A PLAN FOR GRADUATE STUDENT RESEARCH IN ENGINEERING

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IT IS THE AUTHOR'S opinion that a great many graduate students in engineering research fail to achieve their desired objectives in an efficient manner because of poor planning and lack of foresight.

One approach to the solution of complex problems is that of systems engineering and it would seem logical because of its success in so many other areas, to extend its use to the design of a graduate research program. The purpose of this article is to attempt to show how this process could be systematized and to indicate to the student how he might conduct his research program with greater success than that generally achieved.

A system, in general, can be envisaged to consist of five major components; a process, inputs and outputs of the process, feedback and evaluation. A model of the proposed system which incorporates all of the above elements is shown in the figure. Five separate overall phases can be identified: 1. problem formulation; 2. design; 3. production; 4. operation; and 5. completion.

It is not suggested that this scheme is the only one that could be envisaged; nor is it expected to cover every possible contingency. No doubt such a plan does not account for every possible situation that might arise. It does however represent an outline with which a graduate student could organize his research program and does provide guidelines along which the research can proceed.

PHASE I PROBLEM FORMULATION

The student, at the beginning of his research, will usually find himself with what appears to be a rather vaguely defined problem (e.g., "A Study of the Behaviour of . . ." or "An Investigation of . . ."). This vaguity will prevail since at this point the student and his advisor can seldom formulate the research topic in terms of simple explicit questions. The purpose of Phase I is to help overcome this difficulty.

The needs analysis is essentially a critical look at the overall situation with a view to identifying a specific research problem, i.e., an engineering statement of the project. Relevant factors affecting this process, i.e. inputs, include various aspects of the student's character, that of the research advisor and of the University itself.

This analysis will yield two specific outputs. These are, a desired course work program and the definition of a general area in which to perform the literature survey.

The course work program cannot (and should not) be dictated solely by the nature of the research project. However, since one major function of course work is to prepare the student to solve his research problem, the course work program must have some definite relation to the anticipated research activities.

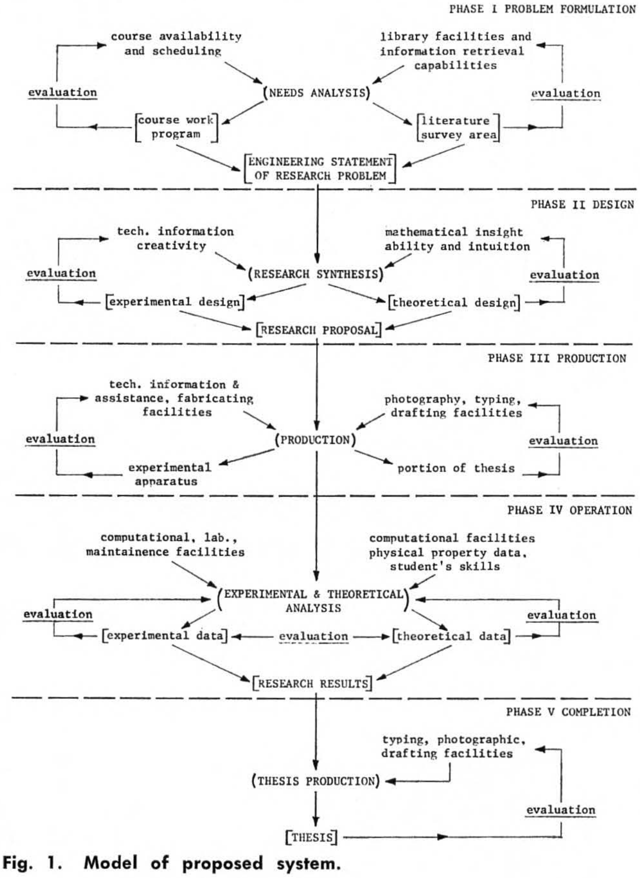
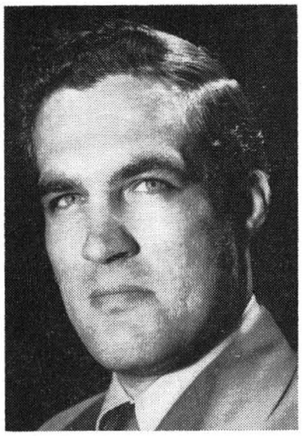


Fig. 1. Model of proposed system.



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Commensurate with the course work, the student should conduct an extensive literature survey. This point cannot be overemphasized. If the student is ever to get a clear picture of what needs to be done, he must be familiar with what has already been done.

