Problem Solving with "The Incredible Machine"*
An Experiment in Case-Based Reasoning

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1 Motivation and Goals

In order to analyze the development, influence and application of experience during problem solving and to draw conclusions for the development of Case-Based Reasoning systems [Ko93, RiSch89] we observed and videotaped test persons while they were solving simple design problems with the computer program "The Incredible Machine"*. The video and audio recordings were protocolled and analyzed.

2 The Experiment

2.1 The Computer Program "The Incredible Machine"

The computer program "The Incredible Machine" (TIM) simulates a design environment in which simple machines can be built by using the 45 provided elements. A selection of these elements is shown in Table 1.

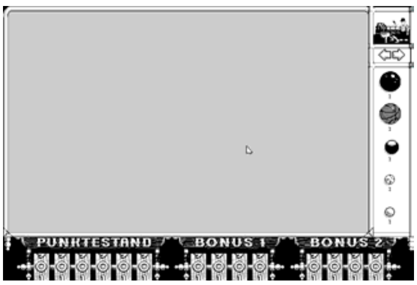

Figure 1: The Main Screen of "The Incredible Machine"

Figure 1 shows the main screen of the program. The machine is built and started in the main window. The parts can be selected from the list on the right hand side of the screen which can be scrolled using the arrows. By clicking on the field in the upper right hand corner of the screen, the environment (gravity, air pressure) is activated and the machine started. The point and bonus display at the bottom of the screen was of no interest to us and deactivated.

2.2 The Setup of the Experiment

During the experiments the test persons were asked to build machines to solve the given assignments. To reduce the pressure they were told, that their machines will not be evaluated in any way and that their time is not limited.

First the test persons had to read the introduction to the experiment and the computer program and were allowed to test the handling of the program. Then they had to solve four obligatory assignments in fixed order and to describe the elements they used in a description booklet. After the first four assignments, they were asked to select two more assignments out of the eight we provided, give the reason why they selected these particular assignments, and solve them. After all assignments were solved, the test persons had to write down the lessons they learned as if they wanted to give hints to a friend, taking this test the next day. Some of the test persons were also asked to solve the first assignment once more.

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* "The Incredible Machine " is a registered trademark of Sierra On-Line Inc., Coarsegold, CA.

We observed 19 test persons (14 male / 5 female) while they solved our assignments. All of them were not familiar with the program beforehand.

Bowlingball	Basketball	Baseball	Rope	Conveyor belt	Belt
Wall	Board	Pipe	Boxing-glove	Pokey the Cat	Trampoline
Ape on a bike	Rocket	Colt	Cannon	Bucket	Cage
Balloon	Pulley	Switch / Outlet	Generator	Electromotor	Ventilator

Table 1: Some of the Elemets available in "The Incredible Machine"

2.3 Data Acquisition and Structuring

The test persons were asked to "think aloud" while they solved the assignments. Their comments and the computer screen were recorded with a video camera. At the end of each experiment the video and audio recordings, the computer files of the solved assignments and the description booklet were available for analysis.

The video and audio recordings were transcribed into a *protocol*, a *task list* and a *solution tree.* The *protocol* is a plain text transcription of the comments and actions of the test persons and the test administrator. The *task list* gives a chronological enumeration of the goals, the actions performed to achieve these goals, the results of these actions, and the new subgoals. The *solution trees* are graphical representations of the problem decomposition and solution space generated by the test person (e.g. Figure 2). The goals of the test person are shown in cursive capital, the hypothetical solutions in normal letters. Variants that have not achieved the posed goal are broken off with a horizontal line. The solution trees do not give a chronological account of the development of the solution but allow to analyze the reuse of elements.

3 Sample Analysis

In order to illustrate our experiments we will describe and analyze part of the experiment conducted with test person 13 (Tp13). A complete analysis of the experiment with Tp13 can be found in [GöBi95].

In the first assignment (Figure 2) the test person is asked to build a machine to propel the ball that rests on the wooden platform on the left hand side into the box to the right.

The test person divides the assignment "Ball in Box" into the sub-goals: "Propel Ball" and "Support Ball". She tries to achieve the sub-goal "Propel Ball" with the variants "Cable pull", "Ball in canon", Boxing glove", "Conveyor belt" and "Ramp and Ball". The combination "Ramp and Ball" is successful and fulfills the sub-goal. "Support Ball" is achieved by means of several trampolines. The meanwhile useless board is left over at the bottom of the screen.

