DOCUMENT RESUME

ED 250 176 SE 045 152

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TITLE	Teaching Logic to Children: An Exploratory Study of "Rocky's Boots." Assessing the Cognitive Consequences of Computer Environments for Learning (ACCCEL).
INSTITUTION	California Univ., Berkeley. Lawrence Hall of Science.
SPONS AGENCY	National Inst. of Education (ED), Washington, DC.
PUB DATE	84
GRANT	400-83-0017
NOTE	26p.; Paper presented at the Annual Meeting of the American Educational Research Association (68th, New Orleans, LA, April, 1984).
PUB TYPE	Reports - Research/Technical (143) -- Speeches/Conference Papers (150)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	*Computer Software; *Educational Games; Educational Research; *Instructional Design; Instructional Material Evaluation; Junior High Schools; Junior High School Students; *Learning Strategies; *Logic; *Problem Solving; Transfer of Training
IDENTIFIERS	*Computer Games

ABSTRACT

Rocky's Boots (RB), an educational game developed for use with Apple computers, is widely considered to be one of the most imaginative and engaging pieces of educational software currently available. RB presents an introduction to the logical concepts of AND, OR, and NOT. Players incorporate these concepts into arguments which are modeled as "machines." This study examined: how students responded to this cognitively challenging and complex game; if they would proceed into the game without external instruction or encouragement; if students with prior computer experience were more proficient at RB; if there was any transfer of skills from RB to linguistic logic problems (or vice versa); and if it was possible to assist students in solving the more difficult problems by providing certain general hints and rules of analysis. Findings, among others, indicate that RB is an engrossing game that students found intrinsically enjoyable and that although the style of interaction with RB differs between boys and girls, both groups showed equal levels of enthusiasm and enjoyment. Recommendations for classroom use of RB (such as offering hints to students after allowing them to explore, experiment, and solve problems) and suggestions for further study are included. (JN)

Teaching Logic to Children:

An Exploratory Study of "Rocky's Boots"

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This material is based upon research supported by the National Institute of Education under Grant No. 400-83-0017. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Institute of Education.

This paper was presented at the American Educational Research Association (AERA) meeting, April, 1984, New Orleans, LA.

Teaching Logic to Children: An Exploratory Study of "Rocky's Boots"

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I. Introduction

Rocky's Boots (hereafter RB), an educational computer game developed for use with Apple computers by The Learning Company of Menlo Park, California is widely considered to be one of the most imaginative and engaging piece of educational software currently available. We assess how students respond to the game and consider the possible cognitive outcomes from playing the game. We also offer a preliminary review of the game and the results of an exploratory study involving seven junior high school students.

The claims made on behalf of educational computer games, by both their consumers (educators) and their producers (computer companies and educational publishers) have been rather exalted: for example, "The new software is developing a set of critical thinking skills the kid won't get from other methods...It's teaching them problem solving skills." (Finkel, 1983) Certainly it is true that the educational use of computers has enormous (and still largely untapped) potential; but research has failed to show that educational computer games foster "critical thinking" or "problem solving"—in fact, researchers are divided even on how to define, let alone measure, such general cognitive skills. RB in particular has received much of this type of praise; we took it as our task to examine in a preliminary way whether such hyperbole is justified.

RB presents an introduction to the logical concepts of AND, OR, and NOT. Players incorporate these concepts into arguments which are modeled as "machines." Moving the cursor from room to room, players are introduced to the components of the game and given an opportunity to experiment with them. The key components are wires, logical connecting gates (AND-gates, OR-gates, and NOT-gates), sensors, and a boot (see Figure 1). In the game rooms are three sensors. Objects of various shapes and colors float past the sensors. Each sensor can detect a color or a shape, and sends out a pulse of "electricity" when it detects an object with that characteristic. The player must build a machine, given the available sensors, that will detect and "kick" specific objects.

