Mathematical Support for an Integrated Engineering Curriculum

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Background, Goals, and Objectives. Seeking improvements over the curriculum currently in place, during the academic year 1996-97, faculty from several engineering programs and the programs of mathematics, physics, and chemistry at Louisiana Tech evaluated the integrated engineering curricula at several universities with the goal to implement a similar program at Louisiana Tech University. Upon this review it was decided to pilot an integrated engineering curriculum at Louisiana Tech University. For papers that describe experiences with integrated engineering programs cf. [Aetal], [BF], [Cetal], [FR], [Mor], and [RPC] (freshman year); [GRGG], [HM], and [RR] (sophomore year); and [CEFF] and [MW] (managing the transition to a new curriculum).

The goal was and is to build an integrated engineering curriculum that produces engineers who can function, succeed, and provide leadership in today's rapidly evolving engineering workplace. This goal is to be achieved with the same type of students who currently enter Louisiana Tech. In mathematics this means that about 5% of the students are ready for calculus, another 55% are ready for precalculus and the remaining 40% start below precalculus. The decision was made to pilot a curriculum with students that are ready for precalculus. The curriculum was to expose students to engineering from the start of and in every term during their college careers. Concurrent classes were to support each other. Intended consequences of better preparation and a streamlined curriculum are higher success and retention rates, higher quality graduates as well as shorter times to graduation.

Designing this integrated engineering curriculum is a major undertaking with many features. In this paper we will focus on two of our objectives, namely

1) The introduction of key theoretical concepts "in context", and
2) The elimination of unnecessary duplication in the curriculum.

Other features will (hopefully) be described elsewhere. We will describe how mathematical content can be re-ordered to make the necessary mathematical tools available to the students before they are needed in other engineering and science classes. The benefits to be derived from small content realignments as described here are less duplication of content in the curriculum and better student understanding of the mathematical as well as the engineering and science content. Indeed, the mathematics will be well motivated through engineering and science courses and the engineering and science courses can focus on their subject rather than ad hoc presentations of mathematics. Many of the arguments on content realignment given here are valid not only for integrated curricula, but for engineering curricula in general. We

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will show how our changes in course alignment and content alignment within courses allow for students to complete all mathematics, physics and chemistry requirements plus an engineering breadth class (such as statics and strengths of materials or circuit theory) each term within the first two years of college. For the present structure of our integrated curriculum, cf. Tables 1 and 2. It should be noted that while we consider the new alignment of content an improvement, it is by no means perfect and will be refined over the next several years. Since the first two mathematics courses are presently in further reorganization (from separate precalculus-calculus to an integrated course) and since the key shifts discussed here happen later in the sequence, we will focus more heavily on the last four mathematics courses.

The Situation at the Start. Teaching mathematics to engineers requires not only the coverage of certain topics (generally single and multivariable calculus and differential equations plus some linear algebra and statistics), but also, if one wants interdisciplinary connections between engineering and mathematics classes, the presentation of certain topics "at the right time". For example, to analyze an oscillating spring in physics one needs some higher order differential equations for the theory and some statistics for the analysis of experimental data. Typically these topics have not been covered in the calculus sequence at the time they are needed in an introductory physics class.

The reason appears to be the difference in the philosophies and work methods of engineers and mathematicians. Mathematicians build theories from a small set of common axioms (for calculus the existence of the real number system) and do not wish to leave logical gaps in the structure that is built. Based on this philosophy the development of calculus follows a fairly canonical sequence. Single variable calculus before multivariable calculus; differentiation, sequences and series before power series and power series solutions of differential equations; etc. Engineers and scientists deal with design problems and experimentally verifiable phenomena in their field. While these phenomena can be described using mathematical language, the degree of sophistication of the mathematical model varies. Experimentally the above mentioned oscillating spring is quite simple, while its mathematical description using differential equations is quite sophisticated for a beginning college student. Conversely, many problems encountered in a beginning engineering class require mathematics no more sophisticated than algebra, possibly involving vectors.

