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Instruction in Experimental Methods: What Should We Be Teaching in Laboratory Courses?

David H. Bridges*
Department of Aerospace Engineering, Mississippi State University, MS 39762

An experimental methods course differs from other courses in an undergraduate aerospace engineering curriculum in that there is no standard syllabus for the experimental methods course. A discussion group within the AIAA Fluid Dynamics Technical Committee was formed to address this issue. Two invited presentation sessions and an invited paper session were held at AIAA conferences. No standard curriculum was produced by these sessions. However, a theme common to most presentations was that students should be taught to think critically about what they are doing in the lab. The largest divergence in opinion was over the "breadth vs. depth" issue. Other common themes were the importance of uncertainty analysis, signal processing, and communications skills. The results of two informal surveys conducted by some of the authors are summarized, and the laboratory courses of other authors are used as illustrations of various practices in experimental methods instruction.

I. Introduction

AN undergraduate course in mechanics of materials will probably cover axial loading, twisting, bending, and the associated stresses and strains. The topics in an undergraduate incompressible aerodynamics course will in all likelihood include potential flow solutions, thin airfoil theory, finite wing theory, and perhaps an introduction to boundary layers. It is reasonably safe to say that, to a certain degree, undergraduate courses for particular topics in aerospace engineering are standardized, at least in terms of their topical content, and that the syllabus for a particular course can be prepared almost completely simply by selecting a suitable textbook.

It would be far less accurate to say that similar standardization exists for undergraduate courses in experimental methods. There is no universally-accepted set of textbooks for experimental methods from which an instructor may choose. There also seems to be no universally-accepted model for an experimental methods course. Some institutions have a two-semester sequence of courses, while others get by with a single semester. Some institutions have laboratory experiences attached to other courses, while others perform most or all of their instructional experimentation within the confines of the experimental methods course. The topics that are covered in experimental methods courses and the specific experiments that are run probably have as many permutations as the number of undergraduate aerospace engineering programs themselves. The only constraint may be accreditation requirements imposed by ABET, the Accreditation Board for Engineering and Technology, and those are not extensive.

It was to address these issues that the author began a discussion group for instruction in experimental methods (IEM) in the Fluid Dynamics Technical Committee of the AIAA. Its purpose was to attempt to determine what should be taught in an experimental methods course or sequence of courses. Three different invited sessions were held at AIAA meetings. The first was an invited oral presentation session at the 2007 Aerospace Sciences Meeting in Reno, the second was an invited paper session at the 2008 ASM in Reno, and the third was an invited oral presentation session at the 38th AIAA Fluid Dynamics Conference in Seattle in June of 2008. This article is an attempt to distill the knowledge gained from these sessions and to pass that knowledge along to the aerospace community.

The presentations in these sessions were made by representatives from industry (Boeing, Gulfstream, United Launch Alliance), government labs (NASA Langley Research Center, Air Force Research Laboratory), and universities (Oklahoma State, Illinois, Texas A&M, Wyoming, Illinois Institute of Technology, and the U. S. Air Force Academy). Some of the participants were members of the AIAA Ground Test Technical Committee, and their presentations included input from the larger industry and government ground test community. A presentation from a researcher at NASA Langley also included input from branch heads at Langley and at NASA Glenn Research

*Associate Professor, Department of Aerospace Engineering, P. O. Drawer A, Associate Fellow, AIAA.

Center. While these papers and presentations would not be considered a "scientific survey" as such, they nonetheless cover a fairly wide range of the experimental community.

It was important for the IEM Discussion Group to obtain input from this range of experimenters, because those who teach experimental methods courses are preparing students who could wind up anywhere on the experimental spectrum. At one end of the spectrum are the design engineers, perhaps using experimental data in their designs but possibly never setting foot (or hot-wire probe) in a wind tunnel again. At the other end are those graduate students and ultimately researchers or professors who will spend the rest of their careers doing fundamental experimental research. Somewhere in between these extremes are the ground test engineers for aircraft manufacturers or research engineers in government laboratories, who are doing testing or applied research. In many universities, all of the undergraduate students will go through the same required laboratory course(s), possibly in a setting where there are no experimental methods electives past the required laboratory course or sequence. Therefore the required laboratory course must provide an adequate preparation for all of the career paths just described. It was the goal of the IEM discussion group to determine what might constitute such adequate preparation.

