

GRADUATE EDUCATION IN TURBULENCE: AN OPINION *

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1 Introduction

In the past ten years or so I have had the opportunity to interview a considerable number of prospective faculty members who had just reached the end of their doctoral programs. From these experiences and the casual encounters at technical meetings with many other recent or near graduates, I have formed an opinion of present graduate education. What I fear represent the requirements of a typical graduate program (the present audience excepted, perhaps) are:

- Take an absolute minimum number of formal courses.
- Hook onto an existing chain of research, preferably one well-funded.
- Make a modest, or even trivial, extension of the previous results.
- Quickly leave for a post-doctoral position, or some unsuspecting ¹ industry or university.

Tony Perry (Professor and Chair, U. Melbourne) addressed this in a somewhat different way earlier, but I'm sorry to say that the implied indictments are the same.

We've heard quite a bit over the past decade (and at this meeting) that in order to meet the technical needs of the nation we need to focus more on applied research in our graduate education programs. This national agenda

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¹Unsuspecting: in the sense that the employer probably expects his new employee to function independently with a reasonable perspective.

appears to be based on the premise that somehow the failures of the past are due to improper directions in graduate education. Now I've thought about this a great deal, and I'm not sure I understand how we are supposed to "direct our students" toward applied research problems — especially if these problems are not fundamental in nature. First, I would argue that most research problems, especially in turbulence, have a strong applications link to begin with. Second, let me state my belief that a proper dissertation research will be fundamental, regardless of whether the topic is applied or more esoteric in its origin. Thus I do not understand the conflict which is presumed nor the remedial steps which are to be taken. What I suspect is being advocated is that we are being asked to deliberately teach students to think in a somewhat sloppy manner, to reason less critically, and to be less concerned about identifying and pursuing those things they don't understand — in short, to be satisfied by simply assembling the old ideas in an uncritical way to provide a quick fix for the problem of the day.

Now I have to confess that no matter how successful my own students may appear to be at these things, I really can't claim the credit. In fact, in my sixteen years at Buffalo and the prior six years at Penn State, I've found few incoming students to whom sloppy reasoning, lack of critical reasoning, and limited concern for fundamentals did not come naturally. My objective as a graduate educator has always been to change them to fundamental thinkers. That I have *not* contributed thereby to thwarting the national agenda is evidenced by the fact that a significant portion of my former students now work in industrial and national research laboratories on problems that are indisputably applied.

Also, let me make it clear that I have had very little success in directing my students toward any special kind of post-doctoral research, applied or otherwise. By the time they are finished with their graduate studies, they really aren't listening to me, or anyone else for that matter. (In fact I've been accused of letting my students graduate when they were so independent that I couldn't stand to have them around anymore.)

2 A proper graduate education?

Now let me tell what I think a proper graduate education should be. The model I believe that is appropriate is the one which has been used through the centuries to train specialists of all types; namely, that of the Master, his Journeymen, and the Apprentices. The Professor is, of course, the Master. The Post-doctoral and Research Fellows are the Journeymen, and the Graduate Students are the Apprentices. Literary writers and historians have documented for us numerous examples of abuse of this system, and perhaps some of them should be of concern for us as well. Apprenticeship is not slave labor. Nor is it purely an educational experience. Ideally the apprentice is learning about both the skills of his trade and about life in a broader context, and is at the same

time performing useful service. This service has two purposes: To compensate for the expense of his sustenance, and to allow him to learn by doing. These can all be kept in balance only if the Master understands clearly that his objective must be to produce a graduate who has acquired the skills to function without his supervision.

In the trade apprentice programs it is usually obvious what the objectives of the apprenticeship are — to make shoes or hats, for example. What are the objectives of a graduate education? What are we trying to train the students to do? While I will not concede that we are guilty of not orienting our students toward applied research (nor will I concede that it even makes sense to try), I will concede that we often do not have a clear picture of what we are trying to accomplish in a graduate program. And I suspect that this lack of a clear objective may be in part responsible for the criticisms which have been directed at us.

I suggest that a proper graduate education:

- Trains students in the application of the scientific method.
- Develops advanced skills in critical reasoning.
- Demonstrates the excitement and satisfaction of finding solutions which unravel the secrets of nature and the puzzles of man.
- Builds the confidence necessary to tackle real problems.

