"STUDYING WITH THE PRINCE"

THE COMPUTER AS A LEARNENG COMPANION

Tak-Wai Chan

Arthur B. Baskin

Department of Computer Science, University of Illinois at Urbana-Champaign

1304 West Springfield Avenue, Urbana, IL 61801, U.S.A.

Department of Veterinary Biosciences, Department of Computer Science

University of Illinois at Urbana-Champaign, 1408 West University Avenue, Urbana, IL 61801, U.S.A.

Abstract – A new class of intelligent tutoring system (ITS) is proposed which we call the Learning Companion System (LCS). In the learning environment of such as system, there are three agents involved, namely, the human student, the computer learning companion, and the computer teacher. As implied by its name, the role of the computer learning companion is to act as a learning companion for the student. To this end, the companion *learns* to perform the learning task at about the same level of the student and both *students* can exchange ideas while being presented the same material. Simulating skill acquisition and actual machine learning are two different approaches to designing the companion portion of the LCS. In the first approach, the performance capability of the companion is controlled by the system while in the second approach, the companion is required to be able to learn as the student does by using the techniques of machine learning. In this paper, we investigate the properties of a learning companion system and some perspectives of these two different approaches to LCS for the domain of indefinite integration.

I. INTRODUCTION

A. Why There was One Who Studied with the Prince

In the past in China, there existed a child who studied with the Prince under the instruction of a royal teacher, as mentioned by the Chinese proverb “Studying with the Prince”. Why? Perhaps the Queen recognized the importance of *learning companionship*. For whatever reason it evolved, the Prince was clearly expected to learn more effectively with the companion than by learning alone.

B. Influence of Social Interaction on Cognitive

The fact that individual cognitive development is influenced by social interactions has been studied or observed by a number of researchers in different areas. In his work, *Mind in Society* (1978), Vygotsky hypothesizes that social interactions play a fundamental role in shaping internal cognitive structures. Vygotsky’s *zone of proximal development* is the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers. He also points out that the role of imitation is particularly important in this concept of zone of proximal development.

Experiments (Doise et al. 1975) have also shown that two children working together can successful perform a task which cannot be performed by children of the same age working alone. A subsequent experiment (Mugny et al. 1978) indicates that “more progress takes place when children with different cognitive strategies work together than when children with the same strategies do so, and that not only the less advanced but also the more advanced child make progress when they interact with each other”. Recent work by Pettito (1985) further illustrates that the approach taken by a pair of students to an estimation task can often be qualitatively different from the approach taken by either student alone. Once the new approach emerges, it then becomes part of the students’ repertoire.

In SOPHIE’s game environment (Brown et al. 1982), researchers noticed that “team player are far less self-conscious than a single informant…in collecting a protocol of a subject who is working alone, it is extremely difficult to get insights into why he rejects certain moves; subjects usually feel no need to justify why they don’t do something… In the two-person team environment, the arguments that naturally arise involve attempts to justify or defeat a proposed move. The record of these justifications provides a rare opportunity to see strategic reasoning un fold and be defended.”

In the context of ‘control’ in problem solving, which deals with the resource allocation during problem solving performance, it seems to Schoenfeld (1985) that Vygotsky’s hypothesis is plausible: “…looking at situations from multiple perspectives, planning, evaluating new ideas, monitoring and assessing solutions in the midst of working problems, and so forth. Where do such behaviors arise, and how does one learn to argue with oneself while solving problems? …. It seems reasonable that involvement in cooperative problem solving – where one is forced to examine one's ideas when challenged by others, and in turn to keep an eye out for possible mistakes that are made by one's collaborators…".

II. DESIGN OF A LCS FOR INTEGRATION

The design of a Learning Companion System (LCS) involves three agents, namely, the human student, the computer learning companion and the computer teacher. The role of the computer teacher is to offer examples, guidance and comments to both the student and the learning companion. The goal of the learning companion is to stimulate the student's learning through collaboration, competition and demonstration. In order to better illustrate the idea of LCS and discuss the two main approaches to the design of the learning companion, we will describe the application of LCS to indefinite integration.

