

# Tradition and Innovation in the Education of Materials for Engineering Students in the 21<sup>st</sup> Century\*

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## Abstract

This paper deals with the transmission of materials knowledge in ways that recognize the broader technical, economic, environmental and social (TEES) conditions in which it takes place. A Materials education today must balance both depth, leading to expertise in the subject, and breadth, allowing material issues to be judged in the light of contemporary TEES concerns of the present and the future. This is consistent with the increasingly integrated nature of technical education with society's need for engineers that can make things happen. Materials teaching already encompasses a great deal. At one time metallurgy, polymer science, and glass and ceramic technology were taught in different departments, even at different universities; today they are generally merged into a single program under the heading of Materials Science or Engineering Materials. There is now a move beyond this, towards what we will call Materials Systems and Design, integrating broader TEES issues with the skills necessary to make an effective engineer. This framework will encompass all the implications of, and trade-offs in, the adoption of materials in innovative design: not just the technical implications such as cost, strength or manufacturability, but also environmental impact, social awareness or material scarcity. Students will also be equipped to take advantage of new information technologies and learning opportunities throughout their careers: this is particularly important for a career that will probably span five decades into the future. Lastly, their educational experiences will prepare them to effectively work in teams in the companies of the future.

*Keywords: Grand Challenges, materials teaching, design-led approach, eco-design, innovation*

## Contents

1. Introduction.....	2
2. Past and present of Materials education.....	2
3. The future: Materials systems and design .....	3
4. Tools for a design led approach.....	5
5. An implementation of the Materials Systems and Design approach .....	8
6. Concluding remarks .....	9
References .....	10

\* The present manuscript has evolved through several communications at the Euromat (2011), ISEE (2012), JSEE (2012), WEEF (2012) and CBECIMAT (2012), including discussions with the academic community and feedback from reviewers and colleagues at these events, both formally and informally.

## 1. Introduction

If we consider education to be the transmission of knowledge, in materials education this transmission is now facing additional changes and demands to its approach. In this white paper we consider such demands and recognise the need to adapt the broader technical, economic and social contexts around materials education in the 21<sup>st</sup> century.

An educator's appreciation of the balance needed between breadth and depth of knowledge is fundamental if we are to produce engineers that can tackle the highly complex problems of this century. Materials are firmly set at the interface of multiple disciplines and will play a decisive role in the future of humanity. Engineering education as a whole is morphing into an all-encompassing discipline, in which data is at the core of systems' decisions and design. It is broadening its scope, from typical silos like Mechanical, Materials, Electrical or Civil Engineering into Engineering Systems, Environmental Engineering, and so on. Even within the silos, attempts are being made at broadening their scope, using design and systems thinking as tools to understand the broader challenges that face engineers.

However, breadth and depth are competing skill sets, in that one or the other is achievable, but it is difficult to accommodate both in an undergraduate curriculum. Materials research & development in the 20<sup>th</sup> century has greatly extended the portfolio of engineering materials and the underlying understanding of materials properties. Advanced research, especially that developed inside higher education institutions, has been absorbed into the engineering and science curricula and made specialization the preferred route for course development. The world outside academia, however, is so varied that it is not possible to equip students with all the knowledge they will need. Hence the undergraduate degree should provide a set of basic building blocks upon which different types of future engineer can build his/her specialism through on-the-job training, professional development and further education. It is therefore important that degrees focus on teaching students to learn, a skill they will require throughout their whole lives to acquire the breadth and depth that they need for their professional development [1,2].

Learning synthesis and analysis (induction - deduction) coupled with a design led approach is one way of achieving breadth without losing too much depth. The interdisciplinary nature of materials enables the opportunity to make materials an overarching theme on which to build the students' knowledge network and practice induction-deduction on a design led approach: formulating hypotheses, testing and discussing them, analysing the results and iterating until they are happy with the results.

