The International
JOURNAL
of
TECHNOLOGY,
KNOWLEDGE
& SOCIETY

Volume 4, Number 2

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www.technology-journal.com

THE INTERNATIONAL JOURNAL OF TECHNOLOGY, KNOWLEDGE AND SOCIETY
http://www.Technology-Journal.com

First published in 2008 in Melbourne, Australia by Common Ground Publishing Pty Ltd
www.CommonGroundPublishing.com.

ISSN: 1832-3669
Publisher Site: http://www.Technology-Journal.com

THE INTERNATIONAL JOURNAL OF TECHNOLOGY, KNOWLEDGE AND SOCIETY is a peer refereed journal. Full papers submitted for publication are refereed by Associate Editors through anonymous referee processes.

Typeset in Common Ground Markup Language using CGCreator multichannel typesetting system
http://www.CommonGroundSoftware.com.

Technological Cycles and their Impact on Science, Engineering and Engineering Education

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Abstract: Large information systems involving mechanisms of duplicating and selecting information have an important common feature -- their cyclic behavior. Technological development does not occur at a continuous steady pace but involves technological leaps and revolutions when an old technology is replaced by a technology of new generation within relatively short period of time. A technological revolution is followed by a longer period of more steady, incremental development. Similar cycles are known in economics, science, history, biology and other areas. We discuss the cyclic nature of the evolution of human knowledge and find that the inventiveness and flexibility of the engineering approach has played a highly positive role at the turning points of technological development. Engineering methodology has to adapt to changing conditions and its ability to learn quickly from both science and environment is one of the main recipes for overall success of engineering. The inventive and active nature of engineering profession is reflected in the realities of engineering education: future engineers do need to be taught science and economics but the styles of education adopted in science and engineering are not the same.

Keywords: Technological Evolution, Science, Engineering, Engineering Education

Technological Evolution

THE TERM “TECHNOLOGICAL evolution” was coined by Czech philosopher Radovan Richta (1968). Unlike "technological development", which implies complete control over the process, “technological evolution” seems to refer to natural forces not dissimilar to the forces of natural selection. We begin our consideration with examination of the similarities and differences between technological and biological evolutions.

The phenomenon of life appears in thermodynamically non-equilibrium conditions where large amounts of exergy are provided by the sun and most of this exergy is continuously destroyed, resulting in overall entropy increase. Yet life forms bring amazing complexity into the world resulting in the preservation of a tiny fraction of exergy from imminent destruction by natural forces. The key element of a life form is information (genes) that can be easily copied (reproduced). This biological copying process is quite reliable but is still characterised by occasional mutations. These mutations are random and a tiny fraction of these mutations may appear to be beneficial to the life forms. The life forms fiercely compete with each other and with destructive forces of the environment. In this process, called natural selection, most of the genetic information is destroyed while species with beneficial mutations survive and come to dominate the population. The principal ideas of the theory of biological evolution were established by Darwin (1859).

The process of biological evolution is, obviously, rather slow and inefficient from a thermodynamic point of view since it is continuously accompanied by the destruction of most (but not all) of the genetic information codes at each step. Deleting information is an irreversible process that must increase entropy and destroy exergy. Shannon’s (1948) fundamental work on information essentially defines information as a negative entropy, which makes information subject to the 2nd Law of Thermodynamics. Hawking (1994) believes that it is the 2nd Law that determines the difference in the physical direction of time as we perceive this difference from the perspective of being “information processing devices”. The useful value of information is determined by the fact that the information could not have appeared without a reason and could have been destroyed in the past but has not been destroyed. From a thermodynamic point of view, we can predict but can not remember the future and we can remember but can not predict the past (since many different pasts correspond to nearly the same present due to irreversibility of increasing entropy and destroying information). This is an interesting contradiction: in order to make information useful we must be able to destroy information that is irrelevant or less useful. Selecting useful information and deleting the rest of it is a routine procedure in any research activity.