A. Indefinite Integration as the Sample Domain

Indefinite integration is not heavily dependent on other mathematical abilities. In fact, after introducing a technique, students can usually work on a corresponding set of near miss practice problems like those in a text book without much trouble. Yet, students consistently have more difficulty in taking examinations and in doing miscellaneous exercises than they should despite many hours of working problems, as noted by Schoenfeld (1978). Part of the difficulty lies in their lack of adequate judgement of the form of integrands. INTERGRATION-KID is our LCS system currently in development.

B. Outline of the Design of Instructional Material

Since our primary goal is to examine the idea of LCS, we confine ourselves to a subset of indefinite integrations at the level of a first year undergraduate e.g. $\int cos^5 x\, dx$, $\int e^x \sin x\, dx$, etc. The pre-requisites are some competence with differentiation and familiarity with some identities. Similar to the organization of the material in a standard text book of calculus, the learning activities are divided into five sessions:

Session a) Introduce the concept of integration.
Session b) Familiarize with basic rules[1] (Table 1).
Session c) Introduce the substitution method.
Session d) Introduce integration by parts.
Session e) Practice miscellaneous exercises.

[1] For simplicity, we omit the arbitrary constant of indefinite integration

This order should be quite obvious. Learning activities of a) are rather like a traditional CAI format where teaching material is presented with simple question and answer interactions between the teacher and the student. Then, starting from b), we introduce the learning companion into the system.

Basic Rules of Integrations	
(1) $\int x^a\, dx = \frac{x^{a+1}}{a+1}$ where $a \neq -1$	(2) $\int c\, dx = cx$ where c is a constant
(3) $\int \sin x\, dx = -\cos x$	(4) $\int \cos x\, dx = \sin x$
(5) $\int \frac{1}{x}\, dx = \ln\lvert x\rvert$	(6) $\int e^x\, dx = e^x$
(7) $\int c\, f(x)\, dx = c\int f(x)\, dx$ where c is a constant	(8) $\int (\, f(x) +/- g(x)\,)\, dx = \int f(x)\, dx +/- \int g(x)\, dx$

Table 1.

III. THE ROLE OF THE TEACHER AND THE COMPANION

An important step in the design of a LCS is to know what will actually happen to all the agents, that is, the trilateral relationship involved in the learning activities (Figure 1). When difficulty or doubt arises, the student may naturally look for the teacher rather than the companion simply because the teacher is the authority on the subject. On the other hand, the student may look to the companion for assistance in order not to face the teacher with a problem. Furthermore, educational goals, the stage of learning and the difficulty level of problems are important factors to be considered.

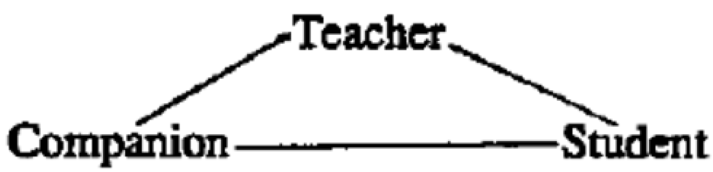

Figure 1.

A. Defining the Role of the Teacher

The job of the teacher is to generate problems, demonstrate examples, explain the format of learning activities, negotiate with the student (e.g. how many more problems the student will do), and make final justifications of the solution and / or retrospective insightful comments. It is only under rare situations that the teacher may interrupt the problem solving process; for example, when the problem is expected to be hard and both the companion and the student cannot solve the problem.

B. Companion as a Competitor

Before a student is able to learn any technique to solve more complex integration problems, proficiency in using the set of basic rules is required. By observing student behavior, we noticed that a student works reliably with problems which are straightforward applications of the basic rules of integration. At the beginning, a student is very careful to choose and apply the proper rule, later on, he can naturally adopt some mental operations, for examples, combining two operators into one macro operator, but still, he refers to the table of rules frequently.

