Commentary

Can Educational Technology Theory and Practice Benefit from Systems Analysis?

P. David Mitchell

INTRODUCTION

The purpose of this paper and the research that underlies it is to identify and introduce several planning and decision-taking technologies for both educational researchers and practitioners of educational technology. Not concerned with specific problems or detailed solutions, it examines classes of problems that are common to operational research in complex systems. Educational technologists, to say nothing of other educators, seem unaware of various recurrent phenomena in the problems and systems they study, phenomena that appear to be operative across system levels. Theoretical understanding of such recurrent processes is valuable whether we are concerned with designing and managing a national education system, a small learning resources centre, educational materials production, or other educational system.

The essence of technology and therefore educational technology is knowledge about relationships (e.g., if we perform action X, there is a probability, P, that outcome Y will occur). But it seldom is clear which action X is most likely to produce the intended result Y. Systems research often may help us clarify our decision-making.

LIFELONG LEARNING IN AN AGE OF TECHNOLOGY

This paper is animated by a concern for education, not simply for classroom instruction. More than half the world's children are *not* in school and the global need for . education has been rising. This forces us to refurbish our ideas about how to implement educational aspirations, as well as to augment existing educational manpower. Perhaps more important is that school costs (in both affluent and penurious nations) rise even more rapidly than enrolments or national incomes. We face an inevitable conclusion, "Les fails s'imposent done avec une evidence irrefutable: aucune pays au monde n'a les moyens

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d'assurer par I'ecole seule 1'education dont sa population a besoin" (Gerin-Lajoie, 1971, p. 5). The social ferment of contemporary society no longer permits the luxury of educational research devoted more to personal satisfaction than to improving the welfare of mankind.

Most individuals in the world are deprived of access to stored human experience-ideas, knowledge, skills and opportunities to acquire them. Such deprivation (because no one can afford to provide them) should be morally repugnant to the educational researcher. To make matters worse, only those persons and nations who develop educational autonomy are likely to avoid self-destructive activities. Adaptation calls for continuous education of all members of society. Thus education (as the optimal organization of personal and social development) implies continuity from its genesis at a parent's knee to death. This functional necessity is not limited to institutions organized to provide instruction. Nor is the needed research limited to traditional manifestations of educational research.

THE SCOPE OF EDUCATIONAL TECHNOLOGY

As an emerging field, educational technology may serve as the nexus of educational research and arrangements for fostering lifelong education. Educational technology embraces a fivefold conceptual mosaic of core meanings: Psychotechnology; Information and Communications Technology; Organizational Technology; Systems Technology; and Educational Planning *(cf.* Mitchell, 1975; 1978). Educational technology has become an area of study and practice concerned with all aspects of the organization of educational systems and procedures whereby resources are allocated to achieve specified and potentially replicable educational outcomes. Educational technology is an intellectual and practical pursuit, not a stable product or machine. The theoretician asks: How are educational processes and systems organized? What resources are needed to produce valuable outcomes? The practitioner asks: How must Education be organized so that the maximum benefits of personal and cultural development can be enjoyed for each expenditure of effort and resources? — a basic educational question and one open to continue philosophical analysis, objective research and pragmatic compromise. As a problem solver, one's methods, techniques and tools, as well as his knowledge and values, are derived from many spheres of activity. Educational technology thus requires educational research, albeit of a different kind than that presented in the typical textbook and critically examined by Bernard (1986).

It is pointless to debate whether current educational technologists are too concerned with the interface between the individual and the structure or content of a subject. Education is conceptualized as occurring within a set of systems within systems which range from one person to mankind's collective intentional organization of educational opportunities. Educational technology stands as a bridge between educational requirements and resources, between theory and practice, between a just, educative environment and cultural evolution. And intellectual technologies such as systems analysis, which translate desired outcomes into plans for an operational system, can build such bridges as readily on the scale of national educational requirements as in organizing instructional subsystems. What matters is that all relevant knowledge and skill be directed to the task of producing good decisions and more effective solutions to applied or theoretical problems. We must not prejudge the best approach to a particular decision.

EDUCATIONAL RESEARCH AND OPERATIONAL RESEARCH

Educational research typically is represented as a scientific investigation of events considered important to education. An important purpose is to provide theoretical and practical knowledge about human behaviour which can be used to make education more effective. Emphasis is placed on problems associated with producing changes in a person's capability and a concern with refining our scientific understanding of instructional processes. Experimental investigations permit testing of presumed relationships in a restricted setting. We need another approach to deal with lifelong education within and without current institutions.

