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On the merits of a unified physics and engineering undergraduate programme of study

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Abstract

The merits of a pedagogic and programmatic unification between physics and several engineering disciplines at the undergraduate level are discussed. Arguments for such a unification are presented, based on the strong overlap of core teaching material and the similarity of career trajectories in the modern job market for physics and engineering graduates. In addition to providing a level of robustness for academic institutions against external factors such as fluctuating student intake numbers, such a merger can also have positive dividends for increased inclusion of minority and female students in STEM fields. The widespread availability and affordability of advanced laboratory equipment, computing hardware/software and other technical infrastructure at the current time is also highlighted as a reason for the practical feasibility of this approach.

Keywords: engineering pedagogy, physics pedagogy, STEM, diversity, undergraduate curriculum design

1. Introduction

The disciplines of engineering and physics, while being intimately entwined, have been socially and pedagogically treated as two distinctly different entities. This is despite the fact that the

professional definition of engineers and physicists is not very clear cut, even from the point of view of the practitioners themselves [1]. For a layperson, an engineer can conjure up the image of someone doing ‘something technical’ in the ‘real world’, while a physicist is more closely associated with a more exotic laboratory setting or a blackboard filled with equations. An indication of this difference can be seen by running a Google Image Search on the words ‘engineer’ and ‘physicist’ (sample images are not depicted here due to copyright reasons but the interested



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reader can try this out on their own). The stark contrast between these two sets of results will be quite noticeable and informative. Most images associated with the word 'engineer' will be of people wearing yellow hard hats in an industrial or construction setting. The images that show up first in the search will generally not be of famous people. Also worth noting is the fact that most of the images will be in colour. In contrast, the search for 'physicist' results in images that are predominantly of famous people (e.g. Albert Einstein, Stephen Hawking). The subjects are mostly photographed in front of a blackboard or at a lecture podium. Interestingly, many of the images will be gray-scale or black and white, indicating a stronger association of the term 'physicist' with an earlier era.

The image search results support the premise that society perceives engineering to be a modern, relatively mundane but more accessible enterprise, while physics is a more esoteric profession for a select few and is associated with ivory towers and possible celebrity status. This tangible difference has roots in historical precedent but is also due to a general lack of understanding of these professions. In many cases the term 'engineer' is erroneously thought to have stemmed from the word 'engine', implying that engineers are people who work with engines and machines. In fact both words are rooted in the Latin word *ingeniator*, meaning someone who devises or constructs in a clever manner [2]. In contrast, the word 'physics' traditionally implies an effort to understand how nature and the universe work; there is no inherent implication to build something. In reality and in the modern world however, physics and engineering are closely connected and there is a large overlap in the training and professional activities of practitioners of both disciplines. This fact has important ramifications in developing modern pedagogical approaches and teaching environments associated with these fields. Most importantly, this brings up a series of crucial questions: At the current time, should the undergraduate training of physicists and engineers be substantially different? Should the various branches of engineering be taught as distinctly separate disciplines at the undergraduate level or can they be merged to a large degree? If so, how and at which stage of the training process? Alternatively, is it

feasible to envision a unified programme of study that can be more effective in preparing students for a wider range of potential career trajectories in these related fields? In this Direction I will attempt to present a unifying perspective on these questions.

2. An overview of current pedagogical practices in physics and engineering

I will start with a general overview of current pedagogical practices for training physicists and engineers in a four year undergraduate degree program. However, since the fields associated with engineering are quite numerous, I will only cover a subset of these areas, which (in my view) are representative of a classic 'engineering' discipline. I will also avoid including disciplines which have a strong professional certification component (e.g. Civil Engineering). The selected disciplines are Mechanical Engineering Electrical Engineering (which encompasses sub-fields such as Electronics, Computer Hardware, Telecommunications, Control Systems, Power Systems, etc). This is not to say that disciplines such as Biomedical Engineering and Materials Science, etc cannot be considered for this type of pedagogical unification but due to space limits I will only focus on the aforementioned two fields.