An undergraduate curriculum in aerospace engineering generally contains a sequence of courses that enables graduates to enter into, and eventually succeed in, one of four broad areas: aerodynamics (including propulsion), flight mechanics and controls, structures, or astronautics. In other words, we teach a sequence of courses in structural mechanics so that our graduates may (eventually) become successful structural engineers. At the same time, we teach a sequence of courses in aerodynamics so that our graduates may (eventually) become successful aerodynamicists, and so on. Of course, each student winds up in one of these areas (or perhaps crosses over into a second), but rarely does all four. The goal of the curriculum is to prepare the student adequately so that the student may choose which career path he or she would like to follow. In meetings of the IEM discussion group, it was decided that the goal of the laboratory course sequence should be no less lofty: the course or courses should prepare students to (eventually) become successful ground test engineers or laboratory researchers, thus placing the possible career path of testing and experimentation on the same level with aerodynamics, structures, etc.. This goal is reflected in the purpose statement adopted by the discussion group to serve as the organizing principle for what follows:

The purpose of a course or sequence of courses in experimental methods is to provide aerospace engineering students with a fundamental understanding of experimental methods and the experimental process such that they will be prepared for successful careers in aerospace-related physical testing or experimentation.

Again, it is recognized that not every student will wind up in a career of testing or experimentation. However, if the purpose is achieved, then every student will be prepared for such a career, and every student who does not enter such a career will have the same level of background knowledge in testing in experimentation as he or she does in the other "roads not taken." In particular, they will be able to use experimental results properly because they will be mindful of the nature and limitations of experiments.

It should be pointed out that the focus here is on the undergraduate education of students majoring in aerospace engineering. Further, in the presentations at the IEM sessions, there was a tilt toward aerodynamics and fluid dynamics and the associated testing areas and methods, particularly wind tunnel testing. This reflects in part the author's membership of the Fluid Dynamics Technical Committee, from which many of the presenters were drawn, and also the participation of members of the Ground Test Technical Committee. It also reflects the nature of the aerospace engineering laboratory courses themselves. It is likely that the syllabi of these courses contain a large proportion of wind tunnel and other fluid dynamics experiments, and relatively fewer structures or flight mechanics experiments. This is due no doubt to the very nature of fluid dynamics and its reliance on experiments for so much of its history. As will be seen, however, what came to be stressed repeatedly in the discussion group meetings and the IEM sessions were some basic principles that can applied to *any* course in experimental methods.

II. Fundamental Ideas

The one concept that was stressed again and again during these sessions and discussion group meetings was that of *critical thinking*, which should be no surprise, as it is (or should be) one of the basic goals of *any* educational curriculum. This concept was expressed in various ways, but it usually boiled down to training the students to *think* about the experiment they were about to conduct: *think* about what had to be measured (and why), *think* about what methods and equipment would be needed to acquire the required data, *think* about what was going on during the experiment, and *think* about their results – did they make sense? The most advanced expression of this concept is the discipline of Modern Design of Experiments (MDOE), a discipline advocated by a number of respondents as a "must" in an undergraduate experimental methods course. This discipline consists of rigorous procedures to ensure that the amount of *knowledge*, and not just data, obtained in the experiment is maximized and that the knowledge is obtained in an optimal manner. Statistics is a significant component of this discipline, and hence would have to be a prerequisite for the experimental methods course. A good example of MDOE applied to a particular experimental technique is given in the paper by Danehy *et al.*[1] on response-surface methods applied to optical measurements. Certainly, for those involved in production-type wind tunnel work or other projects where a large amount of information is needed in a short time on a budget, MDOE is a must. However, it is suspected that most undergraduate laboratory courses would be ill-prepared to include MDOE in their basic curriculum, as the mastery of this discipline might very well take up the majority of the course.

However, it is possible to inculcate the mindset of thoughtful experimentation in undergraduates at a level below that required by MDOE. In their paper on instruction in experimental methods, Anthony and Sondergaard[2] of the Air Force Research Laboratory (AFRL) at Wright-Patterson AFB presented a flow chart which was regarded by many in the IEM sessions as an excellent model to follow. The flow chart is shown in Fig. 1 and is explained in detail in their paper. According to the authors, "[o]ne of the biggest adjustments students have to make after leaving the classroom . . . is the task of planning and conducting their own experiments from initial concept, rather than following pre-defined lab course instructions or step-by-step direction from an instructor" (Ref. 2, p. 4). Anthony and Sondergaard believe that the flowchart can be used to assist students in making this transition.

The process can be broken down into five steps. Step One is to design and plan the experiments. This process requires the formulation of clearly-defined objectives, which can be determined by answering the questions (a) what questions need to be answered by this experiment? (b) why are these questions important? and (c) how are the objectives going to be accomplished? The answers to these questions will lead the engineer to choose the right equipment for his or her experiment, and to develop the appropriate method for acquiring the data. This will include addressing the issues of signal processing where necessary. The planning stage will also involve determining what data must be acquired, and what test conditions must be run, perhaps even requiring an MDOE-type analysis if the test is of significant size. Step Two is to implement the experiment's design. It is important in this stage to make sure that each component functions as it is supposed to, and the best way to do that is to test each component as it is added to the system. This may include an ability to use diagnostic tools for the equipment (such as an oscilloscope, for example) that may not be part of the actual test hardware itself. Step Three is to acquire data, performing diagnostic tests on the data to ensure that everything is working properly. The question to be answered here is, are the data reasonable? Anthony and Sondergaard note a primary challenge for many students entering the laboratory for the first time is the ability to independently recognize, then diagnose, and then fix unexpected problems that arise. Troubleshooting is a key part of most successful experiments. Step Four is the analysis of the data. This includes any digital filtering, spectral analysis, or other signal processing. The experimental uncertainty is determined, and results are compared with theoretical or computational predictions, if possible. Finally, in Step Five, the project must be documented properly. Assuming that everything has worked and all of the bugs have been worked out of the system, the experimenter should have useful data in hand. It is now necessary and critical that the results be reported properly (including an estimate of the uncertainty of the data). If the data can be cross-checked with theory or computational results, the better the final report will be, and the greater the confidence in the results reported.

