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COMPUTATIONAL MODELS OF SKILL ACQUISITION PROCESSES

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In our technology based world there is an urgent need to achieve insight into the complicated issues of skill acquisition and design of learning and working environments. The framework provided by Cognitive Science will be used to gain a better understanding of these issues.

Throughout the paper, we draw parallels between the process of learning to ski and learning to solve problems with the computer. We explicate the remarkable advances in the methods of teaching skiing and analyze the features of the highly successful skiing environment in an attempt to articulate the complex structure underlying a skill acquisition process.

1. Introduction

The widespread and cheap availability of computers is changing our lives and our societies in a dramatic way: computers are not any more the tools only of a small minority of professional people working with them but they have an impact on the working, learning and playing habits of **all** people.

During the last few years, a remarkable shift has taken place in the research efforts of people working in Cognitive Science. There is now a growing interest to understand and to develop cognitive theories how humans learn and perform **real skills**, e.g. reading, writing, solving physics problems, programming computers or doing a complex physical skill (e.g. driving a car, flying an airplane, juggling or skiing) as opposed to solving **puzzle-like problems** (e.g. Tower of Hanoi, cryptarithmetic problems etc).

In this paper we will investigate the complicated issues of skill acquisition and the design of learning and working environments. We will analyse several skills with the help of the computational metaphor. We will especially investigate **skiing** (as a complex, real-time physical skill) and **problem solving with the computer** (as one of the most challenging cognitive tasks) to demonstrate the wide applicability of our framework. Both skills have been greatly enhanced by technological developments. We will develop a theory of simplification and a set of abstractions which will be relevant for the design of technologically based learning and working environments and we will expand the computational paradigm with the insights gained through the detailed examination of a physical skill.

2. Empirical background

The logic and the general laws behind the interactions of a complex skill can best be seen by looking at such different areas like **skiing** and **computer programming.** The ideas and the framework described in this paper are based on the following work:

1) the author has worked as a part time ski instructor for several years

2) he was engaged in a research project (KLING et al,1977) to investigate the use of computers in non-traditional forms (ie the computer was not only used to augment traditional learning subjects or as a giant adding machine but as a general information processing device and as a medium and a tool to explore new ideas)

3) within our research project we have studied the complex interactions between new technologies and reconceptualizations of the subject matter being taught (FISCHER, 1979)

4) this work was not done in an ivory tower, but its feasibility was demonstrated in schools by teaching a wide variety of classes (FISCHER, 1977)

3. Skiing as a success model for a skill acquisition process

Skiing is an extremely complex skill to learn and to perform. Nevertheless, empirical evidence suggests that skiing can be regarded as a **success model** (PAPERT 1977), ie it is an example of a complex skill which is successfully learned by many people. Other examples for skills which can be regarded as success models are:

1) Brasilian Samba school (for a detailed analysis see PAPERT, 1977)

2) reading and writing in the sense that 500 years ago the scribes would have denied that reading and writing could be learned by everybody

3) driving an automobile

We would also like to mention a few areas which we consider to be **anti-success models** (ie the learning process in these areas is not too successful, at least not for the majority of people who are forced to participate):

1) **mathematics:** it is easy to understand that math fails to make sense to a child when it fails to make sense to everyone around him. Things got even worse, when "NEW MATH" was introduced which removed the content of the school work even further away from anything meaningful to the non-mathematician. This is just the opposite to skiing where teaching and learning does not take place outside the situation where the behavior to be learned is relevant.

2) **programmed instruction and learning:** the simple models of the behaviorists did not allow the learner to gain real understanding and to give shape to his tools according to his own taste; he was degraded to the status of a mere consumer.

