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# Where have all the inventors gone?

## Fostering creativity in engineering education with remote lab learning environments

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***Abstract*— Creativity has been proclaimed as one of the key 21st century skills. Facing tremendous problems, creativity and innovation were seen at the key factors of a knowledge-based society, able to cope with ongoing and future problems. Engineers play an important role in addressing these challenges. Their ideas, their inventions, their creativity have brought Europe's prosperity, and it will depend on their inventions and creativity to ensure that progress in the future. This raises the question in what way universities contribute to educate creative engineers nowadays. The slightly provoking essay will present results of a pre-study on fostering creativity in higher engineering education, conducted in the funded German project: "ELLI–Excellent Teaching and Learning in Engineering Education", and will discuss the remote lab approach of the finished EU-project "PeTEX–Platform for E-Learning and Telemetric Experimentation" as good practice example. It resumes with open questions addressing relevant future educational and socio-economic impacts.**

***Keywords-fostering creativity in higher engineering education, higher engineering education research, remote labs, creativity supporting learning scenarios, curriculum development***

## I. INTRODUCTION

Creativity has been proclaimed as one of the key 21st century skills and as the driving force of economic development. With the so-called creative class, comprising different types of creative workers, tackling complex, societal problems ranging from solving economic problems, through creating innovative technological solutions to devising new ways of social entrepreneurship, the role of creativity will increase dramatically in the years to come. Already today, many of the fastest-growing jobs and emerging industries rely on workers' creative capacity, such as the ability to think unconventionally, inventing new scenarios and producing novel solutions. To face this demand, both engineering education and professional engineering fields have to embrace new technologies and design new ways to foster creativity of engineering students and workers.

Reference [1] stresses that the function of creativity is twofold: "from the societal viewpoint, the task of creativity is improvement; from the individual viewpoint, the task of creativity is expression". For [1], these two perspectives of creativity - improvement and expression - were not extremes of one aspect, they should rather be seen as singular levels of investigation – "individual and society interact over time to bring new ideas, products, and solutions into the realm of culture".

### A. *Now, what is creativity anyway?*

Most definitions of creative responses to problems comprise three components:

- Creative responses must represent something different, new or innovative.
- They are of high quality.
- They must also be appropriate to the task at hand or some redefinition of that task.

So, a creative response is novel, good, and relevant [2]. But research on creativity is also based on complementary definitions like:

- The great mind approach ("Big C") vs. everyday creativity (little "c") or individual creativity [3],
- Systemic understandings of creativity [4],
- The subjectivity of creativity [5],

and complementary research perspectives:

- What is/are creative actor(s)? A creative person, a group, an organization, a process, a product, the environment [6]?
- What is creativity especially in engineering and how can engineering educators foster the "creative attitude" [7] in their engineering courses?
- Can high end remote and virtual labs, as presented in [8] and [9], be a powerful means to foster the creative attitude? How can this be done?

### B. *The Role of Creativity in Engineering*

In 2004, *The National Academy of Engineering* defined the impact of creativity on engineering in the following way: "Creativity (invention, innovation, thinking outside the box, art) is an indispensable quality for engineering, and given the growing scope of the challenges ahead and the complexity and diversity of the technologies of the 21st century, creativity will grow in importance. (…) Engineering is a profoundly creative process. A most elegant description is that engineering is about design under constraint. The engineer designs devices, components, subsystems, and systems and, to create a successful design, in the sense that it leads directly or indirectly to an improvement in our quality of life, must work within the constraints provided by technical, economic, business, political, social, and ethical issues" [10].

According to [11] engineers shall be able to "demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem solving". Reference [2] stresses that "being creative requires some amount of deviating from the norm".

But how and where can a teacher 'make learn' students to creatively think and apply scientific and engineering principles in an 'thinking out of the box' mode? Where and how do students learn to design, develop, construct, and operate, artifacts, methods and principles, and forecast behavior and effects with focus on real world problem solving and real world application scenarios? Is there a lack of "spirit of research" in engineering education [12], [13]?

### *C. Creativity and Teaching Engineering*

"Although the idea of creativity is attractive to educators, there is a pitfall as well as a promise. … From the perspective of educators, creativity is often viewed not as an end, but as a means towards ends such as improving problem-solving ability, engendering motivation, and developing self-regulatory abilities" [14]. Reference [14] propose three basic aspects of creativity that researchers see as generally comprising the overlap between creativity and education: Respectively, they are

- The use of **creativity** (or insight**) to solve problems** in other subject areas;
- **Creative ideas for teaching**; and,
- Teaching for or attempting to **enhance the creativity of learners**.

