Self-sustaining and Culturally-adaptive STEM Training Tool

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Abstract

Efforts to attract and retain youngsters to STEM fields cover a wide variety of initiatives. This work presents the architecture of a modular on-line training tool that brings together a number of effective strategies. The integrative approach used permits individual freedom to explore while guiding the student to acquire a broad understanding of engineering disciplines. The student-user interactivity uses query feedback and logs help requests to modify the presentation of material. Remediation is built-in, allowing the student to strengthen basic skills in a low-key environment. Modules created within the generous architectural framework may be added by more advance students. Educators who administer the tool may also contribute modules, as may other educators (for hire), or practicing engineers. Contributions from within a community help make the learning culturally-relevant, and adaptive over time. Problem-solving opportunities posted by corporations through the tool provide a two-way link between schools and business. Bounties posted for solution of business-relevant conundrums can provide financial influx for the education program, helping it to be self-sustaining. A split of proceeds with the students can provide extrinsic motivation. Organic growth of modules and of student participation based on local culture and business makes this approach potentially self-sustaining. The name for this tool is JUNIPER TREE

Introduction

This is a work in progress. No experimental results are reported herein. This paper documents a complete concept for a teaching and remediation tool designed to attract middle school students to science, technology, engineering and math careers, with particular emphasis on under-represented demographics such as females and non-Asian minorities. Juniper Tree incorporates two important features novel to the field of engineering education. First, students solve problems for local businesses. The bounty provided for solutions is split four ways to provide incentives, and the ability for the program to sustain itself financially. Second, students and local educators or engineers add modules to the program. From the basic "seed kit", a local installation of Juniper Tree will, in time, begin to reflect the milieu of these contributors, making it adaptive to local culture, and even responsive to changes in that culture over time.

The Juniper Tree concept arose from a seven month interactive development activity between Packer Engineering, Inc. (Naperville, IL) and Northern Illinois University (DeKalb, IL), hence the acronym: Joint Undertaking by Northern Illinois and Packer Engineering for Research into Teaching and Remediation in Engineering Education. The Juniper Tree icon is shown at right, which is being submitted to the US Patent and Trademark Office.

In the US, women and non-Asian minorities are underrepresented in STEM fields[1]. Yet, STEM jobs are essential to future US competitiveness[2]. These demographic groups face cultural and historic disadvantages which are believed to be a contributing factor to their paucity in STEM fields[3]. The design of Juniper Tree has been developed within this context; with the intent to attract and retain underrepresented minorities to technical fields while investigating both models and methods related to this task.

Educators involved in the Packer-NIU collaboration expressed surprise at the many facets and fields within engineering of which they were not previously aware. Anecdotally, several female participants recalled an early proclivity towards math and science which never materialized into a career choice, but in retrospect – could have. Lack of awareness exists because engineering is rarely taught in K-12 curricula[4,5]. The selection of a broad field for career paths occurs for students in the middle school ages (approximately age 11 to age 14)[6,7]. Longitudinal developmental studies also indicate that middle school ages also mark the end of the most rapid period of mental growth and development, making this age group the "last chance" to reach students[8] who are not already gravitating towards STEM pursuits.

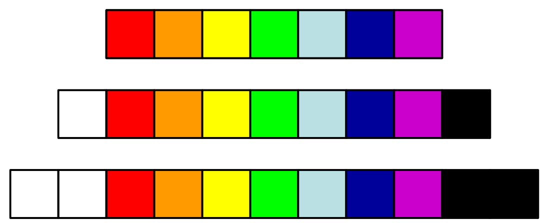
Efforts to enhance and augment existing STEM instruction are many[22,23,24]. The ASEE which sponsors this conference publishes a monthly journal exclusively on these topics (J. Engineering Education). Many such initiatives aim to enhance teacher effectiveness[9,10,11]. In many areas of the country, including our own, middle school teachers often lack the required training to effectively teach science and math, and may even lack certification to teach these subjects[1]. High-mobility students, such as children of migrant workers or of armed services personnel, change schools or miss school often, disrupting the flow for even well-developed curricula with qualified teachers. On-line methods are considered very valuable for this, and other, demographic groups[12].

