ON THE TRAINING OF INNOVATIVE ENGINEERS

O.L. Figovsky
Polymate Ltd.-INRC, Migdal HaEmek, Israel
figovsky@netvision.net.il

ABSTRACT

Innovative engineer is an engineer who has achieved a productive qualification level and developed innovative decision-making in a certain field of science, engineering and technology and its related fields. The need to develop advanced technological systems based on the use of various combinations of many physical, chemical, biological, mathematical and information laws, principles, effects, and models determines the appropriate requirements for engineers' skill level and creative potential . Formation of these requirements is based on a model of a specialist and socially constructed image of a recognized expert in a particular activity.

Инновационный инженер- это высококвалифицированный специалист способный принимать инновационные решения в определенной области науки и техники. Развитие и разработка новых технологических систем, основанных на использовании физических, химических, биологических, математических и информационныхзаконов, принципов, эффектов и моделей предъявляют соответствующие требования к квалификации и творческому потенциалу инженера. Формирование этих требований основываются на модели такого специалиста и его социальном облике, созданные признанным экспертом в данной области.

Economists think the modern world industrial production is in the middle of dominance of the fifth technological wave and we even see the beginning of the realization of some scientific advances of the sixth one.

The actual implementation of the sixth technological wave requires access to a much higher level of development of Technosphere. Just a half century ago some of its technological features could exist only on the pages of science fiction. Improvement of existing and development of many new scientific and technological fields is taking place with an ever increasing complexity of technical facilities and technologies. This leads to an increase in intellectual and material costs for applied research and experimental development. The material costs for realization of specific projects, as well as its successful completion, are determined to a larger extent by the qualification of the people who implement it.

Both scientists and engineers always take part in the development and implementation of innovations. If the innovative project involves the creation of instruments and equipment, then highly skilled workers are added to the project staff. Scientists deal with the scientific sphere, while engineers are tasked with engineering and technology. By definition, science is a knowledge pool based on observable facts and verifiable truths, summarized in the form of structured systems, which can be conveyed to and confirmed by other experts. Unlike science, the activities of the engineer include creatively applying scientific principles to the planning, creation, management and operation of technology which should improve our daily lives. In short, if scientists are exploring nature with the purpose of comprehending its laws, then engineers use the already known scientific laws and principles for the development of economic solutions to technical problems. An engineer's work is an independent type of work and in that it differs from the duties of scientists. In the triad scientist-engineer-worker the engineer is the central figure of scientific-technical progress. Evidence of this is a constantly increasing share of engineering work in the implementation of modern technical facilities. This is due to the increasing complexity of new technologies. Increasing dominance of the flexible automated production plants and machines in the industry in the not too distant future will significantly reduce the manual labor and the number of workers. As for the engineers in enterprises and firms in developed countries, their number will increase. This is due to stiff competition in all sectors of industry connected to the present and future need for constant innovation, carried out mainly in the engineering activities.

The need to develop advanced technological systems based on the use of various combinations of many physical, chemical, biological, mathematical and information laws, principles, effects, and models determines the appropriate requirements for engineers' skill level and creative potential Formation of these requirements is based on a model of a specialist and socially constructed image of a recognized expert in a particular activity. In this case it is a model of a professional engineer. This model, which is acceptable for the specific professional environment, is the ideal end result of the educational process where society receives a specialist with the necessary qualifications for both the current level of scientific and technological progress and also for the future.

Forming a model of an engineer is a complex and ambiguous process. This complexity is due to the fact that there are dozens of engineering specialties. Within each engineering profession there may be several areas of specialization. Most of these areas are in innovation, production and maintenance. In addition, each developed country has a license system to maintain the quality of an engineering education and recognition of engineering qualifications. These systems are implemented in each country, as a rule, by national non-governmental professional organizations. The engineering associations have their own bodies for accreditation of educational programs and certification of specialists. The most authoritative professional organization in the United States and worldwide dedicated to assessing the quality of engineering education programs at universities is the *Accreditation Board for Engineering and Technology USA (ABET). ABET* defines the criteria of a typical engineer through mandatory general requirements for university graduates. In accordance with these requirements and through training graduates must acquire the ability to:

- Apply scientific, mathematical and engineering knowledge

- Plan and conduct experiments, analyze and interpret data
- Design systems, components or processes in accordance with tasks
- Work in teams on interdisciplinary topics
- Formulate and solve engineering problems
- Recognize professional and ethical obligations
- Communicate effectively
- Demonstrate broad erudition, which is necessary for understanding global and social impact of engineering solutions
- Understand the need for the ability to learn constantly
- Demonstrate knowledge of contemporary issues
- Apply the skills and modern engineering techniques needed for engineering work

