

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/245814213>

Creativity and Engineering, Education Strategies

Article · January 2003

CITATIONS

9

READS

59

1 author:



[J. Carlos Santamarina](#)

King Abdullah University of Science and Technology

293 PUBLICATIONS 10,801 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Characterization of Fly Ash [View project](#)



Long-term Effects of Cyclic Loads on Geosystems [View project](#)

CREATIVITY AND ENGINEERING - EDUCATION STRATEGIES -

By

J. Carlos Santamarina¹

ABSTRACT

Creativity is the essence of engineering. Yet, creativity is neither explicitly taught nor promoted in the engineering curriculum. While the nature of creativity remains elusive, there is an increasing body of information related to the components that support creativity, the techniques to stimulate it, the relevance of motivation and commitment, the possibilities of collective creativity, and the circumstances that promote and hinder creative problem solving. This information helps identify strategies that can be incorporated in engineering courses to initiate students in a creative, life-long engineering experience.

INTRODUCTION: INGENUITY... INGENIUM... ENGINEER !

Engineering is the creative application of scientific principles (US Engineers Council). While the manifestations of engineering creativity are overwhelming in everything that surrounds us, the nature of ingenuity and creativity remains elusive. Furthermore, it can be argued that today's educational system neither promotes ingenuity nor provides all the necessary tools to sustain it. In fact, engineering education often appears to evolve towards stifling formalizations and the mere transfer of design procedures or "recipes" from one generation to the next (see de Bono 1976 and Ferguson 1999 for related arguments)

Developments in creativity started with the introspective analysis by scientists and humanists into their own thought processes. In 1886, the physicist Helmholtz identified a period of initial investigation, a period of "reset and recovery", and the occurrence of a sudden and unexpected solution (Arieti, 1976). Later in 1913, the mathematician Poincare added the evaluation and elaboration of the proposed solutions. By the 1920's, the four steps in creative problem solving were already outlined by the political scientist Wallas (1926): preparation, incubation, illumination, and verification.

Consider the following exercise: write the first word that comes to your mind in relation to each of the following nouns: flower _____, color _____, furniture _____. Most respondents answer the same set of words (answers in Appendix A-1). What does this tell us about cultural patterns, the role of education, and our innate cognitive tendencies? What is creativity? Can it be taught?

This manuscript starts by analyzing the creative process and the role of the environment. Then, the possibility of collective creativity is explored. Finally, alternatives to promote creativity among engineering students are suggested. Questions and simple exercises are included throughout the manuscript to invite the reader to participate in the writing of this essay.

¹ Goizueta Foundation Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332

CREATIVITY: DEFINITION, THEORIES

Creativity is the generation of concepts and ideas that are novel to the individual or to the group involved in the exercise (Akhoundi and Santamarina, 1991). While novelty is a required characteristic, evaluation must follow to assess the relevance of the created concept. Finally, ideas that are deemed valuable are elaborated further and executed to bring them to fruition. Without implementation, the created entity vanishes.

The study of creativity is the most outstanding recursive or self-serving case in research: creativity is needed to develop theories to explain itself. There are several theories of creativity, including salient contributions in the second half of the twentieth century by researchers such as Guilford, Campbell, Taylor, Torrance, Stein, Simonton, Gardner, Sternberg, and Amabile (see reviews in Sternberg, 1988).

The analysis of individuals' creative productivity versus age reveals a peak at some intermediate age. This signature suggests the coexistence of two underlying components, one that is responsible for the rise in creative productivity with age, and the other one that causes its decay. The KPA theory hypothesizes that the creative response results from the combination of **Knowledge** and **Processing ability**, brought together by the proper **Attitude/purpose** (Santamarina and Akhoundi, 1991). The KPA theory is sketched in Figure 1.

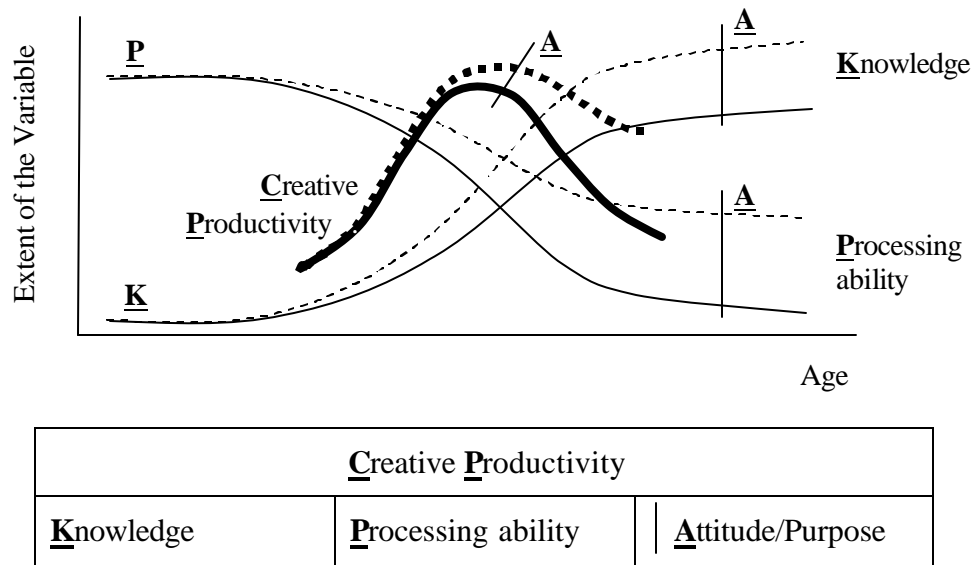


Figure 1: The three pillars of creative productivity in the KPA theory. The peak in creative productivity takes place at an age that reflects the relative balance between the need for knowledge and the ability to process information (after Santamarina and Akhoundi, 1991)

Knowledge availability (K) is herein taken in a broad sense and includes access to information of any form and by any means. Knowledge availability is affected by inherent capacity, interest, training, and cultural patterns. In general, it increases with age until late stages of life. The second component, processing ability (P), involves capabilities such as unrestricted thinking, unconstrained free association, merging of initially disconnected or divergent information, logical inference, organization and visualization of information,



and self-reliance on independent thought. With age, problem solving strategies become entrenched, are gradually plagued by thought patterns and habits, and deepening personal preferences progressively restrict free association and divergent thinking (e.g., excessive emphasis on logical thinking). Yet, there is evidence that other thought processes gain relevance, with more emphasis on depth rather than fluidity (Csikszentmihalyi, 1997).