*** Insert Figure I ***

In one game (see Figure 1) the player might have a blue sensor, a triangle sensor, and a cross sensor, and have to build a machine that kicks "Blue Triangles." The player would build a machine joining the blue sensor and the triangle sensor as inputs into an AND-gate, which would turn on only when both inputs are on. Then the player would connect the boot to the AND-gate output. Whenever a blue object floats by, the blue sensor will turn on, sending a flow of "electricity" through the wires, and whenever a triangular object floats by, the triangle sensor will turn on, but only when both sensors are on will the AND-gate activate, turning on the boot which will pick out the object by kicking it. Each correct object picked out from the sequence earns a certain number of points; if the player gets a perfect score of 24 points, Rocky the Raccoon will come out and dance a little jig. A machine to pick out "Crosses or Triangles," with these sensors, would use an OR-gate, and so on.

The game becomes progressively more challenging as the number of elements increases. In the latter sections of the game, there are additional gadgets (on/off switches, clocks and delays) that can be used to build very complex machines, but they are not strictly logical in nature (they are modeled more on electrical circuitry) and they were not part of this study. In the final section of the game, Rocky's Challenge, very complex problems are presented, and players can actually design original problems to solve.

We found RB to be an especially appropriate subject of study. First, RB, is exceptional in its instructional approach and use of graphics. The directions in each room are clear and lead the player gradually through the introductions of each component and how to build machines. A player can proceed at her/his own pace. Second, RB incorporates several features of computer programming specifically, logic gates, loops, decomposition, and debugging, and of computer learning environments generally. RB exemplifies six features typical of all computer learning environments (Linn, Fisher, Dalbey, Mandinach, and Beckum, 1982). RB is an interactive game, permitting a good deal of experimentation and free exploration. The player is actively engaged at every stage. RB is a precise learning situation, in which attention to detail and specific commands are required in order to achieve a successful solution. RB is a complex game, particularly at its advanced levels, requiring sophisticated planning and debugging. RB's problems permit multiple solutions, and players are given the opportunity to test, dismantle, build and improve their machines as they choose. RB is a consistent game, responding to every player impartially and patiently. RB provides feedback, as players can operate a machine in "slow motion" to trace the path the electricity is taking, detect errors, and revise their solutions accordingly. In short, we selected RB as a subject for study because it is a high-quality and cognitively demanding game which typifies many of the essential features of all computer learning environments.

We were intitially interested in several questions: How do students respond to a cognitively challenging and complex game? How far will they proceed into the game without external instruction or encouragement? Are students with prior computer experience mone proficient at RB? Is there any transfer of skills from RB to linguistic logic problem, or vice versa? And is it possible to assist students in solving the more difficult problems by providing certain general hints and rules of analysis? Some of these questions were answered more decisively than others (see Results and Discussion).

II. Method

Sequence of activities: We first administered two screening tests (described below). We used the results of these tests to select a representative cross-section of students. We then introduced the students to the Rocky's Boots game, and allowed them approximately five hours of practice time to explore and interact with the game. At three points we interrupted the practice: first, with two evaluation exercises, later with a set of five instructional "hints" about solving RB problems, then finally with another set of evaluation exercises.

Screening tests: We administered two tests to the students. First, we administered a version of the Embedded Figures test (FASP, Pulos & Linn, 1980), in which students are asked to find a simple figure hidden in more complicated designs. This test has been shown to be a good indicator of general cognitive ability (Linn & Pulos, 1983). The second test was developed by us for the present study. It contained five story problems. After each story, the students were asked several questions which stressed being able to interpret statements containing the logical connectors "and," "or," and "not." The screening tests were given to one class each of sixth, seventh, and eighth graders (approximately 70 students). We found that the tests gave a broad spread along the dimensions of general ability and logical ability.

Practice sessions: We selected eight students for the study. We asked their age, hobbies, their prior experience with video games or computers, and whether they had experience using a computer or typewriter keyboard. We then introduced in a general way the game and the purpose of our study, and told the students the kinds of activities they could expect to be asked to do.

The students were allowed relatively unstructured practice time with RB. In each session we had the game loaded and ready for them to play, set at the place where they had ended the previous session. We tape recorded and kept written notes for each session. We answered questions when the students asked, but did not try to direct their interaction with the game. RB is designed in such a way, with the maze of rooms, that students had an intrinsic motivation to progress through the game as rapidly as possible (e.g. Lepper & Malone, 1981). Within that frame, we allowed them to explore or experiment as they chose.

