A computer-based tutor for learning energy and power

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Abstract

Educating our future citizens in science and engineering is vitally important to ensure future advancement. Presently, in the light of environmental sustainability, it is critical that students learn concepts relating to energy, its consumption and future demands. In this article, we harness the state of the educational technology, namely Intelligent Tutoring System to teach concepts relating to energy and power. We describe the design and implementation of our computer-based tutor to bridge this knowledge and skills gap. We built a responsive tutoring system with Carnegie Mellon University's Cognitive Tutor Authoring Tools that challenges the students with quantitative problems based on energy, provides immediate feedback to student answers and provides need-based, timely help that supports student learning. We explain our research-based design that provides a friendly and welcoming user interface, displays astute and anticipatory software behaviour, and scaffolds student learning through appropriate clues and hints.

Keywords: İntelligent tutoring, physics education, science education, mathematics education.

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1. Introduction

Learning science and engineering is not limited to students within those majors. Students from every major are required to take science classes to satisfy their college graduation requirements (Seraphin, 2013). Given that science and engineering play an important role in shaping our lifestyle, it is vital that everyone learns about methodologies involved in the sciences (Glynn, Taasoobshirazi & Brickman, 2007). Indeed, in today's world, the food we consume, drugs and medicines that cure diseases, the way we communicate with each other across the globe and the means we use to move from place to place are influenced by breakthroughs in science and technology. In a world with ever-expanding technology, it is vital that students learn the scientific method, so that they may be able to logically evaluate tall claims and emphatic assertions affirmed by politicians and advertisers (Haig, 2010). Despite such pressing need for teaching and learning in sciences and engineering, the quality of education is lagging behind the possibilities offered by today's technology, especially for non-majors (Dehaan, 2005).

Several reasons can be attributed for this predicament. General education-based science courses for non-majors are usually taught in large classrooms with over 100 students at public universities in the United States (Deslauriers, Schelew & Wieman, 2011). In such a classroom, matching students with their peer groups is challenging because students range from freshmen (first-year undergraduates) to sophomores and seniors (final-year students). Moreover, the class is a heterogeneous mixture of students majoring in subjects ranging from liberal arts and social sciences to computer science and engineering (Zollman, 2004). The courses are offered every semester in several sections, so students in a cohesive study group are scattered in different classes due to their individual class schedules. Most of the students in a large classroom do not plan to major in a science field, and so have little knowledge beforehand. Some science concepts require students to visualise abstract processes occurring in 3-D to form diagrams of 2-D illustrations provided in textbooks. Owing to the large size of the classroom, active learning strategies, which have proven to improve learning in sciences, are less commonly available to all students (Meltzer & Thornton, 2012). As most of the learning events in a human brain happen through connection to prior conception and linking a new concept to pre-existing know-how, students from different backgrounds tend to develop misconceptions unique to their life and antecedent experience (Tallant, 1993). Add to this the gender diversity and difference in the nationality of the students, and teaching the student body gets very complex.

Computers and web-based technologies have helped to alleviate this problem to a certain extent (Esquembre, 2002). Learning management systems have enabled the teacher to upload course material in the form of files and audio/video to reach all students (Cavus & Alhih, 2014). By uploading short lectures, a teacher can illustrate a concept or explain a phenomenon. Quizzes and assessment instruments integrated into the learning management system help students get instance right/wrong feedback and save hours of grading load on the teacher (Graf, 2009). Smart classrooms help the teacher explain 3-D stereographic concepts using perspectives in computer-based animations (Wee & Goh, 2013). Computers provide schedule flexibility to students. Since one can access course materials 'anywhere, anytime', travel or work schedules do not affect a student's ability to learn course materials. Streaming video lectures from websites like YouTube have helped teachers supplement their lecture with content produced by other educators, saving valuable class time for other useful activities like peer collaboration and problem-based learning (Haase, 2009). Personal electronic response systems such as 'clickers' have improved communication between students and teachers, helping teachers to clear student misconceptions in the sciences, by providing immediate feedback from students (Martyn, 2007). Virtual labs found on websites like University of Colorado's PHET have enabled students to perform virtual 'hands-on' work to verify or contradict their predictions in a computer-generated 'real-life' situation (Perkins et al., 2006).