Notice that once the objectives are understood, it matters little whether the particular research problems addressed are fundamental or applied — as long as they are consistent with meeting the objectives. There are engineering approximations which must be made because of problems encountered in the normal progress of the research, and unanticipated obstacles which require that the objectives scaled down. As John Lumley (Professor, Cornell U. and keynote speaker) said the other day: “We promise to do a whole lot, knowing very well we can’t do it (paraphrase).” Steve Kline (Professor, Stanford U.) spoke of technology-motivated research, to which John Lumley replied that we have always been doing that. I would agree — at least many of us. We have all chosen research problems which reflect our own interests and our unique personalities. Since many of us come from engineering backgrounds, it is natural that our research problems — whether fundamental or applied — stem from the needs of technology. Some of us are experimentalists, others are theoreticians. Some of us have labs full of devices – probably because we get excited about machines and parts of machines. Others are content to sit at a computer terminal and generate pictures. While still others contribute and receive satisfaction with nothing more than pen and paper.

I argue that if a student is properly educated by the program into which he has entered, he can contribute in *any* environment in which he finds himself after graduation. The particular nature of the problem which he has investigated

for his dissertation is irrelevant — whether applied or fundamental, whether experimental or computational or theoretical. A Doctor of Philosophy program is an exercise in learning to observe and think critically about the world around us. And once one has engaged in this, the effects on him are irreversible. Sadly, it is my suspicion that many students graduate today having produced a piece of research, but having been only minimally influenced by it. They have acquired new skills — computing, measuring, etc. — but have not been transformed into the critical thinkers that constitute researchers. How much of the complaint that contemporary doctorates are not able to approach applied problems is really merely a symptom of this deeper problem?

At the risk of sounding immodest I can offer as example my own students whose research problem were of the most fundamental nature, and who were subjected to the rigorous and fundamental course structure described below. Of the ten Ph.D. students who have graduated over the past twelve years under my supervision, 40% have ended up in universities, and the remainder have been distributed between industrial and national laboratories.² Of the ten, only four are at present actively working in turbulence research. The remainder have carved out new areas of interest for themselves on topics ranging from paper production to applied optics — topics which were in no way related to their dissertations.

What skills did these former students of turbulence bring then to these diverse subjects for investigation? The primary skill brought was the ability to learn about a new subject, and recognize quickly the fundamental aspects of it. It really didn't matter what they had studied in the past nor where their expertise lay. What did matter is that they had learned to learn about something new. Not just the quick shallow overview that enables one to speak glibly and for which so many settle. Rather, they had learned to seek the kind of understanding that comes from taking a subject apart, from dissecting it into its basic elements and identifying those fundamental aspects which both enable an appreciation of what has been done and an identification of what needs to be done. Their success at applied problems far-removed from the fundamental turbulence studies of their graduate years is both a tribute to them and the program from which they sprang. Whatever its methods, the product was good because the program's objectives were clear: Not to publish the results of their research, nor even to get the next grant (although these are certainly worthy subordinate objectives), but first and foremost to change and refine them (the students) into critical thinkers and researchers.

²Note that several have moved back and forth, but the distribution has remained nearly constant. It is interesting that these are approximately the same ratios for the attendance at national research meetings, like the APS/DFD.

3 Formal course structure

The role and number of formal graduate courses is among the most hotly debated subjects of graduate education. One of the advantages of joining a university in its infancy has been the opportunity to formulate from scratch those programs and policies which will later become part of the tradition. I am fortunate, together with my colleagues, to have had this opportunity at Buffalo, and even after sixteen years I am quite pleased with the results of our efforts. To probably no one's surprise the graduate fluid mechanics program we developed bears a strong resemblance to the mechanics program I came through at the Johns Hopkins University in the 1960's. That program probably evolved in similar manner in the 1950's, drawing from the experiences of its gifted faculty at other successful universities, most notably Cal Tech.

Thus there is little new about what we do at UB. What does seem a bit unusual, however, is that we still do it in the 1990's. This is because there seems to have been a major roll-back in the availability of real graduate courses in the 1980's. This is perhaps attributable to increasing pressures on faculty from funded research and undergraduate education, and to the proliferation of PhD programs without the necessary concentration of faculty to offer a broad spectrum of fluid mechanics courses. Since neither of these problems is likely to vanish in the 1990's, our experience in dealing with them at UB may be of some value to others.

