewed competitors may afford better opportunities.

- There might be better funding prospects for new innovators and innovations in the relatively small number of countries that still have steadily increasing investments in R&D.

Another possibility, though only for the very courageous individual, would be to try to improve some specific part of one of the existing research sectors (academic, corporate, or government).

If someone feels personally compelled to pursue innovative R&D and is not satisfied with (or cannot access) any of the options outlined above, the remaining possibility is to try to pursue a research career outside of the official sectors. Several keys are important to make this sort of career path possible:

- In the absence of financial support from the academic, corporate, or government research sectors, it is necessary to seek and obtain alternative sources of financial support for independent scientific work. The nature of those alternative sources will depend upon an individual's specific circumstances, interests, and opportunities, but could range anywhere from taking a normal job that pays well but allows enough outside time for research (e.g., Swiss patent clerk), to marrying into wealth, to accepting internet donations or crowdfunding.

- It is critical to identify and focus on projects that can be accomplished with limited labor (often only that of the individual, or even just some fraction of the individual's time) and very limited equipment, supplies, and other resources. Those considerations will likely limit any work to theoretical analyses or at best very small-scale experimental research.

- Two or more individuals interested in the same or similar areas might pool their time and resources in order to accomplish more and to provide mutual encouragement. Among other possibilities, one might establish or join a "maker space," amateur science club, scientific co-op, or other organization.

- No matter how high the quality of an unaffiliated individual's work might be, that person will likely have great difficulty getting proper consideration from scientific journals, government patent offices, or corporate technology licensing offices. Therefore, without necessarily giving up on those establishment methods for output, one should seriously consider alternative methods of output for any significant scientific results, including freely releasing results on the internet without any possibility of monetary gain in hopes of maximizing the ultimate impact of those results.

1.3 Future Creations

In order to inspire and guide future creators, this book uses the methods of systems analysis (Section 1.2.4.4) to break down all currently foreseeable future creations into categories and subcategories (Fig. 1.4), and to analyze revolutionary innovations within each of those areas, with references to relevant previous research and suggestions for potential future work. The most global categories for revolutionary innovations are simply whether those innovations are (a) not directly and immediately helpful or harmful (pure science, although there may be later applications), (b) directly helpful (applied science), or (c) directly harmful. Subdividing those first two areas leads to a total of ten categories that appear to cover all foreseeable revolutionary innovations:

Chapter 2: Creations in Biology and Physiology are not directly and immediately helpful or applied, yet may have later applications. Primarily, though, they would expand our knowledge regarding biochemistry, biological information flow (DNA, RNA, proteins, etc.), cell biology, organs and tissues, whole organisms, families and histories of organisms, and communities of interacting organisms.

Chapter 3: Creations in Chemistry and Materials are not directly helpful or applied (though they may have later applications) but would directly expand our knowledge of atoms, molecular structures, collections of molecules, chemical reactions, and properties.

Chapter 4: Creations in Earth and Space Sciences are not directly helpful or applied but would expand our knowledge regarding terrestrial geology, the ocean and other water, the atmosphere, other astronomical bodies, and the space in between.

Chapter 5: Creations in Mathematics and Physics are not directly helpful or applied but would expand our knowledge of phenomena, physical laws, and fundamental explanations ranging from microscopic particles and forces to macroscopic objects such as black holes and even the whole universe (or other universes).

Chapter 6: Creations That Improve Humans with regard to their intrinsic properties, health, and/or lives may be divided into categories of those with direct, helpful applications to physical performance and characteristics, mental performance, moral behavior, infectious diseases, noninfectious diseases and injuries, and aging and death.

Chapter 7: Creations That Improve Travel and Human Expansion cover direct, helpful applications in realms including land (and below), the ocean and other water, the atmosphere, space (including space stations, planets, and moons), time, and other dimensions or universes.

Chapter 8: Creations That Improve Resources for Humans include direct, helpful applications regarding food, water, air, the environment, housing, energy, materials, nonhuman labor, and communications.