A similar approach was presented by one of the representatives of the academic community. Edward White of the Texas A&M University presented a paper[3] describing his philosophy of IEM. In his paper, White outlined four fundamental concepts that should be emphasized in an undergraduate experimental methods course: (1) each experiment must be designed to answer a clearly-defined question; (2) instruments that make physical measurements consist of knowable components that operate based on knowable physical laws (referred to by White as the "no black box" principle); (3) every measurement is uncertain to some degree; and (4) clearly and effectively communicating experimental methodology, results and conclusions along with all the appropriate caveats is just as important as generating those results. The similarities between his approach and the approach advocated by Anthony and Sondergaard are clear: students must think about what they are doing before they start the experiment, they should be familiar with the equipment they plan to use, they should recognize the uncertainty in the data, and they should report their results properly.

One point of commonality in particular between the views presented by Anthony and Sondergaard[2] and by White[3] should be noted. The reader will note that both begin with the premise "what question is this experiment trying to answer?" The point is made that in the laboratory courses, the experiments are often categorized by the method being studied, such that the objective of one laboratory experiment might be stated as "learn how to use a hot wire." However, as pointed out in the two papers just discussed, experiments are conducted in the "real world" to answer specific questions, not to learn new techniques (unless, of course, an experimenter happens to be in the business of developing new techniques or happens to have the luxury of running an experiment specifically so that he or she can learn a new technique developed by someone else – probably a relatively rare occurrence in the "real world"). Therefore, both papers stress the approach of formulating the question. Obviously, one of the goals in the experimental methods course taught by White is to teach students about hot wires, but White frames that experiment as answering the question "what are the drag and vortex shedding frequency of a circular cylinder?" In answering that question, students are exposed to the principles and techniques of hot-wire anemometry, but in the context of a specific fluid dynamics problem in which they are using those principles and techniques to answer a specific question.

III. Breadth vs. Depth

If critical thinking is a recurring theme in education in general, then the recurring debate is between breadth and depth. This debate was reflected in the approaches presented in the IEM sessions, from both educators and employers (those industry and government testing and research organizations that employ the graduates of aerospace engineering programs). Do we attempt to teach as many different experimental methods as possible, or do we try to reinforce a few fundamental concepts of experimental methods through fewer but more detailed experimental studies? Educators have to perform a certain "trade study" between breadth and depth whenever they teach a class, in attempting to optimize the answer to the question "How much can I truly teach these students in the allotted period?" Various educators came down on opposite sides of this issue. Some felt that it was important to expose students to, and if at all possible train students in, as many experimental techniques as possible. Others felt that it was more important to educate students in a fundamental philosophy of experimentation such that they would be able to teach themselves any new techniques that they might encounter or that would be developed after the students graduated. Both viewpoints were also represented among employers. Some, including managers at NASA Langley and industry representatives, believed that it was important to train students in as many techniques as possible. Among industry representatives, this viewpoint tended to come from those representing smaller concerns, which is understandable. Those businesses need as much return as rapidly as possible from new employees, and so they would like to see their new hires ready to go from day one. Larger organizations, in which not as much is riding upon each individual, generally expressed a willingness to provide "on the job" training for new experimentalists, essentially providing them with an apprenticeship. For these employers, it was more important that the students have a solid foundation in the fundamental concepts of experimentation and data analysis.

To some degree, the first viewpoint (the "breadth" viewpoint) was represented in the findings of Burrows and Wilcox[4]. They proposed various topics that might appear in the curriculum of an experimental methods course to various members of the AIAA Ground Test Technical Committee (GTTC) and asked them to rank the topics in importance. The top five responses, in order, were (1) wind tunnel instrumentation and flow visualization (including force balances, pressure transducers, and particle-image velocimetry and DGLV measurement techniques); (2) wind tunnel test data uncertainties; (3) performance of a complete (albeit scaled-down) wind tunnel test project from beginning to end; (4) model / wind tunnel sizing, balance sizing, and loads calculations; and (5) test preparation and conduct. Noting that a number of these topics include several subtopics, one could view these five curriculum items as "(almost) everything you might need to know to conduct a wind tunnel test." There are some schools that are willing to undertake such an ambitious challenge. The new aerospace engineering laboratory sequence at Illinois Institute of Technology is an example of such a curriculum[5]. The outlines for the two semesters of the laboratory course sequence are shown in Tables 1 and 2. As can be seen from the outline, the topics cover most of the aspects and many of the techniques of wind tunnel testing. One item of interest in the second semester of the sequence is the set of experiments dealing with powered models, which, while not making the "top five" in the list compiled by Burrows and Wilcox,[4] was named by some of the GTTC respondents as an important topic in an experimental methods course.

