TOMASZ ARCISZEWSKI
the Volgenau School of Information Technology and Engineering
George Mason University
tarcisze@gmu.edu

JEFFREY RUSSELL
College of Engineering, University of Wisconsin-Madison
Russell@eng.wisc.edu

CHANGE DEMANDS RENAISSANCE IN CIVIL ENGINEERING EDUCATION

Abstract

Much has been written about how the world has changed and continues to change at an incredibly rapid pace. Much has also been written about globalization, population demands, water quality, waste management, and many more of the issues that confront human kind throughout the world. It is not the authors' purpose in this paper to repeat the familiar maxim: civil engineering education must change to meet the challenges of a rapidly changing world. Instead, the authors clarify the very real risks of the vectors of psychological inertia, and describe how systems analysis and the theory of inventive problem solving (TRIZ) justify substantive change in civil engineering education and how that could be accomplished.

Keywords: civil engineering education, national and local needs, contradictions, systems analysis, TRIZ, evolution

1. The Fluidity of Rapid Change Surrounds Us

Civil engineering is undergoing rapid changes driven by globalization, growing environmental, safely and security concerns, population demands, the computer revolution, and by scientific advances in fields such as biotechnology, materials science, nanotechnology, and many more. Obviously, such changes demand that students acquire more knowledge than in the past, not only traditional engineering knowledge based in science and math, but also new knowledge that encompasses emerging domains in science and engineering and knowledge in critical areas such as communications, leadership, business management, marketing, and the political process.

Furthermore, students need to learn how to develop novel designs, and that is absolutely necessary to maintain and expand our competitive advantage with respect to other countries and to be adequately prepared to meet coming professional challenges. Therefore, there are strong national needs to expand and enhance civil engineering education (CEE), including educating innovators, i.e. civil engineers with knowledge and skills necessary to develop novel designs, which might be potentially patentable.

Over the last 60 years a strong national trend has taken place in reducing the number of credit hours required for a BS degree in civil engineering. Presently, the US average is as little as 125 credit hours, down from 135 credit hours only 20 years ago. This trend is driven primarily by state funded universities bowing to political pressures to reduce the cost of undergraduate education and to ensure that BS students graduate in four years. Unfortunately, private universities follow this trend mostly to remain competitive.

Today, civil engineering educators struggle with the obvious contradiction between the national and local and state levels needs. The traditional national needs mean expansion of the CEE and a broad-based approach to moving forward. Whereas the local needs are much more often focused on the here and now, attuned to local and community politics and economic conditions; often resulting in efforts to reduce the breadth and depth of CEE. This contradiction cannot be eliminated through quantitative changes within the existing paradigm. Our hypothesis is that the existing situation requires a constant evolution of CEE. However, this will be insufficient and bold action and qualitative, or paradigmatic, changes are required in addition to constant minor quantitative improvements.

The objective of this paper is to present a theoretical justification for the constant evolution of CEE and for paradigmatic changes as well as to demonstatrate how such changes could be accomplished. The authors have developed the paper within the context of Systems

Science and of the Theory of Creative Problem Solving (TRIZ), which is also based on systems analysis. The fact is, the fluidity of rapid change surrounds us. As a profession, we must embrace it because time and change only move in one direction.

2. Escaping the Vector of Psychological Inertia

We are humans and our behavior, including professional behavior, is strongly affected by the ″Vector of Psychological Inertia″ (VPI) [1], [4], [5], [7]. Put in simple terms, as we operate within the VPI we are comfortable it what we know, in our given perspective, and in the manner and methods we employ to achieve our goals. It is understood as a natural human tendency to focus on known solutions in our own domain and to be extremely reluctant to seek solutions outside of our domain. Such an approach provides a psychological explanation as to why it is so difficult to think ″outside the box″ and why so often we follow the vector of psychological inertia (rooted in our experience) instead of following the evolution of the system being considered (See the next section for more on the evolution of engineering systems) (Fig. 1).

The vector of psychological inertia affects even talented inventors, who usually invest a lot of time and effort investigating local lines of evolution within their domain instead of initiating a process directly leading to the desired solution and based on the general patterns of evolution [1], [4], [5], [7], [11], [17].

The vector of inertia accompanies many practices and professions, in nearly every undertaking that comprises the human experience – from ancient times to contemporary life. This does not mean it is a good thing, for the vector of inertia impedes progress whether one considers the development of the latest styles of mobile telephones, or the current crisis facing the newspaper industry. The vector of inertia is characterized by an over-reliance on routine, and a failure to respond to external conditions and circumstances.

