The Scientific Craftsperson: Beauty, Engineering and the Bohemian Researcher

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Abstract. "Engineering" and "Beauty" seem to be diametrically opposed concepts: one concerned with hard reality, experimentation and evidence; the other generally associated with subjective, culturally-shaped experiences. And yet science and beauty are often discussed together, and many parallels have been drawn between the two disciplines. Engineering solutions are often considered beautiful, at least by engineers (think of a Phase Lock Loop, for instance) - but are they? Can the pursuit of beauty help the engineering endeavour? What about elegance - does this concept have any more bearing on engineering? Pushing engineering outside its traditional boundaries, this paper attempts to show that in spite of the dangers of aesthetic rules inevitably steering the judgement of the clinically-minded engineer, beauty and elegance do indeed have an often undermined, but positive effect on the practice of engineering and these values should be nurtured instead of discounted.

1 Introduction

Science and Beauty have walked hand in hand since the beginning of civilization, but their relationship has been a complex one, which continues to evolve through the times. In an age where the natural, irregular, "organic" beauty of nature dominates the everyday life of early populations, man-made precision, which hinted at the metaphysical world of perfection of the gods, becomes "beautiful"; this precision is expressed for example in perfect shapes and perfect colours to replicate the unconscious beauty of nature. Both types of perfection require refined techniques and technologies, which in turn require ever more refined science to allow these techniques and technologies to blossom.

In an era of man-made precision, the concept of Beauty is extended and becomes less literal. In order to progress on this, we will refer to "Beauty" as the sense of awe and pleasure which fills us when observing (in the widest possible sense) something. Returning to Nature we can find beauty in the exploration and description of a Nature-puzzle to be solved and exploited, or in the awe of discovering a sophisticated mathematical fabric underpinning the whole (set of) Universe(s), or simply in the visually attractive patterns created by water as it freezes over a windscreen – indeed the mathematical-physical description of such patterns. In these examples science is either itself the source of Beauty or the mechanism which unveils it from beneath the seemingly unpredictable behaviour of invisible forces. What does it mean to talk about beauty in science? The

easy descriptions of beauty as visually pleasing when applied to 3-dimensional fractal patterns is unsatisfactory: many lay people would consider the symmetry embedded in some mathematical functions, or the sound of a pulsar many million light years away as "beautiful". Often we hear that $E = mc^2$ is "the most beautiful formula in physics", but the answer to "why" will probably be very confused and/or confusing.

Indeed, what makes it beautiful? Perhaps more importantly, is it beautiful for everybody or could you find someone who will be prepared to say that it is "ugly"? Does it depend on the level of understanding of the formula? And if we talk about beauty in Science, what about beauty in Engineering: could this combination of words be even acceptable, or are they such a dichotomy that putting them together cancel each other out?

In this essay I will attempt to link Beauty to the scientific endeavour in a way that allows engineering in the mix, in a pragmatic and indeed practice-oriented way: I will show that an aesthetic assessment of each own work is, if not pragmatically a necessity, an aspiration to keep in mind during any scientific and engineering-related activity. In order to achieve this goal, I will define Elegance as a precursor to Beauty, which I consider a real requirement for good engineering: this will provide the ground on to which to build the thesis I propose.

Of course, this essay does not purport to appear as an authoritative contribution in the philosophical arena: more humbly, it is a set of reflections and musing by the author. I am indebted for the contribution of a number of people who have read and commented on the work, particularly my long-suffering wife Claudia, who, as an artist, has provided me with deep insights in this field and has provided many valuable comments, and my friend Ugo Concilio. Every responsibility for inaccuracies and misrepresentations remain however with the author.

