Why does one need to be taught engineering logic?

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Abstract - **It is not easy to give an accurate definition of engineering. One of the principal questions in defining engineering is whether this discipline has it is own methodology, or the methodology of engineering is fully derived from the methodology of pure science. Scientific knowledge is, undoubtedly, extensively used in engineering, but it is also an arguable point that engineering knowledge is not limited by the knowledge base of pure sciences. Engineering often uses approaches that are practical but not sufficiently rigorous or well-established from a scientific point of view. Inventiveness is an important part of engineering tradition that is difficult to define in precise terms, but its presence is one of the cornerstones of the engineering profession. The differences in the methodologies of engineering and pure science are reflected in the realities of engineering education. Although future engineers must be well-educated people and should be taught science and economics, the style of education of scientists and engineers does not have to be the same. The methodology of science is the most established and validated tool available to modern researchers and, of course, can not be replaced by the methodology of engineering. This, however, does not mean that engineering methodology has no merits of its own. We advocate an inclusive approach to the engineering discipline and relate its future success to the ability of educational institutions to produce broadly-educated specialists.**

Index Terms - Methodology of Engineering and Science, Tertiary Education.

WHAT IS ENGINEERING ?

Every engineer knows that it is not so easy to give an accurate definition of the engineering discipline. After searching through several dictionaries, I discovered that they do not offer identical interpretations of engineering. The definitions given in dictionaries can be broadly classified into three categories represented by the following statements

A) Design and putting to practical use of engines or machinery of any type [1]
B) The application of science to the design, building and use of machines, constructions, etc. Engineering science – Engineering as a field of study [2]
C) The art or science of making practical applications of the knowledge of pure sciences [3]…

One can see that there are significant differences between these definitions. Practical applications are the focus of definition A. Practical use is germane to this understanding of engineering, while scientific knowledge is not. An engineer, according to definition A, is anyone who deals with engines or machines; for example, a skilful technician putting an engine into use is an engineer. Definition B outlines importance of science, from which engineering is derived by applying science to machines and constructions. According to B, engineer must posses a sufficient amount of knowledge and, in modern terms, this probably means holding an engineering degree. On the face of the problem definitions A and B seem to be opposite but, in fact, these definitions have a very significant common feature – engineering, according to both A and B, does not possess its own systematic methodology. Indeed, according to A, engineering does not need one since it is more like a practical skill while, according to B, methodology used in engineering is provided by science. Definition C is essentially different from A and B. It points to the existence of a certain methodology within engineering that is different from the methodology of pure sciences, although the art of intuition is also important for engineering. According to definition C, an engineer is an ingenious person – one who possesses special qualities of engineering knowledge, intuition and inventiveness.

All of these definitions are, of course, linguistically legitimate and the word 'engineering' 'may have different meaning when used by different people in different circumstances. Figure 1 schematically illustrates differences in definitions A, B and C. It seems, however, that definition C better reflects important tendencies in development of engineering and Figure 1C represents most accurately the state of the engineering discipline. The following discussion demonstrates that engineering does indeed possess a certain methodology of its own, which can be called 'engineering logic'. Engineering logic has many similarities with but is not identical to the methodology of pure sciences (the term 'logic' used here does not necessarily represent formal mathematical logic). Science is sometimes understood as a very broad term involving all known disciplines including engineering but, obviously, 'science' should be interpreted here as 'science other than engineering'.

