Getting Good Ideas in Science and Engineering

Perl, L., Martin (1995 Nobel Laureate)

Abstract— ***Good ideas in science and engineering range from the improvement of an electronic device, to the development of a new medicine, to writing a new computer program for better data analysis, to achieving new understanding in a science. I have no certain prescriptions for how to get good ideas. I do have advice and illustrations of what has worked for myself and others. I have warnings about mistakes made by myself and others. I also warn that for every good idea expect five or ten or twenty bad ideas. I write about the need for helpful and skillful colleagues. My goal is to help the reader maintain a way of thinking and a way of carrying out their work that strengthens their creativity.***

1. *Creativity in Science and Engineering*

1.1. Constraints on Creativity

THIS is part of a presentation I made at the VIPSI-2007 JAPAN in Tokyo Conference, May 31 - June 3, 2007. My talk was entitled "Creativity in Science and Engineering ; Sometimes Easier, Sometimes Harder, Than You Expect". This paper contains the part of that talk on getting good ideas in science and engineering. Good ideas include a vast range: invention or improvement of an electronic device, development of a new medicine, achieving new understanding in a science, writing a new computer program for better data analysis and so forth [1]. I have advice and illustrations of what has worked, I have warning about mistakes made by others and myself. I write about the need for helpful and skillful colleagues. My goal is to help the reader maintain a way of thinking and a way of carrying out their work that strengthens their creativity.

I am writing from sixty years in the technical world, first as a chemical engineer, than as an equipment builder and experimenter in physics, mostly in elementary particle physics [2]. I have been an academic most of my life, but though friends and consulting I have also been able to be involved in Silicon Valley's engineering world.

Creativity is sought everywhere: in the arts, in entertainment, in business, in scholarship, in mathematics, in engineering, in medicine, in the social sciences, in the physical sciences [3,4]. Common elements in creativity are originality and imagination. Creativity carries feelings of wide ranging freedom to design and to invent and to dream. But in engineering and science creativity is useful only if it fits into the realities of the physical world.

There are four types of constraints on creativity in science and engineering: conforming with the laws of nature, conforming with observations and experimentation, feasibility, and practicality. These constraints are a challenge but also a pleasure. The pleasure is solving problems and learning about the physical world. It is a contest with nature. In a sense nature is an antagonist; nature is often complicated and nature's secrets are hidden. But nature is a fair antagonist, once a secret is unlocked, once a device or a process works, nature doesn't change the rules.

Well that is almost true, there are the intermittent failures that we all dread. My friend, Michael Godfrey, an expert in electronics and computers, told me recently about an intermittent failure in his computer's hardware. Everything he did temporarily improved the system but the intermittent always came back. After many hours he solved the problem, So on the bad technical days nature is not a fair antagonist.

1.2. The Constraint on Creativity by Physical Laws: Example of the Creation of Energy

Creativity in the sciences is constrained by the laws off nature. For example, a physics law is that energy cannot be created from nothing. Energy can be changed in its form, thus the chemical energy stored in gasoline is changed into the moving energy of the pistons in a gasoline engine. Also mass can be converted into energy as happens in radioactivity, in a nuclear reactor, in a fission bomb, and in a fusion bomb. Always energy must come from other energy or from the conversion of mass, this is summed up in the principle – conservation of energy plus mass.

Many apparently creative attempts to violate this principle have been made for centuries [5]. Some of these attempts use very complicated mechanical and electrical machines in which energy is fed into the machine from the outside, either because of the negligence of the builder or because of fraud. Take the ever recurring proposal for a carburetor that gives hundreds of miles per gallon of gasoline , there is not enough

Manuscript received January 23, 2007.

M. L. Perl is with the Stanford Linear Accelerator Center, Stanford University, 2575 Sand Hill Road, Menlo Park, CA 94025, USA (e-mail: martin@slac.stanford.edu).

chemical energy in a gallon to move an automobile hundreds of miles.

