The Engineering Method: a Framework for Understanding Technology Development

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Abstract

Contribution: This paper offers a general framework of technology development which allows for (a) a systematic approach to analyze technologies' main components, strengths, limitations and forward paths; (b) a better understanding by en- gineers of their practices and their projects; and (c) a clearer way to convey the engineering enterprise to students, non-engineering stakeholders in projects and the general public. *Background:* Technology has been an immense force of material, economical and societal change in the last centuries. Several authors, such as Marshall McLuhan and Kevin Kelly, developed important ideas related to technology and the engineering process, but there seem to remain gaps between these theories to be explored, bridged and extrapolated. *Research questions:* (1) What are engineers' aims in developing technologies? (2) What are technology's main components, and its relationships? (3) What differentiates the engineering enterprise from others? *Methodology:* Integrate previous theories of technology, apply more technical concepts that were not addressed by writers who did not come from an engineering background, and derive consequences from the proposed methods. *Findings:* A proper theory of technology can better guide engineers from several branches to understand their practices and the fruits of their labor. It also aids in explaining these points to stakeholders, students and the general public.

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The Engineering Method: a Framework for Understanding Technology Development

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***Keywords*—Technology studies, Engineering profession, Design process, Technical communication.**

I. INTRODUCTION

Technology is one of the defining terms of our era. The exponential development experienced in the last centuries, from the steam engine to the rocket engine and the microprocessor, is always one of the main points under consideration when looking at the past, as in historical comparisons of civilizations [1] [2], or to the future, as in economic, political and social predictions [3] [4]. Under the guise of the scientific method, science and engineering have been the great enablers of several of those changes.

Similar initiatives were partially developed in previous centuries. Around two thousand years ago, for instance, Hero of Alexandria created a prototype of the steam engine (the *aeolipile*), and Zhang Heng devised a seismograph [5]. However, perhaps there wasn't an adequate "ecosystem" to further develop these ideas at those times and places, as illustrated in the 17$^{\text{th}}$ century by the Royal Society of London, and in the 20$^{\text{th}}$ century by the Vienna Circle and Bell Labs [6].

Although being so pervasive currently, the terms *technology* and *engineering* remained greatly overlooked for centuries. *Technology* was first used in Aristotle's treatise *Rhetoric*, where the words *techne* (art, skill, craft) and *logos* (word, speech, literacy) were combined to represent (a) the study of techniques and (b) useful mechanisms. *Engineering* has it roots in the latin word *ingenium* from 200 b.C., which represents a natural capacity or skill [7]. In the 18$^{\text{th}}$ century, with the Industrial Revolution starting to pick up steam, the German economist and professor Johann Beckmann realized the importance of technology to society, recovering the term from Aristotle's writings and advocating for its teaching in systemic fashion, by separating interconnected techniques such as architecture, chemistry, masonry and manufacturing as dedicated subjects [6].

During the 18$^{\text{th}}$ and the 19$^{\text{th}}$ centuries, several engineering institutes and schools were created, such as the *École Polytechnique* in Paris (1794), the *Eidgenossische Technische Hochschule* in Zurich (1855), the *Massachussetts Institute of Technology* (1865), and the first English and American professional civil engineering societies (1818 and 1852, respectively) [8]. Between 1840 and 1870, the number of engineering schools in the United States grew from two to seventy [7].

Nowadays, recognition of engineering teaching institutions is usually performed by national organizations such as the American *Accrediting Board for Engineering and Technology* (ABET), *Engineers Canada* and the *European Network for Accreditation of Engineering Education* (ENAEE). In other countries, government agencies accredit engineering courses, such as the Brazilian *Ministry of Education* (MEC). Throughout the board, engineering students are expected to go through a few years of scientific and mathematical courses, as well as developing engineering projects, as a fundamental part of their formation. As for professional registration, other organizations such as the American *National Council of Examiners for Engineering and Surveying* (NCEES), the British *Engineering Council* and the Brazilian *Regional Council of Engineering, Architecture and Agronomy* (CREA) evaluate and accredit engineers individually through specific exams, undergraduate curriculum analysis, work experience, recommendation letters or a mixture of these [7]

Besides these more straightforward aspects of technology and its history, several philosophers and writers have tried to define technology in more specific terms, as we shall see in Section II. In Section III, a proposal for the *engineering method* is presented, by exploring the differences and similarities presented by previous authors, and Section IV derives consequences from the method.