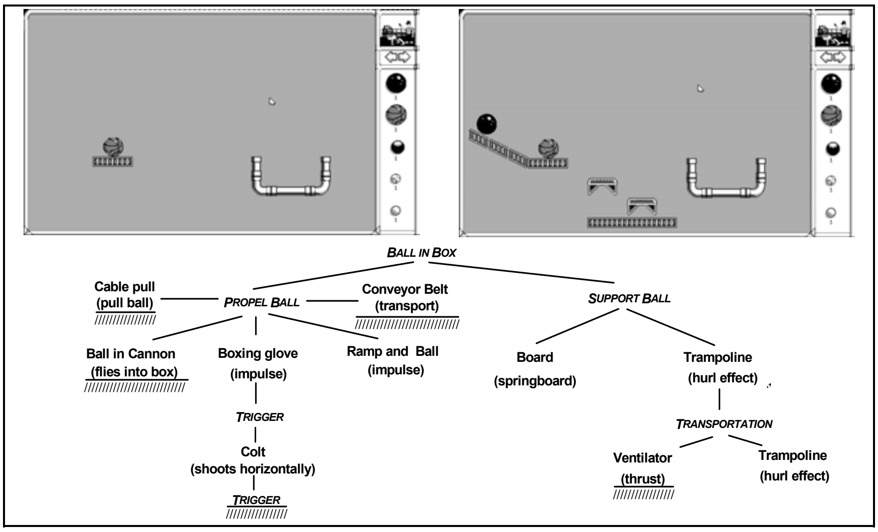

Figure 2 : Tp13, Assignment 1, Solution, Solution tree

The "Boxing glove", which was tried as a solution for "Propel Ball", has to be triggered to function. Such prerequisites cause the combination of elements to groups that work as an assembly. The test persons indexed these assemblies through the function which was originally needed (e.g. "Propel Ball") and retrieved and used them in whole whenever this function was required. Each assembly extended the spectrum of available elements of TIM by one more, previously lacking, element.

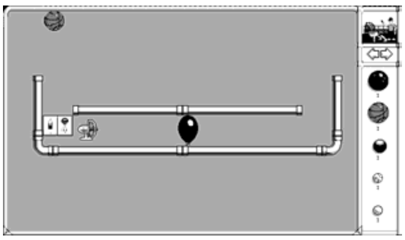

Figure 3: Assignment 2, Solution of Tp13

In assignment 2 the test person had to "Free the Balloon". She solved the assignment by means of a ventilator which was powered by a switch/outlet, triggered by a basketball (Figure 3).

In assignment 3 the test person had to get the basketball which lies on the conveyor belt, around the wall, and into the box. Figure 4 shows the solution of Tp13. Please note the power source for the electromotor and the trampolines that come from assignment 2 and 1 respectively.

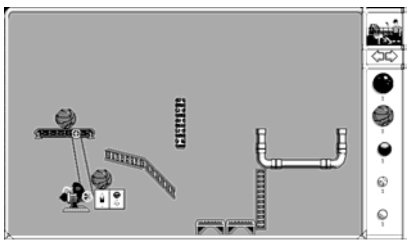

Figure 4: Assignment 3, Solution of Tp13

In Figure 5 the assignment 4 ("transport the basketball underneath the cage into the wooden box") is shown along with the solution and solution tree of Tp13. We can see that the test person split the assignment into the sub-goals "Free Ball" and "Ball to the left". "Ball to he left" was a situation with which the test person had experience and for which she employed the known solution directly. The sub-goal "Free Ball" on the other hand posed a problem to which a solution was found only after various objects and arrangements were tested. Assignments to which the test persons knew solutions, had experience with, can be identified through the deeper, straightforward solution trees of the sub-goals. A shallow tree with many spreading branches, on the other hand, shows that the test person was trying various alternatives and was inexperienced.