## 2. Past and present of Materials education

The subject of Materials can trace back its history for at least 4000 years, a history longer than that of any of the other "disciplines" shown in Figure 1. It evolved from early Metallurgy, which was itself informed by alchemy and by tradition enshrined in folklore. Today, the subject sits at the intersection of Physics, Chemistry, Geo and Bio Sciences, Environmental Science, and Engineering – that is to say as a bridge between the applied sciences and the pure sciences. This breadth is unusual and makes the subject uniquely well-placed to contribute to the solution of many of today's challenges, particularly by:

- Encouraging interdisciplinary thinking that bridges the disciplines shown in Figure 1, an essential ingredient for innovation from cross-fertilisation [3];
- Devising ways in which materials and processes can be made more efficient, less expensive and less environmentally damaging – one of the central challenges in advancing materials in the 21<sup>st</sup> century [4];
- Thinking creatively about material needs in order to meet the changing demands of industry in the next 30 years, and in doing so, linking the science to the engineering [5];
- Introducing students to the Grand Challenges (see section 3 of this paper for a clarification on this) of our time such as future mobility, clean energy and sustainability, all of which require an approach combining information from several of the disciplines shown in Figure 1, plus an appreciation of the role of technology in society.

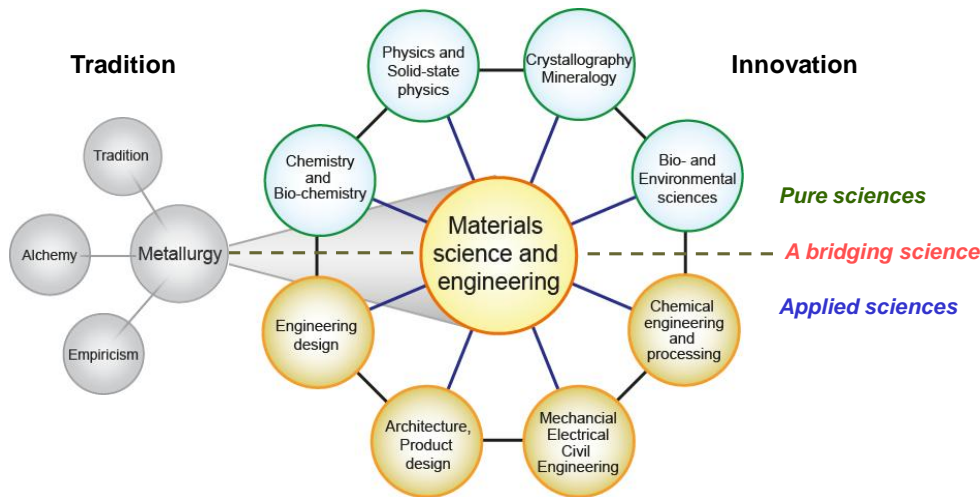


Figure 1: The past and present of materials.

### 3. The future: Materials Systems and Design

A balanced Materials education today must include both depth, providing expertise in the subject, and breadth, allowing material issues to be judged in the light of contemporary economic and societal concerns; looking both at the present and the future and giving engineers the skills to take their ideas forward (Figure 2). This is consistent with the increasingly integrated nature of technical education. Innovative design, today, must include an understanding not only of the technical aspects of products but also of stakeholders' interests and the context in which the products will be used. We have role-models exemplifying visionary engineers able to combine depth and breadth, such as Leonardo daVinci, Gustave Eiffel, Isambard Kingdom Brunel, Wilhelm Daimler, James Dyson and Steve Jobs. We cannot teach all our students to emulate their success, but it remains our responsibility to train students who are not merely specialised experts or non-specialised generalists, but rather a balanced combination of both.

The evolution of materials teaching over the last 40 years has been one of increasing integration. At one time metallurgy, polymer science, and glass and ceramic technology were taught in different departments, even at different Universities; today they are generally integrated into a single program under the heading of Materials Science or Engineering Materials. Broadening perspectives when teaching Materials and Design should come

naturally in a subject that has a tangible, global impact on society. Consequently, there is now a move towards what we will call Materials Systems and Design, integrating broader technical, economic, environmental and social issues into an entity.

The rapid pace at which society as a whole is evolving is pushing teaching methods and course curricula to a new level. The world is changing rapidly and Engineering professionals need to adapt accordingly. Lifelong learning has become an essential skill. The research achievements of today become the engineering practice of tomorrow. This means that undergraduate teaching cannot be based on solutions, but instead must be based on tools and methods to tackle new, as yet unsolved, problems. Today's solutions will not solve tomorrow's problems, but tools and methods are timeless. The context in which our society and our students live is geared to ready-made solutions, no-fuss procedures to get things done rapidly with little or no reflection, when what is needed is to spend time understanding the question before attempting an answer.

