

# TEACHING DYNAMIC FEEDBACK SYSTEMS THINKING: AN ELEMENTARY VIEW\*

NANCY ROBERTS†

A pilot study has demonstrated that dynamic feedback systems concepts can be taught to children as young as ten and eleven years old, when nurtured by a teaching strategy that follows Bruner's emphasis upon the teaching of basic structures.<sup>2</sup> Focusing on the understanding and representation of underlying structures in the area of social studies, the author developed, implemented and evaluated a curriculum to teach children both to read dynamic feedback systems' causal loop diagrams and also to develop feedback diagrams explaining causal relationships among variables discussed in written materials. The curriculum enabled fifth and sixth graders to learn analytic and synthesis skills previously taught primarily to graduate classes at M. I. T. The positive results achieved seem transferable to broader groups wishing to become familiar with dynamic feedback systems thinking and its applicability to social problems.

## Introduction

Management science techniques can be effectively taught at the elementary and secondary school levels. This accomplishment is congruent with the goals of TIMS as stated by its past president Martin Starr, who expressed the desire "to affect the educational system at all grade levels from kindergarten through postdoctoral studies so that management science becomes increasingly relevant and effective" [11, p. 5].

Until recently the impact of management science techniques upon elementary and secondary schools had been limited almost entirely to the use of simulation gaming, usually non-computerized. This paper describes a recent successful effort to introduce dynamic feedback systems thinking, based on the system dynamics approach to fifth and sixth grade students. This pilot study has been followed by use of the prototype curriculum materials at all levels of education, from kindergarten through executive development programs. An effort is now underway to develop materials aimed at secondary students for enabling them to perform more advanced phases of management science model building.

## Explanation of Terms

A dynamic feedback system is an ongoing set of relationships in which the output of an action taken by one person or group eventually has an effect again on that person or group. The dynamic feedback systems approach to understanding management problems has been studied and extensively developed at M.I.T. for the last twenty years by a group led by Jay W. Forrester [3]. Their work was based upon two prior decades of research in the area of feedback control theory and mathematics led by the pioneering of Norbert Wiener. Over the years the approach has spread from business issues to understanding what creates and maintains problems in many areas of social science and economics[4].

A researcher goes through three basic phases when analyzing a problem from the dynamic feedback systems perspective. In the first phase he develops visual feedback diagrams showing the cause-and-effect structure of the system being studied. The second stage is equation writing. Using DYNAMO [8] or an equivalent computer simulation language, the researcher states in precise mathematical form the cause-and-effect relationships he has identified. During the third basic phase the researcher simulates, with the aid of a

\* Accepted by Peter J. Kolesar, former Departmental Editor; received March 1976. This paper has been with the author 4 months for 2 revisions.

† Lesley College and Massachusetts Institute of Technology.

computer, the model he has built. Later phases of the approach involve model validation, computer experimentation, redesign, and continued reiteration of this overall cycle. The pilot project that was tested with the fifth and sixth graders focused on the first phase of the dynamic feedback systems approach . . . the development of visual feedback diagrams showing cause-and-effect structures of complex systems.

### **Rationale for the Project**

The area of social studies in the elementary school curriculum has been criticized for years as a discipline whose focus is primarily on facts. Ten and eleven year old children have traditionally been presented with a sense of history and geography facts that are quickly forgotten. Moreover, children have usually rates social studies as the subject they like least. Bruner suggests these phenomena might be due to the absence in present curricula of any attempt to teach the basic structure of the subject. Bruner makes four arguments for the importance of teaching basic structure:

1. “understanding fundamental makes a subject more comprehensible” [2. p. 23],
2. “the most basic thing that can be said about human memory . . . is that unless detail is placed into a structured pattern, it is rapidly forgotten” [2, p. 24],
3. “an understanding of fundamental principles and ideas . . . appears to be the main road to adequate ‘transfer of training’ ” [2, p. 25],
4. “the fourth claim for emphasis on structure and principles in teaching is that . . . one is able to narrow the gap between ‘advanced’ knowledge and ‘elementary’ knowledge [2, p. 26].