Consider the example of Nokia, the world's largest mobile phone maker. Five years ago Nokia paid a heavy price for being slow to adapt to consumer demand for new clamshell telephone handsets. At the time, Nokia saw its market share dip significantly and reported a 2% drop in first quarter profits. Major competitor Samsung Electronics recorded soaring profits, and an increase of 178% in a year-over-year comparison, marking the company's best quarter ever.

In some instances it takes a full-blown crisis to jump-start an industry and to elevate it beyond the vector of inertia. Such a crisis is confronting the newspaper industry as of this writing. The business model upon which most daily and weekly newspapers were founded has become obsolete, advertising revenues have declined significantly as well as levels of readership. Readers are flocking to internet news sites where they can acquire the news they need for free, and newspapers are scaling back, cutting staff, ceasing to publish in print and maintain an online presence only, and devising new business models in which readers will be encouraged to pay for content.

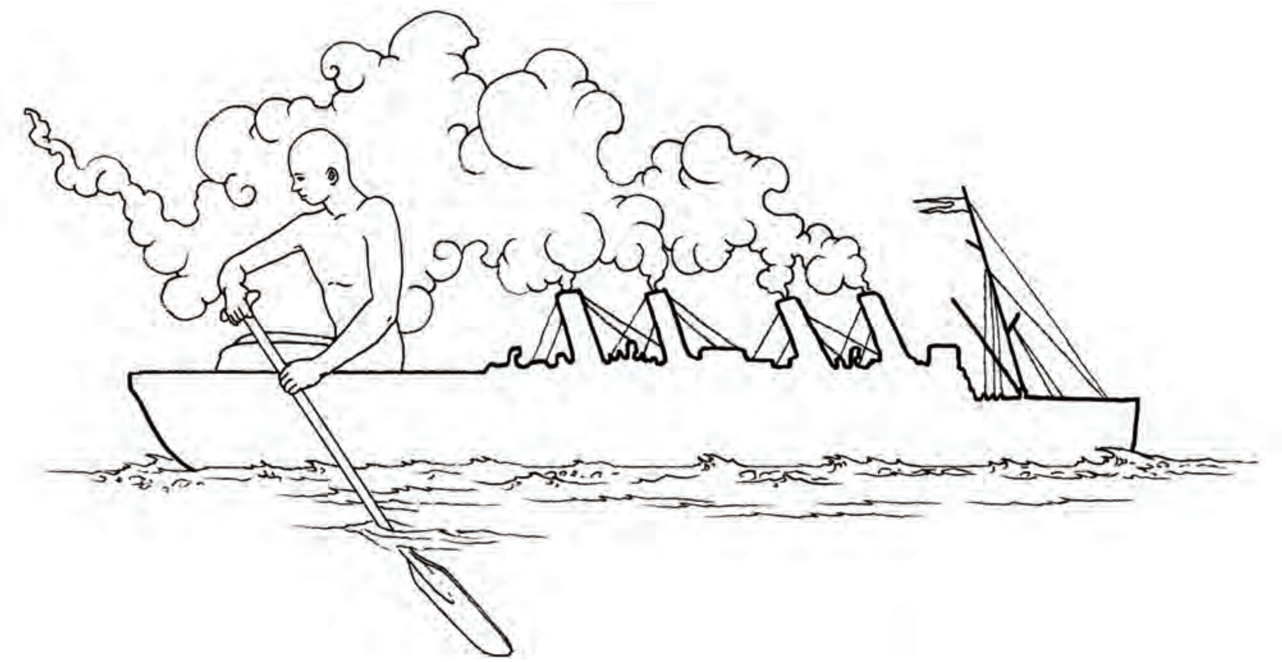

Fig. 1. The Vector of Psychological Inertia

The Internet and the general and wide spread availability of information at any time is one reason why newspapers have been struggling to survive. The organizational and managerial recipes that they have followed have become outdated, and lead to the growth of strategic inertia – the level of commitment to current strategy. As Wright et al. [16] has noted, ″An organization's strategic decision-making must retain or improve the organization's alignment with the external world. In other words, (management) recipes should not be routinely followed and should be changed altogether when appropriate″.