The paper by White[3] expressed what might be considered the "opposing viewpoint." White's approach, discussed in some detail earlier, was to stress his four fundamental concepts of experimental methods. These concepts are presented, along with suitable experimental techniques, in the context of specific fluid mechanic problems. White does not necessarily argue that his fundamental concepts are the concepts that every instructor should seek to instill into his or her students. He does suggest that in determining the fundamental concepts to be stressed in the course, instructors should make sure that their students have a clear understanding of what results the experiments can be expected to provide, be able to interpret the results of those experiments critically, and be able to use experimental results correctly with full knowledge of the restrictions imposed by experimental uncertainty.

Such a set of understandings and abilities will suit well even those students who do not become experimentalists later in their careers and indeed will help the non-experimentalists to formulate the correct questions to pose to professional experimentalists, when the occasion arises. In addition to these principles, and to meet the needs of those students who will become professional experimentalists, instructors, according to White, should keep in mind that it is more important to focus on the fundamental concepts which transcend particular instruments and technologies, rather than focusing on specific details of current instruments which may soon become outdated. Students should be provided with the background in basic principles of instrumentation and experimentation that will allow them to adapt to any new instruments that they may encounter. According to White, the conceptual framework "should be a foundation that enables students to teach themselves new details of experimental practice later as needed and it should serve as a foundation for the creative design of new techniques and instruments" (Ref. 3, p. 4). Further, "the fundamental concepts should be independent of particular technologies that may become obsolete" (Ref. 3, p. 4).

Following a suggestion by White, to implement such an approach in which concepts are tied with techniques in the context of specific fluid dynamic problems, one might use a matrix such as that shown in Fig. 2. In this particular example, each specific experiment emphasizes one particular principle and one particular technique (leading to the diagonal nature of the matrix). Obviously, a particular experiment using a particular technique would probably illustrate several principles (one might use computerized data acquisition in all three experiments, for example), and so the elements on the diagonal might be expanded to form the columns of the matrix. Alternatively, as time in an experimental methods course permits, other experiments might be designed for the off-diagonal entries in the particular example shown in Fig. 2, so that various principles and/or techniques might be re-emphasized in a different context.

Thomas McLauglin, a professor at the United States Air Force Academy, also places a heavy emphasis on teaching experimental methods in the context of specific fluid dynamic problems, as opposed to running "canned" laboratory experiments to teach particular experimental methods[6]. In the program at the Academy, students in the experimental methods course are paired with faculty members involved in research on specific problems. This cadet-centered philosophy is expressed as "Let me involve you in something that I am working on to solve an Air Force problem." The experience of working on "real problems" in a "master – apprentice" relationship has been found to be highly successful in motivating students to become successful experimentalists. The course lasts only one semester and formal lectures and exercises make up only half of the course. There are only eight lectures that cover the basics of measurement techniques for forces, velocities, and pressures, and basic signal processing techniques, such as signal conditioning, filtering, and analog-to-digital conversions. For the rest of the semester, the students, in teams of two or three, work collaboratively with individual faculty members on a test plan developed by the student team and the faculty member. Recently the Academy has instituted a computational fluid dynamics laboratory course with a similar approach. There are challenges to this approach. The students are all undergraduates, with no graduate students to help share the load of mentoring the undergraduate students. There are severe time constraints, with the necessity of completing the research project by the end of the semester. Because these are funded research projects for which faculty members are responsible, this places an additional responsibility on the faculty member for guiding the project through to completion and obtaining results that further the work on the research grant or contract. McLaughlin feels that though the course is both labor-intensive and expensive, the end result – highly-motivated students who strive to succeed as experimentalists – is worth the effort and the funds.