Catering to a variety of learners and providing a personalised experience for students have not been possible until recently. Although intelligent tutoring systems that adapt to the learning preference of a student or challenge the student based on their current level of knowledge have been around for a few decades, they had the following problems:

1. They were highly domain specific: Students of medicine could use a tutoring system for medicine, but not for, say, chemistry (Stankov, Rosic, Zitko & Grubisic, 2008).
2. Creating a tutoring system requires a labour intensive process: They often involved with scores of computer programmers working for hundreds of hours to build a robust system, and
3. Commercially available systems were very expensive: While large universities with a good supply of funding, or a well-funded school district could afford them, institutions with a lesser number of students or inadequately funded school districts found them cost prohibitive.

With the recent advent of teacher authorable intelligent tutoring platforms such as the cognitive tutor authoring tools (CTAT), providing a friendly student interface and customised, teacher authored tutor has become possible (Aleven & Sewall, 2010). Deploying this tutor for use by students was possible through TutorShop, a learner management system made for use with intelligent tutors hosted by Carnegie Mellon University. In this article, we discuss how such a non-programmer teacher created tutoring system that was developed to teach principles of energy and power to students majoring in a non-STEM field.

2. Methodology

The aim of this exercise was to teach the relationship between two important ideas in physics: energy and power. We use these terms in many contexts in day-to-day language, but in physics they have a specific meaning. Energy is used to describe a resource that is needed to do work. The work need not be physical—it could mean running an electrical motor or lighting a home. We need energy for many activities as a society. Transportation in any form requires energy. A walking human being utilises energy from the metabolism of consumed food. A car or a jet airplane uses energy derived from fossil fuels. Industries and factories that produce goods require energy for running machines and processing merchandise. Commercial sectors use energy for operating transportation, farming and other day-to-day business activities. Residential areas utilise energy for lighting their spaces, recreation and learning, cooking, washing and other everyday activities.

This article describes the process of building this tutor that provided such personalised learning experience to the students while getting around the problem of unavailability of human tutors to teach this subject. The next sections describe the contents of the video lecture and the process used to develop tutorial questions for students.

2.1. Video lecture

The lecture started with a brief introduction to energy. The students had already learned concepts relating to fossil fuel use, alternative energy sources such as nuclear energy, wind energy and solar energy. So the students were ready to learn to quantify energy and power. The relevance of energy in the present day context was then explained to students. We need energy to get the work done. While it is obvious to understand that we need energy to run, walk, play and so on, the fact that our electrical equipment such as heaters and transportation devices uses energy in some form was clarified to students. The students were then informed about different units used to measure energy such as joules, calories and British thermal units. The conversion factors used to convert energy from one unit to another was then taught to students. Some practical applications of such conversion, such as studying from journals written in inter-disciplinary fields, were elucidated to students. The concept of power was then introduced. Power was described as the rate at which energy is expended or the rate at which the work is done. Finally, the energy was interpreted as the product of power and time.

Most importantly, our energy companies that bill us for electrical energy usage every month describes our billing in units of kilowatt hour (kWh) of energy. This was emphasised to students. The fact that 1 kWh is a large unit of energy (3.6 million joules) was underscored to students. This video was made with Microsoft PowerPoint 2016 with OfficeMix Add-in (Office Mix, n.d.), and hosted on the OfficeMix website.

2.2. A computer-based tutor

The idea of this exercise was to help students to understand the significance of energy and power in everyday life, and to make them get a quantitative grasp of how various sources of energy enable our current quality of living. While video lecture taught them the basic relation between energy, power and how to quantify these physical quantities, applying these quantities to solve a real-life problem is a different skill. The difficulties they might face when asked to apply the concepts of energy and power for an application-oriented problem is not related to their mathematical understanding; in fact, most students find particularly difficult in utilising their knowledge to solve word problems. Studies have attributed such hardship to the missing link between semantic comprehension, conceptual understanding and other factors required to build a mental model of portrayal for a given word problem.

Research shows that retention of concepts learned can be improved by a step-wise process consisting of knowledge presentation, testing and feedback and personalised hint providing, which is usually done best by a human tutor. Considering the inordinate amount of time involved and the non-availability of tutors, especially for distance learning students, we employed a computer-based tutor. Carnegie Mellon University's CTAT has provided a platform for teachers to employ such computer-based tutors with virtually no coding needed. To make the tutoring experience successful and provide a meaningful learning experience for students, teachers design the tutor's user interface for students, incorporate the desired behaviour expected from students (the 'correct' method), plan how to handle student errors (by providing hints or error messages) and deploy the tutor for student use using a website such as TutorShop, also hosted by Carnegie Mellon University.