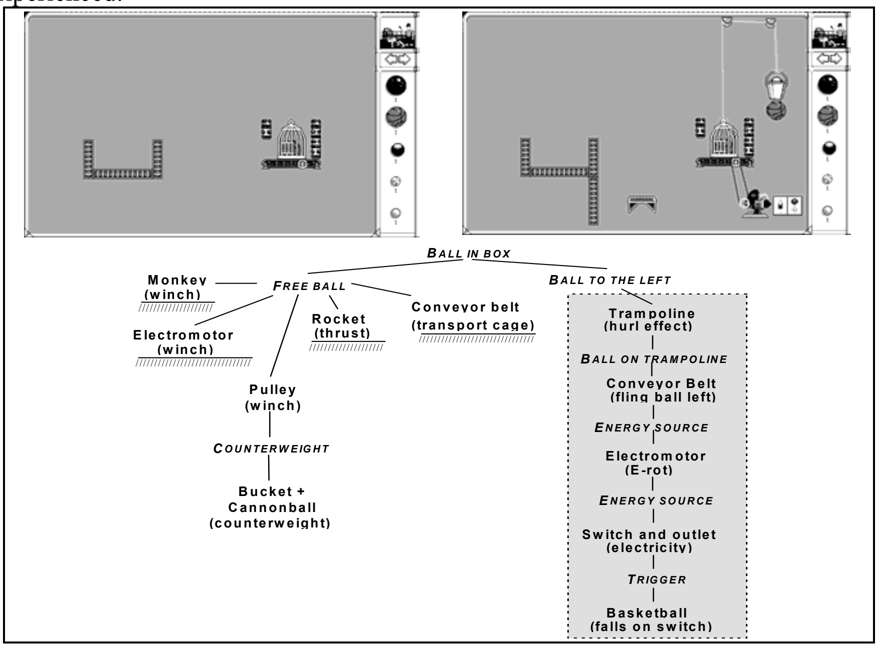

Figure 5: Tp13, Assignment 4, Solution, Solution tree

Figure 6 shows the first assignment the test person chose herself. The ball on the conveyor belt in the upper right corner has to be moved into the containment in the upper left corner.

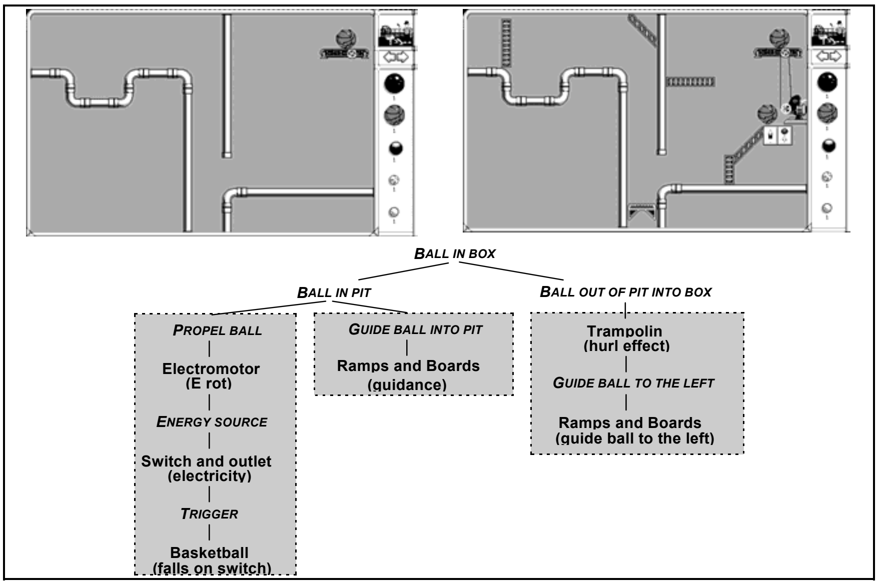

Figure 6 : Tp13, Assignment 5 (first selected assignment), Solution, Solution tree

Tp13 solved the assignment completely by applying prior experience. The "Electromotor/Switch/Basketball" combination from assignment 2 was used to propel the ball, the Trampoline from assignment 1 was used to fling and lift the ball, and several ramps and boards were used to guide the ball into the direction wanted.

Actually assignment 5 could only be solved by using a trampoline. As expected, only test persons that had experience with the trampoline in TIM and knew its peculiar property to generate energy selected this assignment.

Similar to assignment 5, Tp13 solved the second selected assignment also solely by means of experience.

4 Development and Utilization of Experience

4.1 Object Utilization

The test persons comprehended the assignments based on their experience. If they had experience with a similar assignment, they solved it directly and perceived it as a task. If no experience was available the assignment posed a problem and deductive or trial-and-error approaches were applied. Towards the end of the test, especially during the two assignments the test persons chose themselves, the assignments were solved by merely using the objects or assemblies learned during the course of the experiment.