The dichotomy of needs between small and large companies, in the context of the "breadth vs. depth" issue, was framed well by two oral presentations at the June 2008 AIAA Fluid Dynamics meeting in Seattle. One was by Thomas Wayman[7] of Gulfstream Aerospace Corporation, and the other was by Kevin Mejia[8] of ANSPD Laboratories, Boeing Commercial Airplanes. According to Wayman, Gulfstream typically needs experimental work done only as a new product line is being developed, with occasional additional needs when modifications to existing products are being studied. Gulfstream does not have its own wind tunnel facilities and therefore does not have full-time testing staff. Their testing work is contracted out to others, with at least one Gulfstream engineer overseeing the work. It is to their advantage, then, that when a test is required, assigned engineering representatives have a breadth of knowledge about experimental methods and do not require a significant amount of time to become conversant in experimental techniques. On the other hand, ANSPD Laboratories, the wind-tunnel testing group within Boeing Commercial Airplanes, routinely utilize various wind tunnels at home and abroad and typically work double shifts during production test programs, according to the presentation by Mejia. Their wind tunnels and other test facilities have relatively large, full-time staffs. During aircraft development periods which have a high volume of testing, their organization and their Aero customers can leverage this environment to do some on-the-job training of new employees, essentially providing an apprenticeship period for new engineers. However, this period is usually very brief and a new engineer's test responsibilities are expected to grow significantly in subsequent tests. It is to a new hire's benefit to learn the fundamentals of testing during their college.

IV. Common Ground

One of the goals set out for the IEM discussion group when it was started was the development of a common curriculum that might be proposed as a standard for practice. As might be concluded from the previous discussions, consensus on such a curriculum was not found, and given the viewpoints expressed, such a curriculum might not even be desirable. However, there were a few topics that did seem to show up on most lists of subjects that should be included in every experimental methods course. Interestingly enough, practically all of these topics were not specific to fluid dynamic or aerospace engineering subjects, but would apply to any course in experimental methods for engineering. The first such topic was experimental uncertainty analysis. Only the concept of thinking critically about experiments received greater support. According to Burrows and Wilcox[4], "[t]he importance of this … course cannot be underestimated. Thousands of dollars can be spent on a test project and if the uncertainty in the acquired data is unacceptable, the entire effort is wasted." Uncertainty analysis appears early in the curriculum by Williams[5] (Table 1) and is one of the few specific topics addressed in the classroom in the Air Force Academy's experimental methods course described by McLaughlin[6]. The topic was also one of the four fundamental concepts that White[3] felt should be emphasized in undergraduate laboratory courses.

Another topic that was high on the list of subjects to be emphasized, and one that also has general application, was signal processing / analysis. This was often coupled with uncertainty analysis. This was another topic that was included in the list for classroom instruction in the Air Force Academy's experimental methods course, and also appears early in the curriculum prepared by Williams. Anthony and Sondergaard[2] also emphasized this topic, coupling it with the understanding of experimental uncertainty, and White[3] folds it into his second fundamental concept, that instruments consist of knowable components. In the present author's opinion, this is perhaps the one topic area that could stand something of a standardized (or at least suggested) curriculum and a good textbook or reference, as it is generally outside the topic areas of the rest of the undergraduate aerospace engineering curriculum.

The final common topic that achieved consensus among the various groups was communication skills. According to the informal survey conducted by Danehy[9], the topic of communication skills even ranked ahead of experiments for specific subject knowledge, such as boundary layers and wake measurements. All presenters were in agreement that an engineer must be able to communicate the results of an experiment in clear, concise, and correct language, both in written reports and in oral presentations, and that these skills must be stressed in the experimental methods course. Anthony and Sondergaard[2] extended this concept to documentation of the experiment during the planning stages and while in progress. To Anthony and Sondergaard, it is important for students to learn that they should keep a detailed record of exactly what was done and why, throughout the course of an experiment, so that problems may be diagnosed more quickly should they arise and the conditions existing when a particular set of data was obtained are known.

V. The Customers Speak: Two Surveys

In this article, the author has attempted to synthesize the input from various sources, including academics, government researchers, and ground-test engineers. An attempt was made to include input from as broad a spectrum of the experimental research and testing community as possible, and this effort was helped significantly by two works that have previously been cited, the paper by Burrows and Wilcox[4] and the oral presentation by Danehy[9]. The works were helpful because those authors in turn attempted to enlist the aid of others in their technical committees and/or organizations, through informal surveys. The present author believes that given their efforts, it would be appropriate to provide at least the summaries of their surveys here, essentially supplying some of the "raw data" used in the analysis above.

Burrows and Wilcox are both members of the AIAA Ground Test Technical Committee. When they became involved in the IEM effort, they polled industry engineers and members of the GTTC, receiving responses from six experimentalists from industry and NASA. When asked to rank potential topics in an experimental methods curriculum, the experimentalists put them in the following order[4]:

1. Wind tunnel instrumentation and flow visualization (including force balances, pressure transducers, particle-image velocimetry, and DGLV)
2. Wind tunnel test data uncertainties
3. Performance of a complete (scaled-down) wind tunnel test project from beginning to end
4. Model / wind tunnel sizing, balance sizing, loads calculation

5. Test preparation and conduct (operating reports, run schedules, test logs)
6. Composition of test article Statements of Work (SOW)
7. Modern Design of Experiments (MDOE)
8. Powered model design and test techniques
9. CAD fundamentals (creation of figures, checking of part dimensions, review of drawings)

These topics are reflective of the nature of industry wind-tunnel testing and illustrate well the priorities of that community.