Similar and additional qualifications engineer require can be found in other countries' national council lists. Without doubt, each requirement mentioned is important for forming the engineers' professional status. However, this begs the questions: how, within a limited 6 year program, do you train a future specialist with all of the aforementioned abilities & qualities? For a number of professional skills within this learning period it is only possible to achieve the initial skill level, which could be built upon. Subsequent levels are achieved in practice by self-development to fill the knowledge gaps and in continuing study through specialized postgraduate courses.

The initial level of training is based on verbal, visual and practical learning methods, by which the future engineers form a basic system of knowledge that is further broadened through workshops, production practices, courses and laboratory work. The final thesis project, which completes the process of university education, is an effective factor in the integration of acquired knowledge, the development of systematic thinking and a certain level of autonomy in decision-making. However, the project is usually completed under the supervision and with the aid of the instructor in charge of overseeing the thesis work, and it can not bring young professionals beyond the realm of entry-level qualification. In their early career young professionals with an initial (pre-productive) qualification level work under the supervision of more experienced colleagues and do not make independent final technical decisions.

The next level of qualification can be called an applied level. It includes an active and creative application of academically acquired knowledge to solve problems in the area of the person's specialty. Usually it happens through engineering activity associated with production and maintenance. In a production environment, the criteria applied to achieving the qualification level is the ability of the specialist to effectively and independently address emerging manufacturing problems associated with the replacement of components, materials, frequent changes in product design, development and adjustment processes. In the service sector achieving professional maturity manifests itself in independent problem solving tasks related mainly to maintenance, repair and modernization of existing technical systems, instruments and mechanisms.

The highest level of an engineer's qualification can be called a productive level. Such specialists can solve difficult problems during the process of developing new technological devices in a creative way. The creation of new systems, devices and machines in the modern age often requires going beyond traditional scientific and technical fields. Complex technical devices are rarely purely mechanical, electronic or optical. For example, much of the equipment for chemical and biological research or for medical use is a clever combination of various sensors, electro-optics, and analog electronics with microprocessor control systems, and connects to a computer or computer network through a standard or wireless interface. Developers of new technologies, devices, and materials must now know not only their own field of study but also have a grasp of adjacent fields and have a creative frame of mind, and also a good understanding of the fundamental sciences.

Of all the diverse requirements for engineers in general and innovative engineers in particular, the most important is the advanced ability to make decisions that lead to new technical solutions and the ability to find the necessary information and to educate themselves. These qualities are the foundation of the engineer's productivity and creativity. Without denying the importance of such qualities for an engineer as the ability to communicate and persuade, to create and maintain a positive atmosphere and friendly relations in a team, demonstrate knowledge and understanding of contemporary issues, follow the rules of professional ethics, as well as a number of other auxiliary qualities, it is most important to provide, promote and stimulate the development of main skills, chief among which is an inventive (innovative) thinking style, formed from early childhood through school and university, through constant mind development.

Man does not owe his ability to think either to God or to Mother Nature. God created the brain - the organ of thought. But the ability to think is a product of upbringing and education as well as the result of normal development of the biological brain. In this context, the German philosopher Karl Jaspers said: "Most people do not know how to think because people can sneeze and cough from birth, but thinking must be taught." The process of thinking in a logical sense among educated people, including scholars, artists, engineers and inventors, is based on such mental operations as analysis, synthesis, comparison, generalization, classification, specification and abstraction. With their help a man can get to the heart of a problem at hand, and consider the properties of the various elements of the problem, discern the relationships of those elements, and usually a solution is found. Formation of thinking skills should be a mandatory part of the training process, beginning with kindergarten. The thinking process must be developed during everyday education in schools of various levels of training and by addressing practical problems in the fundamental sciences, logic, psychology, technology, etc.

For example, for tasks and problematic situations that require mentally dissecting a complex object into separate parts, situations like this require analytical skills. In the theory of inventive problem solving (TRIZ) the method of analysis is the basis of many techniques for eliminating technical contradictions, for example the principle of segmentation, the principle of local quality, principle of taking out etc. Other times engineers use the reverse process of combining the components of the future system into a single unit, which is similar to a cognitive operation of synthesis. Various thinking techniques are the basis of most inventive methods.

