SLAC-PUB-12850

October 2007

A Contrarian View of How to Develop Creativity in Science and Engineering

Martin L. Perl
1995 Nobel Laureate in Physics
Stanford Linear Accelerator Center, Stanford University,
2575 Sand Hill Road, Menlo Park, CA 94025, USA
martin@slac.stanford.edu

(To be presented at The Eighth Olympiad of the Mind,
The National Academies, Washington, DC
15-16 November 2007)

Abstract

This paper outlines what an individual engineer or scientist can do to increase her or his creativity. It then describes what educators can do and makes two proposals: (a) Reduce the number of courses required for undergraduate and graduate degrees in engineering and science and (b) change the nature of laboratory courses and Ph. D. research so that students have the freedom to try out their own ideas, with the expectation that they will make mistakes and will both expand their creativity and learn more, by doing.

1.Introduction

1.1 Introductory remarks

I look forward to a deeper and more quantitative understanding of creativity as the science of brain research becomes more steadily and securely based in physiology and biology. I am an engineer turned physics experimenter and, at present, my crude and qualitative thoughts about creativity are based on my experience in teaching, research, and working with colleagues in Silicon Valley and academia.

My interest is in creativity in the competent engineer and scientist, not in the star performers. I actually don't believe there is much to learn from analysis of their qualities [1] and I am tired of reading that Keuklé discovered the ring structure of benzene through a dream. Many colleagues and friends have told me about nightmares they have had about their research but not one has mentioned a productive technical dream.

I haven't found statistical and demographic studies of productivity in science [2] useful for understanding or teaching creativity. Austin's *Chase, Chance, & Creativity*,[3] has been more useful to me then most, but I don't agree with his emphasis on chance.

Creativity is a broad aspect of humanity, but in engineering and science has constraints that do not exist in other creative activities such as music and art. An

Work supported by US Department of Energy contract DE-AC02-76SF00515

improvement of computer architecture, a discovery of a new medicine, a new understanding of the behavior of black holes, an improvement in gasoline engine efficiency –all are creative feats that are nonetheless limited by the laws of nature. We may be wrong about a law of nature. For example the consensus that energy producing, cold fusion is not possible is based upon our present understanding of thermodynamics and nuclear physics. The present understanding may be wrong, but that has to be demonstrated by consistent, quantitative experimentation.

There is increasing pressure on technical education at the undergraduate, graduate and young professional levels as the amount of knowledge in engineering and science steadily increases. There is even pressure on the old professionals [4]. The usual response is to move college level courses into high school, move graduate level courses into college curriculum and extend the sophistication and specialization of graduate courses. This is harmful to technical creativity and in this paper I put forth a contrary educational approach.

1.2 Proposals

I have two proposals:
(a) Reduce the number of courses required for undergraduate and graduate degrees in engineering and science.
(b) Change the nature of laboratory courses and Ph. D. research so that the student has the freedom to try out her or his own ideas, with the expectation that they will make mistakes and will both expand their creativity and learn more by doing.

2. Basic abilities and skills for technical creativity

There are some basic abilities and skills that you must have for creativity in engineering and science.

2.1 Competency in mathematics

You must be competent in mathematics even if you are in a field where mathematics is secondary. But you don’t have to be a mathematical genius. The mathematical level should be that of a book such as Kreyszic [5]. You don’t have to carry the properties of Bessel functions in your head, but you should recognize when your calculations need Bessel functions and know where to find their properties.

2.2 Imagination

Imagination is crucial to creativity in engineering and science, imagination within the constraints of known physical laws, experimentation, feasibility and practicality. Begin with the far reaches of imagination at the science fiction level. Then gradually apply the constraints of physical reality. Beveridge in his *The Art of Scientific Investigation* has a marvelous chapter on imagination [6].

2.3 Visualization

In engineering and scientific work it is crucial to be able to visualize how the work can be accomplished [7]. The intended work might be the invention of a mechanical or electronic device, the synthesis of a complicated molecule, the design of an experiment to evaluate the efficacy of a new drug, or the modeling of how proteins fold and unfold. There are many ways to visualize the development of your idea. I draw pictures and do rough calculations in my notebooks. Some primarily use a computer. Others make models. Still, others just carry out the visualization in their heads until most of the details have been worked out. If you are working with others, intermediate technical notes and meetings are necessary. If I am thinking in the wrong direction I prefer to know sooner rather than later.

