Deconstructing (and Reconstructing) the Engineering Laboratory

J. Paul Giolma, Richard D. Swope
Trinity University

Abstract

Scientific and engineering accomplishments prior to and during World War II laid the foundation for significant changes in engineering education-- changes that were further accelerated following the successful launching of Sputnik. Courses became oriented more towards theory and analysis and the engineering laboratory changed to support those courses. Experimentation was used to illustrate fundamental and conceptually difficult physical phenomena and to provide “hands-on” experience. In this process of change, the teaching and practice of engineering design principles began to disappear from the curriculum.

Issues raised and discussed in this paper support a return to design as the primary purpose for the engineering laboratory. The issues include: the purposes and style of experimentation, the roles of simulation and the computer, pedagogical relationships between the laboratory and the lecture, the role of engineering science in support of design, and intended outcomes for students (graduate school vs. immediate career entry).

We provide an example which articulates our goals for an engineering laboratory experience: the gathering of information to support design. Design of Experiments (DOE) techniques are employed to develop a predictive relationship for the dependence of the heat transfer coefficient for a fin as a function of cross-sectional shape, material and convection air speed. The resulting prediction equation is used to design a fin to give off a specified heat rate.

Introduction

Just as the engineering profession has a long enduring and close tie with the basic sciences, the engineering laboratory has often adopted the goals, objectives and methodologies of laboratory experiences in the sciences. A compendium of goals and objectives for an engineering laboratory might look like this:

1. testing and confirmation of theoretical principles
2. gaining a familiarity with instrumentation and other equipment
3. supporting the lecture course(s)
4. experience in obtaining and reporting on data
5. “hands-on experience” and “learning by doing”
6. to gain knowledge of engineering design

This list (or components of it) appears in engineering education literature, books and laboratory manuals from the 1930s to the present, with the probable exception in the present of the last item, design. The authors feel that, except for the item regarding engineering design, the goals and objectives (and the laboratories in practice) are difficult to distinguish from those of the basic sciences. Furthermore, the lack of differentiation between the goals of the sciences and the (immediate) goals of engineering laboratories are symptomatic of historic changes in engineering and engineering education that can be seen from the beginnings of engineering education in this country to the present, but that are most evident in the period following World War II. The typical engineering laboratory of the pre-Sputnik era included a design-oriented flavor. Post-Sputnik laboratories were more science-oriented, following a paradigm of understanding and supporting theory (a principal rationale in the sciences).

In this paper, we will describe a view of engineering education (using the laboratory as a working example) that suggests that the decisions of the 1950s should be reconsidered-- that engineering design should move back to the "head of the list" as a principle factor in the education of tomorrow's engineers.

An Historical Perspective

Even in the "early" days of engineering education in this country, engineering educators were faced with defining and defending engineering as a valued and intellectual profession. Writing in 1939, D.C. Jackson described the founding of engineering programs at the University of Wisconsin in 1891-- "... (the President of the University) Chamberlin was a scientist and he had an intuitive recognition of engineering as a profession relating to the applications of the sciences as being far different from even the highest order of artisanship. He expected us to prove ourselves scientists..." [1]

Following the Allied victory in World War II, other fundamental changes began to take place in engineering education. References to the National Science Foundation (NSF) became frequent in engineering literature. In 1950, a paper in The Journal of Engineering Education expressed the view that "Under the impact of modern science... the necessary link between the 'fundamentals' and 'applications' is often missing in the instruction." [2] In 1953, the Committee on Evaluation of Engineering Education recommended for engineering undergraduates, a greater emphasis on basic sciences with design integrated over the last two years.[3]

The marvelous series of films begun in 1961 under the direction of the National Committee for Fluids Mechanics Films (NCFMF, funded by NSF) highlights the change in experimental paradigm that took place during the 1930s and was finalized during the 1950s: the films support "the lecture/textbook system," experiments depicted are "of fundamental and broad nature," ".. Out of these governing views grew a virtually new component of scientific and engineering education..." [4] While one can certainly argue that the films can provide insight required for design, engineering design is missing from the rationale for the films' production.

We have now lived for more than a generation with the engineering laboratory functioning as a laboratory in the basic sciences, and have a faculty who received their education in that environment.