Although we have denounced biological evolution as a thermodynamically inefficient and slow process, it has achieved remarkable results over few billion years. The pace (and efficiency) of the evolution process accelerates as the result of evolution. Indeed,

THE INTERNATIONAL JOURNAL OF TECHNOLOGY, KNOWLEDGE AND SOCIETY,
VOLUME 4, NUMBER 2, 2008
http://www.Technology-Journal.com, ISSN 1832-3669

being able to adapt and evolve quickly is, obviously, beneficial for survival and thus favoured by evolution (note that an excessive mutation rate may have the opposite effect). Not such a long time ago (tens of thousand years) evolution of human society entered into a new mode which is radically different form biological evolution and can be called technological evolution. Here we understand technology in the broadest possible sense – accumulated knowledge, tools, machines and infrastructure as well as the social structures and mechanisms that support them. The technological stage of evolution is characterised by the development and expansion of non-genetic ways of passing information from generation to generation and by intensification of competition between human groups. Several important events have accelerated the pace of technological evolution even further: mastering food production (i.e. the invention of agriculture about 8000 years ago), taking control over significant resources of exergy (i.e. the industrial revolution of last few hundred years) and the computer revolution of the last decades. Hawking (1988) relates the progress of humanity to replacing genetic forms of information by social forms.

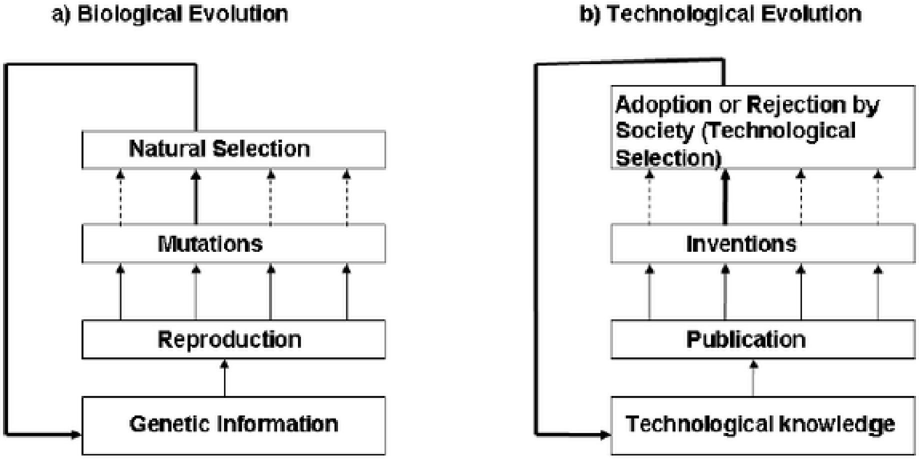

Figure 1: Biological and Technological Evolutions

Evolution has changed its form but the key elements remain the same (see Fig.1): information is duplicated and passed between humans in the form of training, tales, education, books or computer disks; information can be altered as result of inventions or discoveries and inventions can be accepted by the society or rejected (the process of technological selection). Inventing uses the analytical capabilities of a human brain making it, from evolutionary perspective, incomparably more efficient than mere mutations. [Note that human brain is not 100% efficient as a tool of technological preselection: for example, only 5% of granted patents are adopted and commercialised (IPFrontline, 2006)]. Inventions are adopted or rejected by society for all sorts of reasons. Some inventions are rejected because they are rather crude or impractical while other inventions are rejected due to a lack of technological or economic means to put these inventions into practice or, perhaps, due to the inability of the society (or some of its representatives) to accept the prominence of the inventor's ideas. From an evolutionary perspective, it does not matter who is right who is wrong the inventor or the society – the key point is that inventions are either accepted or rejected.

It should be noted that the process of technological selection does not apply to humans as biological species. In a modern society, the survival of an invention has nothing to do with biological survival of its inventor. Various theories of social Darwinism, which were popular in the late XIX century [and actually more related to views of Spencer (1857) than to Darwin's theory], seem to miss this point and confuse biological form of evolution with more advanced forms of evolutionary selection. Once the ability of storing and duplicating information by non-genetic means is created, these new forms of information begin to evolve. Ideas, inventions, technologies and theories are not reducible to genetic information and they compete in a domain that is well beyond the domain of biological competition. To be efficient from technological perspective, a society has to abate the forces of natural selection. Society moderates competition and encourages cooperation between individuals. Elderly people, who would most likely become first victims of ruthless biological competition, live longer to tell their tales and pass their valuable knowledge to next generations. Historically, the ability to adapt and invent may indeed have played a role in survival of different groups of humans. Jarred Diamond (1998) reviews the historical patterns of inventions, their adoption (or rejection) by the society and, in this light, gives a sobering account of human history. The early tribes that were not quick enough to adopt iron swords or domesticate horses faced the fate of assimilation or in extreme cases complete obliteration. This, however, is not the case in a modern society: companies that are not innovative enough to survive simply become insolvent. We also note that the technological evolution and biological evolution have very different time scales. The intellectual power of the inventor's brain makes invention much more likely to be beneficial compared to random genetic mutations. Intellectual selection precedes technological selection and this ensures better overall efficiency and much faster pace of technological evolution. Human brain is trained to emulate or predict the outcomes of technological selection.