Reluctance to evolve CEE is well known, but mechanisms behind it are not fully understood. This often leads to emotional arguments, which create even more resistance to change. We believe that understanding the phenomenon in objective and scientific terms will help us improve the situation. The impact of the vector of psychological inertia is often harmful because it delays progress, as we discussed it earlier in the areas of communication and mass media. In CEE, there are many examples of how the vector of psychological inertia set back necessary changes, such as delaying the elimination of outdated courses, reviewing the curriculum as a system as opposed to a group of courses, or the introduction of new courses. For example, when the evolution of required and elective courses at the Civil, Environmental, and Infrastructure Engineering Department at George Mason is considered, the vector of inertia in action can be easily observed. About 15 years ago a novel required course on computer graphics in civil engineering was introduced, ENGR 183 ″Engineering Computer Graphics″. Its major focus was on teaching practical AutoCAD skills in the context of civil engineering applications. Today, many students take computer graphics courses at the high school and/or learn AutoCad during their summer internships, but the course is still offered. Even more, about a year ago, Dr. Michael Casey introduced a new elective course CEIE 472, ″Building Information Management.″ It represents the state of the art in the area of virtual design and construction and obviously includes the use of computer graphics and the AutoCAD but the old course is still offered and has not been modified to reflect the introduction of the new course.

When CEE is considered, we must be aware of the existence of the vector of psychological inertia and try to deliberately minimize its impact. If we fail to do so, we will make only small quantitative changes within our domain, without the benefit of knowledge beyond the realm of civil engineering. We must always remember that with improvement comes added value.

3. New Approaches Hold Promise and Potential

Systems Analysis

In the late 1940's, cybernetics emerged as a discipline dealing with abstract models of purposeful living organisms, artificial objects, or processes in nature and engineering, which were called ″systems models″, or simply ″systems″. Systems analysis created a revolution in our understanding of nature and engineering, revealing many common behavioral patterns and improving our ability to analyze and predict behavior of various systems. It allows the development of an abstract understanding of behavior of a given system in the context of its feedback with the environment in which it operates, including its past, present, and future responses (feedback) to the evolving environment. Presently, Systems Engineering (SE), a discipline descendent from cybernetics, is recognized as an engineering science and is taught to SE students, and also to civil engineering students. The recently updated and published *Civil Engineering Body of Knowledge for the 21st Century* [6] explicitly recognizes systems analysis as an appropriate and recommended analytical method for civil engineers. Systems analysis, and particularly the concept of a complex adaptive system provide an excellent understanding of CEE in general and objective systems terms.

Theory of Inventive Problem Solving (TRIZ)

The history of TRIZ spans more than 60 years, two continents, and three political systems. Ultimately, TRIZ is a result of efforts of a large group of talented engineers and inventors. TRIZ (a Russian-based acronym for the Theory of Inventive Problem Solving) can be considered as a knowledge system. It contains a class of inventive problem solving methods and a body of abstract engineering knowledge, necessary and sufficient to conduct the generation of inventive design concepts (inventions) in the majority of engineering domains. TRIZ is based on three fundamental assumptions.

The first assumption is that the generation of inventive design concepts in a specific engineering domain can be conducted using inventive knowledge acquired from engineering patents awarded in many engineering domains and in various countries over a long time period, and from other traditional sources of engineering knowledge. Inventive knowledge can be represented as heuristics (heuristic directives) formulated for various specific situations. Such heuristics are called ″Patterns of Invention″.

The second fundamental assumption deals with the evolution of engineering systems, built and abstract. This assumption maintains that when evolution of engineering systems over a time period is considered, they evolve not randomly, but according to objective patterns, called ″Patterns of Evolution″. Patterns of Evolution were discovered by Altshuller and other TRIZ researchers through learning from patents and from the history of engineering [1], [5], [11], [17]. There are nine patterns of evolution (Introduced in Section ″Five Perspectives″).

Finally, Altschuller has assumed that any inventive problem (i.e. problem requiring a novel and potentially patentable solution) requires elimination of contradictions, technical and physical. A technical contradiction is an interrelated pair of technical (abstract) contradictory characteristics of an engineering system. For example, *rigidity versus weight.* A physical contradiction occurs when a given physical characteristic of an engineering system should increase and decrease to satisfy different requirements. For example, the depth of a reinforced concrete beam should be maximized to increase rigidity and minimized to reduce weight. Typically, a physical contradiction results from a technical one. In the example, the technical contradiction is obviously *rigidity versus weight.*

There are many publications on TRIZ available in English, for example [2], [5], [7], [10], [12-15], [17].

4. Assumptions

Our analysis of CEE has been based on several assumptions, provided in this section.