This pilot study attempted to develop a teaching method that takes into account Bruner’s suggestions of focusing on the underlying structure of a subject matter. System dynamics is a method for better understanding the underlying structure of complex situations. Social studies attempts to help children understand the complexities of the world. The author theorized that if social studies educational materials were designed to facilitate teaching a process of problem representation and problem solving, children would then be able to use this process for understanding more complex issues in both the natural and social sciences. Further, as Bruner suggests, if children are able to identify the underlying problem structure, facts encountered during study will more likely be retained.

The author selected Bloom’s *Taxonomy of Educational Objectives: Cognitive Domain* [1] as a guide to measuring the achievement of the elementary school children in this educational experiment. The educational research literature generally supports Bloom’s *Taxonomy* as a guide to the hierarchy of thinking skills [5], [6], [10], [12], [13], [ 15]. The fourth and fifth levels of the *Taxonomy* are congruent with dynamic feedback systems thinking. Bloom defines these levels as:

*Analysis* (fourth level)— “the breakdown of the material into its constituent parts and detection of the relationships of the parts and of the way they are organized” [1. p. 120].

*Synthesis* (fifth level)— “the putting together of elements and parts so as to form... a whole” [1, p. 162]. Both dimensions of “analysis” and “synthesis”, as defined, are essential to Bruner’s concept of structuring.

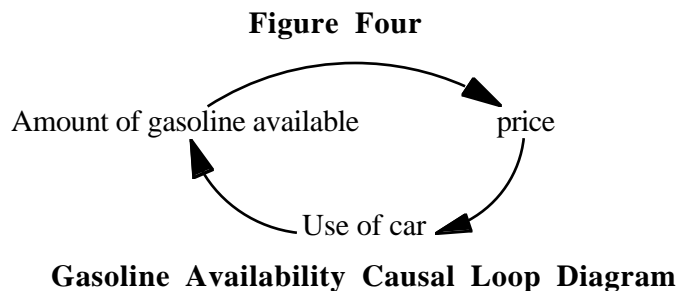
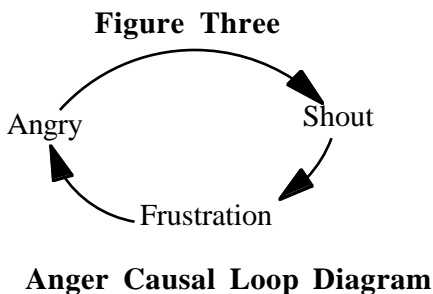
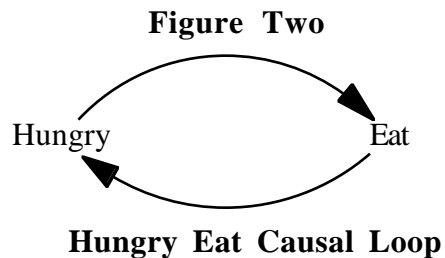
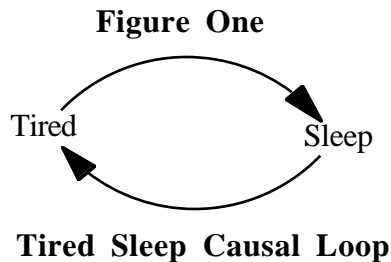
Bloom suggests that to raise a person’s s level of thinking, that person must go step by step up the hierarchical structure of the taxonomy. This would mean starting at the first level, *Knowledge* (fact accumulation). Most elementary school teaching materials, especially in the area of social studies. concentrate at the lower end of the hierarchy of thinking processes, with higher levels of thinking in students not resulting. The thrust of the authors project, however, coincided more with Bruner’s philosophy of education: That is, to develop a strategy for teaching a process to identify underlying structure of social science issues where teaching effort would be concentrated at what Bloom defines as higher level thinking processes.

