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## **Skiing as a Model of Instruction**

Richard R. Burton, Xerox-PARC  
John Seely Brown, Xerox-PARC  
Gerhard Fischer, University of Colorado, Boulder

### **Abstract**

While some work has gone into developing specific learning environments, little has gone into clarifying the general issues that affect the acquisition of a complex skill, especially in a naturalistic setting. A study was made of an extremely complex skill, skiing, to determine why it has become so easy to learn. The goal was to analyze the features of a highly successful learning environment in order to articulate a general theory of learning environments.

### **Keywords**

increasingly complex microworlds” (ICM); constructive bugs; non-constructive bugs;

### **Introduction**

Learning environments can be examined in terms of a paradigm called “*increasingly complex microworlds*” (ICM). In this paradigm, the student is exposed to a sequence of environments (microworlds) in which his tasks become increasingly complex. The purpose of an individual microworld (an example of a specific microworld is “Turtle Geometry” [Abelson & diSessa, 1980] embedded in LOGO environments [Papert, 1980]) to provide the student with a task that he can perform successfully using a simplified version of the final skill that is the goal. This allows the student to focus on and master one aspect of the skill in a context that requires related subskills. As a result, the student learns when to use the skill as well as how to use it. The purpose of the sequence is to evolve the simplified skills toward the goal skill. The ICM framework focuses both on what is learned in any particular microworld and on how to choose the next microworld in the sequence.

A microworld is created by manipulating three elements: the *equipment* used in executing the skill, the *physical setting* in which the skill is executed, and the *task specifications* for the given equipment and physical setting. These manipulations allow the student to focus on the factors that are fundamental to learning a skill, rather than on factors that are not immediately relevant. A critical factor in determining appropriate micro worlds is the process of debugging, or correction of systematic errors. The appropriate microworld can transform "nonconstructive bugs" into "constructive bugs," ones that can be readily learned from. Also, the role of coaching in the ICM paradigm increases in importance with the introduction of simplifications. Finally,

the parallels to other learning environments, particularly computerized ones, make it possible to form a general theory of learning environments (Brown, 1982).

### **Why Skiing?**

Skiing is an extremely complex skill to learn and to perform. It is representative of an important class of real-time control skills, or data-driven skills, where error correction is essential to cope with deviations and sudden changes in the environment. Additionally, skiing is of interest because highly successful methods have been developed to teach it. This is not true for most other complex skills. These methods suggest the criteria that are necessary to design successful learning environments for other complex skills. In addition, skiing provides an intuitively understandable domain, with which many people have personal experience. Even nonskiers can relate the examples used in learning to ski to other physical skills, such as bike riding or windsurfing.

Skiing is an instance of a *success model* (Papert 1976), being an example of the successful acquisition of a complex skill. In skiing, the conditions of learning are more important than the total time or the mere quantity of exposure. This implies that the teaching of skiing has evolved into a highly successful instructional process. The two main uses of a success model are to identify the features that make it successful, and to abstract these features and try to transfer them to less successful learning situations. There is no complete theory to explain why the learning process in skiing was so dramatically enhanced during the last twenty years, but four features are of great importance: redefinition of teaching goals, improved equipment, access to new environments, and better teaching methodologies and conceptualizations.

Factors besides the ones investigated in the study influence the learning process. Primary among these is the factor of motivation. The person learning to ski is highly motivated. This is so for many reasons. Skiing is fun. It provides a wide variety of experiences, since every run is different from the previous run. Skiing is good exercise. It provides a nice change in the life style of many people. Also the novice skier's motivation to improve remains high because ski areas have many expert skiers around. This also means that learning can take place according to the medieval craftsman model, in which the ability of the less experienced skier is enhanced through interaction with the more experienced one (Lave, 1977).

Motivation is an important consideration in the design of learning environments. Each environment in the sequence presented to new skiers maintains their motivation by allowing them to work on a functional set of subskills. The sequence can be arranged so that within each environment there is no focusing on particular sub- skills until the need for that subskill has been experienced.

There are also a few negative aspects of skiing. It is expensive, it is time consuming, and it can be dangerous. For these reasons, the task of identifying the aspects of skiing that make it a success model becomes even more interesting.

