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Teaching for Research in System Dynamics

by

George P. Richardson
Simon's Rock Early College
Great Barrington, Mass

David F. Andersen
Graduate School of Public
Affairs State University of New York
at Albany, Albany New York

Abstract

System Dynamicists must find innovative ways to combine teaching and research in System Dynamics, using teaching to draw a pool of interested students into the subject and using research to teach advanced modeling techniques to intermediate and advanced students.

Four formal designs are presented for combining research and teaching interests. The pitfalls and advantages of each of these strategies are discussed and examples given of the results that may be expected from each approach. Three critical classes of considerations are found to influence the success of joint research-teaching programs: faculty roles and responsibilities, student readiness, and project selection and management. Each class of considerations

is discussed in detail with reference to concrete examples.

Teaching for Research

The problem-centered nature of system dynamics makes it an ideal medium for encouraging student research. For students beyond the introductory level, research on problems in their own areas of interest can be significantly motivating. In addition, exposure to the trials and tribulations inherent in applying system dynamics to real problems, less cooperative and well-defined than the typical modeling exercise, provides the greatest opportunity for student conceptual development.

The need for teaching for research is also suggested by the relatively small number of students moving to advanced work in system dynamics at many schools. Lacking enough students to warrant three or four courses in the subject, system dynamics programs can turn to student research projects as a way of developing competency approaching self-sufficiency. Moreover, teaching for research can help to overcome the lack of a critical mass of system dynamics professionals which exists at many places where the subject is pursued. To some extent student research projects of various designs can supply the atmosphere of exploration and progress that encourages professional growth.

Designs that Teach for Research

While the desirability of teaching for research may be clear, the management of student research projects often proves troublesome, if not disastrous. In this article, we outline and compare four basic designs, with which the authors have had experience, for managing student research projects. After the four basic designs have been presented, the article explores potential pitfalls, reasonable expectations, factors influencing success, and the meaning of 'success' in each design.

Fully-Funded Graduate Research

The Cadillac of the various possible research-centered teaching designs is fully-funded graduate research. Faculty members who have received grants to pursue a specific substantive topic employ graduate students as research assistants. These arrangements, often involving thesis research, do not have many of the classroom management problems discussed below. Typically, the principal investigator retains full responsibility for the project, delegating pieces of the work to graduate students. The research is an integral part of a student's total graduate learning experience.

Although this design is in many ways the best possible one, it will be of little interest to us here. We are more interested in the problems and potential of teaching for research in institutions where the critical mass of professional system dynamicists (including advanced students) is not yet sufficient to support a fully-funded graduate research program.

Class Research Teams

In this design, student research is pursued within a given course. Students divide themselves into groups of two or three, each group selecting a problem to study with the aim of producing by the end of the term a working model and a paper describing their work and conclusions. The instructor evaluates proposals for topics, accepting them or rejecting them. Throughout, the instructor is not directly involved in each project, but acts as an expert resource for all. In the class context, the teacher evaluates each project at the end, the evaluation presumably contributing to the student's grade in the course. Typically students retain a large degree of responsibility for choosing the topic to be studied. The goal of each project is a report that approaches publishable quality or may be of practical use to a client in a consulting relationship. The key to success or failure of these projects rests with the instructor's ability to sense what projects are workable.

The principal danger of class research teams is that problems will be inadequately defined. Work will proceed prematurely toward writing equations or hypothesizing structure before the details of the problem definition are adequately understood. A poorly defined problem means a splintered team effort and little possibility of help from the instructor or the rest of the class.

Adequate problem definitions may still not solve the problem that the instructor, not being knowledgeable in all areas, is sometimes hard pressed to provide the necessary help in model formulation. Often useful is the requirement that each group of students connect with some other (willing) faculty member, who can act in an informal way to supply the area expertise the instructor may lack.

Independent Study Projects

Independent Study projects are a variant of team research projects with the size of the team being just one person. The above caveats concerning logistics, problems and levels of expectation for class teams hold, in genral, for individual projects. However, our experience suggests that several trade-offs exist between the two designs. In individual projects, students have a greater chance to experience the entire range of difficulties and rewards associated with model building. However, especially during the initial conceptualization phase there is an increased danger that students will be unable to make progress. Because of the time-consuming nature of the one-on-one help required, independent study projects are not advisable in a class containing more than five students. Even with such a small class, instructors should closely examine the readiness conditions presented below before starting a class on independent projects.