Architecture

The architecture of Juniper Tree is hierarchical in two dimensions: (1) the flow of student choices down to areas of interest and need; and (2) the details behind each choice which present educational content to the student. To explain how this works for a student, a sample narrative is presented first, demonstrating navigation through the Juniper Tree software.

> *A student sits before a terminal showing various broad topics (e.g. Auto, Bio, Computers, etc). She selects a topic, and a new screen shows artsy animations of sub-topics which may be of interest (e.g. Bio...Nutrition). Under the sub-topic are training modules (e.g. Bio...Nutrition...Fiber). These modules are coded with a color bar showing the basic STEM fields to be covered. An individualized progress box shows fields already covered, so she can fill in her color bar - or focus on an area of particular fancy. Inside the module, the first interaction the student has is with a parameterized simulation. Using on-screen dials, check-boxes and other "knobs", or parameters (e.g. fiber level of breakfast cereal, vegetable choices such as broccoli versus French fries, or the balance of animal meats versus beans as a source for protein…), she adjusts the settings and selects "Play". The simulation proceeds according to her settings, and she watches the progress and outcome – the cause and effect (e.g. peristaltic motions within the large intestine and residence time of ingested toxins leading to degenerative diseases such as colon cancer and heart disease and in a rapidly-accelerated timescale). She re-adjusts*

the knobs, presses Play, and watches the new simulation producing different results. Repeat as desired. An option will be to switch into a mode where various combinations of parameters cycle automatically, and she simply observes. When she's ready, a multiple-choice questionnaire appears which queries her insight into the underlying principles, and to test her nascent powers of observation. Juniper Tree assigns a tentative understanding level to her, based on her results, then activates a self-paced history of the field (or a focus on a key individual), including basic equations and/or key experiments. This forms the launching point to didactic material. The didactic portion culminates in a problem set, solved step-by-step. As the lesson progresses, she may choose Help to whatever level needed to understand the solution. The level of help requested is captured, and used to re-assess the tentative understanding level. Remediation is provided, if needed, on an array of basic skills (e.g. reading comprehension, vocabulary, math). Problems of greater depth are accepted voluntarily by the student. When the student indicates she's ready, there is a test – each question progressively harder (for higher levels). Students are queried to determine how many test questions they wish to take. Her performance on the test question(s) then determines her proficiency level and which colors have been earned for her color bar. The training module is complete.



Juniper Tree is intended to mimic computer games to a limited extent, only in that the student has complete freedom to pursue topics of interest, and can earn rewards along the way. The endpoint, emulating beating or winning the game, is to acquire proficiency in all seven STEM proficiency fields. This can be accomplished at one of three levels of difficulty. As the student uses the Juniper Tree tool, a progress icon is displayed on the screen to convey at a glance which fields have not been completed. Each training module may contain one or more proficiency field, which turn from cross-hatched and muted to vivid rainbow colors upon completion. At levels 2 and 3, students are encouraged to augment their learning experience with creative activities which demonstrate innovative thinking and problem-solving capabilities. The rubric for the color palette is described below.

- White: Solved problem posted by a business
- Red: Life Sciences, Ergonomics, Biomedical Engineering
- Orange: Earth & Environmental Sciences, Civil Engineering
- Yellow: Materials Science & Mechanical Engineering
- Green: Design, Computer Algorithms & System Modeling
- Blue: Mathematics, Experimental Analysis & Economics
- Indigo: Chemistry, Thermodynamics & Factory Operations
- Violet: Physics & Electrical/Electronics
- Black: Created new training module using personal research, or hosted cultural outreach

When Juniper Tree is launched, the opening screen displays main topics in a visually-stimulating manner. Java animations will play, including keywords and hotlinks. Each main topic will include all seven proficiency fields. Students initiate by selecting a main topic of their choice.