Exercises: At two points, one early in the game, one later, we gave the students a pair of RB-type problems to solve. Using a master copy of the game which we could alter, we fixed certain problems in advance for the students to solve. One problem involved building a typical RB logic machine (to our specifications). The other problem involved "trouble-shooting" a RB machine (built by us) which was not working properly. The first pair, administered when the students had achieved a particular phase of the game, were relatively simple. The latter pair, administered after the students were quite proficient at the game, and after the intervention for solving complex RB problems, were considerably more difficult (see Figure 2).

Instructional interventions: When the students had moved into the more difficult phases of the game, and after allowing them to attempt some of the more difficult problems, we offered the following five hints to the students. In our pilot interviews, we had found that students had great difficulty with these problems, became frustrated and discouraged, and sometimes gave up on the game. With these general hints, however, they were usually able to go on and solve even the most difficult problems on their own. Specifically, the hints are:

(1) In ordinary English, there is an ambiguity between "and" and "or" as logical connectors; in a phrase such as "Find the circles and triangles," what we really mean is find anything that is a circle or is a triangle (compare the phrase to "Find those objects that are circles and blue"). In RB, this means the difference between building a machine that kicks "greens and crosses" (requiring an OR gate) and one that kicks objects which are "green and a cross," (requiring an AND gate). Students were frequently confused by these sorts of problems.

(2) Often the predicates given in the problem description do not correspond to the sensors available in the game; as we put it, there was no "positive" solution to the game. Instead, the student must identify the predicate "negatively", that is, by adding a NOT gate to one of the sensors. For example, all the objects in a game are either blue or green; the student must pick out those which are green, but with only a blue sensor. The result

can be achieved by building a machine which kicks "non-blues", which, in this game are the greens.

(3) For more complicated machines, it helps to solve them if one thinks of component "subroutines" which execute portions of the larger problem. This is, of course, a fairly standard strategy in computer programming. For a problem such as "Green Triangles or Blue Circles," it is much easier to solve the "Green Triangle" and "Blue Circle" portions separately, and then to join the two subroutines together with an OR gate.

(4) Before proceeding to build a machine, planning it in advance can have several advantages. Since the cursor can only "pick up" one item at a time, it saves steps to the "supply rooms" if the student knows in advance what pieces he/she needs and does not waste any trips. The act of visualizing (or sketching) what a machine will look like is helpful, because RB uses a mechanical analogy for the logical solutions, and even fairly simple logical solutions may require very complex constructions. For many students, it seemed that errors in construction caused as many problems as errors in conceptualization. Finally, there is a peculiar non-logical problem in RB machines, which is called a "glitch" in the propagation of electricity through the wires of a machine. If there are too many connections between wires, "electricity" can be "held up" in the wires, triggering the boot at inappropriate times. This is not a problem with the logical design of the machine, but in the electrical analogy on which RB rests. Careful planning is often needed to avoid "glitches," and anticipating them in advance can help to avoid this very frustrating problem.

(5) Given a machine that does not work, there are certain procedures that can help in detecting where the trouble lies. One such procedure is to run

the machine in slow motion (RB allows for this), in order to trace the propagation of electricity through the wiring. This approach is virtually essential for detecting glitches. More general troubleshooting tips refer back to the typical problem discussed in these hints.

Other common difficulties are wires which have been improperly connected (again often undetectable without a slow-motion diagnosis); an incorrect sequencing of gates in complex machines; and the mistaken inclusion or exclusion of certain classes of objects by attaching a sensor to a logic gate incorrectly.

With each of these hints, we offered illustrative examples, but left it to the imagination of the students to see where these hints related to particular machines they were building.

III. Subjects

We selected as a site for our study a junior high school on the San Francisco peninsula, not far from the center of "Silicon Valley," The school offered a good mix of different ethnic and class populations, and promised full co-operation with our study. We administered our tests to three classes, comprising sixth, seventh, and eighth graders. We selected eight students from this population: two sixth graders, a boy and a girl; three seventh graders, a girl and two boys (who we planned to run as a pair); and three eighth graders, a boy and two girls (who we also planned to run as a pair). For the students selected, we requested their scores on standardized mathematics and verbal abilities tests. We secured from the parents of these children permission for them to participate in our study. Finally, we arranged for these students to be excused from elective classes on the five days we visited the school.