Creativity requires committing to the task and devoting focused hard work. Therefore, knowledge and cognitive ability are not sufficient. Indeed, the attitude/purpose component plays a critical role: attitude sustains creative productivity and purpose guides it to attain goals. The creative attitude is the decisive inner drive and motivation to explore the new in search of novel solutions and creative ideas. (This is the central piece in motivation-based theories, such as in Amabile, 1989.) It involves perseverance and self-motivation, curiosity to search for the new, interest to seek information, initiative to continue exercising cognitive processes, willingness to accept risks, and intent to create.



Corollaries

Several important consequences can be identified when the KPA theory is adopted as a working hypothesis.

Creativity in different fields. Creative contributions are expected from older individuals in knowledge-intensive fields, and from younger individuals in fields that demand acute processing abilities. Furthermore, knowledge-intensive fields benefit from group work and collective knowledge.

Peak in creativity. The age at the peak in creative productivity (both quality and quantity) varies for individuals in different disciplines, reflecting the relative balance between knowledge and processing. For example, mathematicians are known for their early peak, typically in their 20's, while engineers reach their peak in their 40's and can sustain high levels thereafter, often well into their 70's (Csikszentmihalyi, 1997). There is also some evidence that the knowledge revolution in the last centuries has led to a shift in the peak to later stages in life, reflecting higher difficulty in mastering the advanced knowledge that is required to create new concepts.

Attitude - implications. Proper attitude has a double effect. On the one hand, it activates the creative process. On the other, it can hinder the effects of age on cognitive ability and promote enhanced access to knowledge. As a result, the peak in creative productivity is not only higher with the right attitude, but it can also be extended to later stages in life (see Figure 1). For example, an extended peak or a second peak is found when individuals shift interests to new areas after mid age; in so doing, they carry their accumulated knowledge into the new field, experience new thought patterns, gather new knowledge, and create new associations.

Several additional consequences follow from these observations, including the assessment of creativity, strategies for stimulation, and the role of collective creativity.

IQ AND CREATIVITY - ASSESSMENT

Intelligence is captured under the "processing-ability" (P) component of creativity, and in turn, it has some effect on the potential ability to gather knowledge (K). Hence, intelligence is a necessary but not sufficient condition for creativity (Sternberg, 1996). Among low IQ individuals, creativity is intelligence-controlled, i.e., IQ is correlated to

creativity. However, creativity becomes attitude/motivation controlled among high IQ individuals, and the correlation between IQ and creativity vanishes.

Therefore, proper creativity assessment tools should address the three pillars of creativity: cognitive abilities, knowledge availability in the broad sense, and attitude/purpose. The simple self-evaluation test suggested next provides further information in relation to the social assessment of an individual's creativity.

ACTION. Think about how "you are perceived by others" (not the way you wish you were perceived). Identify all the words in Table 1 that closely characterize how you are perceived. From the highlighted words, select a subset of 8 words that describe you BEST. Then, go to Appendix A-2.

Table 1: Self Evaluation. (read text for procedure)

absent-minded	alert	balanced	cautious	clear-thinking
courageous	curious	dedicated	determined	dynamic
efficient	energetic	enthusiastic	factual	fashionable
flexible	formal	forward-looking	good-natured	greedy-grasping
habit-bound	harsh-strict	helpful	impulsive	independent
informal	inhibited	innovative	involved	modest
observant	open-minded	organized	original	overconfident
perceptive	persevering	persuasive	polished	practical
predictable	quick	realistic	reserved-shy	resourceful
restless	self-confident	self-demanding	sociable	tactful
thorough	understanding	unemotional	well-liked	

The weights for each word tabulated in Appendix A-2 characterize the relative strength of these qualifiers in the personality of creative individuals. Three sets of weights are listed: the original weights suggested by Raudsepp (1981), weights generated from a sample of 45 undergraduate and graduate engineering students (in their early 20's), and weights based on the response by 38 young teenagers in middle school (ages 12-14; only those words that are familiar to teenagers were used in this parallel study by Fernanda Santamarina, 1997). The correlation between weights reported in these three studies is verified in Figure 2.

It is concluded that people have come to associate personal characteristics with creativity. These perceptions are embedded in the culture and young teenagers already evaluate people's creative appearance with the same criteria as adults do. While such a-priori evaluations expedite human interactions, they mark individuals too early in their lives.

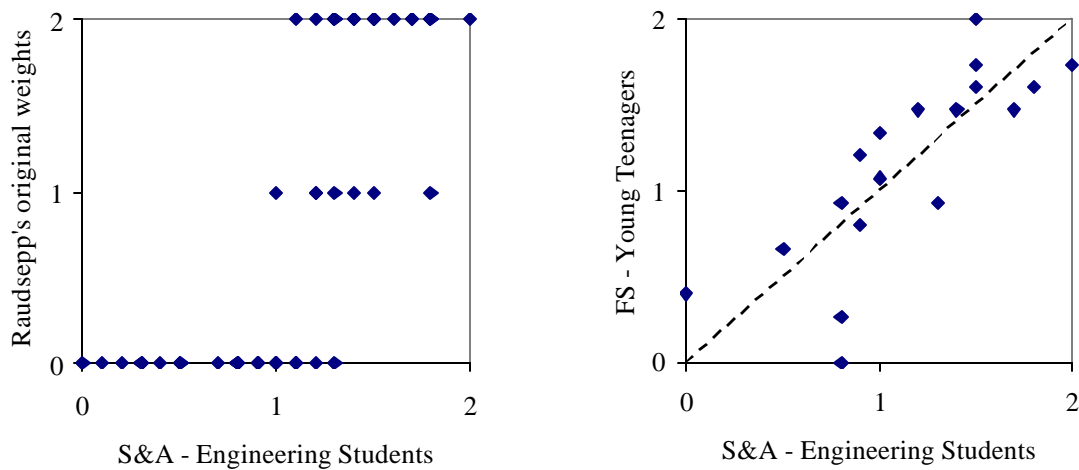


Figure 2. Weight of personality qualifiers found in different studies - Comparison

CREATIVE PROCESS AND ENGINEERING METHODS

The steps in the scientific method bear a strong resemblance to the stages in creative problem solving. Furthermore, a similar sequence of stages are recognized in engineering decision making, for example: Torroja's design method (Torroja, 1958 a&b), Peck's observational approach for design and construction in difficult conditions (Peck, 1969), and Leonards' method for the analysis of failures (Leonards, 1982). This parallelism is highlighted in Table 2.