Applied educational decisions and systems development or management lack the precision and control of a laboratory, involve many variables simultaneously and usually include several — often conflicting — objectives. Further, we need solutions to operational problems qualitatively different from that of the classroom. Improving the effectiveness of education may be achieved not simply by improving instruction but by addressing molar questions that subsume an interrelated pattern of many variables. Nowhere is this more necessary than in considering lifelong learning through inter-play with myriad educational opportunities (e.g., schooling, social and community organizations, vocation-related activities, public media). But it is equally important in using educational systems as instruments for improving educational effectiveness. We need research models that help us to understand, predict, explain and perhaps control human behaviour. Although this applies equally to the student, who needs control his own educational behaviour, what follows is limited to organization and management of other people's education.

In order to avoid misleading discussion we shall not consider unplanned or unanalyzed educational opportunities (e.g., conversation, personal investigations, visits to museum or theatre) which can be exceedingly important for personal development. However, operational research is applicable to investigating such complex problems in order to guide the policy and actions of educational planners. Here we examine tools applicable to common problems of analysis or synthesis. Their use in specific situations may be expected to yield general principles for educational theory.

System Analysis

System analysis is little more than a fashionable term to describe the employment of scientific knowledge, methods, techniques and tools to solve complex planning problems involving the direction and management or allocation, of resources (peoples, materials, money, time) to achieve desired outcomes. Operational research (OR) is distinguished from traditional educational research by its emphasis on system analysis of ongoing operations at a molar level. Phenomena can be investigated holistically in all their multidisciplinary aspects. Description, analysis, explanation and prediction of system behaviour using OR theories and procedures provides a scientific basis for solving problems involving a complex of interrelated entities. It does so in the best interest of the organization as a whole and its clients. Such systems research supplements other educational research.

OR transcends traditional disciplinary boundaries in its focus on the function and structure of a system to obtain information to guide policy and operational decision. To describe a process or complex of interrelated entities typically requires construction of some kind of representation or model of it. We can predict and compare outcomes of alternative strategies or explanations which might obtain with the real system by conducting experiments on the model. OR has produced a number of theories and models that describe recurrent processes which exist in a wide variety of systems. Seemingly diverse phenomena can be described by mathematical or computer models that portray key structural and functional factors. The disciplinary characteristics of the system are unimportant to OR theory.

Identification of classes of educational problems in terms of their amenability to systemic analysis has hardly begun. But the impact for educational research and future practice of educational technology is sure to be profound. No matter what one's sphere of operation, several OR models have the promise of educational application. Here is an introductory description with, however, no attempt to set forth quantitative and computer procedures.

DECISION THEORY

The essence of educational technology research and development is that: the practitioner has a problem with a desired outcome (perhaps several); there are at least two courses of action possible; the decision occurs in a context; and a state of doubt exists over the best activity to select. Some of the variables can be controlled by his decision, others cannot (though they may be controlled by another person). Decision theory permits one to solve a simple problem by constructing a model (based on a verbal problem formulation). The model might be physical, graphic, statistical or algebraic. Note that each of these involves a conceptual model. Analysis of the model permits decision taking to proceed and the solution thus derived is tested and implemented. The aim is to select the most attractive course of action.

Simple, especially repetitive, decisions can be taken easily using a decision table, decision tree or simple algorithm. The efficiency of a course of action is the probability that the action will yield the intended outcome. The relative value of any outcome may be determined by a relatively simple procedure outlined by Churchman (1961).

Atkinson (1971) was one of the first to provide a decision-theoretic analysis of instruction. He hoped to provide an optimal instructional strategy by examining : possible states of nature; alternative courses of action open to the person that may change the state of nature; the resulting alternation; and the cost and benefit resulting from each decision. But this model (reminiscent of Ackoff, 1961) calls for a model of the learning process somewhat more sophisticated than many now in existence. (For a computer simulation model to investigate instructional decisions, *cf.* Mitchell, 1973.) Further, in some cases it may be more appropriate to consider nature and other people as competitive decision takers rather than passive systems. Here game theory might be the more helpful conceptual framework even though this is as yet impractical for planning education. (Game theory is not to be confused with educational games that seldom are linked to this formal theory.)