Our graduate program in Fluid Mechanics is essentially a two-tiered. The purpose of the tier one courses is to rapidly bring the student to a point where he can begin to do serious research. The core of this first level is a two semester course in Fluid Mechanics (using Ron Panton's book incidentally). (Professor Panton, U. Texas was the next invited speaker). The course has a strong mathematical and physical content, and makes liberal use of the NSF Fluid Mechanics film series. This course bears the brunt of the responsibility for taking students from the undergraduate fact-and-skill oriented education from which most of them came, and "turning them on" to the critical reasoning necessary for research. This is not always a painless experience because of their diversity of backgrounds and personalities, and we have learned not to put too much weight on performance in it in our evaluation of a student's potential for further study. (In fact, one of my better students nearly failed it, but is now easily conversant in the special language and thought that is Fluid Mechanics). One semester courses in CFD, Turbulence, and Experimental Methods, Heat Transfer, and Thermodynamics as well as courses taught by other segments of the university (e.g. Applied Math, Physics, Statistics, etc.), allow the student to pursue his own special interests in making up the remainder of this first year.

By the time a student has finished these tier-one courses (usually in the first academic year), it is expected that he will be fully immersed in his research problem. My colleagues and I differ on the relative merits of an MS thesis. My own preference is to by-pass it, and have students proceed directly for a

PhD. The MS degree is offered as a consolation prize to those who for some reason must terminate their studies prematurely. My reasons for this are quite pragmatic and may be of some general interest. At the large state university that is UB, a disproportionate share of the students are first generation college students. While they understand why they are in graduate school, their parents (who may have been most supportive when they were undergraduates) often do not. The combination of home pressures, financial stress, and the usual tensions between advisor and student of bringing a thesis to final form makes them unusually susceptible at this time to the rather lucrative offers industry sets before them. The problem is exacerbated by the unscrupulous practices of recruiters who convince them that a PhD will be of no value - all the while hiring every imported PhD they can attract. After losing several good graduate students this way, I quickly learned to offer neither the frustration nor the opportunity — hence no MS degree!

Once the student becomes immersed in his research, my role as mentor changes. To this point my objective has been to focus him as quickly as possible on his research, while at the same time providing him with the tools to begin. It doesn't take the student long (usually) to figure out that this is where it is at — meaning: you don't finish until you get it right! Once this realization takes hold, the research problem becomes all-consuming and all other interests tend to be screened out. It is now my responsibility to counter this narrowing process by forcing the student to continue to be receptive to ideas over a broader spectrum. We accomplish this *de-focusing* at UB by requiring (over and above departmental and university requirements) that the student take a sequence of advanced PhD level courses in fluid mechanics which are for the most part removed from his immediate research interests.

This second tier, the PhD core, consists of six courses which are offered on a three year rotation and includes subjects like stability and transition, viscous flows, potential flow, compressible flow and higher approximate methods. All of these courses are restricted to advanced students and a special effort is made to incorporate the latest research results by the faculty who teach them (often as an overload and at personal sacrifice). (It is important to note that most of these courses do not correspond to areas of active research by the faculty involved in teaching them, but the responsibilities are nonetheless shared by all in the interests of a quality program.) Our overall objective is to enable the student to walk into any session of the American Physical Society/Division of Fluid Dynamics meeting (or any other fluids meeting) and have a reasonable understanding of what is going on. In other words, we are attempting to graduate real fluid dynamicists in the classical sense.

Aside from its obvious purpose of broadening the student's horizons, there are a number of other benefits from our rather arduous requirements. First, the fact that all the PhD students in fluid mechanics are taking the same course (and usually only one) provides a common denominator for discussion among them. Since the details of one's dissertation are seldom of general interest, in the

absence of this common stimulation, the discussion among students often degenerates to the latest football score. Thus these courses raise the intellectual level of the total graduate experience. Second, these courses remind the student that he is studying fluid mechanics, a fact many seem to forget when overwhelmed by the technical complexities of modern research. This “reminder-of-purpose” seems to help prevent (or at least diminish) the sense of isolation that develops at the darkest hour of one’s research, and provides the perspective of belonging to a community of scholars, the fluid mechanics community. Finally, these in-depth courses make for a better researcher because they develop understanding and confidence at a whole new level. And in this vein I might add that I view them to be even more important for experimentalists than theoreticians. (How many times have you seen experimentalists become glassy-eyed as they were flim-flammed by theoreticians they were not properly prepared to understand, much less refute?).