Table 2. Parallelism between the stages in creative problem solving, the scientific method, and engineering decision methods (after Santamarina and Akhouni, 1991)

Creative Solution	Scientific Method (Winograd and Flores, 1986)	Architectural design (Torroja, 1958)	Geotech. design & construction Peck (1969)	Analysis of failures (Leonards, 1982)
<i>Preparation</i>	Observation	Study project	Assess conditions Working hypothesis Basic design	Collect information
<i>Incubation</i>		List requirements	Determine possible deviations and values to be measured	Identify special facts and features
<i>Idea generation</i>	Propose hypothesis Predict phenomenon	Sketch ideas Adapt, combine	Propose alternative actions and design modifications	Postulate failure mechanism
<i>Elaboration</i>	Elaboration	Solve conflicts Find alternatives	Calculate quantities Plan observations	Evaluate each mechanism against observations
<i>Implementation</i> <i>Evaluation</i>	Implementation Observation	Evaluation Solution selection	Measure Evaluate Modify design	Plan and conduct further investigations

The essential similitude between these methods and the creative process suggests that all these methods are developed to capture the human ability to process information in view of new, innovative, and optimal solutions within the given constraints.

In particular, all methods start with the same first step: compilation of information. Initially, this step could appear to be a mere time consuming task; however, this critical step has a much more profound effect. Following Gauss' or Goethe's example, the "preparation stage" implies becoming completely immersed in the problem or phenomenon, observing and studying it in detail, gradually assimilating it, and intimately feeling it. This involvement is crucial to the creative process.

ENVIRONMENT AND RESOURCES

The early childhood environment, the formation environment, and the current environment affect the individual's creative performance. Results from a questionnaire circulated among engineering students suggest a generalized belief that children brought up in educated, caring, high-achieving families are better prepared to develop into creative individuals. For comparison, Simonton (1988) and Walberg (1988) studied the early environment of high-achieving individuals and noted that most of them had stimulating home environments; but they also found that high achievers may have been sick children, lonely or shy, avid readers, and may have lost a parent at early age.

The professional formation stage (late teens and early twenties) is characterized by the effect of role models and mentors. Geographically or historically detached role models, as compared to close peers, are more readily idealized and become a better source of inspiration as well as a more challenging frame of reference.

The individual's interaction with their current environment determines whether the individual activates their creative potential. Some individuals strive in competitive quasi-Darwinian environments. Others excel in cooperative environments, where everybody contributes and gains. (In analogy to Kropotkin's theory of evolution, this would correspond to an environment with limited resources.) In some cases, very austere or even cruel environments can stimulate some individuals to find a purpose, to delineate goals and to gather energy and motivation to achieve them. Ultimately, attitude is an individual realization or choice, and strong individuals can sustain a creative attitude even in the harshest or most alienating environments. As noted by Frankl (1963), finding meaning or purpose is the essence of survival.

The advantages of intellectually rich and stimulating environments versus the impact of impoverished and inflexible conditions on motivation and cognitive abilities have been corroborated with individuals of all ages, from children to seniors. On the other hand, the importance of resource availability on creative productivity appears overrated; the following observations were made in academic environments (Based on Reitan, 1996):

- Time is the most valuable resource.
- There is a "threshold" for needed resources. Above the threshold, there is a weak correlation between available budget and number/quality of publications.
- In some cases, the correlation between resources and productivity becomes negative, i.e., the more resources the lower the productivity.
- The most important factor is the satisfaction with available resources.
- The positive correlation is improved if resources are used to buy time and to support research assistants.

Moreover, there is a shortsighted perception of "available resources". Results from a recent questionnaire conducted by the author among engineering professors show that most faculty members emphasize individual resources, even though university-wide resources dwarf individual resources in all cases.

ACTION: take paper and pencil and a timer. Choose any object or concept that comes to mind (e.g., leaves, fork, light, pebble, brick, pliers, fence, cord, relativity) and write as many associations as you can generate in 1 minute. (Refer to Appendix A-3)

STIMULATION OF INDIVIDUAL CREATIVITY

A large number of stimulators of creative activity have been proposed in the literature. In some cases, they were identified from meticulous analyses of log books kept by scientists, engineers, and inventors. In other cases they were obtained from anecdotal accounts and self experiences. A compilation can soon be formed to include more than a hundred ideas and suggestions. A brief listing is presented in Table 3, where strategies are organized in reference to the three pillars of creativity hypothesized in this manuscript: knowledge, processing ability and attitude.

Conversely, there are actions and circumstances that inhibit the individual's creative potential, such as: lack of patience, curiosity, flexibility, motivation; aversion to risk, fear; excess of rationalization, defiance, ego; and conformity (Bailey, 1978). Other hindering factors can be identified in engineering practice, in particular the compounded effects of the legal system with codes and standards. While these were originally developed to prevent accidents and injustice, they have become protective shields for engineers and designers, and the emphasis on "common practice" stifles creativity.

COLLECTIVE CREATIVITY

The assembly of components to form a more viable or useful system is an ubiquitous natural development. Neurons connect through synapses to form the brain, distinct bacteria form mutually supportive colonies, and ants form colonies that exhibit very sophisticated group behavior (e.g., army ants – Franks, 1989). Clearly, man-made systems have developed likewise, from machineries and electrical circuitry to society itself.