2.3. The user interface

The user interface of the tutor is the first and only point of contact between the tutor and the student. Information about the problem or question is presented to the student via the tutor's computer user interface. To build a good rapport with the student, it is important to make sure that the user interface is palatable, pleasant and agreeable. In the past decade, a body of research has been performed in various fields of work to determine what works best when it comes to designing and constructing web pages. In this work, we were able to leverage several aspects of such research to develop a functional and practical interface that provides the most benefit to students. We describe some considerations that went into making this tutor below.

Software should allow effective navigation for the user. That is, the user must be able to easily proceed from one screen to another. If this is not possible, the user can soon get disoriented or lose interest. For example, if one enters credit card information on a screen and there is no response from the computer, it gives rise to a dilemma. Should the information be entered again or would it result in a double charge? A rotating wheel, for example, could indicate that credit card information has been read and the payment is being processed. The cognitive load required to browse through multiple links to find important information is a source of disorientation. By providing navigation aids such as grid structured parallel tables can increase clarity and provide a positive experience. In our context of tutoring software, we used stepwise guidance and universally available hint button, and clear instructions, as a helpful aid to mitigate interface disorientation.

2.4. The user experience

While interacting with software, the user must be able to read the text presented on the interface, have a clear logical path to submit their query or ask for help. For example, consider a website for booking airline tickets. If the airline agency wants to attract customers, the ability to reserve tickets should be immediately available on the home screen. In the context of a tutoring system, the input box required for students to enter answers must be available clearly. If a student is stuck and unable to find the answer to a problem, help or hint must be obviously available with a click of a button.

As the interaction between user and software is in progress, the inner working process of the software must be transparent to the user. For example, if the system is searching for information or processing a payment, an icon which represents processing, such as a spinning wheel, is required. Poorly modelled opaque systems that provide no feedback to the user leads to confusion and frustration. In the framework of a tutoring system, we addressed this issue by providing complete feedback (whether the student's answer is wrong or right), a suggestion to ask for a hint and instructions on how to proceed at every step of the problem.

A picture illustrating a user interface template is shown in Figure 1. The topmost section in the tutor shows the title, which immediately hooks the students onto the topic. It provides a perspective for students and subtly influences them on what to expect. The font type of the title is chosen such that the title is seen as bold and clear. This clarity is important to prevent student disorientation, especially in a distance learning environment.
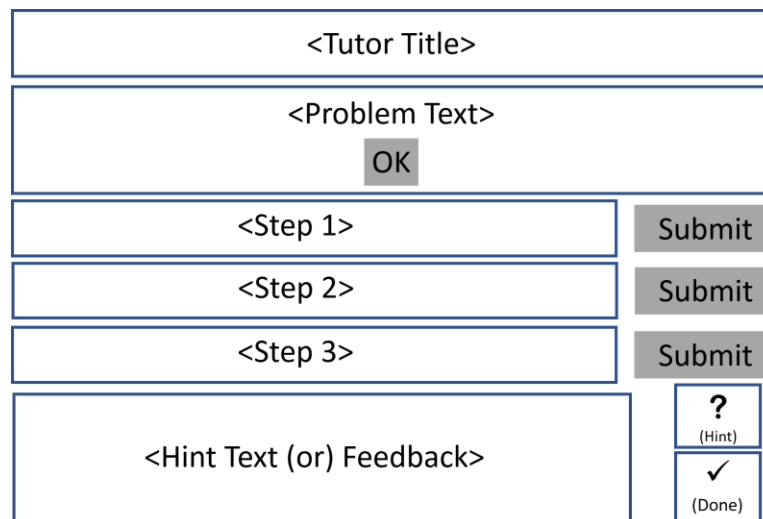

Figure 1. A schematic showing the structure of the student interface used.
<Step 1>, <Step 2> and <Step 3> are hidden at the beginning of the problem.
Once the student reads the problem and gets ready to answer, he/she clicks on 'OK'.

