Math Caper

Teaching Students to Solve Problems with Their Mathematical Toolkit

By Marc Campasano

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ABSTRACT

Many students do not adequately understand how to use math to solve problems, despite years of classes ostensibly devoted to that skillset. Some struggle to apply mathematical methods to the word problems they encounter in math class. Others can solve word problems, but with simplistic heuristics instead of a deep understanding of when and how to apply mathematical methods. Even some high-performing students demonstrate a disconnection between their mathematical reasoning skills and their approach to problem-solving, mathematical or otherwise.

The learning app "Math Caper" teaches late-elementary to middle schoolers how to *solve problems with math* rather than how to *solve math problems*. The app requires and encourages the user to approach math as a *toolkit* to apply to clues and situations. Unlike traditional word problems, Math Caper cases do not give relevant figures to the learner up front. Instead the learner must interview witnesses and gather qualitative and numerical clues at the scene of a crime. Then, with encouragement from in-game characters, the player must apply math to these collected clues to arrive at useful conclusions. This design scaffolds the *process of problem solving*, requiring the learner to think about what information would be useful for solving the case, what math methods they can use to solve it, and what their numerical results mean for the story. By presenting math this way, Math Caper will help the learner better understand how to apply different mathematical methods to all sorts of situations, and not just for solving formulaic "math problems."

THE CHALLENGE: The Problem with Math Problems

This project was inspired by a student I once tutored who was struggling in a college algebra class. I presented her with a word problem from her textbook about a path on a beach. The problem setup suggested that the path was to be understood as one side of a triangle, but the student did not perceive that the text described a triangle. She knew that a triangle was a shape with three sides and three vertices, but was unable to apply this model to the problem even though it described such an arrangement.

Math education in primary and secondary schools does not adequately prepare many students to apply mathematical methods to the problems they will encounter in real life. Some students who are capable at abstract math struggle to apply those skills to analogous concrete situations (Cummins et al., 1988, p. 405). Other students can solve word problems, but only by applying heuristics based on keywords in the text, without understanding mathematical mechanics (Greer, 1997, pp. 294-295). This superficial interaction sometimes leads students to provide answers that do not account for material constraints of the presented problem, or are downright nonsensical. Schoenfeld (1991) called this issue the "suspension of sense-making" when students approach word problems.

Carpenter et al. (1983) documented a famous example. The 1982 National Assessment of Educational Progress (NAEP) asked thirteen-year-old test-takers, "An army bus holds 36 soldiers. If 1128 soldiers are being bused to their training site, how many buses are needed?" Seventy percent of the test-takers correctly divided 1128 by 36 to get 31 with a remainder of 12. Of those students, however, only 23% understood that this meant the army needed 32 buses. 19% said that the army needed 31 buses, and 29% gave the mathematically correct, but materially meaningless, answer "31, remainder 12" (Verschaffel, Greer, & De Corte, 2000, p. 6). Another famous example comes from a study (IREM, 1980) which asked first and second graders "There are 26 sheep and 10 goats on a ship. How old is the captain?" Most students responded with numerical answers constructed by operating on 26 and 10, even though those numbers were irrelevant to the question asked (Verschaffel, Greer, & De Corte, 2000, p. 4).

The above issues pertain to problems translating math lessons to real-world meaning, but many students also have problems with the reverse process. Students who function well with day-to-day mathematical tasks can struggle with analogous questions in symbolic forms. Nunes, Schliemann, and Carraher (1993) found that Brazilian students who could ably do "street mathematics" for commerce and work could not resolve the same situations as symbolic equations or as fictional word problems ("school mathematics"). The researchers attributed much of this difficulty to a "loss of meaning" when real quantities were translated into symbol numbers for calculation (pp. 54-55).

These findings suggest that many children face difficulty transferring the math lessons they learn in school to problem solving in the world, even though they often encounter simulated problems via word problems in class. Research suggests that a major reason this transfer may fail is because students approach word problems with a ruleset that does not apply to problems in the real world. De Corte, Verschaffel, and Greer (2000, pp. 3-4) listed these rules:

1) *Every problem presented by the teacher or in a textbook is solvable and makes sense.*
2) *There is only one (precise and numerical) correct answer to every word problem.*
3) *The answer can be obtained by performing one or more mathematical operations with numbers in the problem, and almost certainly with all of them.*
4) *The problem contains all the information needed to find the correct solution.*

5) *Persons, objects, places, plots, etc. are different in a school word problem than in a real-world situation, and don't worry (too much) if your knowledge or intuitions about the everyday world are violated in the situation described in the problem situation.*

These rules do not carry over from math class into the real world. If students approach math problems with these rules in mind, then they are learning that "math problems" are separate from reality, and they may not understand that the methods involved can solve real problems.