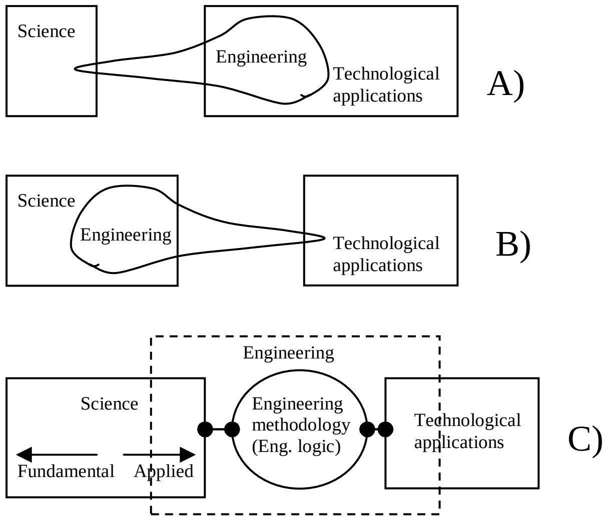

FIGURE 1
PLACE OF ENGINEERING BETWEEN SCIENCE AND APPLICATIONS

ENGINEERING KNOWLEDGE AND METHODOLOGY

An engineer working in an automotive design bureau uses his intuition and suggests a new configuration of the passenger seats enlarging available space – this is a typical example of engineering practice. Engineering as a discipline is concerned with not just making a particular model better but with consistent design and manufacturing of high-quality cars. These days the automotive industry produces much better and more efficient cars than, say, 40 years ago. This happened not because modern engineers became more intelligent than their forebears but because of accumulated engineering knowledge in designing and building new good cars. Engineering knowledge forms the core of the engineering discipline and allows engineers to develop their personal inventiveness.

Engineering knowledge is not necessarily fully interconnected but it certainly does not represent a long list of separate intuitive recipes. Engineering knowledge is, essentially, a structured knowledge that not only tells an engineer what to do but also explains why. Only structured knowledge forms a good basis for continuous, progressive development – one of the prime goals in engineering --- while a 'recipe book' can not offer anything beyond things that are already written there. Blocks of engineering knowledge are linked and interconnected by logic --- a set of formal, intuitive or commonly accepted rules and an understanding of what we can accept as a valid explanation, proof or link. Hence, the engineering discipline is linked to logic but is the logic practiced in engineering essentially identical to the scientific logic?

No one would seriously doubt that engineering derives an essential part of its logic from science – whenever a scientific explanation of a observed phenomenon is available, engineering is happy to use it. There are, however, many cases when engineering can not express its broadly defined problems in terms of science or science does not offer an answer for engineering problems. This is the case when engineering has to invent its own logic and the logics of science and engineering diverge. The prime goal of science is to understand the world while the prime goal of engineering is to improve it. Although, understanding and improving can not be achieved without each other, the difference in goals induces a certain difference in the methodologies. The statement 'there is no solution for this problem' is acceptable for science if the problem is beyond its frontiers but not for engineering, which must offer the best possible solution even if a rigorous treatment of the problem is impossible. An engineer can not refuse to build a new airplane on the grounds that he can not find an analytical solution and does not have a computer powerful enough to resolve all details of the turbulent flow around the airplane – engineer must find solution for this problem using approximate models of turbulent flows. If science does not offer a rigorous solution, engineering must be inventive enough to overcome this difficulty . There are numerous examples of approaches or concepts that were first de-facto introduced and used by engineers and only later were de-jure incorporated by conventional science.

Effectiveness of engineering logic is well illuminated by the development of classical thermodynamics. The beginning of XIX century was characterised by a rapidly growing use of steam engines while the physical science of that time was not yet sure about the nature of heat. In 1824, French engineer Sadi Carnot published his work [4] establishing the best possible efficiency of a heat engine. In this work, Carnot invented an idealised cycle with the best possible performance while using an empirical notion of heat that existed at that time (caloric gas). This is a good example of engineering logic: although a scientific explanation of heat was not available at that time, Carnot was able to establish a correct logical link between temperature of the heat source and efficiency of the heat engine. The principal thermodynamic works of 1850s by R. Clausius [5] and W. Thomson [6] combined the scientific basis of the 1st law declaring physical equivalence of heat and energy with the engineering nature of the second law. The fundamental concept of the 2nd law – the entropy – was introduced de-facto as a useful quantity without explaining its physical meaning. The physical explanation of the statistical nature of the entropy was given only in the late XIX century by L. E. Boltzmann, J. W. Gibbs and J. C. Maxwell.

