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MATERIALS EDUCATION IN THE NEW CENTURY - Experience in Creating an Interdepartmental Materials Science and Engineering Program

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ABSTRACT

We describe new challenges and emerging approaches in Materials Science and Engineering (MSE) education. The discussion is based on the lessons learned from establishing a successful college-wide interdisciplinary MSE undergraduate program combined with a university-wide graduate materials program at the University of California, Riverside (UCR). The undergraduate program uniquely integrates materials education and research with the five departments in the Bourns College of Engineering (Bioengineering, Chemical, and Environmental Engineering, Computer Science and Engineering, Electrical and Computer Engineering, and Mechanical Engineering). The undergraduate curriculum addresses Processing, Structure, Properties, and Performance relationships, but also connects the program and students with other engineers who are the end-users of materials. A partnership with other engineering departments further prevents the MSE from being narrowly focused, as is commonly observed in a small department, or when a program is embedded in another department. The development of MSE at UCR included hiring faculty with joint appointments both in a home engineering department as well as in MSE. These new hires, together with the participating faculty from departments, are responsible for curriculum development and teaching classes to a mixed group of students from the home department and the MSE program. This collaborative approach not only pedagogically benefits educational outcomes but also provides efficiency and cost-saving by utilizing or modifying existing courses and laboratories. The graduate MSE program, introduced a couple of years after the undergraduate program, expands across engineering boundaries and, in addition to five engineering departments, involves two other departments (Physics and Astronomy, and Chemistry) from the College of Natural and Agricultural Sciences. The experience of creating and administering the MSE program at UCR indicates that the partnering approach allows for efficient incorporation of inputs from the end-users, scientists, and engineers of various disciplines in educating materials professionals to meet the challenges of broadening and expanding the field of materials.

Keywords: *materials science and engineering; education; interdisciplinary; program development*

1. IMPORTANCE OF MATERIALS, NEW TRENDS AND IMPLICATIONS FOR MATERIALS EDUCATION

Throughout history, materials have played a prominent role in the economic development and quality of life of humans, tribes, and nations. In many situations, the security and defense of nations also have depended on the availability and optimal use of materials. It is because of this recognition that historical periods have been named after materials – Stone Age, Bronze Age, and the Iron Age. In the early days of civilization, the major expectations from materials were the performance of individual materials as dictated by their mechanical properties. As such, the early dependence was on ceramics, glasses, natural polymers, and their composites. The straw bricks were made by sun-drying mixtures consisting of mud and reinforcing straws or twigs. This situation, however, changed when humans discovered bronze, which replaced earlier tools and weapons. The discovery of bronze enabled military and technological domination. The reliance of humans on copper alloys continued until their dominance for structural and weaponry applications was supplanted by iron and steel, which are much stronger. Since then, the discovery and use of different materials and their composites have continued in an accelerated fashion[1].

As technological development progressed, the demand for materials applications expanded to be used for electrical, optical, thermal, chemical, and biological purposes, to name a few. The expansion also motivated Materials Education to become broad-based, requiring materials knowledge at the fundamental level as well as engineering[2-5]. Increased emphasis on cost, weight, size, and energy dissipation reduction, while still improving product performance, created additional challenges for monolithic materials, as well as opportunities for composites, heterostructures, nanostructures, and other new materials[6-21]. Miniaturization of the electronic components was frequently limited by the interactions of dissimilar materials at a microscopic and nanometer scale. That required incorporation of substantial solid-state physics background into materials education. As such, a materials engineer must now be able to optimize the overall performance of complex systems involving numerous materials. The latter requires a fundamental understanding of the properties and performance of each of the competing materials. Environmental concerns during the life cycle of materials – from raw materials to production, use and disposal – as commonly referred to from cradle-to-grave, have become additional features to consider in their selection and design. Indeed, environmental considerations must also be incorporated into materials education.

The creation of new technologies and industries in today's world begins with the introduction of innovative materials. Some examples include the birth of the semiconductor industry with the introduction of transistors or superalloys that enabled high-performance turbo-superchargers and aircraft turbine engines operating at elevated temperatures. The introduction of new materials has enabled tremendous progress in electronics. Materials replacements, such as aluminum with copper in interconnects or silicon oxide with hafnium oxide as the gate dielectric, have drastically increased chip speed and energy efficiency while allowing for continuous miniaturization of the electronic components and increased integration densities. The progress in photovoltaic and thermoelectric energy conversion is also mainly associated with the introduction of new materials. The increasing global competition for raw materials and energy resources makes the Materials Science and Engineering (MSE) field and major particularly relevant and timely. The US trade in goods with high-technology content, which includes advanced materials and products based on advanced materials, is currently in deficit[22]. Substantial efforts in educating a workforce with interdisciplinary expertise in MSE are needed to address this situation. Today Materials Practitioners need to have a well-grounded materials education, spanning the full spectrum from basic sciences to practical applications of materials. They need to have in-depth knowledge of materials behavior and performance. At the same time, MSE education needs to be broad and interdisciplinary. The latter is particularly important for promoting innovation and creating a culture that produces new ideas and new applications.

The modern-day MSE education further needs to have strong connectivity to the customers and end-users of the materials. Historically, MSE education has evolved from traditional metallurgy, ceramics, and polymer research– a trend that started in the 1970s. Today, around 75% of degree-granting programs have accreditation in Materials Science and Engineering, with the rest accredited in Materials Engineering, Metallurgical Engineering, or other similarly named areas[23]. The shift to a broad-based MSE has created additional opportunities for materials graduates to deal with a range of products used in skyscrapers, to computer chips, implants, and medical devices. At the same time, the broadening of MSE has created challenges of covering both breadth and depth of the field in a nominally four-year undergraduate program.