Selection of the students was made after looking at the results of the tests. For each grade a histogram was constructed of the scores on each of the two tests. The histograms were then divided into quartiles. Selection was made by choosing a student in the third quartile on one test and the same student falling into the second quartile on the other test. The next student was selected from the second quartile on the first test and the third quartile on the second test. This procedure was used for each grade involved. The purpose of this selection proceedure was not to select the highest scoring students nor the lowest scoring students but students that were strong in one of the tests or the other. The dyads from this selection process would be strong in both of the tested areas.

The children who we finally selected for the study were as follows (the names are fictional):

Mike is twelve and enjoys baseball; he is in the sixth grade. He was quite excited about being in the RB study. He had not worked at a keyboard before and was sloppy about hitting the correct keys. Often he would be looking at the screen while hitting keys to move but was off by a key or two. This did not seem to improve as he progressed through the program; in fact as he got more excited the sloppiness got worse. However, he never became discouraged or frustrated.

Julie is a talkative 12 year old in the sixth grade. She plays the piano and has a computer at home (Commodore Vic-20), which she uses mostly to play games (about 1/2 hour per week, she said). Playing RB, she progressed very quickly through the first parts of the game, showing a good deal of enthusiasm and delight in the process. As the problems became more difficult, however, she became quite confused and self-deprecating.

Laurie is a friendly bright twelve year old. She is in the seventh grade and doing well. Her hobbies are reading and collecting stamps. She plays an occasional video game both at home and in arcades. Her mother works at a local business computer company and through that connection she had see RB before the study. She had not built any of the more complicated machines and it seemed worthwhile to have in the study someone who had some previous exposure. There was often a computer at home but it was there for her mother's work, so it was not available for experimenting.

Miguel is a 13 year old 7th grader and Butch a 15 year old 7th grader. Butch rides motorcycles and bikes and plays about 4 hours of video games per week. Butch's family owns an Apple II and he does some programming on it as well as playing games. Miguel plays soccer and also about 4 hours of video games per week. Butch and Miguel went through the game as a pair, tending to specialize tasks: Butch usually at the keyboard, Miguel watching over his shoulder and giving advice— they did trade off occasionally. They enjoyed the game and were "playful" with it , trying unusual combinations and randomly experimenting with materials.

Sue is fourteen years old and is in the eighth grade. Her hobbies are skating, and swimming in her family's pool. She is an avid video gamer and plays the home Atari game for about an hour a day as well as an occasional game in an arcade. She also enjoys television and spends about four hours a day watching it. Sue was excited about participating in the study. She enjoyed watching Rocky dance and was motivated to complete all the machines she attempted.

Rachel was originally scheduled to participate with Sue as a pair. She showed a good deal of enthusiasm about taking part in the study, but when she missed the first two days of interviews, we were forced to remove her from the study and continue Sue's schedule individually,

Ali is a 14 year old eighth grader. His hobbies include building models and racing bikes; he plays about an hour of video games per week. He has used a keyboard before, and showed considerable speed and facility in moving the cursor and building machines. He had a bit of trouble at first grasping certain basic techniques (e.g. how to attach or detach objects, picking up only one thing at a time), but he was able to explain the logical features of the game very well. In fact, he would usually talk through a problem very well, but then have trouble translating his analysis into the "machine language" of RB.

IV. Results

In general, students responded with a great deal of interest and enthusiasm to the game; they all proceeded quickly through the instructional phases of the game (in which the basic features of the game are explained and demonstrated). When the time came to build RB machines, many students had difficulty at first, but gained in proficiency and speed. With the more complex machines of Rocky's Challenge, however, nearly all of them were quite confused, and only a few were very successful at handling these multiple-gate problems.

Screening tests: We administered the tests to 69 students (twelve sixth graders, thirty-three seventh graders, and twenty-four eighth graders). The results were as follows:

*** Insert Table I ***

As can be seen, the scores for 6th and 7th graders were substantially the same, while the scores for 8th graders were noticably higher.