Most traditional four-year programmes of study in these disciplines start out with a year of fundamental studies in basic mathematics and physics. Some programmes traditionally offer classes in basic engineering skills relevant to the discipline (electrical wiring, machining, drafting). The mathematics classes usually cover basic calculus, linear algebra, vector calculus, differential equations, probability, statistics and complex algebra. The physics topics are usually covered broadly (mechanics, electromagnetism, thermodynamics, etc) and are offered at a depth deemed appropriate for a general engineering audience. In many institutions all first-year engineering students sit in the same preparatory classes. Most universities offer introductory computer programming classes to all incoming students. Some also provide training in basic biology, chemistry etc.

The major differences between engineering disciplines start to appear from the second

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year onwards and continue into the third year. Electrical engineering students focus on topics such as circuits, electromagnetics, electrodynamics, signal processing and computer hardware. Mechanical engineering students, on the other hand, focus on areas such as solid mechanics, fluid dynamics, thermodynamics, materials and CAD design. Both groups are expected to take some additional advanced engineering mathematics such as partial differential equations and Fourier transforms. There may also be options to take additional classes such as modern physics or optics classes in both disciplines. In the final year a large focus is placed on technical electives and individual and group projects. The latter are strongly influenced by the research expertise of the faculty and therefore can vary drastically between institutions.

Physics students are also provided with the same fundamental training in basic mathematics and physics, however there is an implicit understanding that physics core material should be taught with more depth and rigour. Since physics departments are usually contained within science schools and colleges, other sciences (chemistry, biology, etc) are also usually presented with more prominence in physics programmes. There are also a wider range of physics-related topics to be taught, including astronomy, relativity, optics and corresponding laboratory experiments. In practice, however, the range of options is usually capped by the practical limits on the number of courses that can fit into a programme and the expertise of the department staff. Apart from somewhat different teaching conventions in some areas (e.g. Gaussian vs SI units in Electromagnetics), perhaps the most fundamental difference is that physics students are traditionally expected to take mandatory classes in quantum physics, which then leads to more advanced related topics being taught in later years, such as solid state physics. The curriculum for engineering students has not traditionally been subject to this expectation, since these topics were not expected to be relevant to most engineering practices in the past. In fact some resistance in incorporating modern physics topics into engineering curricula may still be present [3]. (Note: Students in electronic/electrical engineering are often provided with a 'lite' version of modern physics/solid state

physics in their studies, where a good deal of the fundamental physics and quantum mechanics background material is withheld by design).

In short, the traditional structures for teaching electrical engineering, mechanical engineering and physics are usually designed to provide a strong training in fundamental mathematics and physics in the first years of study followed by subsequent branching into training regimes associated with each discipline. The expectation is that each group will eventually become experts in their own discipline (i.e. electrical engineers will be proficient in electrical/electronic circuits and systems) while having some level of knowledge of the other areas. The important question is whether this pedagogic model is still optimal for the current time.

Given that most undergraduate programmes are limited to three or four years of study, the programme outlines and their differences as described above suggest that in practice, the distinction between these three disciplines (Electrical, Mechanical, Physics) lies in a small subset of classes. In principle it would be possible to envision a single cohort of students who undergo the same basic training in mathematics, physics and sciences and a common engineering core during the first two or three years of the undergraduate programme and branch off into the separate fields in the final years. Despite the apparently practical nature of this approach, the usual practice has been to divide cohorts into separate groups at the very beginning of their studies. In some cases this is implemented in an extremely granular manner for engineering disciplines, with some universities even admitting students in separate and rather narrow sub-fields of a particular engineering discipline, for example offering a bachelor's degree in electronics or control systems.

There are many reasons, historical and otherwise, as to why this pedagogical approach has been predominantly used to draw boundaries between physics and engineering (and within engineering itself). In the context of attempting to design a unified teaching programme, it is instructive and illuminating to look at these reasons. The next section suggests a few of these; some are specific to the disciplines of interest in this work but others are more general in nature.