The broadening of MSE has also led to the question of how to define MSE: is it *a discipline or a multidisciplinary field of study?* Or as stated by Robert Cahn[24] in "The history of physical metallurgy and materials science", materials science was "like a tangle of jungle creepers, hanging heavily between disciplinary trees". To educators, the main concern was how to replenish the curriculum content with broader scientific subjects without eliminating traditional disciplinary topics[25]. To address such concerns, a recommendation emerged from a study conducted by the National Research Council (NRC) in 1989, that undergraduate programs in MSE fields should cover the four basic elements — synthesis and processing, structure, properties, and performance — and on the relationships among them[26]. The four core elements were depicted by a tetrahedron. In terms of manpower and educational needs, the study further recommended that undergraduate Materials Education be centered in materials departments. However, these departments should interact strongly with other science and engineering departments to develop an interdisciplinary materials-related educational program. The NRC report also identified MSE as an intellectually exciting field crucial to the success of U.S. industries, economies, and defense. Nevertheless, a decade later it was reported in another NRC report that it takes many years to introduce new material in place of an existing one[27]. This lengthy time delay applies to all classes of materials from metals to ceramics and polymers, as exemplified by the 59 years it took for synthetic rubber to increase its market penetration from 10 % to 90 %. A similar lengthy delay is also observed among other industrial sectors from transportation to semiconductors, as well as primary materials producers. To shorten the cycle, the report recommended that the MSE community must explicitly link to the end-users and suggested changing the tetrahedron definition of MSE to a pentahedron, with the fifth apex representing end-users needs and constraints (see Figure 1).

While the above-mentioned NRC studies successfully defined the broadened field of MSE, they did not specifically consider the connection between materials design and manufacturing, particularly the use of information technologies in the creation of products or systems. This subject was covered by a follow-up NRC report in 2004 entitled *Retooling* Manufacturing: Bridging Design, Materials, and Production[28]. One of the present authors, RA, was on the committee producing the report. The term "manufacturing" in the report was used to cover the activities broadly from synthesis to processing and manufacturing that are required to conceive a product that will meet the needs of customers, apply them at a systems-level, repair or upgrade them as needed, and eventually retire or recycle them. In other words, the terminology covered the entire life cycle of a material from cradle to grave. The report further recommended the integration of information technology to enable designers and overcome incompatibilities, as well as incorporating non-technical aspects of manufacturing, such as program management, managerial methods, and incentives necessary for the selection of best materials and design technologies.

In 2011, the U.S. government announced the Materials Genome Initiative (MGI), which tasked the scientific and engineering communities to accelerate the pace of materials discovery, design, and deployment by synergistically combining experiment, theory, and computation in an integrated, high-throughput manner[29]. Despite the above-mentioned educational and training expectations, the enrollment in standalone MSE departments remains rather small compared to other science and engineering fields as shown in Table I, which is based on the data presented in the MGI report[30]. The low enrollment, (1.4 % of all undergraduates) makes it difficult to justify hiring faculty as more and more universities adopt enrollment-based budgeting, commonly called Responsibility Center Management (RCM), rather than strategic investment-based budgeting. To address the low enrolment numbers, some institutions have chosen to eliminate or combine materials departments with other departments in engineering or sciences – a major shift in trends and perceptions from forty years ago. Affiliating MSE education with other departments or disciplines may unavoidably affect the overall focus and educational content.

Table 1: Total number of degrees awarded in 2017 for fields that impact the MGI workforce

	Bachelors	**Masters**	**Doctoral**
Total	138,203	51,872	14,200
Materials, %	1.4 %	2.6 %	6.2 %
Chemical Engineering	13,327	2,441	1,169
Chemistry	15,123	2,557	2,990
Civil Engineering	16,398	6,993	1,246
Electrical Engineering	25,715	17,978	2,669
Materials Engineering	1,968	1,371	877
Math and Statistics	25,808	10,294	1,925
Mechanical Engineering	32,747	8,386	1,498
Physics	7,117	1,852	1,826

Notwithstanding the enrollment challenges, MSE programs serve a unique role of being the focal point for campus-wide materials research and education activities besides educating its graduate and undergraduate students. Today MSE is among the most interdisciplinary fields in science and engineering that can influence the quality of research and education in other disciplines. Furthermore, because of their small size and intense research focus, MSE departments and programs can be excellent test-beds for new ideas in interdisciplinary settings.

It should be emphasized that MSE also plays a critical role in manufacturing and technology development and competitiveness of existing and new industries. Lack of emphasis on materials can lead to loss of competencies and markets. For example, according to the Semiconductor Industry Association "the share of global semiconductor manufacturing capacity in the U.S. has eroded from 37% in 1990 to 12% today[31], mostly because other countries' governments have invested ambitiously in chip manufacturing incentives and the U.S. government has not." The federal investments in research pertinent to semiconductor chip technologies were held flat as a share of the gross domestic product, while other countries have ramped up research investments[32]. The situation may change soon since, in the United States Government Fiscal Year 2021, Congress enacted the CHIPS for America Act in the National Defense Authorization Act (NDAA). Maintaining America's global leadership in chip and related materials technologies would require not only enhancement of research and development in electronic materials, but also a new cohort of engineers with Material Science and Electrical Engineering backgrounds. The latter should create a strong motivation for the university leaders to invest in MSE and relevant facilities for nanofabrication, cleanrooms, and microscopy equipment. Finally, the National Science Board's report "The Engineer of 2020" has called on the engineering community to accommodate innovative developments from non-engineering fields, and find ways to focus the energies of the different disciplines of engineering toward common goals. Indeed, materials can provide the focal point for all engineers, as evidenced by the continuation of innovative approaches to attract and educate the best and brightest to the field[33-38].

2. CREATION OF THE UCR MATERIALS SCIENCE AND ENGINEERING PROGRAM

In 2007, initiating the MSE education at the University of California, Riverside (UCR), we adopted a concept of the interdepartmental program as opposed to the materials department or materials group housed in an existing department. From the beginning, it was decided that the interdepartmental program would better reflect the broad interdisciplinary nature of MSE education and research. The undergraduate MSE program involved partnership (co-ownership) with five existing departments at the Bourns College of Engineering (BCOE), in a balanced way (see Figure 1). The balanced partnership approach was meant to avoid the MSE program being narrowly focused under the influence of a host department. An important consideration was efficiency and cost-saving by joint hiring of faculty and utilizing courses and laboratories that already existed and were offered by the participating departments.

