Creativity and Skill in Science

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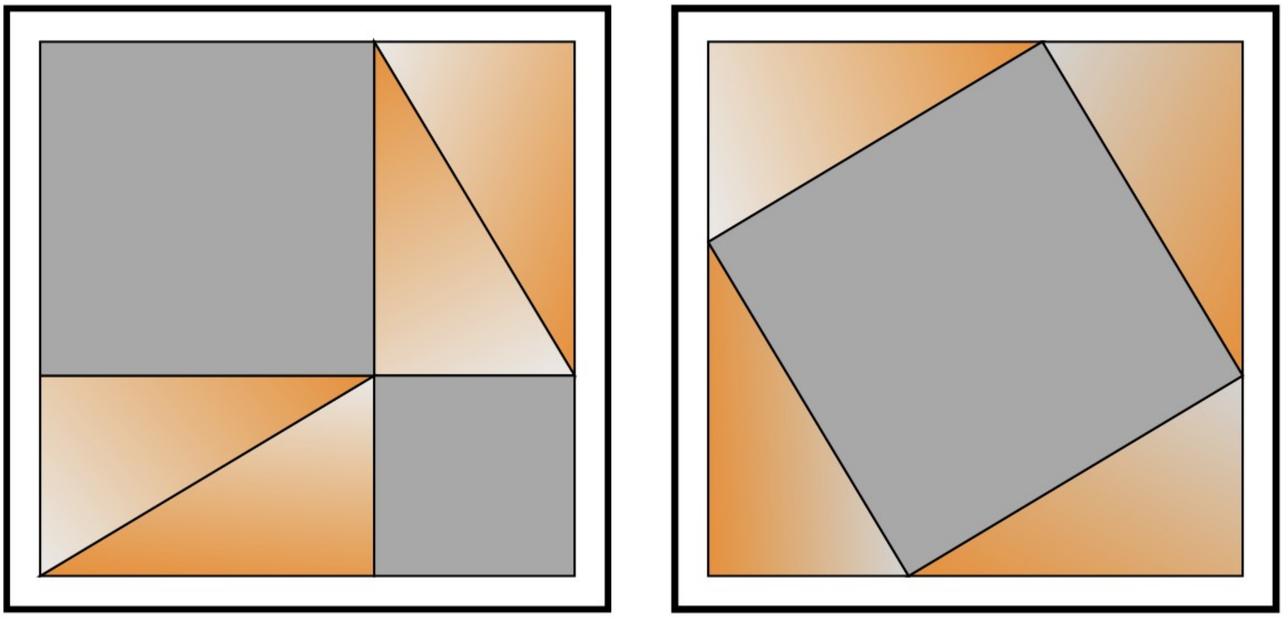
There are probably around a hundred proofs of the Pythagoras theorem. Functionally they are the same; they all prove the Pythagoras theorem. But some of these proofs are beautiful, some are surprising, others are dull. If you “speak maths”, then one proof is a like a poem, and another is like an excerpt from a safety manual. One proof is creative, another one is utilitarian.



At first sight it may seem surprising that something as mechanical, as algorithmic as a mathematical proof can have aesthetical properties. Aesthetical properties are, after all, more commonly associated with art, music, and literature. But the relevant difference between a mathematical proof and a painting does not reside in the human ingenuity or creativity required for either pursuit. The relevant difference is in the tools that are used to express our creativity: cunning jumps in logic in one case, paint and canvas in the other. This could be the end of this essay, but there are aspects of scientific creativity that set it apart from any other form of creativity.