## **The ICM Paradigm**

The acquisition of a complex skill is difficult when the starting state and the final state are far apart. Good learning environments, structured according to the ICM paradigm, provide stepping stones or intermediate levels of expertise, so that within each level the student can see a challenging but attainable goal (VanLehn & Brown, 1980). In skiing, technological advances and the methodologies built around these advances make it easy to get started. This means that practice, or a task' within an intermediate level, is satisfying in itself and not just something that must be endured before the learner can enjoy excellence.

An example of the ICM paradigm is a novice learning to ski. The student begins on short skis over gentle terrain. The short skis make it easier to turn and therefore allow the student to work on higher-level tasks, such as developing a rhythm over a series of turns. Also, since it is easier to get up from a fall, short skis encourage a student to try more difficult maneuvers. The gentle terrain limits her speed and reduces the danger of injury. As the student gains ability within these constraints, she is given slightly longer skis and steeper, more complex slopes, until she is using full-length skis on uncontrolled slopes. At each step, the microworld in which she must perform is made increasingly complex.

The ICM paradigm may be applied to sports other than skiing. A large body of knowledge about skill acquisition is available in the literature of different sports. Textbooks for these sports supply a great deal of knowledge about the critical components and essential stepping stones for the complex skills they describe. They also identify the most common problems and suggest special exercises to eliminate those problems. However, these texts often lack a conceptual framework that would allow them to generalize their knowledge or to structure it according to different criteria. In this study, the process of learning to ski is analyzed within the framework of the ICM paradigm, with the goal of expanding the paradigm. Austin [Austin, 1974] who analyzed the skill of juggling in terms of a computational metaphor, used the resulting analysis to develop novel methods of teaching juggling.

## **Manipulating the Learning Environment**

One of the major design decisions within the ICM paradigm is choosing or generating appropriate microworlds. The primary method of generating alternative microworlds is the manipulation of equipment, physical setting, and task specifications. A taxonomy of knowledge, methods, and heuristics serves as a basis for evolving a theory of learning environments.

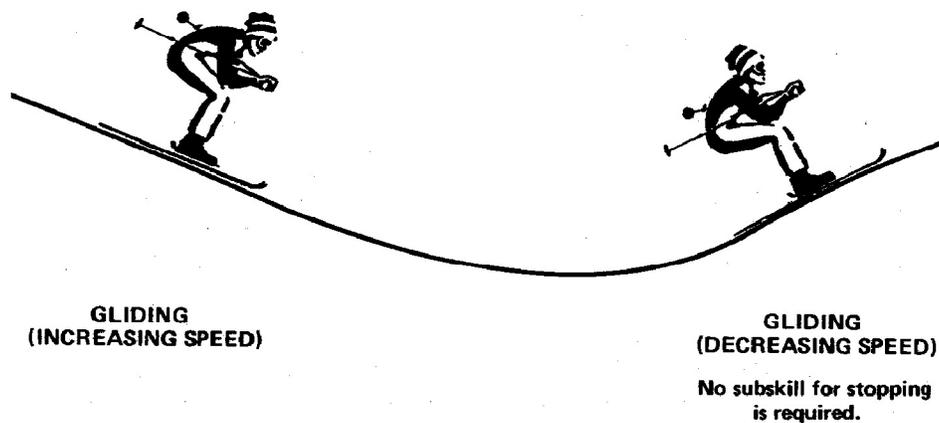
The equipment given a student is changed to create different microworlds. The best-known example of this in skiing is the variation of ski length. In the "graduated length method" a beginner skier is started on short skis. As the student becomes proficient, his skis are gradually lengthened to full-length skis. Short skis are used as transitional objects in the learning process. They make it easier to get started and make early success more likely. Short skis allow the student to focus on and learn the fundamental elements of skiing before going on to more difficult tasks. For example, short skis are easier than long skis to maneuver. Therefore, a student can try different maneuvering techniques to find out which ones are effective. At the next level, when the student has learned the fundamentals of maneuvering, he can go on to longer skis, which give him greater power and hence more speed.