Figure 1 shows the taxonomy of a subtopic. Under a main topic: "Automotive", is a subtopic: "Performance". The student reviews the training modules available in this given subtopic, such as: "Engine and Transmission"; "Tires, Suspension and Drivetrain"; and "Driving Technique". Each training module is color-coded to indicate which STEM proficiency field will be earned upon successful completion of the module. The student selects a training module.

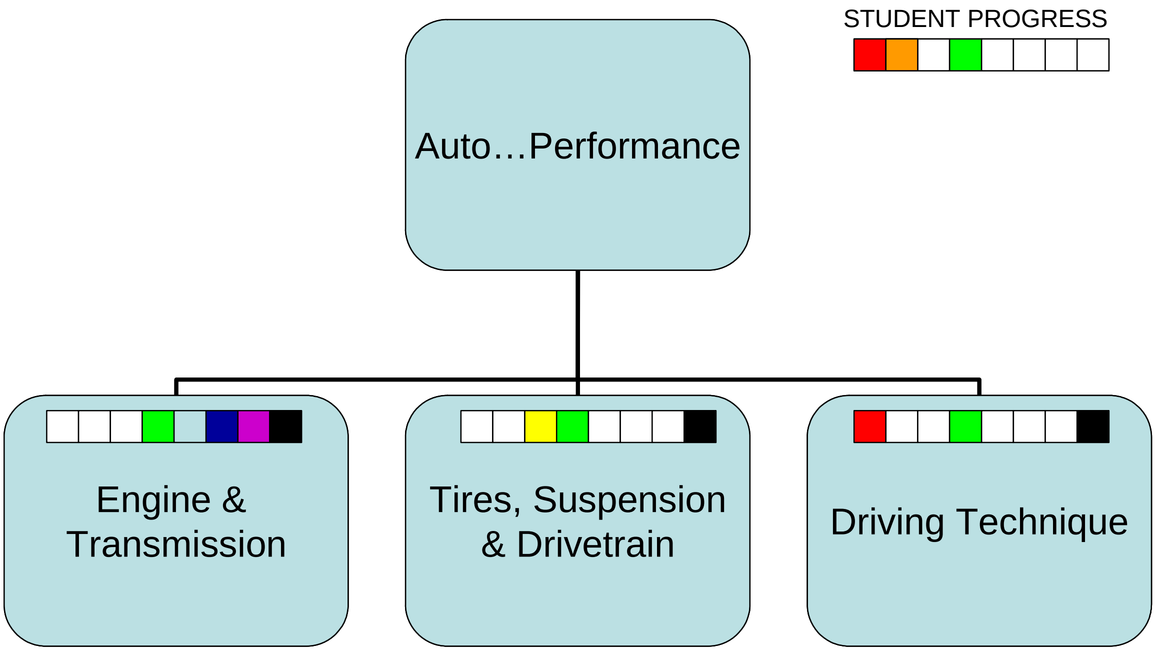


Figure 1. Taxonomy of Subtopic Module

Methodology

Each training module follows a universal sequence. First there is the interactive simulation intended to awaken curiosity and build intuition through observation of cause-and-effect. The duration of the interactive simulation is determined solely by the student. If Juniper Tree were to stop here, it would be little improvement over an instructive simulation, such as PhET (U of Colorado)[13], Interactive Physics (Design Simulation Technologies)[14] or engAPPLETS (NSF)[19]. Where Juniper Tree will surpass these excellent tools is through providing the automated feature which cycles through simulations varying parameters according to an efficient fractional factorial experimental design. This method of active-passive observation intends to reach non-verbal, intuitive learners who may have "math anxiety", characteristics commonly associated with the student demographics which we are targeting. Architectural requirements for this "*metaplay*" feature are listed below:

INTERACTIVE SIMULATION

1. Six adjustable inputs available
2. Draw from lessons – or lessons drawn from simulation
3. Does not need to be graphical
4. Must be easy to modify parameters