Figure 3 intends to project past and present into a possible future of materials teaching. The trend has been to take each of the material realms from the past and create a Materials Science discipline to encompass all of them. Today Materials Science is taught together with other topics like Mechanics, Structures, Design, Environmental Science, and so on. These topics will be brought together in a way that will integrate them under the umbrella of Materials Systems and Design, broadening our

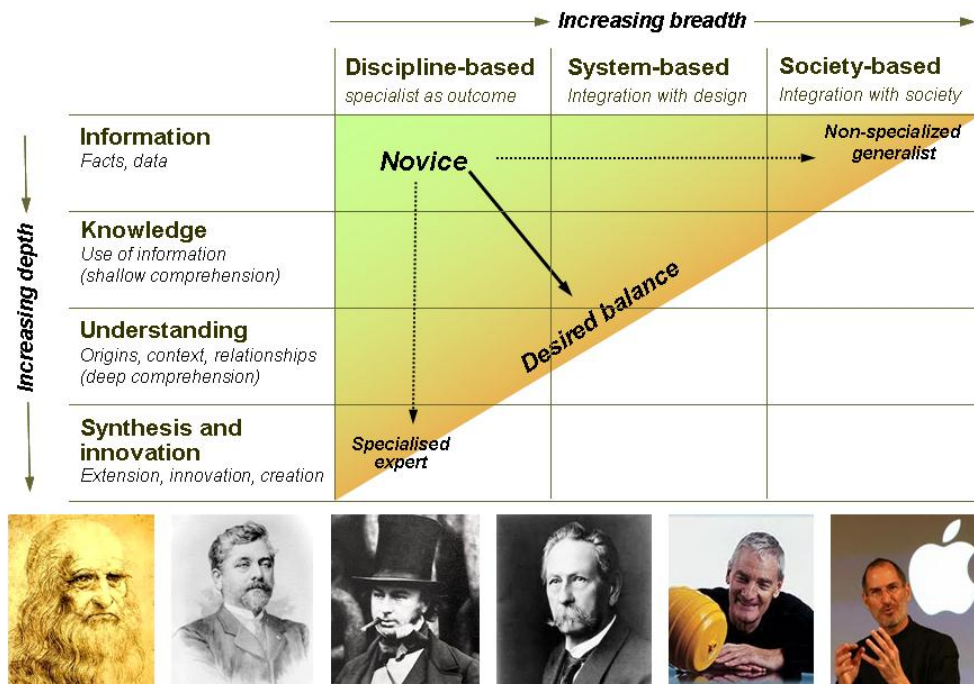


Figure 2. The balance between breadth and depth. The images are those of engineers who, par excellence, combined breadth and depth.

understanding of Materials in a global context where TEES issues come into play. Interpersonal and leadership skills will undoubtedly play a critical role in the future. Engineers will have to master these skills if they are to contribute to the advancement of mankind in a sustainable way and have their ideas realised.

Sustainability is a topic that commands increasing attention from society and touches in on all the TEES issues. It can be studied within the context of Materials Systems and Design in such a way that the whole picture of materials scarcity and related energy concerns can be connected to create a network of knowledge. The following paragraph attempts to create this knowledge network.

How is this breadth to be introduced into a program that, to many observers, is already overcrowded with the specialised, discipline oriented requirements for a deep understanding of the subject? One idea, suggested by Goodhew [6] and developed in a number of teaching programs, is a small number of lectures that take a broad scan of one of the so-called “Grand Challenges” that we face over the next 50 years, [7,8]. Figure 4 shows a selection of those which impact the most on the topic of materials. It is possible to survey an aspect of one of these – wind turbines as a contribution to future provision of energy, for example, or electric cars as a contribution to future mobility – spending

equal time on materials, design, the regulatory restrictions or incentives, and the interests, arguments, influence and welfare of the stakeholders (government, the supply chain, manufacturers, consumers, unions, the public at large, etc). Such an approach lends itself to activity- and project-based exercises in which groups of students explore on their own possible routes to take. Other examples that lend themselves to promote critical thinking between students include desalination as a contribution to future water supply, ultra-affordable housing as a contribution to shelter, pumped energy storage as a way of smoothing intermittent solar power, or some on-going controversial infrastructure development in the local community.