LEARNING: Solving Problems with Math

Math Caper is an app to teach late-elementary to middle school learners to *solve problems with math* instead of to *solve math problems*. This goal entails three subgoals:

1) Math Caper teaches a process for the general task of solving a problem, not just a "math problem." The app scaffolds three phases of problem solving: gathering information, modeling and analysis, and drawing conclusions. The "detective" characters who assist the player as they solve the case will lead the player along this process. This guidance communicates that these three phases are separate tasks, something that traditional word problems do not communicate since they present all the useful data up front and do not force further reflection once the math is solved.
2) Users will learn when and how it is appropriate to apply different mathematical operators and concepts. The learner should understand, for example, not only how to multiply numbers, but when and why it is appropriate to multiply. This requires that the student understand what multiplication *does*, not merely that it can be done with numbers. Again, Math Caper will accomplish this via hints from the detective characters who (when asked) will suggest how to approach a problem. This approach is informed by the literature on effective problem solving. Schley and Fujita (2014) found that a mindset for abstraction

aided the solving of word problems over number-oriented approaches. When they primed subjects to extract the "gist" of a problem, and focus on the "forest" instead of the "trees," those subjects were better able to solve problems. Likewise, Hegarty, Mayer, and Green (1992) found that students solved problems better when they focused on variable names and modeling the problem instead of finding the numbers and looking for keywords to hint at what operations they should perform.

3) Users will learn to apply their mathematical results to a situation in a meaningful way. During the case report phase of the game, they will translate mathematical results into tangible conclusions about the case. In the army buses example above, this means that they will understand that a result of "31 remainder 12" means that the army needs 32 buses.

The guiding learning principle behind Math Caper is *backward design* (Wiggins & McTighe, 1998). Backward design of curriculum begins with identifying the skills and knowledge that students should obtain from the experience. In Math Caper, the goal is that the learner be able to solve realistic problems with math. The next step in backward design is to design the assessment so that the learner must have the targeted skills and knowledge in order to pass. Math Caper cases are such assessments. The purpose of the app is to teach students how to solve problems with math, so the game presents cases that must be solved with mathematical problem-solving. Every hint in the game, insofar as these hints comprise a curriculum, contributes to that end.

DESIGN

The target audience for the case I prepared is students in late elementary to middle school. I targeted this population because the game expects an understanding of the four basic operators and other basic math concepts. The game is about learning how to *apply* the math learned in school to problem situations, not so much about learning how to do abstract math in the first place. This is the age group when students begin modeling more complex geometric and algebraic expressions out of the operators they learn in early elementary school. That said, I believe the Math Caper model could be scaled for grades 1 through 8 with cases at different levels of complexity.

Each Math Caper case begins with the police chief explaining the situation. The player receives large questions (for the case I prepared, “Which pieces in the museum are fake?” and “Who is the burglar?”), which, when answered correctly, will indicate success at the case. The player then goes to the scene of the crime, where they can interview witnesses and suspects. In the course of these conversations, the player learns qualitative and quantitative information about the case. The player can also find visual clues at the crime scene. Some clues will require the player to use their math tools, a ruler and a weighing school, to collect data (see Appendix I for the demo case description, Appendix II for screenshots).

Guiding the player along the way are two detectives, Isaac and Ada, partners on their crime-solving team. These characters are included as “teachable agents” and “ego-protective buffers,” based in the literature (Chase et al., 2009) finding that such characters improve learning by providing a “student” to teach and by absorbing some of the blame for the learner’s errors. Isaac is the department’s top crime-solver and can give hints about what to do next in the case narrative. Ada is an expert mathematician and can help the player see how to use math in a given situation.

When the player is ready, they can opt to answer the core questions of the case. These questions may require straightforward numeric answers (“How long were the lights out?”) or non-numeric answers informed by calculation (“Which suspect is small enough to fit through the escape hole?”). If they answer the questions correctly, the case is solved (see Appendix III for the demo’s solution). If not, they return to the crime scene to try again.