Evolutionary Cycles

The concept of natural selection seems to explain well incremental evolution (microevolution; in biology: simple adaptation of species to environment); revolutionary advances (macroevolution; in biology: creation of radically different new classes of living species) are, however, more complicated and unpredictable. Macroevolution may stall or even reverse its direction and many questions arise that are quite difficult to answer. Should adaptation to the marine environment necessarily result in creating fish, or dolphins, or both? Is human intelligence a normal (likely) or abnormal (unlikely) outcome of evolution? Intelligence is expensive for a living organism since the brain demands approximately ten times more energy per mass than the rest of the body and, hence, must give significant advantages to its owner in order to be supported by evolution. While we all are familiar with the advantages for modern humans of having relatively large brains capable of complex mathematical calculations, what sort of evolutionary advantage did such oversized brains give to the Palaeolithic people? Typically, evolution stimulates big teeth, sharp claws, fast legs and rapid proliferation rather than big brains.

Natural selection may not only advance evolutionary progress but also hamper or stall developments that we see as progressive from a modern perspective. Mammal-like reptiles appeared well before the reign of dinosaurs. These creatures were clearly developing mammalian features and were very successful in the late Permian / early Jurassic periods but, disappeared during the rise of dinosaurs and their relatives. For more than a hundred million years, the natural selection preferred "conservative" dinosaurs to "progressive" mammals. The mammals did not have a chance to develop far enough to become competitive against the deadly efficiency of the dinosaurs, who occupied all top places in the food chain. Highly intensive competition stimulates perfecting existing adaptation mechanisms but may prevent development of radically new ones. In the late Cretaceous, the power of dinosaurs was clearly at display while rat-like mammals seemed insignificant. The future did not look prosperous for the mammals up until the catastrophic Cretaceous/Tertiary extinction event about 65 million years ago. This event resulted in the mass extinction of many species, particularly the dinosaurs (those at the top of the food chain usually suffer most). The competitive pressure on the remaining mammals weakened and they used this opportunity to proliferate, adapt and evolve. Abnormally high concentrations of extraterrestrial iridium at the C/T boundary indicate that a comet impact was likely to cause rapid cooling of the climate for several years and trigger the extinction event (Alvarez et al., 1980). The direct cause of the dinosaur extinction remains unknown. Britannica (2002) indicates that some of the dinosaurs may have survived up until a million years after the extinction event. In any case, the genetic material of dinosaurs was preserved in their direct descendants --- the birds --- and large flightless birds were always eager to take position at the very top of the food chain. Descendents of the dinosaurs must have lost competition for food to rapidly proliferating and evolving mammals (Prothero 2006).

Our interest in this example is determined by the fact that, although the high competitiveness of modern mammals is beyond any doubt, their ancestors were losing competition to creatures with seemingly more primitive organisation. These ancestors certainly possessed potential competitiveness but they were not developed enough to be efficient against fast and dynamic bi-pedal runners and their descendants -- the dinosaurs. Under the similar climatic conditions of late Cretaceous / early Tertiary periods (significant cooling started only 30-40 million years after the C/T event), at least two different stable biospheres could exist; one with dominating dinosaurs and another one with dominating mammals. A switch from one condition to another is a low probability event that is not explained by the routine natural selection process and this consideration has a direct relevance to our current topic of technological progress.

A very interesting example of a generational change in technology is given by the replacement of steam power on railroads by diesels (Churella 1998, Coifman, 1994). All major inventions required to build a diesel-electric locomotive were in place by 1910. The electric locomotives replaced steam locomotives on electrified railroads in several major metropolitan centres and the diesel engine was invented by Dr. Rudolf Diesel in 1893. It is quite clear now that diesel-electric locomotives represent a progressive technology, at least because diesel engines inherently possess three to four times higher thermal efficiency compared to steam engines. Diesels also have substantially reduced servicing requirements and a good low-speed torque. In principle, the diesel railway revolution could have happened around 1920, but, in fact, it was delayed by more than thirty years due to competition created by improving steam locomotives. When no viable alternative to diesel engines existed, for example, in submarine applications at the beginning of XXth century, rapid developments in design and use of diesel engines did happen much earlier.