II. THEORIES OF TECHNOLOGY

In 1877, philosopher Ernst Kapp developed a theory of technology development, arguing that technical artifacts are extensions, projections or continuations of human organs [9] [10]. In that manner, engineers and other technology creators are inspired by their own faculties in the moment of artifact conception, mostly unconsciously, so that, in his view, hooks come from bent fingers, shovels come from hands, and railways and telegraph cables come from the vascular system. Moreover, technology not only supplements human organs, but eventually replaces them.

In 1964, philosopher Marshall McLuhan proposed a similar idea, arguing that technology (or in his words, the *media* - plural for *medium*) is an extension of humankind, its bodies and faculties [9] [11]. Wheels extend feet, hammers extend hands, and electromagnetism extends nerves. However, these extensions happen according to their functional properties, and not in a morphological sense, better explaining, for instance, exactly how wheels extend feet - as feet in rotation. Moreover, he argued that the effects of technology are so pervasive that it "shapes and controls the scale and form of human association and action", in what is now one of his most famous aphorisms: "the medium is the message" [11]. That is to say, humankind drives technology, and vice-versa (more intensely, in McLuhan's view). Examples include:

- The printing press and the Protestant Reformation,
- The Industrial Revolution and the end of slavery,
- Photography and modern art,
- Guitars and rock'n'roll music,
- Music sampling and hip hop culture, and
- The atomic bomb and the Cold War.

In 1993, philosopher David Rothenberg defined technology as an extension of humanity, more specifically of human faculties for which we have an understanding of its inner workings [9] [12]. In that manner, that which is not understood cannot be extended, such as our faculties of judgement and morality.

Rothenberg divided extendable faculties into faculties of action and of thought. *Extendable faculties of action* included bodily extensions (manual labor), transportation and somewhat static structures (roads, buildings, irrigation ditches and so on). *Extendable faculties of thought* included perception (telescopes, telephones and television, for instance), abstraction (calculators, computers, natural languages, mathematics etc.) and memory (photography, audio and video recordings).

Although very similar, Rothenberg's theory departs from McLuhan's by indicating that technology extends human intention primarily, and only secondarily human's faculties. That is to say that technology starts with intention, and may or may not extend a human faculty, as illustrated by the wheel technology.

In 2010, writer Kevin Kelly expanded on McLuhan's ideas by arguing that animals display evolutionary advantages according to their genes, and human do the the same according to their ideas and culture [6]. In that manner, technology would be not an extension of humans' whole bodies, but of a specific organ: their minds. Though not cited by Kelly, his theory greatly resembles Rothenberg's if we take Kelly's term *mind* as *intention*.

Furthermore, Kelly argued that technology presents evolutionary traits, in similar fashion to life on Earth, with enormous amounts of interdependence and inheritance, in an example of combinatorial evolution. For instance, for the internet to work, it requires not only computers and software, but also fiber and copper wires. As for the fiber optics technology itself, it was based on previous developments for glass materials, in a process known in Biology as *exaptation*, where an evolutionary trait is passed on because it fits a new purpose [13].

Kelly was not only inspired by the biological/evolutionary argument for technology, but defended that, along with culture, art, social institutions and other intellectual creations, it composed the seventh kingdom of life, which he called the *technium*. He included in this "greater, global, massively interconnected system of technology" not only technologies and patents, but also the patent system, for instance [6]. Extrapolating the major biological transition events from the first replicating molecule to human societies [14], Kelly completed the chronological sequence as follows:

- One replicating molecule $\rightarrow$ Interacting population of replicating molecules
- Replicating molecules $\rightarrow$ Replicating molecules strung into chromosome
- Chromosome of RNA enzymes $\rightarrow$ DNA proteins
- Cell without nucleus $\rightarrow$ Cell with nucleus
- Asexual reproduction (cloning) $\rightarrow$ Sexual recombination
- Single-cell organism $\rightarrow$ Multicell organism
- Solitary individual $\rightarrow$ Colonies and superorganisms
- Primate societies $\rightarrow$ Language-based societies
- Oral lore $\rightarrow$ Writing/mathematical notation
- Scripts $\rightarrow$ Printing
- Book knowledge $\rightarrow$ Scientific method
- Artisan production $\rightarrow$ Mass production
- Industrial culture $\rightarrow$ Ubiquitous global communication

Kelly also drew from Ray Kurzweil's ideas of the inevitability of the evolution of technology [3], with the technium presenting very strong leanings, such as the steady increases over the last decades in computing power (Moore's law), data storage (Kryder's law), bandwidth and capacity of DNA sequencing. As he put it, "the technium has its own wants". By understanding these tendencies, he argued humankind can be better prepared for the changes to come.

Other authors chose to take a more "textbook-like" approach to the matter. Holtzapple and Reece [7] defined engineers as individuals that combine science, math and economy knowledge to solve technical problems. These authors separated engineers from scientists by the former's focus on practical matters, in the pursuit of reaching clearly-defined technical objectives.

Karl Ulrich took a more holistic approach, by defining *design* as "conceiving and giving form to artifacts that solve problems", with the term "artifact" describing any "product of intentional creation": goods, services, software, processes and so on [15]. The design process was then defined by him as (1) the sensing of a gap in user experience, (2) problem definition, (3) exploration of alternatives, (4) selection of a plan and (5) artifact production. Ulrich also separated the artifact's *function* (its goals, or *what* it does) from its *structural characteristics* (its requirements, or *how* it does it).

Even though these authors developed several important ideas related to technology and the engineering process, there seem to remain some gaps between them to be explored, bridged and extrapolated. This paper tries to perform this exact task in the following Sections, in what could be called the *engineering method*, in addition to the *scientific method*.

III. Technology and the engineering method

Let us start from the main points of the proposed method, and address each one of them along Subsections III-A to III-D:

1) Technology is an extension of man and nature.
2) Technologies have three main factors: the *musts*, the *media* and the *manners*.
3) *Musts*, *media* and *manners* define tradeoffs.
4) Engineers offer the *medium* and the *manner* to the *must*, according to:
   a) The scientific method;
   b) The technology's trade-offs.

A. Technology as an extension of man and nature

Fig. 1: Ancient and modern versions of a bathroom - *nature extended*.

The proposed definition of technology is a less anthropocentric extension of McLuhan's, helping to solve a few of its inconsistencies and complexities. For instance, it is common to illustrate McLuhan's idea with examples such as "wheels extending human motion" and "hammers extending fists", but several counterexamples show the complications of this theory, such as fans, showers and houses [9]. By defining technology as an extension of man and nature, the answer becomes much simpler: fans extend the wind, showers extend waterfalls and houses extend caves (Fig. 1).

The proposed definition avoids philosophical complications by subdividing technologies into three main factors, including Rothenberg's intention as one of them, as exposed in the following Subsection. Furthermore, it also makes it much easier to see the many parallels of technology with nature, from fans and showers to consciously bio-inspired design such as syringes based on mosquitoes' proboscides and self-sharpening shredderers based on rodent's teeth [16].

B. Must, medium and manner

Decomposing technology in these three factors offers better understanding of a given technology, which has been generally overlooked in previous discussions. Preserving McLuhan's terminology, the proposed method stipulates that different *media* can be used to achieve an intention or desire: a *must*. The same *medium* can further be used in different *manners*, depending on the *musts*. Figure 2 illustrates these concepts for an ultrasound image.

In another example, light switches and relays use mechanical and electrical *media*, respectively, in order to extend the following *must*: our choice of day and night. Furthermore, electrical energy can be used in different *manners* [5]:

- If one *must* store electrical energy, the chemical *medium* (*i.e.* batteries) favors direct over alternating current[1], as discharging happens necessarily over a long period.
- On the other hand, if one *must* transmit electrical energy, the mechanical *medium* (*i.e.* copper transmission lines) favors alternating over direct current, due to smaller losses.