Creativity research has focused on individual creativity. Admittedly, the flash of inspiration does take place within an individual; however, it does not occur in a vacuum but within the backdrop of knowledge and understanding that is part of society's cultural wealth. This is the social dimension of creativity or, in Newton's words, "the shoulders of giants" (for related comments, see Gladwell, 2002)

The active, synergistic interaction among participants permits assembling collective knowledge and collective cognitive capabilities, allows cross-fertilization, and helps maintain the motivation required for creative problem solving. Fluent communication and group-minded attitude are required (see insightful observations from game theory, from Hobbes and Rousseau to Nash, in Ridley, 1997.) As the group evolves, members identify their roles, such as (Burgoon, et al. 1980):

- **Group Task Roles:** idea/action initiator, information/opinion giver, information/opinion seeker, elaborator, integrator, goal-orienter, energizer.
- **Group Maintenance Roles:** encourager, harmonizer, tension reliever, gatekeeper, follower.

Table 3. Creativity Stimulation – Brief Listing

<u>K</u>nowledge	<p>Browse books and magazines at libraries and bookstores. Physically browse through stores, supply shops, machinery, equipment shows. Critically read articles in your field and in remote fields. Study previous theories or discoveries (directly related to your problem, and others that could first appear far related) Keep informed of novel ideas. Research the topic of interest in depth (within the field of interest and outside) Study anomalous evidence. Identify all related facts. Benefit from collective knowledge. Form a network of resourceful, knowledgeable individuals. Conduct group problem solving exercises.</p>
<u>P</u>rocessing	<p>Clearly state the problem. "Mutate" it. Attempt to completely redefine it. Exercise critical, in-depth thinking (set time aside every day). Analyze. Exercise free association and divergent thinking. Prepare "mind-maps"⁽¹⁾. Generate a large number of ideas, hypothesis, alternatives. Explore; vary parameters in widest possible range; observe multiple events. Seek beauty, simplicity, precision, improvement. Simplify, magnify, ridicule, fantasize, modify, contrast; remove, substitute, add. Get directly involved. Observe in detail. Question why. Pretend you are it. Feel the problem. Use all your senses. Relate to completely different fields or applications – big picture? Explore / adopt ideas and solutions from different fields. Test them. Prototype, test, observe, describe in detail. Sketch, graph data. Keep a lab-book. Systematically organize information (like solving a 1000-piece puzzle). Summarize. Identify new applications/implications.</p>
<u>A</u>ttitude	<p>Select a great role model. Learn from the great ones. What would they do? Avoid conforming to existing concepts. Strive for new concepts; explore new territory; speculate. Accept the tension in deviating from the standard and the risk in creating. Be positive; identify what is good; leave arrogance aside. Be critical; identify limitations. Learn from mistakes (yours and others). Work hard. Be persistent. Place emphasis on your inner motivation. Convert negative feedback into positive action. Have fun; seek/do something new every day; undertake new challenges. Action creates results. Just get going. You are not done until you implement it...</p>

Note: (1) Mind-maps are graphical representations to capture associations, cause-effect relations, and concept flow in an organized structure (Mindmapping® is a registered trade mark). Several books and software are available to guide effective implementation.

- **Dysfunctional Roles:** blocker, negative, aggressor, anecdoter, recognition seeker, dominator, confessor, special-interest pleader (with loyalties outside the group), joker and sarcastic commenter.

Other conditions that inhibit group creativity include (Bailey, 1978; Gouran and Hirokawa, 1986; Santamarina and Turkstra, 1989): lack of encouragement, no trust or mutual respect, excessive criticism, strong structure and overbearing influence by certain participants, excessive competition, too much emphasis on rewards, perceiving that only the gathered information is important, and limited consideration of all possible alternatives.

THE CREATIVE PRODUCTIVITY OF ENGINEERING FACULTY

Should all engineering professors (i.e., creativity teachers) be creative themselves?

Probably not, in as much as not every English teacher needs to be a great writer. Still, historical data show that great masters have inspired great disciples in all fields, including musicians, painters, scientists and engineers.

In this context, and for lack of better measures, the "academic productivity" of faculty in engineering is used to look into their "creative productivity". While this is a controversial approach, historical performance data collected by cognitive scientists support it: harder-working faculty, with high degree of commitment and persistence have higher number of publications, are more frequently cited and achieve greater eminence than the rest (evidence and references in Simonton, 1988).

The professors in the School of Civil and Environmental Engineering at **Georgia Tech** were invited to provide their curriculum vitae to gather data for this study. (The voluntary nature of the participation may add a self-selection bias to the population under study.) Twenty-one professors participated, out of which only one was female, and only 5 received their PhD degrees 20 or more years ago. (Note: an in depth analysis of these data requires careful consideration of the changes in the academic culture in the last 30 years.)

Observations related to the number of refereed journal publications

The number of refereed journal papers published by each professor every year was tabulated. Most faculty members completed their PhDs having published 2 or less papers (Figure 3-a). Individuals who started their PhD studies after a professional working experience concluded their PhD's with a larger number of publications.

Publication production rates are analyzed in Figure 3-b, where the cumulative number of papers is plotted for each faculty versus time. The origin of time is considered to be the year when the first five 5 papers were published. The data show that the number of published papers per year varies between 1 and 5 across the faculty, with an average sustained rate of about 2.2 papers per year.

Observations related to the number of graduated PhD Students

Professors begin graduating PhD students 3 to 6 years after they obtain their own PhD (Figure 4-a). After graduating the first PhD student, the number of graduated PhD students per year ranges from 0.25 to peak rates of ~2 (Figure 4-b). Considering only professors with less than 15 years after graduation (i.e., those who graduated since 1987), the spread in response is still very considerable (from 2 to 16 graduated students at year 12). The average for this group is about 1 graduated PhD per year.

