An Integrating Teaching Resource for Materials Science and Engineering

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CONTEXT The academic areas of Materials Science and Materials Engineering have different emphasis at different universities. Some would argue that the former is more focused on understanding materials (the *why*) while the latter is more focused on making use of them (the *how*). Together, they constitute an important part of many engineering programs and may therefore be treated jointly as Materials Science and Engineering (MS&E). Teaching resources that integrate these perspectives, spanning the microscopic aspects (structure) of materials and the macroscopic aspects (properties) would be very useful to educators.

PURPOSE In this paper, we describe the development and implementation of a new prototype database with tools for the teaching of MS&E, based on a standard software package for materials-related teaching, with the intention of getting feedback on our ideas.

APPROACH We have investigated a number of curricula and syllabi to identify a list of topics/concepts that appear central to the learning objectives of MS&E and surveyed/interviewed educators teaching MS&E to understand their priorities on the introductory course. Some relevant existing online resources were also reviewed with the aim to strengthen these areas with a more visual and engaging teaching tool. The results from this analysis constituted the basis for the development of a new prototype MS&E software tool.

RESULTS Among the top candidate areas that came out of the syllabus analysis and surveys were: *Microstructure processing (thermal/mechanical)*, *Material characterization and micrographs*, *Binary phase diagrams*, *Crystal structures*, and *Material properties*. The resulting prototype cover several of these topics and is part of a long-term effort to facilitate materials teaching. It integrates a multitude of teaching approaches and is currently being evaluated by professors.

CONCLUSIONS In this paper, we report on the background, development, and content of a new ambitious MS&E software tool for engineering education. The purpose is not to investigate the teaching outcome (yet), but to share our efforts and findings with educators in the field hoping to get feed-back and inspire educational ideas.

KEYWORDS Materials, Software, Teaching.

Introduction

Material Science and Engineering (MS&E) teaching forms part of a number of engineering programs relating to materials teaching, *e.g.*, mechanical (see Figure 1, coloured circles).