Chapter 9: Creations That Aid Nonhumans should be considered for completeness, in addition to categories of creations that aid humans. Included in this category are creations that aid nonhumans on Earth, such as animals, plants, the microbiome, the non-living environment, and human-created entities such as genetically engineered organisms and artificial intelligence. Also included are creations that aid nonhumans elsewhere, such as alien life that we discover, possible alien life that we should not inconvenience with our current activities even before we discover them, and the non-living universe for which we should act as good custodians.

Chapter 10: Creations That Concern Revolutionary Innovation Itself can improve the process for producing creators and creations and thus improve the world, so they are themselves a category of revolutionary innovation. Much can be learned by studying the creators, creations, methods, and systems of revolutionary innovation throughout the past and around the world in the present. Much can also be accomplished by proposing and evaluating potential methods of improving revolutionary innovation in the future, based on ideas from the past and present, as well as new or modified ideas.

Chapter 11: Creations That Are Harmful include those intended to kill, hurt, restrict, control, manipulate, deceive, addict, spy, track steal, damage, destroy, and/or have other harmful effects. Although many research sponsors would undoubtedly be interested in future creations in this category, for ethical reasons they are not discussed in detail in this book. However, precisely because the category is so interesting to many research sponsors, both the quantity and quality of previous revolutionary innovations in this category have been extraordinary. Even those scientists who choose not to pursue future creations in this category can learn much from previous creations in this category, in terms of the new science and non-harmful spinoff applications they have introduced, and also in terms of systems and methods of revolutionary innovation that were harnessed to arrive at those previous creations.

Chapter 12: The Road to Creation, from initially having a revolutionary idea to actually realizing that idea, is usually very long and filled with many obstacles. Whereas the other chapters deal with the scientific difficulties and some methods to overcome them, this chapter covers some of the common non-scientific obstacles (financial, political, cultural, personal, etc.) that one is likely to encounter along the way. In order to prepare future creators for such non-scientific obstacles, this chapter provides some advice from previous scientific and non-scientific innovators, as well as some potentially new advice.

The appendices cover a few small subsets of the above research areas in more detail, in hopes of providing useful pointers for future creators interested in those areas, and illustrative examples of brainstorming and analysis even for future creators who are interested in other areas:

Appendix A: Innovations to Improve Moral Behavior. There are several subcategories of potentially revolutionary innovations aimed at improving the intrinsic properties, health, and/or lives of human beings. One of those subcategories is scientific innovations that could improve human moral behavior. Human society and human history are filled with examples of individual people and collective groups and populations that are governed by the darker side of human nature, causing great harm to themselves and to others. Even the most honorable people struggle with baser instincts and give in to them at least occasionally and briefly. Education, religion, law, and other disciplines have tried with only limited success to improve moral behavior. Just imagine what science might be able to tell us about the fundamental causes and potential solutions for human moral struggles, and consider how much difference that could make in the world. Of course, scientific experiments to understand and to improve moral behavior are themselves fraught with a large number of moral issues, as explained in this appendix.

Appendix B: Innovations to Address Infectious Diseases. Another subcategory aimed at directly improving the lives of humans encompasses methods of detecting, preventing, and treating infectious diseases, including diseases caused by prions, viruses, bacteria, fungi, protists, and helminths. This appendix analyzes subcategories in these areas and proposes some specific ideas that could be investigated further in the future.

Appendix C: Innovations in Advanced Space Propulsion. This appendix delineates and analyzes categories of propulsion suitable for interstellar space travel. In order to send a manned or unmanned spacecraft to other star systems within a sufficiently short transit duration (say several decades at most), the propulsion system must accelerate the spacecraft to an appreciable fraction of the speed of light. All foreseeable methods of onboard propulsion systems are analyzed, including chemical propellants, nuclear fission, nuclear fusion, and antimatter. All foreseeable methods using resources that are not onboard the spacecraft (ramjets, beamed power propulsion, etc.) are also discussed. The most promising areas for future research are identified.