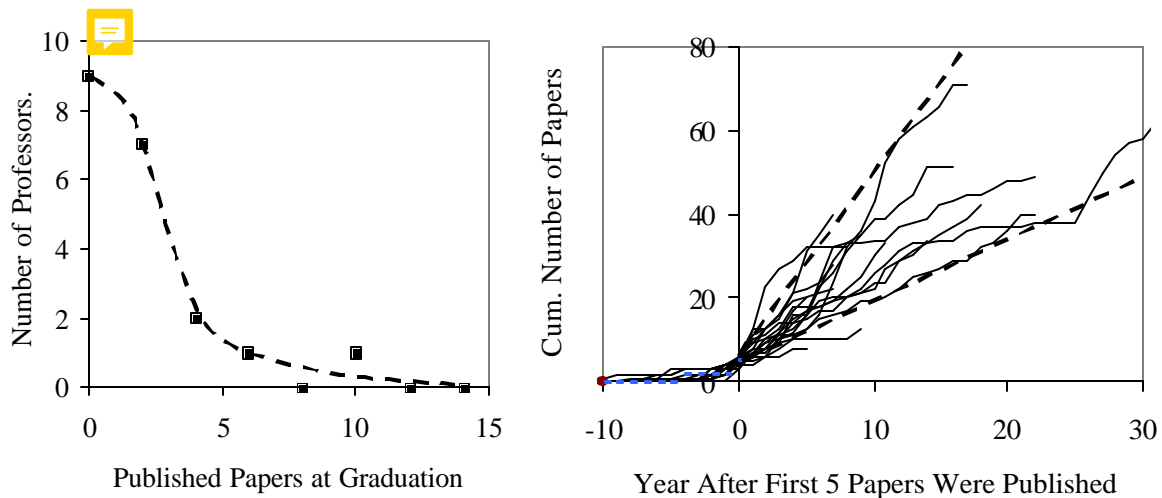


Figure 3. Publication record. (a) number of papers published at the time the professor graduated. (b) publication rate versus time.

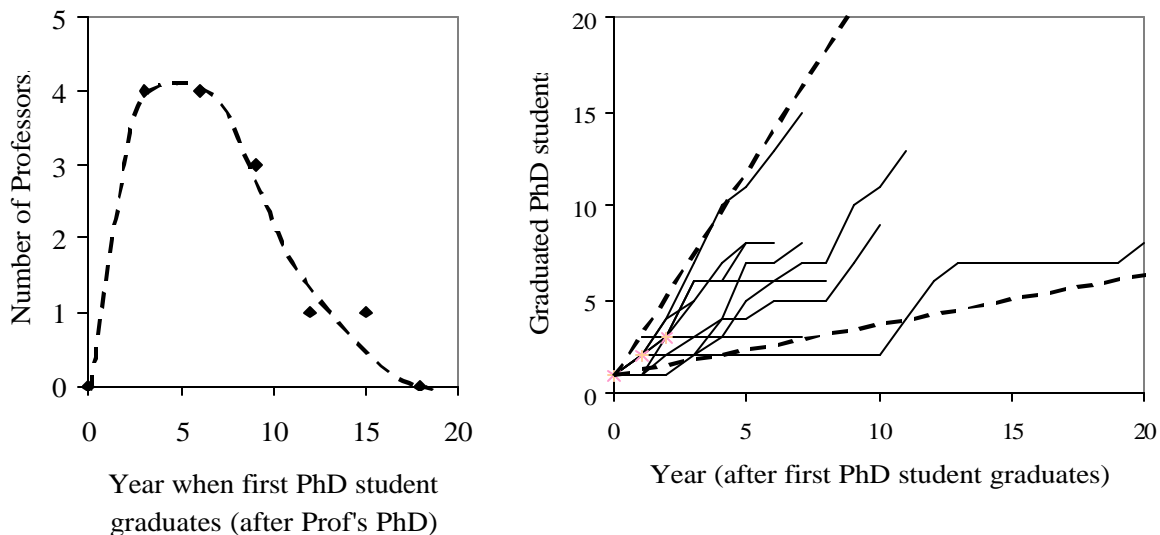



Figure 4. Graduated PhD students. (a) Time to graduate the first PhD student. (b) Rate of PhD student graduation.

Other observations – Stages and Personal Characteristics

The productivity of most individuals shows stages (Figures 3-b and 4-b). The resulting step-like signatures hinder the development of strong statistical relations between short-term and long-term productivity. Yet, it is clearly seen that individuals with highly productive careers exhibit high production rates early on.

On average, a low productivity is observed between the th and about the 25th year after the completion of the PhD, followed by significant recovery afterwards (Figure 5 – Note: only 5 faculty members in the population exceeded 20 years into their careers.) Personal interviews revealed that the low productivity period is related to stages in male personal growth (mid-career crisis typically in the 40's; large number of administrative and off-campus engagements; loss of motivation; consulting, career changes including

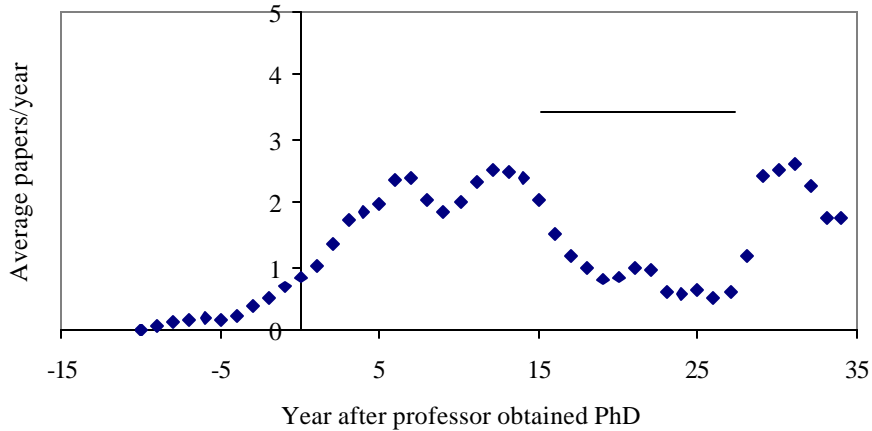


Figure 5. Changes in Academic Productivity with Age

shifts in research direction); and family circumstances (grown up children, college, divorce, health issues and deaths). As observed by L. Rosenstein in a personal communication, the impact of family life on the productivity of women faculty is expected to be quite different: it will probably shift the peak to later in life.