1.1 How not to close a discussion

This essay was conceived just after a discussion with a manager at a company at which I was employed as a design engineer. We were discussing some circuitry to be included into an ASIC (Application-Specific Integrated Circuit) which was responsible for generating a Sigma-Delta modulated stream which, when low-pass filtered, would provide the necessary voltage for a VCO (Voltage-Controlled Oscillator) to maintain a frequency with a fixed, known fractional relationship with respect to a reference frequency. It was a disarmingly simple device, all digital (apart from the low-pass filter) and very small in terms of silicon area; my task consisted in integrating this device into the rest of the IC. Discussing some possible solutions, I mentioned that one would be very beautiful but would need a bit of time to develop, so I will concentrate on the "rougher" basic solution: his answer to that was, in a very serious voice which was meant to indicate that A Very Important Concept was being imparted upon me: "We Don't Do Beautiful". That exchange remained in my head, and is still there – and I think it is destined to remain there as a "foundation memory". My initial reaction was a vague sense of disappointment: the reason why I do electronics is precisely because I find it

"beautiful"; to be told that it is anything but was quite a blow! I then thought that probably he was trying to hurrying me up with my task, so in the coming months I managed to probe further his statement, and indeed found that it was not a spur-of-the-moment thought, but a real conviction. I question now as I did then the strength of that conviction: can you really become a manager of something you don't find beautiful – in fact he is an excellent manager, and I can't really believe that. But that answer hinted at something which I have experienced over and over again: between "beauty" and quick solutions, in industry we always tend to go for the quick solution, however inelegant (in the traditional sense) that is (well, there are limits there, of course). We never did have a discussion about this: the conversations I tried to start about beauty were always closed in sacrifice to the god of Time. Instead, I went away and did what I like doing: I tried to make sense of what I observed.

2 A Concise Treatise on Beauty

Everyone can easily put forward statements about beauty in paintings, poetry, music, sculpture, regardless of our philosophical abilities: Croce points out in his "Breviario di Estetica"[3] that "common people" could easily make the philosopher flush with in-depth discussion on beauty and art, these two subjects being so close to our hearts. However, relating this to science is more difficult territory: can the scientist, often imagined in the typical Hollywoodesque white coat, crazy hair and nerdy attitude, really produce "beauty"? And what about the engineer: this is often seen as an even less plausible actor in the development of beauty, so engrossed with practical issues to solve to lift his/her head to look at the world around. The problem may stem from the romantic idea of the artist as a "damned hero", so embedded in our society that anything else seems rather incongruous: in my experience, when asked to name an artist, most people would mention artists with troubled life histories, who produced high-impact art seemingly at the expense of their own sanity or health[1].

The relationship between science and beauty has been explored by many philosophers, and has become more relevant with the advances of physics which have opened avenues in science towards aesthetics which were not available before. Arthur I. Miller points out that Einstein in 1905 "introduced aesthetics into modern physics by arguing that the "profound formal distinction" scientists made that particles of electrons emit waves of light was unwarranted [...] his discovery that light could also be a particle emerged from his minimalist aesthetic"[6]. And in mathematics in particular, aesthetics has been part of the discourse from a very early age: Greek philosophers found beauty in the perfection of the simple formulae describing complex natural features. More recently, Dirac famously said that "it is more important to have beauty in one's equations than have them fit the experiments"[4].

[1] It is also my experience that those versed in art history typically make different choices

The first problem is to work out whether beauty and science are compatible. In order to address this point we initially equate art and beauty, by identifying producing art as the act of pursuing beauty[2]. Most thinkers, and indeed a first sight most people, would introduce a necessary distinction between art and science: Croce indicates the necessary contraposition between art-intuition and science-classification, where art has an unconscious quality and science is fully conscious. Indeed, Croce considers the two to be diametrically opposed and incompatible, relating to different "esprits". This distinction is to me artificial and indicates a distance from the scientific pursuit: while experimentalism is indeed far from art when a mechanical repetition of actions (itself necessary to the advancement of science in some – most? – cases), history of science is punctuated with examples of beautiful theories/proofs/insights which are akin, for me, to art works. Examples include Maxwell's equations, quantum mechanics, Fourier transforms.

An additional pitfall which needs to be identified in order to avoid distractions is the distinction which needs to be made between the underlying beauty of the natural phenomenon described by a scientific theory and the beauty of the theory itself[3]. The point here is to distinguish, for example, between the "beauty" of the DNA molecule and the environment around it, which allows life to proceed from such a system, and the theories and experiments which led to its discovery: let us, for instance, consider the DNA molecule "beautiful" from a visual perspective, observing the double-helix configuration as our primary focus; the danger is to consider anything related to DNA similarly beautiful. Confusing the two (the observed and the observation) is disastrous for our discussion, because it will lead us into the traps of believing that science can only be beautiful "by reflection", i.e., like a planet which shines of the reflected light of the sun, science can only be considered beautiful if the matter studied is itself beautiful according to some criteria. Quite apart from being rather disheartening for those scientist who work on "ugly" phenomena (again, according to some aesthetic criteria), it diverts us from our quest, because it hides what is really beautiful about science, which in my opinion transcends the subject matter of the scientific produce.