But suppose the accepted physical law is wrong. Here is a place for creativity, but dreaming about a violation of the law is not enough, creativity must be constrained by logic and knowledge. For example, sophisticated modern attempts to violate the conservation of energy plus mass principle often involve present understanding of empty space. Our quantum mechanics picture is that empty space is a mixture of virtual photons and other particles that perpetually move and appear and disappear, this is called the zero-point energy of empty space. But quantum mechanics also holds that zero-point energy cannot be converted into useable energy. Perhaps this tenet is wrong. A proposal to test this barrier to the conversion of zero point energy to useable energy requires a logical revision in basic quantum mechanics theory and experimental proof of the validity of this revision. Account must be taken of previous related experimentation and how extensions of the revised theory affect established experimental results [6].

1.3. Creativity May Not Require Basic Understanding of Biology or Chemistry or Physics if it is Base on Solid Observation, Trial-and-error and Experimentation

Throughout most of our history, material progress in ceramics, in metallurgy, in building materials, in agriculture, in hundreds of products was made by observation, trial-and-error and experimentation. The relevant basic science was unknown. Yet the technological and engineering advances were tremendously creative. Creativity in engineering does not require knowledge of basic science, but knowing the basic science is useful.

Creative engineering with little or no basic science knowledge depends upon the care used in observation and experimentation. About six years ago there was a good example in some research of my colleagues and myself. We decided to search in meteoroids that have fallen on the earth for a possible but hypothetical particle. These meteoroids come from the asteroids that orbit the sun in the vicinity of Jupiter. My speculation was that these hypothetical particles might be plentiful in asteroids. The search depended upon grinding up the meteoroid and suspending the powder in oil, the way pigment is suspended in paint. Broad and profound basic science exists on suspensions of powder in oil. But there was a problem in that that the basic science emphasizes pure powders, while the meteoroid powder is made up of a complicated mixture of different metals and metallic compounds. I went to the experts in fundamental colloid science but they didn’t like the problem, too messy. So we resorted to the old trial-and-error methods used for thousands of years in making suspensions in paints and dyes and inks and drugs. Finally our own experimentation and a suggestion from a lubrication engineer gave us a solution. We mixed in commercial motor oil since one of its properties is to keep in suspension the metal and metallic compounds that are produced by engine wear. It worked! Although we didn’t find the hypothetical particle. the development of the meteoroid powder suspension was pleasantly creative.

1.4. Feasibility and Practicality Constraints on Creativity

Feasibility and practicality are obvious constraints on engineering creativity. Think about the direct use of a nuclear reactor in transportation: automobiles, trains, airplanes, ships. It is not practical to put a nuclear reactor in an automobile or railroad locomotive, or airplane, the reactor is too large, too heavy, too expensive, with radiation shielding and safety problems. On the other hand a nuclear reactor in a ship is feasible and practical.

2. GETTING A GOOD IDEA

2.1. Expect Many More Bad Ideas Than Good Ideas

There is a hard truth about creativity in science and engineering. for every good idea, expect to have five or ten or twenty bad ideas: ideas that don’t work, ideas that are wrong because they violate the know laws of biology or chemistry or physics, ideas that are impractical, ideas that are useless.

Nikola Tesla [7] is an example of a genius engineer, inventor and physicist who conceived and developed bad as well great ideas. His greatest idea was developing alternating current technology, with the financial support of George Westinghouse he finally overcame Thomas Edison’s stubborn and ignorant championing of direct current power transmission. Tesla was able to visualize the phase concept in electric currents, something that often puzzles students these days in spite of marvelous computer graphics explanations. He proposed new ideas and inventions in much of the electrical world: motor and generator design, alternating current transmission, pre-radio wireless communication.

Yet Tesla was wrong in his monumental efforts to send large amounts of electrical power without wires from a transmitting antenna to a receiving antenna, over distances of hundreds of miles, even around the world. He seems to have had two conceptual errors. The electrical power radiated by a transmitting antenna spreads out as the distance from the antenna increases so that as the distance to the receiving antenna increases, a larger and larger receiving antenna is needed to pick up the power. This problem makes the concept impractical at low frequencies, the concept becomes practical at very high frequencies such as with microwave beams or lasers. Tesla's second error was the belief that a receiving antenna could pull in radios waves from an area much larger than the size of the antenna. I don't know how he made these errors, he knew so much.