In 1910, a project to build a diesel-electric locomotive was commenced in the USA and led by Dr. Lemp who was an engineer working for General Electric and communicating with Dr. Diesel. The first prototype was built in 1917. Commercial diesel-electric locomotives appeared in the mid-twenties but were produced in small numbers until the mid-century when steam power was replaced by diesels over a very short period of time. The first diesel-electric locomotives were purchased only because steam power was banned in several major metropolitan areas of the USA to encourage electrification of the metropolitan railroads. Although diesel-electric passenger trains achieved some success in the 1930s (the limited power of the diesel engines was compensated by lightness of these trains), long-distance freight operations were ruled by the steam locomotives. This situation remained unchallenged up until the first diesel-electric mainline locomotive EMD FT was manufactured and demonstrated by General Motor's EMD division in 1939. This unit possessed 1350hp and was designed to be coupled with another FT unit (or with another three units) to pull a freight train. The FT model is renowned for delivering a decisive blow to steam locomotives but, in fact, its power fell well below (even in a multiple set) that of the steam locomotive champions. At that time, the target of the FT was to win a small share of mainline freight, mostly in dry or desert areas, rather than replacing the whole fleet of steam locomotives. The FT model was produced between 1939 and 1945 and suffered from numerous malfunctioning. Even its designer R. Dilworth considered the FT his worst mistake (Churella 1998).

During the war, the American War Production Board did not specifically favour diesel-electric locomotives. The pre-war shares of the locomotive market were more or less preserved and enforced during the war years. The diesel-electric locomotive producers, however, enjoyed increasing profits stimulated by the overall war-time demand and the certainty of Board-regulated contracts and were able to invest these profits into improving the quality of diesel-electric locomotives in anticipation of post-war competition. Diesel locomotives became competitive and, after the war, only very few steam locomotives were ordered by major railways. As the result, diesel fully replaced steam on American railroads in the mid 1950s. Similar changes followed in other countries.Modern observers are inclined to blame the conservative approaches of the major railway companies. It is true, of course, that these companies relied heavily on steam power and were not prepared to replace steam by anything else unless the advantages of the new technology were clearly demonstrated, but the advantages of existing diesel-electric locomotives were not obvious in the 1920s and 1930s. The lower thermal efficiency of steam engines was compensated by the availability of cheap coal, outstanding durability and high power of the steam locomotives. The diesel-electric locomotives had relatively low power, were mainly used for shunting (switching) and did not look that impressive at all compared to streamlined and powerful steam locomotives speeding up and down the mainlines. At that time, the existing diesel locomotives were simply losing competition to the existing steam locomotives. Only the war-driven massive and indiscriminate demand for all available types of locomotives weakened the competition and created conditions for the producers of diesel locomotives to advance their technology. The diesel revolution may have become inevitable in 1950 but in the 1920s and 1930s it was an unlikely (unexpected) event. Early diesel locomotives had potential competitiveness. However, converting potential competitiveness into actual competitiveness required substantial investments, but making large investments into diesel locomotives in the 1920s and 1930s was a high risk strategy [even if the actual economic penalty of this technological change was not particularly high (Felli and Ortalo-Magné, 1997)]. Even General Motors, the owner of EMD, which later became a champion of the diesel revolution of 1950s, considered its subsidiary to be more a liability than an asset. No-one could predict in the 1920s and 1930s the diesel revolution of the 1950s and investments into developing diesel locomotives were very moderate.

The gradual progress induced by incremental inventions is more or less certain and governed by technological evolution. For incremental improvements, it does not matter who personally invents them – these or similar improvements would be suggested by somebody else if the original inventor died in an accident. However, the revolutionary changes in technology, like the outcomes of biological macro-evolution, are not guarantied in the same way. Revolutionary inventions and changes do not automatically come with technological evolution; a revolutionary invention is a low probability event and its prediction with any degree of certainty is impossible. Revolutionary inventions may speed up or retard the pace of progress or may switch history to an alternative route at a historical bifurcation point.