Whole Class Research Projects

At a first glance, whole class research teams might look like another variant on team research projects with the size of the team set equal to the size of the class. However, when a whole class design is used, student/instructor relationships are markedly different along three dimensions.

First, in whole class projects, the burden of problem definition rests more squarely on the faculty person. Since the entire class cannot make progress until a problem is clearly defined, the instructor must initially assume the responsibility for choosing a workable project. Second, the increased level of faculty responsibility for the study implies that the final product of a class research project may look more like a publishable article than a student research paper. Third, when the class reaches a hurdle of some sort, the responsibility for making progress rests more on the faculty member than the students. The overall project may make greater progress, but individual students will gain less experience surmounting difficulties on their own. In general, the difference between team projects and whole class projects pivots on the levels of risk and responsibility assumed by faculty and by students.

In review, we have sketched four designs for combining teaching with research in the classroom. They all differ with respect to the logistics of classroom management, the probable product, and the division of risk and responsibility between students and faculty for project completion. Which design to choose will depend on class size, student readiness and motivation to pursue research, and an individual faculty member's own goals and teaching style. However, certain common factors will be critical for successes in research-centered classes no matter which design is chosen.

Factors Influencing Success

A research-centred class will differ from a class centered on instructor-initiated exercises in two major ways. First, in research, students will deal with the same problem over and over again for the entire term. This iterative process differs significantly from the process in which a student attempts an exercise, does well or poorly, and then moves on to the next exercise. Again and again, a research problem returns to the student, demanding reformulation. Students are drawn more deeply into a single problem than they have ever been before. Managing this in-depth exposure to a single problem can be frustrating to an instructor as well as the students, but if it is well done, students learn much and produce exceptional, often publishable, work.

The second difference between a research-based class and a regular system dynamics class is that students in the former must grapple with the difficult conceptual end of model building. Typically, in a classroom exercise the instructor completes much of the task of framing a problem, presenting the student with a "canned" problem whose solution teaches the student to formulate and test formal models. Two critical steps, problem recognition and system conceptualization, are not taught in this usual process.

An instructor interested in developing a program of in-class student research must consider three stages in such projects: initiating a project, making progress in spite of difficulties, and assembling a final product. A number of problems and trade-offs exist in each of these stages, as the following sections describe.

Project Initiation

At the outset of faculty-guided student research projects, three areas of concern deserve attention: the motivation for undertaking a project, the readiness of both the student and the teacher for such a venture, and the selection of the topic. For the success of the project, the most important consideration - the key determinant of success or failure - is topic selection.

Topic Selection Settling on an appropriate topic for student research is the most difficult part of a system dynamics study. The length of the academic term in which such research is usually carried out imposes a particularly significant constraint. Moreover, for students relatively new to the system dynamics approach, even the recognition of a suitable problem for study is difficult. Past training may have left them with visions of only two kinds of problems - relatively small ones yielding to familiar analyses, and global, apparently unsolvable problems - neither of which is particularly appropriate for a term-long study leading to a feedback model. Topic selection is even more difficult, however, because it includes the high-level tasks of problem definition, initial system conceptualization, and delineation of the scope and purpose of the project.

Whether the design of faculty-guided student research is independent study, in-class term research, or whole-class research, the selection of a topic must be communicated clearly in a written proposal. Minimally, the proposal should include the following sections:

- Problem Definition
  - Verbal description
  - Evidence for the existence of the problem
  - Reference behavior modes
  - Principle variables
- Purpose
  - Purpose of the study
  - Potential uses of a model
  - Initial statement of policy levers

Initial System Conceptualization
System boundary
Levels inthe model
Initial statement of important feedback loops

An initial list of references, annotated, if possible, is often important in the study proposal, but there is potential for misdirection in such a requirement (see "Information Overload"). The list of ingredients for a statement of a topic may seem to go beyond topic selection into analysis. The detail is necessary, however, because all of it contributes to the decisions of the faculty member and the student whether or not to proceed with the study as described.

