ON THE NATURE AND CONDUCT OF TECHNICAL RESEARCH

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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,[1] 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.

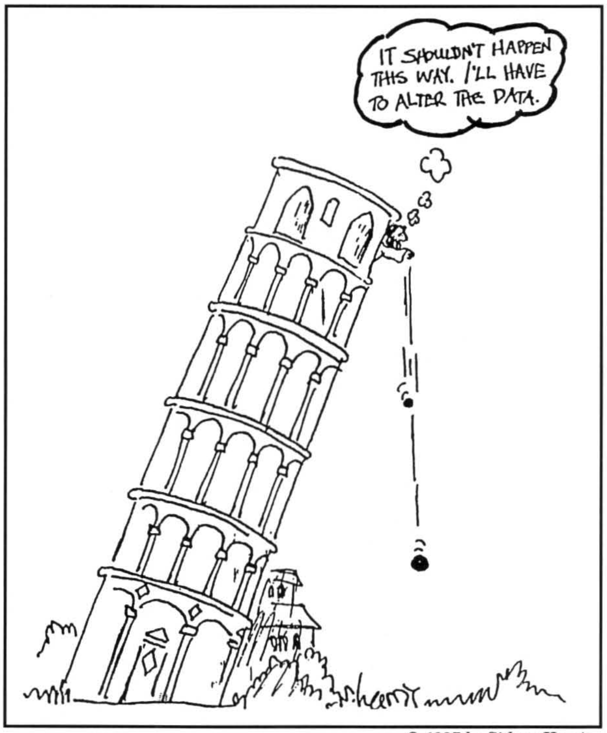

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Figure 1. *Reprinted from* The Physics Teacher, 1992.

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, 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,

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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 some fact by careful consideration or study of a 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 the 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.[1] 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,[2] "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[3] 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 the 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 down side:

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:[4] 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, [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:[5] "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[4] and Oliver.[6] 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[7] is like a manual of investigation while that by Oliver[6] is more philosophical and attitudinal (and delightful to read!). Their Tables of Contents reveal different thrusts (see Table 1).

The National Academy's publication[2] 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 properly 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,[5] "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 stake 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."[2] 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 1
Books on Research

"An Introduction to Scientific Research"[7]
E.B. Wilson, Jr., 1952

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"[6]
J.E. Oliver, 1991

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 1 Discovery
8. Closing Remarks

things to avoid are:

1. *Uncertain values or errors and noise due to unrecognized limits of technique or equipment.*
2. *Prevention of 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 Fermie says[8] that in 1613 Galileo recorded the data needed to discover the planet Neptune. However, by either oversight or by rejecting his own drawing, it took 234 more years for Neptune to be "found."
3) Fermie also says that Michelson decided in advance that electrons had to come in integer values on his oil drops. 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.[7] 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, allows 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.

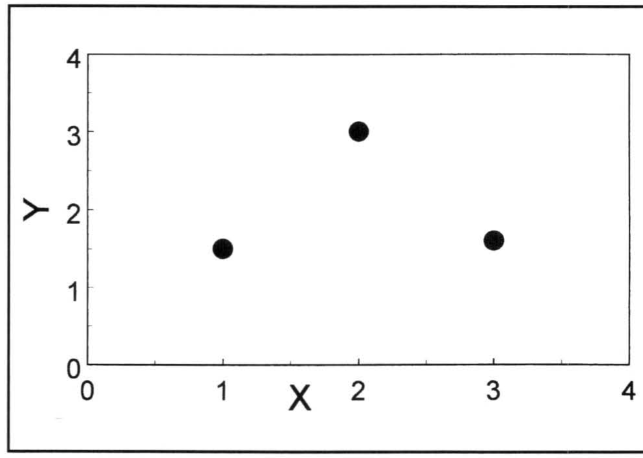

Figure 2. The Three-Point Dilemma: How to Draw the Correlation?

Validating simulation requires the same care as experiment. In addition to the need for awareness about sensitivity, undetected assumptions, and insufficient sampling, there must also be detection of computer-code errors and adherence to reporting only believable significant figures. Multiple checks of limits and consistency are required.

I have heard more than once from Stanford Chemistry Professor Hans Christian Andersen, "Simulation is very seductive. But, like most things seductive, it is not necessarily wholesome." We probably have at least our share of fools and scoundrels in simulation since such care may not always be taken."

Exploration

Linus Pauling has quoted[9] the physicist John Van Vleck as saying, "I have never made a contribution . . . that I didn't

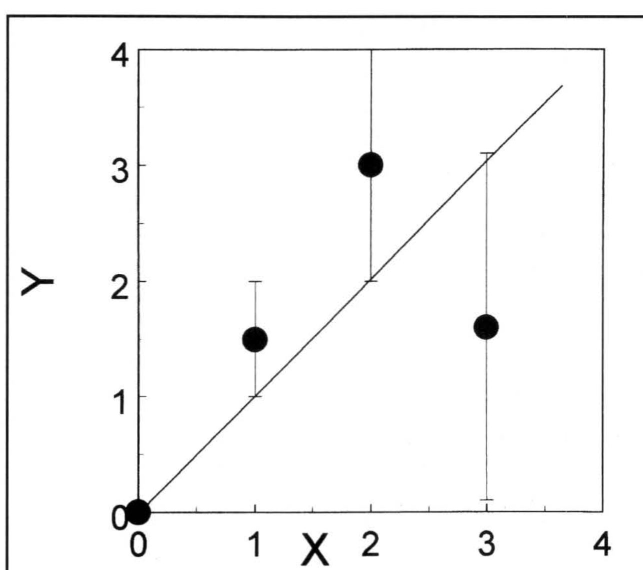

Figure 3. *The Three-Point Dilemma How to Draw the Correlation!*

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).

TABLE 2
Issues in Judgment and Self-Knowledge

1. In selecting the best hypothesis to proceed with, look for:
   - A. Internal consistency
   - B. Accurate correlation and *prediction* of measurements
   - C. Unification of apparently disparate observations
2. Using personal intuition—the good and the bad
   - A. Will one's instincts and experience always lead to advances?
   - B. Is one always motivated by desire for truth, beauty, and quality?
   - C. What is *really* assumed in one's work? Is it a help or hindrance?

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*[5] and is a major portion of the booklet *On Being a Scientist.*[2] 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 Center for Medicine, Ethics, and Law, put it succinctly,[5] "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 productive, 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:[2] "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*[2] lists some troublesome aspects arising from value conflicts in technical research:

<u>Personal Interest:</u> financial involvement, confidential knowledge, etc.
<u>Publications and Openness:</u> false claims of discovery, commercial proprietary secrets, multiple publication of the same work, many short papers
<u>Allocation of Credit:</u> lack of proper recognition, citations, number of authors, and accountability
<u>Errors and Negligence:</u> lax standards and quality, sloppiness, and lack of trustability
<u>Misconduct and Deception:</u> 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 fall 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 established a reputation of honor and standards. Then the process must be carefully executed. The National Academy's report[2] 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 Scientist*[2]
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 Scientist[2] provides some excellent material for engaging students in the issues explored here. The booklet 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 Departmental 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 situation, 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 occasion. 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 technical 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; since we are involved with it, all of its aspects should be of utmost importance to us.

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