3. Results and discussion

In making this computer-based tutor, we first began by asking the following questions: What knowledge of the students do we want to test? How should the questions be framed, so that they are appropriate to the knowledge level of the students? To minimise question framing time and to scale the question generation process, we started out with templates that can be filled with variables such as the amount of energy used, power expended or time taken and the units used for the corresponding variables. Indeed, that was the idea of automating the process with the help of a computer—one can scale the process to cater to a large number of students while increasing the variety of questions that can be generated. To come up with the variety of problems one can make,

we identified the three important variables: energy, power and time. Figure 2 summarises how the relationship between these three variables, and the nature of the question, can be varied. As shown in Figure 2, one can provide energy and power, and ask the question to calculate the time taken for a particular amount of energy to be consumed. Another way is to supply the student with details of an appliance that takes a particular amount of time to consume a given amount of energy. The student can then be asked to calculate the power rating of the appliance. Finally, the power rating for an appliance could be provided and the student can be asked to calculate the energy consumption if the appliance runs for a particular amount of time.

E	P	T
✓	✓	?
✓	?	✓
?	✓	✓

Figure 2. A listing of possible available quantities (√) and unknown quantities (?) for a student assignment problem. E = energy, P = power and T = time.

3.1. Problem template generation

In a normal exam or test, word problems are posed in natural language in a situation involving a practical context. When trying to solve these problems, the students are required to make a connection between concepts learned in a theory class and the problem at hand. If a student solves the problem correctly, it is assumed that the student has understood the underlying physical concept and that he/she is able to apply the correct principle corresponding to that problem. The tutor designed in this article was intended to provide robust problem training to students. To this end, we used problems in this tutor which were more or less minor problems that students would see in a typical exam or test. Considering the focus of this exercise is on energy and power, and given the need for scalability in computer-based tutors, we based this exercise on three different problem templates. As seen in Figure 2, we use three variables for each of the problems. In every problem, two of the variables are given while the third one is assigned for the student to calculate. Based on these requirements, we made three different problem templates as shown in Figure 3.
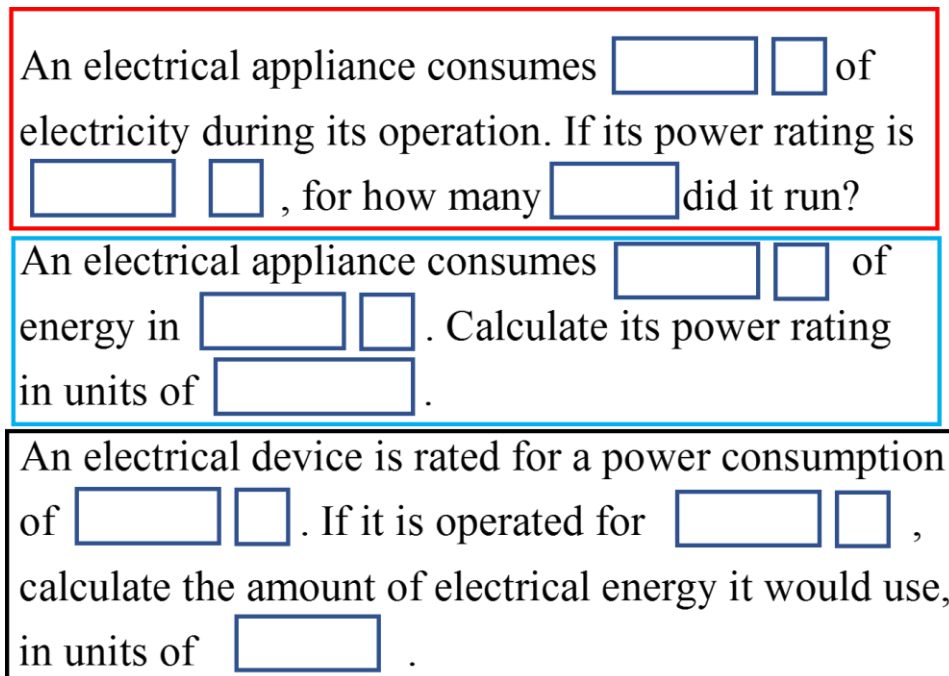
Figure 3. Three different problem templates generated. Each of these templates provides the students with two different variables and asks them to calculate the third variable, in different units.

The three boxes shown in Figure 3 show the three problem templates we used for this tutor. The smaller boxes are used as place holders to hold numbers and units corresponding to every unique problem. For example, a problem based on the first template might read, An electrical appliance consumes 2.30 kWh of electricity during its operation. If its power rating is 1,000 W, for how many minutes did it run? This way, the student is required to not only calculate the correct time for which the appliance runs but also required to express time in the proper units.