Now the benefits to be gained from the program I have outlined do not come for free. In recent years as our fluids faculty has grown at UB, we have “bought” the luxury of teaching these courses with 5-10 students “on-load” by teaching larger sections in selected undergraduate courses. It is my contention that by creatively using audio-visual aids, teaching assistants with recitation sections (see below), and carefully prepared lectures that 160 students can be taught undergraduate fluid mechanics, heat transfer, etc. even more effectively than we can handle 40. (My colleague, Irving Shames, Distinguished Teaching Professor, U.B., has done a spectacular job of this for decades, even without the recitation section.) The reason is that the nature of the material at this level lends itself to this approach. It matters not to the student whether he asks his question to a full professor or to a carefully coached graduate assistant, as long as he gets a cordial reception and an answer (in his chosen language) when he needs it. Most undergraduates in my experience would much prefer to meet a graduate student on their schedule than stand outside my office waiting for their turn. Regardless of the merits of large versus small (if 40 students is ever small!) classes, the important point is that without this compromise, there can be no PhD program! We have a constant quarrel with graduate program reviewers and administrators, who failing to understand our purposes and the compromises we have made, criticize our small graduate courses. To this point at least, we have successfully defended our choices by articulating our reasons.

Finally, it might be objected that these courses detract from the research and lengthen the student’s time in graduate school. I admit that this may be true. However, I would note that no one can do research all of the time, and I suspect most of the time spent on these courses is at the expense of alternative leisure activities. Regardless, what is the measure of a successful graduate program? Certainly not the time-frame over which research is produced, nor even the research itself! Rather, our focus should be on the quality of the product we deliver — the student himself! However important it may seem to be to publish quickly and keep our sponsors happy, if we let these pressures determine our

educational priorities we are letting the tail wag the dog. AT UB at least, the extra time (if any) appears to have been well worth the complications it presented.

4 Learning to be honest

The other day, Rabi Mehta (Senior Scientist, NASA Ames) remarked that graduate students should be taught to teach in graduate school. I agree, but perhaps my reasons are a bit more complicated than might be obvious, hence the title of this section. Specifically, I believe that graduate students should be required to stand before classes as recitation instructors, and I regularly require my own students to do so, *regardless of their source of support!* When I teach a course, they become my instructors. I usually subdivide the course into recitation sections of 20 or fewer students for which my graduate students are responsible. Now you may ask, why would I deliberately interfere with their research in this manner? The most obvious reason (but not the most important) is that their time is less valuable than mine. Also they can be more available to the undergraduates than I can usually be (see remark above). Neither of these is, however, the real reason I impose this requirement on my own students.

The real reason for this extra requirement is to teach them to be honest — before it is too late! Too many times in my career I have encountered people with PhD's who simply could not admit their ignorance in public. How many times in your own experience have you seen a professor respond to a question by insulting the questioner, or by simply waving his hands and baffling his audience with nonsense? And why does this happen? I contend that in large measure it is because he believes that because he has a PhD, he **MUST** not admit that he does not know, or somehow his stature will be diminished. This is, of course, a complete misunderstanding of the meaning of the degree. A PhD is supposed to be an expert in identifying that which we do **NOT** know, and separating it clearly from that which we do **KNOW** and that which we only **THINK** we know. But most of us get trapped in the psychology of the lay world which views us as knowing everything, and therein lies the problem I am addressing.

If a person does not learn to absolutely honest to his questioners **BEFORE** he gets his PhD, it is unlikely that he will be able to adjust later. What better place to learn this than standing before a group of students only slightly less experienced than you. There is no benefit to *not* admitting that you do not know an answer, and all to be gained by answering that you will find out the truth and return with it. And because you are not yet Dr. so-and-so, neither you nor the students before you feel cheated. Telling the truth in this manner, and reaping its positive benefits becomes habit-forming, and these habits remain for a lifetime.