Engineers and physicists have used delta-function in form of 'unit impulse function' or 'point forces' long time before the function was systematically introduce by physicist Paul Dirac [7] as the function which has unit integral and is zero everywhere with exception of one point where it is infinite. Even at this stage, the delta-function remained to be a mathematical nonsense --- the conventional integral of a function which is zero almost everywhere is zero. Only after works of S. L. Sobolev [8] and L. Schwartz [9] mathematicians began to understand that, from mathematical perspective, the delta-function is not a function but a functional. The delta-function and other generalized functions (i.e. functionals) are now widely used in modern mathematics.

EDUCATION IN ENGINEERING AND SCIENCE

Differences in methodologies of science and engineering can be also seen from educational perspective. Although engineering and scientific curricula have many common points, a future engineer and a future scientist are taught not only different courses, they are 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 would like to solve and he 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 for engineering education.

Engineering methodology is a powerful and practical tool that is used not only by engineers but also by scientists. A.N. Kolmogorov is known for the introduction of the theory of the small-scale structure of turbulence that now bears his name [10]. It is less known to engineers that. Kolmogorov is an outstanding mathematician who laid down the foundation of the probability theory by connecting probability to mathematical measure [11]. When Kolmogorov contemplated the probabilistic nature of turbulence, it would have been logical for him to use mathematics of probability theory in conjunction with physical laws of motion to analyse the structure of turbulence. If he had selected this way of approaching the issue, it is most likely that the theory of inertial interval of turbulence would have born someone else’s name – the problem is simply too difficult for a strict solution. Instead, Kolmogorov acted like an engineer. He intuitively determined that the dissipation of energy must be the key parameter for the inertial interval and derived his laws of turbulence from this assumption. It is worthwhile to note that in the early stages of his career, Kolmogorov studied not only mathematics but also engineering and history.

In early 1930s, von Karman -- one of the most renowned engineering scientists and engineering educators -- accepted a position at Cal Tech and moved to 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 of 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 [12] 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.

Differences between engineering and scientific curricula are less pronounced in advanced engineering education fostered in leading engineering education institutions (MIT, Cal Tech, MPhTI, etc.). In these institutions, engineering students are expected not only to learn traditional engineering disciplines but also obtain a broad scientific background that is comparable with the scientific knowledge required for the conventional university degrees in science. Advanced engineers can be found working as engineers, or scientist, or researches in broadly defined interdisciplinary areas. Advanced engineering education is most interesting for the present discussion since its scientific curriculum is similar to that of science degrees, yet this style of education produces very distinct specialists. This distinction is more related to how students are taught than to what students are taught. In traditional scientific education a great deal of attention is paid not only to finding the correct answer but also to ensuring that this is done using proper scientific methodology. To receive a full credit in this tradition, a researcher must present his idea wrapped into a sound methodological framework. In engineering education, the emphasis is placed on achieving overall success in solving a problem: an educated guess is as good as proper mathematical analysis as long as it leads to correct solution of the problem (we stress that correctness of the found solution must always be clearly demonstrated). An engineering graduate is more likely to pay most of his attention to the issue that seems to be the key element of the problem while ignoring everything else. The ability of not only conducting quality research and publishing papers but also quickly solving the problem ('can do' attitude) is an important part of the engineering profession and this is reflected in engineering education.

This article is not intended to suggest that engineering methodology is superior to the methodology of science. Quite the opposite: we do not know anything better than the methodology of modern science that was gradually developed over many centuries. It would be wrong, however, to deprive methodology of engineering from any merits on its own. The successes of educational institutions (and their graduates) that combine inventiveness of engineering with integrity of science, illustrate this point well. The simplistic educational premise of always teaching engineering to future engineers and science to future scientists does not represent the best possible choice. This work explores and explains why this is the case.