Appendix D: Innovations in Unconventional Physics Applications. Unconventional physics applications include travel of objects or messages in time, into parallel universes or other dimensions, faster than light, via teleportation or wormholes, through solid or potential energy barriers, etc. It also includes unconventional physics methods of providing useful energy and/or force, such as "free" energy from the vacuum, reactionless propulsion, inertia control, antigravity, and artificial gravity. In many cases these effects are interrelated—for example, time travel could be turned into faster-than-light travel and vice versa. This appendix identifies categories of known and foreseeable physics that could potentially have such effects. It notes where previous research falls into those categories and points out many areas for future investigation.

Appendix E: Innovations in Nuclear Energy. Rearranging electrons in atoms releases chemical energy. From basic principles, rearranging protons and neutrons within the nuclei of atoms releases roughly a million times more energy—nuclear energy—because the protons and neutrons are much closer together than the electrons. This appendix identifies all foreseeable categories and sub-categories of approaches for extracting nuclear energy, evaluates which ones seem safest and most feasible, and suggests directions for future work.

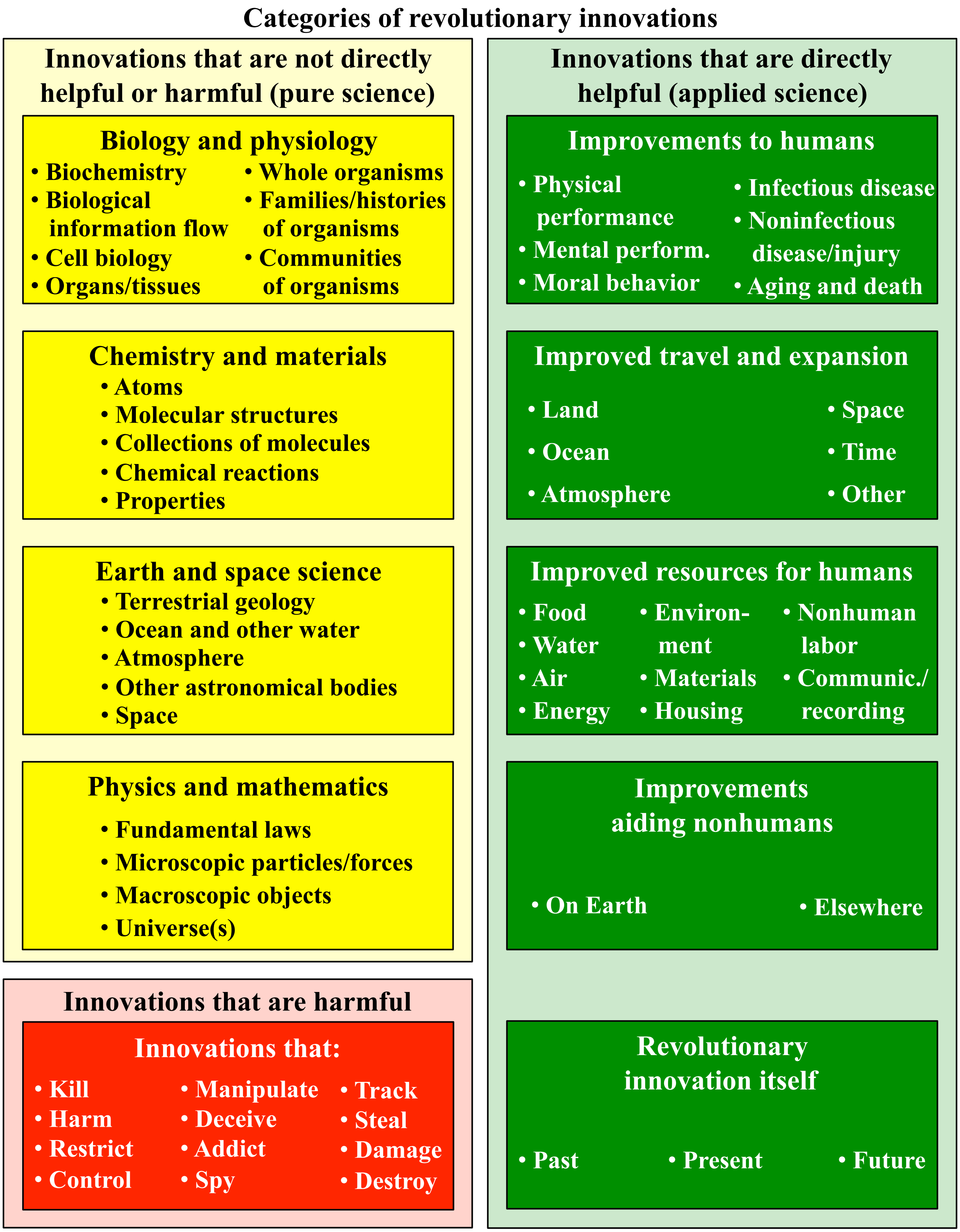

Figure 1.4: Potential future revolutionary innovations can be divided into categories. Chapters 2–11 discuss each of these categories.

1.4 Disclaimers

It would be prudent to note several disclaimers, caveats, and limitations that apply to this book and its methods and suggestions:

- For brevity, I often just use the word "scientists," but past, present, or future creators who make revolutionary scientific discoveries or inventions may have degrees in science, mathematics, engineering, medicine, veterinary medicine, or other fields, or may be students or others with no degrees at all. I do not at all intend to limit the discussion only to those meeting the most rigorous definitions of "scientist," or to overlook distinctions such as science vs. engineering or discoveries vs. inventions.

- Of course, any book of projections about the future will ultimately prove to be at least somewhat inaccurate and incomplete. My hope is that this book will be at least somewhat helpful, and therefore better than no book at all about the future. A map that gets you moving in the right direction can be useful, even if it is imperfect and you have to find a better map further down the road.

- I do not claim that all of the ultimate research goals mentioned in this book will be achieved, let alone when they will be achieved. What does ultimately occur will depend both on the scientific obstacles and opportunities—some of which cannot be foreseen now—and on the personnel, resources, and time that are devoted to particular topics.