A similar survey was conducted by Danehy[9]. Danehy, who works in the Advanced Sensing and Optical Measurements Branch of NASA Langley Research Center, polled primarily branch heads, because they are "the people at NASA who do the hiring"[9]. Danehy received responses from five branch heads or other administrators at NASA Langley and two branch chiefs at NASA Glenn. Those polled were asked to rank in order of importance six broad topics with several subtopics under each broad topic also ranked individually. The results of the rankings and subrankings, in the order of most important to least important, were as follows (the broad topics are shown in bold):

1. **"Intangibles."** Top tier: motivation / initiative; hard worker, creativity. Second tier: a passion for aeronautics / space research; "kindergarten skills" (sharing, "playing nice," etc.); quickness / intelligence.
2. **Analysis skills**. Top tier: critical thinking about success / failures of experiment; formal design of experiments, including response surface analysis. Second tier: error / uncertainty analysis; comparison with theory and/or past experiments. Third tier: use of higher level languages such as Matlab / Mathcad / LabView for data analysis; use of spreadsheets for analyses; least squares (or other fitting techniques).
3. **Experimentation skills**. Top tier: planning or designing an experiment; interfacing with computers (A/D, control, LabView); use of laser-based instrumentation (particle-image velocimetry, laser Doppler velocimetry, planar-laser-induced fluorescence, etc.). Second tier: use of optical instrumentation; combination of off-the-shelf components into a working system to perform an experiment. Third tier: use of conventional instrumentation (force and moment, thermocouple, Pitot probe, hot wire, etc.); use of electronics; design and use of plumbing.
4. **Communication skills**. Top tier: technical writing. Second tier: informal verbal communication skills; brainstorming skills; formal oral presentation skills (including PowerPoint).
5. **Experiments for specific subject knowledge**. The experiments were ranked in the following order, but with no particularly strong preference for any: boundary layer measurements, water tunnel experiment (laminar / turbulent transition), compressible nozzle flow experiment, supersonic blowdown wind tunnel, flow visualization experiment (schlieren, smoke, etc.), lift and drag in a wind tunnel, circular cylinder wake measurements, pressure measurements on a wing in a wind tunnel, shock tube experiment.
6. **Business skills**. Ranked in order: project planning and scheduling, writing and interpreting statements of work, cost / benefit analysis, financial (procurement, costing, etc.).

The contrast between these results and those of Burrows and Wilcox presented previously is probably reflective of the differences between the activities and goals of industry ground-test organizations and government research and testing agencies. From these results and the comments associated with each response, Danehy was able to conclude that NASA expects to perform some on-the-job training of new engineers who have just completed their undergraduate degrees. According to Danehy[9], NASA "wants to hire people who are well-rounded and who understand the full research process: Design and execute experiments, analyze and report." Danehy noted the recurring theme related to the formal design of experiments, and finished with the caveat that the "survey was non-scientific, anecdotal, and had a limited base of contributors," but that its value lay in the fact that it did "provide some indication of NASA's needs and recommendations."

An individual comment from one of the participants in Danehy's survey[9] actually reflects an opinion expressed in the third item in list by Burrows and Wilcox[4] as well as, to a certain degree, the philosophy behind the Air Force Academy's experimental methods course as described by McLaughlin[6]. In the part of Danehy's survey related to analysis skills, one respondent commented that "[i]nstead of being given a prepared laboratory experiment (like I was given), a better simulation of real life research would be to have students form a hypothesis, design their own experiment, execute it, and critically analyze the results and to go through this design / execution approach several times as a student (not just once in the senior project)."

VI. In the classroom (or laboratory)

To this point, this study has focused primarily on what should be taught in the undergraduate experimental methods course. However, as every teacher knows, how these subjects are taught is extremely important. Of particular significance is the need to motivate students to learn the material being presented. The proper motivation for students was stressed in the paper by White[3] and was the foundation for the Air Force Academy's experimental methods course[6]. Three presentations by professors who teach experimental methods courses gave some excellent examples of how to motivate students in the laboratory.

Khaled Sallam teaches an experimental methods course at Oklahoma State University. The objectives of Sallam's experimental fluid dynamics course are similar to those already presented: (1) To enhance the student's understanding of fundamental fluid mechanics principles through performing basic experiments; (2) to provide the student with experience designing experiments and performing measurements; (3) to improve the student's ability to write and present reports on experimental investigations; and (4) to encourage the student to design and conduct experiments suitable for advanced research. A significant portion of Sallam's course involves the use of high-speed imaging and particle-imaging velocimetry[10]. Sallam prefers to use a combination of flow visualization, PIV imaging, and computational fluid dynamics results, because this combination of techniques, all with significant visual components, has increased the students' comprehension of what is happening in the flow, with a resulting increase in their motivation to perform meaningful experiments.