In general, the following characteristics are shared by extraordinary individuals from all realms of life: they reflect extensively on the events of their lives; they are distinguished by their ability to identify their strengths and exploit them, rather than by their raw powers; and they often fail but do not give up, learn from the experience, and convert it into opportunity (Gardner, 1997). The characteristics that are common to productive scientists include (Hogarth, 1980):

- A high degree of autonomy, self-sufficiency, self-direction. High ego strength and emotional stability.
- Superior general intelligence. An early, very broad interest in intellectual activities. Marked independence of judgment, rejection of group pressures toward conformity in thinking. A drive toward comprehensiveness and elegance in explanation.
- A preference for mental manipulations involving things rather than people. A liking for method, precision, exactness. A liking for abstract thinking, with considerable tolerance of cognitive ambiguity. A special interest in the kind of 'wagering' which involves pitting oneself against uncertain circumstances in which one's own efforts can be the deciding factor.
- A somewhat distant or detached attitude in interpersonal relations, and a preference for intellectually challenging situations rather than socially challenging ones. A high degree of personal dominance but a dislike of personally toned controversy.
- A preference for such defense mechanisms as repression and isolation in dealing with affection and instinctual energies. A high degree of control of impulse, amounting almost to over-control: relatively little talkativeness, gregariousness, impulsiveness.

ACTION. List tasks, activities and methodologies that could induce students to explore, train and utilize their creative potential. Consider on and off-classroom settings, individual and collective activities, and information presentation/generation techniques.

TEACHING CREATIVITY

Can creativity be taught through the engineering curriculum? The Knowledge-Processing-Attitude analysis of creativity suggests that individuals with normal intellectual characteristics can be stimulated to maximize their creative potential. In addition, information presented in this manuscript in relation to environmental effects, known stimulators, and collective creativity facilitates the identification of strategies to be included in engineering courses to promote students' creativity.

The teaching of creativity has a limited impact if it is not immersed in problem solving exercises. Therefore, the first step is to revise the style and content of assignments and evaluations in the current course contents, in view of characteristics that stimulate creativity. A simple, yet far reaching modification is to incorporate additional questions in every assignment, with preference on open questions, for example: generate five distinct alternative solutions to the analyzed design; identify three applications of the concept/system under consideration in bioengineering and in lunar colonization; discuss in depth the viability of this design in 50 years, taking into consideration population growth rates in the third world. The spirit of these extra questions or tasks should be guided by creativity stimulators such as those listed in Table 3. Vary the class format and media; some classes can be presented in lecture form while others can be developed collectively, promoting the introspective realization of the topic.

Additional alternatives and exercises are suggested next, without any explicit order. (Note: many of these ideas were generated through a group exercise with graduate students). These tasks are intended to expose students to creative problem solving and personal preferences. Attitude (including purpose and motivation) is the component of creativity that is most difficult to affect as part of the educational program; thus, several alternatives should be attempted to increase the probability of reaching all students.

Self-analysis. Invite students to analyze their own actions and thought processes to identify the most common stifling conditions or habits they fall into. Then, ask them to find alternatives to avoid or lessen their impact.

Identify a detached role model. Recommend the selection of well known individuals so that detailed biographies can be readily found (examples in Gardner, 1993). Assign a progression of tasks to gradually familiarize and associate the student to the role model.

Promote a collaboration-prone mentality. Start with a persuasive team-building exercise (e.g., Earthquake, Fisher and Peters, 1990) to demonstrate that group performance in problem solving surpasses the performance of every individual working alone. Complement this exercise with a self-analysis and group analysis of the roles played by the different participants, and the potential pitfalls in group dynamics.

Creativity starts with action. This is well-known among artists who do not wait for inspiration to overcome the "writer's block" or to get cartoons flowing (e.g., Mankoff, 2002). Yet, the concept applies to all fields. Even if "luck" is invoked, the chances are that serendipity and the creative flash will benefit those who are committed and doing.

Creativity stimulation. Multiple creativity stimulation techniques, such as those summarized in Table 3, have been suggested. A new strategy or method can be introduced in each class, using examples, case histories, and exercises to practice it (examples in von Oech 1990, Ward et al. 1995, Savransky 2000, Root-Bernstein and Root-Bernstein 2000,

Fogler and LeBlanc 1995, Oliver 1991, Drabkin 1996, Meyer 1997). These stimulating techniques should not be presented as the "easy-trick" path to creativity (the cited literature leaves a strong feeling of effortless). As discussed earlier, history shows that great innovators and contributors were extraordinarily committed and hard-working.

Action motivator - Patents. In some courses, assignments or projects could be guided to attain a patent, as a means to create a commitment to action. In this case, students must first identify and review existing patents. This task allows them to become aware of related technology, and may seed alternative mental processes inspired by those used by other inventors. If this patent path is followed, the course materials should include information on intellectual property, patenting process, and trade marks.

Promote a creative attitude, perseverance, and hard-work. Enjoy. Allow for flexibility in assignments so that each student can identify the most fitting and fulfilling parts of the task. Tasks that we enjoy doing are mutually related to things we do best. In turn, enjoyment is a key source of energy, which is required to persevere. Emphasize the importance of intrinsic-over-extrinsic motivation (see Hennessey and Amabile, 1988).

Exercise cognitive abilities such as speed processing, free associations and divergent thinking. This is what the cartoonist Larson calls "brain-aerobics", and has proven to have very impressive effects from children learning math in primary schools, to training chess players and arresting mental ageing in seniors.

Mental abilities need exercising and attitude needs to be sustained throughout life. Plant seeds for life-long interest in continued training creative abilities. A gratifying and enriching course experience will be an indelible reminder.

Practice critical thinking and depth of thought. Assign daily time for creative thinking.

Review the creative thinking process through historical examples and case histories. Demonstrate with a class experiment or design exercise (explore the teaching methodology for engineering design suggested by Parcover and McCuen, 1995, which parallels the stages in creative problem solving).

Identify a purpose. Depending on the topic of the course at hand, this task can be focused on a specific problem or it can address global needs and future engineering developments. In the second case, consider different time horizons (10 years and 50 years ahead), spatial contexts (your city, USA, third world, whole world), and various fields (education, energy, water, urban development, smart systems, transportation). Review inspiring articles (e.g., The New Millennium Colloquium at MIT on the Future of Civil and Environmental Engineering). Encourage in-depth critical thinking. Ask students to identify a set of ten far reaching, probing questions.

Proper problem identification. Encourage the selection of problems that are relevant and challenging (The research team working in England on the nature of DNA knew they were addressing a problem of critical relevance that would change history - Watson, 1968). Recognize that importance does not necessarily correlate with difficulty.