QUEUEING THEORY

Although operational research has yielded many techniques to facilitate decision taking under conditions of uncertainty, one model is salient. The bottleneck problem — too great a demand for immediate access to educational resources — pertains to information retrieval, educational channel capacity, idle production facilities or students arriving at a self-instruction centre. These recurrent waiting line processes are explained by a queueing model which provides an optimal number of service facilities to keep waiting times within acceptable limits. Queueing theory is likely to provide useful explanatory models for many educational processes. However, it is especially useful when we must design and manage many similar services (e.g., self instruction systems; institutions) in which the same procedure can be used to analyze each planning problem even though specific details vary from one installation to another. It is indispensable if we must plan a system to cope with predicted demands for service by recommending the number and capacity of very costly facilities.

A queueing problem involves balancing the costs involved in a system which could have too much waiting time on the part of users (input) *or* service system (idle process time). With a shortage, or inefficient use, of facilities, a queue of arrivals builds up -- a familiar process. But a queue of idle or wasted time on the part of the *server* process occurs with insufficient input demand. With scarce funds, idle service facilities for self-instruction are undesirable.

Education systems are replete with illustrations of queues. The educational cost is difficult to estimate but lost opportunities can be identified as a major cost to society. How can we determine the optimal organization of educational services or facilities to provide acceptable service at an acceptable cost? Redfearn (1973) shows an application of queueing theory as a course design tool, given fixed service capacity service. But how can we determine what is needed to serve a given number of students? Let us illustrate the main ideas.

First we must recognize that a queueing system consists of the processing system and the queue of arrivals. Suppose a learning centre is expected to serve 100 persons who may come at any time during a 15 hour day and each will use a self-instruction facility for an average of 20 minutes (depending on remedial sequences or early departure). How many self-instruction media units will we require? To answer this we might wish to know the average length of the waiting line, the average waiting time, the percent of the time the queue holds one, two, etc. persons, the longest waiting time or percent utilization of the service. Intuitively each unit could handle up to 45 users per day (3 per hour x 15 hours) so three units handling up to 135 users seems adequate. But application of queueing theory, using a simple approximation technique, shows that a problem could arise. Suppose the arrival rate, AR, is 7/hour and service rate (with three units), SR, is 9/hour. The average length of the queue, QL, is *approximated* by:

$$QL = \frac{AR}{SR - AR} = \frac{7}{2} = 3.5.$$

$$\text{The maximum time waiting, } WT = \frac{AR}{SR(SR - AR)} = \frac{7}{18} \text{ hour} = 23 \text{ mins.}$$

How many clients are likely to wait that long for a 20 minute programme, especially if this is a service to out-of-school users? If we try four units, expected QL is 1.4 and WT = 7 minutes; five units reduces QL to .88 and WT to 3.5 minutes. Armed with capital and operating costs we could now decide the best capacity for this system. A similar approach could suggest the number of channels required for ETV on demand or provide a model of an individualized instruction system.

It should be noted that this is a crude approximation. It assumes random arrival rate and random service time and approximates a multi-channel service by a single server. Other assumptions require different approaches. Computer simulation of the system may provide more accurate information and is worth the effort in many situations. But even a crude approximation is better than an unfulfilled wish.

In applying queueing theory, variations in arrival and service rates by time of day or year (e.g., typical *versus* peak demand) can be taken into account as can be expected events (breakdowns, budget changes). Further, self-aggravating queueing situations can be turned into self-improving situations by minor technological or organization changes (e.g., scheduling users or service, providing an alternative to unproductive waiting time). Finally, most queueing systems consist of multichannel, multiphase components, varying priority rules and other complexities. Though these prohibit analytical models they can be studied using computer simulation models. Often a single measure of managerial effectiveness may emerge which otherwise remains elusive. For instance, problems of decentralizing *versus.* pooling facilities may be analyzed in this way. Thus queueing theory is a useful analytical and planning tool for educational research.

MARKOVIAN PROCESSES

Many systems can be described by discrete variables because the result of a decision or change in system state is not continuous (e.g., a behavioural objective is met or it is not; a student chooses one learning system over another). Often we want to know how a system makes a transition from one state to another or to forecast future system states. Markov analysis provides a way of analyzing the current state of a system to calculate the probability of particular transitions and rates or progress through a sequence of states.