In class research teams or independent study projects, a student's written study proposal serves to acquaint the teacher with the proposed problem and to focus the student directly on the difficult task of problem definition. Approval of a topic for study should be contingent upon the clarity of the problem definition and the purpose of the study, the degree of familiarity the student (and perhaps the teacher) has with the problem, and clear evidence that in the time available a model can be completed. The teacher must make a judgement of the do-ability of the project. Guiding rules of thumb are sometimes helpful for both teacher and student, e.g. "no more than four levels (state variables)." It is far kinder to be strict, rather than forgiving, during the phase of topic selection and problem definition. Second and third drafts of a study proposal are often required before clarity, focus, and do-ability are obtained. The teacher's guiding principle should be when in doubt, do not approve.

A written problem statement is also required for whole class research, but in this case the instructor is responsible for the study proposal. Initial system conceptualization, usually a part of an acceptable problem statement, may be done with profit with the entire class, but no doubt the same ground has to be covered by the teacher in camera before presenting the problem as a topic for whole class research. The complexity of the model resulting from whole class research may be greater than that of individual students or teams, given that tasks and sectors of the model can be farmed out to different groups within the class. Complexity of the model or of the problem however, cannot be allowed to manifest itself as a lack of clarity in the problem statement.

Topics most likely to lead to successful models include extensions of existing system dynamics models, models capturing established theory behind familiar dynamic phenomena, and problems arising in systems having vividly clear structure. A student might study, for example, the financial problems of large cities by adding a financial sector to an existing urban model (1). Or he might explore the societal responses to limits to growth by adding societal perceptions and reactions to the structure of WORLD2. (2) Problems involving stocks (levels) as obvious as inventories or capital equipment are far easier to conceptualize than problems in areas such as psychology, for example, where the "accumulations" are harder to discern. The more unfamiliar the topic and the more likely that a study, if successful, might break new ground, the more risky the project. Once again, it must be urged: when in doubt, don't approve.

In class research designs, the teacher must be prepared with "back-up" suggestions for students whose topic selection efforts fall short and who decide that a project of any sort is impossible for them to invent. Some students lack a sufficiently large pool of problems they are aware of and interested in and which are also do-able. Others, armed with a methodolgy relatively new to them, lose courage as they confront a real problem. Teacher preparedness here helps to prevent embarrassment or failure.

Readiness. Model building is theory building. A first requirement for pursuing a study whose aim includes the building of a model is the recognition of the role of models in understanding (structuring) reality. There is evidence that college-age students at an early stage of development may be simply unable to perceive the relativistic nature of the validity of the model. (3). A second and certainly related requirement is a knowledge of the pattern of inquiry in system dynamics. The system dynamics approach to a problem can be described in terms of seven stages of phases (4), which must be listed in an order but which occur in practice iteratively: problem recognition, system conceptualization, model representation, model behavior, model evaluation, policy analysis, and model use. A student who hopes to complete a successful system dynamics study must have some familiarity with all seven of these phases and with the iterative structure they form together.

All seven phases are important, but the first two are often the most difficult. To propose a topic for a system dynamics study, one must be aware of dynamic problems. A concomitant requirement is the skill to look at a problem and find within it a focus that may be stated in graphical terms over time. Problem awareness and problem definition in dynamic terms are often slighted in academic work, even in system dynamics courses, but it is clear that a successful study proposal depends upon the skills and knowledge they represent. Because of the greater teacher role in the whole class research, less student background in problem recognition (and perhaps the other phases as well) is required in that design.

For all the research designs, teacher readiness is as important as student readiness. Because system dynamcis is rather like a "science-aided art", the instructor attempting to guide students in its practice must have talent and experience in the art himself. We venture to claim that an instructor who has not developed at least two models of his own is not ready to guide students in their modeling efforts. It is clear from the focus of this paper that we also feel that the teacher must have thought through the details of teacher and student responsibilities in such projects. The instructor must be ready to help students overcome the hurdles that naturally attend a modeling project: maintaining students' motivations for their projects in the fact of setbacks and the iterative re-thinking that characterizes modeling is one of the teacher's most important and difficult roles.