- Our society constantly evolves, creating ever-growing demands for CEE.
- Globalization of the civil engineering market is a fact and competition is driven primarily by costs, quality, and novelty of designs and services.
- Traditional CEE offered in Europe and in many developing countries, particularly India, is much more extensive than in the US and often of comparable or better quality.
- The extent of CEE offered in this country has gradually been reduced (From 135 credit hours required 20 years ago to an average 125 today with many programs requiring only 120 hours).
- American civil engineers cannot win in the global competitive market based only on cost and quality. They have to develop an innovation-based competitive advantage. Clearly, we won't win on numbers alone and we have to compete with better solutions and better ideas.
- CEE is the key to the future of our profession and in fact the key to the future of our nation.
- CEE is a system operating in an evolving environment.

5. Five Perspectives

Evolutionary Perspective

In accordance with TRIZ (see the Theory of Inventive Problem Solving), the evolution of engineering systems is driven by objective evolutionary mechanisms, called ″Patterns of Evolution″. These patterns are valid in all areas of engineering, including civil engineering education and practice. Many studies, going back to the late 1940's, of the tens of thousands of engineering patents in many countries revealed nine patterns of evolution of engineering systems [1], [5], [11], [17], including:

1. System evolution based on S-curve.
2. Resources utilization.
3. Uneven development of system elements.
4. Increased system dynamics.
5. Increased system controllability.
6. Increased complexity followed by simplification.
7. Matching and mismatching of system elements.
8. Transition to the micro-level and increased use of fields.
9. Transition to decreased human involvement.

All these patterns are relevant to the evolution of CEE, but our focus is only on the first pattern, which is explained here. It says that all engineering systems evolve over their life period following an S-curve pattern when a relationship between a specific system's characteristic and time is considered. That means that during a life cycle of a given system, several distinct evolutionary patterns can be distinguished, each of a different nature. They include the periods of childhood (slow growth), growth (rapid growth), maturity (no growth), and decline (negative growth), as shown in Figures 2 and 3. More importantly, this pattern also means that each engineering system has its life cycle and when it is completed (the system reaches its decline stage) it must be replaced by a system based on a different set of assumptions, on a different paradigm. For example, when planes are considered, there are separate S-curves for propeller-driven planes, turbo-propeller planes, and jet planes. We have a family of S-curves.