The term, Markov process, refers to a mathematically definable sequence of system states in which the state of a system at some point in time does not uniquely determine subsequent system states. Rather they present state determines only the probability of future developments. To illustrate, one can analyse learning as a process whereby some capability state undergoes transformation to a new state, e.g., from not learned to learned. One might do this to investigate the effect of alternative instructional strategies concerned with increasing the probability of the intended transformation. This can be illustrated using a simple matrix where q is the probability that a student's specified capability exists already, 1 - q is the probability that it does not, t is the probability that a transition will occur from the unlearned to the learned state following instruction, and f is the probability that the capability — once demonstrated — will be forgotten over the same time interval (see Figure 1 on next page).

If a person's capability is in state I, it is not known or demonstrable, but when instructional communications are presented, the transition matrix I describes the possible change in state during the designated time period. Rows of the matrix represent the initial state and columns represent its state at the end of the time interval. Although this is a crude model which does not portray the richness of human learning, similar models have proved useful explanatory or predictive devices. And more complicated models are amenable to Markov analysis.

Individual rates of progress through instructional systems can be predicted by treating the sequence of instructional operations as a Markov chain process. Thus, in addition to

Figure 1.
Transition Matrix for Learning/Forgetting.

		Probable State at Time K + 1: Learned	Probable State at Time K + 1: Not Learned
Probable State at Time K	Not Learned $p(\bar{L}) = 1 - q$	t	1 - t
	Learned $p(L) = q$	q - f	f

or

$$I = \begin{array}{cc} & \begin{array}{cc} L & \bar{L} \end{array} \\ \begin{array}{c} \bar{L} \\ L \end{array} & \begin{bmatrix} t & 1 - t \\ q - f & f \end{bmatrix} \end{array}$$

theoretical interpretations of learning and instruction, it is possible to predict the number of students at various places or stages in a continuous individualized education system, the number completing their studies and those who will drop out. Similarly, suppose that a person can be found in any of several courses or learning centres; that students may remain or switch allegiance from one centre to another (due to resources, policies or advertising); and, finally, that a representative sample of students yields data on the probability that a person will remain with the centre initially used. Preparing a matrix of transition probabilities enables one to forecast the number of students in each centre in the future or to analyze the effects of changing system procedures. By knowing what to expect in the future the educational planner is in a position to do something to avoid undesirable outcomes. Providing relevant information is an important aspect of educational research where the potential contribution of system analysis is great.

LINEAR PROGRAMMING

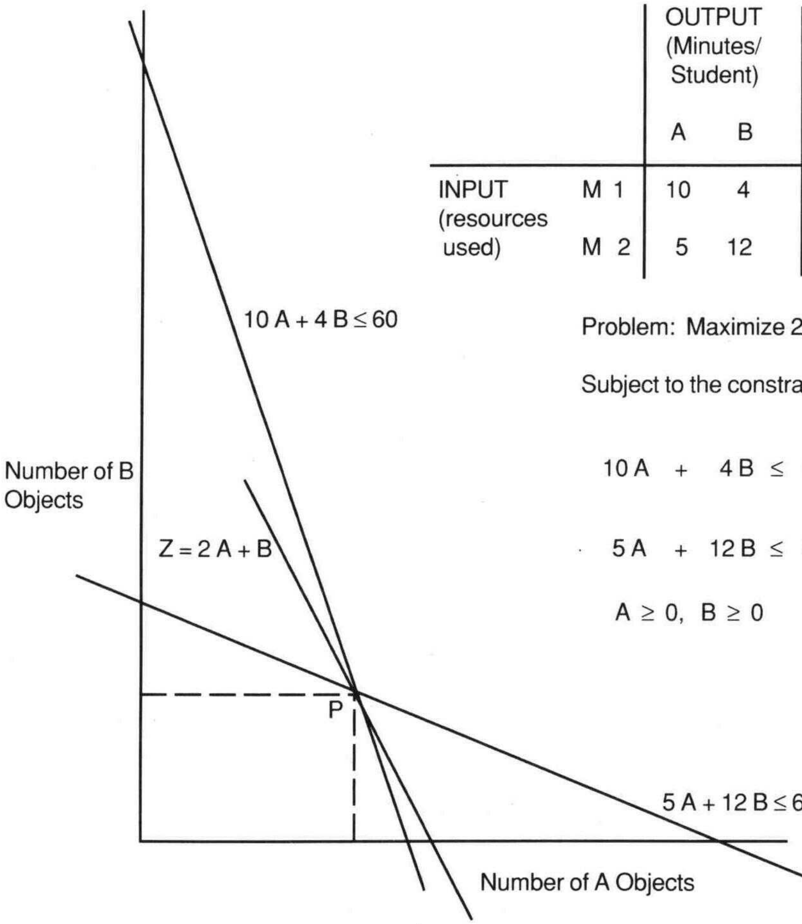
Linear programming (LP) is a mathematical tool for allocating scarce resources to competing demands for them. It helps one to find the best *value* for the total outcome of one's decision while simultaneously satisfying several requirements imposed by the situation. Thus one might allocate production facilities to alternative educational materials or allocate personnel to tasks so as to maximize effectiveness of the system. Similarly, given a set of educational objectives and alternative systems or ways in which students might prepare to meet them, it is possible to formulate an idealized way to assign students to learning activities in order to maximize learning (subject to available facilities and learning rates). The measure of effectiveness to be maximized or minimized could be cost, profit (if you market an instructional product or service), research grants, or any quantifiable measure of *educational* effectiveness. The statement that denotes the objective as a function of controllable and uncontrollable variables is termed the objective function.