Greg Elliott is on the aerospace engineering faculty at the University of Illinois. In his presentation[11], Elliott discussed the laboratory experiences in both the freshman year and in the upper-level laboratory courses. In their AE 100 Discovery course, there is a spacecraft and rocket section and an aircraft design section, in which students are given hands-on experience in solving problems requiring design and data collection. The students build remote-control aircraft and use them to acquire data in-flight. There are two upper-class laboratory courses, a structures and controls lab and an aerodynamics and propulsion lab. In the aerodynamics and propulsion lab, the emphasis is on experimental methodologies, diagnostics, data analysis and presentation, theoretical analysis, and reporting. LabView is used extensively for data acquisition and reduction. Students use the techniques of surface pressure measurements, force balances, hot wires, and Schlieren flow visualization, and are introduced to a number of diagnostic techniques, including oil-flow visualization, planar laser-induced fluorescence, pressure-sensitive paint, and particle-image velocimetry (in the context of "micro-flows"). The primary motivating factor in these laboratory experiences, at least in the present author's opinion, was the sheer professionalism demonstrated in the set of experiments performed and techniques used by the students, as exhibited in the presentation. Elliott's presentation was in part a testament to what can be done in a large institution with sufficient resources.

Another experimental methods course with a slightly different perspective was described in the oral presentation by Naughton[12], who teaches a one-semester graduate course in experimental methods at the University of Wyoming. The course focuses on experiments involving turbulent flow. The first third of this course concentrates on core concepts, which include the reasons behind an experiment, the design of experiments in the context of turbulent flow theory, random data, filtering, uncertainty, and facilities. The second third of the course concentrates on instrumentation techniques such as flow visualization, hot-wire anemometry, and laser Doppler anemometry, among others. In the last third of the course, students are required to design and execute actual experiments. The students are expected to design the experiment, purchase and/or design the necessary hardware, carry out the experiment, analyze the data, and report the results. Undoubtedly the maturity and motivation levels of graduate students are keys to the successful execution of such an ambitious course. However, many of the themes in the context of the undergraduate courses discussed earlier are present in Naughton's course, in particular training in thinking critically about the experiment to be conducted and having the students perform specific fluid mechanic experiments such that experimental principles and techniques are taught in context.

VII. Conclusions

A well-defined curriculum for an undergraduate course in experimental methods was not produced by these sessions and discussions. Common themes that were discovered were critical thinking about experiments, the importance of signal processing and uncertainty analysis, and the ability to communicate the results of experiments clearly. Given the wide variety in experimental facilities available to instructors, it should probably come as no surprise that each will have to find his or her own path in imparting these fundamental principles to his or her students.

Not every engineering graduate will go to work in a lab or a ground test facility. Many may not have direct contact with testing or research for much of their careers. However, a fraction will, some making research and testing their lifetime avocation. While there may have been disagreement among the various others and presenters about specific emphases and approaches, there was strong agreement that the teaching of experimental methods is of critical importance, and is worthy of serious consideration, if for no other reason than for the benefit of that fraction of the graduates who will be lucky enough to find careers in research and testing,

As time and permissions allow, the presentations and papers described in this article will be available for download at https://info.aiaa.org/tac/ASG/FDTC/DG/IEM_DG.aspx .

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Tables and figures begin on the next page.

Tables

Table 1. Outline of first semester of IIT Laboratory Course Sequence (from Ref. 5)

Week	Lecture	Lab Topic
1	Intro to course -- how to keep notes in a lab notebook and write a lab report	Install Labview on computer
2	Intro to Labview programming	Write a Labview VI and acquire signal
3	Measurements and the scientific method	Processing data with MATLAB
4	Using statistics to determine uncertainty	Flow measurement with a rotameter
5	Estimating measurement error -- signal-to-noise ratio	Pressure measurements -- aircraft altimeters
6	Analog circuits I -- Ohms law, RLC	Pitot tube measure of flow speed -- airspeed
7	Analog circuits II -- Op-amps	Temperature measurements with thermocouples
8	Analog circuits III -- amplifiers and filters	High-gain amplification, biasing and filtering with op-amp circuits
9	Midterm quiz	Make up any missed labs
10	Introduction to digital circuits	Controlling high-power equipment with relays
11	Pressure and temperature measurement	Using the DIO to communicate with the oscilloscope
12	Force measurements	Force balance measurement of lift and pitching moment
13	Moment measurements	Measuring lift using surface pressures
14	Heat transfer measurements	Conductive heat transfer experiment
15	Schlieren and shadowgraph visualization	Supersonic wind tunnel experiment to observe oblique shock waves
16	Pitot tube measurements in supersonic flow	Measuring the Mach number in a supersonic wind tunnel
17	Final exam	