The internet has evolved into a formidable tool for approaching exercises of this sort, but students should not think that it is the only resource. Universities and colleges still have libraries and teaching staff in adjacent departments who can provide both ideas and guidance. Local councils have information services that will advise on regulatory issues. The national press carries articles touching on one or another aspect of the Grand Challenges almost every day, many of them reflecting the reactions or concerns of the public at large to major projects, planned or in-progress. Understanding the views and pre-conceptions of

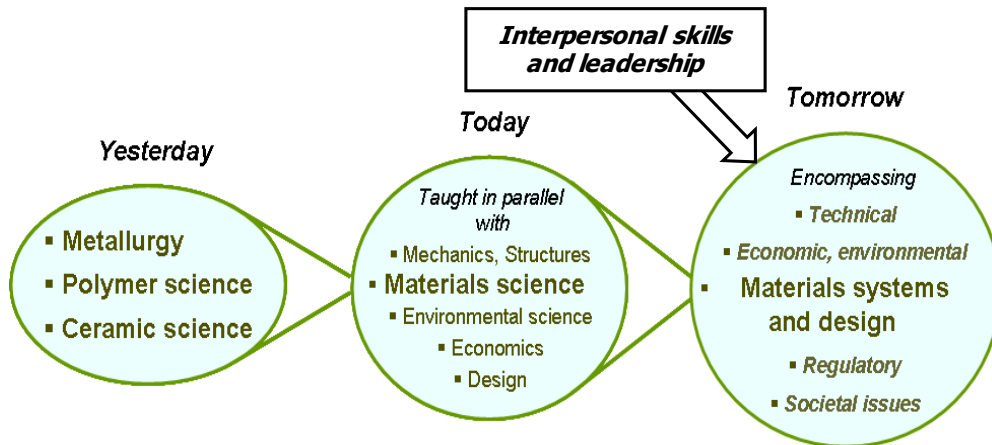


Figure 3. Past, present and possible future of materials.



Figure 4. A number of sources identify a number of Grand Challenges that we face between now and 2050 – roughly the working life-time of our students.

non-technical stakeholders is essential if you are to bring them around to your ideas and make progress.

To the students of today the internet is a utility, as ubiquitous and banal as water coming out of a tap. However they still need to learn how to get the most out of this resource and other technologies. Reliability of data, plagiarism, and obsolescence are some of the issues that students need guidance on so that they can take full advantage of this incredibly rich seem of information.

More structured information can be found in specialised databases, many of which are widely available. Here, we will mention the CES EduPack, a set of teaching resources that can contribute, among other things, to projects like those suggested above. The current release comprises of extensive databases for materials, including their environmental attributes; as well as a database and documentation for materials for low-carbon power systems and energy storage systems. The community of academics using this system have also contributed resources on this topic including a

“States of the World” database [9] that provides economic, political, demographic, and humanitarian data for the nations of the world, relevant in an era of globalised manufacture and trade.

The way of best implementing project-based learning in this context is to follow a design led approach to materials teaching.

#### 4. Tools for a design led approach

Figure 5 illustrates two approaches to the teaching of materials, one science-led, the other design-led. The science led approach to teaching typically starts with the basic building blocks of scientific knowledge on which students will then base their academic and professional activities. However, this approach often fails to create relationships between these blocks. This means that students have a wealth of disconnected knowledge silos but lack the tools to build relationships among them. The way that is traditionally used to overcome this situation

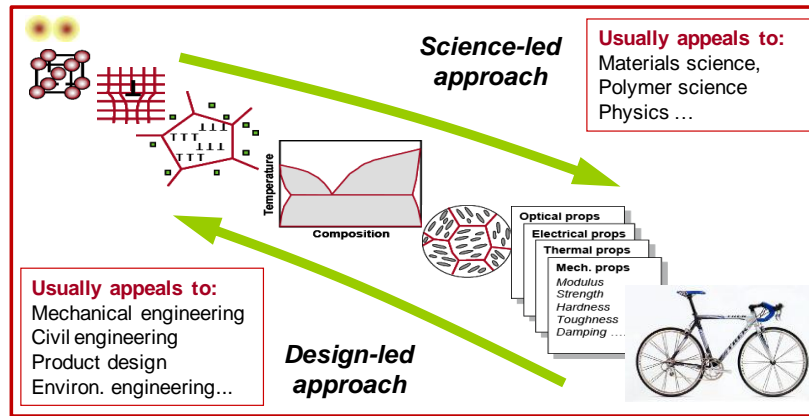


Figure 5. The science led approach and the design led approach.

is to have a capstone design course, usually in the final year of study, in which the students use all their knowledge to solve a design problem. However, this may not be enough to capture all the TEES issues that arise in a real life design. A constant awareness of this broadness is necessary for the students to tackle design from day one on their undergraduate degree [10].