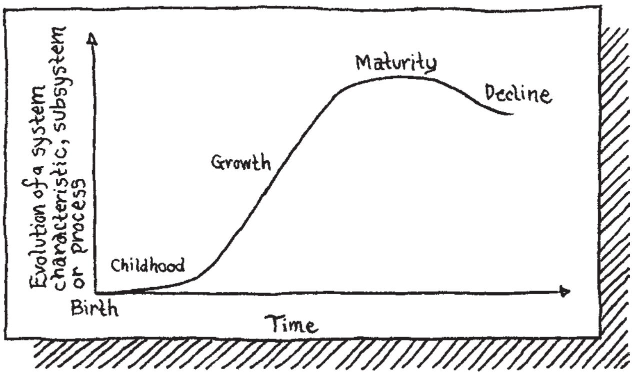

Fig. 2. System Evolution: S-Curve

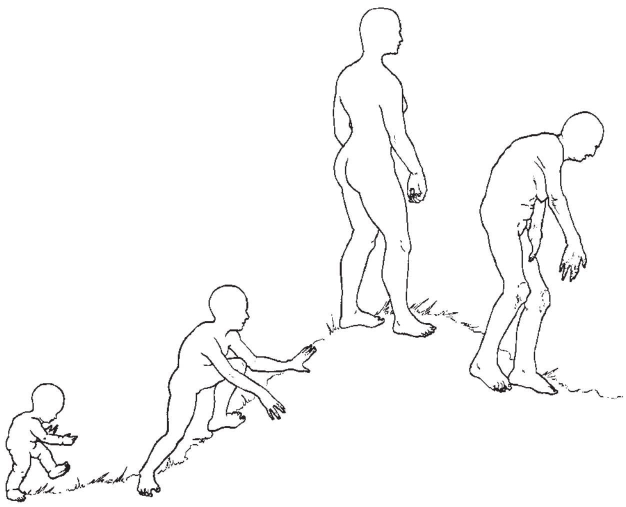

Fig. 3. S-Curve in Action

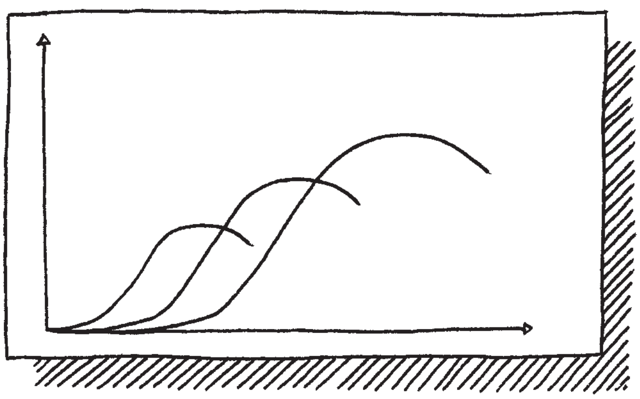

Fig. 4. Family of S-curves

In general, evolution of a system can be presented as a class of S-curves. Each separate curve represents evolution within a given paradigm or a quantitative evolution. A transition between curves represents a paradigm change, a qualitative change, or a revolutionary change.

In the area of CEE education, we can distinguish at least two paradigms, each with its separate S-curve when the success of our profession is considered, measured by our prestige, salaries, attractiveness to the best and brightest students, and other factors. Until about a hundred years ago, civil engineering education was based on the *"master-apprentice paradigm"*. Throughout many centuries of practice, educating engineers was more an art than a science. Such teaching was a combination of rote learning (memorization of known facts and heuristics) and of acquisition of knowledge through learning by example and hands-on experience. An apprentice would produce abductively new hypotheses (plausible rules or heuristics) describing his/her recent experience and inductively verify them in the context of examples from experience. In this way, an apprentice would acquire not only new knowledge but would also learn how to conduct induction and how to abductively generate hypotheses, or new ideas about engineering (See Glossary for our definitions of induction and abduction). Abduction, or inference to the best explanation is the key to human learning and creativity. Therefore, the master-apprentice model of education produced not only civil engineers but also leaders and inventors. Unfortunately, it was time-consuming, costly and could produce only a limited number of engineers. Table 1 illustrates civil engineering knowledge associated with this paradigm [9].

At the end of the 19th Century, progress in science, particularly in mathematics and physics, changed the dynamics of engineering education. These changes resulted in a growing trend to teach engineering as a science, to focus on the "scientific", or the mathematical foundation of engineering. In this way, a *"scientific paradigm"* emerged and the focus of

Table 1. Civil Engineering Knowledge: Master-Apprentice Paradigm ([9], accepted)

		Categories			
		Scientific	Engineering	Civil Engineering	Domain - specific
Factual knowledge	Facts				XXX
	Models				
Procedural knowledge	Deterministic procedures				
	Heuristic procedures				XXX
Rules	Decision rules				
	Heuristics				XXX

engineering education changed. Instead on building a qualitative/holistic understanding of engineering based on heuristics, as before, the focus shifted to acquiring formal knowledge, an inflexible knowledge system. As a result, deduction, the process of deriving the consequences of what is assumed, became the main form of reasoning at the expense of abduction.

Deduction allows verification of a given hypothesis in the context of existing knowledge, but it cannot be used to generate a new hypothesis. Thus, an engineer trained mostly in deduction is an excellent follower, focused on satisfying existing regulations and rules of practice but unprepared to take the lead and to produce the new ideas that are critical to innovation and progress. The civil engineering knowledge associated with this paradigm is shown in Table 2. There is a significant difference with respect to the knowledge associated with the Master – Apprentice Paradigm ([9], accepted).

Today, the primary focus of civil engineering education is on analysis, on building quantitative understanding and numerical optimality, as it is in science. This analysis is mostly based on deduction. Civil engineering knowledge is still partially heuristic, although over the last century it has been supplemented by all kinds of mathematics- and physics-based theories, including complex mathematical models. We are all proud that civil engineering has become a science, but at the same time we are becoming painfully aware that the price for this progress is the loss of our creativity and excessive focus on the quantitative aspects of our profession. This shift from art to science has ultimately led to civil engineers losing their leadership and being inadequately prepared to deal with the complex challenges of the 21st century.

The scientific paradigm in civil engineering is today simply insufficient. It has to be critically examined and replaced by a new paradigm preserving its all-obvious advantages but at the same time providing knowledge, skills, and styles necessary for today. In the context of the S-curve Pattern of Evolution, the present evolution of CEE reached a period of decline and a paradigmatic change is a must.

Contradictions Analysis

The identified contradiction between national and local needs in CEE can be presented in the form of both technical and physical contradictions in accordance with TRIZ [1], [5]. Such formulations provide additional insight and allow using TRIZ ″Inventive Principles″ to find novel ways to eliminate the contradiction, although this is not the focus of this paper.