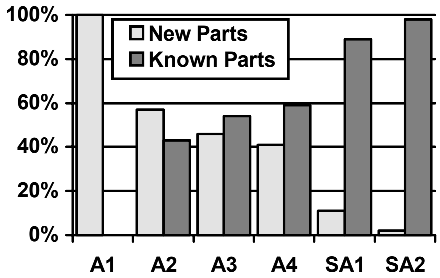

Figure 7 : Development of the usage of known parts

Figure 7 shows the average percentage of new and previously known parts among the parts the test persons used to solve the assignments A1 to A4 and the two selected assignments SA1 and SA2.

One should note, that at the end of the experiment the test persons had in average used only 15 out of the 45 available parts (i.e. %33). Thus the reservoir of available new parts was by no means exhausted. The jump in the decrease in new parts from assignment 4 to the two selected assignments shows, that the test persons preferred assignments to which they could think of a solution in terms of their experience.

However, the unreflected application of experience to solve the assignments did not necessarily result in the most efficient and effective solution.

4.2 Object Identification

To achieve the goal "Free Ball" in assignment 4 (Figure 5 on previous page) test person 13 tried the "Monkey", the "Electromotor", a "Pulley", a "Rocket" and a "Conveyor Belt". While the "Monkey", the "Electromotor" and the "Pulley" are used to provide a similar function (i.e. "to pull") the "Rocket" and the "Conveyor Belt" provide different functions (i.e. they "push" or "move away"'). The test person tried objects with *different functions* to achieve *one purpose*.

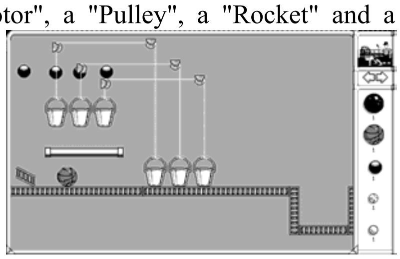

Figure 8:Tp6, Solution to Assignment 6 (Selected Assignment 2)

One function of an object was also used to achieve *different purposes*. In selected assignment 2 ("Get the basketball around the buckets into the box", Figure 8), test person 6 used the property of the bowling ball to fall (i.e. the function to store and release potential energy) to increase the weight of the buckets for a pulley and to create an impulse to propel the basketball.

By means of the description booklet, the solution trees and the protocols we saw, that the test persons assigned several functions to each object. The identification and selection of an object was done by comparing the function the object can fulfill with the desired purpose and evaluating the applicability of the object.

4.3 Development and Utilization of Methods

In the course of the experiment, the experience of the test persons did not only increase with respect to the objects they used, but also concerning the methods they applied to perform the actions necessary to achieve their goals. The basic actions we observed are described below.

4.3.1 Assessing the Assignment

The first action that the test persons performed was to assess and understand the assignment. The test persons achieved this by repeating, reformulating or summarizing the situation. Thereby the assignment was

- changed from a problem to a task by putting it into relation with previous experience and reformulating it "in their own words"
  `"The ball has to be transported into the box. That means I have to build something around the wall so that the ball gets into the box." (Tp15/A3)`
- divided into sub-goals
  `"In principle all I need is something that joins the support of the ball with the box and something that hits against it."(Tp10/A1)`
- solved on an abstract level.
  `"The ball has to get over the wall first. Behind the wall it is easy, I will just take a ramp and let it roll down." (Tp8/A3)`

4.3.2 Retrieving suitable solutions

In order to solve the assignments, the test persons had to retrieve, i.e. search and select appropriate solutions.

The test persons used mental objects on various levels of concretization as templates for search. The following forms could be observed :

A) Searching with no solution in mind: This, most abstract form of search can be considered a sort of brainstorming. The test persons saw the problem and started flipping through the list of parts to find something suitable by inspiration.
   `"Now let's see what else we have, what else one can do." (Tp8/A1)`

B) Searching with a concept of abstract objects in mind: In this form the test persons had a kind of functional description of the object(s) they needed in mind and searched the part list using this description.
   `"Now I need something which moves it (the ball) upwards." (Tp11/A4)`

C) Searching with a concept of known objects in mind: In this situation the test persons had a model of the machine, built out of objects they are familiar from their everyday experience, in mind, and tried to find something similar in the list.
   `"I am going to build a conveyor belt, convince the ball somehow to fall on it and transport it there afterwards. Let me see what parts I will find.."(Tp6 / A1)`

D) Searching with a concept made of TIM Objects: In this most concrete form, the test persons knew what they wanted in terms of TIM objects and looked for these objects in the list.