## Dynamic Feedback Systems Strategy

For this study the author developed a social studies unit (a series of topical activities) including a pre-study unit and a post-study achievement test following Bloom's *Taxonomy*, a computerized *World 3 Game*, and two sets of dynamic feedback systems exercises [9] The unit was designed around the focal issues of the computer game. The game was developed by the author from a dynamic feedback systems computer model [7] concerned with the current and future problems of worldwide natural resource usage, pollution, food and population growth. The unit consisted of a series of self-directed activities of a social studies/science nature. For the unit work the class was divided into four group following the topics of the game: natural resources, pollution, food and population. In each group the chairman recorded the activities which each person chose to do. The remainder of the unit was self-directed. The children worked on these activities for eight weeks. At the conclusion of the unit each group presented its work to the rest of the class by explaining its bulletin board display, reporting on its research and experiments, and presenting any skits or other oral activities.

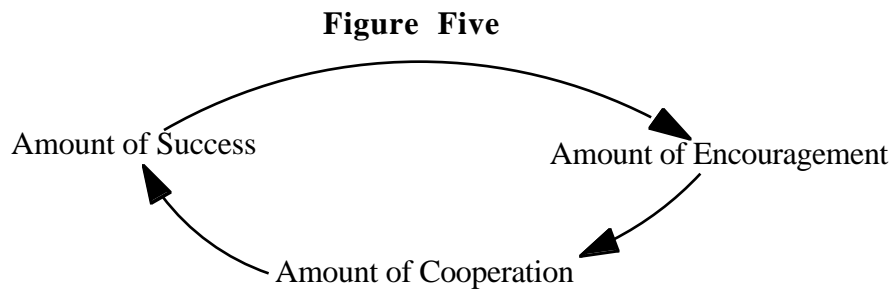
During the time of individual unit work, the author worked with small groups of students using the author's dynamic feedback systems exercises. To introduce these exercises to the class a lesson was devoted to develop the concept of cause-and-effect. First the author's "Arrow Game" was played. A large paper arrow was handed to a student with a sentence to complete. For example, "Being tired causes me to (sleep)." The student would complete that sentence and start another one. For example, "Sleeping causes me to (\_\_\_\_\_)" and hand on the arrow. The object of the game was to complete the circle. This demonstration of circularity introduced the notion of feedback. As each circle was completed, a causal diagram was drawn on the blackboard, such as in Figure 1. Other cause-and-effect sentences used in the Arrow Game, and sample diagrams they elicited, were:

1. Being hungry causes me to \_\_\_\_\_. (See Fig. 2.)
2. Being angry causes me to \_\_\_\_\_. (See Fig. 3.)
3. A gasoline shortage causes \_\_\_\_\_. (See Fig. 4.)



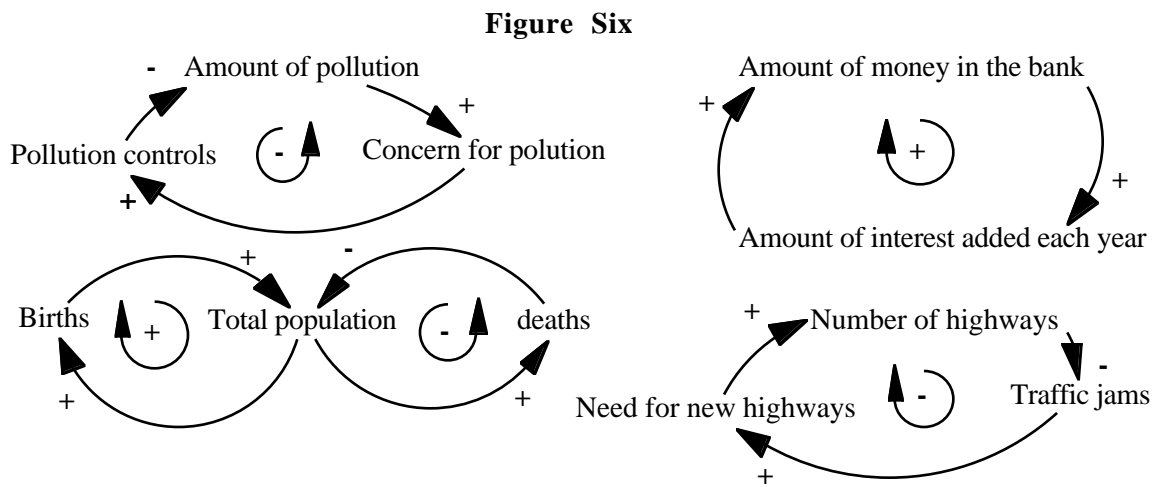
The second part of this introductory session consisted of the class playing the *Broken Square Game* [14]. The game is played by handing each of the five players in a group parts of several squares. Each game group's task is to complete five equal squares. The game rules prohibit talking. The player's may only voluntarily give pieces of squares to each other. The team that wins is generally the team that learns to