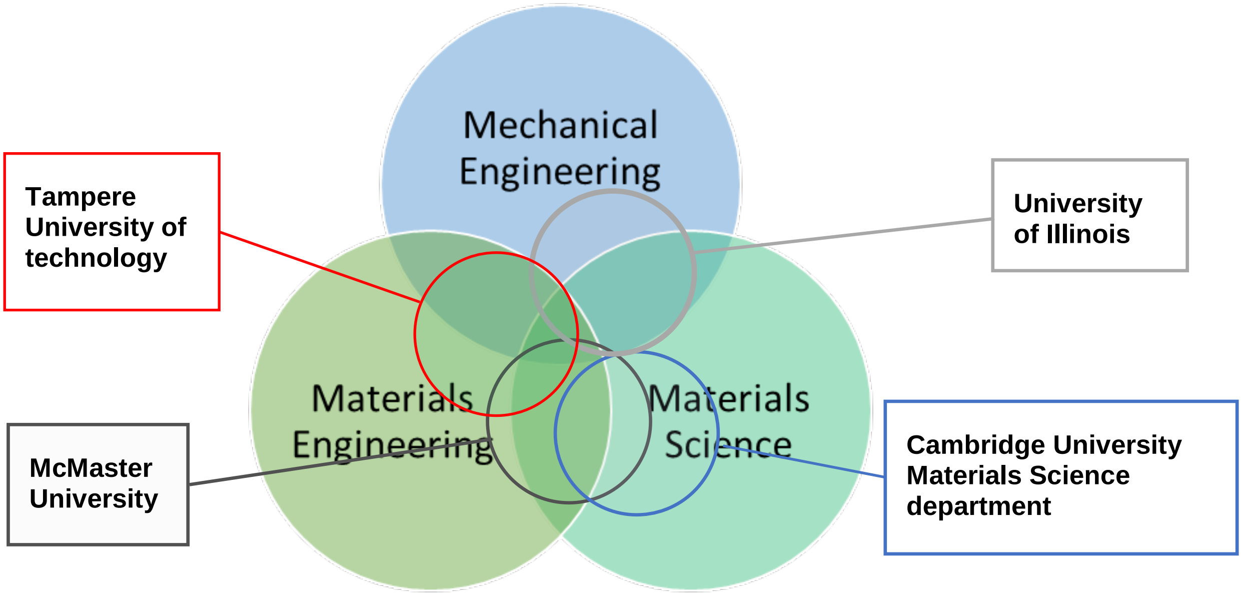

Figure 1: Venn-diagram of educational disciplines showing the emphasis placed on the subsets in the MS&E Curricula/Syllabi at four of the Universities included in this study

Traditional Materials Science courses tend to be *Science-driven*, focussing on the atomic and microscopic scales to develop an understanding of material behaviour. Materials courses in engineering tend instead to be *Design-driven* (see Figure 2), with more focus on applications and selection (Ashby, 2016). This paper considers the further development of an existing software teaching resource, CES EduPack (Granta Design, 2017), to provide a tool that can support integrated teaching with either or both of these approaches.

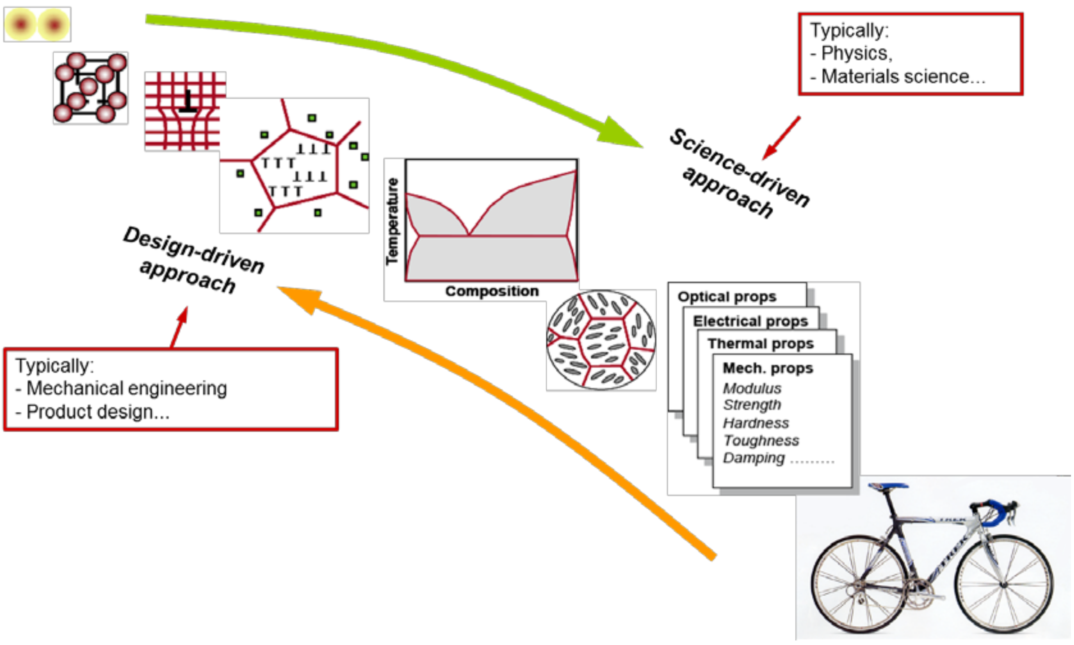

Figure 2: Design-driven and a Science-driven teaching approaches to the teaching of Materials

Background and Methodology

Syllabus Comparison

Globally, University Curricula of Materials Science and Engineering vary considerably. Six relevant syllabi (see Table 1) were studied to identify target areas and key learning outcomes. The selection was designed to reflect both geographical differences and the differences in approach depicted in Figure 2. Figure 1 indicates how they compare.