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"Here I will first put a seesaw and afterwards some of those wooden
ramps. The boxing glove in the back. If that does not work the
ventilator." (Tp12/A6 - second selected assignment).
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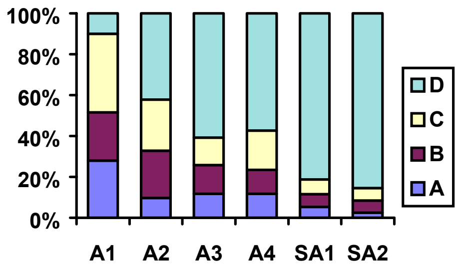

Figure 9: Development of search types

Figure 9 shows the development of the mental objects used for search for all test persons in the course of the experiment. It can be seen that Form D, being the most concrete form, constantly increases. The small amount of D type search in assignment 1 is due to the fact that some of the test persons tried out the program before they started with the first assignment.

Although search starts with a more or less abstract concept in mind, it always ends with looking up the part in the parts list. After a part is found in this list, the selection process, where the basic suitability of the object is determined, takes place. The result of the selection is a part that is moved into the main screen to be used in the machine. Following forms of selection could be observed:

I) Select after considering for some time: An object is found, but not selected immediately. The test person evaluates the object, seems to consider its suitability. Most of the time the cursor rests on the found object.

II) Select spontaneously: An object is selected without any time delay as soon as it appears on the list. It seems as if it does not matter if exactly this object is retrieved, any object of the class would do.

III) Select directly : An object - and only this object - is being sought after and selected in the list.

O) No selection : It also happens, that test persons look at a part for some time and then change their minds.

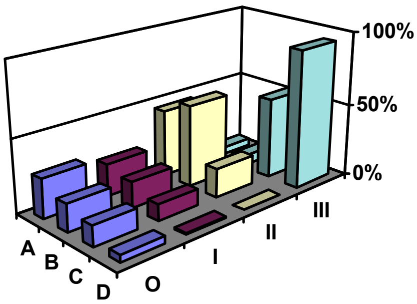

Figure 10: Combinations of search and selection types

Figure 10 shows for all test persons, over all assignments, the type of selection method applied with respect to the mental object type used for searching. Obviously, the more concrete the object the test person had in mind during the search phase is, the more concrete the selection type. The selection types II (select spontaneously any fitting object) and III (select exactly one) seem to be complementary to each other. The maximum of the type II selection occurs when the test persons look for a solution with a concept made of abstract objects (B). Any object that satisfies the functional description can - and apparently is- selected.

The selection of type III, on the other hand, has its maximum value when exact definitions of the searched objects are given. The more abstract search types (A,B) yield more abstract types of selection results (O, I).

4.3.3 Evaluation

One of the fundamental steps in problem solving is the evaluation of the objects with respect to the expectations. We could observe that the test persons applied evaluation methods on various levels of concretization to objects on various levels of concretization (Table 2).

Mental evaluation (abstract)	A hypothetical object is tested by thinking how it would behave (MM). `"Lets' take a rocket ... but that's going to destroy the ball!" (Tp5/A9)`	A realized, existing machine is tested mentally. Often the test persons pointed at what they think would happen when the machine is activated (MR). `The Tp wants to start the machine, then stops and raises the right hand wall of the box with another piece of wood "...just in case..." (Tp16/A1).`
Real evaluation (test, concrete)	Parts of a machine which is planned, are being tested to see how they would behave if the machine was built (RM). `"Maybe a trampoline .. let's see, where does the ball roll to ?" (Tp6/A3).`	A realized machine is evaluated by starting it on the screen, thus performing a real test (RR). `Tp has fixed a balloon to the bucket and starts the machine - but nothing happens. "How many balloons does it take to make it work?" (Tp8/A6).`

Table 2: Evaluating solutions on various levels of concretization by combining objects and methods

Figure 11 shows the development of the evaluation types the test persons applied during the experiment. Evaluation of type RM could only be observed (or identified) once. It is possible that this type is included in the RR type evaluation count. The evaluation of type RR is the most concrete and efficient evaluation method and is increasingly used by the test persons.