Our contradiction can be formulated as a **technical contradiction** between the **complexity** of a system and its **speed**. In this case, the complexity of CEE can be considered as a feature measured by the number of courses and their differentiation, and the **speed** of its delivery can be considered as a feature measured by the number of years necessary to deliver all courses required for graduation. TRIZ provides three inventive principles, which can be used to eliminate this technical contradiction. They include those of ″Prior Action″, (No. 10), ″Replacement of a Mechanical System″, (No. 28), and ″Rejecting and Regenerating Parts″, (No. 34). These inventive principles can be used to reinvent CEE and they are not fully described in this paper. However, their initial interpretation in the context of CEE provides a glimpse of opportunities for civil engineering educators willing to accept and take bold action.

The principle ″Prior Action″ can be interpreted in two ways [15].

1) Carry out all or part of the required action in advance.
2) Arrange objects so they can go into action in a timely manner and from a convenient position.

The first principle recommends a pre-civil engineering education understood as a required 1-4 year program to be taken BEFORE entering a civil engineering program. The second principle can be interpreted as a recommendation to divide incoming civil engineering freshmen into several cohorts in accordance with their knowledge and analytical intelligence, as measured, for example, by IQ. Each cohort would be provided an appropriate instruction and allowed to take demanding courses when ready.

Table 2. Civil Engineering Knowledge: Scientific Paradigm ([9], accepted)

		Categories			
		Scientific	Engineering	Civil Engineering	Domain - specific
Factual knowledge	Facts	XXX	XXX	XXX	XXX
	Models	XXX	XXX	XXX	XXX
Procedural knowledge	Deterministic procedures	XXX	XXX	XXX	XXX
	Heuristic procedures				
Rules	Decision rules	XXX	XXX	XXX	XXX
	Heuristics				

The principle ″Replacement of a Mechanical System″ can be interpreted as substituting traditional testing laboratories and facilities by virtual ones. More generally, this principle also means using distant learning and an all IT-based means of instruction. There are two interpretations of the inventive principle ″Rejecting and Regenerating Parts″:

1) After it has completed its function or become useless, reject or modify an element of an object.
2) Immediately restore any part or an object, which is exhausted or depleted.

In the first case, when a student fails a prescribed number of exams, he/she is immediately expelled from a program or offered a number of required non-credit courses to improve his/her performance. The second heuristic can be interpreted as conducting constant performance monitoring and immediate feed back in the form of individual counseling and tutoring to failing students.

Our fundamental contradiction can be formulated as a **physical contradiction** when the **number of courses** in civil engineering education is considered. This number must be increased and reduced at the same time. Both interpretations of this contradiction clearly demonstrate that it cannot be simply eliminated through quantitative changes within a given paradigm. This elimination requires a qualitative, or paradigmatic change, in addition to obvious quantitative improvements.

Complex Adaptive Systems Perspective

CEE can be considered as a Complex Adaptive System, which has three unique features:

- It is complex and has a sufficient number of subsystems and components allowing changes in its structure and components
- It has an ability to adapt, to change its structure and components as feedback to the changing environment
- It has an ability to learn, to acquire knowledge through inductive learning about its behavior and environment

In general terms, a complex adaptive system can be described as a learning system with an ability to undergo both qualitative/structural and quantitative/component level changes in response to its changing environment.

The still prevailing approach to civil engineering education is non-systemic. When CEE in a given department is considered (a specific program), it is usually assumed that a selected combination of courses is optimal and frozen in time. In addition, CEE usually operates only in the context of a given university and of a local community of civil engineering practitioners, no matter how society, engineering, and the entire world evolve. However, when it is considered as a complex adaptive system, an entirely new understanding of the situation emerges. The environment of a given complex adaptive system, in our case a program offered by a given department, can also be considered as another complex adaptive system. It has a number of subsystems, including:

- An educational subsystem with coursework offered through civil engineering departments in this country and abroad
- A social system with national and international components
- A science subsystem representing national and global science and its evolution
- A cultural subsystem
- A political subsystem

All these subsystems evolve, most likely following their own separate and unique lines of evolution. As a result, the behavior of the environment cannot be entirely predicted and it produces often unexpected and undesired inputs to the education system, forcing it to evolve constantly and to change its behavioral patterns. Such unpredictable and unexpected behavior is called ″emergent behavior″ and must be recognized as a real possibility in the case of CEE. Usually, we do not immediately know how to comply with an emergent behavior, but being aware of the possibility of its occurrence is a proactive way of being responsible and concerned about the future.