Fig. 2: Illustration of technology's three factors: human sight extension (*must*) via sound imaging (*medium*) and quadrature detection (*manner*). Profile ultrasound view of the author's daughter in November 1st, 2017.

Given this threefold decomposition, it can be seen that technology's extensions may occur for more than one factor, non-exclusively. In the examples of fans, showers and houses, one could argue that they not only extend natural *media* (the wind, waterfalls and caves, respectively), but also human *musts*: coolness, cleanliness and protection. No understanding is lost, and a false dichotomy is avoided.

C. Technology and tradeoffs

Changes in *musts*, *media* and *manners* always involve trade-offs, due to physical, biological, economical and political constraints, among others [17]:

- During the Industrial Revolution, the advent of electrification as opposed to burning oil for illumination (a change in *medium*) presented a trade-off between cost

[1]The company *AC Biode* claims to have an AC battery with proprietary catode/anode technology, but reports lack further details.

of implementation and ease of use, as well as cost of maintenance. The same is valid for asphalt- and stone-paved streets [5].
- When the Bell Labs engineer Harold Black developed the concept of the negative feedback for electric circuits (a change in *manner*), he traded amplifier gain for stability, bandwidth and noise reduction [18].
- In computer science, lossy data compression methods offer a trade-off between rate and distortion, a direct consequence of Claude Shannon's concept of entropy [19].
- In computer programming, choosing between using look-up tables and processing inputs offers a speed/memory usage trade-off (also known as the *space-time trade-off*), due to the preponderant Von Neumann computer architecture [20].
- In machine learning, choosing between deterministic algorithms and neural networks offers a trade-off between human ingenuity for algorithm development and processing power. Typical algorithms also present the commonly-defined *bias-variance trade-off* [21].

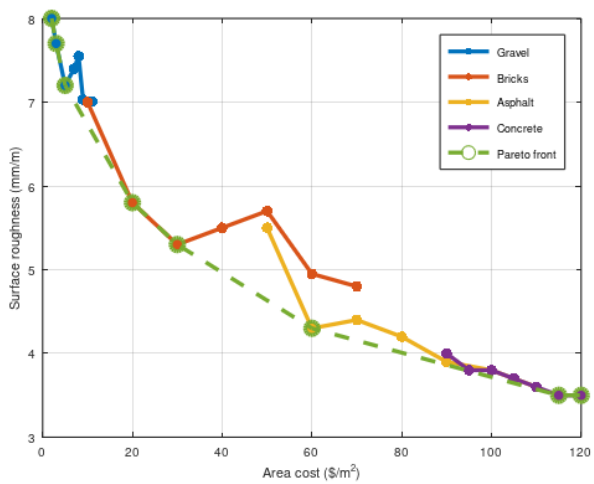

Fig. 3: Trade-off analysis of a **hypothetical** example of a civil engineer projecting a house driveway with different materials and suppliers. Each hypothetical supplier's material offers a cost per area, in dollars per meter, and a surface roughness, in mm per m.

1) Trade-off analysis: Trade-offs cannot be understood by a single variable, by definition. They require multi-variable analysis in order to define the problem's Pareto Front, which is given when technology is further developed until it reaches its limits [22]. A Pareto-optimal point is then obtained, meaning a situation where a improvement in one variable means degrading another variable.

For instance, a civil engineer projecting a house driveway may choose between several materials, such as gravel, bricks, asphalt and concrete. Each material can be evaluated by several criteria, such as area cost and surface roughness, for example. Figure 3 presents hypothetical values of each material, where each point corresponds to a different supplier. Ignoring maintenance costs:

1) *In a purely economic analysis*, the cheapest material at the location would be chosen,
2) *In a purely comfortableness analysis*, the material that presents least roughness would be chosen, and
3) *An economic/comfortableness analysis* would require a compromise between both variables, according to the maximum budget available.

It is important to note that all of these analyses offer Pareto-optimal points, as well as any point in the Pareto front. Changing from the cheapest to the most expensive material implies in a value increase for the roughness reduction, and vice-versa.