Reconstructing the Engineering Laboratory

At Trinity, we are attempting to redesign our curriculum to make the infusion of engineering design concurrent with the teaching of engineering fundamentals. Our primary purpose for the laboratory is the gathering of information to support engineering design. With that purpose, experiments can still clearly meet the other goals usually associated with engineering laboratories (teach fundamentals, support the lecture, etc.). The converse (design as a sub-goal or objective) doesn't seem to function well, at least in current practice.

Placing design as the primary objective for a laboratory or for a specific experiment gives a broader sense of purpose-- the laboratory has a connection to the practice of engineering. Other issues in laboratory experimentation likewise gain a sense of greater purpose: modeling and simulation become tools for design, the lecture improves by coupling to practice, and engineering science/theory relates to both physical examples and connections to supporting design.

The style of the laboratory can greatly influence the effectiveness of our design-oriented approach. A laboratory course with relatively few experiments seems much more capable of including design principles in some depth, while a course with many short experiments (e.g. weekly) might only introduce some design principles, and those with little depth. The latter may be more appropriate for the earliest introductory laboratory courses (circuits and electronics in our present curriculum) and the former for later laboratories, taken when the student has more depth and experience in both engineering science and design.

A Working Example (Heat Transfer Laboratory)

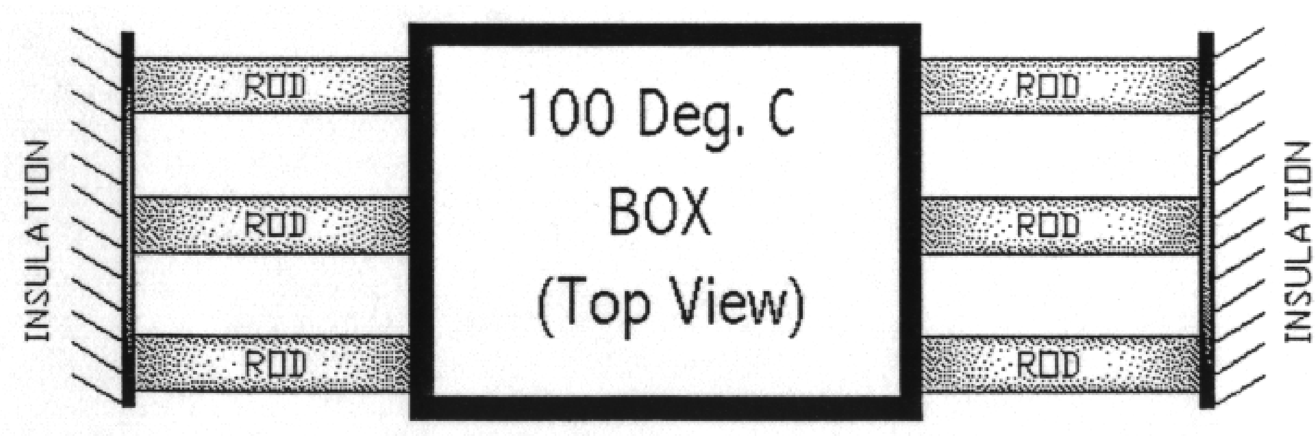
In the mid 1980's we began the transition to design oriented laboratories by formulating all of the experiments for our senior level Heat Transfer laboratory as design questions. A total of six experiments was done over the course of a semester and each was preceded by a pre-lab lecture one week before the experiments were to be done. The topics were synchronized with the lecture course which the students were taking simultaneously. The pre-lab lecture focused on the questions of what information was needed to complete the design and what experiments were needed to get that information. Background theory, instrumentation, data acquisition and analysis, and other relevant topics were presented as needed, all with an eye on the basic design requirements and constraints. It was here that we first introduced our students to Uncertainty Analysis and how it could be used to help design the experiments and select appropriate instrumentation. After the experiments were done the students were required to write up their results as either formal design reports or letter reports. We found this package contained too much material for a one credit course and the students often fell behind.