cooperate the quickest. Following the game a discussion was held about the students' feelings while playing the game. The following causal-loop diagram was created by the class to explain what happened during the game.



**Game Cooperation Causal Loop Diagram**

At the conclusion of this lesson a flannel board was left in class entitled "Label the Loops". Also left were fifteen sets of flannel-backed loops (examples given in Figure 6); and +, -, +arrow, and -arrow symbols. The students were asked to label each arrow head with either a + or - symbol. A + indicates the variable at the head of the arrow changes in the same direction as the variable at the tail of the arrow. A - indicates that the variables change in opposite directions.



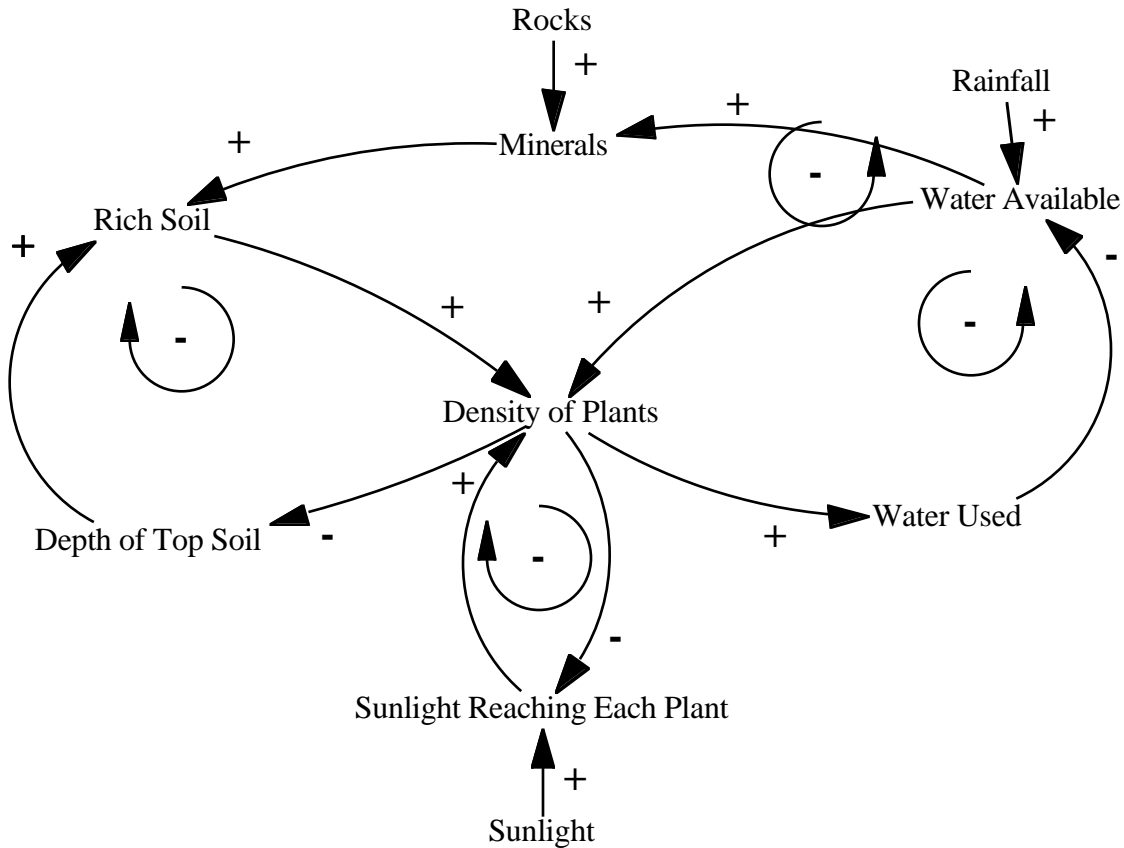
**Examples of Flannel Board Causal Loop Diagrams**

The students then determined whether the loop was (1) a positive feedback loop (symbol here), indicating the system behavior continued to change in the same direction. or (2) a negative feedback loop (symbol here), indicating oscillating or goal-seeking behavior.


