Department of Chemical Engineering
University of Virginia

GRADUATE PROGRAMS HANDBOOK

August 2017
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HOW TO SUCCEED IN YOUR GRADUATE EDUCATION

Graduate studies in chemical engineering leading to MS and Ph.D. degrees offer students an opportunity to mature to an advanced stage in their profession while contributing to the advancement of science and technology. The purpose of this note is to communicate the faculty’s perspectives on how you might do this in the most effective and satisfying manner.

Research (An article written by Professor O’Connell is attached in the Appendix for your reference.)

To be able to make useful and recognizable research advances students are expected to carry out the following independent activities:

- Reading and study. Regular reading of literature related to your research project is expected. This involves searches of journal databases and regular perusal of current issues of major journals in chemical engineering, your research area, and science and technology. You can work with your advisor to determine an appropriate list for your area of research. Looking in literature of related areas for new connections is also very valuable. ChE has provided a CHE Research Tools tab on UVA Collab for your use as well.

- Commitment. Graduate research requires your full-time dedication and year-round effort. A typical workweek will require 50-60 hours in the lab. To facilitate information exchange with others and for safety reasons, the bulk of those hours should include the period from 9 am – 5 pm Monday through Friday as much as possible. Graduate students are expected to be involved with their projects between semesters and during spring break. One week of vacation around Christmas holidays and one week during the summer is reasonable. Any periods of vacation or leave should be discussed with your advisor in advance.

- Taking ownership. Ph.D. research involves students taking “ownership” of their project. By the time students’ finish, they should have become experts in their area. They will not think they work “for their advisor,” but that they are working for THEMSELVES and their PROFESSION by being fully self-motivated to answer the questions they are working on. Another aspect of becoming an independent researcher is taking initiative in seeking advice from and discussing ideas and solving problems with fellow graduate students and faculty not only within the department, but also outside the department and University.

- Documentation. Research requires documentation of the work that is done and it is easy to forget or omit details that can prove vital to discovery or progress. Contemporaneous note-taking helps in communication, remembrance and organization. It is imperative to keep a laboratory notebook. All patents require careful documentation of the work performed, which must be signed and dated.
• **Publications** are the indicators of success and how a field progresses. Writing articles is an essential part of the graduate experience. As a result, there are expectations that a number of manuscripts will arise from a thesis or dissertation.

• **Oral presentations** are another way that research results are transmitted and are an especially good process for students to experience. They also represent an excellent opportunity to gain exposure in the field and receive feedback to one’s research. Thus, all students, especially doctoral students, should present research results at national and international meetings. Regional or local meetings are also valuable. Students should take the initiative to seek out and propose the meetings at which they wish to talk.

• **Timeline**. The target time needed for the completion of the Ph.D. is 4–5 years. To facilitate this process the Departmental policy is that advisors will expect to fund Ph.D. students making satisfactory progress for 4.5 years. Approval of the Departmental faculty is required to extend funding to a student beyond this period.

**Coursework/Seminars**

• Graduate classes are intended to reinforce your fundamental understanding of chemical engineering and to help you become independent thinkers. As a result, the assignments and course structure are different from undergraduate classes because less direction is given in the subject; homework, examinations and projects are broader and more open-ended; and teachers expect student initiative in seeking the most important aspects. Graduate students are expected to treat their classes and class work as times of questioning, diligence and thoughtful pursuit of knowledge. In addition, students are encouraged to take courses outside of their department to broaden their knowledge base.

• Departmental seminars are intended to help students broaden their educational experience beyond the narrow focus of their thesis research. Therefore, regular attendance at departmental seminars is expected. Students are encouraged to ask questions of seminar speakers. It is also important to engage your fellow students in thoughtful discussion of their research. Group meetings and thesis defenses are forums in which this kind of discussion is encouraged.

• Advanced education includes helping others to learn. It is also recognized that through the process of teaching others, one’s own understanding of the course material is strengthened. Thus, Ph.D. students are required to serve as a graduate teaching assistant for at least one semester.

**Service**

• Professional status requires service attitudes and action. Graduate students are expected to contribute to the processes that make their educational environment function. Thus, while there are a variety of ways this could be done, ranging from coordinating a seminar to serving on the graduate student advisory group to organizing an intramural recreation team, all students should volunteer to donate time and effort to fill needs in the university or the community. Students should also become members in professional associations related to their field, such as the American Institute of Chemical Engineers and the American Chemical Society.
OVERVIEW of GRADUATE PROGRAMS

The Department of Chemical Engineering offers graduate programs leading to these degrees:

   Master of Science (M.S.)
   Master of Engineering (M.E.)
   Doctor of Philosophy (Ph.D.)

With the exception of an M.E. degree program offered using a distance-learning format, http://cgep.virginia.edu/chem.html, all graduate study in the Department requires full-time attendance.

Master of Science and Master of Engineering

The Master of Science degree requires an independent research effort culminating in a written thesis that must be defended before an examining committee; the Master of Engineering degree may include completion of an independent project of more limited scope than that required for the M. S. Both programs include a "core" group of five first-level graduate courses dealing with the fundamental aspects of chemical engineering. These courses comprise half (15 credits) of the minimum 30-credit requirement for the Master's degree. The M.S. degree requires three elective graduate courses while the M.E. requires three to five elective graduate courses. In general, terminal M.E. students do not receive financial aid from the department.