2.2. Reducing the Frequency of Your Bad Ideas

The way to reduce your frequency of bad ideas is to try to make sure that you understand the physical laws and the neighboring technology relevant to your new idea. Colleagues, the literature, the Web can be of help. Sometimes you have to keep going until you are the expert on the idea and you discover the show-stopper.

2.3. Turning a Bad Idea Into a Good Idea

But don't kill the bad idea prematurely. A bad idea can evolve into a good idea. The evolution into a good idea can be a short process, turning a bug into a feature, quoting my colleague Eric Lee. Or the evolution from bad to good can be long and tortuous.

3. Required Skills and Temperament

3.1. Understand Your Skills and Temperament in Choosing Your Field

You must take account of your temperament and skills in choosing your technical field or science and your interests in that. Don't try to fit yourself into any particular image of what a scientist or an engineer should be [8]. But there are four basic skills you must have: mathematical competence, a good memory, a talent for visualization, and a powerful imagination.

3.2. Mathematical Competence

You must be competent in mathematics although you don't have to be a mathematical genius. I can do original calculations in many areas of physics: Newtonian mechanics, electromagnetism, fluid mechanics, quantum mechanics; but I cannot work in complicated and abstract mathematics, and so I am precluded from understanding string theory, perhaps that's a good thing. I speculate about new ideas in physics and about experiments that might be interesting but I don't work on experiments based on mathematical ideas that I don't understand. Thus my mathematical knowledge does limit the range of my experimental work, but so far I have found plenty of experiments that interest me. Summing up: moderate mathematical knowledge and ability is needed in engineering and science [9].

3.3. A Good Memory

A good memory is crucial, not only so that you can easily remember formulas and facts, but so that you can recall where you last read or heard something that you want to retrieve. Yes there is now Google, but Google is not enough.

I don't know if I will ever work again with colloidal suspensions of complicated minerals, but I remember much about our studies, the look and behavior of good versus bad suspensions. It is very useful to keep a detailed notebook containing notes photographs, graphs, problems, solutions.

3.4. Visualization

In engineering and scientific work it is crucial to be able to visualize ahead of time how the work could be accomplished [10]. The intended work might be the invention of a mechanical or electronic device, it might be the synthesis of a complicated molecule, it might be the design of an experiment to evaluate the efficacy of a new drug, it might be the modeling of how proteins fold and unfold. The range of visualization modes is large. In my research I make preliminary engineering sketches of the mechanical and optical parts of the proposed experiments. In my early days I used tracing paper and a T-square, now I usually use a computer program. But my electronics knowledge is primitive and I must depend on colleagues to visualize the best electronics to use.

Different kinds of work require different kinds of visualization. Spread sheets or flow charts may be best. Always, the importance of visualization is to find the best way to proceed and to avoid mistakes and to perhaps find alternative solutions and related good ideas. Visualization is much more than planning, it involves incorporating your knowledge and experience and intuition in thinking how the work will go. It is seeing ahead as broadly and deeply as you can.

3.5. Imagination

Imagination is the fourth crucial ability required to be creative in engineering and science, imagination with the constraints I wrote about at the beginning of this paper: known physical laws, correct observation and experimentation, feasibility, practicality. Begin with the far reaches of imagination at the science fiction level, then slowly apply reality constraints.

3.6. Laboratory Skills

An important question is the extent of your hands-on skills and laboratory skills[11].Are you good at working with tools, at building equipment, at running equipment – electronics, microscopes, telescopes… This is my strength. I am an experimenter in physics. because I like to work on equipment, because I am mechanically handy and because I get great pleasure when an experiment works. But hands-on skills do not have to be your strength. Isadore Rabi, who was my doctoral research supervisor at Columbia University in the 1950's had no hand-skills. His graduate students, all learning to be experimental physicists, used to say that it was important to keep Rabi's hands away from our equipment, otherwise he would surely break something. Yet

Rabi won a Nobel Prize for advancing experimental atomic physics. In choosing what you work on, evaluate the extent of your hands-on and laboratory skills.