An interesting perspective on the hand-held electronic calculator is to view it as a piece of equipment used as a transitional object in learning mathematics. It creates a microworld in which the student can focus on the concepts of a problem rather than on the calculation. The task of solving the problem is therefore simpler. The calculator also helps to avoid the discouragement of wrong answers due to calculational mistakes.

Why did it take so long for someone to think of using short skis in the learning process? For one thing, skiing itself changed. Twenty years ago people wanted to ski fast in straight lines, for which longer skis are better. Now the final state of expert skiing involves more turning, which is facilitated by short skis. For another thing, teaching by the graduated length method requires a different instructional organization. To be economically feasible, the new method needs large ski schools where students can rent short skis instead of buying them. The economic considerations that have hindered exploration of transitional objects in learning to ski will not be as important when they are employed in computer-based learning environments. In computerized environments, the transitional objects are symbolic structures rather than physical structures.

Short skis are not the only technological improvement in the equipment used in skiing. Safety bindings reduce the fear and eliminate the catastrophic consequences of wrong behavior, thereby supporting an active approach to mastering new challenges. In an interactive computer system, the "UNDO" command, which undoes the effects of the previous command, supports a similar type of exploration because it reduces the risk involved in making errors. Ski tows and gondolas provide access to new environments in the form of moderately steep and wide glaciers with snow conditions suited to the early phases of the learning process. In addition, they increase considerably the time that people can actually spend skiing.

Great care must be taken to choose a microworld in which the simplified skill is *isomorphic* in its most important components to the final form of the skill. In juggling, the skill of ball handling can be practiced with one or two balls. This develops the necessary subskills of tossing and catching, as well as hand-eye coordination. However, the easiest form of three-ball juggling, called cascade juggling, cannot be simplified to an isomorphic two-ball juggling [Austin, 1974].



**Figure 1: How physical environments can simplify the skill of skiing**

Controlling the physical setting is another method for creating microworlds. Skiing is an integrated collection of subskills. A major aid in learning any complex collection of skills is the opportunity to practice the subskills independently. Microworlds must be found or designed to allow a learner to exercise particular skills. For the beginner skier, gliding and stopping are two essential subskills that have to be learned. But stopping cannot be practiced without gliding, and gliding is dangerous unless one knows how to stop. In Simon's words, skiing is not decomposable, only "*nearly decomposable*" [Simon, 1981]. The problem can be solved by choosing the right setting. By the choice of a downhill slope that feeds into an uphill slope, the subskill of stopping is avoided (see Figure 1). This example leads to a rule: "*The decomposability of a skill is a function of the structure of the environment as well as of the skill itself*". Modern ski areas provide another manipulation of the environment that simplifies the skill of skiing. They provide the novice with constant snow conditions. A beginner can first learn to maneuver on packed slopes without having to worry about the variabilities of ice or deep powder. For one learning to play tennis, the ball-shooting machine provides a similar form of simplification. Receiving a stream of balls at the same velocity and in the same location removes some of the variables from the process of learning a stroke.

The wide variety of slopes in a large ski area has another important impact on learning. It allows the coach to choose a physical setting according to the needs of the learner and allows the sequence of microworlds to be tailored to the *individual learner*.

The manipulation of learning environments is a dynamic process. It is possible to alter the microworld by changing the task specification. The student may be asked to perform different tasks with the same equipment in the same setting. For example, a skier may be instructed either to traverse down a slope or to follow the fall line, the steepest way down, depending on what subskills are being perfected.

The manipulation of task specification is also used to teach higher-level skills. When a skier is presented with a gentle slope, she may be instructed to view turning simply as a means of going where she wants to go. Later, when presented with a steeper hill, she may be instructed to view turning as a means of controlling her speed. Task specification is a way to focus the student's attention on the important factors in a microworld.

Technological improvements have eliminated certain prerequisites for skiing. That is, they have simplified skiing by removing inessential parts. It is no longer necessary to spend a whole day of hard physical exercise to gain a thousand meters of elevation in order to ski one nice run. The goal of skiing is traversing slopes successfully, not developing stronger muscles and better physical condition by climbing uphill for several hours. If climbing were one of skiing's top-level goals, the use of gondolas and chair lifts would hardly be appropriate simplification. Clarifying the top-level goals may imply a different standard of measurement for the hierarchical ordering of the subskills and a corresponding change in the sequence of microworlds.