Progress in Math Caper is marked by the solving of cases. The individual cases would either be part of one package, or presented as a series under the Math Caper name. If packaged together, the player could also be rewarded with "promotions" to their rank within the police department.

The key to an effective Math Caper case is that it is not just traditional word problems in disguise. By design, Math Caper cases are more immersive than word problems, and will leverage the cultural form (Horn, 2013) of detective stories to prevent students from turning on their "word problem rules." Learners will interact with characters and stories to simulate how data is gathered and problems are solved in more realistic situations than simple word problems. This will hopefully heighten the narrative force of the case, teach students that quantitative information is to be found in the world, and lead them to consider what information would be most useful to find. Some cases could require out-of-game research to especially emphasize this dynamic.

It is critical that Math Caper model situations where using math would be appropriate were the case real. Authentic situations are an effective way to close the gap between math problems and reality (Verschaffel, Greer & De Corte, 2000, Ch. 4). There should be no math for its own sake in the app, no mysterious locks that arbitrarily require the player to do long division, and no characters who unrealistically struggle with adding, just waiting for the player to help. The purpose of Math Caper is to illustrate that *math is useful*, and it should be portrayed as exactly that. The math in these cases should lead the player to meaningful discoveries that it makes sense to discover through calculation. Math should never be an obstacle or a chore, never "chocolate-covered broccoli" that is just busywork in a narrative wrapper (Bruckman, 1999).

Placing math in a realistic problem-solving context sets Math Caper apart from the competition. A Google search for terms like "math problem solving app" yields plenty of results, but most of the apps train students to answer traditional word problems. Consider this question from a word problem app[1]: "One morning, Wilfred counted the tadpoles in a river. There were 3 white tadpoles and 10 more blue tadpoles than white tadpoles. How many blue tadpoles are there?" This question, illustrative of the trend, is contrived. In the real world, the student would just count the blue tadpoles (and in the real world, tadpoles aren't white or blue). Questions like these are just "math problems" wrapped in narrative, not real problems to be solved with math.

Some apps teach methods that only work for textbook math problems. One app[2] highlights keywords in a sentence to figure out what to do with the numbers in the problem. This teaches students to approach word problems in a mechanistic way unsuited for real understanding. It emphasizes strategies that Hegarty et al (1992) found that subpar problem solvers were more likely to use. This "key word method" can lead to troubling, if humorous, situations where students use subtraction if a problem protagonist's name is "Mr. Left," even if it's an addition situation, since the name triggers their "How many are *left*?" strategies (Schoenfeld, 1991, p. 323).

Math Caper takes its cues from what the most effective math teachers do in their classrooms. Chapman (2002) reports that "exemplary" high school math teachers taught problem-solving with a focus on student-centered pedagogy over rote application of methods, with a focus on exploration and inquiry. In Math Caper, rote strategies are nearly useless, given the structure of the game. The entire experience is framed as an inquiry based in the student's mission and curiosity.

EVIDENCE

In the spring I tested a paper prototype of Math Caper with two girls in the target age group. I asked them to think aloud as they grappled with the case, making sure that they were doing the sort of problem-solving thinking I wanted the game to teach and that the case, in general, was

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[1] https://itunes.apple.com/us/app/math-word-problems-step-by/id967074124?mt=8
[2] https://itunes.apple.com/us/app/math-shake-problem-solving/id900783507?mt=8

compelling and coherent. I also used pre- and post-interviews to assess attitudes toward the product (see Appendix IV for the questions).

These user tests were very encouraging. One tester called the game "a completely better way of doing math than tests … I wish school used math games instead of math quizzes and math books. They're a lot funner." Both enjoyed the experience and shared the details of the mystery to family members. Their experiences indicate that the math difficulty is about right for their age, though every user I tested with (including adults) needed some hints to finish.

My measures did not communicate clearly whether Math Detective can effectively *teach* problem solving. My testers generally already understood what they needed to do in each situation. A very important part of the game that was left out of these tests was the in-game problem-solving and math-modeling guidance, which in these tests was accomplished through my own hints.

SPRING UPDATES

In the spring I changed the name of this project to "Math Caper" from "Math Detective." The name "Math Detective" is already taken by an existing app (not similar to this one). A lot of mystery-themed math games exist, but the name "Math Caper" is not yet taken.