2.1. Separation of duties and expectations

A fundamental reason for this distinction has been that engineers and physicists were generally expected to have different career trajectories and therefore had to be trained differently. Engineers were expected to be more ‘hands-on’ and practical and physicists more involved with the fundamentals and theory. While this may have been the case for a 19th or 20th century engineer or physicist, it is most likely not applicable in the current time, due to the strong overlap in career trajectories, as will be discussed in section 3.

2.2. Concerns about information overload and limited time

Concerns about information overload, especially considering the limited number of total hours that are available within any programme of study are reasonable, however it is quite possible to envision a carefully optimised curriculum that can effectively avoid this issue. For example, a close inspection of many undergraduate programmes reveals many instances of repetition; in many cases engineering and physics students are taught Fourier/Laplace transforms several times in different classes (e.g. Engineering Mathematics, Mathematical Physics, Fourier Optics, Signal Processing, Control Systems, etc) In an optimally designed curriculum this topic could be taught only once in an effective manner, thereby opening up space for teaching other concepts.

2.3. Concerns regarding breadth vs. depth

The traditional belief that aiming for in-depth training in a narrow area is superior to a broader but less-specialised training regime is still quite pervasive [4] (the proverbial ‘Jack of all trades and master of none’ argument). The issue with this view is that it assumes focussing on a specific field inherently provides depth, while a broader view is necessarily shallow. However, what is sometimes viewed as ‘depth’ in pedagogy is only the rote learning of antiquated concepts. The Karnaugh map, which is taught in electronics courses as a tool for manual minimisation of logic expressions, is a good example of this. While the Karnaugh map is a mainstay of most digital logic courses and textbooks [5] and is straightforward to teach

(and assess), it also offers very little understanding of how digital logic actually works. Moreover, it is rarely used in modern engineering practice [6], since logic minimisation can now be done through the use of widely available software tools. A similar case, arising in control systems pedagogy, is the manual plotting of root loci [7], a graphic process developed in the late 40s to investigate the behaviour of the roots of a control system in response to changes in a design parameter (e.g. gain in a feedback loop) [8]. While there may be some pedagogical benefit in the traditional practice of having students laboriously learn to plot the root loci curves by hand [9], it is questionable that this is worth the considerable time students need to put into learning this approach, given the availability of digital graphic plotting tools. However, despite the apparent disappearing role of these somewhat archaic tools in modern engineering practice, the traditionalist view is that they need to be taught in standard electronics pedagogy to achieve ‘depth’. On the other hand, as mentioned before, most electronic engineering courses often bypass the basic quantum mechanics concepts on which diodes, transistors and other semiconductor devices are built upon (in part to make room for teaching topics such as the aforesaid Karnaugh map). This eventually results in shallow treatment of many important topics, such as Bloch waves and electronic band structure in crystals. In essence, the pursuit of topics that are traditionally perceived to be important for achieving depth (but are actually out-dated and unnecessary) results in the sacrifice of important fundamental concepts (which provide actual depth).

2.4. Training students to carry out pre-determined job duties

The expectation of potential employers to have access to a pool of pre-trained graduates has been an important factor affecting the structure of educational programmes. In the past this may have been a reasonable expectation, given that employees tended to spend several years (or even their whole career) with a single employer working in a narrowly defined area. In the current time this is not necessarily the case anymore and graduates can expect a wide range of options in a dynamically changing field [10].

2.5. Targeted optimisation of the learning experience

Aiming to provide an optimal training based on the anticipated career trajectory of graduates is another reason for drawing boundaries between disciplines. In this pedagogic model the student is only subjected to teaching material that is deemed to be useful during their anticipated career. To state an obvious case, engineering students are not taught veterinary science since it is highly unlikely that they will use this in their profession (though counterexamples may exist, even for this rather extreme example, e.g. for some branches of bioengineering). Note, however, that some teaching cultures offer additional alternatives to students (e.g. the major/minor system in the USA). This notwithstanding, within the major degree the same adherence to teaching subjects perceived to be ‘immediately relevant’ to the students’ career can be observed. However, anticipating the training needs of students is not an exact science and is also likely to be influenced by the preferences and personal interests of the individuals in charge of designing the programme of study, in addition to changes in job market demands.