Another distraction is the identification of criteria for beauty which refer to senses; for instance, using "symmetry" as a criteria confuses the issue because it cannot applied to all scientific produce. I don't mean to limit symmetry to what is visible, as this quality can be applied abstractly to a number of mathematical representations when we extend symmetry to indicate formulae which don't change following rotations and translations; rather, I question the perspective of some to draw the conclusion that "symmetry is a criterion for beauty" be-

[2] This is not necessarily a satisfactory equation, but it will serve as a starting point for the discussion. Indeed, we can use it in this context where we are not concerned with the relationship between art and beauty; thus the equation can be useful to introduce a shortcut between "beauty" and "the pursuit of beauty"

[3] Of course, for "theory" one can substitute any scientific endeavour. I will often refer to "solutions", in a reference to my previous mention of the Nature-puzzle

cause most people would consider symmetrical objects beautiful, confusing the pleasure obtained through a visual experience with a more general idea.

It could be said that as scientific theories are representations of reality, truthfulness is a requirement for beauty; this, however, would draw us back into the trap of believing that beauty can only refer to nature, again confusing the observed with the observation.

So, what is beautiful? Is beauty objective – and whether it is or not, can we identify a set of criteria to draw a line (hard or otherwise) between "beautiful" and "ugly"? As I indicated above, "aesthetic" is a branch of philosophy with a long history (although the term is relatively modern, and appeared in the middle of the 18th century as the title of a work by Baumgarten); as such, many diverse theories have been put forward to identify, precisely, "what is beauty", from the most intuitive idea that "beauty is something which gives you pleasure for the senses", which we classify as "hedonistic", to beauty (or rather art, at one time identified with pursuit of beauty) as expression of the divine (medieval aesthetic, St. Augustine) or the "absolute" (Schelling, Hegel), to the modern perspective which refutes a normative definition of beauty and instead focuses on the piece of art itself. Alas, a proper dissertation on the subject would be beyond the focus of this essay, and will be left to reader to investigate the history of aesthetic further. However, it is important to mark some points in this rich history. The first point to observe is that, while modern aesthetic attempts to refute a normative approach[4], this position is unsatisfactory for our investigation[5]. An observation which we come back to is from Kant: something beautiful appears "purposive without purpose"[6], i.e. it appears to have a purpose, but no specific purpose can be found. This point is important and will be discussed later. A more important contribution to note for our discussion is Denis Dutton's proposal of six universal signatures for human aesthetic[2]:

1. Expertise or virtuosity. Technical artistic skills are cultivated, recognized, and admired
2. Nonutilitarian pleasure. People enjoy art for art's sake, and don't demand that it keep them warm or put food on the table
3. Style. Artistic objects and performances satisfy rules of composition that place them in a recognizable style
4. Criticism. People make a point of judging, appreciating, and interpreting works of art
5. Imitation. With a few important exceptions like abstract painting, works of art simulate experiences of the world
6. Special focus. Art is set aside from ordinary life and made a dramatic focus of experience.

[4] Pareyson for instance proposes that a piece of art is successful according to a norm (or set of norms) defined within the piece itself, and the norm defines the invention and the criteria for the artwork

[5] The reader will forgive me for not pursuing this aspect further in this paper

[6] "Critique of Judgment"