Virtually the entire training of an engineer should involve the formation of systematic thinking, based on the whole variety of cognitive processes, forms and methods of thinking. In contrast to the cognitive processes, forms of thinking are the formal structures of organizing ideas development. Psychologists distinguish between three forms of thinking - notion, opinion and inference. Inferences can be made on the basis of notions and opinions. An inference can be inductive, deductive, and by analogy. In turn, an analogy can be straight, subjective, symbolic and fantastic. Thanks to analogies, for example, known ways of formulating and solving problems in one branch of human knowledge can be applied to another branch and vice versa. Albert Einstein’s statement is very significant here; his analysis of the struggles and experiences of Dostoevsky’s protagonists facilitated him in the formulation of new tasks in the area of physics. So Einstein was able to use the principles for solving life’s challenges applied by Dostoevsky in his masterpieces to set goals and solve entirely new problems in physics, which eventually led to discoveries around the theory of relativity.

Most engineering colleges and universities lack courses designed to teach students the basic skills of innovative engineering. This is due to a limited amount of training hours and a traditional education system in these schools. These reasons do not permit the creation of a separate section of courses, whose purpose would be the practical application of acquired knowledge in the development of creative and systemic thinking, creative imagination, teaching analysis and synthesis, system engineering and methods of formulating and solving inventive problems.

This need is long overdue and requires, in addition to the regular required courses, training of special, highly- qualified engineering-teaching staff with practical work experience as innovative engineers. The purpose of these engineer-educators will be to integrate and apply the student's academic knowledge for solving engineering tasks and actual projects. In addition, it requires modernization of curricula and teaching methods, as well as their adaptation to the needs of this aspect of engineering training. The essence of this upgrade is making fuller use of the didactic potential of each subject to deal with practical examples of problems in various subject areas.

To some extent this problem is solved by a teaching method proposed by the authors of that article. It allows the efficiency of the educational process to be significantly improved towards expanding interdisciplinary perspectives and developing systemic thinking. The basis of this method is the principle of two-dimensional learning (let's call them vertical and horizontal dimensions). The vertical component of the curriculum is based on logically structuring educational material within the investigated domain, where the older topics are the basic foundation for subsequent ones. So the learning process goes from simple to more complex. To give additional horizontal component of the same topic an instructor defines the place of that topic in the current interdisciplinary space (in the systemic knowledge framework) and gives examples of its engineering application in its own area together with other areas where the same principles can be applied.

Here are simple examples of using the two-dimensional model of training.

Example1. Physics. Electricity. Ohm's Law. Basic concepts formed in the previous topics: electromotive force, electrical resistance, electrical current (electrical engineering), the inverse proportional relationship (mathematics). The vertical dimension of learning: explanation of the physical essence of Ohm's law and finding an unknown value of the triad of parameters (voltage, resistance or current).

The horizontal dimension of learning includes:

a) A list and short abstract of practical problems based on the theory of linear electric circuits and the use of Ohm's law for their solution (calculating cross-section of electrical wire for power transmission and winding wires of electric machines, the choice of fuse, the calculation of heating elements, the calculation of additional resistors and shunts for the measurement circuits etc.);
b) formulating and clarifying similar laws (isomorphism) with the general semantic and mathematical model:
   - Ohm's law for magnetic circuits;
   - Ohm's law for pneumatic and hydraulic circuits;
   - Ohm's law for mechanical drives (transmissions);
   - Ohm's law for railway rolling stock, etc.
c) Ohm's law as a particular case of the generic law of action of the driving force on physical objects;
d) a general law of action of the driving force on physical objects (an interdisciplinary definition of Ohm's law): "The result of the impact of the driving force on any physical object (body or particle) is directly proportional to the magnitude of the force and inversely proportional to the resistance exerted by the object during its motion";
e) Definition of various driving forces: the linear mechanical, mechanical torque, hydraulic, pneumatic (gas), osmotic and light pressure, electromotive force (EMF), the magnetomotive force (MDS), and others;
f) Definition of various types of resistance: electric, magnetic and aero-and hydrodynamic, rolling friction and sliding friction, and others;
g) Definition of opposing forces and how they differ from the resistances.

Example 2. Basic algebra.