Table 1: Description of the courses selected to represent relevant syllabi

#	University	Degree	Course Syllabus
1	Tampere University of Technology (Finland)	MSci	Materials Engineering
2	Cambridge University (UK), Material Science	MSci	Materials Science
3	University of Illinois (US)	BSc	Materials Science and Engineering
4	McMaster University (Canada)	BSc	Materials Engineering
5	University of New South Wales (Australia)	BE	Materials Science and Engineering
6	Kyushu University (Japan)	MSci	International Materials Science and Engineering

Outcome of Curriculum/Syllabus Analysis

The learning outcomes, or in some cases the corresponding content of the syllabus, were compared and analysed for the six courses mentioned above. These are summarized in Table 2, below.

Some concepts that appear important to the desired learning outcomes (see marking in Table 2) were extracted and summarized below. These areas become main candidates for components of a MS&E resource:

- Microstructure processing (heat treatments etc.)
- Material characterization and micrographs
- Phase diagrams
- Crystal structures
- Material properties

In this paper, we have extended a previous study (Fredriksson, 2015), where the methodology is described in greater detail. In that study, a small survey (n=10) of professors that were experienced users of the software platform was conducted to probe the relevance of main concept areas similar to these key learning outcomes. A number of informal interviews have also been conducted to clarify the findings.The results of the survey, shown in Table 3 further down, was therefore also used to guide the development described in this work. It represents software development that is a first major step towards an integrated tool for integrated teaching of the materials science and engineering subject. Depending on feedback, further development will be guided by these outcomes.

Table 2. Learning outcomes from selected syllabi (from web) projected onto discipline: 1 Tampere University of Technology (Finland), 2 Cambridge University (UK), Materials Science Dep, 3 University of Illinois (US), 4 McMaster University (Canada) 5 University of New South Wales (Australia), 6 Kyushu University (Japan). Key concepts are marked in bold font.

#	Learning outcomes/content relating to Materials Engineering	…relating to Materials Science	…relating to Mechanical Engineering
1	• Broad knowledge of the **material properties**, their utilization, and **development of these properties** to meet the requirements set by different applications. • Broad knowledge on the development, properties and **behaviour of metallic and ceramic materials under various conditions** and in different applications. • Understanding of **manufacturing technologies** and how they are used to affect properties and structure	• Understand basic **structure-property relationships**. • Understand research **techniques and methods**. • Knowledge with emphasis on **structure/properties** of polymers and biomaterials	• Understanding **how to utilize properties** in practice, apply knowledge in **materials selection**
2	• Some attention to processing and what are the results of that. Often analysed through **microstructural behaviour** as well	• Property relations to **microstructure, material analysis methods, microstructure processing.** • Understanding the cause of the properties/results. • Investigating **material behaviour**	• Very brief introduction to **material selection** and merit indices
3	• Materials Synthesis and processing cover the **methods to alter the microstructure**	• Understanding of materials via **microstructure, predicting properties** and looking at their causes. **• Techniques of microstructural analysis** • Atomic bonds	• Many courses eventually lead to the application of **material properties** in design. • Courses on pure mechanics
4	• Minerals and **materials preparation, extraction, manufacturing, processing**. • Polymer synthesis, **metallurgy**. • Selection of processes for industrial applications (with much attention to Iron and **Steel making processes and their selection**). • Application of materials in electronics and fabrication techniques for electronics. • **Corrosion protection**.	• Nature of **defects in microstructure**, functional properties, **crystal structure**, bonding. • Thermodynamics in materials, **Phase diagrams** • **Crystal structure** properties and analysis. • Being able to mathematically model diffusion processes, **creep, corrosion** (separate course on corrosion and sustainability). • **Microstructure and mechanical property relations** (especially for **failure**)	• **Materials selection** based on materials properties. • Laws of **thermodynamics**
5	• **Microstructure control** and its application to commercial materials. • **Sustainable materials processing** (design of sustainable systems). • Common methods of metal forming. • Behaviour of common aluminium and nickel alloys to illustrate **microstructural principles**. • **Ceramic processing methods**. • Heat and mass transfer in **metallurgy**	• Microstructure and structure-property relationships. Crystallography Micromechanisms of **deformations, fracture, fatigue, creep**. • Functional properties of materials. • **Materials characterization**, • Diffusion and kinetics. • **Phase transformations** (see web). • Polymer science ranges from chemistry to full scale commercial manufacturing.	• Deformation and yielding, **failure, mechanical behaviour of materials** (with references to microstructure where applicable). • Pure thermofluid dynamics and heat transfer.
6	• Innovations and rapid advancements in materials to achieve ultimate performance • **Develop new advanced materials** • **Processes** for developing advanced materials	• Understanding the **structures and properties** of various materials • **Knowledge about metals, alloys, ceramics, semiconductors, and composites**	• Mechanical properties of advanced structural materials • Casting and Weld **Process Technology** • Smelting and **resource recycling** • Solving **environmental problems**.