Doctor of Philosophy

The major elements of the doctoral program are:

   (1) Research Examination and Admission to Doctoral Study
   (2) Selection of Doctoral Advisory Committee and submission of Plan of Study
   (3) Dissertation Proposal and Admission to Candidacy
   (4) Teaching assistant experience
   (5) Research
   (6) Dissertation and Final Defense

A student's doctoral work is carried out under the direction of an Advisory Committee chaired by the major research advisor and appointed by the Associate Dean for Graduate Programs upon recommendation of the Department Chair. Each program of study is tailored to the student's individual needs and objectives.

The Ph.D. qualifying procedure consists of two parts: (1) an oral and written research examination and admission to doctoral study; and (2) dissertation proposal and admission to candidacy. The research examination is used to evaluate research aptitude and has both written and oral parts. The student, in consultation with the research advisor, develops a dissertation proposal that is presented and defended publicly. A successful defense of the dissertation proposal results in admission of the student to candidacy for the doctorate. Finally, the student prepares a written dissertation based on original research and defends it in a final, oral examination.
It is expected that the Ph.D. program will be completed in five years beyond the B.S. degree or three years beyond the Master's degree.

August 2017
MASTER'S PROGRAMS

The Department of Chemical Engineering offers graduate programs leading to Master of Science (M.S.) and Master of Engineering (M.E.) degrees. Basic ("core") course requirements (see below) are identical. The M.S. degree requires an independent research effort culminating in a written thesis while the M.E. degree requires additional course work and completion of an independent project of more limited scope than that required for the M.S.

Purposes

A master's degree, either M.S. or M.E., fulfills several roles in the overall scheme of engineering education. Its first -- and surely its most important -- function is to enable students to solidify and enhance the knowledge and skills developed in the ever more demanding undergraduate curriculum. Another purpose is to provide students with an opportunity to carry out significant research or project work independently, with the advice and guidance of a faculty member.

Finally, a master's degree program permits students to undertake some specialization. Virginia's graduate chemical engineering program offers such opportunities in a number of fundamental areas of chemical engineering (fluid mechanics, mass transfer, thermodynamics, reaction engineering, molecular simulation) and in various aspects of applied chemistry and chemical technology, biotechnology, biochemical engineering, catalysis, electrochemistry, environmental engineering, materials, rheology and surface science.

Program duration

The master's program is ordinarily begun in the fall semester, with the required course work being taken during the fall and spring semesters. Thesis research or project work, begun during the academic year, is then carried out on a full-time basis during the following summer and academic year.

Students must complete all requirements for the M.S. degree within five (5) years after admission to the graduate program and must complete all the requirements for the M.E. degree within seven (7) years after admission.

Degree requirements

A minimum of thirty (30) credits -- or "semester hours" -- of graduate level courses are required for a master's degree, either M.S. or M.E., in chemical engineering. Degree candidates must complete an approved plan of studies incorporating the following:

(1) For the M.S. degree: *

a) A minimum of 24 credits of graduate course work including the five chemical engineering core courses.

b) A minimum of 6 credit hours of research carried out under thesis course, ChE 8998.

c) Presentation of an acceptable thesis based on research conducted under ChE 8998.
(2) For the M.E. degree: *

   a) A minimum of 30 credits of graduate course work including the five core chemical engineering courses.
   b) Of the 30 required credits, a maximum of 6 may come through enrollment in CHE 7995.

All candidates for master's degrees should regularly attend the graduate seminar (ChE 7796).

Transfer credit may be approved for inclusion in the plan of studies for the master's degree. Only graduate courses completed at another institution of recognized standing will be considered. Candidates for the M.S. degree may include a maximum of six (6) semester hours of transfer credit; candidates for the M.E. may include a maximum of twelve (12). Application for transfer credit is made on the Request Approval of Transfer Credits form located at: http://www.seas.virginia.edu/advising/allforms.php

Chemical Engineering Core Courses

The "core" courses are a group of five first-level graduate courses:

   ChE 6625 - Transport processes
   ChE 6665 - Techniques for chemical engineering analysis & design
   ChE 6615 - Advanced thermodynamics
   ChE 6618 - Chemical reaction engineering
   ChE 6630 - Mass transfer.

Persons who have completed equivalent work elsewhere before entering the program will not be required to take the corresponding course at UVa.

Advisors

Newly enrolled graduate students will be advised by the Graduate Program Coordinator. Soon after the start of the fall semester, new graduate students will receive a list of current research topics being offered and will select a topic for their thesis dissertation. The faculty member with whom the student will work then becomes his or her advisor.

Plan of study

Each candidate for the master's degree must submit a Plan of Study (available in the department office), approved by the advisor and the department. It is most appropriate to prepare this during pre-enrollment at end of the first semester of graduate study.

The recommended course load for master's degree candidates is four 3-credit graduate courses per semester. Students who wish to carry more than four courses in a semester must secure the recommendation of their advisor and the approval of the departmental faculty.

Application for degree
Candidates for the master's degree must make formal application on the Application for Graduate Degree form (http://www.seas.virginia.edu/advising/allforms.php) as well as through SIS. Deadlines for application are:

- October 1 for January graduation
- February 1 for May graduation
- June 1 for August graduation

**M.S. thesis and examination**

After the student's MS thesis has been approved by his/her advisor, an examining committee will be appointed. This committee consists of at least three UVA faculty members; two faculty members must be from Chemical Engineering. The Final Examination Committee form (http://www.seas.virginia.edu/advising/allforms.php) is used to request appointment of the examining committee. Copies of the thesis should be given to the committee members at least one week before the date of examination.