In session b), both the student and the companion work at a set of problems offered by the teacher simultaneously but independently. They are requested to work on the problems slowly and accurately. After they have finished, they compare solutions, discover mistakes and self-correct the mistakes in their own solution. If there remain mistakes not discovered, the teacher points them out. Those correct solutions will receive credits. Then another set of problems is generated by the teacher. Later on, both the student and the companion are required to solve the problems (e.g. $\int (ex - x - 3)dx$) in one step without consulting the table of basic rules. This additional requirement will encourage the peers to use more macro operations and to memorize the basic rules.

C. Working Collaboratively with One Working While the Other Watching

In sessions c) and d), a student learns new techniques in order to solve more complex new integrations. The solution plan in employing these techniques by students can be divided into three phases. The first phase is to choose the right substitution, the second phase is to differentiate the substitution. For more complex problems, this phase also verifies whether the substitution chosen is appropriate. In the last phase the original integration is transformed to a simpler one and then solved. To master these techniques, it is important for the student to have the first hand experience of solving the whole problem with some external help if needed.

In these two sessions, while one is working on a problem, the other is watching and ready to give suggestions if asked. If they both run out of ideas, then the teacher may interrupt. The learning activities in this session can be represented by the following ATN-like graph (Figure 2).

D. Working Collaboratively on the Same Problem via Responsibility Sharing

The problem in session e) are of various levels of difficulty and may require different kinds or combinations of heuristic strategies and techniques. Working on this type of problem, where all goes together, the student has to constantly make a judgement, proceed, then another judgement and so on. At some point in the process, if the solution path looks to be improving, then proceed or seek a heuristic in order to continue; otherwise, back up. About the judgement at that stage, Schoenfeld (1987) recommends what he calls the *three phases model*, “try simple things before you use more complicated techniques, and only when you’ve exhausted to the possibilities of these do you try some of the *shot in the dark* techniques.”

In this session, the protocol of activities for the student and companion is negotiation, decision and working. One is responsible for decision making and the other is for execution, that is, working the problem according to the decision. The negotiation occurs in a rather simple form. The one who will make decisions first suggests using integration by parts and specifies what is *u* and what is *dv*, then he explains how the problem is similar to the previous one. Then the one who will work on the problem makes a different but plausible suggestion and explains why, if he finds one. Next, the one who is responsible to make decisions decides which suggested strategy to use and the one who is responsible to execute works on the problem according to the decision. This procedure repeats until the next decision point. The roles alternate.