Continuing the evolution of the concept that engineering laboratories should primarily support design, we decided to include Design of Experiments (full factorial analysis), optimization and sensitivity analysis but to do so would require that we do fewer experiments per semester. We now do only three experiments in the heat transfer laboratory, one dealing with fins (illustrated below), one with forced convection over a flat plate, and one with a shell and tube heat exchanger. To accommodate the additional material, the pre-lab lectures are expanded slightly (our students have exposure to these topics in earlier courses in our design sequence). The experiments for each problem are conducted in two sessions, one week apart. The data from the first session is examined to ensure that everything is going as expected and if so the second session is used to collect a second set of data (one replication). The following example illustrates the process in detail:

A box containing electronic components is to be supported by six (6) rods as shown below in top view. In addition to providing support for the box, the rods are also to provide cooling for components located at the rod/box interface. In order to function optimally the components must be maintained at 100 ^{o}C and each rod must remove 3 $\pm$ 0.3 watts. A large supply of rods is available from another project and they all have been found to be structurally adequate. The rod materials are Aluminum and Steel and the cross-sections are either round or square (1.27 cm diameter, or 1.27 cm across the flats). Your job is to specify all of the relevant parameters for the rods (fins) so that the above heat transfer requirements are satisfied. Additional information is given below.

	ALUMINUM	STEEL
Density (Kg/m^3)	2707	7833
Thermal Conductivity (W/m ^{o}K)	167	54
Specific Heat (KJ/Kg ^{o}K)	0.87	0.465
Cost ($/Kg)	13.50	1.72

Air temperature: 0 ^{o}C,   Vertical air speed range: 0 to 2 m/s
Minimum rod length: 2 cm,   Maximum rod length: 8 cm



In the pre-lab lecture we review the solution for the temperature distribution and heat transfer in a fin (which has previously been covered in detail in the companion lecture course) and determine that we need the convective heat transfer coefficient values to complete the design. Of course, this information is available in the literature and we tell the students so. But we also explain that they will be faced with other situations where there will be no available information and they will have to do experiments to get it. The point of this "pretend" problem is to learn how to proceed when there is no other option but to go to the laboratory.

We decide to do a full factorial analysis on three factors with two levels each. This requires that we do eight distinct combinations which are done in random order. The chosen variables are material, cross-sectional shape and circulating air speed. The orthogonal design matrix shows the proper combinations to examine (see Schmidt[5]) . Based on an uncertainty analysis of two types of experiments which could be done to determine the heat transfer coefficient (steady state or transient) we decide to go with transient (see Moffat[6]). We also decide that thermocouples will be adequate for our temperature measurement needs, based on a discussion of response times and accuracy, and that one sample per minute will suffice. Data is acquired using a computer driven data acquisition system and stored for later analysis. Further, we decide that the transient cooling of the rods can be adequately analyzed using lumped capacitance methods (Boit Number < 0.1).

After all data is collected, the convective heat transfer coefficients are computed from the data. Analysis of variance is then employed to develop a prediction equation (with material type, cross sectional shape and air speed as independent variables) and error bounds for the coefficients. This information is then used in the equation for heat flow from a fin to find the best (lowest cost) performing fin. The final result is a set of specifications for the fin material, cross-sectional shape, length, and the air speed.

From the prediction equation the students find that the heat transfer coefficient is not much dependent on the material, somewhat dependent on the shape and very dependent on the air speed. The dependence on material comes from the fact that we are in fact measuring the overall heat transfer coefficient (including radiation). While small, this effect is measurable in our experiments and the result leads to a discussion of radiation which follows in the lecture course. Design, theory and experimentation are thus linked together with the result that the students learn more (we hope!) and are exposed to some connections between the sciences, mathematics, engineering sciences and engineering design.

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Biographical Information

DR. J. PAUL GIOLMA is an associate professor in the Department of Engineering Science at Trinity University and a P.E. in Texas. He received the BSEE from the University of Florida, and the MSEE and Ph.D. from Carnegie-Mellon. Since joining Trinity in 1979, he has been teaching undergraduates and performing research in energy and signal processing. Dr. Giolma is a member of ASEE, IEEE, Sigma Xi, Tau Beta Pi and NSPE.

DR. RICHARD D. SWOPE is a professor in the Department of Engineering Science at Trinity University He received the BME, MME and Ph.D. from the University of Delaware. He has been active in research in curricular design, gas bubble formation in viscous fluids, energy losses in turbines, and cardiovascular system response. He is a member of ASEE, AAUP, ASME and Sigma Xi. In 1994, he became a Fellow of ASME.