After the thesis has been approved by the examining committee, the Report on Final Examination will be sent to the Dean from the department. The student is responsible for submitting the thesis electronically through LIBRA. (http://libra.virginia.edu/)

**PLEASE NOTE THAT CHE REQUIRES THAT THE BIBLIOGRAPHY INCLUDE TITLES OF JOURNAL ARTICLES**

**M.E. project report**

A final report is required for the project work undertaken (ChE 7995) to satisfy the requirements for the Master of Engineering degree. This report must be approved and graded by the student's advisor. This approval constitutes the final examination for the ME degree. It is also the responsibility of the student to request his/her advisor submit an Engineering Analysis Assessment, Engineering Design Assessment and the student’s Engineering Plan of Study Assessment to the department and Dean’s Office.

**Quality of work**

Graduate students are expected to maintain high standards of quality in their graduate courses and in their thesis research or project work. Any graduate student whose grade-point average (GPA) in graduate level courses falls below B (GPA = 3.0) will be placed on probation. Such students will be subject to dismissal if the cumulative GPA is not raised to 3.0 within one semester.
DOCTORAL PROGRAM

GENERAL

Possessors of the doctorate are understood to have mastered in depth a segment of human knowledge and to have contributed significantly to that body of knowledge. The doctoral program includes advanced course work but emphasizes the conduct of original research.

In assessing prospective candidates for the doctorate, the faculty will consider the student's overall academic record, prior performance in research, and the evaluations of appropriate references. Formal requirements for admission to doctoral candidacy include, in addition to advanced course work, satisfactory performance on the Research Examination, and the preparation of an acceptable dissertation proposal. In all of these, the student will be expected to demonstrate familiarity with the fundamental concepts and techniques of chemical engineering and, above all, to be able to apply these concepts and techniques to original and ill-defined situations.

PROGRAM STRUCTURE AND DURATION

The major elements of the doctoral program, described in detail below, are:

(1) Research Examination and Admission to Doctoral Study
(2) Selection of Doctoral Advisory Committee and submission of Plan of Study
(3) Dissertation Proposal and Admission to Candidacy
(4) Teaching assistant experience
(5) Research
(6) Dissertation and final examination

The Ph.D. qualifying procedure culminates with Admission to Candidacy and consists of two parts: (1) the oral and written Research Examination and Admission to Doctoral Study; and (2) the Dissertation Proposal and Admission to Candidacy. Students apply to undertake each of these two qualifying steps using forms appended to the back of this document.

Residency requirements for the degree are set by SEAS.

FINANCIAL SUPPORT AND SATISFACTORY PROGRESS

As detailed in their offer letter of admission, students admitted to the University of Virginia Department of Chemical Engineering Ph.D. program receive a stipend and all tuition and fees will be paid by the Department as long as the student maintains satisfactory progress. The University also pays for health insurance for all full time graduate students who choose to accept the University’s health plan.

Satisfactory progress in the University of Virginia Chemical Engineering Ph.D. program requires:

1. A graduate student to successfully find a suitable research advisor approved by the Department of Chemical Engineering in their first academic year.
2. Passing the Ph.D. qualifying exam.
3. A grade of “satisfactory” assigned for research credit hours.
4. A cumulative GPA of 3.0
5. Since students are generally expected to complete the Ph.D. program in 5 years beyond the B.S. degree, financial aid is not guaranteed beyond 5 years after matriculation at UVA. Continued funding past 5 years is at the discretion of the advisor and approval of the department.

1. RESEARCH EXAMINATION AND ADMISSION TO DOCTORAL STUDY

All Ph.D. students must pass a Ph.D. research examination in the beginning of their second year. After passing the Ph.D. research examination, the student may elect to complete an M.S. degree, but is not required to do so (unless specifically deemed necessary by the faculty or research advisor.) The Research Examination is to be taken within one month after completing the first summer of research. The student must describe, in both written and oral forms, his/her research progress to that time as well as plans for further work. Although the motivation, background and technical originality of the research are important components, the overall goal is to assess the student’s aptitude for research. The written document and oral presentation will be limited in length. Following the oral presentation to the faculty, exam committee, faculty serving on the committee will ask the student questions on their research, which will include a focus on connections to core chemical engineering principles, e.g., Thermodynamics, Transport, Fluid Dynamics, Heat Transfer, etc. The outcomes of this exam are pass, pass with conditions, or fail. Students failing the exam taken in September will have an opportunity to retake the exam at the end of the fall semester.

Students must indicate in writing their intention to take the Research Exam when it is announced.

Admission to Doctoral Study is a formal action of the departmental faculty. It indicates acceptance of the student into the ultimate research phase of the doctoral program.

In order to be admitted to doctoral study the student must have:

1. completed a program of advanced course work, here or elsewhere, equivalent to the departmental course requirements for the Master’s degree
2. passed the Research Examinations
3. demonstrated, to the faculty’s satisfaction, a capability for independent research of the quality expected for the doctorate.

2. Selection of DOCTORAL ADVISORY COMMITTEE and submission of PLAN OF STUDY

A student's doctoral work is carried out under the direction of Doctoral Advisory Committee. Within one semester of Admission to Doctoral Study, the Doctoral Advisory Committee (http://www.seas.virginia.edu/advising/Form%20Doctoral%20Advisory%20committee.pdf) should be appointed for each student by the Associate Dean for Graduate Programs upon recommendation of the department chair and the Plan of Study (available in the department) should be prepared and promptly submitted. The committee, chaired by a ChE faculty member other than the research advisor, should have three Chemical Engineering faculty and at least one UVA faculty member from outside the student's department and major curriculum study area. This Committee should meet with the student as early as possible to begin assisting the student in development of research plans, in the
selection of additional graduate courses, and in the timely preparation and submission of the dissertation proposal.