IS SCIENCE ALWAYS RIGHT?

What can be done to protect new technologies that are uncompetitive at present but, if they are given a chance to develop, may become the mainline of technological progress in the future? In technological developments, this protecting role is entrusted to the fundamental science that 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. Thus, usefulness is the major criterion in engineering, but not in science, which has to develop its own criteria of 'right' and 'wrong'. These scientific criteria represent what is broadly called 'logic': we accept a scientific concept or explanation if it appears logical to us and reject it otherwise.

In theory, fundamental science must perform its role of protecting valuable discoveries from 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, outstanding submissions of E. Galois introducing group theory in application to the solvability of polynomial equations [13] 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 on non-Euclidean geometry [14] 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 much later discovery by A. Einstein of the general theory of relativity (GTR) [15] that 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 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. In 1916, K.Schwarzschild found a solution of the GTR equations corresponding to what is now called a black hole [16]. 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 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. Develompent of science is not continuous but cyclic. This cycle was first noticed and consistently analysed by philosopher Tomas Kuhn [17] who views 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 inevitable replaced by a new paradigm and this event is seen as scientific revolution.

If a discovery is pressured into existence by overall technological development, it can be found by several scientists simultaneously and independently. If a discovery comes ahead of its time, it is more likely to be found by a single person while others do not have even any slightest interest in it. In most cases, revolutionary works were rejected more due to indifference than because of somebody's malicious or corrupt intent. The scientific methodology would do a good job is assessing a work that follows established lines while assessment of a rare work that designated to break established postulates can not be done within these postulates. Any formal system of assessment appears to be incomplete in comparison with the complexity of nature. It worthwhile to mention that K. Godel's theorem [18] formally demonstrates inherent incompleteness of all sufficiently complex formal (axiomatic) theories (i.e. theory can not formally assess correctness of some of its statements). In application to our consideration, the Godel theorem means that science can not have any formal algorithmic reviewing procedure that can always guarantee distinguishing correct and incorrect results. In most cases science does distinguish (or can distinguish in principle) rights from wrongs and encounters principal problems only when its established methodologies or approaches are questioned.

These examples are not intended to produce impression that science always makes mistakes in principal questions while engineering does not. There are examples of significant engineering misjudgements and remarkable, nearly prophetic predictions originated by science. One possible example of such predictions is that of Turing machine [19] which represents a generic mathematical model of a computer suggested before computers were designed and built as realistic devices. The concept of the Turing machine stimulated development of the computer technology and led to almost ubiquitous use of computers in the end of the same century. The positive examples, however, can not change the fact that, from time to time, science makes significant mistakes and, sometimes, an idea, which has been rejected by science as something that is not proven, can be accepted by engineering: 'this may be not proven yet but let us try if it can do the job'. Here, we advocate not blaming the scientific methodology for all previous mistakes it made but understanding its inherent limitations. When a problem is well within an area thoroughly explored by science, replacing rigorous analysis by an educated guess is a risky strategy that can not be advocated especially when errors can be damaging for the society. 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. Whenever there is a need for new ideas and approaches, the inventiveness of engineering discipline can become a decisive factor ensuring successful outcomes.

ENGINEERING PARADIGMS

In spite of many notable successes of science, technological progress in general and the engineering discipline in particular often have to deal with various situations when science misjudges the principal direction of its advance or fails to provide the required scientific tools. In this case, the major options available to engineering are:

A) proceeding forward blindly by trial and error;
B) waiting until science becomes capable of offering some guidance;
C) proceeding forward while inventing new engineering approaches compensating for the absence of rigorous scientific tools

One may notice that these three options correspond to the definitions of engineering given in the first section. Historically engineering has, perhaps, resorted to a mixture of all these strategies but there is an obvious advantage in proactive strategy C. This option not only invigorates technological progress but also stimulates science to move its frontiers forward by introducing scientific rigor and understanding into approaches that initially appeared as purely engineering tools.