2.4 Hands-on and laboratory skills

When choosing what you work on in engineering and science, honestly evaluate the extent of your hands-on and laboratory skills. Are you good with tools, with repairing equipment, or perhaps with using a microscope? You cannot be creative if your daily work involves activities that weaken your confidence and self esteem. You can still do design work or theoretical work. Or, if you want to participate in the hands-on world, find a partner or a group with which to work.

My Ph. D. thesis advisor, Isidore Rabi, was given the Nobel Prize for his experimental work, but he had few hands-on skills. His graduate students were afraid to let him get close to their apparatus. When he came to the laboratory we immediately engaged him in conversation at the door, hoping he would get bored and leave. In spite of his hands-on limitations, he had a deep, mysterious way of understanding and visualizing experimental work.

2.5 Computers

Computers have changed the world of the engineer and scientist. Learn to use a packaged general computing program such as Maple, Mathematica or MATLAB. I use Maple because my friend Marvin Weinstein is a Maple expert and I can always go to him with problems. I find the best way to make progress in computing is to have an expert as a resource. The Internet is a great time saver for looking up references and reading papers. It is also great for looking up facts such as the properties of Bessel functions, but don’t try to learn Bessel functions from the Internet - for that you need a textbook. The curse of the Internet is email. I look at mine no more than once a day and keep my finger on the delete key.

3. Developing good ideas in engineering and science: what you should do

3.1 Good ideas

Good ideas in engineering and science take many forms including: simplifying a consumer electronic device, improving a surgical procedure, discovering something new in topology, or developing a technology for finding life on planets outside the solar system – and the list goes on and on. Bringing a good idea to fruition brings pleasure and recognition to the practitioner, as well as career advancement and money. And so it is fulfilling on many levels to get a good idea and make it work.

But for every good idea, expect to have five or ten bad, wrong or useless ideas. This is my experience from fifty years of observing the creative work of the engineers and scientists that I know. Some times the bad idea does not survive a conversation or some clear thinking over a weekend. But sometimes you get to the stage of building a prototype or an experiment or publishing a paper before you realize it is a bad idea. And sometimes the thing is already built.

Gilbert's *The World's Worst Aircraft* is full of horrifying example of bad engineering ideas [8]. In science sometimes it can take a century for a bad idea to be defeated; phlogiston and the electromagnetic ether are examples. There are many reasons why ideas are bad – perhaps it violates physical laws, or a competitor has a better product based on the same idea. The only way to proceed in creativity is to use 'patience and fortitude' [9] in looking for the good idea.

Unfortunately most histories and biographies in engineering and science neglect the abundance of bad ideas. This is partly due to hero worship and partly due to the writer not being an engineer or scientist. They just don't know about all of the bad ideas, and nobody bothers to mention their abundance. I hope I don't make too many enemies by pointing out that books about Einstein's work usually err in this direction. After enthusiastically discussing his stupendous early work they spend little space on his many erroneous ideas on unified field theory after 1925, and the fact that he ignored important strong and weak forces. For example, Isaacson in his recent, popular 500 page book on Einstein [10] devotes only a few pages to ideas that didn't work. Where is the young engineer or scientist to learn about the prevalence of wrong ideas in the work of great engineers and scientists?

Edison's laboratory style is a marvelous example of the success that can come with acknowledging that most ideas turn out to be useless and yet continuing to give everything a try. But my favorites, by far, are the entertaining, overblown accounts of Francis Jehl [11].

Finally, don't try to hide a wrong ideas or wrong results, for as Medawar [12] says, "The important thing is not to try to lay down some voluminous smoke screen to conceal a blunder".

3.2 Good ideas and the technology you use

To get a good idea you must be immersed in some technology: biological, electrical, mechanical, or mathematical. You must be interested in, and perhaps even enchanted by some of the technology, software, or mathematics you use. Then the bad days are not so bad. Another advantage of being enchanted by a certain technology is that you will be more likely to think of improvements and variations. You should be fond of the technology that you use, but not so much in love that you are blind to the possibility that there may be a better way. Also, avoid the natural tendency to ignore technology that is 'not invented here'.