The importance of clarifying top-level goals can also be seen in programing. As computing becomes cheaper, concerns about computational efficiency will be replaced by concerns about cognitive efficiency, about how to facilitate the understanding and writing of programs. This change in perspective will require new conceptualizations and methodologies, which will lead to

a new set of microworlds for the acquisition of the skills of programming and problem solving [Fischer, 1977].

The range of possible micro worlds that can be created using manipulations of a learning matrix is much larger than the range of useful ones. The designer of a learning environment must look carefully at what each microworld does for the overall goal. Four possible uses for a microworld come to mind. A microworld can provide:

1. The right entry points into an environment, making it easier to get started on a subskill.
2. An environment in which the student feels safe, allowing him to focus his attention on learning skills.
3. Intermediate goals or challenges that are, and seem to be, attainable.
4. Practice of the important subskills in isolation, allowing the common "bugs" to occur one at a time instead of in bunches.

A complicating factor in choosing microworlds is that nonmonotonic relationships often exist between manipulations of the microworld and the corresponding simplifications of the task. For example, skiing on a moderately sloping hill is a useful manipulation because the student can more easily maintain control of her speed. But the relationship between the slope of the hill and the nature of the task is nonmonotonic. That is, if the hill is too flat, it may be impossible to attain enough speed to turn. Another example of this sort is that skiing is difficult on a slope with big moguls, or mounds of snow, but when one is initiating turns, small moguls can be very helpful. Microworlds cannot be chosen simply by picking extremes in the factors involved.

Another concern in choosing a microworld is the danger of *oversimplification*. Skiing is representative of an important class of real-time, data-driven control skills. This means that a sudden, unexpected change in the environment requires high-order error correcting and debugging skills to cope with the deviations. If the microworlds are too friendly, they may suppress the development of these high-order skills. The skier must learn to cope with deviations, such as icy spots or rocks that lie hidden under soft snow.

Developed ski areas simplify the task of skiing because their operators close avalanche areas and keep the skier away from crevices, pack down the slopes, and rescue people if they get hurt. This situation implies that people skiing only in these areas never acquire the planning and debugging knowledge they need to move around in more hostile environments. One danger of task simplification is that it may lead to unjustified extrapolations. One of a coach's jobs is gradually to reduce the level of protectiveness, leading people to the right new challenges. A student should not be allowed to ski too long in an environment which does not require stopping, because there are very few runs with this characteristic. Another danger of simplification is that perfecting performance in one environment, such as packed slopes, may reduce the willingness of a skier to practice in another environment, such as powder, because the difference between his performance in the two environments may be too great. Both of these dangers can be seen in efforts to teach computer programming that start with BASIC. The linear nature of a program in BASIC and the small size of solutions to typical introductory problems often lead students to develop debugging strategies that do not generalize to large programs. One such strategy is to trace through a program one statement at a time. Some students also resist leaving

friendly, albeit limited, BASIC environments, in which they can adequately solve small problems, for the complexities of data declarations, functional decomposition, and advanced control-structure statements. These extrapolations are not ones intended by those who designed the learning environment. Rather, they arise from inappropriate generalizations made by the students using the microworlds in BASIC. Understanding the inappropriate generalizations that can develop in each microworld is one of the tasks facing a learning environment designer.

## **Debugging**

Debugging plays a central role in the pedagogical underpinning of the ICM approach. As a student moves from one microworld to another at a higher level of complexity, she may need to modify her knowledge in several ways. New subskills may be introduced that must be mastered (e.g. skiing over moguls. Changes in the environment may require new interactions between skills (e.g. stopping and turning at the same time). And some skills that were idiosyncratic to a microworld may have to be unlearned (e.g. keeping the skis pigeon-toed during a snowplow has to be replaced with letting them run parallel).