The results of the evaluation were not only influenced by rational arguments but also by subjective impressions such as knowledge regarding the object, sympathy, previous successes, complexity and the availability of "chic" alternatives.

4.3.4 Adaptation

Adaptation is the process of changing the solution after it has been evaluated. Two main types of adaptation were observed: mending, in which the quality of the existing solution is increased, and repair, in which the goal is to make the object fulfill its function (again). The function structure of the machine stays the same during mending, but is changed during repair.

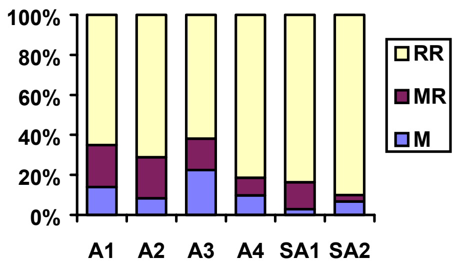

Figure 11: Development of evaluation types

Table 3 summarizes the actions that the test persons performed to adapt their "machines"

<table>
<tr><td rowspan="6">Adaptation</td><td rowspan="3">Mend</td><td colspan="2">Adjust</td></tr>
<tr><td colspan="2">Duplicate effect</td></tr>
<tr><td colspan="2">Replace</td></tr>
<tr><td rowspan="3">Repair</td><td colspan="2">Add</td></tr>
<tr><td rowspan="2">Remove</td><td>Leave Out</td></tr>
<tr><td>Delete</td></tr>
</table>

Table 3: Adaptation Types

In the course of the experiment, with increasing experience, the test persons tended to mend more than to repair. They could foresee how the objects will perform and only had to make small adjustments to their machines. Only in assignments that posed problems they had to apply several repair steps, i.e. try out alternatives. This can also be deduced from the development of the solution trees.

4.3.5 Acquiring Information

During the experiment the test persons used various methods to obtain information (Table 4).

<table>
<tr><td rowspan="4">Inform</td><td rowspan="2">how</td><td>ask</td><td>expectant
without expectations</td></tr>
<tr><td>test</td><td>look at
start</td></tr>
<tr><td>what</td><td colspan="2">identification
handling
triggering
function
arrangement</td></tr>
<tr><td>when</td><td colspan="2">during search
before selection
after selection</td></tr>
</table>

Table 4: Types of Information Acquisition

Simply asking the test administrator is the information acquisition type observed most. The test persons either asked if their expectation was correct or what the function of an object was. With growing experience the need for information decreased and the test persons preferred to test their hypotheses instead of asking the test administrator.

5 Summary and Conclusion

By means of the experiments described above we analyzed the development, utilization and influence of experience during problem solving.

We could see that while assignments to which the test person had no experience, were conceived as problems, assignments to which experience was available were conceived as tasks. The test persons understood an assignment through the experience they had with similar situations.

The solution trees that an experienced person generated were more straightforward and deep whereas an inexperienced person had to try out various alternatives and thereby created a shallow solution tree with many branches. Towards the end of the experiment the test persons solved the assignments by almost purely using their experience. This did not always result in the most optimal solution, sometimes the obvious was overlooked.

The test persons indexed the assemblies they built through the function these could fulfill and treated them as new, previously lacking, parts. They memorized all functions they knew a part or assembly could fulfill and applied the object whenever a purpose that could be achieved by means of its function(s) was needed.

In order to solve problems the test persons combined methods in various degrees of concretization with objects (mental models) on different levels of concretization.With growing experience both the mental models of the machine and the methods applied became more concrete. The effects of this concretization could be observed during assignment assessment, solution retrieval, evaluation, adaptation and information acquisition.

We believe that by taking these aspects into account the efficiency and effectivity of case-based reasoning systems can be increased. Although the basic actions we observed correspond to the steps proposed in standard case-based reasoning literature there is still a lot we can learn from the way "we" solve problems.

6 Literature

GöBi95 M.Göker, H.Birkhofer, "Problemlösen mit 'The Incredible Machine', Ein Experiment zum Falbasierten Schließen", in Proceedings, Case-Based Reasoning Workshop at the 3rd. German Expert Systems Conference, Kaiserslautern 28.2-1.3.1995, B.Bartsch-Spörl, D. Janetzko, S.Wess eds., Lernende Systeme und Anwendungen, Fachbereich Informatik, Universität Kaiserslautern LSA-95-02.

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