On large scales, evolutionary changes do not occur at steady pace. When a new generation gains a decisive advantage over its competitors or favourable environmental conditions, the generation leaps forward rapidly expanding and multiplying its numbers (as schematically illustrated in Fig.2,). Here we deliberately follow the terminology introduced by Jarred Diamond (1998), who characterised rapid development of humans 50 000 years ago as the "Great Leap Forward". The expansion is followed by diversification and growing competition within the generation. This may be seen as an "arms race": members of the new generation have to compete with representatives of the same generation that are much better adapted than those from obsolete generations. In order to stay at the same place, one needs to run fast, find a good niche, adapt quickly and specialise. The available area becomes densely occupied allowing for existence only on small margins of available resources. The generation achieves high efficiency in utilisation of the resources and competing against this generation becomes a very difficult task. A dominant generation must be also successful in suppressing its possible alternatives whether these alternatives possess potential advantages or not. The efficiency of the dominant generation, however, comes at a certain price – the price of losing stability. Specialisation works well in a stable environment but in changing conditions (due to various reasons: natural disasters, climate changes, exhausting of resources or rise of a new strong competitor), the members of the generation may find their specialised skills useless and their margins insufficient for survival. The ability to kill large herbivorous dinosaurs is useless for a predator if no more dinosaurs can be found and the ability to manufacture superb steam locomotives is unlikely to be a key to company success in the second half of XXth century. In conditions of small margins and limited resources, any extinction of a particular species or insolvency of a particular company generates a chain of extinctions/insolvencies. Mass extinctions ultimately reduce competition and this creates favourable conditions for another generation to leap forward. The dominance of the old generation tend to collapse rather than to simply fade out (dinosaurs did not evolve to become mammals – this is not good news for humans who are much more dominant than any other species on Earth could ever be). Leaping cycles, which are illustrated in Fig. 2, are known in economics, history, science & technology and other areas. A large leaping cycle can be supplemented by leaping cycles of smaller scale and significance.

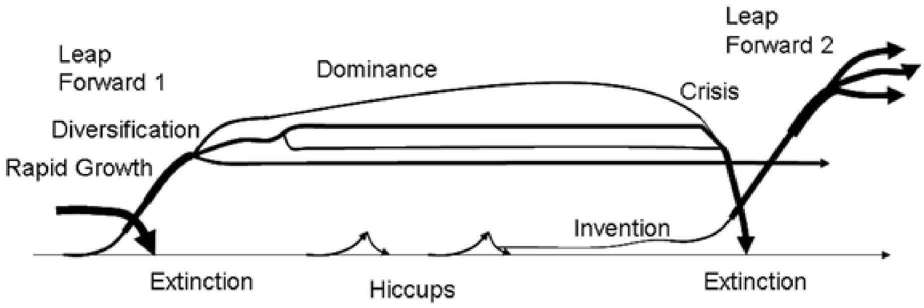

Figure 2: "Leaping Cycle" -- Macro-Evolution at a Large Scale

Natural or technological selection reliably stimulates incremental progress but may in fact act against progress in the case of revolutionary changes. Evolutionary selection is a blind instrument that promotes existing competitiveness but does not recognise the potential for future progress. Many potentially progressive adaptations may disappear without a trace due to this pressure. Revolutionary leaps forward are low probability events that are difficult to predict but, inevitably, these events still occur from time to time. After a revolutionary change it may seem that these changes should have happened much earlier and there were errors, failures or even malicious attempts to suppress the progress (evolutionary hiccups). It should be remembered, however, that the progressive and practical nature of a new technology becomes obvious and commonly accepted only when the technology begins to leap forward. No one can seriously blame a carnivoral dinosaur for having a mammal for breakfast.

Comparative Roles of Science and Engineering

The competitive pressure of natural or technological selection can not only advance progress but, under certain circumstances, hamper it. The latter case raises a question whether humans can and should tune technological (and maybe biological) evolution in attempt to protect "mammals" from "dinosaurs". The part of the question with "should" is not trivial; by attempting to fix something that we do not understand well we can interfere with the laws of nature and do more harm than good. Indeed, we do not have a universal tool that distinguishes "mammals" and "dinosaurs"; what seems to be progressive now may appear to be rather regressive in the future. As the situation stands at present, mankind is too powerful to play a role of one of the Earth's species competing with each other, but is not advanced enough to control evolutionary processes and play a role of an intelligent creator --- this situation does not seem to be sustainable in the long term. At the same time, mankind can adapt and learn from its mistakes. For example, when it became clear that economic forces may experience hiccups, countries learned how to deal with these problems. In any case, it seems that the nature of human intelligence is in interfering with everything it can and the question of whether we should interfere with laws of technological evolution has been already answered by realities of human development.