The above described difference makes the consistent teaching of undergraduate students difficult and it is one of the major challenges in designing an integrated engineering curriculum. Oversimplifying the situation the engineers' or scientists' statement will be "I need these tools NOW to enable me to adequately discuss this phenomenon", with the mathematicians' reply often being "We canNOT provide the tool YET, since the prerequisites have not been covered". Both points-of-view are valid within their respective areas. The nature of recorded mathematics is linear and logically without holes. Any change in this setup would distort the students' view of mathematics. Not to mention that teaching, say, partial derivatives without first differentiating functions of a single variable can be overload for many students. On the other hand, engineering and science courses that only tackle problems for which all mathematical prerequisites are present are potentially very uninteresting, especially in the first two years of college for students that start with precalculus.

Traditionally there are two ways of tackling this problem.

1) One can build what mathematical tools are necessary in the engineering and science classes themselves, or
2) One can delay certain engineering and science classes until after the necessary mathematical prerequisites have been taken.

Aside from the obvious benefit of formally having all mathematical tools “in place”, both approaches have their problems. Building mathematical tools “on the spot” can force students to struggle so much with the mathematics that the engineering/science content looses priority in the students’ mind and is not as well understood as it could be. Delaying classes until after their mathematical prerequisites have been taken is not an option if we are to have an engineering class every term. Moreover such delays can lead to delays in graduation or to terms in which students take only mathematics and electives. (For example, in many curricula any class that requires the use of differential equations would become a junior level class taken after the calculus sequence and differential equations.)

What “advanced mathematics” is needed when and (how) can we provide it? This is the key question for a mathematician involved in teaching engineering students. For the framework of the Foundation Coalition at Texas A&M University an answer is provided in [BF]. For a new view on the prerequisite structure of mathematics curricula, cf. [OP]. Naturally the answer will depend on the calendar of the institution as well as on the requirements of the classes to be supported. Louisiana Tech University operates on a quarter calendar, but awards semester credit hours. A typical 3 semester credit hour class meets three times a week for 75 minutes each time. The calculus sequence consists of four 3-hour classes Calculus I-IV, differential equations is a separate 3-hour course and there are two precalculus classes (precalculus algebra and precalculus trigonometry) that are both 3-hour classes. The quarter system has proven to have advantages as we move away from the traditional lecture format, since the longer class periods are more conducive to cooperative learning. For content realignment there are also certain advantages to having three terms per academic year rather than two (there are more places to shift courses to). However our key idea (the shift of two blocks of topics) should translate easily into a semester system. Our approach is characterized by the desire of staying reasonably close to traditional alignments (otherwise the amount of class materials to develop can become too large), while still achieving our goal of content integration. With the calculus sequence itself being very canonical, the idea was to shift a few key topics into the sequence, while developing calculus with a standard text ([St] at Louisiana Tech University). Thus “advanced topics” translated into “non calculus sequence topics”. In cases where it was not possible to provide the mathematical background for an engineering or science class, the engineering/science class was moved in the curriculum. The sequence ultimately conceived for students ready for precalculus or calculus is as follows

Table 1. Freshman Year Course Sequence.		
Fall Quarter	***Winter Quarter***	***Spring Quarter***
ENGR 120, 2hr, [EJMN], [FL], engineering profession, study, teaming, problem solving skills	ENGR 121, 2hr, [EJMN], [Ei], [FL], problem solving, technical reports, design project	ENGR 122, 2hr, [EJMN], [Ei], basic mechanics, electricity, energy, design project
Elective, 3 or 4hr, typically combined precalculus algebra and trigonometry using [SP]	Math I, 3hr, [St], single variable differential calculus	Math II, 3hr, [St], single variable integral calculus
Chemistry 100, 2hr, [Eb], measurement, atomic symbols, chemical formulas	Chemistry 101,103, 2hr+1hr lab, [Eb], atomic and molecular structure, bonding mechanisms	PHYS 201, Physics I, 3hr, [HRW], Newtonian Physics
English 101, 3hr, composition I	English 102, 3hr, composition II	Elective, 3hr