While a designer should strive for simplifications that reduce the chances for incorrect generalizations, this is not always possible nor necessarily desirable. In skiing, an instructor has the problem of how to deal with the poles. Even though they are quite important for the advanced skier, the only major skill a beginner needs to learn is to carry them so that he will not hurt himself. While practice without poles would prevent formation of any inappropriate skills, empirical evidence suggests that eliminating the use of poles is not a useful simplification. Even if the poles are used incorrectly, they still support balance and mobility, and it is apparently easier to unlearn an incorrect use of poles than to incorporate the poles into a skill learned without using them from the beginning. The goal of a sequence of microworlds is not to remove all chances for misconceptions but, instead, to increase the possibility that a student will learn to recognize, learn from, and correct her own mistakes.

An important characteristic of a Piagetian environment (Papert, 1978), is the notion of a "constructive" bug. The learner gets enough feedback to recognize a bug, to determine its underlying causes, and on this basis to learn procedures to correct the bug. This notion contrasts sharply with the notion of a "nonconstructive" bug, where a student may recognize he is wrong but does not have the necessary information to understand why.

A critical design criterion for selecting the right microworld is finding one that transforms nonconstructive bugs into constructive ones. In the domain of skiing, there are several possible environmental supports for such a transformation. For example, if the skier leans too much into the hill with her upper body, a change to a steeper hill will indicate this to her because her skis will start to slide out from under her. Or if she holds her knees too stiffly, trying to stay on the ground while skiing over a bumpy slope will point out her inflexibility. Or if she does not ski enough on the edges of her skis or if she makes turns too sharply, a slope with soft snow, where she can observe her tracks, will indicate where each of these conditions is occurring. In all of these cases, the microworld is chosen to allow the student to use what she is currently experiencing to debug her technique.

A good coach knows a large number of specific exercises designed to transform non-constructive bugs into constructive ones. These exercises are goal-directed toward certain bugs. His expertise must include the ability to distinguish the underlying causes, which may be hidden and indirect, from the surface manifestations of the bugs. To mention just one example: lifting up the back end of the inside ski in a turn provides the skier with the feedback that most of his weight is on the front end of his outside ski, where it should be. Exercises of this sort, which provide the basis for *self-checking methods*, are of vital interest and are essential in teaching and learning a physical skill (Carlo, 1974; DVSL, 1977), whereas in the cognitive sciences, research in *self-checking methods* is still in its infancy (Brown & Burton, 1978).

Another way to turn nonconstructive bugs into constructive ones is through the appropriate use of technology. The most obvious example is the use of a video camera, which helps the student to compare what she was doing to what she thought she was doing. Similarly, a computerized learning environment that records study sessions allows a student to review what she has done and perhaps to correct her own bugs.

### **Coaching**

Acquiring a complex skill, even when supported by a good learning environment and the appropriate technology, does not eliminate the need for a good coach. The introduction of simplifications increases the importance of a coach. The coach must be able to accomplish four goals:

1. Make sure that within each microworld the right subskills are acquired, instead of ones that later have to be unlearned.
2. Design the right exercises, provide the right technology, and select the right microworlds to turn nonconstructive bugs into constructive ones.
3. Demonstrate a task the way a student did it in order to maximize the student's chances of recognizing his bugs.
4. Explicate knowledge in terms the student can understand and execute, that is, give good instructions.

The need for executable advice is illustrated by the many books that are written from the instructor's point of view. The student often receives advice, in the book or on the ski slope, that she cannot execute. An example of such advice is, "*Put your weight forward*," which is given to skiers who do not know where their weight is. The instructor tells the student the what without telling her the how and without providing her with knowledge or procedures to translate the what into the how.

Executable advice is distinguished from observable advice. For example, when the student is skiing in powder snow, the advice, "*Your ski tips should look out of the snow*," is observable by the student. That is, the student can see whether his ski tips stick out of the snow or whether they are buried below the surface. But the advice is not directly executable. The corresponding *executable advice* would be, "Lean back," or "Move your weight back" if the student knows how to shift his weight. This advice is not directly observable.

The interesting dependency relationship is that the “*what*” can be used to control the “*how*”. As a process becomes understood, the language of the process changes from how to what. This change has characterized the movement from machine language to higher level programming languages in computer science. In a high-level language, the programmer tells the computer what to do, leaving many low-level details that need to be expressed in machine language to the compiler.