What can be done to protect the “mammalian” technologies that are uncompetitive at present but, if given a chance to develop, could become the mainline of technological progress in the future? In technological developments, this protecting role is entrusted to fundamental science, which sees merits in a discovery that seems absolutely impractical in present conditions. Engineering, on the other hand, is most interested in discoveries that can be used now or in the near future and, thus, should be significantly affected by technological cycles. Usefulness is the major criterion in engineering, but not in science, which is expected to stay above day-to-day competition and has to develop its own criteria of “right” and “wrong”.

In theory, fundamental science must perform its role of protecting valuable discoveries from the short-term influence of the market competition but, practically, it is not free from its own hiccups. Scientific logic replaces practicality as the ultimate referee of scientific truth. The rules of logic must be thoroughly tested and can not be changed rapidly at someone’s will. This makes these rules inherently conservative and rejective of radically new ideas. In addition, science is part of society and can not be free from various social interests even if objectivity and impartiality form the cornerstones of the scientific methodology. The ultimate scientific paradox is that science, which is supposed to protect new ideas, sometimes tries to kill them. Examples of 'scientific hiccups' are numerous and well known.

The revolutionary ideas of Abel, Galois, Lobachevsky, Boltzmann, Gibbs, Schwarzschild and many others were initially rejected by the scientific community. It would be a mistake to simply blame ignorance or selfishness of other scientists for these significant mishaps. For example, the outstanding submissions of E. Galois (1830) introducing group theory in application to the solvability of polynomial equations were reviewed by the best mathematicians of that time – Cauchy, Fourier and Poisson -- who failed to understand that work. The pioneering work of N. I. Lobachevsky (1823) on non-Euclidean geometry was rejected by another prominent mathematician, M.V. Ostrogradsky, who did not see any rationale in this new theory. Although we now know that Lobachevsky was right and Ostrogradsky was wrong, this judgment is based on the much later discovery by A. Einstein (1916) of the general theory of relativity (GTR), which deals with curved non-Euclidean spaces. On the basis of knowledge that was available to him at that time, Ostrogradsky’s opinion was actually quite reasonable: Lobachevsky’s work was, indeed, irrelevant to contemporary science. Today we see Lobachevsky as a provincial intellectual whose work was not appreciated by the metropolitan establishment but, in the middle of XIXth century, he was the Rector of Kazan University publishing his dubious ideas in a journal which was printed by the same university. Following the introduction of GTR, K.Schwarzschild (1916) found a solution of the GTR equations corresponding to what is now called a black hole. No-one believed in black holes, including Einstein himself (although it is worthwhile to note that Einstein did not try to prevent publication of these results and held Schwarzschild in high regard). Black hole theories became popular only in the 1960s after the discovery of quasars.

Science is a complex system with a very large information base and various ideas competing against each other for the right to be commonly accepted. It is inevitable that development of science is subject to the pitfalls of evolution considered previously and has its own leaping cycle. This cycle was first noticed and consistently analysed by philosopher Tomas Kuhn (1996) who views the history of science as a sequence of paradigms successfully replacing each other rather than a continuous accumulation of scientific knowledge. A dominant paradigm tends to retain its power beyond the limits of its productiveness but is inevitably replaced by a new paradigm and this event is seen as scientific revolution.