We do not have a complete theory to explain why the learning process in skiing was so dramatically enhanced during the last twenty years, but we are convinced that the following features were of great importance:

1) redefinition of teaching goals and elimination of prerequisites

2) improved equipment (e.g. safety bindings to provide a protective shield, sharp edges for icy slopes)

3) access to a variety of environments (e.g. packed slopes and powder, wide and flat glaciers)

4) better conceptualizations and teaching methodologies (e.g. graduated length method)

5) demythologization (it is not as difficult as it seems to be, not only experts can do it, the underlying intuitive knowledge of the experts can be explicated and communicated)

We believe that a necessary precondition for a new technology to become the basis for a success model is that it can be regarded as a **convivial tool.** ILLICH (1973) characterizes them as follows:

"Tools are intrinsic to social relationships. An individual relates himself to his society through the use of tools that he actively masters, or by which he is passively acted upon. To the degree that he masters his tools, he can invest the world with his meaning; to the degree that he is mastered by his tools, the shape of the tool determines his own self-image. <u>Convivial tools</u> are those which give each person who uses them the greatest opportunity to enrich the environment with the fruits of his or her vision.

Tools foster conviviality to the extent to which they can be easily used, by anybody, as often or as seldom as desired, for the accomplishment of a purpose chosen by the user".

4. The computational metaphor

One of the beliefs of the people working in Cognitive Science is that the computational metaphor could lead to a breakdown of old displinary boundaries. Our attempt to develop computational models of skill acquisiton processes uses the paradigms and the framework of Cognitive Science to extrapolate knowledge from the successful enterprise of teaching and learning skiing.

4.1 Entry points, transient objects and microworlds

Teaching or learning a **complex** skill is like solving a complex problem: the starting and the goal state are too far apart. One of the main problems for the beginner is: how to get started and how to find stepping stones which provide intermediate goals and serve as stable subsystems to build upon.

<u>Entry points</u> get the learner started to learn a new skill or a new domain of knowledge. In skiing, walking around on flat ground with skis gives a first experience that there are objects longer than shoes attached to the legs of the learner. Entry points do not lead to the final form of the skill but to a microworld which is constructed through an appropriate simplification of the final skill.

A <u>microworld</u> is defined as a "delimited piece of reality in which certain ways of acting and thinking work particulary smoothly and transparent without being disturbed by other components which the final skill will eventually require". The challenge for the designer is to provide microworlds which have this property but are also not too far apart from reality.

Possible uses of microworlds are:

1) they make it easier (in some cases: they provide the only possibility) to get started

2) they acclerate the acquisition of a skill

3) they provide intermediate goals that are challenging and attainable

4) they provide practice on the important subskills in isolation, allowing the common bugs to occur one at a time

5) they eliminate the need for prerequisites, overcoming the problem that people get bored before they have ever dealt with the real skill

Transient objects are conceptual or physical entities which lead from one microworld to the next one. They have to be sufficiently close to things already known, so that they can be easily internalized and they also have to be sufficiently new to give a smooth transition to the next microworld. The use of transient objects is genetic; after the new level of expertise is reached, they are no longer needed.

There are many situations where these concepts can be used with advantage. **Turtle Geometry** (PAPERT 1980) has proven to be a good entry point to the world of programming and problem solving. It introduces in a natural way the notion of a procedure and therefore encourages people at a very early stage to describe problems and programs at several levels of abstraction. Physical turtles (crawling around on the floor) provide a transient object from a concrete world into the more abstract world of TV images and programs.

4.2 A sequence of increasingly complex microworlds

To create just one microworld is in general not sufficient to make the transition from the starting state to the final form of the skill. We need more stepping stones or intermediate levels of expertise so that within each level the student can see a challenging but attainable goal.

The best example of a sequence of increasingly complex microworlds in skiing is the **graduated length method (GLM).** The student begins to ski on short skis over smooth and flat terrain. The short skis allow him to develop rhythm, to turn easily and to get up from a fall. The smooth and flat terrain limits his speed and reduces the danger and his fear. As the student gains abilities within these constraints, he is given slightly longer skis and he moves to steeper slopes until he is finally using full length ski on arbitrary slopes.