The proposal I turned in at the end of winter quarter included a "crime lab" feature where the player could use "lab tools" (actually math operations) to convert numerical "clues" into new useful numbers. I cut this feature from the game and put greater emphasis on the partner detectives as hint-providers for teaching purposes. I cut the lab for three reasons:

1) This feature would have been difficult to implement (for me) and to use (for the player). There are a lot of numbers in Math Caper. Every object and person in the game can be measured and weighed, whether or not the data is important. The UI for this feature, to encompass all this data, would have looked like a spreadsheet, which is less than ideal for

young users. I did not want to cut the quantity of numbers in this game because part of the challenge is for the user to determine what they need to know in a world full of data.

2) I workshopped Math Caper with Chris Bennett at his game design workshop in May, and he emphasized that the experience should just do one thing very well. The crime lab was a major feature separate in its UX and feeling from the rest of the game. Having the player shift back and forth from the crime scene to the lab would throw off their flow.

3) Due to the open-ended aspects of this game, and the fact that it is a goal not to hold the player's hand too much, I came to believe that the best way for the player to model situations and explore numbers would be with pencil and paper. There are too many things they can do with the in-game data to develop a system that can handle all possible inputs without limiting them to forced answers. The new hint system nudges them in the right direction without modeling situations for them completely, and I think letting the player use the intuitive pad-and-paper way of brainstorming and tinkering is better than anything I can put on screen.

FINAL UPDATE

I gave myself the goal of having a completely functional prototype of the game by expo at the end of July. I began programming in May and had a digital prototype ready for testing by early July. This prototype replicated the paper prototype, with better art by my artists, plus music, and included Isaac and Ada. My digital tester had a similar reaction to the paper testers: she very much enjoyed the game, and her work and spoken reactions demonstrated that she was using problem-solving skills in the intended way. She successfully used Isaac and Ada's hints to guide her, though I did still give her some hints myself (see Appendix V for her notes).

The version displayed at expo was the same as tested, with the final art and music and small fixes. The game was popular at expo, and two users completed the game without my help—the first people to do so.

CONCLUSIONS

Overall I am very pleased with Math Caper, what I accomplished with it, and the reactions to it. Math Caper succeeded at making math fun, and effectively communicated how math could be useful, as evidenced by my testers' reactions. I have received several requests for playable copies of Math Caper and had an excellent reception at expo.

I am also pleased with how Math Caper communicated a solution to the abstract problem of transferring "school math" to "street math." My panel at my final presentation all understood what I was talking about and how Math Caper was a viable solution to this hard-to-pin-down dilemma.

I wish I had more evidence of a before-and-after improvement in transferring math skills from school to real life. I have excellent qualitative evidence that students were using math to solve problems. I have less evidence that Math Caper *taught* them those strategies, although I know some users consulted Isaac and Ada to solve the case. More rigorous testing, possibly in conjunction with classrooms, would help shore up this goal.

In future iterations of Math Caper, I would like to include real-world information gathering. Many of the people who encountered Math Caper noted that a game about real-world problem solving could effectively integrate search engine research and real-world information. I chose not to put this in the sample case for complexity reasons, but could easily integrate it into future cases in the Math Caper line.

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Appendices

APPENDIX I – Game Introductory Text

INTRODUCTION

Congratulations! You're the newest Math Detective in the Number City Police Department! As a Math Detective, it's your job to solve crimes using your puzzle-solving skills and math knowledge.

The Department has given you a standard-issue magnifying glass, measuring tape, and weighing scale. You can examine, measure, and weigh any object or person at the crime scene using these tools. Investigating the evidence with these tools is essential for any Math Detective! You can also talk to people using the "talk" tool.

You should also bring your own calculator and paper and pencil to take notes and work on math.

You're not alone on your adventure. As they say, three heads are greater than or equal to one. You've got two of our most experienced Math Detectives on the case with you. Ada is our top mathematician. You should speak to Ada if you're stumped with a math problem. Isaac is our best investigator. Speak to Isaac if you need help finding or understanding evidence.

CAPER #1: TWO PLUS TWO IS FORGERY

Last night there was a burglary at the Mathsonian Museum of Art and Science. The burglar left a ransom note stating that they switched three items with fakes. They demand $3.14 million dollars in exchange for the stolen items.

The Mathsonian is a new museum that has its grand opening in eight days. Only the museum employees have been in and out. There's no evidence of a break-in.

There are security cameras, but the burglar somehow turned off the system and erased yesterday's videos. You can learn more about this if you visit the security office.