We should start off by defining what science is. This is easier said than done, as there are several schools of thought about its definition and its practice. But all of these have the two key ingredients in common, perhaps first pointed out by Francis Bacon, that science combines a theory, these days usually described in mathematical language, and repeatable observations.[1] From these two ingredients, science progresses through induction and extrapolation, and new observations. Ultimately, the agreement of theory with observations is the judge of the success of this progress. If the observations contradict the theory, then something must give. It is not allowed to have theory and observation contradict each other, although in the exploratory phase of any line of enquiry such contradictions may occur. These contradictions may be the signs to further progress, or the stop-signs at a cul-de-sac. Good scientists are often those that are best at avoiding

1 In this definition, mathematics is not a science. For the purpose of this essay I will group mathematics together with the sciences as they are deeply interwoven in practice.

the cul-de-sacs. To use the apparent contradictions between theory and observations to find your way forward requires creativity.

This is exemplified by the great revolutions in physics that occurred in the early twentieth century. Around the start of the twentieth century physics had gathered increasingly confusing observations and insights in established physical theories that seemed to be in contradiction. This did not lead to a standstill in physics. Some of the greatest minds in physics used these contradictions as a springboard to the development of relativity theory and later quantum mechanics. The leaps of imagination required to understand these developments are still a challenge to current students of physics. Both theories are deeply strange and beautiful. Both are creative masterpieces that explain most of what we can observe in nature. Interestingly, they are also in apparent contradiction with each other. This contradiction has been keeping theoretical physics busy for the past decades.

Besides strange and beautiful, these theories are also highly technical. There are a lot of pre-requisites on the physics and mathematics side, before you can understand relativity theory or quantum mechanics in detail. However, there are several good popular science books around that explain the outlines of those theories to the interested layman.

The technical skill and rigid precision required to work in science at first sight appears to stifle creativity. It might appear that a scientific paper is bound by hard rules and convention, while a piece of art is created by the free flow of ideas and actions. But to do so we would be making the wrong juxtaposition. I will argue that the opposite of creativity in science is not precision or technical skill; it is utilitarianism.[2]

There is no particular trait that sets scientists apart from artists, except the technical skills they use to express their pursuits. And like all technical skills, scientific skills take a lot of effort to learn. The difference is that many people try to attain the skills associated with “the arts” while fewer try to attain those associated with “the sciences”. Incidentally, many scientists are great musicians. The opposite seems to happen rather less (a famous counter-example is Edward Elgar, who was a keen amateur chemist). Science to most non-scientists occurs behind closed doors, both literally and figuratively. Creativity and beauty in science often cannot be appreciated by the non-scientist. The derivation of the Planck radiation law is a thing of beauty, but this beauty is only accessible if you understand the language of physics and mathematics.

Such contrasts between knowledge of the sciences and the arts is largely a cultural problem: it is often accepted that the public knows little about science and the scientific method, while it is assumed we all know about the key works of art. At a cocktail party you would stand out if you admitted that you never read anything by Shakespeare, but it would be accepted without an eyebrow raised if you admitted to ignorance of Einstein's ideas, or even perhaps to not knowing who Einstein was in the first place.

This is a well-known cultural separation, famously pointed out by C. P. Snow in his 1959 Rede lecture on *The two cultures*. Apparently it sparked quite a debate at the time. There are no obvious signs that anything has changed since then. Widespread scientific illiteracy and innumeracy unfortunately remains. A recent poll by the National Numeracy[3] charity indicates that around half of the adult population in the U.K. have numeracy skills roughly equivalent to those expected by children at primary school.[4]

It does not need to be so. Much of this cultural dichotomy has to do with the kind of things we teach in our schools. What is the canonical curriculum; what do we expect young

2 The use of the word utilitarian here refers to the common usage as designed to be practical or useful, not in the limited philosophical sense, for example, as associated with John Stuart Mill.

3 See http://www.nationalnumeracy.org.uk/home/index.html

4 For examples how innumeracy affects our society, see John Allen Paulos: *Innumeracy; mathematical illiteracy and its consequences.* Hill & Wang, New York, 2001.

people to know when they leave school? Take this one example. One of the most basic insights in mathematics is the realization that there are numbers that are not fractions. We call these numbers irrational numbers; the well-known number “pi”, the ratio between the circumference and the diameter of a circle, is one such irrational number. The proof of the existence of irrational numbers is about two-and a half thousand years old. It is based on mathematics that any eleven-year old can understand, and it is a genuinely beautiful proof.[5] When I study it, it gives me a similar intellectual stimulus as listening to Bach's Goldberg variations. There is beauty, surprise, profoundness. Why is this not also part of the intellectual baggage of any educated human?