The conceptual novelty of the MSE program at UCR in terms of the core elements of materials science and engineering was the evolution from the pentahedron concept proposed by the NRC. The UCR model includes engineers from various disciplines as crucial end-users to better connect materials education with end applications. This concept enables students to incorporate the fundamentals of the materials structure-properties-processing-performance relationship early in their education, and throughout their degree program. It also allows students to fully appreciate the increased value of the materials on their integration in an engineering system, rather than being produced and marketed as a standalone material. Indeed, except for a few specific uses, materials become more valuable based on their functionality. The interdepartmental structure of the program allowed to naturally incorporate this modified concept in MSE education. Moreover, since the program collaborated with all five engineering departments and used the elements of their curriculum, MSE students had more interactions and expanded professional networks with other engineering students. The senior design projects also involved interdisciplinary teams. For example, an MSE student with an interest in electronic materials would work in a senior design team with electrical engineering, learning from them the end-user needs for electronic devices and systems. Understanding the end-user needs and constraints is important for materials engineering in selecting the right material and synthesis approaches.

The general approach and design of the undergraduate MSE program at UCR are illustrated in Figure 1. Its top panel shows a general approach where expertise required for educating students on the Processing, structure, properties, and performance relationships are provided by faculty specializing in Electrical Engineering, Mechanical Engineering, and other relevant disciplines. The bottom panel of the illustration shows the specific design of the interdisciplinary MSE program. Five departments – Electrical and Computer Engineering (ECE); Mechanical Engineering (ME); Chemical and Environmental Engineering (CEE); Bioengineering (BIEN) and Computer Science and Engineering (CSE) – provided expertise, training, and mentoring sufficient to cover all aspects of the modern MSE field.

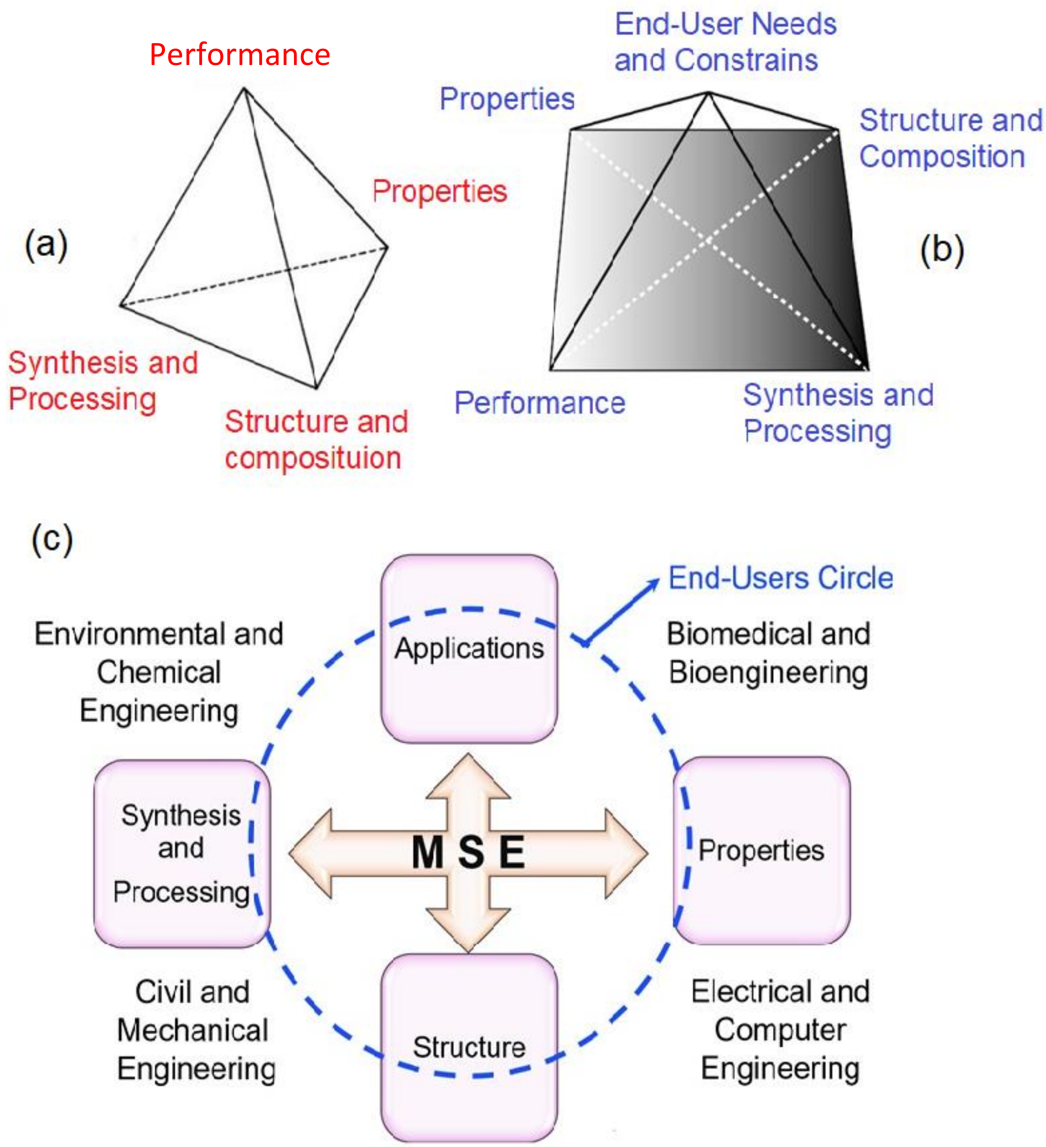


Figure 1. Multidisciplinary research and education approach for materials science and engineering programs. The top panel shows a general approach while the bottom panel shows the specific design of the interdisciplinary undergraduate MSE program at UCR. The UCR undergraduate MSE Program involved participating faculty members from all five engineering departments listed in the schematics.

An MSE Program Committee, consisting of the MSE Program Chair and one representative of each BCOE department, was formed for approval and management of the MSE Program as well as the courses within the curriculum. In the early phase of the MSE Program, the teaching faculty has been drawn from BCOE with the approval of the Dean and the Chairs of the respective departments. Most of the courses, which constituted the MSE curriculum, had already been in existence and offered regularly by different departments. However, these courses were modified to emphasize aspects of MSE and host department and were then cross-listed with MSE major following the standard UCR procedures. Therefore, the courses included in the MSE major curriculum had either specific MSE subject abbreviation (*e.g.*, an introduction MSE course for the freshmen) or the host department subject abbreviation (for example ME, CEE, etc.) or the cross-listed abbreviation (*e.g.*, ME/MSE). This approach was instrumental in the fast and efficient development of the program with minimum additional budget spending.