A doctoral Plan of Study (available in the department) listing the courses taken as part of the Ph.D. program and tailored to the interests and needs of the individual student, is developed in consultation with the student's Doctoral Advisory Committee. The plan must satisfy all requirements of SEAS. Courses taken in pursuit of a Master's degree in this Department or elsewhere may be included in the doctoral Plan of Study.

Although there are no specific departmental course requirements for the doctoral degree, the Plan of Study should ensure both depth in the specific research area and breadth in chemical engineering and related sciences.

3. DISSERTATION PROPOSAL AND ADMISSION TO CANDIDACY

Doctoral students are required to prepare a written Dissertation Proposal. The proposal should indicate the purpose and objectives of the work to be undertaken, the current state of the art with bibliography, and the strategy to be followed and techniques to be employed in the research. Preliminary data, calculations, and/or theoretical developments may be included in support of the proposed work. The proposal will be presented orally and discussed publicly. The Doctoral Advisory Committee will serve as the Dissertation Proposal Exam Committee.

The purposes of the dissertation proposal are:

(1) to determine if the student's knowledge of the area chosen for research and the pertinent literature is adequate
(2) to determine whether the proposed work, if completed, would provide the basis for an acceptable dissertation
(3) to advise the student on general approaches and specific techniques that may be helpful in the proposed research.

If, in the judgement of the advisory committee, the student's proposal is not satisfactory, the student may be required to submit a revised proposal for further discussion with the Advisory committee.

The dissertation proposal should be completed within two years of completing the research exam (doctoral qualifying exam). Upon successful defense of the Dissertation Proposal, the student will be admitted to candidacy for the doctorate.

PhD students are encouraged to consult with their thesis committee not later than six months prior to the thesis defense to briefly discuss progress since the thesis proposal and plans for work to complete prior to the defense.

4. TEACHING EXPERIENCE

To contribute to the educational and professional development, each doctoral student must serve as a graduate teaching assistant for a minimum of one semester.

5. RESEARCH
Research begins as soon as the student has chosen a research advisor. Research remains a primary focus of the student throughout enrollment in the graduate program and should be completed in four and a half years for students entering with a B.S. degree or in three years for students who enter with a Master's degree in chemical engineering.

6. DISSERTATION AND FINAL EXAMINATION

Finally, the candidate must present and publicly defend a dissertation based on his/her independent original research to a committee that includes the Doctoral Advisory Committee and one additional member for a total of 5 faculty members. Dissertations should be submitted to committee members two weeks prior to the defense date.

PLEASE NOTE THAT CHE REQUIRES THAT THE BIBLIOGRAPHY INCLUDE TITLES OF JOURNAL ARTICLES

SEAS forms may be obtained from http://www.seas.virginia.edu/advising/allforms.php (see page 16)

August 2017
Worksheet

The following is provided as a personal worksheet to plan/record your progress

Graduate Research Advisor _________________

MS Plan of Study _________________________

Core Courses:  
ChE 6615 _________
ChE 6618 _________
ChE 6625 _________
ChE 6630 _________
ChE 6665 _________

Other Courses:  
(usually 6000 _________
or above) _________

Research Credits: _________

Research Exam _________
(Aug./Sept 2nd year)

If chosen or required:
M.S. Final Examination Committee ____________________
Defense and Electronic Submission of M.S. Thesis to LIBRA ____________________

In the semester immediately following receipt passing the Research Exam or receipt of
M.S./Non-Terminal M.E.:
Doctoral Advisory Committee ________________
Doctoral Plan of Study ______________________
Courses & Research Credits:

Ph.D. Dissertation Proposal Presentation ____________
Ph.D. Final Examination Committee ______________
Ph.D. Dissertation Defense ____________________
Research Student Laboratory Check-out Form __________
Electronic Submission of Dissertation to LIBRA __________
APPLICATION FOR RESEARCH EXAMINATION

To: Graduate Program Coordinator

I wish to take the research examination for the Ph.D. in chemical engineering when it is offered in _______ of _______.
(month) (year)

Name (print): __________________________________________

Signature: ____________________________________________

Date: _________________________________________________
Research Student Laboratory Check-out Form

Name: ____________________________

This form is to be turned in to Ms. Faulconer upon completion of laboratory work but no later than three weeks prior to graduation by any BS, terminal ME, terminal MS, or PhD student who has conducted research in the ChE department. It is to be signed by the degree candidate and approved by his/her research advisor plus a lab representative (senior grad student or research associate appointed by the advisor who will be remaining in the lab). A degree will not be approved until this signed form has been filed.

1. All laboratory wastes associated with my project have been picked up by the Office of Environmental Health and Safety.
2. All unused chemicals have been assigned to another person in the laboratory, placed in Chemical Engineering common stores, or have been sent to the Office of Environmental Health and Safety.
3. All samples, apparatuses, laboratory notebooks, etc. have been stored in a manner acceptable to the research advisor.
4. My laboratory work area has been cleaned to the satisfaction of my research advisor and designated laboratory representative.