There are many examples here that ought to be in the canon of human knowledge, and this is not just for the purpose of participating in a civilized discussion at a cocktail party. The sciences also serve an important societal purpose. For example, the current discussion about human-made climate change is skewed by the rantings of scientifically illiterate and politically motivated campaigners, on both sides of the argument. To properly understand climate change requires a good understanding of the physics of radiative transfer, not an easy subject at all, but certainly something of which most can understand the basics. The quality of the arguments along with the resulting policies would improve enormously if the participants actually knew what they were talking about. Surely, this is an important enough issue to take scientific background seriously. This is just one example, but there are many key societal issues that can only be seriously discussed if the scientific background of the participants is sufficient. Examples of such issues include: energy safety, genetic manipulation, euthanasia, terrorism, drug policy, and the list of important issues just goes on. The current president of the Royal Society, Paul Nurse, in his 2012 Reith lecture made a passionate plea for the importance of scientific understanding and knowledge to improve our society.

Notwithstanding the obvious importance of science to our well-being, the free-thinking scientist seems to be in the eye of the public a dangerous figure. Think animal labs, cloning of embryos, genetic manipulation, climate science. Nuclear power has always kept the negative image that stuck to it from nuclear weapons. This leads to public relations disasters and panic when any accident occurs in a nuclear power station. Now it is politically difficult to promote, or even discuss nuclear power, when it might well prove to be the only viable option which does not pump unacceptable CO_2 levels into the atmosphere, while at the same time keeping the lights on. (This last point should of course be a matter of informed discussion.) But the overarching theme remains that there is mistrust of the freely acting, creative scientist. Of course, in most cases the scientists only developed the physics and the technology; it was the politicians and the society they represent that produced the side-effects.

Now we can come back to creativity in science. It is no wonder that science is not often associated with creativity when scientific illiteracy is so widespread. To understand scientific creativity, to “get it”, requires scientific knowledge. But this knowledge is not elitist: to become a great scientist, you need to know science at the highest possible level, but to appreciate scientific creativity you can get by with knowing about the important grounding ideas of science. Most people will never become great jazz musicians, but many come to appreciate its intricacies and complexity, which usually requires quite a bit of training of the ear.

In his essay *Two concepts of liberty*[6]*,* Isaiah Berlin describes how to achieve positive freedom, we need to give ourselves the tools, skills, and understanding to be able to pursue our goals. If we do not possess the abilities to achieve what we aim for, we are not

5 The proof is based on a *reductio ad absurdum*, a technique where the opposite of what is to be shown is assumed, and then this is proven to lead to absurd results.

6 Isaiah Berlin: *Liberty*. Ed. Henry Hardy, Oxford University Press, Oxford, 2002.

free. A mathematical proof irrefutably decides which option is the correct one out of a set of possible options. But this does not reduce the number of options. With the proof we have expanded our knowledge and we are free to make the next step forward. Without the proof, we are stuck at the base; we are not free to move on.

To become a good musician, you must practice a lot.[7] It is widely appreciated that much of this practice is essentially rote practice; think of the scales and arpeggios that classical musicians need to master. This is true for science as well. Richard Feynman, in his majestic *Lectures on Physics,* suggests to his students that, to become a good physicist, you need to simply practice the important mathematical techniques over and over again. Feynman says[8]:

> Errors in algebra, differentiation, and integration are only nonsense; they're things that just annoy the physics, and annoy your mind when you're trying to analyze something. You should be able to do calculations as quickly as possible, and with a minimum of errors. That requires nothing but rote practice – that's the only way to do it.