In contrary to that, [15] nominates some teachers' inherent factors that hinder the expression of student's creativity:

- **Teachers' prior experiences** during their own school and university years; reproduction of these practices across time, place, person;
- Prevalence of **teacher-dominated convergent teaching** approaches; personal need for order
- Teachers' **need to stick to the plan**; place on the acquisition of facts;
- Teachers' view that **unexpected student ideas are disruptive**; even soon-to-be teachers generally **prefer expected ideas** over unexpected or unique ideas;
- **Wrong beliefs**, behaviors, and assumptions **about students' motivation** and the role of creativity in the classroom;
- **Scripted curricula** represent the most extreme form of convergent teaching, separating learning from the development of creative thinking.
- **Teaching to the test** and increased use of externally mandated, fact-based tests.

Teaching to the test points students aware of what is really valued and important: "…the kind of examinations we give really set the objectives for the students, no matter what objectives we may have stated" [16]. "Regardless of how teachers encourage their students to share their creativity, unless teachers also include expectations for creativity in their assignments and assessments, then the message is clear: Creativity really doesn't matter" [15].

Reference [15] resumes that "Encouraging creative thinking while learning not only enlivens what is learned but can also deepen student understanding. This is because, in order for students to develop an understanding of what they are learning, they need … to come up with their own unique examples, uses, and applications of that information. In order for this to happen, expectations for novel yet appropriate applications of learning need to be included in classroom assessments of student learning".

But where, how, and when shall engineering students generate these competencies in classes, that base for several reasons still on common teaching approaches?

## II. Fostering Creativity in Higher Engineering Education

Regarding creativity in the field of engineering education, some work has already been done: e.g. [17] presents the creative platform, a concept that focuses on confidence, concentration, motivation and diversified knowledge. But a concrete didactic scenario for engineering education is missing. Such a scenario is delivered e.g. by [18], and [19], combining principles of enhancing creativity with problem based learning and project based learning in engineering education.

The research project "ELLI – Excellent Teaching and Learning in Engineering Education", funded by the German Ministry of Research and Education between 2011 and 2016, follows a different strategy to foster and evaluate creativity. Its sub-project "KELLI – fostering creativity in engineering education" is based on the combination of results, outcomes and consequences of two finished research projects: "Da Vinci – fostering creativity in higher education" and "PeTEX– Platform for E-Learning and Telemetric Experimentation", and a first pre-study, already conducted in KELLI, presented and discussed now.

### *A. Da Vinci - Fostering creativity in higher education"*

The results of the German research project "Da Vinci – fostering creativity in higher education" (supported by the German Federal Ministry of Education and Research BMBF, 2008-2011) show, that creativity in higher education (across all disciplines) consists of six different aspects [20],[21],[22],[23] (see Fig 1):

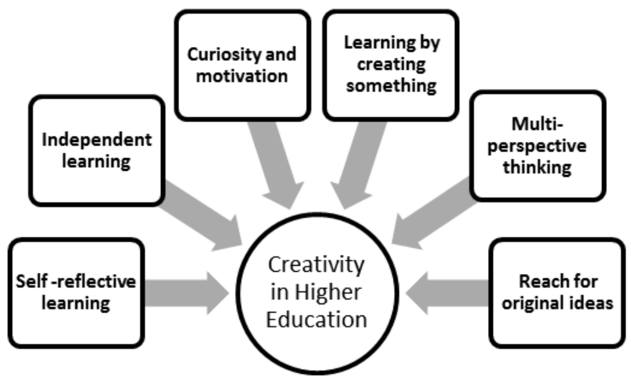


Figure 2. 6 facets of creativity in higher education

1. **Self-reflective learning** – learners break out of their receptive habitus and start to question any information given by the teacher. An internal dialogue takes place and knowledge becomes "constructed" rather than "adopted".

2. **Independent learning** – teachers stop to determine the way students learn. instead, students start for example to search for relevant literature on their own, they make their own decisions about structuring a text or they even find their own research questions and chose the adequate methods to answer it.

3. **Curiosity and motivation** – this aspect relates to all measures that contribute to increased motivation, for instance the linking of a theoretical question to a practical example or presenting.

4. **Learning by doing** – students learn by creating a sort of "product". Depending on the discipline, this might be a presentation, an interview, a questionnaire, a machine, a website, a computer program or similar. Students act like "real" researchers.

