System Dynamics as a Strategy for Learning to Learn

David N. Ford[1]

Abstract

Following their formal education managers face processes and organizations which are too varied, complex and dynamic to be designed and managed solely with solutions provided in school. To be successful managers must learn independently and apply new knowledge throughout their careers. How can managers learn how to learn about complex systems without the aid of experts? A system dynamics program can train managers how to independently learn about complex systems by developing manager's ability to build new solutions instead of providing solutions. This paper describes a three stage strategy which uses a simple experiential learning model, its operationalization and implementation with a combination of techniques including apprenticeship, reality-based cases and experimentation to develop skills for independent learning. Incompletely addressed barriers to learning to learn provide the basis for strategy improvement.

Introduction

The intellectual challenges which managers face are growing as the systems in which they must operate and manage become increasingly complex. These systems have many different types of components which interact through structural feedback, the circular causality inherent in systems in which the impacts of an agent's actions return to affect that agent. These relationships are characterized by delays and nonlinearities which make understanding how the system behaves and why difficult and therefore difficult to manage (Richardson, 1991). Consider the design of a program to reduce illegal drug use as an example. The system includes (at a minimum) drug suppliers and sellers, users (casual and addicted), drug prices and supplies, law enforcement and judicial organizations and their actions, penal systems and the victims of drug-related crime. Each of these components is related to several others in ways which vary with the current and expected conditions and actions of others. For example law enforcement agencies can respond to an increase in recreational drug use by increasing arrests and thereby the risk of detention for drug users. The increased risk can reduce drug use after a delay in recognizing the increased risk and adjustment of drug use behavior by recreational users. These systems are difficult to understand (Sterman, 1994) and manage (Homer, 1993) and can generate well intended but counterproductive such as increased crime due to increased arrest rates (Friedman, 1976).

To address challenges such as these managers need the ability to develop knowledge about specific complex systems that can then be applied to find solutions. This knowledge may be developed individually or as a part of a team of domain and methodology experts who are collectively seeking a solution. Regardless of the size of the learning unit, due to the

[1] Associate Professor, System Dynamics Program, Department of Information Science, University of Bergen. Norway. <David.Ford@ifi.uib.no> <http://www.ifi.uib.no/staff/david/>

complexity or novelty of the system or both learning must often occur without an a priori source of understanding about the system in the form of a system expert. Therefore the learner must develop that understanding. We call the development of such independent learning skills "learning to learn". One objective of educational systems is to prepare managers to successfully address such complex issues by developing the knowledge which is necessary to find solutions but may be unavailable until the manager addresses the problem. Since knowing how to learn about complex systems is not natural (see Sterman, 1994 for a discussion) managers must be taught how to learn when expert assistance is not available. An important challenge for educators is how to help managers learn to learn. The development and testing of strategies for this purpose is a critical step in effectively reaching this goal.

Challenges in Learning to Learn

Learning can be described with the development of different types of cognitive skill. A fundamental form of learning focuses on acquiring and remembering facts (broadly defined). In this form exact and specific answers are known and available. No methods or procedures beyond memorization must be applied to obtain solutions. The range of problems which can be addressed is limited to those with solutions which are known and stored. Examples include learning the alphabet, addition tables or the names of the continents. A second cognitive skill focuses on the application of procedures. In this form exact and specific solutions are not directly available but procedures for finding solutions are. Clear measures of solution value are also available for judging the quality of the application of the procedures. For example when an engineer determines the size of a steel beam for an office building he or she follows a specific procedure and produces a set of alternative beam sizes which meet minimum safety criteria. While every beam size for every possible office building condition is not available the procedure provides an exact means of finding alternative solutions. The relative value of different beams as a solution can be assessed with known and clear criteria (e.g. weight or cost). Other examples include word problems, games such as chess and design operations such as optimization.