Linear programming's usefulness reflects its ability to help economize. The objective function assumes proportionality (e.g., a production centre produces twice as much in two time units as in one) which may not hold in practice. Although many feasible solutions can exist for a LP problem, the aim of LP is to find that unique solution that satisfied the constraints and maximizes the value of the solution to the decision taker.

There are essentially three ways to go about linear programming: graphically; analytically; or with a standard computer programme. For a simple problem a graphic solution is easy. Suppose you must prepare modules for a learning centre that has a limited capacity for media 1 and 2. Course objectives fall into two broad categories, A (e.g., evaluation and synthesis) and B (memorization). Research has shown that, in a given time, media 1 enables 6 students to achieve an A or 15 to achieve a B objective while media 2 helps 12 to achieve an A or 5 a B. What is the optimal assignment of objectives and media to maximize the value of this system, given that class A is considered to be twice as important as B? A graphic solution is illustrated in Figure 2. (For more complex problems, requiring more than two dimensions, use a computer.)

Figure 2.
Summary of Solution to Linear Programming Problem.

		OUTPUT (Minutes/ Student) A	B	TOTAL TIME (Minutes)
INPUT (resources used)	M 1	10	4	60
	M 2	5	12	60



Problem: Maximize 2A + B

Subject to the constraints:

$$10A + 4B \leq 60$$

$$5A + 12B \leq 60$$

$$A \geq 0, \; B \geq 0$$

Can LP provide a useful theoretical model or is it limited to economizing decisions of practical import? If we assume the degree of learning to be a linear function of the time spent learning, it is possible to formulate a LP model that portrays the appropriation of each of many different concepts as a result of participating in different categories of educational activity that are subject to restrictions (e.g., the amount of time or human and material resources available is limited). Such a model also assumes we can assign, for each student, the relative educational value of each activity. Having done so, however crudely, it should be possible to investigate effects of different learning strategies — including undisciplined haphazard choice — and to compare them with an optimal strategy calculated to the most valuable utilization of time and other resources available. Such an approach is limited however to a single decision problem.

DYNAMIC PROGRAMMING

Some problems must be broken down into a series of smaller problems (decomposition) and the solution of the original problem is synthesized form the solution to the subproblems (composition). Dynamic programming is such a multi-stage problem solving approach. It solves for a stochastic series of sequential decisions with the outcome of each depending on the previous decision in the series. It is essentially an extension of the LP concept (which assumes a static system with one transition to a new state) to many choices dealing with uncertainty. The *decisions* included in the structure of a DP problem are opportunities to change the values of state variables in a probabilistic manner; each decision is to change the state and maximize the value of the subsequent outcome.

Teaching is essentially an adaptive multi-stage decision process so DP may be a useful analytic tool for the researcher. Since the instructional designer often must apportion the kinds and amounts of adaptation requirements between the instructional system and the student, DP is a useful concept to consider; the paucity of applications makes this an area ripe for research.