When the environment of CEE is considered as a complex adaptive system, the traditional static understanding of CEE is simply inadequate and most likely wrong. Using it potentially may be harmful because it offers a simplistic understanding of the situation and puts its users in a disadvantageous position with respect to educators making decisions based on the complex adaptive system model of CEE.

Globalization Perspective

US civil engineering companies are involved in a fierce competition for market share – indeed for survival – with competitors from many countries that offer significant labor cost advantages. Changing the course of US civil engineering education to emphasize creative problem solving will create a novelty-driven competitive advantage. In addition, novel engineering solutions that directly address the specific challenges of a project can often produce significant cost savings [8].

Today, globalization of civil engineering work is an objective trend driven by costs, by the high quality of traditional civil engineering education in many developing countries, and by progress in information technology that has made outsourcing not only feasible but also inexpensive. Such a trend cannot be simply reversed; the proportion of engineering work being outsourced will continue to increase. The obvious consequence of such outsourcing will be reduced demand within the US for civil engineering services. Unfortunately, that may lead to the mass elimination of civil engineering jobs in this country, especially those related to routine work.

In practical terms, outsourcing can be offset, at least partially, only if a new demand for civil engineering services is created. Such demands will be driven by novel solutions and products, clearly the result of fresh thinking, creativity and unrelenting innovation. This work will have to utilize state-of-the-art knowledge and will require engineering creativity. Innovation and creativity combined with the highest levels of expertise will be the added value that prevents non-routine work from being outsourced, at least as long as this country maintains its competitive advantage in research and development and uses and applies recently acquired knowledge in a creative way to produce novel solutions.

Legacy Perspective

The future of civil engineering in the US depends on the quality of our successors. If high school students know that civil engineers are only followers and do mostly highly repetitive, routine work, the best, brightest, and most talented students will never enter civil engineering programs or will soon transfer to other disciplines such as electrical or computer engineering. Unfortunately, this is more than a pessimistic prediction; it is a troubling trend occurring in many civil engineering programs.

High salaries and job security are not enough to attract the brightest students. They are looking not only for material benefits but also for emotional awards, including novelty and excitement. Today there is not much excitement in civil engineering education and practice. The still strong enrollment numbers provide only false comfort. These numbers are more a reflection of the Internet bubble burst and of a still relatively strong demand for civil engineers than of the intellectual attractiveness of our profession. Also, we should be aware that the ongoing real estate crisis has already reduced the demand for civil engineers specializing in land development and that may lead to declining enrollments. If we are looking for permanent solutions, we need to restore the past glory of civil engineering, and the excitement of being a civil engineer must be recreated.

Reconnecting civil engineering with creativity – with doing non-routine work – generates excitement. We can transform civil engineering education by teaching students how to become creative problem solvers, inventors leading the generation of novel solutions that contribute to the fundamental needs of society and advance our civilization.

6. Conclusion – A Storied Past. A Boundless Future

We live in a rapidly changing world in which progress in information technology and computing drives significant changes in science and technology, fuels globalization, and changes our society. In this context, for our profession to survive and especially to grow, CEE must continually evolve and never stop re-inventing itself. The five perspectives on CEE evolution noted earlier clearly explain why such evolution is simply a must.

CEE is a complex adaptive system, in constant motion. However, most of this consists of quantitative, gradual improvements without structural change. From time to time, environmental changes simply force civil engineering programs to adapt through qualitative changes requiring significant structural changes like the introduction of new outcomes, elimination of existing outcomes, changes in the required levels of performance, and significant changes in course offerings.

The marketplace demands that we continue to push for reform. As a profession, we must meet future challenges with the best ideas, and at the lowest cost. That is the key to competitive advantage in a global market. "Conventional approaches to such unconventional demands simply will not get the job done. Systematic innovation in products and processes is an imperative for competitive leverage" [12].

Today, we have to recognize that the evolution of CEE must become a part our activities and that championing continual changes and improvements is simply a part of our responsibilities to society and to our students. Change requires time and effort and the vector of inertia is always hovering about. It is time for us to realize that we are too great a profession to limit ourselves to small dreams, and inaction is simply not an option. The stakes are just too high.

Glossary

- **A system** is a set of interrelated objects (subsystems) working together to provide a specific function, which could not be provided by a single object or any subset of objects belonging to a given system.