This flannel board was used as the basis for the third lesson. The author led the class through labeling the loops with the appropriate symbols and explaining the suggested behavior of each loop.

The first set of written exercises developed by the author was then introduced to the class. The students were asked to read and explain (in writing) as many of the causal-loop diagrams as time permitted until the next lesson. These exercises contain sixteen diagrams and question sets covering such topics as supply and demand cycles, population, thermostatic control systems, and urban dynamics. Figure 7 is one example exercise. Over the next few weeks the author met with each child in a small group setting and listened to the student explaining dynamic feedback systems causal-loop diagrams. The overt focus of these exercises was the development of analysis skills.

## FOREST DEVELOPMENT



The above diagram shows 4 feedback loops that influence forest development.

1. All the loops are  which means: \_\_\_\_\_
2. Write a few sentences explaining each loop. The resulting paragraph should explain how a forest maintains \_\_\_\_\_.

**Figure 7. Sample Dynamic Feedback Systems Diagram Exercise.**

Once the class understood how to read causal-loop diagrams, the author asked the children to take written material (stories) and explain the underlying structure described in the stories by drawing causal-loop diagrams. Each story in this second set of exercises developed by the author describes a different situation drawn from the personal experiences of children and from the natural and social sciences. Two examples follow.

### Story No. 2—The Case of the Missing Muscles

John admired Adam's muscles. Adam was an all around good athlete. He could play baseball and hockey well/ He was one of the fastest runners in the class. Most of all, he could do ten pushups at the beginning of the school year. Now in April, he could do twenty. This is what especially impressed John. In September John could do five pushups. He had to do them in camp that summer and without any practice John

could do five pushups in a row. Now, in April, John was sure he could do at least eight or ten. But when it came to his turn in gym, he could barely do three pushups.

1. What do you suppose caused Adam’s muscles to strengthen over the winter and John’s muscles virtually to disappear?
2. Draw one causal-loop diagram that might explain both boys’ situations.
3. Can you write a story about yourself or one of your classmates that is similar to this?

The children developed causal-loop diagrams to explain this situation and responded to the questions posed above.

### Story No. 5—The Oil Crisis

One aspect of the oil crisis, as explained by an economist, was the starting of a “vicious circle”. This vicious circle was begun by agreements made by the Arab oil producing countries in 1971 called the Teheran and Tripoli Agreements (named for the cities in which the meetings were held). Here these countries agreed to raise the price of oil. The rise in oil prices meant that these countries then made more money. They made so much more money that they could not possibly spend it all. Realizing this, these countries decided not to produce as much oil. They knew that eventually their oil supply would run out so they might as well make it last as long as possible.

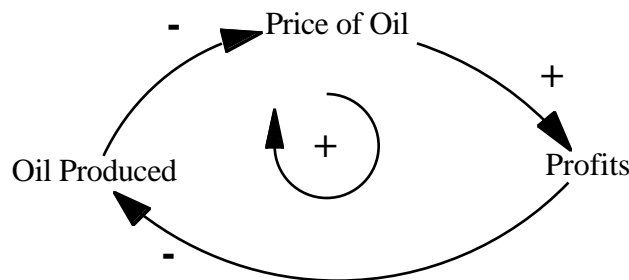
Because there was less oil being produced in the world, and more oil was needed every day, a scarcity of oil developed. This scarcity of oil forced the oil prices to go up even higher, continuing the “vicious circle”.