Table 2. Sophomore Year Course Sequence.		
Fall Quarter	***Winter Quarter***	***Spring Quarter***
ENGR 220, 3hr, [RSM], Mechanics: statics and strengths of materials	ENGR 221, 3hr, [SD], EE Applications: network theorems, AC circuits	ENGR 289, 3hr Thermal Sciences: work, heat, laws of thermodynamics, entropy, cycle processes
Math III, 3hr, [Sch], [St], Basic differential equations and statistics, multivariable differential calculus	Math IV, 3hr, [St], multivariable integral calculus, vector analysis	Math V, 3hr, [St], [Zi], sequences, series, differential equations
M&MSc 201, [Cal], 2hr+1hr lab, Materials Science	PHYS 202, Physics II, 3hr, [HRW], Electric and magnetic fields	
The remaining coursework in the sophomore year is controlled by the programs. To avoid scheduling problems, Materials Science and Physics II are optional in some programs.		

Guiding principles in the design of the course sequence were the linkage of content across the courses whenever possible and, especially in the sophomore year, the presentation of key engineering content as early as possible to allow students to start taking classes in their major. For example one goal was an alignment that would allow electrical engineering students to finish a second circuit theory course by the end of the sophomore year. Naturally the "linkage of content" vs. "as early as possible" principles present the same conflict as the philosophical conflict described earlier. Tradeoffs certainly were necessary. For example, with multivariable calculus only possible to finish in Math V in any implementation it was decided to follow up Physics I with a mechanics class, not with Physics II as is often done. Note that the mathematics sequence is essentially the precalculus, calculus, differential equations sequence with some rearrangements and some topics inserted. Interestingly enough our emerging list of needed "early non-calculus topics" obtained by analyzing the existing engineering and science classes was fairly short. The topics are

1) Separable first order differential equations,
2) Linear differential equations with constant coefficients (homogeneous and with time dependent inhomogeneity)
3) Statistics: probability, mean, variance; normal, exponential, uniform distribution
4) Interpretation of data: Central Limit Theorem, confidence intervals, hypothesis testing

Having answered the "what", the next question is where. The above topics can be presented without significant breaches in logic right after a presentation of single variable differential and integral calculus. (As seen in Tables 1 and 2, this is where the topics were inserted in the sequence.)

Indeed, the conceptual framework for a treatment of differential equations is present after single variable calculus and many texts ([St] among them) offer a short chapter on first-order differential equations at this point. Higher order constant coefficient differential equations are somewhat more problematic. To find the solution of homogeneous constant coefficient differential equations the standard approach is to set the solution up as $y=e^{\lambda x}$ and then find λ, which could be complex. Naturally for complex exponents the complex exponential function is needed, which requires knowledge of the power series expansion of e^x. With time being of the essence, it is problematic to develop sequences, series and power series at the end of Math III (largely equivalent to the second calculus of four) in order to introduce the complex exponential function and then treat differential equations. The authors' solution was to follow the path described in [La] and define $e^{a+ib}:=e^a(\cos(b)+i\sin(b))$. In this fashion a complex exponential function with the right properties is available to solve differential equations and in case of complex solutions, linearly independent real solutions can be extracted as always by taking real and imaginary parts. The series definition of the complex exponential function thus becomes a theorem later in the sequence. For another approach to linear higher order differential equations "early", cf. [HHG].

A similar picture presents itself for statistics. After discussing improper integrals the students have all conceptual tools available to understand the listed topics. There are two minor breaches in the order of presentation that the authors decided to accept.

1) Without multivariable calculus it is not easy to prove that the area under the standard normal curve is indeed 1. The formal proof was postponed to the multivariate integration part of the course (in [St] as homework exercise 30 in section 12.4) and numerical estimates were used as statistics was covered. (Formally we knew that with any precision epsilon we decided to choose the integral was within epsilon of 1.)
2) The proof of the central limit theorem is beyond the scope of all calculus and engineering statistics texts that the authors surveyed. Thus, no proof was presented by the authors either.