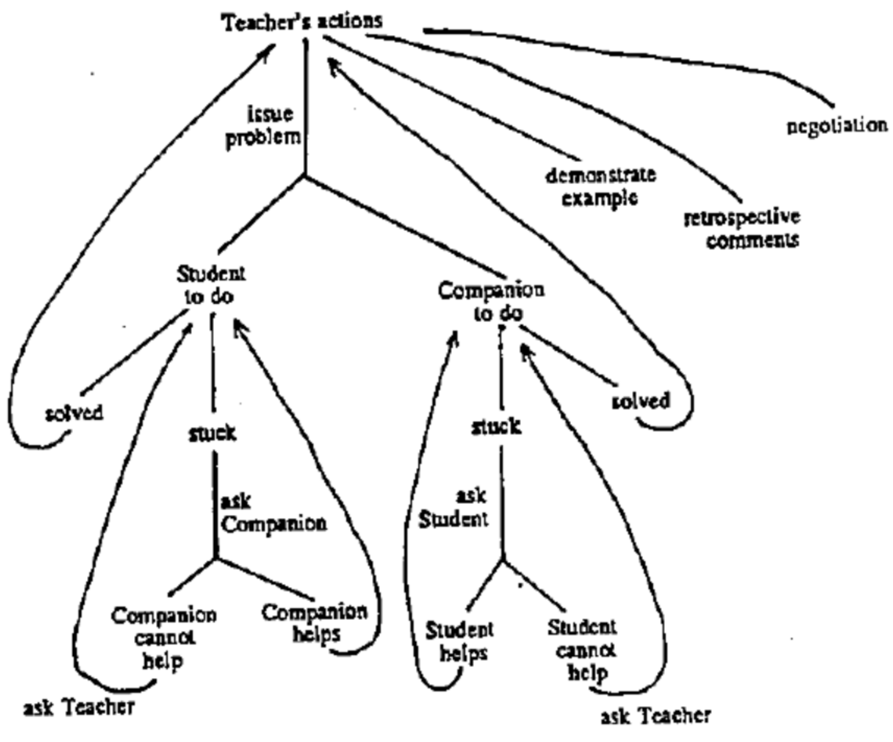

Figure 2

IV. EXAMPLES OF LCS INTEGRATIONS

The following stylized scenes give an illustration of how the student's learning can benefit from a LCS learning environment with respect to the protocols designed above. More subtleties of the advantages of LCS can be revealed in such scenes.

Scene 1

Teacher: "Here is a problem, $\int \sqrt{2-sin3t}\, cos3t\; dt$ *, would the Companion try it?"*

Companion: "u=3t seems to be a good substitution. Now $\frac{du}{dt} = 3$ *, so* $\frac{1}{3}du = dt$.

Then the original integration

$\int \sqrt{2-sin3t}\, cos3t\; dt$

$= \int \sqrt{2-sinu}\, \mathrm{cosu}\, \frac{1}{3}du.$

Oh! I don't know how to continue. Do you have any suggestion, Student?"

Student: "How about trying the substitution $\mathrm{u} = 2 - \mathrm{sin3t}$ *?"*

Companion:" Okay!

$\mathrm{u} = 2 - \mathrm{sin3t}$

so $\frac{du}{dt} = \cdots$

.

.

.

.

I've got the answer!"3

Teacher: "Before going further, it is worthwhile to look back over some of the problems we have just solved:

$\int e^x \cos(e^x + 1)\, dx$ *with substitution* $\mathrm{u} = e^x + 1$ *;*

$\int \frac{x^2 dx}{4-x^3} = \int (4-x^3)^{-1} x^2 dx$ *with substitution*

$\mathrm{u} = 4 - x^3$,

$\int x^2 e^{(1+x^3)} dx = \int e^{(1+x^3)} x^2 dx$ *with substitution*

$\mathrm{u} = (1 + x^3)$ *, and*

$\int \sqrt{2-sin3t}\; cos3t\; dt$ *with substitution* $\mathrm{u} = 2 - \mathrm{sin3t}$.

There are two interesting observations here:

(1) All the integrands (e.g. $e^x \cos(e^x + 1)$ *in* $\int e^x cos\,(e^x + 1) dx$ *) are products of two functions where one is simple and the other is more complex and for every substitution we chose the inside function of the*

more complex function, for example, $(1+x^3)$ *is the inside function of* $e^{(1+x^3)}$.

(2) *If the inside function is a polynomial, the polynomial is one degree higher than the simpler function which is also a polynomial. Since differentiation of a polynomial will decrease its degree by one, that may explain why this choice can work, for example,* $\mathrm{d}(1+x^3)$ *will lead to* $3x^2dx$ *and* x^2dx *is what we need. Also, it is quite easy to see that when we differentiate* $1+\sin 3\mathrm{t}$ *,* $\cos 3\mathrm{t}\,\mathrm{dt}$ *will drop out."*

Here the student *helps* the companion by offering an important suggestion. The student is partially involved in the process of solving the problem by watching the companion work and being ready to help. Furthermore, the student can see possibly different strategies for the problem used by the companion. In addition, at this particular scene, the student learns that *picking a correct substitution is important* in solving the problem. Notice that if the teacher does not present a negative example like that (taking $\mathrm{u}=3\mathrm{t}$), or if the student does not make any sub-optimal substitutions, then a negative example, and thus a piece of useful information, might not be noticed by the student. Moreover, at the end of a set of practice problems, the teacher looks back and offers insightful comments.