- **A complex adaptive system** is a system with three major unique features:
  - It is complex, and has a sufficient number of subsystems and components allowing changes in its structure and components
  - It has an ability to adapt, to change its structure and components as feedback to the changing environment
  - It has an ability to learn, to acquire knowledge through inductive learning about its behavior and environment
- **Deduction** is a form of logical reasoning in which existing knowledge and new data are used to verify hypothesis about data
- **Induction** is a form of logical reasoning in which existing knowledge and new data in the form of examples are used to verify new hypothesis about data.
- **Abduction** is a form of logical reasoning in which existing knowledge and new data are used to generate new hypothesis about data, which, if verified by deduction or induction, can be used to expand existing knowledge.
- **Contradiction:** ″Every great invention (a creative design concept) is the result of resolving a contradiction″ [1]. Therefore, generation of inventive design concepts involves the elimination (resolution) of contradictions. There are two types of contradictions: technical and physical.
- **Technical Contradiction** is an interrelated pair of technical (abstract) contradictory characteristics of an engineering system. For example, *rigidity versus weight.*
- **Physical Contradiction** occurs when a given physical characteristic of an engineering system should increase and decrease to satisfy different requirements. For example, the depth of a reinforced concrete beam should be maximized to increase rigidity and minimized to reduce weight.
- **Inventive Principles** are heuristics acquired from patents and other sources. They are intended for the elimination of technical contradictions in the process of creative design concepts generation. In the early 1970s, Altshuller created the set of 40 inventive principles. Today, there over 400 inventive principles (called ″Operators″ in I-TRIZ) available.
- **Patterns of Evolution** are objective patterns describing changes in an engineering system over a long time period. They are valid in all engineering domains.

References

[1] Altshuller G., *The Innovation Algorithm*, Moskowskii Rabochii Publishing House, (in Russian), 1969.

[2] Altshuller G., *Creativity as an Exact Science*. Gordon and Breach, Science Publishers, Inc., 1984.

[3] Altshuller G., *And Suddenly the Inventor Appeared, TRIZ, the Theory of Inventive Problem Solving*, Technical Innovation Center, Worcester, Massachusetts 1996.

[4] Altshuller H., Boris Zlotin B., Alla Zusman A., Philatov V., *Searching for New Ideas: From Insight to Methodology; The Theory and Practice of Inventive Problem Solving*, Kishinev: Kartya Moldovenyaska, Publishing House, (In Russian), 1989.

[5] Altshuller G., *The Innovation Algorithm*, Technical Innovation Center, Worcester, Massachusetts. 1999.

[6] American Society of Civil Engineers. *Civil Engineering Body of Knowledge for the 21st Century, Preparing the Civil Engineer for the Future*, Second Edition, 2008.

[7] Arciszewski T., *ARIZ 77 – An Innovative Design Method*, Journal of Design Methods and Theories, 22(2), 796-820, 1988.

[8] Arciszewski T., *Civil Engineering Crisis*, ASCE Journal of Leadership and Management in Engineering, 6(1), 26-30, 2006.

[9] Arciszewski T., Harrison C., *Successful Civil Engineering Education*, the ASCE Journal of Professional Issues in Engineering Education and Practice, accepted, 2008.

[10] Clarke D., *TRIZ: Through the Eyes of an American TRIZ Specialist*, Ideation, 1997.

[11] Clarke D., *Strategically Evolving the Future: Directed Evolution and Technological Systems Development*, special double issue, ″Innovation: the key to Progress in Technology and Society,″ Arciszewski, T., (Guest Editor), Journal of Technological Forecasting and Social Change, North-Holland, 64(2-3), 133-153. 2000

[12] Fey V., Rivin E., *Innovation on Demand: New Product Development Using TRIZ*, Cambridge University Press, 2005.

[13] Kaplan S., *Introduction to TRIZ, The Russian Theory of Inventive Problem Solving*, Ideation International, 1996.

[14] Orloff M.A., *Inventive Thinking through TRIZ*, Springer, 2003.

[15] Terninko J., Zusman A., Zlotin, B., *Systematic Innovation, An Introduction to TRIZ*, St. Lucie Press, 1998.

[16] Wright G., van der Heijden K., Bradfield R., Burt G., Cairns G., *The Psychology of Why Organizations Can Be Slow to Adapt and Change*, Journal of General Management, 29(4), 21-36, 2004.

[17] Zlotin B., Zusman A., *Directed Evolution: Philosophy, Theory, and Practice*, Ideation International, 2006.