Despite their wide range of applications the preceding two forms of learning are inadequate for complex systems. Sterman (1994) describes seven barriers to learning in and about complex systems: dynamic complexity, imperfect information, confounding and ambiguous variables, poor scientific reasoning skills, barriers to effective group processes, implementation failure and misperception of feedback. In circumstances characterized by these features previously developed solutions are inappropriate or not available and no fixed procedure can be applied to directly develop alternative solutions. Additionally, the basis for judging the quality of alternative solutions can be unclear. Even the questions to be answered may be ambiguous, uncertain or multifaceted. Learning which develops new knowledge for use in developing solutions for these systems is required. This form of learning focuses on strategies for using tools and methods to build useful knowledge. Consider the challenges of developing a policy to control the size of a deer population on an isolated plateau over many years. Several objectives may contribute to the goal of such as policy. Should a manager of this ecosystem seek a smaller healthier deer population or a larger weaker population? The means of measuring and evaluating objectives such as deer health may also be difficult. In a simple model the deer population changes dynamically in response to the grass which the deer eat and the wolves which eat the deer (Ford, 1997). By setting annual deer and wolf hunting levels and the amount of grass to plant each spring a manager can influence the deer population. However due to the nonlinear and delayed reactions of the wolf, deer and grass populations to each other the impacts of any given policy are not static or easily determined. Furthermore, no useful algorithms are available which can provide solutions. What strategy can managers use to select hunting and seeding levels which form an effective policy? Knowledge concerning how each of the three policy levers impacts each of the three populations over time must be developed before an effective policy can be developed. How can managers develop the skills required to build this kind of knowledge?

Barriers to learning about complex systems prevent learning which is based on the transmission of known solutions or explicit procedures from experts to managers from adequately preparing managers to address complex problems in complex systems. However in addition to the previously described barriers we have observed unique characteristics of independent learning which cause it to be difficult to learn, including:

- Independent learning is a process and therefore is more abstract than learning known specific facts and procedures. This requires managers to generalize and apply perspectives with multiple levels of aggregation.
- Independent learning can require a change in the manager's mental model (Doyle and Ford, 1998) of the learning process from a more structured and rigid knowledge base or set of steps to a more flexible iterative process (Argyris, 1985).
- Verifying that independent learning has occurred and therefore facilitating skill development is difficult because the proper use a flexible set of procedures is less recognizable than many other learning indicators.
- Learning to learn is heavily dependent supporting on conditions which are difficult to provide, assess and facilitate such as safe learning spaces for experimentation.
- Learning to learn often includes questioning and adjusting objectives and measures of those objectives.

The challenges of learning about complex systems and independent learning have been identified and discussed. However this is inadequate for improving the performance of managers. An operationalized strategy for developing learning skills to manage complex systems is required to overcome the challenges of independent learning. We propose such a strategy in the next section, then describe its operationalization as an initial test of its effectiveness and conclude with an evaluation of our strategy.

A Strategy for Learning to Learn with System Dynamics

We propose that developing experimental learning skills in a system dynamics program structured for that purpose can be an effective strategy for training managers to learn independently. Our strategy is based on a simple model of experiential feedback learning called the OADI learning cycle (Figure 1). The model has its roots in the Plan-Do-Check-Act model of the continuous improvement methodology developed by Shewhart and Deming (Shewhart, 1939; Shiba et al., 1993), adapted to learning by Koffman (Kim, 1993) and has been applied to individual and organizational learning (Kim, 1993; Roth and Senge, 1995). In the OADI learning cycle each letter represents a fundamental learning activity: **O**bserve, **A**ssess, **D**esign or **I**mplement. Observation includes perceiving and describing the system of interest including its processes and agents, their characteristics and objectives. Assessment compares the condition of the system to goals and evaluates the impacts and consequences of any differences. During design possible solutions to the mismatch between the system and goals are generated. These designs are applied through implementation. Learning is continuous in this model, with implementation being followed by observation of the effects of the implemented design on the system.