Scene 2

Teacher: "Here is a problem $\int e^x \sin x\, dx$ *for you both."*

Student: "I suggest trying integration by parts with $\mathrm{u}=e^x$ *and* $\mathrm{dv}=\sin x\,\mathrm{dx}$ *since the integrand is a product of two different functions; furthermore, there is no obvious choice."*

Companion: "With the same reason, it is also plausible to try integration by parts with $\mathrm{u}=\sin x$ *and* $\mathrm{dv}=e^x dx$*."*

Student: "I prefer my choice."

Companion: "Okay! $\mathrm{du}=e^x$ *and* $\mathrm{v}=-\cos x$ *, so*

$$\int e^x \sin x\, dx$$
$$= -e^x\cos x - \int(-\cos x)\, e^x dx$$
$$= -e^x\cos x + \int \cos x\, e^x dx."$$

Student: "No progress. Come back and try your previous suggestion."

Companion: "Okay! $du=\cos x\, dx$ *and* $v=e^x$*, so*

$$\int e^x \sin x\, dx$$
$$= e^x\sin x - \int e^x \cos x\, dx"$$

Student: "Again, no progress. Any suggestion, Companion?"

Companion: "Now! $du=e^x dx$ *and* $v=\sin x\, dx$*, from the last step, we have*

$$e^x\sin x - [e^x\sin x - \int \sin x\, e^x\, dx]$$
$$= \int e^x \sin x\, dx.$$

Student: "Strange! This is the original integration. We've been going nowhere! Any *suggestion, Companion?"*

Companion: "No!"

Teacher: "You were on the right track! You may back up to the previous step. Instead of $\mathrm{u} = e^x$ *and* $\mathrm{dv} = \mathrm{cosx\,dx}$ *, try* $\mathrm{u} = \mathrm{cosx}$ *and* $\mathrm{v} = e^x$.

Companion: "Okay! $\mathrm{du} = -\mathrm{sinx\,dx}$ *and* $\mathrm{v} = e^x$ *. We now have,*

$$e^x sinx - \int e^x\, cosx\, dx$$
$$= e^x sinx - [e^x cosx - \int e^x\,(-sinx) dx]$$
$$= e^x sinx - e^x \mathrm{cosx} - \int e^x\, sinx\, dx$$

Moving $-\int e^x\, sinx\, dx$ *to the left hand side, we get*

$$2\int e^x\, sinx\, dx$$
$$= e^x sinx - e^x cosx\ .$$

Therefore, $\int e^x\, sinx\, dx = (e^x sinx - e^x cosx)/2$ *."*

Teacher: "This is a rather difficult integration. It works because…"

This problem is particularly difficult because no similar problems have been solved before. In addition, the structure of the integrand gives no hint concerning which is *u* and which is *dv*. As we can see, both the student and the companion are "shooting in the dark". It is easy for one to make decisions hurriedly without careful consideration. Thus, the student may flounder and easily give up if working alone. However, in a LCS environment, the student gets some assurance from the companion's feedback even though it is not always reliable. In fact, if one has to defend or to unfold his reasoning process. Moreover, through looking for other possibilities suggested by the companion and justifying the companion's reasoning, the student's view of approaching the problem is broadened.

V.SOME LEARNING TASKS OF THE COMPANION

If the student is to learn from the companion, the companion's performance must advance along with and be approximately matched to that of the student. In the same way that most students learn a single task with a limited effort, the learning companion's efforts should be limited to a scale similar to that of the student. For example, if a student cannot solve a problem within ten minutes or after three attempts, he may regard the problem as unsolvable and give up. Likewise, the companion may only be allowed a few attempts at a single problem. Furthermore, the companion should be able to benefit from a teacher who knows the domain well and gives advice. The companion can observe the student's work; he can have all the useful background knowledge and related common sense knowledge (e.g. the notion of complexity of an expression) that the student is assumed to have. Of course, he has a good memory. Nevertheless, the companion only learns those skills that would be important for the student to learn, thus, the critical problem of building a learning companions is to identify the most important concepts and heuristics to be learned by the human student.