Our consideration shows that the appearance of engineering as a discipline with its specific methodology that we call here 'engineering logic' was predetermined by the technological progress. The nature of engineering logic, which appears to be both rational and flexible at the same time, is determined by the need of advancing the technological progress. In its most general understanding, engineering is the knowledge core of technological progress: engineering is interested in knowledge that can be used to improve the world while science is interested in any type of knowledge.

The role of engineering, however, does not remain static and some of these changes are germane to our discussion. In the age of the industrial revolution, the leadership in technological progress clearly belonged to engineering while science had to follow and give new engineering discoveries proper explanations [20]. Although science was relatively inexperienced, discoveries and inventions were near the surface and anyone could make a discovery. For example, Botanist Brown discovered the fundamental physical effect of Brownian motion and speech therapist Bell invented a telephone.[21] At that time, outstanding personal qualities seemed to be as important as (if not more important than) scientific knowledge. A traditional engineer was a person to be admired. First, he would have to design a bridge, then perform all necessarily calculations, then manage the bridge construction project and finally, confident of his creation, the engineer would stay highly visible to everyone in the first vehicle driven across the bridge. These old engineers represented a remarkable combination of inventiveness, knowledge, leadership and social responsibility; they possessed unrivalled social status and were undisputedly at the helm of the technological progress.

Engineering discipline still seems to prosper in the modern technological environment but changes in the status of an engineer are becoming more and more noticeable. Modern science has learned from its past mistakes and can claim a series of outstanding achievements. Inventing is more a matter of sustained research while discovering something without science seems to exist only as a hypothetical possibility. Anyone doing research or investigation even with the purpose of creating a practical device is seen as a scientist rather than an engineer. Traditional disciplines fill all possible knowledge space and overlap each other. Typically, any modern engineering project is closely connected to modern science and deals with economic, environmental, legal and social issues. Technological progress has blurred the boundaries separating disciplines and significantly extended the knowledge base expected of an engineer. The frontiers of pure science have advanced forward and many fields, previously useless from practical point of view, have moved into the practical domain. Although linking science and industry used to be the cornerstone of the engineering profession, industrial decisions are now taken by managers – people who are specially trained to make decisions, mostly on economic grounds.

The changes in status of the engineering profession can be illustrated by the following test. Launching a space mission is essentially a high-tech engineering project that may, from time to time, also involve some scientific goals (for example, determining the composition of Jovian atmosphere). Thus, the people working at NASA should be seen in most cases as engineers, sometimes as scientists and in very few cases as officials (managers, officers, bureaucrats). The Google web search engine returned the following number of hits:

TABLE I
WEB SEARCH RESULTS

Search string	2006	2007
"NASA engineers"	240 000	191 000
"NASA scientists"	931 000	495 000
"NASA officials"	346 000	295 000

One can assume that the found web pages refer to the same professional people working for NASA, yet their high professional status is associated by the media and public opinion with profession of a scientist rather than that of an engineer.

THE FUTURE OF ENGINEERING

The possible responses of the engineering profession to new challenges of the modern world are in line with the options discussed previously. Options A and B presume restricting the scope of engineering discipline by leaving anything that has something to do with science to scientists, anything that has something to do with economics to economists and so on. The future of engineering confined by this narrow understanding of this profession, which is isolationist and inward looking, does not appear to be glamorous: engineers will become technical labourers performing well-defined tasks under directions of scientists, managers or bureaucrats.

Another vision for the future of engineering profession is offered by option C that views engineering as proactive, interested in everything that may advance technological progress and closely cooperating with other disciplines. Engineers, according this view, are inventors, thinkers and leaders bearing the ultimate responsibility for technological..Engineering is quick to learn from pure sciences and move into new areas whenever advances of science offer a new opportunity for technological progress. Whenever science is trailing behind rapidly developing technology, engineering is happy to play a leading role and stimulate appearance of new theories and methodologies. The engineering approach is always practical and characterised by the ability to see a bigger picture through incorporating a particular scientific or industrial problem into the broader context of technological development. Engineering is conscientious about socio-environmental issues and aware of various economic constraints. In industry, engineering is the leading force that ensures responsible operation of existing facilities and advancement of new technologies into industrial practice.