The resulting MSE program became truly interdepartmental. In a sense that no department acted as a single host department to MSE major students. At the same time, each participating department offered a focus area within the MSE program by designating a set of technical electives, which emphasized a certain aspect of materials science and engineering. For example, ECE was coordinating the technical electives in the focus area "electronic materials" while CEE was coordinating courses in the "materials synthesis" focus area. The UCR concept of MSE education with the participation of the engineering departments is further illustrated in Figure 2. The structure ensures that MSE is treated as the field rather than a discipline at the undergraduate level while providing a large variety of technical electives to specialize in. The students graduating with a BS in MSE with specific focus areas can also be included in the statistics of the departments responsible for this focus area.

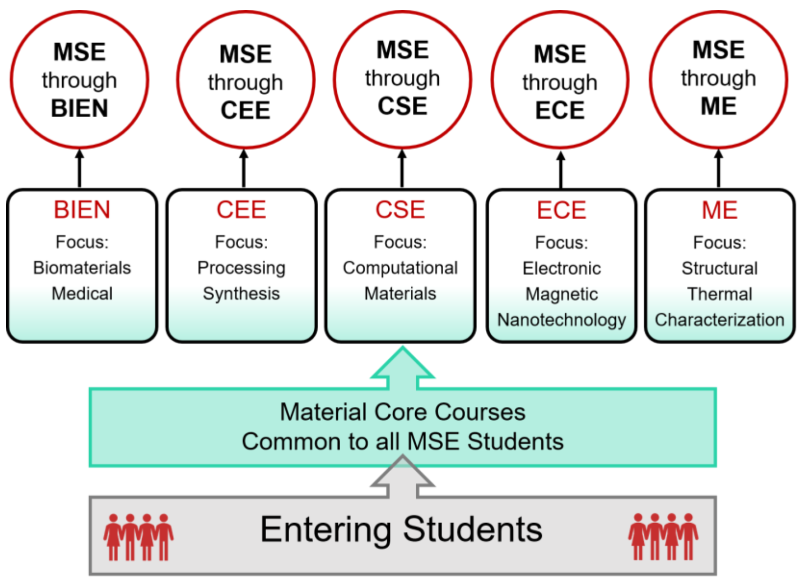


Figure 2. Structure of the UCR model for undergraduate education in materials science and engineering. Students apply directly to the MSE Program by selecting an MSE major in their application form. At the first stage, all MSE students take the same core courses. At the second stage, the students select specialization among those offered by MSE Program. Each specialization has an affinity to a particular department via participating faculty members, course offerings, technical electives, and senior design projects.

Initiating the work on designing the MSE Program at UCR, we kept in mind new developments and areas of opportunity in materials and attempted to make the curriculum responsive. From the other side, we were aware of the broadening of the field while curricula have become shorter as universities have been forced to reduce B.S. degrees to a maximum of 128 credits. As a result, subjects common in the older days of materials education are often missing from MSE curricula today. The missing subjects include Analytical Chemistry, Physical Chemistry, Statistics, Statics, Strength of Materials, Mass and Energy Balances, Deformation Processing, Thermal Processing. While some of the largest MSE departments can afford to offer many courses as electives and have enough students to justify them, smaller departments cannot. For the UCR's new program, we relied on course offerings that had mixed MSE and non-MSE participants. At the same time, these courses were broadened by introducing materials application and end-users-based topics.

During the first two years of the MSE curriculum, students take general education courses (mathematics; physics; chemistry; breadth requirements) and lower-division courses offered by the participating departments. To introduce and familiarize incoming students with the basics of materials science and engineering, a dedicated MSE course, MSE 1: Fundamentals of Materials Science and Engineering, was designed and offered. During the third year, the students took the materials core courses, which were offered jointly by all departments. There was no strict division of how many courses were to be taught by each department. Some departments, which had more faculty with the relevant expertise and existing courses, such as Mechanical Engineering, taught more than others. The materials core courses have been selected to maximize the use of the existing courses (with ME, EE, CEE, CHEME, ENVE, CSE, BIEN subject abbreviations) while covering the topics essential for the MSE program. Figure 3 shows an example MSE curriculum offered to the new coming students.

First year		
First quarter	Second quarter	Third quarter
➢ English 1A, English Composition ➢ Math 9A, Calculus ➢ Chemistry 1A/1LA, General Chemistry ➢ MSE 1, Fundamental of Materials science	➢ English 1B, English Composition ➢ Math 9B, Calculus ➢ Chemistry 1B, General Chemistry	➢ Math 9C, Calculus ➢ Chemistry 1C, General Chemistry ➢ BREADTH: Humanities/ Social Science

Second year		
First quarter	Second quarter	Third quarter
➢ Math 46, Differential Equations ➢ Physics 40A, Physics (Mechanics) ➢ BREADTH: Humanities/ Social Science ➢ Chemistry 112 A, Organic Chemistry	➢ Math 10A, Multivariable Calculus ➢ Mechanical Engineering 10, Statics ➢ Physics 40B, Physics (Heat/Waves/Sound) ➢ BREADTH: Humanities/ Social Science	➢ Math 10B, Multivariable Calculus ➢ Physics 40C, Physics (Electricity/Magnetism) ➢ Electrical Engineering 1A/1LA, Engineering Circuits Analysis ➢ Computer Science 30, Intro to Computational Science & Engineering

Third year		
First quarter	Second quarter	Third quarter
➢ Chemical Engineering 135, Chemistry of Materials ➢ Mechanical Engineering 114, Introduction to Materials Science and Engineering ➢ Electrical Engineering 138, Electrical Properties of Materials ➢ Engineering 180W, Technical Communication	➢ Mechanical Engineering 110,Mechanics of Materials ➢ Chemical Engineering 100, Engineering Thermodynamics ➢ BREADTH: Humanities/ Social Science TECHNICAL ELECTIVE	➢ Mechanical Engineering 156, Mechanics Behavior of Materials ➢ Materials Science and Engineering 160, Nanostructure Characterization Lab ➢ TECHNICAL ELECTIVE ➢ FREE ELECTIVE

Fourth year		
First quarter	Second quarter	Third quarter
➢ Statistics 155, Probability and Statistics for Engineers ➢ Materials Science and Engineering 161, Analytical Materials Characterization ➢ BREADTH	➢ Materials Science and Engineering 175A, Senior Design ➢ TECHNICAL ELECTIVE ➢ BREADTH: Humanities/ Social Science	➢ Materials Science and Engineering 175B, Senior Design ➢ TECHNICAL ELECTIVE ➢ BREADTH

Figure 3. Example undergraduate curriculum for MSE students at UCR. The vision behind curriculum development was maximum utilization of the relevant existing courses offered by participating departments via cross-listing with the MSE Program. Some of the courses have been modified to better serve students in both the department and the program.