- Furthermore, I do not claim that all of the ultimate research goals mentioned in this book even *should* be achieved. There may be good ethical or societal reasons for not achieving some of them.

- To try to minimize how quickly the contents of this book become outdated, I have endeavored to view the scientific fields, issues, and possibilities in as broad and general a fashion as possible, and with as long-range a perspective as possible. The unfortunate disadvantage of that approach is a loss of details that cannot be discussed without making the book unbearably long and/or rendering it rapidly obsolete. Please consult current experts and publications in your particular field of interest to ensure you consider any relevant new advances or details that I do not address.

- Likewise, the Bibliography has been carefully selected and limited to try to minimize how rapidly it becomes obsolete. Many of its references are textbooks or other works that are rather general and likely to remain at least mostly useful for some time. Other references were so groundbreaking when they were first published that they are likely to remain relevant to the path taken by a research field even many decades later, or at least worthy to serve as role models for how revolutionary innovators can practice their craft.

- This book does not offer advice on specific lab experiments, let alone the methods to perform them safely. **Students should always have adult supervision for any experiments or other activities!** Everyone of any age should always read and follow the safety precautions and other instructions that come with scientific supplies. Also make sure you know and follow the rules for your school, organization, or government. Everyone should always wear personal protective equipment that is appropriate for their activities.

- Since this book is based on my own personal experience, it is heavily weighted toward English-language sources and U.S. institutions. There may be important sources or institutions in other countries that are not covered in this book, and some of what is covered here may not be applicable to other countries. Please feel free to consider (or find analogs for) whatever parts of the book seem useful for your own personal situation and ignore the rest.

- If you have any suggestions for improvements, corrections, or additions for this book, please let me know. I hope to update it periodically. If this book is deemed sufficiently useful, perhaps others might even be willing to update it after I am no longer around.

- My advice in this book is only presented as suggestions, not at all as requirements or constraints that must be followed in order to succeed. If you find some different or better way to produce revolutionary innovators or revolutionary innovations, that is great. If you have better ideas, please let me know, or you can write your own book to help future creators.