Your first goal is to figure out which three items in the museum are fakes. The descriptions near each exhibit say how each piece is supposed to be. If the burglar wasn't an expert, maybe the fakes aren't perfect copies.

Your second goal is to figure out who the burglar is! Investigate the suspects and look for clues around the museum to figure out who did it.

INSTRUCTIONS

Click on doors and signs to move around the museum.

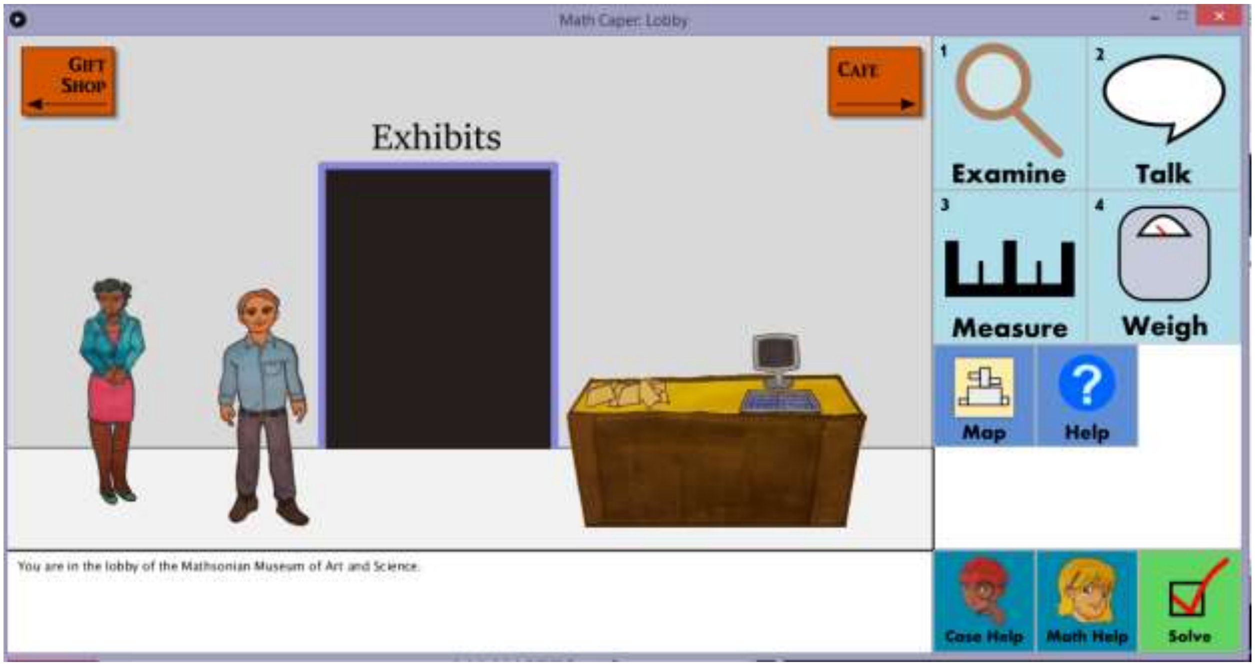
Select your tools from the upper-right (or use the number keys). Click on people and objects to use the chosen tool.

The museum map, these instructions, and the clues you find will appear in the menu to the right. Click on them to view them.