The design-led approach is inherently broad in scope, limited only by the design brief itself. Our students can learn to tackle this broad perspective supported by project based learning. The tools our students need to learn will primarily have to provide breadth, supporting depth when needed. This provides meaning to the most difficult topics.

A way of teaching and learning about engineering materials, especially with students from typical engineering degrees, like mechanical engineering, is to make a parallel between the process of design

and the process of materials selection, explaining the flow of information between the two processes (see Figure 6). Since these two processes will influence and be influenced by manufacturing, this too will have to be studied. Furthermore, because design can be performance-driven or cost-driven, manufacturing plays differing roles in each. For a performance driven design, the selection of the materials is crucial, and the manufacturing process is secondary in that it is selected as a consequence of the performance needed from the product. If cost is driving design, the manufacturing process becomes the most important parameter and the major factor in early design stages. The material will be a consequence of what the manufacturing process dictates. In real life, however, nothing is that straightforward, but for teaching purposes, explaining the extremes is usually enough to have students thinking critically [11].

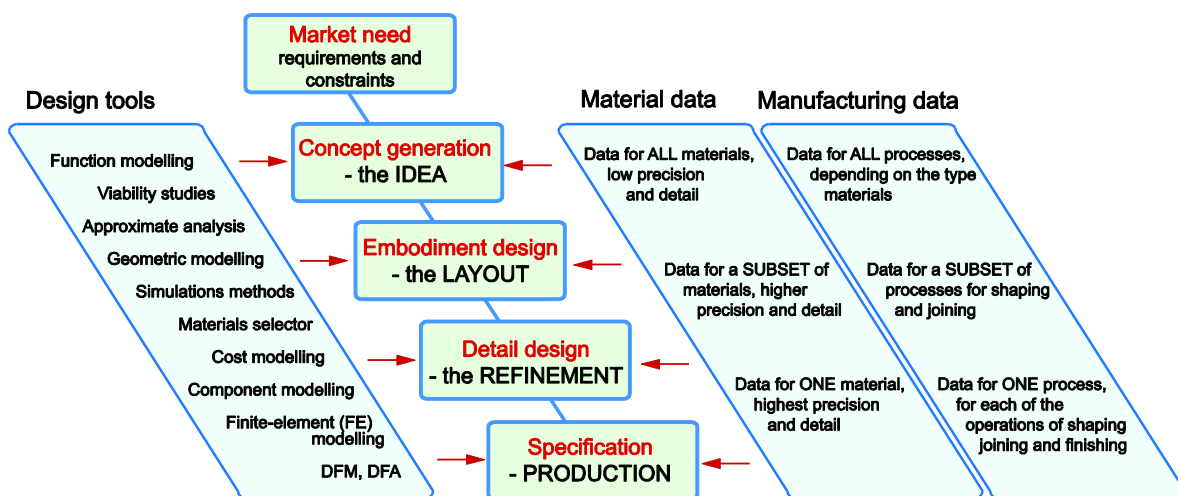


Figure 6. The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage, but at very different levels of breadth and precision.

Here is an example of a possible student project, based on the design flow shown in Figure 6. Considering the requirement for a sustainable means of in-land transportation, a bicycle is a possible solution. The first decision in the design of the bicycle is the configuration. From this follows the loading of the components that make up the configuration – the first constraint is that the choice of section and of material must carry these loads safely. The material choice is further refined by adding constraints of tolerance to atmospheric corrosion, expected life, provision for acceptable end-of-life process. The required material properties can be obtained by a combination of processing and/or alloying; this is made possible by the specific primary elements needed and their bonding and crystal structure or other micro structural arrangements. Thus the design requirements provide a reason to “drill-down”, so to speak, to a discussion of materials properties, processing and microstructure. Now looking at the environmental impact of the bicycle (remember that it should be sustainable) you then need to reason in a different context: What materials impact the most on the environment? Would the bicycle require maintenance? How will it be disposed of at the end of its life? What is the cost of ownership? Should the person own the bicycle, or should it be rented? There is the question of ethical sourcing of materials: are they produced locally? If not, are they sourced from a country with an acceptable record of treatment of its work force? Is a bicycle a respected means of transportation culturally? Would it encourage other people to have bicycles

too? Would it have a social impact in your local community? Would a “green” bicycle impact well on the public perception of the company for whom this design exercise is carried out?