Thus why teach as a PhD student? It makes for a better scholar — one whose integrity has tempered by his own experience. And there are, of course,

the additional benefits of learning to be articulate and confident in public. And finally, it is an opportunity to learn in a whole new way. I don't think I ever really learned anything until I had to speak about it and defend my views about it in public. To some degree, at least, I suspect that this is true of all of us.

Does a regular teaching requirement slow down the student's progress in his research? Again I ask, What is the objective of his graduate program? The objective is the student himself and his preparation for handling himself when he leaves. Thus, even if it does slow him down, the benefits are more than worth the delay — if we properly keep our objectives in view!

5 The role of the professor

There is a constant tension in many universities between teaching and research. I believe this tension to arise in part, at least, from an inadequate (or even wrong) understanding about why we do research in the university. While it is true that we have obligations to society to apply our collective brain-power to their needs, and we also are driven by our own curiosity, I suggest that the primary justification for research in academia is that it is our teaching tool for these apprentices we wish to train. Just as we can not teach writing without writing materials, nor reading without books, you cannot teach how to research without doing it. Thus from this perspective, research is as much a part of teaching as standing in front of a class and lecturing.³

Now if this is all so obvious, how did the tensions arise in the first place? My suspicion is that we, the professors who supervise research students, are responsible for most of the confusion. This is because that in our quest for fame and glory as researchers, we have forgotten what our mission was. I contend that the proper measure of a PROFESSOR's success as PROFESSOR is not his own research as measured by his grants and publications, nor even the publications resulting from that of the students under his supervision. The only real measure of his success as PROFESSOR is WHAT HIS STUDENTS ACCOMPLISH AFTER THEY LEAVE HIS SUPERVISION.

Now this is probably hard medicine for most of us who fight for the next contract, promotion or raise by driving our students to produce. And in doing so we have been sucked into a system which rewards us for these activities — perhaps more because they make the administration or university look good in some survey than because they measure our contributions as educators. Yet in the final analysis, if we are to masquerade as educators, then we must be evaluated as such. And the only real measure of our success is the ability of our students to contribute independently after they leave us. If they graduate and are never heard from again, or are so destroyed emotionally or physically that

³In my department at UB, we actually compute workloads by assigning a classroom equivalency to the research supervision of graduate students.

they can not function, what does it really matter how many *Journal of Fluid Mechanics* papers were published from their dissertations?

I like to think that I am a good enough researcher that I could take a chimpanzee and produce research of sufficient quality to be published in JFM. (This should not be inferred to be an evaluation of JFM or any other journal!) A much greater challenge for me is to take an insecure undergraduate whose horizons are bounded by the small world in which he has lived, and transform him into a confident scholar who believes himself to be among the best in the world at what he has chosen to do. Thus a big part of my task has to be to build not only his reasoning skills, but his confidence. However gratifying it may be to me for him to think I am brilliant, until he thinks he is as smart as I am, I have failed.

And how can this great ego massaging be accomplished?

- First, by proving to him through an arduous program that he is truly competent. (We've already discussed some ideas for this above.)
- Second, by allowing him the freedom to discover things on his own. (In this day of high pressure funded research, it is hard to stand back and take the heat from impatient sponsors while we allow our students to find their own way, but that is exactly what we must do if we are to accomplish our objectives as educators. One of the greatest challenges I face with students is to not yield to these pressures and intervene too early.)
- Third, by exposing them early and often to the rest of the scientific community. (Frequent appearances and presentations at scientific meetings are a must if they are to come to believe in their own worth and have a proper perspective on it. Again, these opportunities come at some cost to the professor who would like to be presenting the work himself and probably would do a better job.)

These guidelines offer a considerable challenge, especially to those who are just beginning their careers in academia, since they must be evaluated before they can be judged by the accomplishments of their students. My advice to them: Try to develop research ideas of your own, independent from the problems on which your students are working. That way you are not inextricably linked to their success or failures, at least on a daily basis. And whatever the pressures, *never* forget why you are in the professor business in the first place: STUDENTS, STUDENTS, and STUDENTS!!! Ultimately you will be measured by what they do when they leave you.

6 Funding of Graduate Education

The issue underlying the setting of many educational priorities is that of funding. No where is this more evident than in graduate education. However, in spite of

the importance of quality graduates to our national economic health, as best I can tell we have no national strategy for funding graduate education. Moreover, I would argue the attempts to tinker with the system during the Reagan years in the White House were wrong-headed and counter-productive, largely because they too failed to understand and appreciate the objectives of a proper education (at any level, in fact). If the objectives were not clearly understood, can it be surprising that the result of the changes have made them more difficult to achieve?