Based on trade-offs and the Pareto front, it can be seen that changes in *media* and in *manners* can generate great advantages over legacy technologies, or *zero-day exploits*, in software engineering parlance. That is because new curves are then added to the space of the multi-dimensional analysis, as illustrated in Fig. 3. Changing *media* can be more revolutionary, and changing *manners* can be more efficient:

- The first Industrial Revolution changed several *media*, such as electrification and asphalt pavement.
- Black's negative feedback loop involved a change in circuit topology (*manner).*
- The choice between deep neural networks and deterministic algorithms involves a change in the programming *manner*, since both both rely on the Von Neumann architecture.
- Table tennis Japanese champion Hiroji Satoh was the first to use a sponge in the racket (*medium*), forever changing the sport. The rubber sponge increased the ball's velocity and greatly reduced the striking sound, confusing his opponents [23].
- Royce Gracie won the first Ultimate Fighting Championship in 1993 despite huge bodily disparities to his opponents (up to 30 kilograms) by employing his father Hélio Gracie's jiu jitsu methods, which heavily rely on body levers, wedges and fulcrums (a change in *manner*) [24].
- Dick Fosbury introduced the now-standard Fosbury Flop in high jump during the 1968 Summer Olympics. The jump was previously known at the time, but athletes didn't employ it because it was too dangerous to perform prior to the advent of the deep foam matting. In this case, a change in *medium* permitted a change in *manner* and a revolution in the sport [25].

2) Symbiotic relationships: Kelly calls the technium the seventh kingdom of nature, and indeed there are many biological concepts that can be applied to the relationships between technologies, albeit with some anthropocentrism involved. A technology is developed to offer a *must* or face extinction, so that the trade-offs listed previously configure a clear *competitive relationship* between technologies under a given scope. Furthermore, there are symbiotic relationships between technologies in the technium, and with humanity as well.

Symbiosis is defined as the close long-term relationship between species, and it can be classified as mutualistic, commensalistic and parasitic [26]. *Mutualistic relationships* are those that are beneficial for both species [27]. The internet, for instance, depends on hardware and the electric grid, and this justifies the use of electronic and energy technologies, helping avoid their extinctions. *Commensalistic* and *parasitic relationships* are both beneficial for a species, but neutral or costly for the other, respectively. Commensalism can be seen between a given technology and its accessories, such as cars and car trash cans and cellphone mounts [28]. Parasitism is a bit harder to find. Perhaps it can be seen in technologies that engender their own demise, like classical computers being used to develop quantum computers.

With regards to humankind, not only are we highly dependent on technology, but it also depends on humankind to keep growing and evolving, configuring a mutualistic relationship. Deep neural networks, for example, depend on past data from humans for learning, supervised or not [21].

D. The engineering method

Fig. 4: Delicate meeting of engineering traditions: restoration of ancient Greek temple at the Athenian Acropolis in 2017. Modern techniques could rebuild the temple, but that would go against the place's *must*: preserving cultural heritage. Not maintaining the temple, on the hand, would also go against it.

From the previous points, it follows that an engineer's role is to offer the *medium* and the *manner* to the *must*. The term *medium* encompasses a very broad array of human and natural creations, from computers and rockets to languages and mathematical notation, so that *engineering is best described by technology development under the scientific method and its main tools: mathematics and logic*. Figure 4 illustrates this concept with the meeting of ancient and modern engineering traditions at the Athenian Acropolis in 2017.

Historically, engineering has been crudely associated with "things", as in tools and techniques, as opposed to "people", as in health, law and language-based occupations [7]. Technology has been progressing into increasing miniaturization, abstraction and emulation (specially in software, nanomaterials and electronics), making less sense to speak of engineering in terms of "things" and "people".

Nevertheless, the emphasis on the use of the scientific method for the engineering enterprise strengthens the case for it, given the immense success of science over the centuries. Furthermore, it is the preferred approach taken by the organizations that accredit engineering teaching institutions and professionals such as ABET, NCEES and CREA, where math and science are considered fundamental for the engineering practice. In that manner, other branches of human endeavour such as graphical design, law and linguistics also develop technologies, but not engineering technologies under our definition.