The CES EduPack is a teaching tool that helps in answering some of these questions in an exploratory virtual environment but using real life data about materials properties, behaviour and environmental impacts. It was designed to support teaching in ways that augments both the students’ experience and knowledge about materials. The visual nature of this tool helps the student capture at a glance where materials stand in relation to each other along one or several dimensions. Easy to construct plots, like the one in Figure 7 help students grasp the ranges of both properties in each material family, but also enquire why the differences among different materials arise. This enables a discussion on the reasons for this behaviour, exploring materials architectures, bonding, microstructure and chemistry. It sets the stage to understand how thermal and mechanical treatments affect some properties but not others and it ultimately facilitates a way into materials processing and manufacturing costs, also supported by CES EduPack.

Additionally, the student can also think more broadly using CES EduPack. It includes an Eco-Audit tool, the output of which is illustrated in Figure 8. This tool allows “what-if” scenarios of different choices of materials, manufacturing processes and end of life potential in terms of energy and CO2 emissions.

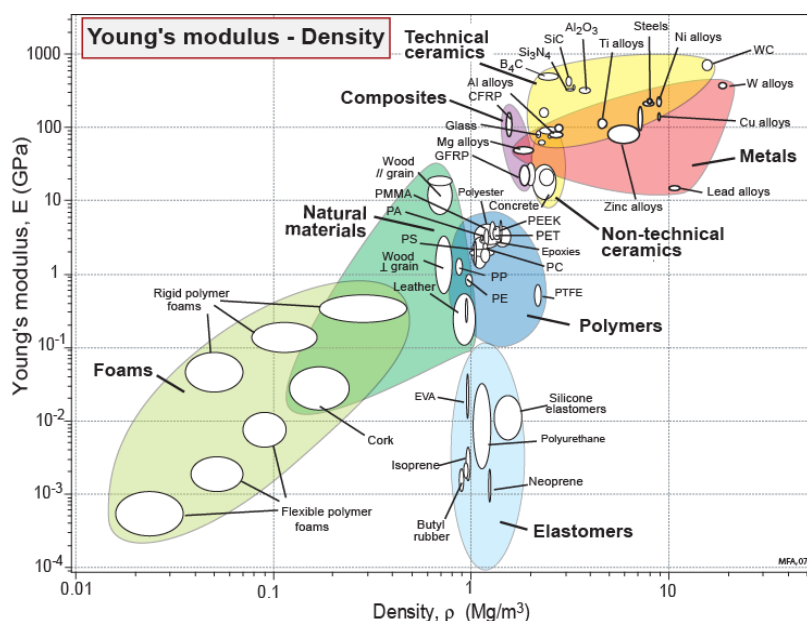


Figure 7. A map of Young's modulus versus density, showing the different regions that each material family occupies.

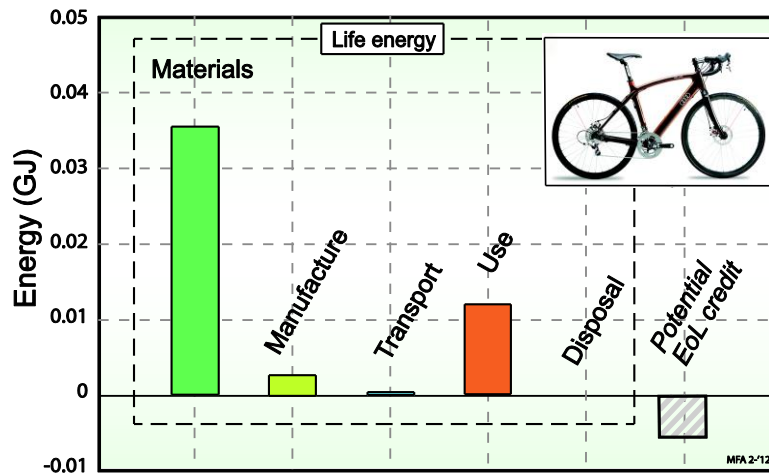


Figure 8. The impact of each of the phases of life of a typical bicycle (values for 1000 passenger.km).