__________________________________________  ____________________________
Degree Candidate Signature                      Date

Approved:

__________________________________________  ____________________________
Research Advisor                               Date

__________________________________________  ____________________________
Laboratory Representative                       Date
<table>
<thead>
<tr>
<th>Degree</th>
<th>Form Required</th>
<th>Form Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ph.D.</td>
<td>Request appointment of your advisory committee.</td>
<td>Doctoral Advisory Committee (may be re-submitted if changed)</td>
</tr>
<tr>
<td>Ph.D.</td>
<td>Submit a report of your PhD (qualifying, preliminary, comprehensive) examination. You MUST also submit the program-specific qualifying exam assessment form (below)</td>
<td>PhD Examination Report and Program Specific Qualifying Exam Report</td>
</tr>
<tr>
<td>MS and Ph.D.</td>
<td>Request appointment of your final examination (defense) committee</td>
<td>Final Examination Committee</td>
</tr>
<tr>
<td>MS and Ph.D.</td>
<td>Submit a report of Final Examination, to be completed at exam. You MUST also submit a Thesis and Dissertation Assessment form and (Ph.D. only) a certificate of completion of the on-line Survey of Earned Doctorates</td>
<td>Report on Final Examination and Thesis and Dissertation Assessment Survey of Earned Doctorates</td>
</tr>
<tr>
<td>MS and Ph.D.</td>
<td>Official Cover and Approval pages which include the Dean’s signature, to be completed at the final exam or after required corrections are complete. No faculty/committee signatures are needed for these pages which become the first two pages of the thesis/dissertation.</td>
<td>Thesis/Dissertation Cover and Approval Pages</td>
</tr>
<tr>
<td>ALL Degrees</td>
<td>Request change, exception or waiver to SEAS academic requirements.</td>
<td>Request Requirement Change, Exception or Waiver</td>
</tr>
<tr>
<td>MS/ME</td>
<td>Request approval of transfer credits/courses—will appear on U.Va. transcript (limit 6 in MS/12 in ME/ 15 in CGEP). Must be processed at least 2 weeks prior to graduation (including receipt of official transcript with final grade).</td>
<td>Request Approval of Transfer Credits</td>
</tr>
<tr>
<td>ALL Degrees</td>
<td>Request change of program/department or degree</td>
<td>Request Program Plan Change</td>
</tr>
<tr>
<td></td>
<td>Students should use this form to request a change of enrollment limit/status in order to switch from or to full/part-time (12 credits is full-time, less than 12 is part-time).</td>
<td>Change of Enrollment Limit/Status</td>
</tr>
<tr>
<td>MS and Ph.D.</td>
<td>Request use of SEAS graduate level (=&gt;5000) courses taken while a UVA undergraduate student. Courses must have NOT been used for the undergraduate degree.</td>
<td>SEAS Graduate Course Approval</td>
</tr>
<tr>
<td></td>
<td>Students should use this form only to make schedule changes that cannot be made by using SIS.</td>
<td>UREG’s Online Course Action Form</td>
</tr>
</tbody>
</table>

Outcome Assessment Forms
- Engineering Analysis Assessment
- Engineering Design Assessment
- Engineering Dissertation Proposal Assessment
- Engineering Oral Communication Assessment
- Engineering Plan of Study Assessment
- Engineering Technical Writing Assessment
- Engineering Thesis & Dissertation Assessment

Program-specific Qualifying Exam Forms
- Chemical Engineering
ON THE NATURE AND CONDUCT
OF TECHNICAL RESEARCH

JOHN P. O'CONNELL
University of Virginia • Charlottesville, VA 22903 USA

In 1589, a young man carrying a number of different spheres trudged to the top of the Leaning Tower of Pisa and proceeded to make an impact on history. After centuries of speculation about whether solid bodies of different sizes and densities would fall at the same or different rates, Galileo Galilei’s famous demonstration showed that mass and density make no perceptible difference in the rate of fall. His apparently courageous (or perhaps arrogant?) act of actually conducting the experiment and the ultimate impact of his results have been a source of inspiration for generations of scientists, encouraging them to take the “path less traveled” in making their own discoveries of significance.

According to Gerald Holton, Galileo was like most of the “scientists” of his era—quite different from today’s scientist. He performed most of his experiments privately and did not write about them (some historians challenge whether he did any experiments). But, back then as well as now, science was a search for cosmic truths based on thematic presuppositions—that is, beliefs and instincts pushed things forward. Thus, true to the science of his time, Galileo would have been convinced of his view about equal rates, and if the experiment had turned out different from what he expected, he might have been tempted to deal with the crisis in an unacceptable way, as Sidney Harris illustrates in Figure 1.

It is this story—and the cartoon’s “rest of the story”—that comprise the dual themes of this paper. The notions of what technical research is and how it is carried out are examined.

John O’Connell is H.D. Forysth Professor of Chemical Engineering at the University of Virginia. He received his BS from Pomona College, his BS and MS from MIT, and his PhD from the University of California Berkeley. He taught thermodynamics and statistical mechanics as well as materials science for chemical engineers at the University of Florida from 1966-88. His research on fluids involves theory, molecular simulation, and experiment.

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Figure 1. Reprinted from The Physics Teacher, 1992.

especially in light of today’s technology and objectives. But, even when we know what to do, we have to deal with various pressures—the pressure to produce, the limitations on our resources, the calls for elimination of everything that is not immediately and directly applicable, and the demands to “fix up” an ailing research establishment. These pressures may lead us away from the true quest of research and into unprofessional conduct. My goal here is to help research advisors and their coworkers to more fully appreciate technical research and to improve their performance. The references listed at the end of this paper are only a few of the many available, and there is a wealth of material in them.
The rewards of a life spent in research are both personal and communal, although the latter is often not fully appreciated. Research findings contribute to the total body of knowledge, giving research scientist a valid sense of community and commonality.

especially concrete suggestions. Finally, I will demonstrate one way to use the case studies in the National Academy’s booklet[2] to give graduate students some experience with research dilemmas and allow them to practice both group work and oral communication.