Reactions to RB: The other difference we discovered was in the manner of problem-solving, and attitudes expressed, by boys and girls playing RB. While there was no substantial difference in their successfulness at playing the game, boys and girls showed different degrees of confidence, independence, and adventurousness in their approach to the game. Girls seemed to enjoy RB as much as the boys did, and performed as well, but girls frequently expressed uncertainty and self-doubt—even when they were correct—while boys in general expressed confidence and certainty—even when they were incorrect.

For example, RB is designed with practice rooms and optional activities which are not essential for mastery of the game; we specifically allowed the students to spend as much or as little time at these activities as they chose. At one extreme was the attitude of Julie, who, when entering a practice room, asked in a surprised way, "I can do anything I want?" She generally was very cautious and showed excessive care about her manipulation of the elements of the game. At the other extreme were Butch and Miguel, who entered one practice room before reading the instructions on the different components they would find there. They simply proceeded to "mess around," connecting objects to each other more or less randomly at first, but gradually discovering by trial and error the functions of many objects. Between these extremes, boys and girls tended to differ generally in their willingness to explore or push the limits of the game.

As a second example, we asked the students, when they had built a machine

Table I: Screening tests (by grade)

	Embedded Figures (possible score = 15)	Logic Screening test (possible score = 21)
6th n=(12)	7.8	13.4
7th n=(33)	6.4	14.8
8th n=(24)	10.3	16.6

Table II: Screening tests (by sex and grade)

Males	Embedded Figures	Logic Test
6th n= 6	8.5	13.8
7th n= 16	5.4	12.5
8th n= 6	10.8	17.2

Female	Embedded Figures	Logic Test
6th n= 6	7.2	13
7th n= 17	7.3	16.9
8th n= 18	10.2	16.5

to solve an RB problem, to predict how the machine would work, and whether or not it would pick out the correct objects. Boys tended to answer with an abrupt "It will work" or "Sure" (even when the machines were incorrect). The response of girls was strikingly different: Julie often said "whoops" or apologized for making mistakes. She also expressed doubt about her machines, not expecting them to work even when they were properly designed. Eventially she did appear to become more "realistic" in her assessments. A few lines from her transcript:

—"okay, now I just have to think of something...I'm not sure this will work..What's supposed to happen is...[surprised]..It works!"

—"Maybe...Nope, I have to put it over here...I know what to do...First...I know what to do...Not quite, this isn't going to work...[machine doesn't work]...I didn't think so."

—"That was easy...I wonder why I didn't do that...I'm doing very bad...It won't work...[machine works]... I hope I remember."

—"It's never going to work; I'm just warning you that...What am I doing?...I'm being dumb...I'm being very dumb...Ah, this is going to work...[machine works]."

Here Laurie describes some of what she is feeling as she progresses through the program:

"This takes a lot of thinking."

(She said this when she was building a particularly difficult machine.)

"I don't think you should have picked me.... I'm getting frustrated...."

The other facet of this characteristic was how the students responded when a machine failed. As can be seen in the quotes above, girls tended to attribute failure to themselves and their inadequacies; boys tended to respond by quickly trying to fix the problem. Often their quick solution was as incorrect as the original mistake—Ali, Butch, and Miguel, were particularly overconfident in this way.

As a third example, boys and girls differed in the frequency and kind of comments they made about the game (as recorded in our transcripts). Mike had a difficult time with the keyboard. He frequently pressed the wrong keys, and when he was excited he did even worse. However, this problem never seemed to bother him. One of the girls, on the other hand, said, "I'll have to take a typing course. I'm not very good at this." One of the students we interviewed in a pilot study said, "I like this game because it doesn't tell you you're wrong." As we noted, one of the strengths of RB does seem to be the tolerance of the game for multiple student responses and its "patience" with incorrect solutions. We also asked the students whether they considered RB to be play or work. Ali's response was typical for the boys: "play." Sue's response was typical for the girls: "work, but fun."

Finally, we noted a difference in the <u>kinds</u> of questions girls and boys asked, and <u>when</u> they asked them—but not in the overall number or frequency of questions. Girls tended to ask <u>anticipatory</u> questions, for example when they were in the practice rooms, requesting advice about how to approach a task. Boys tended to ask <u>immediate</u> questions, for example about a particular machine, requesting specific problem-solving advice. However, in this case, as in the others, it needs to be noted that both interviewers were male, and that this fact could explain some difference in the responses of boys and girls, because of the students' attitudes or feelings, or because of possible subtle differences in how we treated boys and girls (although neither of us were conscious of such). When we first designed the study, we did not think that male/femalé differences would be an important dimensions; consequently, we did not use female interviewers. (For more detailed descriptions of the interviews, see Appendix.)