5. **Multi-perspective thinking** – learners overcome the thinking within the limits of their disciplines or prejudiced thinking. They learn to look automatically from different points of view on an issue and they use thinking methods that prevent their brain from being "structurally lazy" [24].

6. **Reach for original ideas** – learners aim to get original, new ideas and prepare themselves to be as ready-to-receive as possible. Getting original ideas cannot be forced, but by the use of appropriate creative techniques and by creating a suitable environment (that allows making mistakes and expressing unconventional ideas without being laughed out or rejected), the reception of original ideas can be fostered.

Within the Da Vinci-project, twenty qualitative interviews with German experts and an online-survey of all teachers from three universities in the Ruhr area were conducted. Everything that was said by teachers about creativity in higher education fits in one or more of these six presented aspects. This suggests that these six aspects in their entirety describe what constitutes creativity in higher education. But it was also shown that different disciplines tend to focus on different aspects.

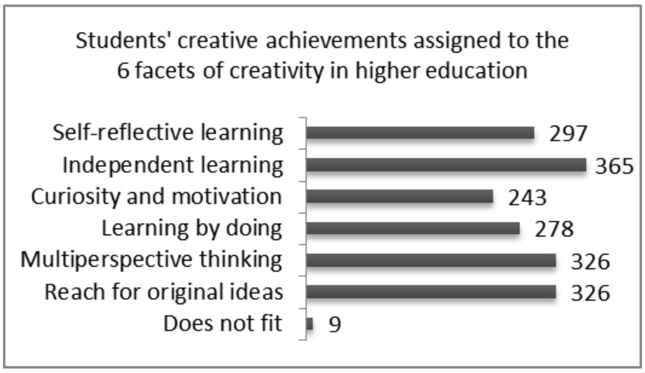


Figure 1. Validation of the 6 facets of creativity in higher education

In the KELLI subproject of ELLI, we analyzed against this background in a first analytical pre-study the module descriptions of six engineering education curricula (Manufacturing Engineering and Electrical and Electronic Engineering IT) of three German universities (Aachen - which is Germany's most prominent and leading technical university - , Bochum, Dortmund) in order to get to know which aspects of creativity are fostered in today's engineering education.

As a result, fostering the creativity-aspects 1 (self-reflective thinking), 3 (curiosity and motivation), and 4 (learning by doing) is highly developed in both courses of all three universities. With one exception these aspects have shares of over 50%. On the other hand, the aspects 2 (independent learning), 5 (multi-perspective thinking) and 6 (reach for original ideas) can be found only in small proportions with percentages below 50%, in aspects 5 and 6 with one exception even below 10%. (see Fig. 2).

To sum up, these pre-analysis of the module descriptions shows that in the considered courses students were encouraged to think critically and self-reflective. They had to demonstrate motivation and commitment in their courses and they were trained to "create" something, to work practically. Independence, collaborative development of ideas and the exchange with other disciplines and for open-minded discussions, scenarios and experiments, however, were almost not required and promoted.

And together with empirical experiences in engineering education a picture of diligent students is emerging, who rather work conscientiously on given tasks than finding new problems, questions and solutions on their own and in discussion with others. Also, the fact that in some of the courses the students were not free to choose the topic of their thesis reinforces this picture. Instead, they have to choose it out of a pool of given topics developed by the teachers. In this way, many learning processes that require creativity weren't done by the students, but by the teachers only!  That is:

- Detection of relevant research questions,
- Deliberation whether an issue is workable,