Like the course work (which is evaluated by examinations), the literature survey itself should be evaluated. It is important, when attempting to formulate a problem, to be sure that the literature survey is complete (within reason) and that the student has a fairly good comprehension of the pertinent related research material. It is not uncommon for students to spend a great deal of time trying to solve problems which are either unsolvable or have already been solved. The evaluation of the literature survey should be conducted by the student and his advisor on a fairly regular basis throughout Prase I.

The graduate course work together with the literature survey should eventually lead to a crystallization of the specifics of the research problem and hence to a relatively clear engineering statement of the project. This becomes the major input to Phase II.

PHASE II DESIGN

This phase of the process represents the first step toward finding a solution to the problem previously formulated.

Generally speaking the research activity will call for both theoretical and experimental analysis. The relative importance of each will of course depend on the previous activities. One can loosely describe three different kinds of relationships between experiment and theory and it is helpful if the student recognizes them at this stage. They are:

1. An experimental analysis to confirm or deny some previously documented theoretical analysis.
2. A theoretical analysis to be performed to ascertain the important parameters responsible for a particular observed behaviour. (More often than not this observation has been made by the research advisor in some prior experimental work).
3. Experiment and theory are developed simultaneously, one complementing the other in an attempt to a) learn the important parameters and observe a real system's behaviour and b) to predict system behaviour both within and outside of the range of experimental analysis.

The first approach has one serious pitfall in that the student can attempt to design the experiment to confirm (or deny) the predictions of a theoretical model which (due to various assumptions and approximations) is in itself far removed from reality. Hence the experiment becomes the representation of a fictitious situation and the subsequent experimental results can serve very little practical purpose. The second approach above has the inherent drawback that the student himself, in an attempt to explain an observed phenomenon, can become enveloped in the fog of his theoretical hand-waving and risks losing sight of the actual physical system under consideration.

Assuming approach (3) is utilized the Design Phase should entail the simultaneous development of appropriate experimental and theoretical models. Let us consider each of these activities separately to establish the important inputs and outputs of each of the sub-processes.

Exactly what patterns of behaviour the experiment must be capable of illustrating should be relatively well established from Phase I. A successful design must have as inputs the pertinent technical information from equipment suppliers and a certain amount (the more, the better) of that somewhat elusive property, creativity. Both of these are essential to a good experimental design. At the same time, a dialogue must be established and maintained between the student and technical support staff. All too often a poor design is the result of the student's inability to comprehend the difficulties associated with the construction and operation of the experimental equipment. This results from the common lack of exposure that graduate students have had to the "nuts and bolts" world of practical engineering. The experience of the machinist, the tech-

A methodology for research does exist and the scheme described herein represents a useful and valid approach to this problem.

nologist, and any resident project engineer is a commodity to which the student must avail himself if he hopes to produce a workable experiment.

Also important to the above activity is the interchange of ideas between the student and other students working in similar fields. The greatest contribution that these colleagues may make however will usually be in the area of the theoretical model proposals. Other students do not have as clear a picture of the aims and purposes of the experimental analysis and hence can usually contribute little to the design of the experiment. However the basic laws of nature as represented by the usual mathematical symbols should be reasonably well understood by all involved in research. In this case it is not unlikely that other students may be able to suggest possible approaches to the structuring of the theoretical model.

The theoretical model proposal at this stage is really no more than an attempt to define the pertinent equations, assumptions, approximations, etc., that are necessary or required. In this regard a vital input is the student's mathematical insight. This is much akin to the creativity input of the experimental design process. Both of these properties are rather intangible and will vary radically depending on the particular student's abilities.

As with any other process there must be an evaluation phase. When the student and his advisor are reasonably confident of their efforts, an evaluation should be conducted by some committee. The composition of this committee is a matter for each particular institute to decide, but would usually include two or three faculty members and perhaps even one or two students whose activities are aligned with those of the student and his advisor.

A written proposal of the aims and purposes of the research along with the experimental design and the suggested theoretical approaches should be presented to the committee for study and evaluation. The committee should look for shortcomings, apparent hurdles and errors in analysis or judgment. It should then make suggestions accordingly. The outcome of this evaluation will be suggested modifications to the experimental design and possible guidance to the solution of the theoretical model.

Following this, the student is ready to enter the next phase.