The Undergraduate Program Committee was charged to formulate the educational objectives and outcomes of the MSE program, along with the guidelines of ABET, professional societies, and industries. The objectives were to prepare students (i) to be employed as materials engineers or in related engineering, science, or managerial positions, using and improving their skills based on the demands of the job; (ii) to enter graduate or professional degree programs; (iii) to be effective team members; and (iv) to be responsible engineers, professionals or scientists who demonstrate ethical and professional responsibility and continue to learn through a variety of educational experiences. The specific MSE Program outcomes were defined as the graduates equipped with (i) an ability to apply knowledge of the scientific and engineering principles underlying major elements of materials engineering, *i.e*., structure, properties, processing, and performance of materials; (ii) an ability to design and conduct experiments relevant to materials science and engineering, and to analyze and interpret experimental data; (iii) an ability to identify, formulate and solve materials selection and design problems; (iv) an ability to work in multidisciplinary teams; (v) an appreciation of professional and ethical responsibility and importance of continued learning after graduation; (vi) an ability to communicate effectively; (vii) a basic understanding of the impact of engineering on society, including economy and the environment; (viii) an elementary understanding of contemporary issues in materials science and engineering. Based on inputs from MSE graduates and employers, the formulated program objectives and outcomes were deemed appropriate, not requiring major modification during the first decade of the program's existence.

As mentioned earlier, one of the challenges for undergraduate MSE departments has been coverage of properties and performance of all materials and as well as incorporations of manufacturing as a continuum with synthesis and processing. The programs have required topics in humanities and social sciences in addition to basic science and engineering topics. To cover all these topics in one debarment, as listed in Figure 4, requires a large number of faculty members, which cannot be justified based on the number of students taught and based on credit hours generated. Traditionally, departments have chosen to concentrate on one class of materials, such as metals, ceramics, or polymers, or focused on teaching materials function without much emphasis on materials classes. The former refers to vertical integration within MSE, whereas the latter is horizontal.

At UCR, our approach was not to create a stand-alone materials department, but to form a partnership among engineering departments so that faculty can teach courses pertinent to both MSE and their home departments. To fully achieve this goal and refine the MSE curriculum, new core faculty members were hired with joint appointments in MSE and a home department. The expectation from the new faculty was to have their teaching responsibilities to satisfy the needs of both the department and program. The teaching assignments were scheduled by the chairs of MSE departments and the home department. With this approach, teaching productivity of the home department, *i.e*. the number of students in a class was increased with the attendance of students from the MSE Program. More importantly, pedagogically the class material had to be enhanced to satisfy the needs of both MSE and the home department. A welcoming outcome of the approach having materials practitioners and users in one class benefited both groups, even in fundamental classes dealing with thermodynamics, electronic, chemical, or mechanical behavior. Teaching to both materials practitioners and users was particularly beneficial to senior design classes as it enabled both groups to select and design with specific materials. The implementation of the MSE Program objectives and outcomes have been achieved *via* vertical and horizontal integration (see Figure 4).

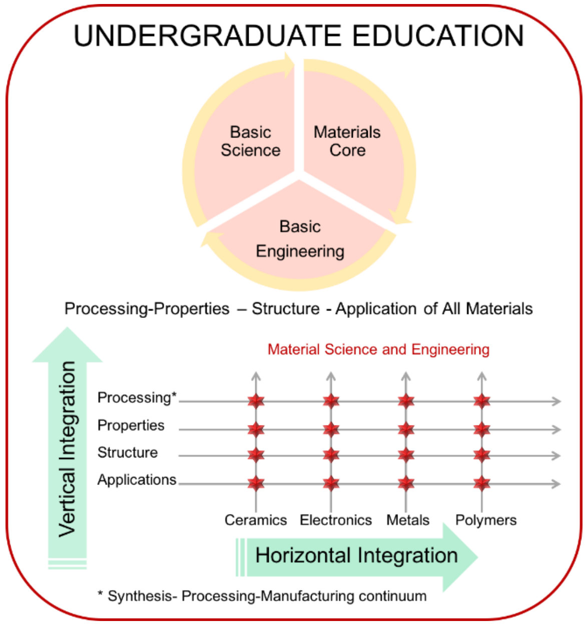


Figure 4. Schematic of the undergraduate education components in materials science and engineering, showing horizontal and vertical integration.

From the start, the BCOE departments participating in the MSE Program realized the benefits that the program would bring. Every department participated in the MSE core faculty search. The allocation of the core MSE faculty lines constituted an addition to the regular faculty lines planned for each department separately. Most of the departments welcomed the MSE faculty members who split their teaching between the department and the program. Other faculty members with materials interest are also affiliated with MSE as participating faculty members. Their affiliation enhanced MSE tremendously, as well as benefiting them when they applied for grants, specifically in areas or grants that emphasized interdisciplinary research. The program received positive reviews from peers and media. Since the program's inception in 2007, undergraduate MSE enrollment has grown relatively steadily despite strong competition from numerous other MSE departments and programs in California (see Figure 5). The first response to the US News and World Report ranking form was submitted by MSE Program in 2011. It was extremely encouraging that subsequently the two years old UCR MSE program was placed among the top 25 % – 30 % of all MSE departments and programs.

In 2012, the undergraduate MSE program was reviewed by ABET and received full 6-year accreditation. A summary of the ABET Final Statement identified that (i) The Bourns College of Engineering has developed a strategic thrust for materials-related research that permeates all departments. In so doing they promote interdisciplinary education and research in a synergistic way that enhances all aspects of research and education. This approach is innovative and appears to be benefiting the students. (ii) The program is intertwined with the other existing programs. Students develop multidisciplinary perspectives and contribute a valuable material impact to the educational experience of students in other programs. For example, students must participate in capstone design courses organized by other departments. Thus, the materials science engineering program students are prepared to be effective in the context of an engineering community at a level that is substantially above the norm.