The microworlds are created through appropriate **simplifications.** Heuristics used in creating microworlds are the following:

1) reduce the number of subskills to get started (e.g. automatic transmission in a car, packed slopes in skiing, integrated programming systems)

2) start with a version, representation or model which is closest to the student's previous experience and knowledge (to learn a new programming language is different for people knowing FORTRAN than for people knowing LISP)

3) eliminate the danger of making irreversible mistakes (e.g. keep the skier away from crevasse and rocks; provide an UNDO command and back-up files in programming)

A necessary precondition for the creation of microworlds is the possibility to decompose the task into functional units. It will be shown later that technology can have a major impact to increase the decomposability of a task.

4.3 Naming

Our knowledge and our understanding of naming things has greatly increased awareness of the need to create symbolic structures for computer programming. This understanding allows us to extrapolate the implicit knowledge of a good teacher and of a good coach about the role of naming in the instructional process.

The impact of the computational metaphor with respect to naming will be shown by using an example from skiing again. One of the naming schemes which comes to our mind first is to talk about a left and a right ski (and corresponding parts of the body). It turns out that these **hardware**-based names are inadequate, because they are not invariant. If a skier crosses a hill, the correct position requires that his uphill ski and the uphill side of his body is slightly advanced, his weight is on his downhill ski and so on. The terminology "uphill" and "downhill" is much more adequate, because it stays invariant independently which way the skier is going which is not true for "left" and "right" which changes after each turn. These **process**-based names greatly simplify the description of the skill.

Our example can be carried even further because it can be used to indicate the need for **different name spaces.** Besides crossing a hill, the other major activity which a skier does during a run is turning. And the uphill-downhill naming scheme is inadequate for turns, because the names change within this subprocess and they become ambigous in the middle of the turn. We have to use other descriptive terms to characterize a turn. In ski instruction "inside" and "outside" are used. They again have the merit to stay invariant during the whole process of turning.

Our empirical studies in program understanding have shown that the relevance of descriptive names can not be overestimated and that they can substantially improve the cognitive efficiency of a program (BOECKER and FISCHER 1980).

5. Towards a theory of simplification

One of the major design decision within our model of skill acquisition processes is choosing or generating appropriate microworlds. The primary means for doing this is through simplification. This section describes a taxonomy of knowledge, methods and heuristics that could serve as a framework for a theory of simplification.

Introducing simplifications in the learning process creates the need for **debugging** (similar to the linear approximation theory in problem solving (SUSSMAN, 1975)). By definition, we will leave out things in early microworlds, we have to debug interferences and we have to coordinate and interface the subskills, if we introduce more complex versions of the skill. If we would insist on perfection from the start, the learning process would stall at the first step. There is also a need for a **coach** or a teacher: the learner will be introduced to simplified versions of the new skill which will provide him with a microscopic or local view of the total learning process. The instructor, who should have a macroscopic or global view, has to guide the learner, he has to make sure that the learner does not pick up bad habits that will later expand into major blocks and he has to give him advice and encouragement when to move on. Debugging and coaching are considered in more detail in FISCHER, BROWN and BURTON (1978).

5.1 The impact of technology

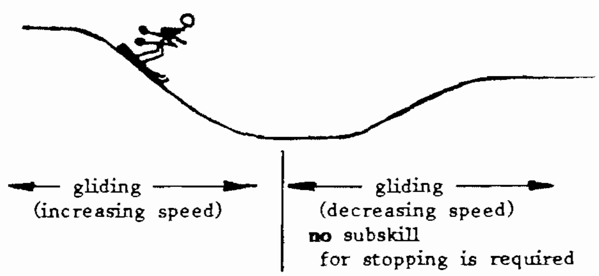
Simplifications are possible in each of the three major components of the learning process: the **skill** required to perform the task, the **equipment** involved in doing the task and the **environment** in which the task is executed. In most cases it is not just one of the components, but their synergistic interaction that leads to the most adequate sequence of microworlds.