Knowledge. A single course cannot significantly change the knowledge an individual possesses; however, it can cause a dramatic change in the individual's position and commitment towards gathering knowledge from the almost infinite pool of information that is available. There must also be motivation to learn as part of the problem solving strategy; the "action learning" program is based on this premise (Marquardt, 1999).

Knowledge motivator: Prepare a review paper. Motivate students to become deeply involved in the problem, phenomenon, or challenge under consideration, by requiring its

detailed study and observation. Findings should be documented in a review manuscript. The preparation of this document is a unique opportunity to practice the systematic organization of information, like assembling a large puzzle to discover a picture. (An exceptional example is Mendeleev's organization of the limited information that was available on chemical elements in 1860's, leading to the periodic table.) Depending on the context, the preparation of this document can also emphasize depth, breadth, insight, logic, clarity and precision. It may require the collection of the most meaningful published studies or the listing and review of related patents.

Browsing and networking. Assign a hands-on task in relation to an open-ended project (not open-ended goal). As part of their response, students must provide evidence of having spoken to a prescribed number of experts, and browsed through related stores.

Collective creativity. Select a project to be solved in groups. Networking should be encouraged to bring into the group expertise and diversity of background and knowledge. Note that the literature on "collective learning" is beset with contradictory results in relation to benefits and drawbacks; select a challenging project to emphasize a creative problem that benefits from collective knowledge, capabilities and energy. The class implementation can follow multiple paths. For example, the task can be solved in stages, with intermediate presentations and discussions where participants in all groups help identify advantages and weaknesses in all designs (promote positive attitude by requiring to list three positive observations for each negative one). After the presentations and discussion, groups go back to work on benefiting from cross fertilization.

CLOSING THOUGHTS

To paraphrase Alan Kay, the best way to predict the future is to create it. Engineers are meant to be actors of change and creation. Therefore, engineering education must address all creativity components: convey rich, in-depth knowledge and teach procedures to gather knowledge; educate and exercise multiple processing abilities; and emphasize the importance of a creative attitude supported by great commitment, hard work, and perseverance. The three components must be maintained to sustain a long productive and creative engineering career.

Creativity starts with action...

ACKNOWLEDGEMENTS

Prof. Yao taught us with unsurpassed dedication and contagious great attitude; he always highlighted the clarity in simple fundamental concepts. Valuable suggestions were provided by J. Alvarellos, J. Dodds, F. Francisca, H.K. Kim, J.S. Lee, G. Narsilio, A. Palomino, L. Rosenstein and T.S. Yun. Colleagues at Georgia Tech patiently participated in questionnaires and interviews. Cecilia, Santiago, Fernanda and Francisco provided insightful comments and were willing test subjects on many occasions. Many ideas presented in this essay developed from enriching discussions with Kambiz Akhouni, and are captured in a series of co-authored essays between 1989 and 1992; a compilation of these essays is available from the author.

REFERENCES

- Akhouni, K. and Santamarina, J.C. (1991), MetaStates, Compilation of Essays on Creativity, Polytechnic University, Brooklyn. (Available from the author).
- Altshuller, G. (1999), The Innovation Algorithm, Technical Innovation Center, Worcester, MA, 312 pages.
- Arieti, S. (1976), Creativity, the Magic Synthesis, Basic Books, NY.
- Bailey, R.L. (1978), Disciplined Creativity for Engineering, Ann Arbor Science, Michigan, 614 pages.
- Burgoon, M. Heston, J.K., and McCroskey, J. (1980) Communication Roles in Small Group Interaction, in INTERCOM Reading in Organizational Communication, Eds. S. Ferguson and SD Ferguson, Hayden, Roshelle Park, 412 pages.
- Csikszentmihalyi, M. (1997), Creativity, HarperPerennial, New York, 456 pages.
- de Bono, E. (1976), Teaching Creativity, Pinguin, New York, 268 pages.
- Drabkin, S. (1996), Enhancing Creativity When Solving Contradictory Technical Problems, *J. Prof. Issues in Eng. Education and Practice*, Vol. 122, no. 2, pp. 1-5.
- Ferguson, E.S. (1999), Engineering and the Mind's Eye, MIT Press, Cambridge, 241 pages.
- Fisher, J. and Peters, D. (1990), Earthquake, Organizational Learning Tools, Novi, Michigan.
- Flowers, W. (2000), Innovator, Innovatee or Somewhere Between?, Lecture Series on Innovation, Georgia Institute of Technology.
- Fogler, H.S. and LeBlanc, S.E. (1995), Strategies for Creative Problem Solving, Prentice Hall, New Jersey, 203 pages.
- Frankl, V. E. (1963). Man's Search for Meaning: An Introduction to Logotherapy. New York: Washington Square Press.
- Franks, N.R. (1989), Army ants: A Collective Intelligence, *American Scientist*, 77(2): 138-145.
- Gardner, H. (1993), Creating Minds, Basic Books, New York, 464 pages.
- Gardner, H. (1997), Extraordinary Minds, Basic Books, New York, 178 pages.
- Gladwell, M. (2002), Group Think – What does 'Saturday Nitght Live' have in Common with German Philosophy?, *The New Yorker*, December 2, pp 102-107.
- Gouran, D.S. and Hirokawa, R.Y. (1986), Counteractive Functions of Communication in Effective Group Decision Making, in Communication and Group Decision Making, Eds. RY Hirokawa and MS Poole, Sage, Beverly Hills, 315 pages.
- Hennessey, B.A. and Amabile, T.M (1988), The Conditions of Creativity, in The Nature of Creativity, Ed. R.J. Sternberg, Cambridge University Press, New York, pp. 11-38.
- Leonards, G.A. (1982), Investigation of Failures, *ASCE J. Geotechnical Eng. Division*, Vol. 108, pp. 185-246.
- Mankoff, R. (2002), The Naked Cartoonist, The Black Dog & Leventhal, New York, 144 pages.
- Marquardt, M.J. (1999), Action Learning in Action, Davis-Black, Palo Alto, 259 pages.
- Meyer, P. (1997), Quantum Creativity, Contemporary Books, 195 pages.
- Oliver, J.E. (1991), The Incomplete Guide to the Art of Discovery, Columbia University Press, New York, 208 pages.