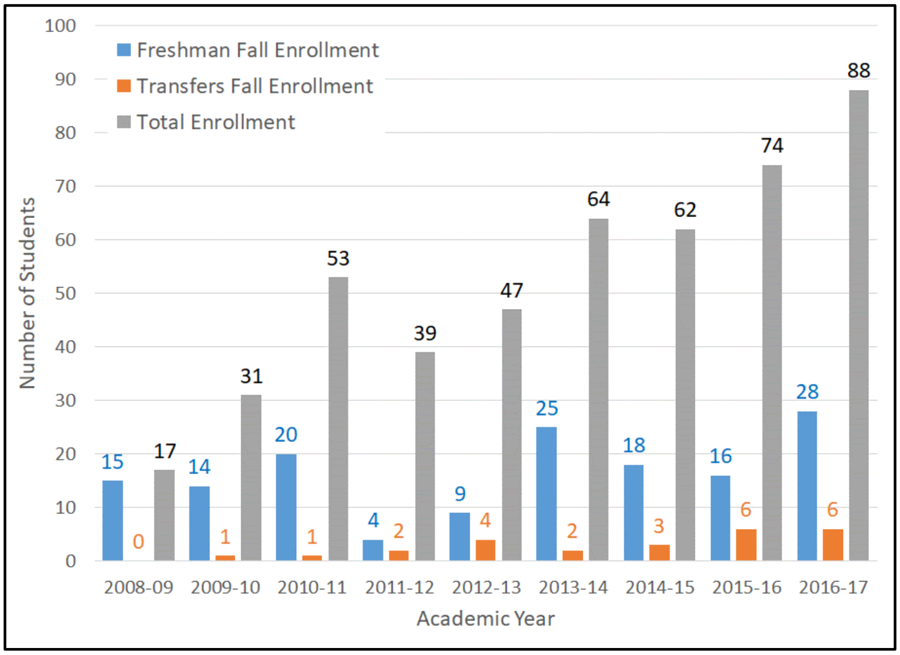


Figure 5. Undergraduate MSE program enrollment at UCR.

3. SPECIFICS OF DEVELOPING THE GRADUATE MATERIALS SCIENCE AND ENGINEERING PROGRAM

The UCR MSE Program development started with the introduction of the undergraduate degree, followed by the graduate MSE program. The graduate MSE program, introduced in 2009, went across the college boundaries, and in addition to five engineering departments, involved two most relevant departments, - the Department of Physics Astronomy, and the Department of Chemistry, from the College of Natural and Agricultural Sciences (CNAS). The campus-wide nature of the graduate MSE program was selected to enhance the research collaboration among faculty members and offer Ph.D. students a broad range of research topics and facilities. We also understood at the time that the creation of the MSE program will have a positive effect in terms of funding and graduate student recruitment opportunities for faculty both at BCOE and CNAS. A separate broad pool of Ph.D. applications, with materials or engineering backgrounds, was beneficial for a number of chemistry and physics professors. Likewise, the MSE Ph.D. applicants with solid-state physics or chemistry backgrounds were in high demand for some professors at engineering departments.

The main reason for staggering the undergraduate and graduate program implementation was that the timeline for creating an undergraduate program in the University of California (UC) system is substantially shorter than that for the graduate program. The undergraduate program approval is the campus level decision while the graduate program proposal has to be considered and approved at the UC system and even state legislative levels. The experience of running an undergraduate MSE program even for one year, before submitting an MSE graduate program proposal was extremely valuable.

To establish graduate curricula collaboratively, an MSE Graduate Program Committee (GPC) was formed which consisted of one faculty member from each participating department and the Graduate

Advisor who also served as a Chair of GPC. This Committee was responsible for overseeing courses, curricula, admission, degree requirements, administration of the student assistantship awards, and other policy matters. The role and place of the Graduate Program Committee within the MSE Program are illustrated in Figure 6.

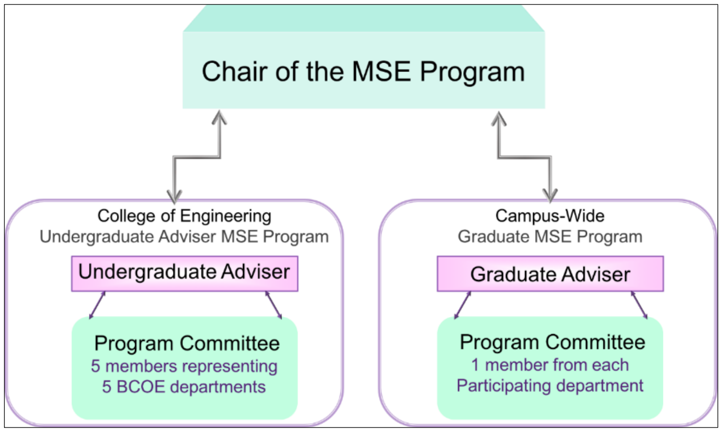


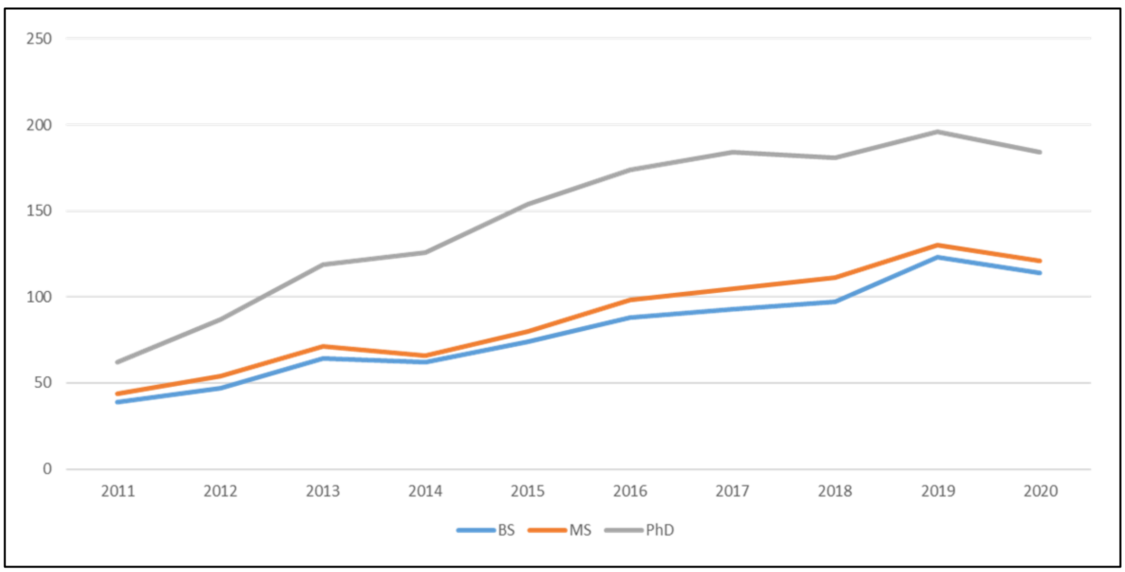
Figure 6. Structure of the campus-wide MSE Program at UCR for undergraduate and graduate education. The graduate program was approved a couple of years after the introduction of the undergraduate program.