The only other mentionable departure from a traditional calculus sequence that we encountered was to shift coverage of sequences and series to the beginning of MathVI (equivalent to the differential equations class). This move was necessary to assure coverage of vector calculus in time for the second Physics class. Since a portion of the differential equations class was covered earlier in the sequence, no topics in Differential Equations had to be sacrificed. Notes ([Sch]) that support the early coverage of differential equations and statistics were developed by the first author and are available at [SchHP].

Sample benefits derived from the new content alignment. As the integrated curriculum is currently taught for the second time, more insights into possible content (re)alignments emerge. For example, it is more natural to present basic differential equations parallel to Physics I (impossible in the first iteration as the notes [Sch] were developed after the first year was taught). This shift is planned in the next iteration as the proposed sequence at the end shows. In the following we describe some of the alignments that seem to better support (presently and in the future) the development of needed skills in our students.

1) Functions are presented from more points-of-view than before since functions as graphical or numerical data frequently occur in the ENGR120-122 sequence parallel to the first year of mathematics. Thus students see the rule of four (verbal, symbolic, graphical and numerical presentation of topics) not just as a pedagogical principle, but see how it is necessary to translate between these presentations, as different representations occur naturally in different fields.
2) In the first physics course the concept of the derivative is reviewed and its interpretation as obtaining the velocity from position data is deepened. The definite integral is presented parallel to the first physics course and the recovery of position data from velocity data is a common topic. The idea of summing large numbers of infinitesimal quantities is ever-present in the physics class. Students thus obtain a deeper understanding of the methods and applications single-variable calculus.
3) The presentation of statistics early in the sophomore year supports the evaluation of experimental data in the laboratory components of the ENGR220-222 classes. Students will have the mathematical background to interpret experimental data at a more sophisticated level than "typical" sophomores.
4) The parallel development of vector calculus and the theory of electric and magnetic fields will allow mathematical results and physical principles to reinforce each other.
5) The planned presentation of differential equations parallel to the first physics class will allow the thorough discussion of spring-mass-systems in physics with mathematical results and physical principles reinforcing each other.

With better support for engineering and science classes through the mathematics sequence given, these classes can spend less time on mathematics and develop their subject at a deeper level. However the trade-off is not a one-way street. For example

1) Students work extensively with vectors in physics and mechanics before the subject of three dimensional vectors, dot and cross products is introduced in mathematics. Thus this re-introduction can be shortened or changed in focus. Students that know the physical applications of dot and cross products can now concentrate on more geometric interpretations (area and volume computations).
2) Uses of calculus that are more sophisticated than what can be found in a typical calculus class are shown in other classes. For example in mechanics, students had a project in which they computed how much a given light pole (aluminum, 100ft high, annular cross section, .5in thick, diameter at the bottom: 10in, diameter at the top: 7in, weight of light

assembly on the top, approx. 150lb) contracts under its own weight. Their only tools were calculus and knowledge how a rectangular parallelepiped of aluminum contracts under axial loading. The reasoning needed to set up the model is a very good exercise for sophomores.

3) Computer skills in MathCAD and EXCEL are acquired once in one engineering class and then used throughout the sequence with no (re-)introduction of packages necessary.

Preliminary Evaluation. The presentation so far was deterministic and the mutual support that courses can give each other should be evident from the presentation. With small adjustments the arguments so far should apply to a large number of institutions. While our objectives could thus be considered achieved, more fine-tuning is certainly needed. For example, in the current implementation some of the vector calculus needed in the middle of Physics II is presented at the end of Math V, i.e., some topics are in closer proximity, but not quite aligned right yet. (Also recall the pending shift of some differential equations topics to the freshman year.) Therefore further evaluations and realignments will be necessary. Another issue is to include more conceptual work with differential equations than we do currently. The designers of the first two Math courses are currently investigating the feasibility of a combined Precalculus-Calculus I course. A proposed mathematics sequence (with precalculus and calculus still separate) for our second pilot group of 120 students is given at the end of this paper. Reader's comments on further opportunities for better alignment would be appreciated.