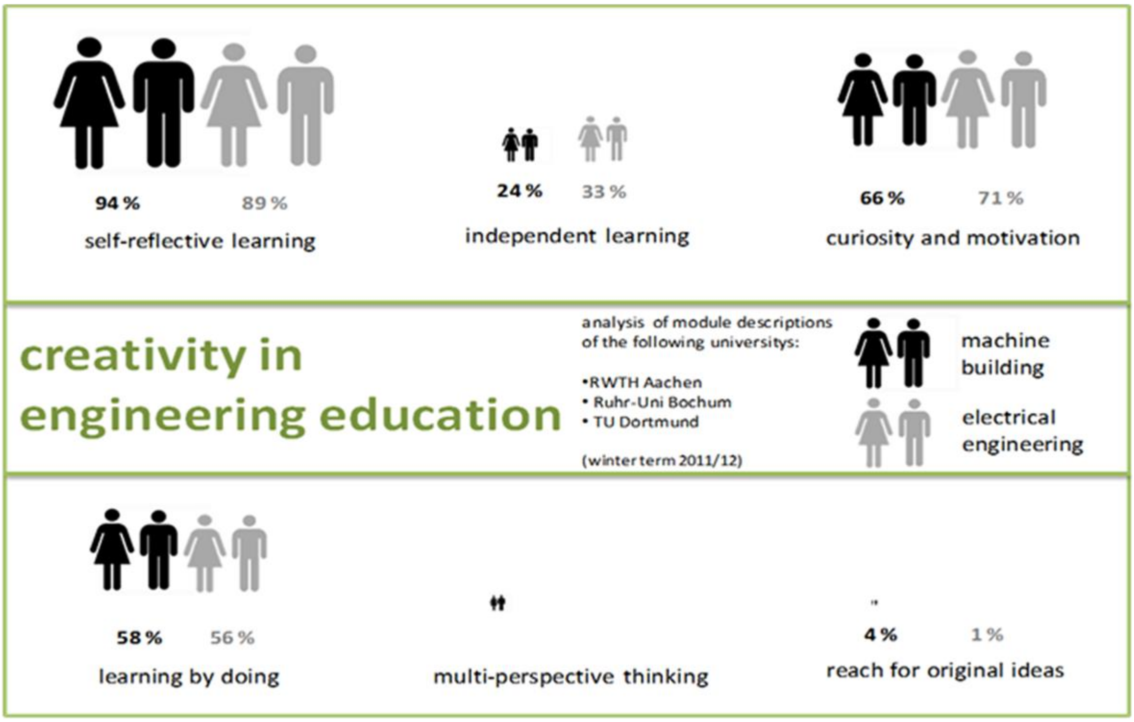


Figure 5. creativity in engineering education

- Creation of a structure and the assessment of eligible methods.

Due to this, students aren't able to see the "bigger picture" of their discipline, which is only seen by their teachers. They don't get in touch with the "spirit of research":

- (collaborative) Reasoning about current issues in the community,
- Setting up and discussing new (and sometimes as well risky) theories,
- Making of own decisions and seeking collegial advice.

When students are able to see the "big picture", they get a feeling about the value and importance of their work. Through these findings, the question arises whether this understanding of fostering creativity in engineering education is appropriate. However, students seem to have a different understanding of creativity. A (interdisciplinary) survey (n=320) at TU Dortmund University (Germany) shows that students regard "openness", "freedom", "stimulation", "inspiration" and "empowerment" as factors that promote their creativity.

But anyway, these results of the finished pre-study need to be treated very cautiously; they depend on a very small, arbitrary sample of only six courses from three different universities. Further qualitative and quantitative research will be done.

## III. Practice Example: Fostering Creativity in Higher Engineering Education with a Remote Lab Approach

The didactical concept of the "Platform for E-Learning and Telemetric Experimentation" (PeTEX) is one example [25],[26]. The PeTEX system is designed for the usage in higher education and for workplace learning [27],[28].

PeTEX combines a tele-operated experimentation platform (material testing, particularly forming, cutting, and joining) with a collaborative learning environment based on Moodle [29],[30]. It provides three different learning levels deploying three different didactic approaches, addressing three different problem types [31],[32]. The three levels correspond to three of the six facets of fostering creativity (see table 1).

### *1) Three Consecutive Problem Levels to Foster Different Facets of Creativity*

#### *a) Beginner Level Learning with Interpolation Problems*

Students in the beginner-level are guided through the learning platform. They are asked to create predefined and expected order in a given complexity of elements and actions by identifying, assembling and executing all given elements and actions in the right order to solve the task, in the PeTEX case to conduct predefined experiments correctly. These predefined experiments consist of interpolation problems. According to [33],[34],[35] interpolation problems consist of three elements:

- a predefined starting point (1),

- a concrete terminal point (2), and
- a concrete and predefined solution process how to bridge the gap between starting point and terminal point (3).

The challenge of this kind of problem is to correctly fulfill a sufficient complex task according to the given and scripted path. It deals with recognizing of and acting in complexity: e.g. understanding the manual, identifying the relevant units of the real equipment introduced in the manual. The next step is to combine, assemble, and connect these elements in the right scripted technical and logical order in order to fulfill the predefined task, and to produce the expected results.