Naively this rote practice can be considered to stifle creativity. But, as in Berlin's argument on positive freedom, it is the opposite. When during lectures I try to convey the intricate beauty of thermodynamics to my students, many of them actually do not not see beauty; they can only see an algebraic swamp on the blackboard. Any subtle twist of an argument, any profound insight in the material is largely invisible to students who struggle with the mathematical tools needed to do thermodynamics. For those students there is no creativity on show, there just is turgid formalism.

On exams, the outcomes often follow a predictable course: those who do not possess the required technical skills get stuck at stage one; those who are proficient in the required technical skills see beyond the mathematical formalism, because they internalized it, and they start to see the underlying physical ideas and use their creativity to come up with relevant insights in a problem. Marking exam scripts is usually not the most inspiring occupation, but when I see a student shine with creativity, I know that this student enjoyed the material. The student can play with the material, look at it from all sides, see the caveats, see the intricate connections, see a beautiful edifice which they can build further when they become scientists themselves. But the pre-requisite is always the technical skills, skills that can only be internalized through rote learning.

Such rote learning is needed at all levels. Times tables are boring but to make any progress with numerate skills, they are essential. Being able to use a calculator does not solve the problem of innumeracy; in fact, it probably makes it worse. Innumeracy is the lack of insight in numbers, it is not whether you are able to do a sum; a calculator can do a sum. With a calculator we can calculate the energy usage of all the televisions left on in stand-by mode, but it does not provide the understanding why switching of the television at night does not solve the problem of climate change. To gain insight in numbers, the connections between them need to be clear in the mind. That is why children need to learn times tables, not how to use a calculator. To make any creative connection in a numerate subject, the basic structures need to have been internalized.

There are pleas to make the school curriculum less rigid. Ken Robinson[9] has argued for many years that the current school curriculum stifles creativity. This may well be true, but it does present a particular problem for the sciences. As I have argued, creativity in science

7 Malcolm Gladwell famously suggested that 10,000 hours of practice are required to become truly proficient in any advanced skill. See Malcolm Gladwell: *Outliers: the story of success.* Allen Lane, London, 2008.

8 R. P. Feynman, M. A. Gottlieb, and R. Leighton: *Feynman's tips on Physics. A problem solving supplement to the Feynman lectures on physics.*Addison-Wesley, San Fransisco, 2006.

9 See http://sirkenrobinson.com/skr/

is only possible when technical skills are internalized. Nobody would argue that daily reading practice stifles creativity; it is essential for progress in so many fields. The same is true for numerate skills; they are essential for any meaningful creative progress in science. This is the great challenge of eduction: how can we teach our children the necessary skills without dampening their natural enthusiasm and curiosity for scientific enquiry? This requires a difficult balancing act: science is only exciting and ultimately creative when done by numerate pupils. And, of course, this balancing act can only ever be achieved by highly numerate and scientifically literate teachers.

The particular challenges that scientific creativity pose remain at every level where science is done. In science practice there is an increasing emphasis on “impact”, “knowledge exchange”, and “outreach”. With such a change in emphasis, successful researchers need to be experts in salesmanship and publicity, sometimes at the expense of technical skills. Promotion cases at universities routinely reward salesmanship (success at obtaining grants, or at making a splash in publicity) ahead of scholarship.

Such a change of emphasis away from the technical pre-requisite to the utilitarian outcome has the potential to stifle the creativity in science. Ultimately, this will cost us dearly. Creativity is not just a flourish on scientific pursuit. Creativity is the engine of scientific pursuit.

Scientific research at universities is largely funded by taxpayers with moneys divided by dedicated funding agencies. Under political pressure those agencies focus more and more on “impact”. Any research proposal now needs to provide a “pathway to impact” (or some other euphemism) to indicate how the research is going to be used in the wider society (read “how it will economically benefit U.K. Plc.”). Although this may appear to be a reasonable requirement of the taxpayer on the science done in those ivory towers, it results from general ignorance of the scientific process and it is hurting science and stifling creativity. Ultimately, the economic returns of our science will diminish as a result.