3.2. Problem structure variation

Querying the students with the same problem structure, albeit with different numbers, can soon get monotonous. In addition, it can constrain the students' thought process as they are made to repeatedly think in only one particular direction. To avoid this, research has shown that interleaving many different types of problems, even though they are based on the same mathematical principle, can help the students to think more holistically, challenge their thought process and streamline their ability to apply problem-solving regarding concepts relating to energy and power. One way to vary the problem structure, while still maintaining scalability and template structure is to vary the units which express quantities such as energy, power and time.

A visual representation is provided in Figure 4. Here, we have three different variables, each of which can be expressed in different units. So, we proceeded by working out a branching tree which provides possible combinations of units for energy, power and time. Energy can be expressed in different units, joules (J), kilojoules (kJ) and kWh. Corresponding to each of these units, the power rating of an electrical appliance can be expressed in common units of watts or kilowatts. For each of those combinations, the time for which an appliance is run can be expressed in units of seconds, minutes or hours. We observe that there exist 18 unique set of units (joules/watts/seconds, kilojoules/watts/minutes, etc.). Each of these unique sets poses a different type of mathematical calculation for students, engaging them differently and pulling them towards a different thought

process every time. This prevents the problem solving from getting monotonous and keep them occupied during the entire problem-solving session.
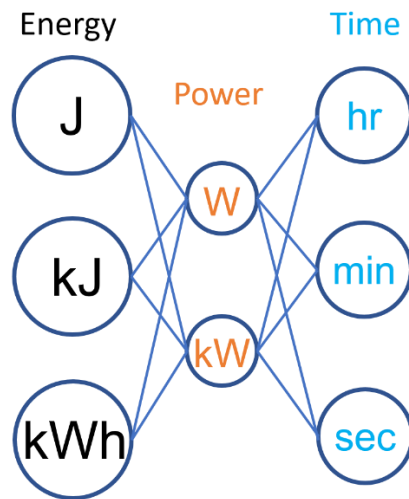

Figure 4. Listing of different permutations of variables being used in the problem template. Corresponding to these different possible units for energy, power and time, 18 possibilities of question types with different unit combination are possible.

3.3. Scaffolding and support

In education and learning, scaffolding refers to a process through which a teacher provides helpful suggestions to support student's understanding of the instructional material. Scaffolding reduces the cognitive load of the student in the learning process, minimises the time taken for mastering material and prevents misconceptions or erroneous understanding by the student. As the student begins to study new material, he/she probably comes with some pre-conceived notions about the topic. Such pre-conceptions are made by the student's past experiences or current educational background. As a result, it is possible that the student may not be able to understand the new material correctly. So in the early stages of learning, students usually require more scaffolding. As they begin to get mastery on the topic, scaffolding is gradually removed.

As an example, let's consider the first student interface shown in Figure 5. In this problem, the student is provided the amount of energy consumed by an electrical appliance and its power rating. They are asked to calculate the amount of time it has been running for. Let us suppose the student is trying to complete the first step and they have no idea on how to proceed. They first read the problem, click 'OK' in the Problem Text and proceed to enter Step 1. When they ask for a hint, the hint is provided to them in three clues as follows:
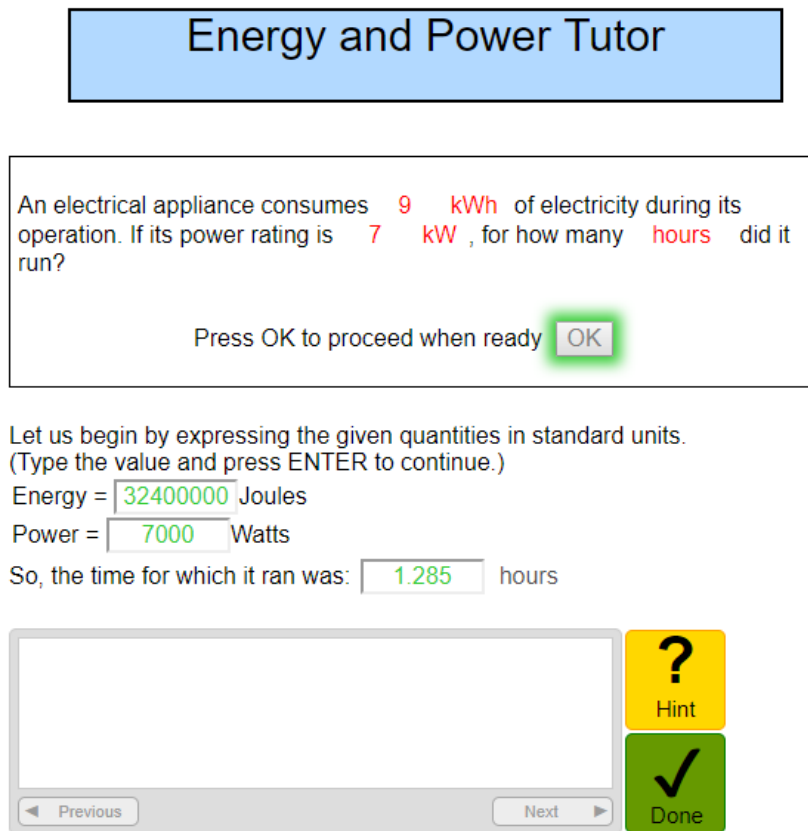
Figure 5. A screenshot of the tutor interface as viewed by the student.
Once the student is ready to answer the problem, he/she clicks 'OK'. They are then showed
the other steps of the problem to be completed, one after another, one step at a time.