Survey of Current Resources Available

We have reviewed the content of some online resources for MS&E teaching. These included:

DoITPoMS, *Dissemination of IT for the Promotion of Materials Science***,** a freely available teaching resource created by the Materials Science Department of Cambridge University (2017). It offers teaching and learning packages, lecture demonstrations, a library of micrographs and short videos.

ASM International offers an extensive library of Micrographs, Phase diagrams, Crystallographic structures and Failure Case Studies (ASM International, 2017).

F*A*C*T, the Facility for the Analysis of Chemical Thermodynamics, created by Ecole Polytechnique and McGill University in Montreal (Bélisle, 2015), provides thermodynamic data for engineering alloys and compounds.

MATTER is a resource for Materials Science created by the University of Liverpool (MATTER, 2015).

These all cover important parts of MS&E but cannot act as integrating tools for general materials teaching. A previous small survey of actual needs and priorities for MS&E databases among teaching professors (Fredriksson, 2015) can be useful for guidance.

Survey of Needs and Priorities

Table 3. Outcome of survey concerning critical preferences of data tables in EduPack (n=10)

3. Considering your needs and competition with alternative tools on the market (critically), would data tables on the following properties be valuable to you?

Alternatives explained:

Yes=Valuable, or **No**=Not valuable enough (no need/added value)

	[*frequency*]	
Suggested Data Tables for a Level 2 Database	***Yes***	***No***
1 Microstructure Processing Data Table (heat treatments etc.)	[10]	[ ]
2 Materials Characterization and Testing (SEM, Tensile testing, etc.)	[6]	[2]
3 Micrograph Images Data Table (Optical/SEM etc.)	[10]	[ ]
4 Phase Diagram Data Table (Binary alloys)	[7]	[2]
5 Crystal Structure Data Table (Images etc.)	[6]	[3]
6 Functional materials in the MaterialUniverse (piezoelectric etc.)	[7]	[3]
7 Nanomaterials Data Table (1D, 2D, 3D etc.)	[5]	[3]
8 Material Failure Data Table (Case Studies etc.)	[7]	[1]
9 Your own suggestion: ***Thermodynamic Data, Case studies on manufacturing progress ratio***		

We conclude from this (non-comprehensive) background research that, although large databases of ***phase diagrams*** and ***micrographs*** are available, these are focused on research and are likely to be overwhelming to students rather than engaging. A resource that connects the two together and provided a sensible journey/narrative through the material by way of ***microstructure processing***, such as heat treatments, is still needed. Data on ***material properties***, such as the functional materials, were also found desirable.

Results

The Existing Software Platform

The methodology for (linked) materials and process selection was originally developed to support the basic steps in the technical design process, suitable for engineers. It is implemented in the CES EduPack platform and it is described extensively elsewhere (Ashby, 2016). The tools available, to store, find, display, compare, link and use materials data work equally well with other types of data; indeed, they have been used to create databases as widely diverse as French wines, Sustainable Development and Garden plants.