PHASE III PRODUCTION

After consideration of the recommended design modifiications, the construction of the experimental equipment can be undertaken. Much of this construction will often be performed to a large extent by persons other than the student (i.e., machinists, electronics technicians, etc.). As a result he will find some time available. However instead of continuing to develop the theoretical model, the student can receive a great deal of satisfaction in beginning to prepare his thesis. At this point many of the figures can be drawn (especially those pertaining to the experimental apparatus) and at least a good portion of the introduction can be completed. In addition to the fact that this procedure is time-saving, it provides something of a welcome relief from the intense activities leading up to the committee evaluation of Phase II.

The length of time required for Phase III will depend of course on the complexity of the experimental design, the availability of machinists, drafting facilities and so on. The evaluations shown in the figure should be conducted by the student and his advisor and may entail the building of prototype equipment, the running of preliminary experiments to check-out the apparatus, the modification of figures and write-up etc.

At the end of this production phase, the student should be ready to enter Phase IV.

PHASE IV OPERATION

It is this phase of the overall process that will yield answers to the research problem. Most of the activities here will be conducted solely by the student since, to be sure, he will know more about the research project than anyone else. The performing of the experiments and attempting to solve the theoretical model become a rather private affair. The dialogue between the student and advisor will be primarily a transfer of information from the student to the advisor relating the progress of the research.

The experimental and theoretical analyses are indicated in the figure as a single process even though, of course, they can hardly be conducted simultaneously. Nevertheless, both must be conducted at regular intervals (i.e., a test program followed by theoretical analysis follow-

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ed by another test program and so on). Undoubtedly, the completion of any one sub-process will indicate to a certain extent the subsequent sub-process.

The inputs to this process include the student's skills and attitudes, the availability of computational facilities for data reduction, curve-fitting etc., and other equipment and facilities (e.g., chemistry laboratory, darkroom, maintenance equipment etc.).

As with all other processes there will be an evaluation stage. During this time the experimental data is compared with existing data and with the predictions of the theoretical analysis. Modifications to the experimental test program can thence result. Similarly the theoretical data is evaluated in terms of required accuracy, range of variables considered and is compared with the experimental observations. The evaluation here could lead to a modification of the analytical techniques and a relaxation or tightening-up of certain approximations.

Eventually, after perhaps several trips around the feedback loops, there will be compiled a complete set of research results that satisfied the problem initially formulated in Phase I. This is however, not the end of the graduate student's activities. The information collected in Phase IV is of little value until it is transmitted to others. This is normally accomplished by the writing of a report or thesis.

PHASE V COMPLETION

Of all the graduate student's activities, this one tends to be the most tedious. The excitement of discovery is over. There remain the rather mundane tasks of preparing assorted graphs, tables and drawings and in the seemingly endless writing and rewriting of text.

Throughout its production, the thesis will be constantly evaluated in terms of its accuracy, clarity, and completeness. After a period of time (usually much longer than anticipated), the thesis will be completed to the satisfaction of the student and his advisor. It will, at that time, usually be subjected to the further scrutiny of other readers and quite possibly further changes could result. In addition an oral defense of the thesis will normally take place.

The thesis, the output of Phase V, is in fact the physical satisfaction of the need first considered in Phase I.

CONCLUSIONS

In an attempt to make graduate students aware of the various aspects of a graduate research program and to enable such students to cope with them in an efficient manner, a formal systematic procedure for graduate research has been suggested. This plan is felt to be applicable to most situations. Deviations from it can be conceived; however, they would in general be a reflection of an individual's inability to adhere to a formal logical systematic plan for research. It is the writer's contention that, like the design process itself, a methodology for research does exist and that the scheme described herein represents a useful and valid approach to this problem. □

SLATTERY (Continued from page 176)

ing or developing courses in momentum, energy, and mass transfer, are faced with unchanging alternatives: survey or in-depth study? I will agree with you if you maintain that every course is a survey. But I will also insist that we do have more of a choice here than is commonly apparent in most areas.

Years ago, there was not much of a decision to be made. It was essential that a student have an in-depth understanding of piping design, heat exchanger design, and (distillation, extraction, absorption) column design, since nearly all of our students went into either petroleum refineries or the large-scale production of chemical intermediates. While these are still very useful skills to have at one's command, they are not sufficient for the wide variety of industries that are becoming possibilities for employment.

The beginning graduate sequence that I have been discussing here is a survey of momentum, energy, and mass transfer. By no means can you tell a student everything that is important to know in two or three quarters. My aim in teaching these courses is to fill in some of the more glaring holes that are of necessity left by a typical undergraduate sequence and to give a student a good foundation upon which to grow, no matter whether he is thinking in terms of a terminal M.S. or Ph.D. degree. □