One could easily draw parallels between these signatures and science: "beautiful" science is considered to be "difficult"; "style" could refer to different schools of thoughts on a particular subject; criticism can be found in the peer-review process, for instance; imitation can go in parallel with re-use. As for non-utilitarian pleasure and special focus, although scientific discoveries can be said to be driven by "need", in reality the theory which describes the phenomenon and the experiments devised to investigate nature are, in my view, entirely works of the mind and in themselves can be enjoyed for their own sake and are set aside from ordinary life. Consider for instance the theory according to which dark matter permeates the Universe: assuming it "beautiful", it does not provide me with shelter or food, and indeed is set aside from ordinary life, but it does provide me with a dramatic focus of experience. And indeed we can apply the above signatures to the theory and consider it beautiful. But Dutton's signatures are not the end of the story: being universal they risk encompassing too much. However, the strength of the signatures is that it bridges the objective and subjective parts of beauty: if I cannot appreciate the virtuosity of a piece of art I cannot consider it beautiful; thus, a sense of "responsibility" is required on the part of the beholder and his/her knowledge becomes part of the appreciation of beauty not just as fruition of beauty but also as a determining conscious act.

Karl Popper delivered in 1953[7] a lecture[7] where he attempts to draw a line between science and pseudo-science, and arrives at a set of conclusions on the nature of science[8], which I use as the basis for the bridge between aesthetics and science:

- Science is courageous: it must allow the risk of being refuted
- A good scientific theory is a prohibition
- Irrefutability is a vice of science

The first thing to notice in this list is that it applies mostly to quite revolutionary steps in the progress of science: Popper was extremely impressed by Einstein's proof of General Relativity by Sir Arthur Eddington who organized an expedition to observe the solar eclipse of 1919 and showed that light is indeed bent by gravitational fields as expected by Einstein's theory. Kuhn correctly points out that most science is instead an accretion on existing knowledge: while Popper describes the "romantic hero" of science (see previous section), Kuhn talks about the "busy bees" who make up most of the knowledge by contributing small parts to greater ideas. It appears to me that Popper introduces some sense of aesthetic in the scientific discourse, in particular when he talks about risk. Observe that this position is very different from that of those philosophers who consider science to be the result of mechanical observations thus precluding science from any aesthetic activity for the lack of intuition. Rather, Popper seals the non-mechanical element of intuition and consequently an aesthetic perspective onto the scientific

[7] This lecture was subsequently published in the reference indicated in the bibliography

[8] Popper also indicates additional criteria more related to testability of theories, which I don't think are relevant in the current discussion

progress, warning of the risks of confusing the two aspects, mechanical accretion of knowledge and pure intuition not supported by observation. Kuhn counters that in reality the work of the scientist is far from the beautiful theories, and focuses instead on experiments: "the exploits of Copernicus or Einstein make better reading than those of a Brahe or Lorentz"[1]. Is beauty lost here? No: in my opinion, the aspiration of the scientist is still the beautiful theory, the ground-shifting discovery, the Higgs boson with the "wrong" weight, the Fourier transform. The other observation is that science and art are courageous in similar ways, pushing the boundaries of what's known and exploring the impact of new theories on existing knowledge, imposing distinctions and prohibitions and being open to debate/tests.

3 Beauty in STEM

"Armed" with the basic tools introduced above, we can finally approach Beauty in the STEM subjects (Science, Technology, Engineering and Mathematics) in steps or degrees, and this will be helpful to our final aim. We first look at a subset of what is beautiful, and I will use the term "elegance" for the quality of these instances. I will consider "elegance" a subset of beauty because in my definition something elegant might not be beautiful, while something inelegant cannot be beautiful. Of course, I am "overloading"[9] this term for my purposes here, but the word and its everyday meaning is in line with my aims.

I will use a normative approach for the definition of elegance and beauty in science: I intend these "norms" however more as guidelines than rules.

We can identify a set of criteria for elegance in science:

1. Clarity or effortlessness – an elegant solution, experiment, proof, theory can be understood by those familiar with the context, and the general idea can be grasped by those not familiar. This is the quality of an elegant work to appear as self-evident
2. Generality – it applies not only to the problem at hand, but can be re-used with the necessary modifications in other contexts
3. Control or coverage – an elegant solution covers the problem completely. This does not mean that it does not have limitations, rather that the limitations do not preclude breadth of application
4. Adherence to Occam's Razor – "entities must not be multiplied beyond necessity", the solution is economical and efficient

These four criteria can be applied to science and engineering works at various levels: experiments, theories, but also computer programs or computer languages themselves. I have chosen these criteria from my experience and they are therefore open to criticism (i.e. they risk to be refuted, as a good theory should).