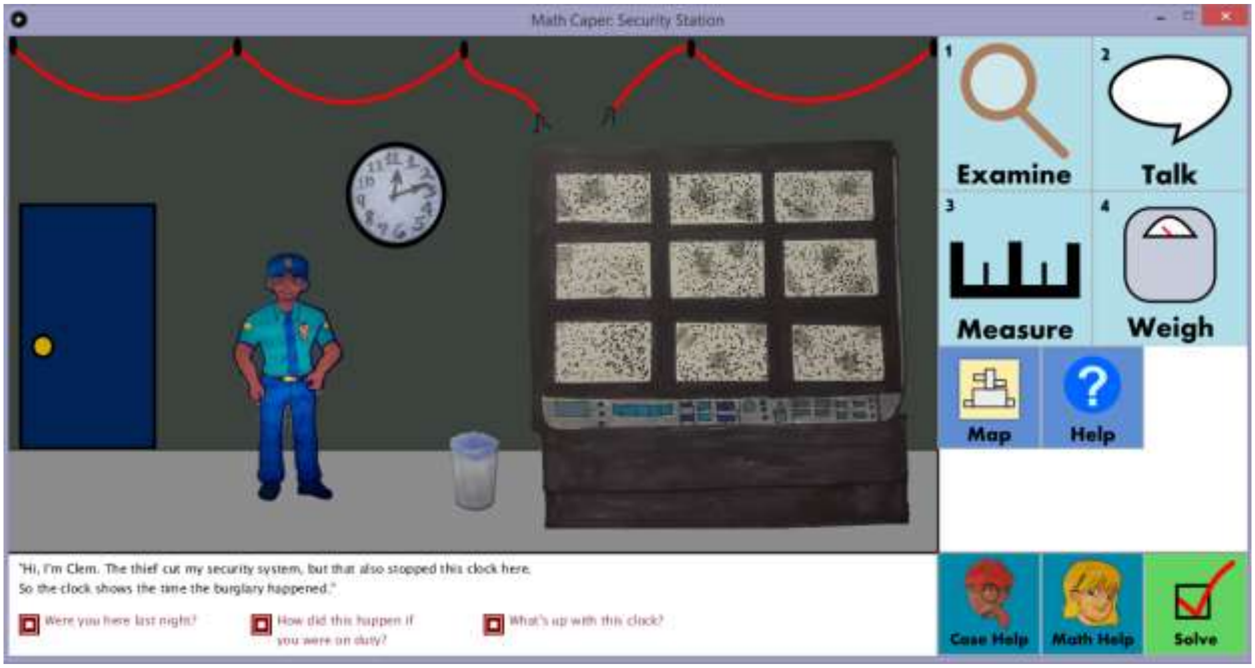
Your partners Ada and Isaac are in the lower-right corner.
 - To get a math hint, enter a room or click on an object you want help with and then click on Ada.
 - For help with the overall case, click on Isaac at any time.

When you are offered a choice, click the square next to the choice you want.