Technology development has been steadily blurring these lines. For instance, laws, contracts, philosophical systems, recipes and manuals could be seen as software, where the machine code is run on biological hardware, and architecture and graphical design could be seen as applied geometry, which is itself a part of mathematics. On the other hand, software developments have offered more and more examples of the automation of human capabilities, such as applications in natural language processing with ChatGPT [29] and image generation from text with DALLE-E [30]. Furthermore, ancient engineering *did not rely* on science and high-level mathematics in order to build large-scale structures such as pyramids, cathedrals, stupas and aqueducts, and technologies like the telescope and the microscope actually *enabled* much of scientific development. These counterexamples highlight the mutual feedback existing between technology and society, showing that our definition may be circumstantial, although relevant for a large time-frame. This mutual feedback is further explored in Subsection IV-B.

1) Engineering and technology development: When engineers design projects in a *top-down approach*, they start with the *musts* to choose the *media* and *manners*. In a *bottom-up* approach, the reverse happens [7]. Evaluating the *musts* helps defining the project's goals (functional requirements), and evaluating the *media* and *manners* helps defining the project's requirements (non-functional requirements). Engineers then evaluate the trade-offs between *musts*, *media* and *manners* and make a project decision.

In the design process, repeatedly asking "Why?" gives the engineer broader and broader views of the *musts*, and repeatedly asking "How?" gives more focused views of the *media* and *manners* [15]. For a menial example, consider a light switch:

1) **Why would someone want a light switch?** To control room illumination.
    a) **Why would someone want to control room illumination?** To choose between reading and sleeping in bed.
        i) **Why would someone want to choose between reading and sleeping in bed?** *And so on.*
2) **How would someone switch the lights on and off?** By mechanically opening and closing the connection between two electrically charged terminals.
    a) **How would someone mechanically open and close the connection between terminals?** By moving a metal connection between terminals.
        i) **How would someone move a metal connection between terminals?** *And so on.*

The same process can be performed for other technologies, such as a clapper and a wireless home automation system. It is up to the engineer to provide the most adequate solution for the problem, according to the scope of the project. For instance, a bedroom and an intensive care unit room may require different room illumination solutions. The engineer must also decide at which level of “Why?” and “How?” questions to stop.

The higher the virtualization and the abstraction, the harder it is to define the *must*[2]. Engineers can be in the psychological domain at this point. Modern project development practices, such as Agile methodologies, try to walk the team’s way through iteration, like a gradient descent algorithm.

In trade-offs, engineers usually pick the problems they can live with:

- When using negative feedback in circuits, engineers increase system complexity (harder to design and maintain) to have better stability, larger bandwidth and noise/distortion reduction.
- Signal processing techniques transfer expert knowledge to silicon strata.
- When choosing to work with deep neural networks, engineers increase computation and data availability requirements in order to automate hard-to-define *musts*, such as natural language processing and image generation from text.

2) Engineering branches: Engineering careers have been traditionally separated by *medium*, by *must* and by *manner*:

- ***Medium*:** Electrical, Chemical and Mechanical.
- ***Manner*:** Power Systems, Electronic, Software and Energy Engineering.
- ***Must*:** Civil, Aerospace, Automotive, Telecommunications, Automation and Biomedical Engineering.

These branches have grown organically through the decades, showing great superpositions and symbiotic/mutualistic relationships. Software, for instance, is studied in more than one of those branches, has applications throughout the spectrum (from systems’ modelling to project management and automation), but it also depends on hardware and energy to exist, as well as transportation, telecommunications and so on.

Given that the *must* is provided by the *medium* and the *manner*, this dependence is reflected in the relationships between engineering branches. For example, Electronic and Energy Engineerings do not provide a *must* in themselves, but for other branches, like Aerospace, Automotive and Biomedical Engineering, to name a few. In that manner, the following distinction between engineering branches is proposed, borrowing from web development terminology:

- **Front-end engineering branches** deliver the *must*;
- **Back-end engineering branches** deliver the *medium* and the *manner*.