2.6. Concerns regarding implementation costs

The impracticality and associated expenses of providing technical resources for training all students in a large cohort to use a wide range of experimental and professional tools is another reason for limiting student numbers in a discipline. While this was truly an obstacle in the past, advances in manufacturing and the widespread adoption of technology in the past two decades has resulted in making many scientific and industrial tools available at much lower costs. An obvious example is the cost of high-performance computing. In the 50s and 60s, only a few institutions could afford to have any sort of computing capability, while at the current time multiprocessor, multi-terabyte computers and laptops are available at relatively low costs.

2.7. Marketing strategies

As suggested in the introduction, social perceptions of the physics and engineering professions

are often not grounded in reality and practice [11]. All the same, these perceptions need to be considered in the process of attempting to attract potential students (and their families, who will, in many cases, bear the burden of paying for part or all of the tuition expenses). At a higher level, governmental views of higher education activities are also affected by such perceptions, which then influence policies for supporting and funding higher education institutions. This has sometimes encouraged universities to design their programmes of study based on perceived short-term marketing drivers rather than long term (and possibly more practical/realistic) requirements. In an era of increased marketisation of academia [12] this practise is becoming more widespread, though it is questionable if such an approach will yield desirable results in the long run.

In the next section I will follow up these issues in more detail by presenting arguments as to why, at this point of time, many of the concerns mentioned above have much less impact and relevance.

3. The case for unified physics and engineering pedagogy

A well-designed unified programme of study for physics and engineering can bring about a multitude of pedagogic and administrative benefits. In particular, in the case of smaller institutions, it will provide a single umbrella programme of study, under which a large number of faculty with diverse expertise and interests can teach and carry out research. This broad diversity of talent and interests will provide robustness to internal and external disruptions to the academic landscape (e.g. retirement or departure of individual staff members, fluctuations in student numbers and their career preferences, job market demands, and changes to funding policies and priorities). Another important benefit, especially for smaller institutions is the inclusivity factor. It is an established fact that ethnic and female minorities are less represented in STEM fields [13]. Smaller cohorts of students will thereby contain even smaller numbers of these under-represented groups, which can lead to a sense of isolation and alienation [14]. On the contrary, a large unified group of undergraduates taking the same

core curriculum is more likely to contain larger numbers of incoming under-represented students, thereby leading to the creation of larger supportive social groups and structures.

From a pedagogic point of view, it is important to bear in mind that as science and technology advance, the boundaries of a basic general education also move forward, albeit with a time lag. For example, some of the maths and physics topics currently taught at the high school level were on the cutting edge or even unknown a century or two ago (e.g. matrix theory). In the 1950s access to semiconductor devices such as the transistor was only possible at specialised research facilities such as Bell Labs; nowadays a high school student can order advanced microcontrollers with a few mouse clicks. The same goes for lasers, 3D prototyping tools and advanced numerical simulation hardware and software, to name but a few. At the same time, the relevancy of some traditional skills and practices lessens with time. For example, drafting mechanical designs by hand was a valuable skill in the past; the availability of advanced CAD tools has largely replaced this practice. Therefore, it is important to have an ongoing evaluation and discussion about teaching material that can be removed from the curriculum without much negative effect and the topics which can take their place.

To be competitive, the engineer and physicist of today may need to be proficient in a wide range of skills, including CAD design, electronics, optics, digital/analog interfacing, coding, robotics, thermal analysis, image processing and the like. Even up to a few decades ago, each of these areas was traditionally a self-contained field of study and expertise. (e.g. few mechanical engineers were expected to have image processing skills; not every electronics engineer would expect to use a laser in their day to day work).

Another important driver in proposing a unified programme of study in physics and engineering is the changing employment landscape and demands of the job market. Unlike the physicist or engineer of past decades, who may have spent their entire career working for one or very few employers and within a narrowly defined area of expertise, current graduates will most likely change employers many times over the course of their career. More importantly, they

may drastically change their field of practice. For example, it would be quite normal nowadays for a physics bachelors graduate to work at a bioengineering company, then do a PhD in electrical engineering, become a big-data analyst in an investment company and after a few years switch to a government science advisory job. The same trend is present in academic higher education. Many physics PhD and Masters graduates have undergraduate degrees in engineering and vice versa. Given this type of career trajectory, it is not clear why the undergraduate training should still adhere to a rigid training regime designed along an pre-anticipated and narrowly-defined career path.