1. Draw a feedback diagram showing the “vicious circle” this economist points out.

A vicious circle is an example of a positive feedback loop. A positive feedback loop is one that continues going in the same direction, eventually exploding. A positive feedback loop is labeled with a (+ symbol here) in its center.

2. Label each arrow with either a + or -.

One resulting causal-loop diagram which could be used to explain this situation is shown in Figure 8.



**Figure 8. Example Solution: The Oil Crisis Causal-loop Diagram**

Some of the additional titles in the set of nineteen stories, indicating their wide range of areas covered, are:

1. The Body Temperature System
2. Rabbits and Lynx in Northern Canada
3. The Tragedy of the Sahel
4. Insulin and the Balance of Body Sugar
5. The Workings of an Ecosystem

Again, over the next few weeks, the author met with each child at least once, and often more, to discuss the stories and their behavior as depicted by the students’ diagrams. The author found it took working through three or four stories together in a small group before the children began drawing competent diagrams of their own. The overt focus of this set of exercises was the development of synthesis skills.<sup>1</sup>

## Test Development and Results

A set of pre- and post-achievement tests was constructed following Bloom's *Taxonomy* to determine the effectiveness of this teaching/learning unit. (A complete discussion of the test, its reliability, and the statistic results is available in [9].) The contents for the first three sections of the achievement test were drawn from the world problems social studies unit the students had been studying. The questions for the last two sections of the test, which attempted to measure the student's ability to do analysis and synthesis level thinking, were drawn from general system dynamics exercises used at M.I.T. These last two test sections were testing the students' ability to use the system dynamics process for understanding underlying structure of complex ones.

The test questions were edited by several members of the M.I.T. system dynamic group to assure technical accuracy. The tests were then administered to two sixth grade classes (independent of the classes used in the later study) to check clarity of directions and questions as well as appropriateness of vocabulary level. The two sets of test scores, resulting from a random division of questions into a pre-study test form and a post-study test form, were correlated for reliability. The correlations of the pre-test and post-test forms were 0.97 and 0.96 for the two classes.

Table 1 clearly shows that statistically significant learning occurred (as measured by post-study minus pre-study scores) at all levels of the taxonomy for both the fifth and sixth graders actually involved in the experimental project.

Further statistical analysis of the test data indicates that the sixth graders did not learn significantly more at the IV and V levels (those levels involving dynamic feedback systems thinking) than the fifth graders. The testing also indicates that IQ did not seem to be a significant determinant of achievement.

**TABLE 1**  
*Statistical Analysis of Results of Achievement Tests*  
*Pre vs. Post Scores*

		Test Section Results Corresponding to Bloom's <i>Taxonomy</i> Level		
Grade	<i>n</i>		<i>U</i> *	<i>z</i> **
6	27	I (Knowledge)	70.5	5.118
		II (Comprehension)	120.5	4.289
		III (Application)	162.0	3.646
		IV (Analysis)	209.0	2.764
		V (Synthesis)	59.0	5.698
		Total Test Scores	85.5	4.828
5	23	I	81.0	4.006
		II	62.0	4.525
		III	117.5	3.321
		IV	166.0	2.235
		V	23.0	5.793
		Total Test Scores	59.0	4.519

\*Man-Whitney *U* Test

\*\*All *z* scores are significant at the 0.01 level.

## Conclusions

Based on the statistical tests, the author concluded that this group of fifth and sixth graders was taught dynamic feedback systems thinking, a management science approach that focuses on understanding and representing underlying structures of problems usually taught at the college level or beyond. Further, the study suggests that this approach to problem structuring (analysis and synthesis) can be taught, at least to younger children, as effectively by a teacher with no previous background in the field as by one with several years of experience. The fifth grade class was taught by a volunteer whose experience was in teaching foreign languages at the secondary level. This woman was briefed before each class presentation and in addition went through the dynamic feedback systems diagram and story exercises on her own. Since no statistically

significant difference was found between the fifth and sixth grade achievement scores on level IV and V, the author feels that lengthy teacher preparation in this way of thinking is not a prerequisite to teaching this subject to younger children. Moreover, at the end of the study, both the regular classroom teachers involved felt they could teach this subject using the sets of exercises developed for the study.