A separation of both energy and CO<sub>2</sub> emissions in the various phases of life of the bicycle (these include raw materials production, manufacturing processes, transportation of raw materials during manufacturing, use, disposal, and end of life decision) help the student identify choices that minimize the environmental impact of the bicycle. If the production of the raw materials is the most energy consuming phase of life, then the student can use the software to find a material with a lower embodied energy. If the use phase has the greatest impact, it helps to reduce weight. CES EduPack suggests strategies to do this, but care must be taken with other factors, as often a change in design may affect other aspects that were not foreseen. This again enables a way into a fruitful discussion on the implications of design changes.

The data available in CES EduPack can be presented in a way that is suited to either first year undergraduate students or more advanced students. Specialized editions can be used for research in specific areas like aerospace, bio-engineering or architecture, with further information on materials specifically used in each field.

## 5. An implementation of the Materials Systems and Design approach

As mentioned before, introducing all of this in a degree is not simple, and introducing it in a single course is even harder. However, a successful attempt was made at introducing the Grand Challenges in an Engineering Materials course from the second year of a five year integrated MSc

degree in Mechanical Engineering at the Technical University of Lisbon, Portugal, from 2009 onwards [12]. The Engineering Materials course follows another course on Materials Science, where the basics of atomic structure and bonding, dislocation theory, etc., are laid out. The Engineering Materials course was previously set around mechanical testing, thermal and mechanical treatments of metals and a long and exhaustive description of each material family: polymers, elastomers, ceramics, glasses, metals and hybrids. However, due to the breadth of materials that are now commercially available, this approach is becoming inadequate. Even differentiating between material families is becoming increasingly difficult since they overlap in various dimensions. Figure 9 shows the evolution in the number of materials available in 1900 and at present. It is clearly shown that there is now an extensive overlap of material families and that the universe of materials available to the designer is considerably larger now than it used to be. As a consequence of this extensive description of materials during the 14 week semester, students would gradually stop coming to class (except for the lab classes, which were compulsory) and from a pool of around 250, only 50 or so students would turn up by the end of the semester.

From 2009 onwards a new approach was tried, based on the use of CES EduPack when appropriate. Instead of describing phenomena, the course was constructed using a design-led approach; starting from products and ending up in the atoms, when appropriate. The fundamentals are uncovered (or revisited) where needed, with a clear motivation for doing so. For example, if one needs to design a new bicycle frame, what materials could





propose that materials teaching will evolve into Materials Systems and Design, and that this is a framework providing a foundation of skills needed to be an effective engineer over a long career. This framework will encompass all the implications of and trade-offs in the adoption of materials in innovative design: not just the technical implications like cost, strength or manufacturability, but also technical, economic, environmental and social issues.

To produce effective engineers capable of realising their ideas and adapting to new technologies and future challenges, courses need to help students develop skills as well as knowledge. Tools are fundamental in providing these skills and knowledge, but also the breadth and depth that is needed in this century.

Summarising, to adapt their learning to the needs of the 21<sup>st</sup> century, students need:

- Expertise in materials science
- To understand the design process
- The ability to work across disciplines.
- To integrate economic, social and environmental aspects, for example by using the Grand Challenges as a basis.
- To learn leadership skills in order to make things happen.
- The ability to take advantage of information technology.
- Life-long learning skills.

It is the belief of the authors that broadening the knowledge base in an interdisciplinary course such as Materials Systems and Design can help in changing students' attitudes towards society and the environment without neglecting technical and economic concerns. Data can provide the basic needs for a systems perspective to take shape, and that is exactly where CES EduPack can play a catalytic role in enabling this perspective.

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**Marc Fry** is Director of Granta's Education Division and has as an Engineering Degree from Cambridge University. The Education Division of Granta currently works with over 800 universities and colleges worldwide. It develops CES EduPack specifically to support/enhance materials, design and sustainability teaching in engineering education.