The structural hierarchy of the software is shown schematically in Figure 3. It is based on a set of high quality *Data tables* that are maintained and expanded in a way that is not reliant on academic funding for long-term stability. The second tier, *Visualization* (the ability to make property *Charts*) is part of the software framework and provides opportunities for better understanding of data. New advanced and interactive software *Tools* enable material selection and Eco Audits (streamlined environmental life-cycle investigations). Projects based on the use of the software meet many of the assessment criteria of ABET accreditation and the CDIO Syllabus.

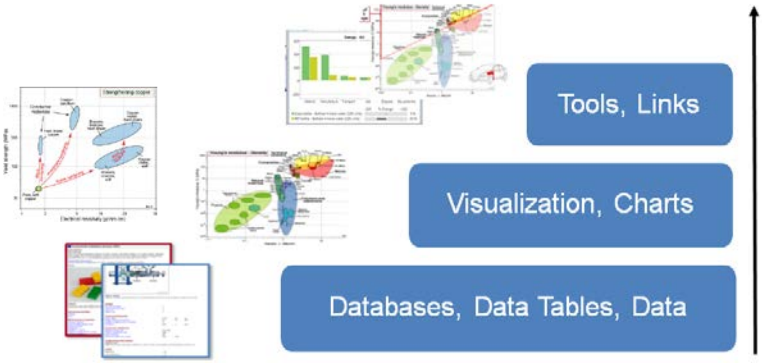

Figure 3: Structural hierarchy of the software: Data as the basis, Visualization to enhance understanding and Tools or Links to make decisions in creative tasks, such as design

The Materials Science and Engineering Extension

Based in part on the work described in the *Background and Methodology* section above, we have developed a prototype add-on database to support the teaching of MS&E, schematically illustrated by the tetrahedral icon at the centre of Figure 4. The database contains a set of linked data-tables (outer ring of Figure 4) that connect key information and concepts from the atomic to engineering scale, from processing to performance, and from science to application, spanning the spectrum displayed in Figure 2. These concepts were all identified in the survey as being of underlying importance in the teaching of MS&E. Some data-tables are expanded versions of those already found in the basic (Level 2) database of the software; others are unique to the MS&E Package.

The **Materials** and **Processes** data-tables lie at the heart of the set. The first contains data records for the properties of structural, functional and biological materials. The second gives access to data records for shaping, joining and finishing processes, with schematics and images of processes. The **Elements** data-table contains data records for the basic properties of the elements of the Periodic Table; they are linked, where appropriate, to records in the other tables giving one-click access to relevant fundamental atomic properties. The **Phase Diagrams** data-table contains 14 of the most common binary phase diagrams. The **Process-Property Profiles** data-table allows the effect of processing on properties to be explored and the associated **Structure and Mechanism Notes** give insight into structural changes that are used to manipulate properties.

The Homepage (Figure 4), acts as an interactive portal to the data-tables and the associated student resources and tools.

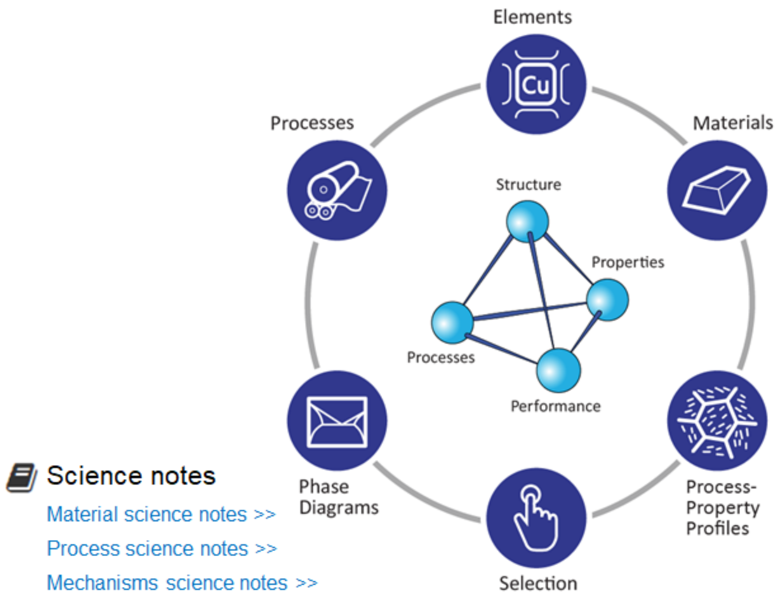

Figure 4: The data-structure of the MS&E database. This schematic appears as the Home Page of the database. Clicking on any one of the six icons activates that component of the database