Finally, the classroom teachers recognized the interdisciplinary nature of dynamic feedback systems thinking and its applicability to many aspects of the curriculum. The school's science specialist participated in several classroom sessions during the course of the study. The fifth grade classroom teacher, who is also the mathematics teacher, said she now plans to include dynamic feedback systems diagramming in the flow diagramming unit that is part of her math curriculum. The sixth grade classroom and language arts teacher felt that book characters could be discussed from a dynamic feedback systems point of view. The research results and field experience, though small sample and speculative at this time, seem positive enough to warrant further experimentation with this strategy for teaching a process for understanding problems.

Since this study was completed, further curriculum development has taken place. A set of feedback materials consisting entirely of pictures has been created and is being field tested with kindergarten and first grade children. The same sets of exercises used with the fifth and sixth grade are being used in trials across the country with high school students, college undergraduates in a variety of courses from physics to history, and executive development students at M.I.T.'s Sloan School of Management. Recently a team has formed under the author's leadership within the M.I.T. System Dynamics Group to develop additional curricula that would enable secondary school students to build and simulate system dynamics models. When available this new material should also be useful for other students as well, especially college undergraduates with nonquantitative backgrounds. Further successful efforts in the directions indicated in this paper can broaden significantly the audience for understanding and potentially using management science thinking tools, and can begin the process at the appropriate starting point, in the elementary schools.

<sup>1</sup>Copies of the complete text of dynamic feedback systems exercises may be obtained from the author (M.I.T., E40-253, Cambridge, MA 02139) for the price of reproduction.

## References

1. Bloom, B. (Ed.), *The Taxonomy of Educational Objectives: Cognitive Domain*, David McKay, New York, 1956.
2. Bruner, J.S., *The Process of Education*, Vintage Books, New York, 1963.
3. Forrester, J.W., *Industrial Dynamics*, The M.I.T. Press, Cambridge, MA, 1961.
4. -----, "Industrial Dynamics—After the First Decade," *Management Science*, Vol. 14 (1968), pp. 398-415.
5. Klein, M.F., "Use of the Taxonomy of Educational Objectives: Cognitive Domain in Constructing Tests for Primary School Pupils," *The Journal of Experimental Education*, Vol. 40 (1972), pp. 38-50.
6. Madous, G.F., Woods, E.M., and Nuttall, R.L., "A Causal Model Analysis of Bloom's Taxonomy," *American Educational Research Journal*, Vol. 10 (1973), pp. 253-262.
7. Meadows, D.H., Meadows, D.L., Randers, J., and Berens, W.W., *The Limits to Growth*, Universe Books, New York, 1972.
8. Pugh, A.L., III, *DYNAMO User's Manual* (Fifth Edition), The M.I.T. Press, Cambridge, MA, 1976.
9. Roberts, N., *A Dynamic Feedback Approach to Elementary Social Studies: A Prototype Gaming Unit*, Unpublished doctoral dissertation, Boston University, 1975 (available from University Microfilms, Ann Arbor, Michigan).
10. -----, "Further Verification of Bloom's Taxonomy," *The Journal of Experimental Education*, Vol. 45 (1976), pp. 16-19.
11. Starr, M.K., "Message from the President," *OR/MS Today*, Vol. 4 (1975), p.
12. Stedman, C.H., "An Analysis of the Assumptions Underlying the Taxonomy of Educational Objectives: Cognitive Domain," *Journal of Research in Science Teaching*, Vol. 10 (1973), pp. 235-241 .
13. Stoker, H.W. and Kropp, R.P., "Measurement of Cognitive Processes," *Journal of Educational Measurement*, Vol. 1 (1964), pp. 39-42.
14. Weitzman, D., "Break the Ice with Five Squares," *Learning*, Vol. 3 (1974) pp. 32-37.
15. Willson, I., "Changes in Mean Levels of Thinking in Grades 1-8 Through Use of an Interaction Analysis System Based on Bloom's Taxonomy," *The Journal of Educational Research*, Vol. 66 (1973), pp. 423-429.