Table 2. Outline of second semester of IIT Laboratory Course Sequence (from Ref. 5)

Week	Lecture	Lab Topic
1	Intro to course	
2	Intro to Simulink and dSPACE	Intro to dSPACE 1004
3	Fundamentals of dynamic data acquisition I	Acquiring and displaying spectra with dSPACE (virtual spectrum analyzer)
4	Fundamentals of dynamic data acquisition II	Measuring oscillating flow speed amplitude with a hot-wire anemometer
5	Fundamentals of dynamics data acquistion III	Measuring lift characteristics of a wing
6	Designing experiments to achieve a desired level of accuracy	Flight control in a wind tunnel -- a pc-based autopilot
7	Midterm exam	Make-up lab week
8	PID controllers	PID control experiment with dSPACE system
9	State Space Control	State space control experiment
10	Midterm quiz	Make-up lab week
11	Fluid power systems I	Propulsion experiment with Jet Engine I
12	Fluid power systems II	Propulsion experiment II
13	Fluid power systems III	Fly-by-wire control of an airfoil -- part 1
14	Gyroscopes	Fly-by-wire control of an airfoil -- part 2
15	GPS fundamentals	Fly-by-wire control of an airfoil -- part 3
16		Gyroscope experiments
17	Final exam	

Figures

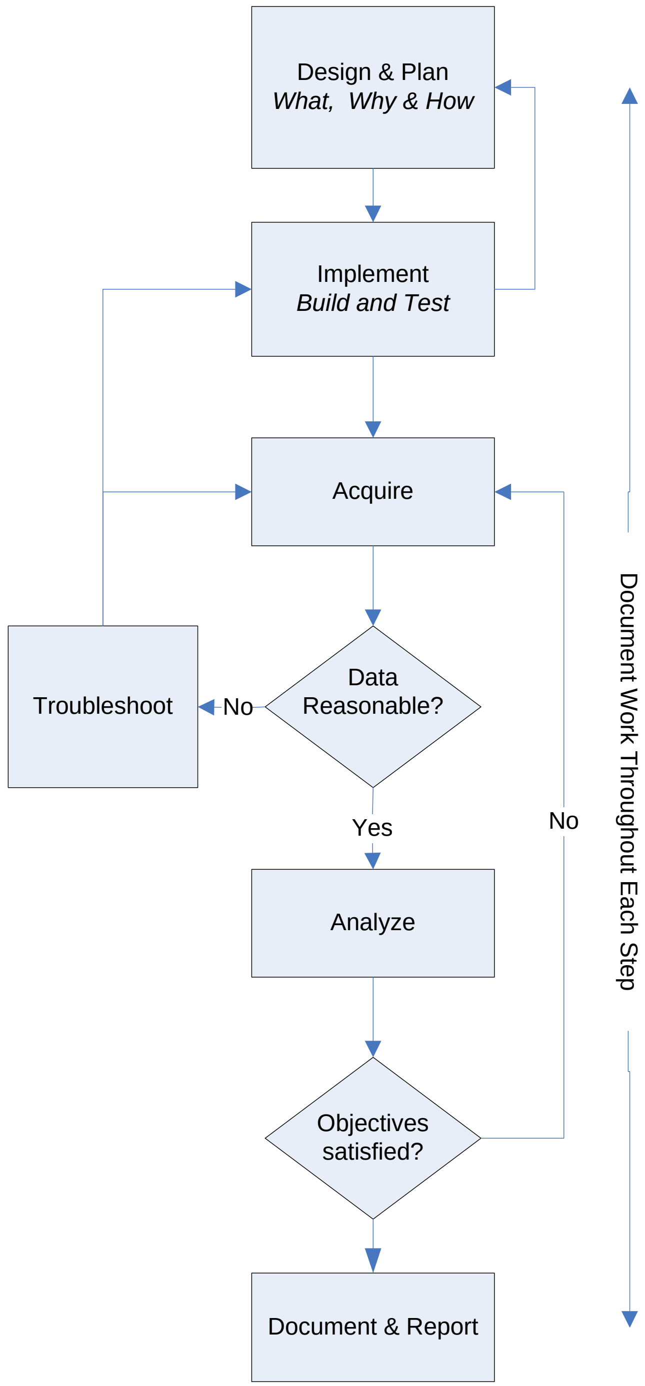

Figure 1 Experimentation planning flowchart (Fig. 7 in Ref. 2)

Principle \ Technique	Pressure transducer	Strain gauge	Hot-wire anemometer
Calibration / uncertainty analysis	**Velocity profile in pipe flow with Pitot-static probe**		
Data acquisition		**Stresses in a beam in bending**	
Signal processing			**Drag and shedding frequency of circular cylinder**

Figure 2 Instructional "grid" with specific experiments that stress particular principles and techniques