Much harder than questions on content alignment is the question whether the new approach is more successful than the traditional curriculum. With only data from the first pilot group of 39 students available we clearly cannot draw firm conclusions as the design is not fixed yet and our sample is quite small. Tables 3 and 4 show the success and retention data for the students in the first pilot group.

Table 3: Students Earning an A, B, or C in the Integrated Program vs. the Traditional Program

	Precalculus	Calculus I	Calculus II	Chemistry I	Chemistry II	Physics I
Integrated	69.2%	92.0%	95.5%	84.6%	96.0%	87.0%
Traditional	63.2%	49.1%	36.9%	61.5%	64.3%	76.3%

Table 4: Retention data in the integrated pilot group

	Students starting	Remain integrated	Remain engineering, not integrated	Remain at Tech, not in engineering	Left school
Total	39	20	9	8	2
Women	8	3	2	2	1
Minorities	4	3	1	0	0

Success as well as retention data are encouraging. If we accept the premise that after precalculus all students should have the same basis to start calculus, then the success data in calculus is outstanding. On the other hand we are comparing a self-selected group (with probably above average motivation but ACT scores not significantly different from average precalculus eligible students) with regular calculus students (who however are mostly engineers). Thus the a priori above average motivation of the pilot group may have tilted the scales in favor of the pilot group. The high success rate in the first chemistry class might support the hypothesis that we started with stronger students. Then again the average success rate of the pilot group in precalculus shows that we may not have. On retention it is worth mentioning that most of the attrition occurred after Precalculus (only 24 students total entered Math II). Again this could be used to argue that only strong students were retained who then were able to re-enforce each other's success. The question if the students entered were above average or if the integrated curriculum "lifted them up" cannot be answered conclusively, as specific pre- and post-tests (aside from the ACT and course exams) were not administered.

The reader can easily see how the data (like most data that involve a system as complex as human nature) can be interpreted in many ways. Our concluding statements can thus only be founded on informal observations in the classroom and comparison to other classes the authors have taught. The success rate of more than 50% for the whole freshman *year* exceeds the success rate of the average calculus *course* and incidentally also the success rate of most individual classes the authors have taught. Students are very motivated in class and ask excellent questions as to how particular mathematics will be applied in engineering. At the end of a sample problem a common question is what one would do if the parameters in the original problem were different (the authors do not recall hearing this question too often in a traditional class). This special type of atmosphere is an underlying feature of the integrated curriculum that should not depend on the individual group of students. The environment in each class is geared towards discovery and the answering of "hard" questions. Thus an uncompromising quest for complete understanding becomes second nature to students fairly quickly.

Finally content integration can have surprising positive consequences. The following happened in Math III and can be seen as an incident where the content integration certainly was very successful. In the introduction of the definite integral the first author gave the students discrete velocity data and asked how to recover the distance traveled. The intent was to motivate the use of Riemann sums to lead up to the definition of the definite integral, both of which weren't formally introduced yet. One student's answer was to fit a polynomial to the data (ENGR 121), use the fact that the derivative of the position is the velocity (Math II, Physics I) and find the antiderivative (Math III) which then needs to be evaluated at the starting time and the ending time. The difference is the approximate distance traveled. Clearly this student has a good understanding of the underlying physics, the possible uses of curve fitting for approximations and the mathematics of antiderivatives. Now all the first author had to do was come up (quickly) with another way to direct the class towards Riemann sums.