SIMULATION

An educational system or decision problem can often be investigated by recreating the effects on the system of relevant inputs through time. A simulation is a procedural model which expresses a dynamic relationship between variables in precise terms (e.g., in the form of a flow chart, set of decision tables or algorithms). By carrying out the sequence of operations on variables and parameters of the model with assigned values we can predict what might happen in the real system including long term effects of decisions. Thus simulation involves features of both classical experimentation and formal analysis in a way that provides great flexibility for educational technology. Usually a simulation is processed on a computer where one can rapidly test hypotheses concerning theoretical questions and practical problems. Simulation models, e.g., of different queueing systems and decision processes, can be investigated using fairly standard procedures. Simulation models are possible not simply for processes or institutions but also for policy decisions. We could even produce a model of the nation of global society to present to mankind the probable effects of present and proposed activities, and to generate and describe alternative courses of action. This might bring into existence new arrangements to foster lifelong education.

Some simulations are useful not for studying the system but for investigating the decision processes of educational managers whose normal behaviour in interplay with the system is difficult to"analyze. Thus a computer simulation of a classroom with 30 students can be used to study instructional planning by teacher trainees or to compare such decisions with those of experienced teachers (Mitchell, 1973). Operational gaming denotes simulations of this sort. Games have pedagogical uses too since they can stimulate both understanding and interest in participants.

CONCLUSION

An imbalance of judgement seems inevitable between educational researchers who focus mainly on statistical techniques and related experimental design principles and those who struggle with practical problems of operating systems. This is complicated by the inability of one person to be expert in all the disciplinary approaches inherent in education. Systems thinking can untie these opposing tensions by providing a common perspective on problems of communication and control (cybernetics), the rigour of scientific and technological research, and the scientific models of operational research *(cf.* Appendix; Ackoff, 1961). Nonetheless we must beware lest we yield, unwittingly, to societal pressures to measure educational activities and human dignity largely in terms of utility. The means-ends language of contemporary techniques distracts us from a vision of man as a temporal being in dynamic equilibrium with the rest of nature. The professional world view and aims of the educational technology researcher/practitioner surely must transcend technocratic distortions if optimal education is to be achieved.

In this paper I have introduced several models suitable for operational research in Education. (A list of suggested readings may be obtained from the author.) Models of this sort are intended not to replace but to supplement traditional educational research procedures. Their usefulness is paramount in but not limited to applied educational research. Improvements in educational technology theory and practice can be expected as educational researchers and decision takers develop competence in operational research.

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APPENDIX

A MODEL EDUCATIONAL SYSTEM ANALYSIS CURRICULUM

Contemporary research and progress indicate that the mainstream of technological thought has been quantitative. Far from providing a restrictive scope, a good grounding in system analysis and operational research techniques should expand one's capacity of comprehension, regardless of his special interests in selected aspects of educational technology. It can truly prepare him to be a generalist.

As an educational programme, the detail with which a curriculum may be specified varies from a terse, molar level (e.g., to develop competence in system analysis) to the extremely refined level of detailed behavioural objectives. In this model curriculum the following intended learning outcomes were established as the first level of resolution. In the Educational Systems Analysis courses offered at Concordia University each of these is elaborated in considerable detail. (Time constraints permit only a cursory treatment of some.)

The student is expected to develop capability in:

1. methods of system description and systems modeling using block flow diagrams and flow graph theory;
2. scientific and technological research methodology;
3. understanding, formulating and using probability theory;
4. evaluating parameters of a theoretical model from available data by statistical inference;
5. understanding, setting up and solving problems of rational decisions using the theory of games;
6. understanding, formulating and using matrix methods to analyze system problems;
7. understanding, formulating and using a Markovian Decision Model;
8. setting up and solving the optimal assignment problem;
9. setting up and solving linear programming problems;
10. formulating and solving problems involving curvilinear or non-linear

programming;

11. setting up and solving dynamic programming problems;
12. analyzing, setting up and solving queueing (waiting line) problems;
13. measurement and evaluating of educational systems;
14. analyzing and controlling costs of educational technology projects and proposals;
15. establishing policies for decoupling systems through inventory control models;
16. describing and using management planning models;
17. educational systems management;
18. computer programming; and
19. constructing, using and interpreting simulation models.
20. The student will begin to develop a cybernetic worldview in which static systems, dynamic systems, purposeful or goal-seeking systems, self-organizing and conscious systems evolve through an exceedingly complex series of mutually adaptive equilibrium responses.