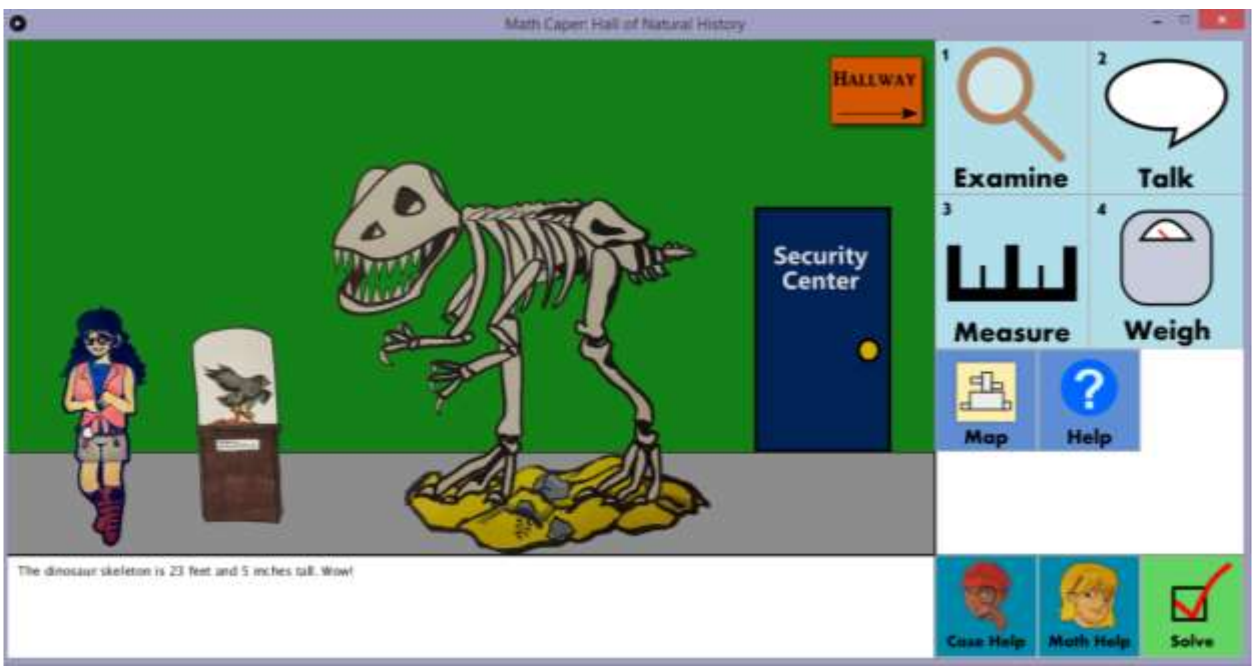
APPENDIX II – Screenshots



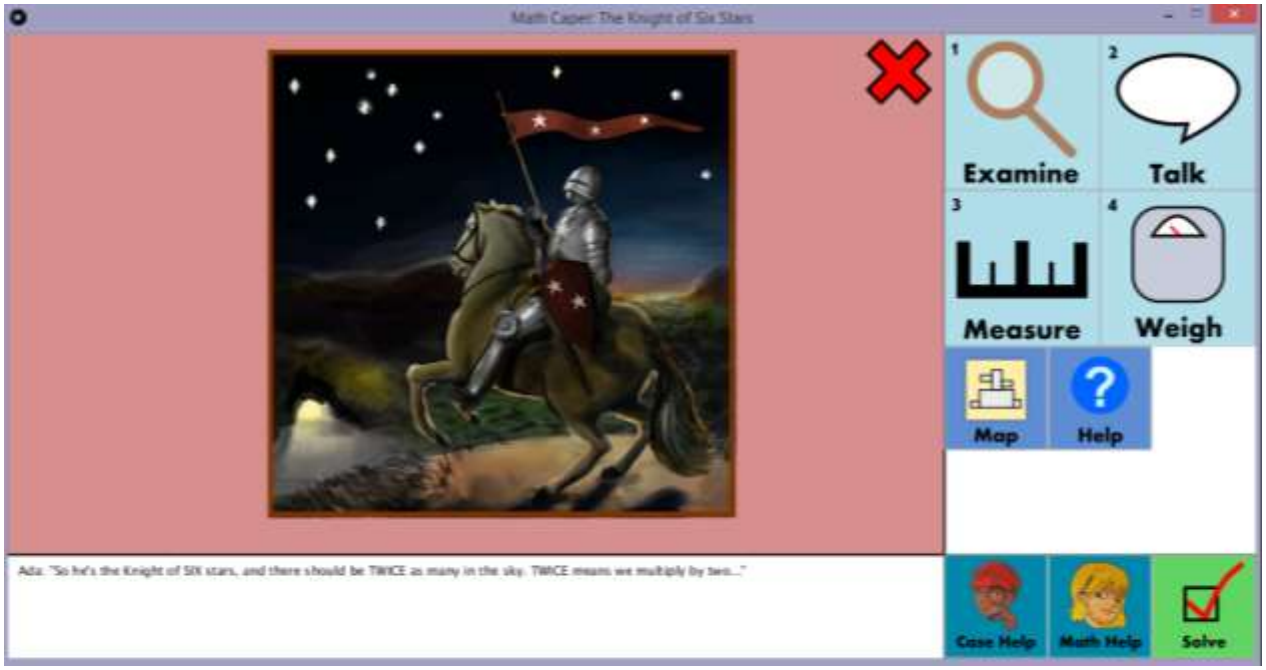
The lobby of the museum in Math Caper: Two Plus Two is Forgery. On the right is a menu with the four essential tools of the game (at top), Isaac and Ada (bottom), and reference materials (middle, to be filled in with more tools over the game).