Another reason to avoid specialisation early on in the training process is that in many cases students (and their families) may not have a realistic idea about what practitioners of a certain discipline actually do on the job. As mentioned above, in some cases degree specialisations have become extremely granular, such as offering an undergraduate degree in control systems engineering. Given the strong dependence of control systems engineering on differential equations and systems theory, coupled with the fact that many incoming engineering and physics students may not have a strong background in basic calculus, let alone differential equations, one wonders if the decision to choose between control systems engineering and, say, electronic engineering or physics is an informed one in many cases.

All the above arguments suggest the positive aspects of a unified program in physics and engineering. However, there is also a large downside in actively discouraging this unification (i.e. by artificially separating the fields of study.) This has to do with the mental boundaries that are created with such a separation [15]. For example even in this day and age it is not uncommon for some engineering students to not want to learn computer programming, since they feel it is not in their expected domain of expertise [16]. Likewise, electrical or mechanical engineering students may graduate from their studies thinking that quantum physics is an exotic field that they will never become involved with, since they were effectively discouraged from studying the topic through their traditional curriculum design. However, the facts are that at the present time, most engineering

jobs require good coding skills and that quantum technologies are becoming increasingly important in both disciplines [17]. It is therefore the responsibility of the university or department to anticipate and encourage student forays into these areas, rather than to impede them by creating artificial mental barriers during their training.

4. Implementation feasibility

A reasonable question that may be raised regarding the above approach is whether such a unification is actually feasible, given the practical limits on programme duration, teaching resources and students' information retention capabilities. In this section I will offer perspectives on why I believe this is not a major concern.

Firstly, the concept of training undergraduates with combined engineering and physics expertise is not without precedent. Many universities offer crossover degrees under the titles of 'Engineering Physics' or 'Applied Physics'. The latter is usually an offshoot of a physics degree program while the former is often offered through engineering departments. In addition, the similar concept of a 'Renaissance Engineer' has been proposed [18]. While these have mainly approached the crossover by viewing it as an add-on to the original program, they nonetheless support the possibility of creating a unified pedagogical approach from the ground up. More recent developments, for example the integrated engineering programmes of study at University College London [19] demonstrate a growing interest in this type of curriculum unification.

Another possible concern is that there may not be sufficient time in the programme to effectively cover all aspects of a specific engineering or physics discipline at a required depth. In response, the first point to bear in mind is the wide career trajectory possibilities of engineering and physics graduates at the present time, as mentioned in the previous section, which advises against extreme specialisation and specificity at the undergraduate level. Secondly, and possibly more importantly, a close examination of the fundamental topics in physics and engineering unveils a large amount of overlap. For example, the mathematical model behind a simple mechanical mass-spring system and a resistor-inductor-capacitor

electrical circuit is a second order linear differential equation. There is no reason why both models cannot be introduced within one cohesive programme, rather than two disparate topics (and in fact both topics are often covered at the same time in a control systems module [7]). As another example, the electromagnetic wave equation and Schrodinger's equation in quantum mechanics share very common features, such that it has allowed researchers combine concepts from both disciplines with spectacular results (e.g. combining the concept of electron transport in crystal lattices with light propagation led to the concept of photonic crystals [20]). Thus, by leveraging overlap and links in an effective manner, a carefully designed curriculum can be created to teach the common core of topics to all students in the same undergraduate programme within reasonable time limits.