All the students who played RB had difficulty with multiple-gate solutions. However, older students (Ali, Butch, and Sue), when we presented them with the hints, seemed to "get the idea" and could then solve more complex problems on their own.

<u>RB excercises</u>: We used the exercises primarily as a way of judging the effectiveness of the hints we had given the students: we did find that students were able to solve more complex problems, both in Rocky's Challenge and in the exercises we designed, when using the advice we offered. Especially helpful seemed to be the "decomposition" hint, involving the analysis of a complex RB machines into component "subroutines" that could be solved separately. The use of "negative" solutions, however, was a very difficult concept for the students to grasp; although they could directly apply the hint when it was related to a specific machine, they could not generalize it to new situations.

V. Discussion

It should be re-emphasized at this point that this study was not designed to establish conclusive or generalizable hypotheses concerning RB. We wished to explore some informal hypotheses, but also to generate potential hypotheses for future study. In this section we will offer a general evaluation of RB, a discussion of its usefulness in schools, and some of these suggested hypotheses for future study.

Student interest: The first thing to be said about RB is how much the children enjoyed playing it. Some of our most vivid memories during the interviews were of Julie, squeaking with pleasure as she found out new things that the objects in RB could do; Mike, who brought his baseball glove devotedly to every RB session, but who gradually became so interested in RB that he forgot his glove in the classroom after a session; Ali, who was so engrossed in RB that he didn't even look up when a crowd of students came into the computer room and began playing loud and active "Star Wars" games on the other computers (the interviewer, on the other hand, was quite distracted); and Laurie, who when interrupted by a friend told her, "Sorry, I can't talk to you now," barely looking up from the game.

RB is an engrossing game that students find intrinsically enjoyable. Students particularly seem to enjoy the "building" aspect (girls as well as boys) and the process of "decomposition," breaking a problem down into component steps. The colorful visual elements and mechanical analogies for logical concepts found in RB seem to reinforce this satisfaction. The RB world is highly structured in that students are led through the basic sequence of lessons in an ordered fashion, and the problems to be solved set specific constraints on appropriate solutions. In contrast however, RB is a very open and exploratory environment, since within those structures almost unlimited variation and initiative are possible As previously mentioned there is a phase of the game in which students can even design their own problems to solve, although none of our students got that far. RB offers an excellent balance between explicit instruction and independent problem solving. Where students do play the games in pairs, moreover, the fact that RB provides an external and visual model for logical processes enables one student to see and follow the thinking of another, and so to collaborate in the process of problem-solving.

We also found that although the style of interaction with the game differed between boys and girls, both groups showed equal levels of enthusiasm and enjoyment. This observation reinforces the idea that when the content of a computer activity is not gender-biased, both boys and girls show equal interest and facility with computer tasks. RB and games of a similar nature offer the possibility of introducing computer skills to a broad audience and of posing cognitively demanding tasks in a setting that appeals to both boys and girls.

Understanding RB: RB is not without some shortcomings, however, and there were some consistent patterns of difficulty students encountered while playing the game. When students are in a hurry and skip over early rooms of the tutorial (as they do), they later encounter a device or a "block" that they don't know how to handle. Given the self-directed nature of the instruction, this outcome is inevitable, and perhaps not undesirable if it creates an opportunity for the student to figure out the problem alone. But when the block is due to ignorance of a mechanical feature (for example, that two outputs cannot be plugged into the same input), it can lead to frustration and defeat before it leads to creative problem-solving. If RB is revised, it might include a new feature, namely that the door to a new room doesn't open until the learning activity for the present room is successfully completed.