4. Luck

The importance of good luck in engineering and science is much oversold [1]. There are the overworked examples: Alexander Flemings discovery of penicillin when mold settled into a Petri dish; Wilhelm Röentgen's discovery of X-rays when he found that there was an emission from cathode ray tubes that fogged covered photographic plates. However good luck is almost always related to priority. In Röentgen's example there were many physics laboratories using cathode ray tubes and photography, within a few years the discovery would have been made somewhere else.

On the other hand, it is very important to avoid bad luck, the basic avoidance principle is the same as being careful when crossing a freeway. In engineering and science most bad luck is caused by mistakes in calculation, mistakes in design, mistakes in measurements, mistakes in experiments. I have had bad luck, perhaps you have too, by going into a project that didn't smell quite right to me, but I kept hoping for the best.

5. Colleagues

5.1. The Lone Scientist and Inventor

There is the popular image of the creative scientist who works alone, an image particularly powerful in medicine [12]. There is Louis Pasteur inventing pasteurization and then Pasteur learning how to treat rabies while fighting off the ignorance of his medical world.

In engineering the myth of the lone inventor is harder to sustain. There is Charles Goodyear and his sister Harriet discovering the vulcanization of rubber. How to make rubber insensitive to temperature and solvents was an outstanding trial-and-error problem in Goodyear's time and the two of them had the advantage of knowing from the work of others what did not work.

5.2. Colleagues and Friends in Science and Engineering

Today every engineer and scientist is immersed in her or his technical community, a community with some colleagues, some friends and many competitors.

You can't know everything in your field and you don't have to know everything. In many areas of science it is getting harder and harder to have the time to do both experimental work and extensive computing and original theory. In addition most of us do not have all the skills required to be creative in our field. You may be skilled in visualization of mechanical design but have little skill in visualization of electronic design. You may have little experience and no interest in using computers for numerical simulation and modeling. The solution is to work with and depend on colleagues and friends.

5.3. Find Colleagues Who are Smarter Than You and Know More

I always look for colleagues who are smarter than I am and who know more than I do. The obvious advantages are she or he may be able to solve a problem that has a produced a dead end in your work, if they can't solve the problem they can point you in possible directions for solution, and they can help you expand the scope and variations of your work. Most important, smart and knowledgeable colleagues can save you lots of time.

5.4. Avoid Colleagues Who are Fast and Showy Talkers, in Fact, It is Best to Avoid Such People In General

Many engineering and science people like to be fast talkers and appear to be fast thinkers. These external qualities get mixed up with internal qualities indicating creativity. I have found no correlation in the engineers and scientists that I have known over sixty years. Some creative people are fast thinkers and fast talkers, some are slow to think and to talk. The problem in associating with fast thinkers and talkers is that they often interfere with the process of developing a good idea, particularly when one is turning a poor idea into a good idea.

Richard Feynman, the most famous physicist after Einstein, was a fast thinker and talker, ever eager to show off his brilliance.. I met Feynman half-a-dozen time. I found that for me he was inhibiting not inspiring.

6. The Art of Obsession in Engineering and Science

6.1. The Importance of Obsession

When you are imagining and visualizing an idea that you expect to be fruitful it is important to be obsessed with the idea. Think about the idea as much as possible, neglecting boyfriends, girlfriends, children, spouses. Obsession will bring immersion of your mind into all the aspects of the idea: what has been done on related ideas, compatibility with physical laws and mathematics and logic, feasibility, practicality, extensions, variations. As the work continues into reality whether it is building a prototype or beginning experiments, continue with the obsession.

6.2. When to Give Up the Obsession

The art of obsession includes knowing when to continue and knowing when to quit. Sometimes the development of a good idea runs into trouble: you run out of money or a competitor has a better product or better experimental results or you run up against a subtle violation of a physical law. Then drop the obsession quickly. I have seen many careers ruined by persisting with an obsession If it is a good idea it will be eventually revived. If it is a bad idea, good riddance.

Acknowledgment

I thank Professors Hironori A. Fujii and Veljko Milutinovic for inviting me to VIPSI-2007 JAPAN and for many stimulating conversations. I also greatly appreciate have learned a great deal from the speakers and attendees at this conference. This work was partially supported by Contract DE-AC02-76SF00515 with the U. S. Department of Energy.

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