There are other important aspects of coaching. The coach must:

1. Draw the borderline between free and guided exploration, for free exploration in a dangerous environment could end up with the student in a crevice or an avalanche.
2. Decide when to move on in order to avoid simplified versions of the skill that cause bad habits.
3. Be aware that coaching is more important at the beginning of the acquisition phase than later on. A conceptual model must be created, entry points must be provided, and self-checking methods must be learned, so that one can then self-coach.

## Conclusions

The examination of skiing has clarified the relationship between holistic, activity based learning and subskill or task analysis. Within each microworld that a beginning skier goes through, a particular aspect of the skill is focused on. But this skill is not executed in isolation. The student must still do simplified versions of many other skills required to ski. Simplifications of other interacting subskills let the student learn not only the particular subskill but also how it is used in the context of the entire skill. Focusing on a particular subskill allows important components of the skill to be easily learned, while simplifying the microworld ensures that the student learns how the subskill fits with other subskills without having complete mastery of those other skills as well. The analysis of skiing according to the ICM approach provides better insights into the complex issues of skill acquisition and design of learning environments.

## Notes (by Gerhard Fischer, October 2004)

1. This article is a modified and extended version of an earlier article: Fischer, G., Burton, R., & Brown, J. S. (1978) "*Analysis of Skiing as a Success Model of Instruction: Manipulating the Learning Environment to Enhance Skill Acquisition.*" In Proceedings of the Second National Conference of the Canadian Society for Computational Studies of Intelligence.
2. The lessons learned from this research is further discussed in a section “Toward a Theory of Pedagogical Simplifications” (p 133-135) in the following book: Wenger, E. (1987) *Artificial Intelligence and Tutoring Systems: Computational and Cognitive Approaches to the Communication of Knowledge*, Morgan Kaufmann Publishers, Los Altos, CA.
3. The material in reference Fischer, G. 1977 provided the foundations for the following book: Boecker, H., Eden, H., & Fischer, G. (1991) *Interactive Problem Solving Using Logo*, Lawrence Erlbaum Associates, Inc., Hillsdale, NJ.

## References

Abelson, H., & A. A. di Sessa. 1981. *Turtle geometry: the computer as a medium for exploring mathematics*. Cambridge: M.I. T. Press.

Austin, Howard. 1974. *A computational view of the skill of juggling*. Massachusetts Institute of Technology, AI Memo no.330.

Carlo. 1974. *The juggling book*. New York: Random House.

Brown, J. S. 1982. *Learning-by-doing revisited for electronic learning environments*. In M. A. White, ed. *The future of electronic learning*. Hillsdale, N.J.: Erlbaum.

Brown, J. S., & R. R. Burton. 1978. *Diagnostic models for procedural bugs in basic mathematical skills*. *Cognitive Science* 2: 155 -191.

DVSL (Deutscher Verband für das Skilehrwesen). 1977. *Skilehrplan*, vols. 1 -7. Munich: BLV Verlagsgesellschaft.

Fischer, G. 1977. *Das Lösen komplexer Problemaufgaben für naïve Benutzer mit Hilfe des interaktiven Programmierens*. Ph.D. Dissertation, University of Hamburg

Lave, J. 1977. *Cognitive consequences of traditional apprenticeship training in West Africa*. *Anthropology and Education Quarterly* 8(3): 177-180.

Papert, S. 1976. *Some poetic and social criteria for education design*. Massachusetts Institute of Technology, AI Memo no.373.

Papert, S. 1978. *Computer-based micro-worlds as incubators for powerful ideas*. Massachusetts Institute of Technology, AI Laboratory.

Papert, S. 1980. *Mindstorms: children, computers, and powerful ideas*. New York: Basic Books.

Simon, Herbert. 1969. *The sciences of the artificial*. Cambridge: M.I.T. Press.

VanLehn, K., & J. S. Brown. 1980. *Planning nets: a representation for formalizing analogies and semantic models for procedural skills*. In R. E. Snow, P. A. Frederico, & W. E. Montague, eds. *Aptitude learning and instruction*, vol. 2: *Cognitive process analyses of learning and problem-solving*. Hillsdale, N.J.: Erlbaum.