TABLE I. Three consecutive learning levels, corresponding to the problem types and three facets of creativity

| **Learning Levels** | **Didactic approach** | **Problem type** | **Creativity facet** |
|---|---|---|---|
| **1. level: Beginner** | scripted learning paths | interpolation problems | 1.self-reflective learning |
| **2. level: Intermediate** | real world scenarios | synthesis problems | 4. learning by creating something |
| **3. level: Advanced** | research based learning | dialectic problems | 6. reach for original ideas |

The main creativity facet addressed by that kind of task is to break out of the receptive habitus, to create and internalize psycho-motor operation chains and first experiences of basic principles, and to start questioning the given information by transforming them into correct action.

*b) Intermediate Level Learning with Synthesis Problems*

In the intermediate-level, learners have to transfer their knowledge to given real-world scenarios and are encouraged to perform their experiments in a self-directed way. According to [33],[34],[35] real world scenarios relate to synthesis problems which consist of three elements:

- a predefined starting point (1),
- a concrete terminal state (2), and
- lack of a defined solution process to bridge the gap (3).

The challenge of this problem type is to find, to develop and to deploy a sufficient solution path to a given problem consisting of a presented starting point and an expected terminal point by applying divergent and convergent thinking to find and implement an appropriate solution for the given problem. The creative final product is the developed solution which is gained mostly "by doing" and the competencies the learner has gained with this kind of tasks are generated with "learning by doing" according to the creativity facets presented in this paper.

*c) Advanced Level Learning with Dialectical Problems*

Learners at the advanced level have to design own research questions and to develop the appropriate experiments. According to [33],[34],[35] those dialectical problems consist of

- no predefined starting point
- no predefined terminal point
- no predefined solution process

The challenge is to apply the developed knowledge, skills, and competencies of the learners to find and define novel and origin problems as research questions, defining a starting point, a final state, and the means for gaining it, like a concrete new product, prototype, theory, process.

*2) Dealing with Increasing Complexity in PeTEX for Fostering "The Spirit of Research"*

The more the students have worked with PeTEX, the more freedom they get to define their own research problems and to find the answers on their own. Furthermore, PeTEX provides collaboration, not only with other students (from other universities and even other countries), but also with lifelong learners. In summary, PeTEX offers an important contribution to foster the "spirit of research" by providing to the students more and more "openness", "freedom", "stimulation", "inspiration" and "empowerment" as factors that promote their creativity (see Fig. 4 and Fig 5.).

## IV. Radical Consequences and Challenging open Questions

It remains unclear whether these points also play an important role from the perspective of the teachers and, furthermore, parts of the society:

- What wishes and visions do teachers, researchers, industry representatives, professional association

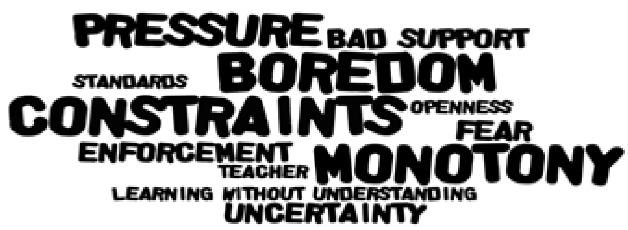


Figure 6. Students' perspective on factors that hinder creativity


Figure 7. Students' perspective of factors that foster creativity

representatives have with regard to the education of tomorrow's engineers and to their creativity and their "spirit of research"?

- Are open experimentation and trying out new ideas, the search for the unknown new really important for a society in a globalized world economy?
- Does our economic society indeed need diligent professionals who execute given tasks instead of developing their own initiatives?
- What kind of education will be needed, if a society wants to bring up future inventors who are able to cope with the future problems?
- How to train teachers efficiently and successfully in creativity fostering techniques?
- How to foster creativity and interdisciplinary knowledge in engineering education courses and curricula?

These questions should soon be discussed in a broad social debate. Further studies on the impact of teaching creativity in engineering education need to be done urgently.

## V. CONCLUSIONS

The essay posed two main questions: What means/is creativity in the context of higher engineering education and is there a lack of creativity fostering education in engineering curricula? To answer these questions, the essay presented results of a first curriculum survey as pre-study, conducted during the first stage of the nationally funded ELLI project.

The pre-study confirms the lack of spirit of research in the chosen sample of engineering education curricula. Since the results of the pre-study depend on a very small, arbitrary sample, further qualitative and quantitative research will be done.

Furthermore, the paper discussed the remote lab approach of the finished EU-project "PeTEX–Platform for E-Learning and Telemetric Experimentation" as one successful practice example on fostering creativity, and resumed with open questions addressing relevant future educational and socio-economic impacts.

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