The program offered a Master's Degree, following Plan I (with thesis) and Plan II (without thesis, but with comprehensive exam), and a Ph.D. Degree. The faculty-approved responsibilities of the Graduate Program Committee included (i) the review and recommendation of the actions on the proposed new graduate courses and changes in the existing graduate courses; (ii) recommendation of any changes in M.S. and Ph.D. degree requirements; (iii) review of the applications for admissions and providing the admission recommendations to the UCR Graduate Division; (iv) review and approval of the petitions for the advancement to candidacy for the Ph.D. degree; (v) approval of the recommended appointments for the Graduate Examination Committees, M.S. Thesis Committees, Ph.D. Dissertation Committees and submission of these recommendations to the Dean of the Graduate Division; (vi) recommendation of candidates for the graduate fellowships; and (vii) review of the teaching assistants (TA) evaluation reports from the students and faculty. The Graduate Program Committee also prepared the study plans for the entering cohort of Ph.D. students (see Figure 7).

Year in Program	Fall	Winter	Spring
1st Year	MSE 200: Survey of Materials Science (4) Colloquium in MSE (1) MSE 201: Thermodynamic Foundations of Materials (4)	MSE 202: Crystal Structure and Bonding (4) Colloquium in MSE (1) EE 202: Fundamentals of Semiconductors and Nanostructures (4)	MSE 203: Theory of Electron Microscopy and X-Ray Diffraction (4) Colloquium in MSE (1) ME 266: Mechanics and Physics of Materials (4)
2nd Year	CEE 246: Surface and Interface Phenomena (4) Colloquium in MSE (1) Directed Research (1-6)	EE 206: Nanoscale Characterization Techniques (4) Colloquium in MSE (1) Directed Research (1-6)	EE 220: Applied Ferromagnetism Colloquium in MSE (1) Directed Research (1-6)
3rd Year	Colloquium in MSE (1) Dissertation Research (8-11)	Colloquium in MSE (1) Dissertation Research (8-11)	Colloquium in MSE (1) Dissertation Research (8-11)

Figure 7. A sample study plan for Ph.D. students in MSE offered to the first cohorts of graduate students in the campus-wide MSE Program.

During the first two years of its existence, the graduate MSE Program had one Graduate Advisor who was responsible for all matters about current students and applicants to the program. The interdepartmental nature of the program, the need to coordinate with multiple department chairs, made the workload of the Graduate Advisor substantial. As a result, the workload was divided between two Graduate Advisors, one representing BCOE and another CNAS, in such a way that one advisor was responsible for the recruitment and admission and another advisor handled all questions of the current students. Together, the MSE Graduate Advisors performed the following functions: (i) chaired the Graduate Program Committee; (ii) coordinated the recruitment activities for the Graduate Program; (iii) coordinated the advising sessions for the graduate students; (iv) held orientation sessions for the incoming graduate students on various aspects of the graduate study; (v) ensured completion of annual reviews of the student performance, and (vi) provided counseling to graduate students without research advisor (*e.g.* M.S. Plan II students). From the other side, the faculty research advisors helped students with curriculum planning, research, examination preparation and provided M.S. thesis and Ph.D. dissertation supervision. The newly created MSE Graduate Program demonstrated outstanding growth (see Figure 8). This growth was exceptional as compared to other interdepartmental programs created on the campus in past years. The MSE Program successfully passed an internal review conducted by the Graduate Council during the third year of the program's existence with an external review held in the sixth year. As is the norm for all graduate programs at UCR, the MSE Program thereafter is evaluated by an outside team of experts once every six or seven years. The timeline for the program establishment and other pertinent information are given in Box 1.



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
BS	39	47	64	62	74	88	93	97	123	114
MS	5	7	7	4	6	10	12	14	7	7
PhD	18	33	48	60	74	76	79	70	66	63

Figure 8. Enrollment trend in MSE Program at UCR since its establishment.

The UCR MSE program has a different organizational structure from those at other University of California (UC) campuses, such as at UC Berkeley (UCB) UC Los Angeles (UCLA), UC Santa Barbara (UCSB), UC Davis (UCD), and UC Irvine (UCI). The undergraduate and graduate degrees in materials at UCB and UCLA are offered through the well-established and individually housed Department of Materials Science and Engineering. The materials program at UCD and UCI, on the other hand, was initially in the Department of Mechanical Engineering, and later became part of the Department of Chemical Engineering and Material Science. At UCI, materials were part of the Department of Chemical Engineering and Material Science but now is a standalone department. The Materials Science and Engineering Program at UC San Diego (UCSD) is an interdepartmental program with the participation of faculty members from several departments. In terms of its organization, the UCR program is closest to that in UCSD. However, the interdepartmental arrangement is optimum for UCR, which is a smaller campus within the UC system. It also allows the campus to capitalize on the existing research strengths and close collaboration among faculty from different departments. The UCR MSE teaching faculty are mostly the MSE Participating Faculty members who have full-time appointments at a department in BCOE and CNAS.