On the same note, an aspect of engineering training that traditionally used up a considerable amount of students' time within a training programme was the process of learning the specific tools and skills of each trade. For example, up to a decade or two ago, engineering students were expected to be adept in manual skills such as soldering and circuit prototyping (for electronics) and drafting engineering designs (for mechanical engineering). The nature of such activities is such that they required a large amount of practice time to gain an acceptable level of skill and dexterity. Due to technological advances, such skills no longer play a central role in an engineer's day to day work. Electronic boards and mechanical prototypes can be produced to order at an external provider without the direct involvement of the engineer. Likewise, hand-drafting of designs has given way to electronic CAD design, which is a skill that can be picked up in a fraction of the time needed to master traditional hand drafting. Such instances, together with the vast information resources provided through modern online resources means that today's students have the opportunity to gain a much broader set of skills in a set amount of time compared to their counterparts of earlier eras. As a result, the time released by not having to learn traditional skills can be then utilised for other purposes, for example acquiring a broader set of fundamental knowledge in the physics domain.

Also, advances in technology and the associated drop in equipment costs mean that instruments and resources such as oscilloscopes, lasers, optical microscopes, scanning electron microscopes, 3D printers, etc can now be made universally available to all students within a large cohort, rather than limiting them to segments of the student body. This will allow undergraduate students in a unified program to become acquainted with a wide range of tools which were previously only available to practitioners of distinctly separate professions.

Finally, in the past few decades another factor has resulted in a major paradigm shift. This is the universal availability of advanced computing environments. In the earliest years of computers, systems had to be hand-coded by specialised computer experts and the notion that an untrained physicist or engineer could become involved with this process was not initially entertained. As software packages such as LINPACK and EISPACK [21] became available, it became feasible for scientists to write their own customised simulation code using these tools. The availability of specialised and user-friendly programming environments such as Matlab® and Mathematica® further streamlined this process. In particular, the availability of specialised toolboxes in Matlab® meant that engineering-specific disciplines such as signal and image processing were now readily accessible to a wider group of scientists, including physicists. Not only did this mean that computational projects could be carried out much more efficiently, but it has also facilitated discipline hopping, for example enabling more researchers to combine physics with artificial intelligence and machine learning [22].

As another example, in recent years finite-element software packages such as COMSOL®, together with the abundance of computing power and memory storage space has enabled a ‘Multiphysics’ approach to engineering and physics endeavours. Through such modelling environments, scientists and engineers can easily build extremely realistic, detailed and cross-coupled models of systems and phenomena across a wide range of fields (i.e. structural engineering, heat transfer, electromagnetics, optics, semiconductor physics, etc) [23]. In the past, running simulation projects at this level of complexity and

multi-disciplinarity would probably have required several separate teams of experts to develop bespoke code within their respective fields of research, while with the current tools a single trained researcher can develop and link many multi-disciplinary models on their own and in a much shorter amount of time. This effectively enables an engineer or physicist to move across and combine scientific fields in a much more streamlined manner, which leads to more multidisciplinary projects, increased career flexibility and job opportunities. However, to fully benefit from the availability of this type of simulation tool it is necessary to train individuals effectively in the fundamentals of the science underlying these areas, which is another motivation for providing a broad undergraduate training in engineering and physics within a unified educational framework.

5. Conclusion

The arguments presented in this Direction highlight the fact that modern undergraduate programmes of study in engineering and physics possess a significant common content core. Moreover, the current areas of practice and career paths of graduates in physics and several engineering disciplines have significantly larger overlap compared to past decades. Therefore, at this point of time there is unique opportunity and reason to merge these programmes into a single cohesive and comprehensive programme of study. The dividends of such a merger will be far-reaching in terms of relevancy to modern career trajectories and skills requirements. It will enable schools and universities to be more agile and flexible in offering training options to students. In addition, this will positively address the challenges in student recruitment and retention in the STEM fields (especially in the case of female and minority candidates), in particular for smaller institutions, where fluctuations in incoming student numbers can even result in complete closure of schools and departments.

It is to be expected that such a change towards programme unification will meet significant resistance from adherents to the traditional pedagogical cultures of the engineering and physics disciplines. On the other hand, the increasing

number of universities and departments offering successful Engineering Physics, Applied Physics, Integrated Engineering and other similar cross-disciplinary programmes of study offers solid support for the motivation and feasibility of such a unification.

Data availability statement

No new data were created or analysed in this study.

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