The basic skills. The designer of a learning environment can select/create some beginning microworlds for developing particular subskills in isolation. Some of the basic physical skills (e.g. to learn a certain rhythm, to strenghten certain muscles, to improve the mobility) of skiing can be taught without skiing. Students can develop these subskills without having to deal with the interactions and side effects of the whole aggregate of subskills. In a computer based environment the skill of programming can be simplified in many different ways through incremental systems, filtering templates and other software packages which decompose a complex system into simpler units.

The equipment. The best known example of a simplification with the help of equipment is the use of short skis in the graduated length method (GLM; see 4.2). But short skis are not the only technology which is important for skiing. Safety bindings reduce the fear and eliminate the disastrous consequences of wrong behavior and therefore support an active approach to mastering and exploring new environments.

Computer based environments offer even more possibilities in this direction. The transitional objects are **symbolic** structures which are easier to construct and easier to change to be adopted to new purposes. Arbitrarily sophisticated support systems can be constructed which monitor the user and protect him from most of the pitfalls (e.g. an autosave feature can reduce the chances to lose the workspace).

The environment. Gliding and stopping are two essential subskills for the beginner in skiing which have to be learned. But stopping cannot be practiced without gliding and gliding is dangerous unless you know how to stop; in SIMON's (1969) words: the system is only nearly decomposable. The problem can be solved by choosing the right environment:



Integrated personal computer systems (like the ones built around LISP, LOGO and SMALLTALK) free the beginner from learning many prerequisites (e.g. how to deal with the operating system, how to save files etc) before he can start solving problems with the help of the computer. These examples lead to the following statement: **the decomposability of a skill is a function of the skill itself as well as of the structure of the environment.**

Modern ski areas have made another important contribution to the simplification of the environment. They provide the novice with constant snow conditions. A beginner can first learn to maneuver well on packed slopes without having to worry about the variabilities of ice or powder. Integrated computer systems serve the same function: whether a user is writing, debugging and running a program or composing a piece of text or music, he should always be exposed to the same system (even mistakes should not take him out of his protected environment).

The wide variety of slopes in a large ski area has another important impact on learning. It allows the coach to choose a microworld dynamically according to the needs of the learner; this eliminates the need to force every learner through the same sequence of microworlds. NEGROPONTE's (1977) notion of idiosyncratic computer systems points in the same direction.

5.2 The change of top-level goals

Technological improvements have eliminated certain prerequisites for skiing by removing inessential parts. It is not necessary any more to spend a whole day of hard physical exercise in order to gain a thousand meters of elevation to ski one nice run. The goal of skiing is skiing (which implies the feeling of losing gravity and gliding downhill) and not getting stronger muscles and a better physical condition by climbing uphill for several hours. If climbing uphill would be one of our top level goals, the use of gondolas and chair lifts would hardly be an appropriate simplification towards the acquisition of these skills. Different top level goals will require different hierarchical orderings of the subskills and correspondingly different sequences of microworlds.

The impact of microelectronics on Computer Science theory illustrates this point: most computer science curricula include a course on switching theory, even though this theory is largly irrelevant to the present-day practice of computer design, because it is based on an obsolete cost function (minimizing the number of switching components) and ignores the cost and delay caused by long communication paths (SUTHERLAND & MEAD, 1977).

6. Conclusions

As opposed to computer based environments where little experience is available, in skiing we can analyze a development which has taken place. We believe that the coming computer culture has the potential to create success models of learning, working and playing. But this will only take place if the physical penetration of computers into offices, schools and homes will be combined with a **symbolic penetration of computer concepts, metaphors and language into our culture.**

Despite its origins, Computer Science should not be restricted to a concern with computers. We believe that it can become the part of science which can deal successfully with the most complicated and dynamic processes.

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