Beauty extends elegance and we introduce the following additional criteria:

[9] A term borrowed from Computing, where a function can be overloaded if it has different semantics based on the number and type of input parameter and output

5. Virtuosism – a beautiful solution resolves a difficult problem, and/or challenges our preconceptions and knowledge
6. Intuition – a beautiful solution hints at something beyond the problem at hand and has far-reaching consequences (an instantiation of Kant's "purposive without purpose")

3.1 The Fourier Transform

As an example of beauty in science, I propose the Fourier transform. This is a mathematical tool which describes an arbitrary function[10] in terms of sinusoids of different frequency and amplitude. It is a remarkable method, and applied to technologies we use in everyday life; it also enables scientific methods and observations which further our understanding of physics, chemistry, astronomy to name a few disciplines. We can apply the criteria defined previously:

1. Clarity - The idea of a signal as composed of sinusoids of different frequencies and amplitudes is surprising to begin with, but becomes simple to relate to when observing a diagram. Most people use a graphic equalizer for their HiFi stereo - a direct application of the Fourier Transform
2. Generality - Fourier discovered this method while working on heat transfer and yet the very same method is used for anything from audio processing to radio communication
3. Control/Coverage - the constraints applied to the method are not a major limitation and the Transform is applied successfully in most applications
4. Occam's Razor - the Fourier Transform is powerful in its "economicity"; consider for instance the ability to deploy a Fast Fourier Transform (FFT), a method which simplifies the traditional Fourier Transform to make it available for deployment in digital computation platforms - or even by hand
5. Virtuosism - The idea of translating a complex, arbitrary waveform into its frequency components is such a divergence from the sensory perception of reality that it challenges our knowledge and preconceived assumptions. Moving from the actual observed light into analysing the colour components, astrophysicists are able to determine the composition of planets' atmospheres and stars, which in turn enables them to infer a history of the celestial bodies
6. Intuition - the "magic" of the Fourier Transform is that it opens a window on a completely different way to observe reality: the Transform itself is a mere mathematical tool, but the implication that every signal we observe (or make devices to observe) is composed of simple repeating waveforms of different amplitude and frequency has a metaphysical quality to it, and inspires us to consider corollaries which bring us far away from the original proposition

3.2 The Phase-Locked Loop

Elegance in Engineering is a more slippery concept to an extent, but as an example consider the Phase-Locked Loop (PLL). This device (which can be developed

[10] The arbitrary nature of the function is in fact limited by a number of constraints

mechanically or electronically) is able to track an incoming waveform and keep the output phase locked to the input phase. It is an important development in technology, enabling for example efficient and affordable modulation and demodulation of radio signals. It is a fundamental building block of many electronic devices, used for instance in clock generation.

Applying the criteria:

1. Clarity - The function of the PLL can be easily explained and is typically understood by undergraduates of engineering courses
2. Generality - The PLL is applied very widely in industry
3. Control/Coverage - The PLL device has very limited caveats in its deployment
4. Occam's Razor - The PLL is "economical" in that it requires limited boundary conditions to operate

However, I contend that the PLL does not completely satisfy the additional two criteria:

5. Virtuosism – This is covered, as the PLL does indeed resolve a complex problem which would require significant effort to resolve with alternative solutions (consider radio modulation and demodulation before the PLL)
6. Intuition - this is the criteria which I believe the PLL does not completely satisfy. Under scrutiny, the PLL operation can be described completely and it does not appear to open up different ways to consider reality

Thus, I propose that the PLL is an Elegant solution rather than Beautiful.

3.3 Beauty and Elegance: Necessity or Indulgence?

We now come to a fundamental tenet of this essay. I contend that "beauty" and "elegance", and the pursuit of these, are not only desirable aspects of the scientific and engineering endeavour; they are *necessary*:

- Beautiful and elegant solutions are clear and easy to understand intuitively. Examples are software coding, electronics design, chemical processes etc.
- This clarity makes portability and enhancements more reliable and predictable
- Such solutions also require less maintenance and additional follow-up work, as they have generality and coverage as defining features
- They are optimal as they adhere to the Occam's Razor rule
- Beautiful scientific solutions have an element of virtuosism and appeal to our intuition, which fills us with awe at the unending complexity of Nature, intended in the widest sense

A suitable metaphor which can be used here equates the scientist to the traditional "artist" and the engineer to the traditional "craftsperson". The artist explores the boundaries and challenges assumptions about aesthetic; the craftsperson exploits and develops ideas to turn them into practical deployments. It is

important to point out that the two are related: the two agents influence each other's work, enabling a complex interplay between artistic élan, technological constraints, business opportunities, customer appreciation. The parallels between the artistic and scientific endeavour are very appropriate to bring the scientific pursuit of beauty and the engineering focus on elegance on terms more closely related to everyday life.