The content, in more detail, takes the following form:

The **Elements data-table** provides fundamental data about the elements of the Periodic Table: nuclear, electronic, atomic and crystallographic data, and mechanical and thermal properties, environmental characteristics as well as global geo-economic and criticality standing. It is linked to the other data-tables giving direct access from their records to the relevant element-records.

The **Materials data-table** has the same format as the Level 2 Materials database, with two major expansions. They are:

- Records for **functional materials**, including magnetic, magneto-caloric, piezo/pyro/ferroelectric, semiconducting and thermoelectric materials.
- Records and data for **biological materials**, including molecular building blocks, natural fibres, tissues (both soft and mineralized), woods and wood-like materials.

The **Process data-table** contains records for 109 shaping, joining and surface treatment processes with schematics and images of the processes as well as their data and text descriptions. For engineers, a cost model allows the costs of alternative processes to be compared. Links between Materials and Processes allow selection of materials by their processing options and vice-versa.

The **Phase Diagram data-table** gives access to phase diagrams for 14 of the most widely used engineering alloys. There is also a tool to explore microstructures of selected phases.

The **Process-Property Profiles data-table** illustrates control of properties by processing. It contains seven sets of records chosen to illustrate how processes such as alloying, heat treatment, mechanical working, sintering and foaming, change mechanical, thermal and electrical properties. These can be visualized in trajectory charts.

Comprehensive sets of **Science Notes** are accessed from the Home Page (Figure 4, bottom left). They give background to material properties, to processes attributes, and to the mechanisms that underlie properties and the way processes change them.

Summary and Conclusions

As outlined above, we have used initial research and feedback to create a prototype add-on structure for a potential Material Science and Engineering teaching resource based on CES EduPack. This database combines information on microstructure processing, binary phase diagrams and Functional- and Nanomaterials added to the existing data on engineering structural materials and processes in the software. It takes advantage of the interactive and visual information, and the linking of data tables, already available in the software.

The database is already a working prototype, but the tools could be further developed and improved, for example, an extended phase diagram tool or processing-property visualizer, to name a couple of possibilities, with details still to be determined from user feed-back.

In conclusion, the authors hope that this paper and subsequent interaction, will give us the opportunity to better understand Materials Science and Engineering teaching in Universities, what resources are already in current use and what new resources would be most valued. Our next step is to encourage people to give feedback and comments on our new resources. This can be contributed at: http://teachingresources.grantadesign.com/databases-development-ongoing/material-science where also the latest development of this database is posted.

References

Ashby, M.F. (2016). *Materials Selection in Mechanical Design (5th edition).* Oxford, UK: Butterworth Heinemann.

Fredriksson, C., Melia, H., Cesonis, J., *An Introductory Teaching Resource for Materials Science and Engineering*, Proceedings of the 2015 ASEE Annual Conference, Seattle (USA), June 14-17, 2015

ASM International. (2017). Retrieved, September 1, 2017, from http://www.asminternational.org/materials-resources/online-databases

Bélisle, E. (2017). The Facility for the Analysis of Chemical Thermodynamics. Retrieved, September 1, 2017, from http://www.crct.polymtl.ca/fact/

Granta Design. (2017). Retrieved, February 1, 2015, from http://www.grantadesign.com

MATTER. (2015). Retrieved, February 1, 2015, from http://www.matter.org.uk

University of Cambridge. (2015). Dissemination of IT for the Promotion of Materials Science (DoITPoMS). Retrieved, September 1, 2017, from http://www.doitpoms.ac.uk