Students do have trouble with the concept of "NOT" and the confusion of "AND" with "OR." It is easy enough to say that a NOT-gate "does the opposite" of its input, but students seem to interpret this concept in various inaccurate ways, and show more difficulty in using this gate than any other—for example, with the subtle difference between NOT (blue OR circle) and (NOT blue) OR (NOT circle). The confusion between "AND" and "OR" seems partly due to a confusion between them in ordinary language: when the description for a game says "Blue AND Circle," the machine requires an AND-gate; but when it says "Blues AND Circles," the machine requires an OR-gate. Conversely, the inclusive "OR" has "AND" within it: "Blue OR Circle" includes all things that are Blue AND Circles. Because the logic gates in RB are defined in linguistic terms, and are labeled by the logical terms "AND," "OR," and "NOT," there is a prima facie presumption that facility with linguistic logic will carry over into RB. One might also suspect that learning to handle complex logic problems with the mechanical analogues in RB will then help later in handling linguistic logic problems—perhaps by diagraming, for example—but we saw very little of this in our students. These topics, we believe, merit future study.

Students also have trouble with problems involving more than one logic gate. Even when they can verbally analyze the problem, students of these ages seem to have an extremely difficult time translating their decomposition into RB elements. What is suggested by student performance in our interviews is that going from "Blue Circles" to "Blue Circles OR Green Triangles" is not simply an additive process, but one that requires keeping one part of the machine in mind while working on the other. That is, more of thinking of several things at once than of separate and sequential steps. In any event, this feature of the game seemed to cause special difficulty for these students.

Recommendations for classroom use of RB: For this reason we recommend the use of a "high explicitness" approach to using RB with students of this age group. After allowing the students to explore, experiment and solve as difficult problems as they could, we intervened with "hints" that prevented the students from becoming frustrated, and which allowed them to go on and solve even more complex problems. Our hints modeled this "high-explicitness" approach.

In particular, there does appear to be a need for the external materials to make clear the ambiguous nature of the terms "AND" and "OR" in ordinary language, and for explaining "NOT" as a logical concept. The benefit of doing so would be to facilitate not only solving RB problems, but also using these concepts in ordinary language. Second, students also appear to need a more gradual transition into multi-gate logic problems: for example, one could present an explicit breakdown of a complex machine into component subroutines, and a demonstration of what happens when different logic gates are linked in various sequential patterns.

Third, students at this age do not seem to grasp the approach of "negative solutions" very readily. Explicit explanation of this strategy might help them to acquire and use it. Finally, it may be a useful strategy to urge students to sketch out their proposed design for a machine before building it. This approach would not only help students plan which pieces they need to collect from the "supply rooms," but would tend to encourage a deductive approach to problem-solving in the game, rather than the more inductive "trial and error" strategy that some students exhibited (inserting logic gates one at a time until they found one that worked).

Suggestions for future study: RB presents three kinds of opportunities for further experimental study. First, RB may create opportunities for developing certain relevant cognitive skills and overcoming attitudinal "blocks" that students might have to computers. Second, as a cognitively demanding task in its own right, RB requires creative and problem-solving responses from its users that constitute worthy topics of study themselves. Third, RB provides an environment in which differences in cognitive style or developmental stage, particularly those related to logical problem-solving, can be modeled and studied.

Given a small sample, we were left with more questions than answers:

(1) Is there a relationship of performance on RB to analyzing verbal logic problems incorporating the same concepts? Does practice with RB improve the ability to solve those problems (or vice versa)? Alternatively, is there a deeper cognitive skill that underlies both abilities?

(2) Is there a relationship of performance on RB to learning computer programming? Does practice with RB improve the ability to learn programming?

(3) Are the skills of decomposing multiple-gate problems simply "additive" or do they involve a cognitive "leap"? Why are "negative solutions" so difficult to master for students in this age group?

(4) Are the attitudinal and strategic differences we found between boys and girls more broadly characteristic? Are these simply affective traits or do they relate to real cognitive differences? How are the activities of exploration and experimentation, and the types of questions asked by students, related to success at RB? What are the different problem-solving strategies employed by boys and girls, and are these related to success at RB? Do these