- Task 1. One car started to drive to town B from town A while another car left town B toward town A at the same time. One of the cars can go the distance between these cities in "*a*" minutes, and the second one in "*b*" minutes. After how much time will they meet? Basic concepts: distance, time, speed. Solution: $T = a * b / (a + b)$.
- Task 2. Two painters begin painting a room at the same time. One can do all the work in "*a*" minutes, and the second one in a "*b*" minutes. What is the combined time needed for them to complete the work?
  Basic concepts: are. Time, work, speed. Solution: $T = a * b / (a + b)$.
- Task 3. Two electrical resistors are connected in parallel. One of them has a resistance of "*a*" Ohm, and the second one of "*b*" Ohm. What is their total resistance?
  Basic concepts: resistance, conductivity. Solution: $R = a * b / (a + b)$.

First of all, students should solve these problems separately. Then they should explain why the problems related to mechanics, economics and electrical engineering have the same solution (a common mathematical model). You can then summarize, with the active participation of students, that similar problems with the same mathematical model can be created in many other areas, but they all can be united by one definition: "If two (or more) of the productive factors simultaneously working on achieving a joint final result, the outcome is equal to the inverse of the sum of their performance."

An important aspect in the realization of the didactic potential of these tasks is to explain two opposing concepts: productivity and resistance. A car's performance is its speed, which is the distance covered per unit of time. Labor productivity is the amount of work done per unit of time. A resistor's output is its conductivity (the value of an inverse resistance) as a parameter that determines the amount of current passing through it. Next, you must indicate and explain the essence of semantically related parameters when applying mathematical models: productivity, electric current, magnetic, heat, air, hydraulic, transport, information and other streams. The resistance to the movement of a car is a combination of factors (friction, air resistance), which it must overcome and which does not allow the car to move freely. In Task 1 values "*a*" and "*b*" are measures of resistancei; if they were zero, the car would cover the distance between cities instantly. Resistance (the slowing down factor) of a painting process (task 2, the values of "*a*" and "*b*") is due to limited technological capabilities, lack of good organization, poor working conditions, fatigue, aversion to work, etc. In its absence the work would be completed very quickly. Resistance (task 3, the values of "*a*" and "*b*") is the property of a material which hinders the passage of electrons. In the absence of electrical resistance in a circuit the application of a source of electromotive force creates an infinite current. Thus, if we talk about achieving a certain result within a certain time, that time is proportional to a resistance. It should be noted that even the value of electrical resistance correlates with the time factor. It is numerically equal to the time it takes an electric charge of 1 Coulomb to pass through a resistor (with non-zero resistance) under a constant electromotive force of 1 Volt.

Two-dimensional didactic, as demonstrated in simple examples, immediately prompts extra thinking, taking the student beyond the scope of the subject and creating an associative link with existing systemic knowledge in its various incarnations and perspectives. For a student with developed creative thinking, accustomed to interdisciplinary perception of topics of study, it would spark additional interest in (rather than rejection of), a proposal to state the general case of Ohm's law for a bicycle chain or to formulate Newton's first law in a psychological interpretation. Such "creative" students often become innovative engineers in high demand everywhere, since they are capable of tackling even "insoluble" problems. One organization needing such experts is the DARPA - Defense Advanced Research Projects Agency (USA). This Agency needs people with strong creative imaginations and a non-trivial style of engineering thinking in order to:

- make a suit to provide protection from enemy fire and bad weather, promote wound healing and increase the efficacy of human body;
- make soldiers and equipment invisible to the enemy across the electromagnetic spectrum whilst still allowing the use of the full spectrum to detect the enemy;
- look beyond the horizon, as well as through water, land, and walls;
- create a flying car and a flying submarine, as well as a UAV able to be airborne for months or years, etc.

A modern engineering education system should nurture and develop students with the high creative capabilities required to tackle such problems. This requires substantial changes in methodology.

The idea of multi-dimensional learning is not new. Even the famous French mathematician, philosopher, physicist and physiologist Rene Descartes once wrote: "All sciences are so interconnected that it is easier to learn them together, rather than any one of them separately from the others." And again: "The pronouncements of the learned can be reduced to a very small number of general rules." This means that there is a relatively small number of systemic elements of world knowledge, which in various combinations and relationships can form a much larger number of subsystems (domains). The elements of systemic knowledge include laws, theorems, axioms, rules, principles, effects amd mathematical and semantic models. Separate scientific disciplines are built out of these as from bricks. The same elements of knowledge in an unmodified or modified form may be applicable to different subsystems and subjects. This confirms the principle of isomorphism, which states that many different phenomena and processes though different in nature have similar properties and characters and therefore the same formal mathematical descriptions. The main principle of the two-dimensional learning approach is that of systemic quality, and is the associative binding of a topic under study with other subject areas and application of practical problems pertinent to the subject.