3.3 Colleagues

Colleagues who are supportive and helpful will aid in the development of a good idea and shorten the time you spend on bad ideas. And as emphasized by Medawar, it is important to [12] remember that technicians are colleagues, too.

4. Getting good ideas in engineering and science: what the educator should and should not do

4.1 We overeducate

As engineering and science keep changing and expanding, we educators keep pushing the students to learn more and more. Repeating my introduction, we move college level courses into high school, move graduate level courses into the college curriculum and extend the sophistication and specialization of graduate courses. The student's time is filled with studies, homework, and testing. There is little time for the student to play with ideas, to dream about discoveries and inventions. We overfill the student's time and the student's head. Below I will discuss two proposals that will alleviate this.

4.2 Reduce requirements for degrees

I propose that the course requirement for undergraduate and graduate degrees be reduced to basic subjects. For example, the course requirements for a physics doctorate should be limited to advanced courses in classical mechanics, quantum mechanics, electromagnetism, quantum field theory and statistical mechanics, as well as intermediate level courses in solid state physics and elementary particle physics. The students might take other courses such as cosmology, string theory, advanced fluid mechanics, or biophysics depending on how they want to spend their time.

Teach students to learn as they go in their work or in new projects**.** Teach them that they don't have to do extensive study to move into new technical areas, they can learn a subject or a technology as needed. Emphasize learning by doing.

4.3 Change the nature of laboratory courses and Ph. D. research

I propose that laboratory courses be revised so that there is an emphasis on process and problem solving rather than finishing prescribed experiments. Allow the students to try their own ideas and to make mistakes. As an undergraduate in chemical engineering I hated chemical quantitative analysis, and the finicky methods I learned were soon made obsolete by the march of technology. It would have been much better if I could have set my own analysis problems.

There is an over emphasis on 'original research' as a requirement for a Ph. D. The work is usually part of a larger, ongoing research program. It is primarily training in R&D. Reduce the pressure on the doctoral student by not depending on them to justify the professor's salary or grant. Encourage students to tryout their own ideas, make, and learn from their own mistakes.

Acknowledgement

I am very grateful to Professor Veljko Milutinovic of the University of Belgrade and Professor Hironori Fujii of Tokyo Metropolitan Institute of Technology for stimulating discussions on the subjects of creativity and innovation.

This work was partially supported by Contract DE-AC02-76SF00515 with the U. S. Department of Energy.

References

1. D. K. Simonton, *Creativity in Science,* (Cambridge Univ. Press, Cambridge, 2004).
2. P. Stephan and S. Levin, *Striking the Mother Lode in Science*, (Oxford Univ. Press, New York, 1992).
3. J. H. Austin, *Chase, Chance, & Creativity,* (Columbia Univ. Press, New York,1978].
4. M. L. Perl, *On Learning in Engineering and Science When Old*, SLAC –PUB 12701 (2007), to be published.
5. E. Kreyszig, *Advanced Engineering Mathematics*,(Wiley, New York, 1988). This is a twenty year old book but this demonstrates that the mathematics we usually need changes slowly.
6. W. I. B. Beveridge, *The Art of Scientific Investigation*,(William Heinemann, London, 1953).
7. E. S. Ferguson, *Engineering and the Mind's Eye*, (The MIT Press, Cambridge,1993).
8. J. Gilbert, *The World's Worst Aircraft*, (St. Martin's Press, New York,1975)
9. Quotation from Fiorello LaGuardia, Mayor New York City during the 1930's Depression years.
10. W. Isaacson, *Einstein,* (Simon & Schuster, New York 2007).
11. F Jehl, *Menlo Park Reminiscences*, (Edison Institute, Dearborn, 1936-1941). This three volume edition is out of print but can be obtained from used book dealers. Dover Publications, New York, has republished the first volume.
12. P. B. Medawar, *Advice to a Young Scientist*, (Harper & Row, New York, 1979).