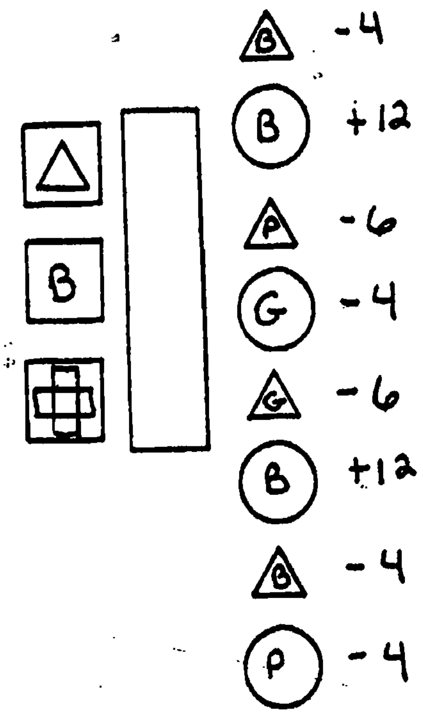
differences relate to learning differences in other related areas of study: computer programming, mathematics, science?

FIGURE 1

EXCERCISE SET ONE

1) Build a machine to kick the appropriate objects.

Blue Circles



2) What is wrong with this machine?

Blue Triangles

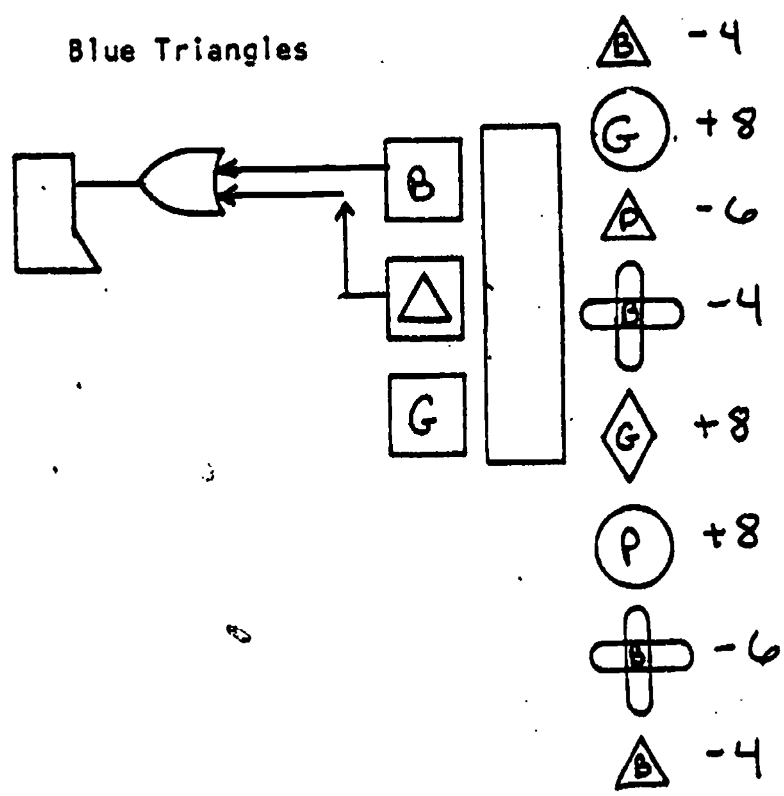
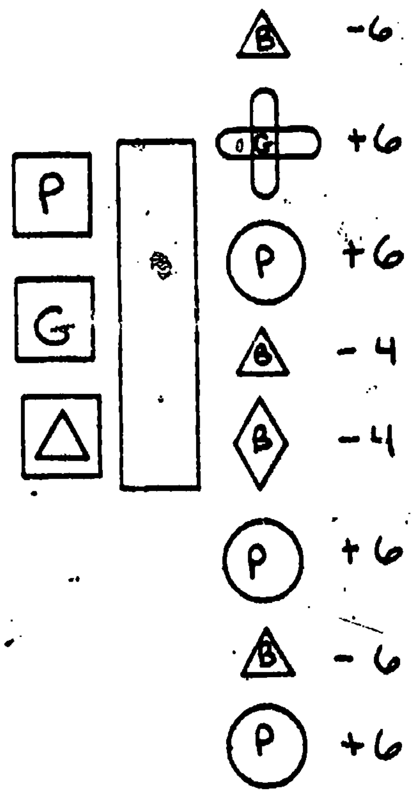


FIGURE 1

EXCERCISE SET TWO

1) Build a machine to kick the appropriate objects.

Circles and Crosses



2) What is wrong with this machine?

Circles or Green Diamonds