1. *How many joules of energy did the appliance consume? Note that you should express your answer in units of joules.* In some problems, energy consumed by the appliance is expressed in a different unit, but the students have to convert to units of joules to get this step right.
2. *To convert kWh to joules, multiply by* 3.6×10^6. To convert kJ to joules, multiply by 1,000. Here, we assume that the student is stuck due to lack of knowledge about unit conversion.
3. Enter (answer) and press the 'Done' button. Finally, we provide the answer to the student, hoping that they reflect on how this answer was obtained, and work on successive problems with greater ease.

A flow chart showing behaviour of the tutor and how a student progresses through hints to arrive at a correct answer is shown in Figure 6.
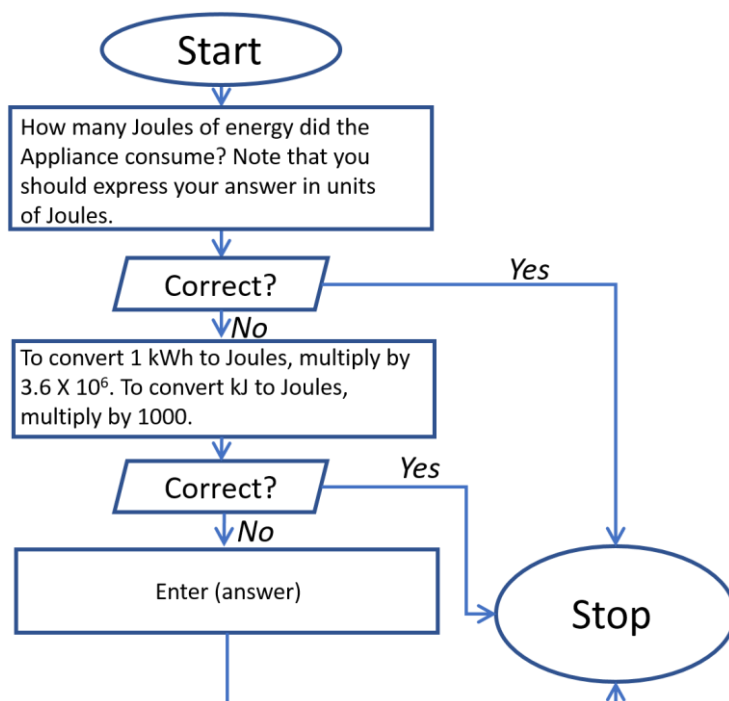
Figure 6. A flowchart describing tutor behaviour and its interaction with the student.
Different levels of hints (clues) are provided at different stages of a particular problem step.
The hints range from general (first) to specific (third).

4. Conclusions and further work

In this work, we have demonstrated a three-step learning path to understanding the concepts of energy and power, as it appears in the physics curriculum for students who do not major in STEM subjects. The students were initially provided a short video lecture (about 5 minutes), provided a teacher programmed computer-based tutor that challenges them with questions from concepts learned in the lecture, and given scaffolding and support to bridge gaps in their knowledge. All the resources used for this exercise is available free of cost for educational purposes, so teachers and students from various economic backgrounds can make use of these features.

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