The method of two-dimensional didactics significantly expands the professional horizons of students and to a large extent determines their professional mobility in the future. Professional mobility allows an expert to adapt to new technological conditions by learning new technology and equipment as well as quickly acquiring missing skills and switching to another specialization. Professional mobility implies a high level of generalized professional skills based on interdisciplinary ideas and the practical application of mathematical models, physical, chemical, biological and information laws, rules, principles and effects. Rapid changes in technology and equipment make professional mobility an important component of the qualification structure of an engineer.

A high educational level and well developed thinking abilities are prerequisites for solving particular problems, but do not guarantee the absence of systematic errors which must be subsequently found and corrected in those solutions. If a developer or a development team is guided only by individual or group experience in system development, errors are inevitable and they may affect the viability of the project being developed. Individual experience does not always include all possible influencing factors in the variety of conditions with various manifestations which must be taken into account when designing a new and complex system. This is important because the set of factors taken into account not only determines the quality of a new system, but also the consequences of its subsequent implementation in real life. Positive and negative experiences of the development of engineering projects and their implementation facilitates the formulation of a unified approach to supporting the whole life cycle of systems from concept and design to production, operation and disposal. This approach, , called *systems engineering*, allows the development of sophisticated high-end systems even in the presence of many constraints: structural, technological, economic, ergonomic, safety, reliability, EMC, climatic, environmental, etc. Systems engineering is holistic, focused on the final product approach responsible for the creation and execution of processes, covering various engineering disciplinesl; it addresses the needs of customers and direct users of the product. This approach is implemented through the use of methods of achieving high quality and reliability, as wall as cost effectiveness and compliance to the project or program schedule throughout the life cycle of the system.

Disorganized thinking without any clever methodology often leads to sorting through myriads of options trying to find a solution to a complex problem. There are various methods of managing creative thinking which substantially reduce the time needed to find an acceptable or close to ideal inventive solution to a problem. The most effective of the existing methods is TRIZ - the theory of inventive problem solving. Structurally, classical TRIZ consists of the following sections:

1. Laws of Technical Systems Development.
2. TRIZ Information Fund.
3. Vepolny analysis of technical systems (structural substance-field analysis).
4. ARIZ inventive problem solving algorithm.
5. TRI creative imagination methods.

TRIZ accelerates the inventive process by removing an element of chance: sudden and unpredictable insight, blind search and rejection of alternatives, subjective factors, and so forth. In addition, the aim of TRIZ is to improve quality and increase the level of invention by removing psychological inertia and enhancing creative imagination. The use of TRIZ develops creative thinking, and also allows one to predict the development of technical systems and solve problems of any complexity and in any field.

Thus, an innovative engineer is an engineer who has achieved a productive qualification level and developed innovative decision-making in a certain field of science, engineering and technology and its related fields. Above all the foundations of such skill level are: quality of education in the fundamental sciences and technical subjects, proficiency in computer technology, software and design techniques necessary for a particular field, knowledge and use of modern methods of information search and retrieval, system engineering and methods of enhancing creative thinking. Emphasis on the practical use of acquired knowledge should be present in the process of training future engineers, as well as improving the system of postgraduate education and learning. Such programs require serious changes in the way engineers in general and innovative engineers in particular are trained.

The most advanced teaching methods are designed for highly motivated students. The final result depends greatly on the student's desire to acquire particular skills and become a member of the professional community. Professional motivation is determined by the student's personality and the surrounding society. Personal motivation is focused on the solution to a specific issue or problem. Its emergence is due to various reasons and circumstances. These can be of a professional, social, personal and academic nature. In the field of education personal motivation is usually the basis of various learning techniques like problem-solving, search and research methods. A student is not regarded as a vessel to be filled or a lamp to be lit! This idea belongs to J.H. Pestalozzi - one of the most famous teachers in the history of mankind. When either a student or a specialist is genuinely puzzled by a specific problem he or she becomes a pragmatist searching and sifting through all possible information and carefully interpreting it in the search for a solution. Desire (motivation) and persistence in solving problems is an essential component of success. The renowned actor and director Charlie Chaplin in this regard, said: "People often ask me how did I get an idea which inspired this or that movie. I still can not comprehensively answer this question. Over the years, I realized that ideas come when they are passionately sought after, when your consciousness is transformed into a sensitive camera, ready to capture any momentum, impulse of imagination - then a piece of music or a sunset can suggest some great idea. " There are cases when personal professional motivation grows into a general motivation, when a specialist or a student, fascinated by the prospect of solving an interesting or socially significant problem realizes that his or her current level of expertise is not enough to do it, and decides to improve in the chosen specialization or even change career and acquire another skill set.