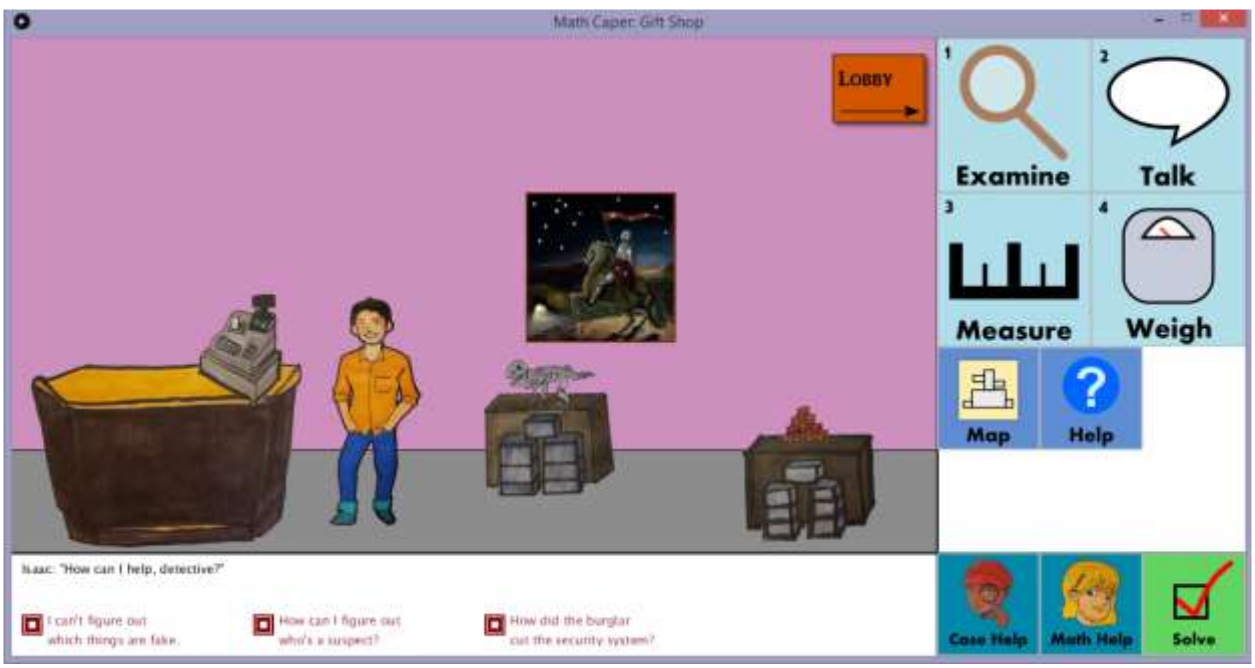
In conversation with a character.



Measuring an object with the measure tool.



Asking Ada for help analyzing an object.



Asking Isaac for help with the case.

APPENDIX III – Demo Solution

THE FAKE OBJECTS

The Chain of Asymptoth in the ancient relics room is a fake. The item description says that the chain's 17 links each weigh 0.2 pounds. There are indeed 17 links in the chain there. 17 x 0.2 = 3.4, so the whole chain should weigh 3.4 pounds. If you weigh the chain, you'll find that it's 4.1 pounds. That's too heavy to be real.

"Half of Me" in the modern art wing is a fake. The sculpture, of modern art curator Damien Wirst's legs, is supposed to be half of his height and half of his weight. If you measure and weigh Damien, you'll find that he's 6 feet 2 inches tall and weighs 190 pounds. The legs measure 3 feet 1 inch tall. 6"2' / 2 = 3'1", so that checks out. But if you weigh them, one is 47.5 pounds and the other is 36.2 pounds. 47.5 + 36.2 = 83.7, but 190 / 2 = 95, so the legs don't weigh enough.

"The Trial of Anne von Syne" in the paintings wing is fake. Adding up everyone mentioned in the description, there should be 23 people in the picture. There are instead 25.

THE BURGLAR

Larry Munk, the gift shop manager, is the burglar.

The password to the front desk computer is 1891. The note on the desk says that the password is the year Theodore Mathson's dog was born. The Mathson family portrait in the paintings wing was painted in 1903 for the dog's twelfth birthday. 1903 – 12 = 1891.

The clock in the security office stopped the moment was security system was cut, at 12:14 AM. If we compare this time to the check-in/check-out log on the computer, we can see who was still checked-in when the burglary happened.

The wires cut in the security office are 14 feet off the ground. If we compare the supply closet inventory on the computer to the actual supply closet, we can see that a 3-foot pair of clippers and a 3-foot step ladder are missing. 14 – (3 + 3) = 8, so 8 feet are unaccounted for. The wires are so high that the burglar must have cut it with their arms reached up, so anyone whose arms can reach 8 feet high is a suspect.

Two parts of a footprint appear in the supply closet and natural history wing. One is 4.3 inches long and the other is 5.7 inches, but there is 1 inch of overlap between them. (4.3 + 5.7) – 1.0 = 9.0, so the suspect has a 9-inch foot.

The only suspect who was in the museum at 12:14 AM, can reach his arms above 8 feet, and has a 9-inch foot is Larry.

APPENDIX IV – Pre- and post-questionnaire

<u>Pre-questionnaire</u>
How do you solve word problems in school?
How often do you use math in real life?
Do you think the math you use in school is useful in real life?
Can you invent a problem you would use math to solve?

<u>Post-questionnaire</u>
Was Math Caper fun?
What were the steps you took to solve the case?
How did you use math to solve the case?
Could you connect the math you learned in school to this case?
Can you invent another problem you would use math to solve?

APPENDIX V – Tester notes