Thomas Kuhn[10] presents one model of science where scientific progress happens in paradigm shifts, where old models are rejected in favour of new ones. The Copernican revolution may be the most famous example of this, and the previously mentioned developments of relativity theory and quantum mechanics are two other examples. Outside those paradigm shifts, most of science is occupied with experimenting and testing the prevailing paradigms. It is not that this “normal science” is not valuable; it is essential to building up a strong evidence base for existing paradigms, but in itself it does not push science forward in any great fashion.

In my own experience such paradigm shifts happen all the time, but at a small scale – at this level the words “paradigm shift” are of course rather grandiose.[11] This is the practical dimension of creativity in science. Those small-scale paradigm shifts are not world changing, and they are usually only of interest to a specialized group of practitioners, yet this is how progress in science is made. At this level, the “normal science”, the science devoted to consolidating and testing existing paradigms, is a somewhat dull “turning the handle” exercise. Unfortunately, our funding models are geared towards supporting the latter type of science. The small-scale paradigm shifts that we are truly interested in cannot be described in a pathway to impact. They require creative leaps of imagination leading to unanticipated outcomes.

Would a newly commissioned piece of visual art be of any value if everyone knew beforehand how it should look? Would a piece of research be of any value if the outcome

10 Thomas S. Kuhn: *The structure of scientific revolutions.* Univ. of Chicago Press, Chicago, 1962.

11 Grandiose wording is routinely being used, though: some funding agencies ask researchers to report how many “breakthroughs” have happened since the last report. Imagine the marvellous world we would inhabit if every scientist had some breakthrough every couple of months.

was to a large part predetermined? Clearly, the answer to both questions is a resounding "no". Yet, there is a constant pressure, a constant "nudge" to make science more utilitarian: "what will the outcome be of your research, and how will it be useful?" If the outcome was known we wouldn't need to do the research, yet this Catch-22 situation is endemic in science funding. Again we are trying a difficult balancing act: all scientists will agree that their research should be important to society but it can only be truly important if there is the creative freedom to do the kind of science that may lead to truly novel findings. Ultimately, only creative science, unfettered by utilitarianism, will provide true value for money.

Even in industry an emphasis on creative freedom pays in the long run. The big technological companies used to have research labs led by enlightened ideals that were less driven by project outcomes, and more by the nourishment of basic ideas. Under these enlightened ideals, scientists at Bell Labs developed the first transistor, leading to a Nobel prize for Shockley, Bardeen and Brattain, and, of course, the technological revolution of the past 50 years. In the same laboratory, mathematician Claude Shannon produced his theory of information entropy, providing the mathematical foundation of modern communication technology and a large part of modern theoretical physics. Work at Bell Labs earned six Nobel prizes in physics along with several other inventions that changed the world. None of these would have been helped or predicted by a pathway to impact. In fact they would have hindered it. Since the 1990s Bell Labs have been transformed by the usual mergers and management re-structurings to promote cost-effectiveness. Only a handful of scientists now work on basic physics research.[12] One of the few memorable recent outputs of the successor to Bell Labs was a highly publicised case of scientific fraud.

Utilitarianism is the opposite of creativity. Both act on progress, scientific progress in this case, but in creative progress the direction is by definition free; if it was pre-defined it could not be called creative. On the other hand, utilitarianism sets the direction of travel; it defines properties of the endpoint and we just need to turn the handle to get there. By shifting the focus from the creative basis to the utilitarian endpoint of scientific pursuit we will kill the golden goose.

Truly enlightened science funding must allow for the unexpected, and not just pay lip-service to it. A truly enlightened school curriculum should also allow for the unexpected. Creativity only flows when people have the tools to express their creativity, and the intellectual space to pursue it.

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12 For a report see *Nature* **454**, 927 (2008) doi:10.1038/454927a