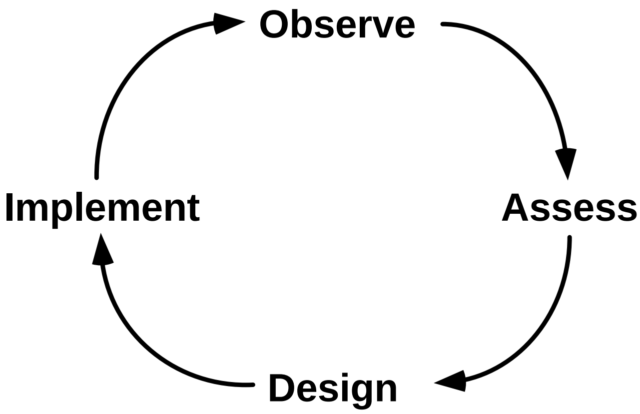

Figure 1: The OADI Learning Cycle

A simple example of describing learning with the OADI learning cycle is a project manager attempting to keep his or her project on schedule and in budget. The manager *observes* that the project budget and estimated costs are equal but that the deadline is four months away while the estimated time required to complete the project is eight months. The manager then *assesses* that he or she will lose their job if the project is late, *designs* a solution of increasing the labor on the project by hiring more people to close the schedule gap, *implements* the design by doubling the project staff, *observes* that the new hiring has reduced the time required to the available four months but that the estimated costs now exceed the budget. The manager *assesses* that he or she will lose their job if the project is over budget, *designs* a solution to lay off half the newly hired staff, *implements* the new design, and the learning continues. Sterman (1994) describes learning in several forms which can be described with the OADI learning cycle. As will be described, system dynamics plays a central role in this strategy by providing a set of tools for each of the four learning activities in the OADI learning cycle.

The strategy described here has been developed and chosen for a particular reason. Our ultimate goal is to develop research skills in managers. Research is a process of developing knowledge by testing potential answers (hypotheses) to important questions with data (Frankfort-Nachamias and Nachamias, 1992). The ability to learn independently is the basis for research. Products of the four learning activities of the OADI learning cycle generate both intermediate and final research project products. For example the observation activity generates a description of the context and existing theories concerning an issue and the design activity generates hypotheses. These skills are as valuable to practicing managers as they are to formal researchers. The final result of learning as described by the OADI learning cycle can be improved performance through the implementation of a successful design, as is often the goal of applied research. Alternatively the final result can be an assessment that a design contributes to the knowledge which is often the goal of more theoretical research. The OADI learning cycle can prepare managers for research because it is a model of learning by testing designs (i.e. research). Training managers to think and learn like researchers is consistent with the independent learning skills needed to address complex problems.

An Operationalization and Initial Test of the Strategy

We operationalize and test our strategy for learning to learn by implementing it in our Master's of Philosophy in System Dynamics program at the University of Bergen. The program trains students to use the system dynamics methodology to understand and improve complex systems. A primary goal of our program is to develop independent learning skills in our students - the ability to learn. Here we describe our program as an example of the implementation of our strategy. We operationalize our strategy in three overlapping stages, each which develops a particular type of skill: awareness of learning needs, basic learning activities and management of the learning process. All three stages are necessary in the order listed for learning to learn. We apply our strategy twice with each set of students. Our strategy is first applied in the first three courses of our program in the relatively narrow context of teaching students about complex systems using the system dynamics methodology. From the student's perspective this portion of our program is "about system dynamics". Our strategy is applied again in the final course of our program and during thesis work in a more general context to teach our students formal research tools and methods which extend those shown developed the first application. From the student's perspective this portion of the program is largely "about research". Although the focus of the two applications are different both implement the three basic stages of our strategy: develop awareness of learning needs, basic learning activity skills and the management of the learning process.

Stage 1: Developing Awareness of Learning Needs

Despite the prevalence and difficulty of the challenges of learning to learn described above the need for developing skills in independent learning are not obvious. In fact many complex systems appear deceptively easy to manage (Sterman, 1992). Convincing managers and students of their need for effective independent learning skills is a first step in learning to learn. Therefore effectively demonstrating the challenges inherent in designing and managing complex systems and the need for independent learning skills is critical. The first course in our program begins with a participatory exercise in managing a simulated business environment. In "The Beer Distribution Game" (Sterman, 1992) participants fill orders for beer from their customer and place orders for beer with their supplier with the goal of controlling the size of their inventory. The supply chain includes the structural feedback, delays and nonlinear relationships characteristic of complex systems while remaining completely exposed to the participants. Orders are filled and placed and inventory levels and orders recorded for a simulated 35 - 40 weeks in response to a single stream of customer orders. Participants find it extremely difficult to perform well in the Beer Distribution Game (Sterman, 1989). Typical performance is ten times worse than optimal. Orders and inventories oscillate with increasing amplitude despite a static stream of orders from customers. An interactive debriefing session after the game identifies the challenges of managing systems and the need for an ability to learn about them as a part of finding solutions to problems such as inventory management. Students learn from the Beer Distribution Game that even apparently simple systems can generate very complex and problematic behavior. Additional examples develop and support the need for independent learning skills throughout the program.