Finally, in any of the research designs, the time will surely come when the model does not behave properly and the student turns to the instructor for redirection. The instructor must be prepared to find faulty structure, discover "bugs" and save the day when all seems lost. A healthy mix of experience, intuition and an extensive mental catalog of elementary structures and behavior are the teacher's best preparation. Luck helps. Readiness for the trouble-shooting role is particularly critical in the whole class research design, in which the teacher will often be saddled with the entire responsibility for saving the project when it stalls.

Motivation. In the face of difficulties in the project and the normal, repetitive, iterative nature of the model-building process, the student's belief that its all worth the trouble may falter. The strongest motivation for students pursuing teacher-guided research is the promise of greater competence. The difficulty and the learning possibilities inherent in one's first significant modeling project should be continually emphasized. The final product may serve as additional motivation, if for example, the goal is a publishable study (or the beginnings of one).

The topic is a strong motivator in the team research and independent study designs: the student has the opportunity to do original work on a problem of his own choice. The motivations of the faculty member for coordinating such research are primarily the rewards of teaching. There is also the benefit of a diversity of research projects and the atmosphere of an active system dynamics research group, even though one may not actually exist outside the class.

In whole class research, some students will be exicited by a given topic and others will not. The primary motivation for students in this design is the opportunity to work on a real problem and a relatively large model under the direct guidance of an experienced system dynamicist. The faculty member's motivation, in addition to the rewards of teaching, should include publication. The project can well serve as the initiation or development of an area of personal research, leading perhaps to funded research.

Making Progress

In all the research designs, motivation during the project will at times undoubtedly flag. Modeling is more rewarding - but more annoying - than many of the other academic undertakings students will try. The designs have to be structured to attempt to insure that progress will be made with clear consistency. The biggest problem the teacher faces is how to help the student over the hurdles that will inevitably appear. Careful project staging or timing can help to minimize the hurdles, as will sensitivity to common hurdles such as an "information overload".

Hurdle-jumping Next to topic selection, hurdle-jumping is the student's and the teacher's biggest problem. Projects must be designed to anticipate hurdles and minimize them; they won't be eliminated. Difficulties of all kinds will appear: levels will be unclear; a casual-loop diagram will resist all attempts at quantification; the model will oscillate when it shouldn't; an inventory will become negative; and so on. Perhaps the biggest hurdle is the modeling process itself: its iterative nature makes progress sometimes difficult to perceive. Fortunately, while hurdles may be troublesome, they are also the points in the process where the greatest learning can occur.

Problems that appear near the beginning of a study are usually conceptual, concerning questions of problem definition, aggregation, system boundary, and so on. Later, technical difficulties are more frequent, such as finding errors in computer code, writing an appropriate rate equations, and finding the cause of exploding oscillations. For solving conceptual problems there is no substitute for familiarity with the system involved. A clear study proposal incorporating a vivid problem definition is therefore indispensible. It is fair to say that over half of the conceptual hurdles that appear can be traced directly to a poorly formulated problem. Technical hurdles are easier to overcome than conceptual ones. Particularly useful for analyzing errant model behavior is a mental catalog of elementary structures and behaviors. Seeing an oscillating structure, for example, embedded in a more complex model is worth many computer runs and sensitivity tests to understand model behavior.

Hurdle-jumping in class team research and independent study projects requires extensive teacher time and one-on-one counseling. The time-sequence for the project has to allow for it. To hold the time to a minimum one should never try to debug a model without a computer run attached to a list of the model's equations and a rate/level flow diagram showing the model's structure. Sometimes it can occur that technical problems will lead back to problems of conceptualization. Hurdles that are that drastic can appear insurmountable to the student, and much teacher involvement, even to the point of suggesting a back-up project, may be necessary.

When hurdles stand in the way of whole class research, the teacher may be in a more difficult position than in team or independent study research. The difficulties may be more complex, traceble to several different sectors of the model (with different authors), and they often appear during class and require immediate teacher response. A simplified, highly-aggregated model underlying a complex class model may be useful, for example, as Randers suggests (5). Otherwise there are few armaments for the teacher in this design other than experience, preparation and wit.

Project Staging (Timing)

Management of student research projects in all designs is made easier by a clear sequence of check points at which written reports (or, less desirably, conferences) are required. The first such report should be the study proposal, as outlined previously. Following progress reports, perhaps two weeks apart, should focus on developments in model assumptions and specific structure. As model runs and tests begin to appear, one or more reports should present preliminary results, prior to a final report of the project. These check points are necessary to keep the teacher abreast of developments in each project or in each sector of a whole class model. Lacking them, the teacher must spend too much time "getting up to speed" on a student's work in order to help him overcome any difficulty.