First, the assumption is that researchers want to do the best they can. If they fall short, it is probably not because they want to get away with the minimum amount of work possible or, worse, that they just don’t care or, worst of all, that they cheat. Human frailty, limited experience, and value conflicts are usually the cause of confused behavior.

"A Corollary to Murphy’s Law"
Do not ascribe to maliciousness what can be ascribed to
incompetence
ignorance
insensitivity
While sometimes bad things are intended, mostly they’re not!

Also, although the discussion in my resource materials is often couched in terms of “science” because many of the leaders and speakers are scientists, the truths discussed here also work for engineering and engineering science research. Applied research has the same ultimate effect as does basic research: “to make claims about the world that are subject to empirical tests.”

WHAT IS RESEARCH?

The most relevant definition of research in the 1971 Oxford English Dictionary is:

“Research. 3. A search or investigation directed to the discovery of new facts by careful consideration or study of subject; a course of critical or scientific inquiry.”

Early usage includes:

“The matter lies deep in Nature and requires much research...[to] unfold it.”

W. Holder, 1694.

“Our most profound researches are frequently nothing better than guessing at the causes of phenomena.”

J. Robertson, 1799.

This definition is pretty dry, perhaps circular, and even depressing—as are most definitions. Interestingly, the idea of research has been around for centuries, yet it is young in human history. Also, scientific truth is not fixed and universal. Not only does the “truth” evolve, but even the methods of scientists to decide about truth change and continue to develop.[3] But there seems to be a force that attracts people of all persuasions, all over the world, to observe and develop new, more accurate, more complete, and more useful descriptions of the physical, biological, and social world.

WHY DO PEOPLE DO RESEARCH?

What is it that drives people to conduct research? It is, after all, a process that can consume lives. The geneticist, Barbara McClintock, observed,[4] “I was just interested in what I was doing. I could hardly wait to get up in the morning and get at it. One of my friends, a geneticist, said I was a child, because only children can’t wait to get up in the morning to get at what they want to do.” What a wonderful way to live!

Success at research can engender the joy of triumph. A book by Sinderman[5] describes both the techniques and the rewards of a life spent in scientific research. Although such views can encourage a person to consider such a commitment, real experience is needed to decide if the effort is personally worthwhile.

The rewards of a life spent in research are both personal and communal, although the latter is often not fully appreciated. Research findings contribute to the total body of knowledge, giving research scientist a valid sense of community and commonality. The positive aspects most researchers cite are

1. They like it: it is exciting and fun.
2. Success can yield personal and communal triumph.
3. They associate with people who care about similar concerns.
4. Challenging assumptions and seeking new things are stimulating.
5. Confidence comes from relative freedom and responsibility.
6. They belong to a community based on trust and honest recognition.
7. The results can make positive impacts on society.

Of course, there is also a downside:

1. Many failures in measurements or hypotheses are found (Murphy’s Original Law: "If anything can go wrong, it will").
2. Disagreements over results, interpretation, or credit sometimes arise.
3. Success is sometimes minimized because of different value structures ("It must have a practical use!").

The most negative view of research that I have found was expressed by Sir Francis Bacon: what research encounters in the "subtlety of Nature, the secret recesses of truth, the obscurity of things, the difficulty of experiment, the implication of causes, and the infirmity of man’s discerning power,

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[will make it so that] men are no longer excited, either out of desire or hope, to penetrate farther."

There really are more downs than there are ups to research, so a young person considering it as a career should concentrate on the positive aspects and take to heart what molecular biologist Stanley Prusiner said: "It's OK not to understand everything"—especially in the beginning.

The issue of who should do research is treated very well in the books by Medawar and Oliver. They describe some personal traits that indicate who might have a high probability of success. It is important to remember that technical workers are not all the same. Medawar says, "Scientists are people of very dissimilar temperaments doing different things in very different ways. Among scientists are collectors, classifiers and compulsive tidiers-up; many are detectives by temperament and many are explorers; some are artists and others artisans. There are poet-scientists and philosopher-scientists and even a few mystics." This description includes researchers of all disciplines, including modelers, who are often not given full status in the enterprise. Done well, a successful model advances knowledge and practice by finding the essentials of a behavior, giving an understanding of the relative importance of contributions to a complex situation, and creating a reliable basis for implementing the knowledge.

HOW DOES ONE DO RESEARCH?

There are many books on how to do research; some are in the bibliography. The book by Wilson is like a manual of investigation while that by Oliver is more philosophical and attitudinal (and delightful to read!). Their Tables of Contents reveal different thrusts (see Table 1).

The National Academy's publication gives another approach that shows the issues associated with the social foundations of research. Research is not the popular stereotype of a "lonely, isolated search for truth." In particular, today's "scientific research cannot be done without drawing on the work of others or collaborating with others. It inevitably takes place within a broad social and historical context, which gives substance, direction, and ultimately meaning to the work of individual scientists... An individual's knowledge property enters the domain of science only after it is presented to others in such a fashion that they can independently judge its validity."

This "collaboration" occurs through conversation, computer mail, meeting presentations, manuscripts (which are scrutinized by reviewers before publication), and published papers. "This process of review and revision is critically important. It minimizes the influence of individual subjectivity by requiring that research results be accepted by other scientists. It is a powerful inducement for researchers to be critical of their own conclusions because they know that their objective must be to try to convince their ablest colleagues." Nobel Prize winner Michael Brown advised.

"Think of every way possible to shoot down your own idea before you can begin to accept it." It sort of works just isn't good enough! One should ask, "Would I take my job or career on this result?"