In session b), if a student is able to write down the following integration in one step without hesitation,

$$\int 5\ cosx\ dx = 5\ sinx$$

$$\int 4\ e^x dx = 4e^x$$

then he has been acquiring a new *macro* rule (collapse of operator sequences),

$$\int rf(x)dx = r\ eval(\int f(x)dx\ )$$

where r is a number, f(x) matches an integrand of the integrations listed in the Table 1 and eval($\int f(x)dx$) means the evaluated integration of f(x), for example, eval($\int cosx\ dx$) = sinx. According to the basic rules listed in Table 1, the sequence of operations would have been

$$\int 5\ cosx\ dx \overset{(7)}{=} 5\int cosx\ dx \overset{(4)}{=} 5\ sinx$$

$$\int 4\ e^x dx \overset{(7)}{=} 4\int e^x dx \overset{(6)}{=} 4e^x$$

Therefore, we can see that two elementary steps have collapsed into one. Learning macro operators or schemata has been addressed in the explanation-based learning research (DeJong et al. 1986, Laird et al. 1984).

In session c) and d), sets of near miss problems corresponding to the intended heuristics are given to the student. For example, as mentioned in Scene 1,

$\int e^x \cos(e^x + 1)dx$
with suitable substitution $u = e^x + 1$

$\int \frac{x^2 dx}{4-x^3}$ $(= \int (4 - x^3)^{-1}\, x^2 dx\ )$
with substitution $u = 4 - x^3$,

$\int x^2\ e^{(1+x^3)}$dx
with suitable substitution $u = (1 + x^3)$, and

$\int \sqrt{2 - sin3t}$ cos3t dt
with suitable substitution $u = 2 - \sin3t$.

A heuristic to learn is:

> if the integrand is a product of two functions, then pick the "inside" of the more complex function as the substitution.[2]

[2]After the student notices such a pattern, the teacher may reveal the essential heuristic: if the integration is of the form $\int f(g(x))h(x)dx$ where the h(x) is different from g(x) by at most a constant factor, then choose the substitution u = g(x).

This is typically viewed as similarity-based learning with a sequence of positive examples (Michalski 1983).

In session e), through working the various kinds of practice problems, the student learns meta-heuristics (Lenat 1983), e.g., the Schoenfeld's three phases model.

Of course, both the student and the companion are taking advice (learning by taking advice or being told, Mostow 1983, Hass et al. 1983) from the teacher—an important source of learning.

VI. MACHINE LEARNING VS. SIMULATION APPROACHES

In the simulation approach, the companion's performance is *controlled* by the system in order to adapt to the student. A simulated companion may have deliberate sub-optimal behavior in order to match skill with the student. On the other hand, in the machine learning approach, the growing knowledge of the companion, which results in improved performance, is acquired through machine learning techniques. In this approach, the student's learning is more likely to benefit from observing how the companion learns. The companion explains his learning process, his discoveries and his hypotheses derived from what he has learned.

A. Machine Learning Approach

Research in machine learning has identified different machine learning techniques – many of which are inspired by human learning and implemented into computer programs. One obvious potential application of machine learning to ITS is to learn those techniques which could enhance the effectiveness of a student's learning. In particular, in addition to learning the domain knowledge, a machine learning-based LCS provides an appropriate environment for a student to learn how to learn. The student can learn from the *disciplined* and *explicit* behavior of the machine learning techniques implied by the companion. If a student employs learning techniques in a disciplined way, he is in fact exploiting and extending the space of possible approaches to a learning task rather than relying on the mysterious 'inspiration' or 'cleverness'. Also, if a student knows explicitly what learning techniques are effective in a given domain, he may transfer those techniques to other domains when appropriate in an active way rather than by spontaneity.

Knowledge representation is a particularly important and difficult problem for a machine learning approach to designing a companion. For example, LEX is a machine learning program which learns heuristics of indefinite integrations (Mitchell et al. 1983, 1986, Utgoff 1986). Each heuristic is represented by a version space (Mitchell 1977). While version spaces are an elegant way to represent heuristics, it is not sufficient to represent all the heuristics to be learned. Examples are meta-heuristics, heuristics with exceptional cases and the intended purpose of the heuristic (Mitchell et al. 1983). Also, the grammatical description language for generation adopted by LEX cannot incorporate useful mathematical knowledge. For example, $\sin x$ and $\cos x$

have similar properties, in differentiation which may also be inherited in integration.