For the past few decades (the “Post-Sputnik Era”), a significant portion of graduate student support has come from research grants to individual faculty members. I do not agree with the sometimes expressed view that this linking of research funds and graduate support necessarily corrupts the system. If research funds are given primarily to those with the best ideas and track records (and one must assume this to be the case, at least on the average), then one can argue that graduate education is enhanced by this external support since it insures that a significant portion of the students will be advised by those best able to do so. Obviously, this can only happen if there are entry points into the system of funding for new research advisors, not only young investigators but older rejuvenated ones as well. ⁴ Before leaving this point let me remark that the efforts of the past decade to provide for young investigators, together the shrinking budgets (in real dollars) for individual investigators and the “center-ization” of significant fractions of the remaining funds, have had the effect of concentrating the advisement of PhD students disproportionately in the youngest and most inexperienced faculty. However, bright the young turks may be, this can hardly be regarded as a reasonable utilization of resources.

In spite of the abuses which can arise from evaluating faculty by their research funding, let me state that I do believe that it is appropriate to use research support as *one* of the measures of graduate faculty performance, since the awarding of grants is in and of itself an external evaluation of the quality of one’s ideas and work. However, I personally do not believe either grant support or publications to be among the most important measures (especially in tenure considerations), and very much reject the bean-counting evaluations which often replace a thoughtful analysis of one’s contributions.

Now having defended the system, let me concentrate on what I believe to be its short-comings. I have already indicated how I believe it has corrupted our thinking in academia, and particularly how it has distorted our self-evaluations. However, this is not the fault of the system, as much as of the people who have chosen to exploit it. The principal problem of the *research* funding system as regards graduate education is that it is only superficially concerned with

⁴It is often overlooked by Contract and University administrators alike that the vitality of one’s ideas and ability to exploit them are very much influenced by the cycles of normal life (eg. marriage, divorce, health, sickness, and the multitude of family problems arising from children and aging parents). Lack of productivity from these causes is usually only permanent if exacerbated by administrative decisions which fail to recognize what is really going on.

education. Now this is in spite of the fact that many of the agencies funding basic research in universities evolved, at least in part, because of perceived inadequacies in graduate education in this country in the 1950's. Simply put, agencies which were intended to further the scientific agenda of the country by providing for the training of scientists, have become largely agencies for forwarding the scientific agendas of the people who run them. Now this is not meant to be a criticism of those people, whether they be individuals in the government employ or committees of scientists chosen from our peers. Nor is it meant to imply that the government should not set priorities nor direct resources into particular areas of research which it deems to be particularly relevant at a given time. Rather, my criticism is directed at that the system which sends monies to universities with little or no commitment to finish the students who are expected to carry out the work.

But, you might object, NSF and most other basic agencies are very concerned that their funds be used to support graduate students, and regularly require reports showing that the funds are so expended. True, but when is the last time one of your students was able to complete his Ph.D. dissertation while being supported by the grant under which his studies were initiated. In my experience, NEVER! Not in a single case has the grant been of long enough duration to allow the student to complete his program (typically four to five years from BS degree). In every case I have been forced to beg, borrow or steal from subsequent grants, usually intended for different tasks, to allow the student to bring himself and his work to reasonable completion. In most cases, the expected renewals did not materialize because the national agenda was perceived by the agency to have changed. Or even more often, the contract monitor had changed and the replacement wanted to pursue his own agenda. The progress of the work, or even impact of the results already produced was seldom an issue. And in the few cases it was, it was because of the necessity of using the present grant to finish the students initiated under the previous one.

Now it might be argued that I simply have not adapted to the funding realities, and allow my students to take too long. I indicated earlier my opinions of the products of advisors who have made this adaptation. In spite of my problems in finishing the research and keeping the student solvent, I am reasonably pleased with the end product. I am especially happy that extended and expensive post-doctoral positions have not been necessary to remedy the deficiencies of their graduate education. However, I am not happy with the aggravations, uncertainty, and financial duress which has been unnecessarily endured in order to reach this end. Nor am I happy with tensions which invariably arise between sponsors who want results on their time-table and university investigators who are dependent on students for those results.