General professional motivation is the action of a certain stimulus or inspiration, which determines not only the choice of profession but also the motive behind persistent day-to-day work fulfilling the duties and meeting the challenges of the chosen profession. It is formed not only under the influence of various factors and realities surrounding a person, but also as a result of career studies. The most highly influential factors of surrounding reality are the level of respect and prestige which the family and society in general show towards representatives of different professions. Noticeably, there were periods in the history of humanity when several outstanding composers created music of highest quality, in other periods there were talented artists and painters, in yet another it was the turn of the physicists. Obviously the prestige of a profession in society is of great significance and influence on the choice of career, as well as the needs of society for one or another occupation and the role of different professions in society. Where does the assurance of somebody’s calling come from? There are people (usually very few) who have a distinct talent for music, maths or languages. But there are many more simply talented young people who would have great success in either biology, medicine, physics or other areas. And it is in that situation that the current prestige of a profession, its public persona and how the media respect it exert a major influence. As a result a young person may start to think (consciously or subconsciously) that semiconductors, lasers or space rockets are his or her calling. However, recent decades in developed countries saw a significant drop in the interest of youth in science and engineering and much less desire to participate in developing new technology. Lawyers, management and medicine became the prestige professions. Egineering specialities are missing from that list. As a result many students who are admitted to engineering and technology departments of universities actually have lower average abilities which prevented them from going to currently more prestigious departments. There are less people willing to create new technology than willing to manage or trade, to be lawyers, actors, top models or bankers. The majority of talented youth is drawn or 'drained' to the non-manufacturing, service areas of the professional pool, which inevitably weakens the scientific, engineering and inventive potential of society. One example would be modern Israel. It has highest number of lawyers per capita in the world. Nevertheless that fact does not lead to decrease of those wanting to study law at university. There is similar situation in modern Russia, where to be an engineer, technologist or scientist is absolutely not prestigious and even *anti-prestigious*.

That situation requires governmental agencies, media and popular science organizations to make a U-turn towards raising the prestige of scientific and engineering occupations. The USA is now drastically changing its attitude towards the education and professional orientation of school students.

Part of new government policy is to provide substantial advances in science and technology. These plans were announced in US President Barack Obama's speech April 27, 2009 at the annual meeting of the National Academy of Sciences. He said: I want us all to think about new and creative ways to engage young people in science and engineering, whether it's science festivals, robotics competitions, fairs that encourage young people to create and build and invent - to be makers of things, not just consumers of things.

Realization of a new sixth technological wave will lead to the emergence of new scientific and technological fields which in turn will inevitably lead to an increase in numbers of engineers. The new technological era will widen the list of engineering specializations. Global economy will increase competition even more and as a result, changes in technology will become even faster in all areas of human activities. To maintain the competitiveness of products now and in the future engineers need to have high levels of qualification, an innovative mind-set, professional mobility and strong motivation. In the face of these predicted radical changes in science and technology society needs to attach a greater importance to engineering activities and to change the principles, methods of and approaches to organizing the system of engineering education.

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Prof. Oleg L. Figovsky is the founder, Director R&D of International Nanotechnology Research Centre “Polymate”. Novel nanotechnologies invented by prof. Figovsky were a base for establishing a few of industrial production in USA, Canada, China, Mexico, Russia and Israel. He is also the President of IAI (Israel), member of European Academy of Sciences, Foreign Members of two Russian Academies of Sciences (REA & RAACS), the chairman of the UNESCO chair “Green Chemistry”. For few of his inventions in nanotechnologies he received gold and silver medals at the IENA-98 (Nurnberg, Germany). From 1999 he is the editor-in-chief of the journal “Scientific Israel – Technological Advantages”, from 2008 – of the “Open Corrosion Journal”, from 2012 – of the RPCS-journal (USA). In 2006 he received the Gold Angel Prize, as the author of more than 500 inventions, and in 2007 NASA Nanotech Briefs®’ Nano 50™ Award, **Prof. Figovsky is now Director R&D of US investment and transfer technology company “NanoTech Industries, Inc.”.** Prof. Oleg L.

Figovsky has more than 500 patents and has published and lectured extensively. In 2013 his monograph **"Advanced Polymer Concretes and Compounds"** will be published in USA.