B. Simulation Approach

In the simulation approach, the increasing skill of the companion is directly coded as part of the companion rather than being produced as a result of machine learning. The simulation companion essentially makes selective use of the complete domain knowledge available to the teacher. The increasing performance of the companion can be derived from a succession of discrete simulation programs which each simulate a different level of performance. Selection among these programs is made based on the student's increasing skill can be obtained using a knowledge base driven simulation. In this approach to simulation a single problem solving engine is given access to an increasingly complete knowledge base. In either approach, any information provided to the student about how the learning takes place must be explicitly included in the simulation.

In order to explore the impact on a human student of a learning companion system, the companion need not actually learn. The image presented to the student must be that of a companion whose skill advances in roughly the same way as that of the student. While machine learning techniques provide a natural explanation ability for the student and an ability to expand the LCS paradigm to a wider domain that hand crafted simulations of problem solving performance, the sophistication of the learning companion is beyond the scope of current learning system. For this reason, we are exploring the LCS paradigm through the implementation of INTERGRATION-KID which uses the simulation approach rather than the machine learning approach.

VII. THE SPECTRUM OF LCS

In principle, it is possible to introduce a learning companion to a tutoring system on *any* domain. In particular, LCS is not restricted to the problem solving context. A student may be accompanied by a learning companion in learning concept. For example, in learning the concept of variables in beginning algebra using discovery mode, suppose the student successfully generalizes the pattern $11+3=3+11, 2+1=1+2$ and $100+20=20+100$ to a rule $\mathrm{a}+\mathrm{b}=\mathrm{b}+\mathrm{a}$. However, the rule induced by the companion may be a literally different one, $\mathrm{x}+\mathrm{y}=\mathrm{y}+\mathrm{x}$. Now the student has to justify this alternative answer.
The wider view of LCS should not be limited to the one described above. In fact, the paradigm of LCS represents a board spectrum of ITS design due to the possible varieties on the number and the identities of the agents in a LCS. Each of these varieties gives rise a particular cognitive issues to the student's learning.

First, it is possible to have no teacher involved. For example, in learning simple linear equations, the student may provide rules (e.g. distributive rule) and some examples to the learning companion. Then the student may observe how the companion solves the problems and improves performance. In this way, the student *learns how to learn by teaching the learning companion.* In fact, Neves (1978) has developed a system to learn to solve linear equations.

To the other extreme, it is possible to have multiple teachers with different persona. For example, there may be a patient teacher and a demanding teacher. The student may choose one of them to response adaptive to his own learning style.

LCS may also be a simulation of peer group learning, which means more than one learning companion with different knowledge level or persona involved in the learning environment. For example, with companions at different levels of performance, the student can compare both sub-optimal and optimal performance in learning. Another example is learning with one simulated and one machine learning companion. Finally, a companion could be a human student. In this case, LCS is an environment to support and control distributed learning activities.

VIII. CONCLUSION

In this paper, we have discussed the idea of a Learning Companion System. In the learning environment of a LCS, the human student is studying with the computer teacher and the computer learning companion. In the simulation approach of LCS, the learning behavior of the companion is simulated while in the machine learning approach, the companion learns with machine learning techniques. The machine learning approach of LCS could possibly be one of most interesting application areas of machine learning. However, due to the sophistication of the learning companion, we are using the simulation approach to explore the LCS paradigm through the implementation of INTEGRATION-KID.

Acknowledgment

The authors would like to thank for support and stimulating discussion with Howard Aizenstein, Alfrida Chan, Lisa Chiu, Peggy Chow, Dr. Richard Dennis, Jyy-Ing Lee, Ken Smith and Jian-Ping Zhang.

References

Please refer to the other file.