In addition to these rather obvious consequences of not providing support for long enough periods of time, there are ethical questions and practical consequences as well. Foremost among the former is whether a university, department or faculty member can in good conscience accept any PhD student with the im-

plied promise to support him which is present in all letters of admission to graduate school with financial support. The fact that these letters are qualified by phrases about the availability of funds mean little to the entering student who does not understand the practical realities of what this may entail for him personally. And when they finally do strike home, he is well into a program and has little choice but to continue or lose everything. It is then no small wonder that many leave graduate school (even with a PhD) cynical about both science and the system. Nor can it be surprising that a significant proportion of their equally qualified, but more discerning undergraduate classmates decide to avoid graduate school entirely. The problem is not helped by the fact that it is often these unhappy graduate students whose support has expired who are the very ones we install as teaching assistants in a effort to keep them around until they can finish, thereby enlightening the next generation about the realities of graduate school.

The problem, quite simply as I see it, is that the sponsoring agencies fail to recognize two things: First, that the student is as much a product of the research effort as the results he produces. Second, that it is unrealistic to expect any PhD program to be completed within the two to three year period of most research grants. The solution to the first problem just requires acknowledging the truth of the statement. A solution to the second is as simple as making funding commitments for more realistic time periods, say five years, even if the levels of funding must be proportionately reduced. These changes, coupled with a bit more integrity on the part of faculty advisors in taking on students in the first place, would go a long ways toward alleviating the problem.

Let me make it clear that I do not advocate the direct funding of graduate students via national research fellowships and traineeships, at least not on a greater scale than at present. However well-intended these programs may be, their impact is often more mischievous than useful. First, they can have the effect of leaving the student in sole charge of his program and in control of his own research. While neither of these is intrinically bad, they can leave the student as a foster-child in a system which does not work that way. This second class status is exacerbated by the fact that these student grants pay little to none of the real expenses of the education beyond tuition. For example, they contribute little to the overhead of maintaining the research environment, its staff and equipment, nor do they contribute significantly to the support of the advisor, a necessity in modern research universities where faculty like to be paid. Thus they at most can be used to supplement research support which has been obtained elsewhere, or to finish off a student after the major expenses of his research have already been incurred. When used as the primary vehicle for the support of a PhD program, they become, in fact, simply a means for one funding agency to leach the support of other agencies who are properly bearing the expenses of their programs. That these programs are allowed by universities at all is a measure of the desperation of the university community which uses them to survive.

I do not believe the principal question to be the level of the support for the individual student, and have, in fact, come to believe that a certain amount of financial sacrifice is an essential ingredient to a reasonably paced PhD program. Our efforts over the past decade to compete for quality students by buying them have not in my experience produced better students. Far more important than the amount of the funding, assuming it to be at least subsistence, is that it be stable throughout the program, and that it be tied to at least general research objectives. The former insures that the student need not panic and abandon his efforts prematurely, while the latter insures a quality advisor and focuses him more quickly on his objectives. Thus, I would not advocate a wholesale overhaul of our system of research funding for graduate students; merely a more clear recognition of what its objectives should be and a greater sensitivity to what is necessary to achieve them.

The question of proper support for graduate studies is not one which can be taken lightly if we are not to be totally dependent on imported talent by the end of the next decade. We have already witnessed the effects of the absence of a national policy for graduate support by the high percentage of PhD's received in this country by non-Americans. These percentages are reflected in the hiring of PhD's to fill the demand for highly qualified people by universities, industry, and government. To-date these needs have largely been met by at least the products of our own system of higher education. In the next decade, more than half of the engineering faculty in this country will retire. The impact of this impending avalanche and the short-fall in our domestic production of their replacements is already being felt in the rapid escalation of faculty salaries relative to those of industry and government. This has already led the government to place ceilings on how much they will reimburse faculty from research grants, and may have played at least a subconscious role in the decisions to shift funds toward younger investigators (who make less, at least less than their contract monitors). With the emergence of Europe and Asia over the next decade, it is unlikely that the brain drain on which we have come to depend will continue, so these strong upward pressures on salaries will be felt outside universities as well.