Stage 2: Developing Skills in the Basic Learning Activities

In stage 2 our strategy for learning to learn turns to training in the four basic learning activities of the OADI learning cycle. We have observed that the four fundamental learning activities are often difficult to develop competence in and difficult, impossible, unethical or time consuming to perform. An example is implementing a design to improve a nation's economy by changing the work ethic of its citizens. We use an apprenticeship model based on demonstration followed by mimicking with feedback, repetition and slowly adding complexity while withdrawing assistance to develop skills in multiple tools for each action (Figure 2). The majority of these tools are part of accepted system dynamics methodology and part of a traditional system dynamics curriculum. Students are trained to initially focus their observations of complex systems by describing the nature of systems and problems and graphically depicting dynamic behavior in ways that suggest relationships among system components. Basic assessment skills are developed by writing focusing questions which capture problems in concise forms such as "What ordering policies minimize inventories in the Beer Distribution Game?" System mapping at the conceptual level with methods such as causal loop diagramming (Goodman, 1988; Richardson and Pugh, 1981) help managers assess systems and design possible solutions. Beginners also learn how to design by expanding their modes of thinking. For example the concept of behavior being driven by structural feedback instead of exogenous influences is often a fundamentally new and different perspective. The implications for complex systems (e.g. policy resistance and counterintuitive behavior) alter how managers see problems and potential solutions. Developing the practice of making assumptions explicit and clear is critical at this stage. Beginners implement potential solutions by applying their dynamic reasoning to conceptual models.

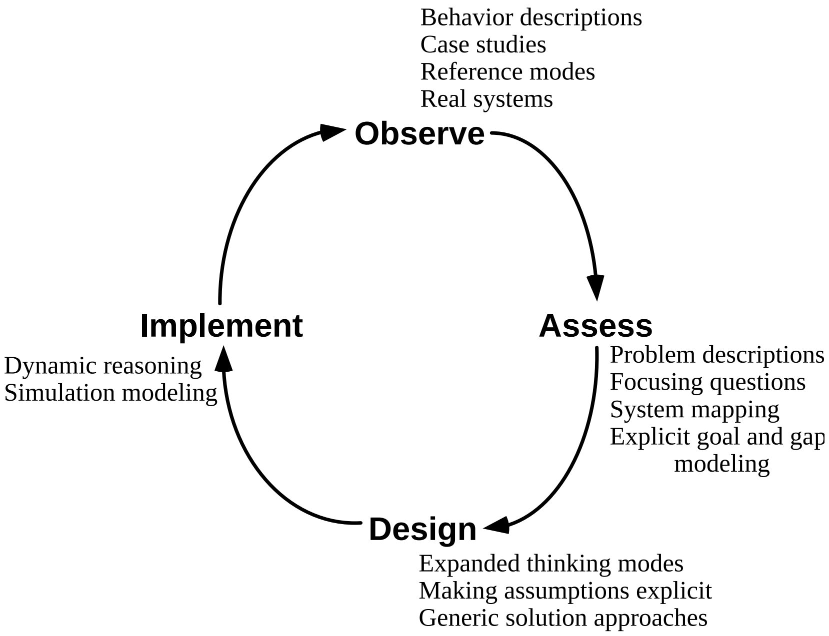

Figure 2: Tools for Developing Skills in Basic Learning Activities

Tools of increasing complexity and capability are gradually introduced as students develop competence in fundamental system dynamics tools. For example to further develop observation skills we use professionally prepared business cases and mathematical descriptions of behavior such as describing oscillating behavior with amplitude, frequency and phase shift. More advanced assessment tools include the explicit modeling of gaps between system conditions and objectives and the specification of performance as transient or steady state. Design approaches for more advanced managers include generic solution approaches (e.g. system archetypes and controller designs) and advanced technology such as computers to reduce delays and improve information transfer. Advanced implementation include building simulation models of complex systems which can be used to test designs.

Stage 3: Developing Skills in Managing the Learning Process

A primary challenge in operationalizing our strategy is that although the OADI learning cycle is a useful conceptual model learning in practice is not nearly as simple as the process depicted in Figure 1 or as easy as implied by the project management example above (Sterman, 1994). We have observed several characteristics of independent learning which make managing the independent learning process difficult:

- Moving from one basic learning activity to another may incur delays and changes which impede the effectively taking the next learning action. For example the delay between implementing a new education program and observing the impacts on managers may make observation more difficult and less accurate.
- More than one iterative one path through the four learning activities are possible and required for effective learning. For example repeated observation and assessment may be required to obtain a useful understanding of the system and its relations to the objectives prior to beginning the design of solution alternatives.
- Which sequence of learning actions is effective is not obvious or easily identified