The creation of the MSE Graduate Program substantially increased interaction and collaboration between BCOE and CNAS faculty. Professors from the Department of Physics and Astronomy and Department of Chemistry, who were participating faculty in the MSE Program, started to actively recruit Ph.D. students who applied to the MSE program. These students had different educational backgrounds, sets of skills, and motivations, which allowed them to complement the research teams of either Physics or Chemistry major students. One of the examples of increased interdisciplinary cooperation among UCR faculty was the creation of the new Center on Spin and Heat in Nanoelectronics Systems (SHINES). The Energy Frontier Research Center (EFRC) SHINES was funded by the US Department of Energy in 2014. It was led by the Physics professor but included several professors from BCOE and involved many MSE Ph.D. students. The SHINES EFRC explored the interplay of spin, charge, and heat to control the transport of spin and energy to achieve significantly higher energy efficiencies in nanoscale electronic devices. Among many accomplishments in research and education, SHINES has published 180 peer-reviewed articles since 2014 (until April 2020), 31% of which appeared in high-impact journals. Increased publications numbers from UCR in the category of “Materials Science & Engineering” resulted in exceptionally high standing of UCR in the Shanghai Ranking (see Figure 9).

Ranking	University Name		
21	University of Chicago	217.0	
22	University of California, Santa Barbara	215.4	
23	California Institute of Technology	213.4	
24	Tohoku University	209.3	
25	National University of Singapore	209.3	NUS
26	Swiss Federal Institute of Technology Zurich	204.7	ETHzürich
27	The University of Tokyo	204.3	
28	University of California, Riverside	201.8	
29	University of Wisconsin - Madison	200.7	
30	University of Science & Technology of China	199.6	
31	Peking University	199.1	
32	University of Paris – Sud (Paris 11)	197.4	PARIS SUD

Figure 9. Shanghai Ranking in the category of “Materials Science & Engineering” for 2018, indicating UCR as number 28th in the world in this category. Other universities with close ranking are shown for comparison. The introduction of the MSE Graduate Program increased interactions among faculty from the engineering departments and natural sciences, *i.e.* physics and chemistry.

4. CONCLUSIONS AND OUTLOOK

We described the challenges and emerging approaches in materials science and engineering education in the new century. The discussion was based on the lessons learned from the creation of a highly successful interdepartmental undergraduate and inter-college graduate MSE Program at UCR We described the arguments for and against an interdepartmental program *vs.* an individual department for materials education and provided statistics illustrating the MSE program development. By its design and implementation, the UCR MSE Program embodied emerging priorities and challenges that have faced materials education since the second half of the last century. Without a major investment in a new department, and without the constraints that a department structure imposes on the range of what it can offer, the UCR MSE program draws from a wide range of disciplines, and feeds graduates into a wide range of engineering and science fields, from nanotechnology to aerospace, from energy to the sustainable technologies and environmental protection. Most significantly, the UCR MSE Program represents a novel approach to educating the next generation of engineers. The UCR MSE undergraduate and graduate programs are both interdisciplinary as it cuts across departmental and collegiate lines. The faculty from various departments and with different backgrounds participate in the program. The program development was facilitated by the fact that BCOE and CNAS already had a substantial number of faculty members who carried out experimental, theoretical, and computational research in materials science and engineering. The MSE program was designed to be complementary to the existing programs and to add to the strengths at both BCOE and CNAS. The improvement of the UG curriculum in both MSE and participating departments, enhancement of collaborative graduate training, and as well synergistic research development have been additional benefits. We hope that the experience of creating the interdepartmental UG and inter-college Graduate Materials Science and Engineering Program can help to develop approaches for future materials education and research.

BOX 1

TIME-LINE FOR CREATION AND DEVELOPMENT OF MSE PROGRAM AT UCR

- July 2005: Professor Reza Abbaschian becomes the Dean of Engineering at UCR.
- September 2006: Dean Abbaschian appoints Professor Alexander A. Balandin to chair the MSE Program Committee, which is formed with representatives from each BCOE department: Electrical Engineering, Mechanical Engineering, Chemical, and Environmental Engineering, Computer Science and Engineering and Bioengineering. The committee's charge is to prepare the proposal for the college-wide undergraduate MSE program.
- January 2007: The Founding Chair A.A. Balandin submits the MSE Undergraduate Program proposal to the campus Committee on Educational Policy for approval. The first MSE Faculty Search committee is formed to hire MSE Core Faculty members. The committee includes representatives from each BCOE department.
- May 2007: The work for creating the campus-wide MSE Graduate Research and Educational Program is initiated.
- June 2007: UCR Academic Senate meeting approves the MSE Undergraduate Program leading to B.S. degree in MSE. The program starts the student recruiting activities.
- July 2007: The first MSE Core Faculty members join the MSE Program and BCOE. Professor

Balandin is appointed the Chair of the MSE Program and charged with running the undergraduate program and developing the MSE Graduate Program. The first MSE staff members are hired.

- September 2007: MSE Program welcomes its inaugural class of 20 undergraduate students.
- December 2007: The proposal of the MSE Graduate Program is submitted for consideration to the BCOE faculty. The proposal is supported by 40 founding faculty members and chairs of the participating departments, including all BCOE departments and two CNAS departments.
- January 2008: The proposal for the campus-wide MSE Graduate Program is submitted to the Executive Vice Chancellor, the Provost, and pertinent campus committees.
- August 2009: The University of California President approves the campus-wide UCR Graduate Program leading to MS and Ph.D. degrees in MSE.
- June 2010: The first three students with a BS degree in MSE graduated. The students transferred from other colleges and/or majors.
- September 2010: The first cohort of 10 Ph.D. graduate students is welcomed by the MSE Graduate Program.
- November 2011: The first response to the US News and World Report ranking form is submitted by MSE Program. The US News and World Report favorably rank the newly created program, placing it in the top 30%, above many well-established MSE departments.
- February 2012: MSE Program moves to a new Materials Science and Engineering building.
- June 2012: MSE submit its first self-Study to Engineering Accreditation Commission (EAC)
- August 2013: MSE received its first full ABET accreditation.
- September 2017: The first MSE Board of Advisors' meeting provided feedback for further development of the program.
- July 2018: MSE submit its second self-Study to EAC.
- August 2018: Shanghai Ranking places UCR as number 28th in the world in its Academic Subjects' ranking category "Materials Science & Engineering".
- September 2019: MSE received full ABET accreditation until September 2025.

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Alexander A. Balandin

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SUPPLEMENTAL RESOURCE:

REDACTED PROPOSAL FOR THE GRADUATE MSE PROGRAM AT UC RIVERSIDE