"Science has progressed through a uniquely productive marriage of human creativity and hard-nosed skepticism, of openness to new contributions and persistent questioning of those contributions and of the existing consensus." And, as mentioned before, this process of validation also evolves as our knowledge and techniques advance.

WHAT KINDS OF CHALLENGES ARE ENCOUNTERED IN RESEARCH?

There are many problems involved in the performance of research. After all, if it could be done easily for fun and profit, everyone would plunge right in. Among the many issues that could be discussed, I will address only a few.

**Experiments and Data Treatment**

“To learn the secrets of Nature, we must first observe.”

Roger Bacon

“Developing theories without data is like making bricks without clay.”

Sherlock Holmes

“But ask... of the earth... and [it] shall teach you...”

Job 12:7-8

After realizing the importance of conducting experiments, we need to use the results in the most effective ways. Some

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<td><strong>Books on Research</strong></td>
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| **An Introduction to Scientific Research**
  1. Problem: Choice and Statement
  2. Searching the Literature
  3. Elementary Scientific Method
  4. Design of Experiments
  5. Design of Apparatus
  6. Execution of Experiments
  7. Classification/Sampling/Measurement
  8. Analysis of Experimental Data
  9. Errors of Measurement
  10. Probability/Randomness/Logic
  11. Mathematical Work
  12. Numerical Computations
  13. Reporting Research Results |
| **The Incomplete Guide to the Art of Discovery**
  1. About Discovery
  2. Strategy for Discovery
  3. Tactics for Discovery
  4. Personal Traits and Attitudes for Discoverers
  5. Caveats
  6. A Few Views and Comments on Science
  7. The Inside Story of Discovery
  8. Closing Remarks |

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things to avoid are:

1. Uncertain values or errors and noise due to unrecognized limits of technique or equipment.
2. Prevention or independent verification because of incomplete description of measurement conditions and/or analysis.
3. Distortion of reality by rejection/retention of inappropriate data points.
4. Prejudicial conclusions about the quality of a model from using incomplete or biased data.

We know that data can be fallible; this means that an organized and searching skepticism is necessary. The key question is how to work so that truth is maximized?

Consider three cases involving great scientists:

1) Lord Rayleigh discovered the element argon by noticing that the density of nitrogen gas prepared by absorption of oxygen from air differed from that of gas prepared by chemical formation. Considering the cause of the discrepancy led to the conclusion that there was more than just oxygen and nitrogen in air (which, in turn, had originated with the observation that these were the dominant and reacting components of air).

2) Physicist J. Donald Fermi said that in 1613 Galileo recorded the data needed to discover the planet Neptune. However, by either oversight or by rejecting his own discovery, it took 234 more years for Neptune to be “found.”

3) Fermi also says that Michelson decided in advance that electrons had to come in integer values on his oil drop. As a result, he threw out a bunch of data that yielded 1/3 values and thus lost the opportunity to discover quarks at the same time.

Examining and validating all the data can result in more than meets the eye.

The treatment of measured data is handled thoroughly and well in the book by Wilson.31 I learned of a favorite case of MIT’s pioneering chemical engineering professor Warren K. Lewis that might also be illustrative—the “Three-Point Dilemma” (see Figure 2). At first glance, it seems impossible to make sense of these data. But a correlation could be valid with information from a rigorous theory (such as the value at x = 0) and experimental uncertainties (see Figure 3). While the data may seem very rough, that’s not the point: informed analysis gives maximum knowledge.

**Simulation**

Recent advances in computers allow computation, imaging, and synthesis of phenomena in incredible ways. Using it as a tool in our research repertoire, the computer pushes us amazingly far into quantitative descriptions of Nature, allowing examination of multitudes of models, and creates images at all scales of distance and time that are unavailable experimentally. Simulation has become the most ubiquitous and hottest methodology ever known.
get by fiddling with the equations.” Pauling then added his own aside, “I’ve never made a contribution that I didn’t get by just having a new idea. Then I would fiddle with the equations to help support the idea.” (Here, “fiddling” does not mean faking or fantasizing—it means assessing the important and unimportant contributions and doing exploratory calculations. In that way, inadequacies in sign, trend, form and magnitude, including omissions, can be found, and one can connect proposed adjustments to physical and chemical insights.) Note that in both styles there was equation fiddling. Such fiddling was probably the dominant mode of quantitative exploration before extensive computations were possible. In this modern age of ever-increasing computer power and ease, we must remember that people should do the thinking and machines should do the work.

**Judgments, suppositions, and beliefs**

If Galileo had really encountered the spheres falling as depicted in the cartoon at the beginning of this article, he could respond as pictured only if there were evidence to the contrary and he knew why the Pisa experiment was flawed. But that would not be “altering the data.” Now we are better at developing our ideas while maintaining awareness of hazards in the process (see Table 2).

### WHAT ARE SOME OF THE ETHICAL ISSUES OF RESEARCH?

In addition to mastering the various techniques for gathering information, researchers must also recognize many ethical aspects. The US scientific enterprise has recently been questioned and threatened because of human issues. Today, the cartoon reaction could result in disbarment.

We must examine how the values of science are understood and practiced, especially in “conflicts of values” situations. This is the central focus of an article in *Science* and is a major portion of the booklet *On Being a Scientist*. Research programs in chemical engineering do not usually encounter such issues directly, but we abdicate our responsibilities as technical professionals and informed citizens if we do not consider what is involved in the ethical issues of technical research. Note that this introduces the one thing that research is supposed to avoid—irrationalities. They appear because research is a human process.