Learning to learn requires developing the skills required to manage the OADI learning cycle as well as perform the individual learning activities. This aspect of our strategy is as important as developing the ability to use individual tools but receives inadequate focus and training by educators. The apprenticeship approach is applied again with three significant differences from the process described above for the basic learning activities to train students to manage independent learning :

- **Separate development of tool and process skills:** Training in the learning process is separate and distinct from training in the use of individual tools. Students in our program can develop skills in the use of a tool or the management of the use of several tools in which they possess competence but not both simultaneously.
- **Simple familiar content:** Examples and exercises in managing the learning process are simple and familiar enough to allow students to focus on the iterative learning process and not the content of the problem.
- **Explicit iteration:** The iterative nature of the learning process is demonstrated explicitly. In a traditional learning strategy processes such as model building are presented as occurring once perfectly to produce the completed final product. While potentially impressive this hides the actual iterative process used and (more importantly) fails to demonstrate what managers and students should expect and practice in the independent learning process.

Barriers to Successful Strategy Implementation

Our experience with the strategy has identified several barriers to its successful implementation. We suspect that this subset of the barriers to learning about complex systems in general (see Sterman, 1994) applies to practicing managers as well as to our students. The primary observed barriers and some of the actions taken to address them are:

- **Risk aversion:** Risk-averse students have more difficulty in learning independent learning because of their discomfort with experimentation which may "fail" in the sense of not give a correct and final solution quickly. Independent learning requires taking initiatives which develop knowledge but not solutions, becoming comfortable with failure and adept at how to use failure to improve. Our program provides students with safe places for experimentation with privacy in the form of personal computer accounts and facilities and individual assignments, opportunities for fast and relatively easy iteration and freedom from forced public demonstration of skills. We encourage students to learn experientially by emphasizing the role of assignments and with "deep water" projects which require experimentation.
- **Discomfort with uncertainty and ambiguity:** Learning is more difficult when conditions, systems and outputs are not constant, when there is no one answer (uncertainty) or when these components are unclear (ambiguity). We focus on learning processes more than the products of those processes in evaluating our student's work, valuing processes as "better" or "worse" instead of "right" or "wrong" and provoke thought and processing by responding to questions with questions instead of providing answers. The tools and learning process model of our strategy assist in providing a framework for ambiguous problems and systems.
- **Lack of interest in topic:** Uninteresting topics and unrealistic contexts lead to a lack of commitment to find solutions. We use reports from newspapers and magazines on topics of natural interest to our managers (e.g. current events, drugs and love), manual and computer-based management flight simulators and professionally developed business case studies to lure students into the learning space and maintain their interest. For example in one assignment students use system dynamics to explain the fate of Romeo and Juliet (Radzicki, 1993).
- **Passive learning model:** Some students prefer a passive learning role in which the instructor or reading material provide the lessons to be mastered or the exact set of steps and tools to apply. This approach can be efficient for some types of learning and this mode of learning may be the only approach which students or managers have experienced in their formal education. However independent learning requires an active constructivist approach to learning by both the manager and instructor. These students need gentle introduction and guidance to develop a constructivist approach to learning.
- **Difficulty in reflecting on experience and observation:** Thoughtful reflection and objective self evaluation is essential to independent learning. These skills are difficult to develop and require a degree of maturity and self-confidence which is incompletely developed in some students. Practicing independent learning can help develop reflective abilities.

Conclusions

Our strategy for training managers to learn independently uses three overlapping stages to develop skills: building awareness of learning needs, training in basic learning activities and the management of the independent learning process. Based on several years of experience the strategy appears to be effective with the majority of our students. These successes support the continued use and development of this strategy. However a few students have not responded well to our approach. These cases can help us identify areas of improvement and the limits of our strategy. We are currently evaluating the impacts of our strategy on our students to identify areas of effectiveness and potential improvement. Preliminary results indicate that progress in learning to learn has been constrained by limits on the ability of some students to reflect, generalize, self-evaluate and develop a constructivist learning model. Although educational culture and history play a large role in creating these limits improvement of our strategy can help reduce their impact. Future research can address how to overcome these barriers. By doing so our strategy for learning to learn can be applied to a broader spectrum of students and practicing managers and thereby prepare both to successfully manage and design complex systems.

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