Sequence of Topics AYs1998-2000, Mathematics Sequence, Integrated Curriculum, Louisiana Tech University (content may shift and change slightly in the actual implementation)		
Fall, Year 1	**Winter, Year 1**	**Spring, Year 1**
Precalculus, [SP] Ch 1 – Functions, Graphs and Models Ch 2 - Linear and Quadratic Functions Ch 3 – Polynomial Functions Ch 4 – Rational Functions Ch 5 – Exponential and Logarithmic Functions Ch 6 – Trigonometric Functions Ch 7 – Analytic Trigonometry Ch 8 – Additional Topics in Trigonometry Ch 9 – Equations of the Conic Sections Ch 10 – Linear Systems and Matrices	***Calculus, [St]*** Ch 1 – Functions and Models Representing functions, parametric curves, inverse functions and logarithms Ch 2 – Limits and Derivatives Tangent and velocity problem, limits, continuity, derivatives Ch 3 – Differentiation Rules Derivatives of polynomials, exponential, logarithm and trigonometric functions, product, quotient chain rule, implicit differentiation, linear approximation	***Calculus, [St]*** Ch 4 - Applications of Differentiation Related rates, graphing, optimization, L'Hospital's rule, Newton's method Ch 5 - Integrals Definite and indefinite integrals, fundamental theorem of calculus, substitution, integration by parts, partial fractions, numerical integration, computer algebra systems ***Differential Equations, [Sch]*** Ch 1 – Differential Equations Basic definitions, spring-mass systems, LRC circuits, solvable first order DEs (mostly separable), Euler's method Ch 2 – Linear Differential Equations Existence and uniqueness of solutions, linear independence, constant coefficient equations, undetermined coefficients, variation of parameters
Connections to All courses – data representation, problem solving, modeling (these connections emphasized throughout)	***Connections to*** Physics – velocities, acceleration	***Connections to*** Physics – spring mass systems, forces, moments, pendulum EE – differential equations that later on occur in LRC circuits

Fall, Year 2	Winter, Year2	Spring, Year 2
Calculus, [St] Ch 5 – Integrals (remainder) Areas, volumes, improper integrals ***Statistics, [Sch]*** Ch 3 – Single Variable Continuous Statistics Probability distributions and density functions, uniform, exponential, normal, Student's t Distributions, mean, variance, sample statistics, central limit theorem, measurement errors, confidence intervals, hypothesis testing, single sample t-test. ***Calculus, [St]*** Ch 9 – Vectors, Geometry of Space Vectors (review), lines, planes, functions, surfaces, cylindrical and spherical coordinates Ch 11 – Partial Derivatives 2d-, 3d-limits, partial and total derivatives, chain rule, gradient, extrema, Lagrange multipliers Ch 12 – Multiple Integrals Double integrals over arbitrary regions and in polar coordinates	***Statistics, [Sch]*** Ch. 4– Multivariable Statistics Joint distributions, independent random variables, chi-square test for independence ***Calculus, [St]*** Ch 12 – Multiple Integrals (cont.) surface area, applications (statistics, mechanics), triple integrals in rectangular, polar and cylindrical coordinates Ch 10 – Vector Functions Space curves and their derivatives, arc length, curvature, parametric surfaces Ch 13 – Vector Calculus Vector fields, line integrals, curl, divergence, Green's and Stokes' theorems, divergence theorem Ch 8 – Infinite Sequences and Series Sequences, series, convergence tests ***Statistics, [Sch]*** Ch 5 – Discrete Statistics Discrete Probability, Bernoulli, binomial, Poisson, geometric distribution, discrete hypothesis tests, normal approximations	***Calculus, [St]*** Ch 8 – Infinite Sequences and Series (cont.) Power series, Taylor series, binomial series, series used to solve differential equations (introduction) ***Differential Equations, [Zi]*** Ch 6 – Series Solutions of Linear Equations Ordinary points, singular points, Bessel and Legendre equation Ch 7 – Laplace Transform Definition, inverse transform, transforming derivatives, integrals, periodic functions, Dirac delta function, linear systems Ch 8 – Systems of Linear First-Order Differential Equations Theory, homogeneous linear systems with constant coefficients We expect to have some time left at the end of this sequence. In this time further topics could be discussed or (preferably) we will stretch the sequence a little to allow more thorough coverage of individual topics.
Connections to All courses – measurement, statistical evaluation of data Statics, Physics – moments, centers of mass	***Connections to*** Physics – vector fields, Maxwell's equations All courses – statistical evaluation of data	***Connections to*** EE – transform techniques, use of circuit theory problems as examples

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