Margaret Somerville, director of McGill University’s Centre for Medicine, Ethics, and Law, put it succinctly, “Good ethics depends on good science. If you’re not doing good science, you’re not even in the ballpark of doing good ethics.”

### Classifying the issues

We need to be aware of what we get into with research. One’s sense of values must be established and prioritized at the very beginning. Only a prepared mind and spirit can stand up to the pressures that students encounter (be produc-tive, get good grades, initiate a lifelong career) and those that faculty encounter (keep funding, attract coworkers, balance education, research, and service activities) and still maintain academic freedom and values. While there are many ways to phrase and rank these values, I like what eminent physicist Alvin Weinberg said: “A sense of responsibility is the trait I would put at the top. A scientist can be brilliant, imaginative, clever, with his hands, profound, broad, narrow—but he is not much as a scientist unless he is responsible.”

The booklet *On Being a Scientist* lists some troublesome aspects arising from value conflicts in technical research:

- **Personal Interest**: financial involvement, confidential knowledge, etc.
- **Publications and Openness**: false claims of discovery, commercial proprietary secrets, multiple publication of the same work, many short papers
- **Allocation of Credit**: lack of proper recognition, citations, number of authors, and accountability
- **Errors and Negligence**: lax standards and quality, sloppiness, and lack of trustability
- **Misconduct and Deception**: fabricating data, falsifying results, plagiarism, cover-ups, reprisals against whistleblowers, malicious allegations, violation of due process in handling complaints

### Action in cases of unethical conduct

First, we must not be tolerant of—much less support—substandard conduct, especially when it comes to unethical behavior. If we know a wrong has been done, we are obligated to act. Inaction can cause problems ranging from mere obstruction to real damage to one’s own research, particularly to the credibility necessary to have one’s results trusted. Furthermore, if breach of trust is broadly found, the whole research community could suffer under a cloud that maligns everyone, generates counterproductive regulations, and fosters widespread public doubt.

To take action in such cases requires courage and careful preparation. The essential first step is to have already estab-

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**TABLE 2**

**Issues in Judgment and Self-Knowledge**

1. In selecting the best hypothesis to proceed with, look for:
   - Internal consistency
   - Accurate correlation and prediction of measurements
   - Unification of apparently disparate observations

2. Using personal intuition—the good and the bad
   - Will one’s instincts and experience always lead to advances?
   - Is one always motivated by desire for truth, beauty, and quality?
   - Can you be assured that the good you do is not a hindrance?

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lished a reputation of honor and standards. Then the process
must be carefully executed. The National Academy’s re-
port22 recommends:
1. Long before the need arises, establish your own credibility.
2. Discuss the case with a trusted friend or advisor.
3. Find out your institutional procedures by
   • Calling your academic Office for Research (Vice Provost?)
   • Reading the general publications listed in On Being a
     Scientist23
4. Carefully choose the proper time to “put it in writing”—this
   is a major step.
5. Seek confidentiality, but don’t expect it. If you see a situation
   coming, plan ahead.

AN ACTIVITY FOR GRADUATE STUDENTS

On Being a Scientist23 provides some excellent material
for engaging students in the issues explored here. The book-
et can be studied individually, in groups, or in a class. There
are nine short case studies given as sidebars in the main body
of the text, along with an appendix discussing them. The case
titles are:

- Publication Practices
- Plagiarism
- Credit Where Credit Is Due
- Sharing of Research Materials
- Fabrication in a Grant Application
- A Conflict of Interest
- Industrial Sponsorship of Academic Research
- A Career in the Balance
- The Selection of Data

Each case study has a brief background of the situation
with “real people” expressing opposite sides of the issues,
followed by one to three questions that attempt to bring out
the reader’s view. The appendix provides some guidance, but
does not establish “the” answer.

I made use of the material in the context of the Departmen-
tal Graduate Seminar. First, I gave a talk that was essentially
the same as the text of this paper. After questions and a
discussion, I requested the departure of all those who were
not chemical engineering graduate students or who did not
wish to participate in a deeper experience of the issues. I
then asked the remaining students to break into groups of
three, and I gave each group a copy of one of the cases. They
were told that in three weeks, they would all be required to
present the Graduate Seminar under strict rules. Each group
would be given five minutes and four overheads to present
their case, which should include a description of the situ-
ation, the issues, and their own resolution of the case. I also
asked faculty members to volunteer as an advisor for each
case. The students were expected to meet with the faculty
member for discussion, and most of them did. Prior to this
exercise we had issued guidelines for oral communications
(based on the AIChE Speaker’s Manual) and the students
seemed to use this information to their advantage during
their preparations. To promote community feelings about
the effort and to provide a benchmark, I also gave out
“Speaker Evaluation” forms for the students to judge the
quality of my presentation. The compliments and criticisms
were consistent with my assessment of my talk.

The day of student presentations was an excellent occa-
sion. The seminar attendance was the largest in months, and
the presentations ranged from quite good to superb. Finally,
a survey of the students was taken about the difficulty of
understanding and resolving the cases—some proved harder
than others, but the students found all of them interesting.
The faculty said that some groups really “got into”
their cases, but no one was heard to say that the time and
effort were wasted.

CONCLUSIONS

This paper has tried to introduce “eager, thoughtful, and
reverent” workers to understanding and materials about tech-
nical research—what it is, why people do it, how it’s done,
some of the difficulties, and what to do about unprofessional
conduct. Hopefully, some responsive chords have been struck.
Research is challenging; some of our involvement with it, all of
its aspects should be of utmost importance to us.

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