Under this definition, *front-end* and *back-end* engineering branches present a clear mutualistic relationship. Telecommunications and network engineers, for instance, rely on the work from electronics and energy engineers, among others, and these in turn depend on the former to maintain the profession.

[2]As Steve Jobs once said, “People don’t know what they want until you show it to them. That’s why I never rely on market research. Our task it to read things that aren’t yet on the page.” [31]

IV. Consequences

After laying out the proposed method, this Section presents a few consequences that can be derived.

A. Natural and artificial media

Technology and nature present a mixed relationship, due to the ambiguous term *natural*. On the one hand, technology is seen as *unnatural*, since it does not *occur naturally*. On the other hand, technology is *natural* in the sense that it is built over *natural media*, albeit transformed ones.

Fundamentally, this separation between technology and nature comes from a false opposition between humankind and the rest of the universe, which is extended to technology (philosopher Alan Watts argued modern society is not materialist, but abstractionist [32]). According to Kelly, technology is not artificial, but a tendency of nature, the technium. However, this hypothesis is very hard to confirm scientifically, due to the extreme small sample size of the experiment: a single human civilization.

Anyway, this continuum from nature to humankind and the technium offers a better understanding of the techno-ecological landscape: technology is made *by nature* (humankind[3]) and also *of nature* (natural means). However, the continuum *nature-humankind-technology* does not imply equilibrium between its parts automatically, as discussed in the following Subsections.

B. The must-medium dance

Musts and *media* are ecological, presenting mutual feedbacks: a technology not only meets a *must*, but creates new ones. Books require bookshelves, cars require safety equipment, better health requires better retirement plans, and more information requires better understanding. This argument and its consequences were expressed in McLuhan’s aphorism “the medium is the message” and in Kelly’s statement “the technium has its own wants”. For instance:

1) Photography extends memory.
2) Digital photography extends processing, transmission and storage capabilities, via filtering, histogram matching, image compression and so on.
3) Digitization then generates abundance of data, which devalues photography, as opposed to painted portraits, for instance.
4) Image processing then devalues memory, in the sense of Shannon’s Information Theory: a photograph processed by an Instagram filter lowers the signal-to-noise ratio, but is usually preferred by users over the unfiltered image [19].

As the possibilities for *musts* and *media* increase, this creates layers upon layers of complexity. Ever-increasing complexity in technological ecosystems is creating what Kelly called the *technium*, as illustrated in the following progressions:

- Horses $\rightarrow$ Carriages $\rightarrow$ Bicycles $\rightarrow$ Cars $\rightarrow$ Airplanes $\rightarrow$ Rockets and satellites $\rightarrow$ Autonomous vehicles.

[3]Until artificial intelligence does not self-improve.

- Abaci and parchments → Logarithm tables and books → Digital calculators and computers → Internet and distributed systems.
- Artisans → Civil, Mechanical, Electrical and Chemical Engineering → Software, Aerospace, Telecommunications, Automation, Biomedical, Power Systems, Electronic and Energy Engineering.

C. The must-medium spiral

The scientific method is based on repeatability and gradual construction from the past, and our technology embraced these ideas, favoring interdependence and standardization. Furthermore, a fundamental mathematical concept led science from the beginning: *function optimization*, as in Newton's problem of the body of minimal resistance, Lagrange's multiplier method and the physical principle of least action. It could be argued that this optimal-driven, interdependent and standardized approach to problem-solving led humanity from artisan manufacturing to mass production.

In this manner, after developing their *optimization muscles*, technologists have driven (and have been driven by) *media* and *manners* towards atomization, encapsulation, miniaturization, real-time operation, abstraction and customization [5] [6]. In an optimization-led framework, the *medium*/*must* relationship spirals, necessarily, with several opposing/complementary views:

- **Techno-optimism:** *must* prevails over *medium*, and the spiral is productive. Examples include:
  - Science enthusiasts,
  - Growth-based economists,
  - Francis Fukuyama's End of History hypothesis,
  - Ray Kurzweil and the Law of Accelerating Returns.
- **Techno-pessimism:** the *medium* prevails over *must*, and the spiral is destructive. This is illustrated by:
  - Modern concerns with atomic and biological weapons, fake news and climate change,
  - The Bulletin of the Atomic Scientists' Doomsday Clock,
  - Artificial-Intelligence takeover prophets such as Elon Musk and the Terminator and Matrix movie franchises,
  - Proponents of the Great Filter solution to the Fermi paradox,
  - Malthusian and Marxist theory.
- **Techno-skepticism:** the spiral should be consciously delayed by careful adoption of technologies after extensive testing and evaluation. Amish communities, for instance, adopt this techno-worldview [6].
- **Techno-conservatism**: the spiral is unnecessary, as the best technologies are usually the oldest. Author Nassim Taleb illustrated this view with the Lindy effect, which estimates the life expectancy of technology and ideas proportionally to their age [33]. For example, we can expect ancient technologies such as clothing, restaurants and wine to outlive recent ones, such as computers and cellphones.
- **Techno-periodicity:** the spiral could be cyclical, for all we know. Given the lack of archeological confirmation, this view is illustrated by theories of lost civilizations, such as Atlantis and the Silurian Hypothesis.

Religions take different approaches to human *musts* [34]:

- The Buddhist doctrine links the end of wanting (attachment) to the end of suffering, and consequently the spiral as well.
- Reincarnationist doctrines in general emphasize the spiral of wanting with its wearing-out and the consequent end of reincarnation cycles.
- Christian ethics links acceptance of suffering (cross-bearing instead of wanting) to future eternal gratification.
- Along with Judaism and Islam, Christianity sees suffering as a heavenly teaching tool, where God is testing man.

D. Engineering and design

Whenever engineers transfer part of the decision-making to the end user, they partially fail to extend the technology they offer, unless customization is a *must*. For instance, a digital camera may offer automatic exposure control for the general public, and manual control for professional photographers, but manual control for the general public is perhaps an unnecessary transfer of decision-making.

In the engineering practice, employing the same kinds of solutions for a wide range of problems can be a simple, but perhaps dangerous alternative. In psychologist Abraham Maslow's words, "I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail" [35]. A good example was the *dot-com bubble* of the early 2000s, when investors poured huge amounts of money on any kind of Internet-based company, regardless of market fitness. There is therefore a fine line between *top-down* and *bottom-up* approaches.

E. Engineering and exaptation

As the *technium* favors evolutionary processes such as exaptation, several ideas born in scientific, mathematical, engineering and economic contexts should be presented to a wider public in order to provide better solutions to modern problems, or at least a better understanding:

- **Positive and negative feedbacks** are greatly present in economics, politics and public policies, to name a few;
- **Trade-offs** are not only fundamental in engineering and economics, but also in political discourse and political science, specially at the Pareto Front;
- **Entropy, channel capacity and signal-to-noise ratio** are concepts that can be extended to communications in social networks, to news and fake news filtering, and to education;
- **Antifragility**, or the ability to improve from randomness, could be taken into consideration in education and public health discussions.

F. Engineering popularization

In order to better present the engineering enterprise to students, project stakeholders and the general public, it is important to emphasize the *media* and the *manners*, as non-engineers are more used to the *musts* than to the ways they are obtained. For instance, billions of people use electric energy, world-wide communications, computers, cellphones and mobile applications, but they are mostly unaware of the math and logic involved. This is specially true in video game development, which may involve the use of high-level mathematics such as quaternions and vector calculus.

V. Conclusion

Technology has been a major driver of change in the material, economic, and societal spheres over the past few centuries, and despite the significant contributions of scholars such as Marshall McLuhan and Kevin Kelly, there are still gaps to be explored and bridged in current theories of technology development. This paper proposed a general framework for the engineering method, providing a systematic approach to analyze the main components, strengths, limitations, and future paths of technologies. This framework enables engineers to better understand their practices and define their projects, as well as provide a clearer way to communicate the engineering enterprise to non-engineering stakeholders, students, and the general public. We believe that the engineering method has significant potential to improve the field of engineering and its related industries, and we encourage further exploration and application of this approach.

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