In a well-established area of knowledge, engineering tends to use the tools developed by science and be mainly concerned with practical application of these tools. If, however, the old framework can not resolve the issue and a good leap forward is needed, relying on intuition may be the only option available. Engineering as a discipline is not free of hiccups but these hiccups are different from the hiccups of pure science. Traditionally, engineering more than science is reliant upon inventiveness, common sense and educated guesses. Whenever there is a need for new ideas and approaches, the inventiveness of the engineering discipline can become a decisive factor in ensuring successful outcomes. Engineering has methodological differences with science --- engineering is more likely to accept and use an approach based on its usefulness even if the approach lacks rigorous justification. For example, rapid development in aviation and aerodynamics in XX century resulted in the formulation of the concept of boundary layer, which first understood as a physical layer of air around an airplane (Prandtl, 1952). Progress in asymptotic methods, which followed the development of aviation, converted the term "boundary layer" into a general property of singularly disturbed mathematical equations (Nayfeh, 1981). In technological development, engineering plays a dual role: engineering connects pure sciences and industrial applications and also stimulates the development of new approaches that only later become incorporated into rigorous sciences.

Science and Engineering from Educational Perspective

In technological society, education plays the principal role of passing information from generation to generation. Evolutionary efficiency of this form of transfer of information is grossly superior compared to biological information passed to next generations in genes. Without education, technological evolution would be simply impossible.

The differences in methodologies of science and engineering can be also observed from an educational perspective. Although engineering and scientific curricula have many common points, a future engineer and a future scientist are not only taught different courses, they are also taught differently. A scientist is expected to learn, become a top specialist in a selected, relatively narrow field and then move forward the frontier of knowledge in this field. An engineer will have much less freedom in selecting problems that he/she would like to solve and he/she is supposed to select the best available scientific tools and provide the optimal solution for this problem. Thus a research engineer needs to have a broader scientific knowledge than (although, maybe, not as deep as) that required from a scientist. An engineer should be able to move promptly between scientific fields and quickly learn the details of scientific approaches that are needed to solve a practical problem.

The benefits of teaching science to engineers are commonly accepted and do not need to be advocated. A future scientist, however, can also significantly benefit from being taught some engineering-style courses. Any student would benefit from innovativeness, independent thinking, a wide scope of perspectives, visual clarity, informal style and other features typical of engineering education.

In early 1930s, von Karman -- one of the most renowned engineering scientists and engineering educators -- accepted a position at Cal Tech and moved to the United States. Von Karman was known as a strong proponent of giving a broad scientific education to engineering students. This, however, was not the point that von Karman had to argue in Cal Tech: by that time the need for sound scientific education of future engineers was well-understood in top American engineering universities such as MIT and Cal Tech and these institutions were employing many outstanding scholars. The point that von Karman put forward during his tenure in Cal Tech and later in his book (Von Karman and Edson, 1967) was that engineers should be taught mathematics differently from mathematicians. While mathematicians are presented with formal derivations in from of axioms and theorems, engineers, he argued, should learn mathematics by applying it.

The future of engineering is not predetermined: its role for tomorrow is, to a large extent, determined by today's realities of engineering education. Making an inventor, leader and thinker out of every single graduate is probably an unachievable goal in any discipline, but engineering education should not be a constraint limiting the graduate's ability to become an inventor, leader or thinker. The short-term interest of a particular industry in producing a bunch of narrow specialists trained for a particular job (quite routine in many cases) must be balanced by the long-term interests of that same industry and the rest of society to obtain broadly educated and inventive individuals. In present conditions, the prestige of the engineering profession is determined by the ability of educational institutions to supplement their en masse production of engineers with advanced engineering education, containing a broad knowledge base and an emphasis on creative intelligence and ingenuity. Even if some advanced engineering graduates may choose to become scientists, managers, entrepreneurs or politicians, their achievements would still advance the key engineering values.

Conclusions

Evolution of large systems involving duplication and competitive selection is suggested to have common features. At large scales, these systems tend to display a cyclic behaviour which is characterised by a periodic (rather than continuous) development. This behaviour is called here "leaping cycle". During this cycle a new successful generation achieves and sustains a dominating position but is ultimately replaced by another generation. The cycles are known to exist in historical and economic developments, in biological evolution and technological progress. The differences between these complex developments are profound and should not be underestimated. For example, biological evolution applies to biological species while technological evolution deals with inventions, ideas industrial and social structures more than with particular individuals. The common behaviour at large scales in the systems that have most radical differences at smaller scales is the most interesting feature of the leaping cycle. It is interesting that, despite its highest intellectual content, science is not free from its own cycles that bring a new dimension into ongoing and versatile interactions between science, engineering and education.

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My major research interest are in the area of fluid flows, turbulence and combustion but development of technology, evolution of human knowledge and their influence on tertiary education are also within my main professional interests.

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