- Parcover, J.A. and McCuen, R.H. (1995), *Discovery Approach to Teaching Engineering Design*, *ASCE J. Prof. Issues in Eng. Education and Practice*, Vol. 121, no. 4, pp. 236-241..
- Peck, R.B. (1969), *Advantages and Limitations of the Observational Method in Applied Soil Mechanics*, *Geotechnique*, Vol 19, No. 2, pp. 171-187.
- Raudsepp, E. (1981), Princeton Creative Research Inc., Princeton, NJ.
- Reitan, B. (1996), *Creativity and Innovation in Research Groups*, Swedish Council for Building, Stockholm, 135 pages (Review of more than a dozen studies in USA and European countries).
- Ridley, M. Ridley, M. (1997), *The Origin of Virtue*, Viking Penguin, UK, 295 pages.
- Root-Bernstein, R. (1989), *Discovering*, Harvard U. Press, Massachusetts, 501 pages.
- Root-Bernstein, R. and Root-Bernstein, M. (2000), *Sparks of Genius*, Mariner Books, New York, 401 pages.
- Sanchez, M. (1999), *Dessarrollo de Habilidades del Pensamiento – Creatividad*, Tecnológico de Monterrey, Editorial Trillas, 200 pages (Guia del Instructor – 311 pages).
- Santamarina, J.C. and Akhouni, K. (1991), *Findings in Creativity and Relevance in Civil Engineering*, *J. Professional Issues in Engineering Education and Practice*, vol. 117, pp. 155-167.
- Santamarina, J.C., and Turkstra, C.L. (1989), *Human Factors and Communication Problems in Foundation Engineering*, *Foundation Engineering: Current Principles and Practices*, F.H. Kulhawy ed., vol. 2, pp. 857-868
- Santamarina, M.F. (1997), *Perception of Creativity Among Young Teens*, Science Project, Sandy Springs Middle School, Atlanta, Georgia.
- Savransky, S. D. (2000), *Engineering of Creativity – TRIZ*, CRC Press, Boca Raton, 394).
- Simonton, D.K. (1988), *Creativity, Leadership and Chance*, in *The Nature of Creativity*, Ed. R.J. Sternberg, Cambridge University Press, New York, pp. 386-426.
- Sternberg, R.J. (1988), *The Nature of Creativity* (collection of articles), Cambridge University Press, New York, 454 pages.
- Sternberg, R.J. (1996), *Successful Intelligence*, Plume, New York, 303 pages.
- Torroja, E. (1958-a), *Philosophy of Structures*, University of California Press.
- Torroja, E. (1958-b), *The Structures of Eduardo Torroja*, F.W. Dodge Corporation.
- von Oech, R. (1990), *Creative Whack Pack*, US Games Systems Inc., Stamford, Connecticut, 196 pages.
- Wallas G. (1926), *The art of Thought*, Harcourt, Brace, NY.
- Ward, T.B., Finke, R.A., and Smith, S.M. (1995), *Creativity and the Mind*, Plenum Press, New York, 274 pages.
- Watson, J.D. (1968), *The Double Helix*, 2000 reprint available from Simon and Schuster, New York.
- Winograd, T. and Flores, F. (1986), *Understanding Computers and Cognition*, Addison-Wesley Publishing, Readings, Massachusetts, 207 pages.

APPENDIX A

A-1. Word Association. Forty to sixty percent respond (Flowers, 2000)

flower rose color red furniture chair

A-2. Self Evaluation. Identify the weights listed under SA corresponding to each qualifier you selected in Table 1. Then, add the weights.

Rating: 10 <sum<14 You are perceived as being very creative
 6.5 <sum<9.5 You are perceived as having standard creativity
 2 <sum<6 You need to work on the image you project...

WORD	SA ⁽¹⁾	R ⁽²⁾	FS ⁽³⁾
absent-minded	0.8	0	0.0
alert	1.2	1	
balanced	1	0	
cautious	0.3	0	
clear-thinking	1.2	0	
courageous	1.1	2	
curious	2	2	1.7
dedicated	1.4	2	1.5
determined	1.2	1	
dynamic	1.3	2	
efficient	1	0	1.1
energetic	1.5	2	
enthusiastic	1.5	2	1.6
factual	0.9	0	
fashionable	0.4	0	
flexible	1.3	2	
formal	0.5	0	0.7
forward-looking	1.4	1	
good-natured	1.1	0	
greedy-grasping	1.1	0	
habit-bound	0.1	0	
harsh-strict	0.7	0	
helpful	1	0	1.3
impulsive	1.3	0	
independent	1.7	2	1.5
informal	1.3	1	0.9
inhibited	0.3	0	

WORD	SA ⁽¹⁾	R ⁽²⁾	FS ⁽³⁾
innovative	1.8	2	
involved	1.2	2	1.5
modest	0.9	0	0.8
observant	1.5	2	2.0
open-minded	1.8	1	
organized	0.9	0	1.2
original	1.8	2	1.6
overconfident	0.9	0	
perceptive	1.7	2	
persevering	1.6	2	
persuasive	1	0	
polished	0.8	0	
practical	0.8	0	0.3
predictable	0	0	0.4
quick	1.1	0	
realistic	0.8	0	0.9
reserved-shy	0.5	0	
resourceful	1.5	2	
restless	1.1	0	
self-confident	1.5	1	1.7
self-demanding	1.4	2	
sociable	1	0	
tactful	0.9	0	
thorough	1	1	
understanding	1	0	
unemotional	0.2	0	
well-liked	0.9	0	

- (1) Values obtained by Santamarina and Akhouni, from a random sample of 45 engineering students. Participants were asked to identify the 10 words that best describe a creative individual, and then the 5 words that describe the creative individual the least. Weights listed in the table reflect frequency mapped onto a 0-to-2 scale.
- (2) Raudsepp (1981) original values; the methodology used to determine them is unknown.
- (3) Values obtained by Fernanda Santamarina (1997). Sample: 38 young teenagers ages 12-14. The analysis resembles the one by Santamarina and Akhouni.

A-3. Free Association

Typically, individuals list 10-to-20 word associations in one minute. The number of listed words decreases if close associations are required; however, the number increases when subjects are encouraged to generate divergent ideas and associations from varied contexts. Training can significantly increase the number of listed associations.