Thus if we are to meet our national needs, and avoid pricing ourselves to a level where the public decides that science is a luxury it can do without, there must be a national agenda for graduate education! And if we are to be happy with the products produced by it, that agenda must recognize what a proper graduate education is!

7 Final Word

I would like to conclude my remarks by considering briefly the impact faculty advisors have on graduate students. It was noted with humor by visitors while I was at Penn State that John Lumley's students all drove red sports cars and wore moccasins. And with good reason, many did. And in my own lab, there

seemed to be a remarkable number of pickup trucks which appeared after my own purchase of one. While these were perhaps coincidental, they open for discussion the much larger question of the influences we have on our students beyond the obvious efforts to educate them. Let me illustrate by two examples.

A number of years ago, several of my students and I were participating in a short course on flow measurement at Washington State University. We had given similar courses before and had attracted a wide variety of students ranging from novice engineers to experienced scientists. At this particular course, one student immediately attracted our attention by her insightful comments and questions. It was clear that she had a different perspective than most, but seemed particularly tuned to our own way of looking at things. This was first called to my attention by my students who commented that it seemed as though she had been educated in our laboratory. After some questioning we learned she had received a PhD from a university which we did not recognize for its contributions to turbulence research, nor did the name of her dissertation advisor even register. How could someone from so far away from our own intellectual heritage, reason and express herself so like us. It was only after several days of being puzzled that the pieces finally fit. At Cal Tech some years earlier on the large chart celebrating the hundreds of academic descendants of Professor Hans Liepmann, I had seen the advisor's name listed as a fourth generation member of that list, my own generation. Neither his advisor nor mine had ever worked under Hans Liepman, nor had any of us even studied at Cal Tech. Both of our advisors, however, had studied under his first student, Stanley Corrsin, at Johns Hopkins. Obviously the intellectual heritage had been passed through four generations so clearly intact that both my students and I immediately recognized it as our own.

The life-changing impact we have on our students was further driven home to me by an incident which occurred in an undergraduate gasdynamics course I taught last spring. I had not previously taught such a course, nor had I ever even taken one. I acquired the responsibility in a last minute teaching shuffle, so accepted the book which had previously been used. In the middle of a lecture on why the isentropic sound speed is the appropriate choice for the speed of sound propagation (There are other possibilities, like the isothermal, etc.), it occurred to me that the text's explanation ("Sound waves travel too fast for significant heat transfer to occur.") was probably hog-wash, and I so informed the students. After a rather long excursion into the entropy equation, and the nature of sound waves we decided that, in fact, it was the weak amplitude of the sound waves that was crucial to their isentropic propagation. Our finding was summarized in a few rather cryptic sentences (on the blackboard) stating our result and criticizing the book's statement. You can't imagine my astonishment when one of my graduate students appeared a few days later with the notes from that lecture and a copy of the classical text by Liepmann and Roshko (written in the early 1950's at Cal Tech). There in a footnote, almost verbatim, were my words. So profound had been the impact on my thinking by my mentor, and on

him by his, and so forth, that both my analysis and words seemed predestined.

The personal examples above, I believe amply illustrate both the best and the worst of graduate education. That the explanation I was challenging was still being offered in undergraduate texts, after having been trashed so many years earlier, shows that not all of the traits we pass on through our students are good. Just as we subconsciously learn from our parents the near-reflex responses we use in raising our own, so do our students learn from us. And just as we try to screen out by adult analysis those things we have inherited which are not good, so must we as advisors enable our students to improve on our legacy to them. This we can do if our primary object has been to teach them to think. And that should be the real goal of any education.

The comments and ideas expressed above are a highly personal view of graduate education in fluid mechanics and turbulence. Certainly I am not naive enough to believe that my ideas are the only ones which will work. History certainly would dispute that. Also I'm not really old enough (45) to even be able to say with confidence that these ideas have worked for me. However, I suspect that most of what I have said has been gleaned from my own experiences, observations, and particularly my associations. To the extent that this is true, then it is reflective of traditions begun by von Karman, Prandtl and Taylor (intellectual giants of the field in the first half of this century), not to mention their highly successful students and students of students, some of them my mentors. Thus if the objective of a graduate program is to produce independent thinkers who continue the tradition, and if I have correctly devined why these men have left us such a legacy, then I am on very firm ground indeed. Regardless, I thank you for the opportunity to refine my own thinking, and to share it with you.