It is useful if the periodic reports include a plan for the work to be accomplished during the next two weeks or so. Such a "management by objectives" technique keeps the student focused on a workable sequence of tasks leading to a final worthy product in the time available, while avoiding some of the problems deadlines generate. In addition, the teacher is kept aware of the work the student plans to do and can redirect if the focus is misplaced.

Information Overload. There are too many possible hurdles to overcome in a modeling project to list them all, but one is common enough and destructive enough to be singled out: the "information overload" phenomenon. Too often students head for the library to collect large amounts of data about their problem before they have sufficiently unambigious conceptualization of the problem and the system with which they are concerned. If more than an hour of preliminary bookwork is necessary to state the problem, then the project is probably unsuitable for a term-long modeling study in the first place; the study proposal should have been denied. Even given a well-focused problem, students too often feel that progress toward a model must wait until all the relevant parameters and initial conditions that might appear in the model are accurately researched and verified. But a system dynamic model need not have the accurate population or tax base of New York City to capture the dynamics of impending fiscal insolvency. Too much information too soon can blurr the student's view of what is dynamically important. The phenomenon of the information overload is sufficiently common and paralysing that we are prompted to claim that one should not go to the library until a model structure is already hypothesized.

Product

A final factor influencing the success of a research-centered class effort is the definition of the final product. In our experience, the output of class projects may be broadly divided into four categories, distinguished by the audience for the research and whether or not the contact with the audience is real or imagined. (See Figure 1).

Figure 1

	CONSULTING	PUBLISHING
REAL	Clients pays for services rendered by project.	Project results in academic publication
HYPOTHETICAL	Project directed at hypothetical non-paying client.	Project intended for personal growth and satisfaction.

We have found that students have been able to complete successfully all four kinds of projects (although some of the final polishing work may spill over beyond the limits of a one-semester course). The most difficult projects are those which place students in a serious consulting relationship with a client who actually pays for professional services rendered. At a second level of difficulty the goal of a student's work is a publishable journal article. Students reaching either of these levels require substantial professional sophistication and probably some prior access to a client organization or some experience with publishing.

However, even those students who may not be able to produce a "real" product should be encouraged to strive toward such a product. Our experience has been that difficult questions surrounding problem definition and system conceptualization can be more easily solved when a research effort is directed toward a clearly defined audience or client, even if hypothetical. In general, a dynamic problem cannot be clearly defined without a specific client or audience in mind.

The intended audience can also help to settle questions of the form of the final product and who carries the primary responsibility for it. Normally, at least several redrafts of a report are required after the major ideas have solidified if the report is to be published or meet client specifications. Students are often willing to leave a project before it has been put into a final polished form. Faculty "ownership" in a project assures that the final product will nearly approximate professional standards. Even if students are not able to attain a polished product they should be made aware of the types of standards usually applied to professional work. In general, realistic expectations suggest that a publishable model will not be completed by the end of one semester.

Realism further suggests that not all student research projects will reach the stage of a working model or a set of policy recommendations. Since the modeling effort is nonetheless likely to be highly educative, the lack of a working model or a sense of completion need not imply failure. Success must be defined in terms of process as well as product. It is reasonable to expect that class research teams will produce in the course of their study a complete and adequate problem definition and intuitive system conceptualization, replete with references and documentation. This portion of their final product should have a strong "face validity", matching what is known about some real problem. It may take most of the course for some groups to reach this stage of understanding. It is also reasonable to expect at least a partial statement of a quantitative model. It is likely that some groups will not be able to preproduce their reference modes before they must cease work on their models; some may not even reach the stage of trying to run computer simulations. If a model is produced, it is very likely it will have the highly aggregated structure of what Randers calls an initial "conceptualization model". (6)

Summary

Four designs for managing teacher-guided student research have been presented: fully funded graduate research, class team research, independent study, and whole class research. The authors find from their experience that the possible obstacles in undertaking in-class research are dwarfed by its potential for significant student and faculty growth.

FOOTNOTES

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