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 the same industry and the rest of the 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 by advanced engineering education with a broad knowledge base and an emphasis on creative intelligence and ingenuity. Even if some of the advanced engineering graduates may choose to become scientists, managers, entrepreneurs or politicians, their achievements would still advance the key engineering values.

The role of engineers in modern society is important not only for engineers themselves. Societies with a high status of engineers tend to be socially stable, technologically progressive and, ultimately, quite prosperous. The nature of the engineering profession combines practicality and imagination, stability and development, social responsibility and individual achievements. In its broad understanding, engineering is the very central point of our modern technological society with pure sciences and industrial manufacturing, rigorous disciplines and arts, state bureaucracy and free enterprises – all of them are positioned around engineering's middleground. In coming decades, our technological society will have to go though a series of significant adjustments determined by changes in energy supply. It is difficult to speculate about the more remote future but the keys for new technologies resolving energy problems of coming decades are going to be in hands of engineers.

REFERENCES

[1] *Dictionary of Science and Technology*, Chambers, London 1999.
[2] *Oxford Dictionary*, Oxford University Press, Oxford, 1992.
[3] *Macquarie Dictionary*, 3rd edition, Macquarie, North Ryde, 1997.
[4] Carnot S. N. L., *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance*, Bachelie, Paris, 1824
[5] Clausius R.J.M., 'Über die bewegende Kraft der Wärme', *Poggendorffs Annalen*, 79, 1850, 368-500.
[6] Thomson, W. 'On the dynamical theory of heat', *Math. and Phys. Papers* 1, 1851, 175-183.
[7] Dirac P.A.M. 'The physical interpretation of the quantum mechanics', *Proc. Roy. Soc*. A 113, 1926, 621-641.
[8] Sobolev S.L. ' Methodes nouvelle a resoudre le probleme de Cauchy pour les equations lineaires hyperboliques normales', *Mat. Sbornik.* 1(43), 1936, 31-79.
[9] Schwartz L., *Theorie des distributions*, Dunod, Paris, 1950.
[10] Kolmogorov A.N., 'Lokalnaia struktura turbulentnosti', *Dokl. AN SSSR*, 30(4), 1941, 299-303
[11] Kolmogoroff A.N., *Grundbegriffe der Wahrscheinlichkeitsrechnung*. Springer, Berlin, 1933
[12] Von Karman T. and Edson L., *The wind and beyond*. Little Brown & Co., Boston, 1967.
[13] Galois E., 'On the condition that an equation be soluble by radicals', written in 1930, published in 1846 by J. Liouville in his *Journal de Mathématiques Pures et Appliquées* 11, 1846, 385-394.
[14] N.I.Lobachevsky's major work, *Geometriya* was completed in 1823, fully published in 1909
[15] Einstein A, 'The Foundation of the General Theory of Relativity', *Annalen der Physik*, 49(7), 1916, 769-822.
[16] Schwarzschild K., 'Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie', *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften* 1, 1916, 189-196.
[17] Kuhn T.S., *Structure of scientific revolutions*, The University of Chicago Press, 1996.
[18] Godel K., 'Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme', *Monatshefte für Mathematik und Physik* 38: 1931, 173-198.
[19] Turing A.M., ' On computable numbers with an application to the Entscheidungsproblem', *Proc. London Math. Soc.*, 2(42), 1936, 230-265
[20] Johnston S., Gostelow P. and King J., *Engineering and society*, Harper Educational, Pymble, NSW, 1995.
[21] Asimov A., *Biographical encyclopedia of science and technology*, Doubleday, N.Y., 1982