Just as the artist and craftsperson uses and develops the available technology to their pursuits, so do the scientist and the engineer. In this context, the Engineer is a "scientific craftsperson": this agent invents new solutions to technical problems, translates the ideas of the "bohemian researcher" into practical products, provides the bohemian researcher with new and refined technologies to pursue new, beautiful science.

In summary, I consider that what moves us to further knowledge is science is not just our insatiable curiosity, but also a pursuit of aesthetic satisfaction which transcends the senses - in a way, scientific pursuit is *essentially beautiful* in a pure sense. Notice an intriguing parallel with (post-)modern art - a parallel we will not explore further in this paper.

4 Conclusions

Looking back, strictly speaking that (ex-)manager was indeed right: we (engineers) don't do beautiful - instead, we engineers "do elegant". But I don't believe the attitude of considering the idea of "beauty" in engineering with disdain, as an unnecessary distraction from the necessary work at hand, is correct. Introducing "elegance" is a way to introduce aesthetic appreciation in the engineering practice, however, seeing it as a burden, an incidental by-product of the work of the snowed-under engineer is limiting its application. What is the alternative to elegant work? Inelegant work requires regular re-work; re-use and extension of inelegant work require understanding of the original caveats and limitations, hampered by lack of full coverage of a problem; its use outside the strict letter of its manual (itself a work of engineering, thus subject to the same elegance criteria!) can have unexpected results. Thus inelegant work requires unnecessary resources which could be saved by more work on the aesthetic value.

And what about science, and in particular research? I believe that researchers have the privilege of aspiring towards beauty as an everyday endeavour; this privilege should indeed inform the choices and any work undertaken. It is true that a balance needs to be struck between what I call the bohemian aspect of the research and the day-to-day drudgery of literature reviews, computations, analysis etc. However, keeping in mind the higher ideal of Beauty during this work can only help in making the work more appealing and may lead to unexpected developments.

Finally, a necessary digression. I have avoided deliberately mentioning "truth" throughout the essay, but this is indeed an important concept in this context, especially to explain an aspect discussed previously. A pitfall which should be avoided at all costs is to equate beauty and truth: this equation we have already

discounted previously, but apart from the mistake of inferring beauty from truth, an even more dangerous mistake is to infer truth from beauty. Ian Glynn in the epilogue to his book "Elegance in Science"[5] reports an excellent example of this mistake related to the way data is encoded onto the DNA molecule (a warmly recommend read for every scientist). I mentioned before that "scientific pursuit is essentially beautiful in a pure sense": the price to pay for that is that at the end, truth defines the success or otherwise of scientific work. Art has no such shackles and is therefore free to explore beauty - a privilege not afforded to the scientist.

So my closing remarks are that beauty is not simply incidental to science, but a fundamental aspect of it. Engineers are the scientific craftspeople informed by aesthetic just as much as by science. A reassessment of the aesthetic value of the scientific and engineering endeavour would make us more efficient, more effective and, more importantly of all, *happier and more satisfied individuals.*

References

1. *Citicism and the Growth of Knowledge*. Cambridge University Press, Cambridge.
2. *The Routledge Companion to Aesthetics*. Routledge, 2002.
3. B. Croce. *Breviario di Estetica*. Adelphi Edizioni S.p.A., Milano, 2007.
4. P. Dirac. A thing of beauty. *Scientific American*, 1963.
5. I. Glynn. *Elegance in Science*. Oxford University Press, 2010.
6. Arthur I. Miller. A thing of beauty. *New Scientist*, 189(2537), 2006.
7. K. Popper. *Conjectures and Refutations*. Routledge and Kegan Paul, London, 1963.