5. "Metaplay" will cycle through up to (2^6)/2 or (2^6)/4 combinations of parameters
6. Student can observe metaplay from start to finish
7. Student can interrupt metaplay and go manual
8. Student can start manual, get tired, and revert to metaplay
9. Student can start manual, quit on demand

When the student is ready to move on, Juniper Tree presents a questionnaire to test observation skills and insight. The purpose of this questionnaire is to make a preliminary assessment of the capabilities of the student. Note that this assessment will be refined during a subsequent step, using the Artificial Intelligence principles of data fusion and fuzzy logic, prior to delivery of the testing material upon which completion is based. The universal structure of the questionnaire is shown below, including a scoring rubric for making the preliminary assessment.

OBSERVATION & INSIGHT

1. Test observations with 9 questions – weight =1
    a. Yes (+/-1)
    b. No (+/-1)
    c. Not Sure (0)
2. Test cause and effect with 6 questions – weight = 2
    a. True (no penalty for wrong answer)
    b. False (no penalty for wrong answer)
3. Underlying principles with 3 questions – weight =3
    a. Multiple choice – 4 choices
    b. Answers: right, right-made-wrong, plausible-but-wrong, bogus, randomized
4. Maximum score = 30
    a. 0-10 = LEVEL 1
    b. 11-20 = LEVEL 2
    c. 21-30 = LEVEL 3
5. Randomizer for test questions from instructor
6. Form for creating these

Relevance is considered essential when introducing STEM fields. As a student sees the progress of technology through time, it becomes richer and more meaningful than simply being presented with the current state-of-the-art as a *fait accompli*. Using the preliminary assessment from the questionnaire, a condensed history of the science and engineering of the field is presented. Students with limited observation and insight (Level 1) are given a cursory overview, or an engaging narrative of a key figure in the field. Creators of the history portion prepare a Level 3 history in a modular format, and tag each module with the comprehension level to which it applies. In both cases, mild interaction from the student is solicited to help keep them engaged on on-topic. The flow of history elements has been developed with contributions from several professors and professionals in the engineering history field, and is shown below.

ENGINEERING HISTORY

1. Everyday observations
2. Defining Moment or Discrepant Event
3. Breakthrough Insight
4. Groundbreaking Experiment (may be reversed with 3)

5. Early Controversy
6. Red Herrings & Dead Ends
7. Mathematical Description
8. Advances & Improvements
9. Key Experts, Seminal Tomes, Centers of Learning
10. Relation to other technologies
11. Current state and applications
12. Future Opportunities

If the student quits the topic after (or during) the history presentation, at the very least, he or she will have been exposed to material which will broaden their understanding of STEM fields, and link them to everyday activities. They will also perceive the living nature of knowledge, see how the scientific method results in a constant refinement and evolution of knowledge in essentially every field of endeavor. Many people do not learn in a linear, sequential fashion, but instead respond best to brief snippets of information, forming a meta-model in their minds as they sample. These are characteristics commonly associated with some of the student demographics we are seeking to attract and retain, and the Juniper Tree tool allows this type of approach without penalty or hiccup.

The next, and most important, portion is a didactic lesson and interactive problem-solving session. During this phase of the educational delivery, the didactic lesson is tailored to the students' preliminary assessment level. During the interactive problem solving, help is provided at each step. Juniper Tree monitors the use of help by the student. This information indicates where remediation may be necessary. Remediation is suggested to the student in a pop-up screen, but is purely voluntary. The use of the Help feature also provides further indication of the understanding level of the student learner, and this data is fused with the preliminary assessment to obtain a more accurate estimate of the understanding level. A trail through the interactive practice problem is displayed in a thin slice of the screen, so that the student can go back a level if they suddenly find themselves lost. This is an especially attractive feature of the Juniper Tree concept, since becoming "lost" during a classroom lecture can provide an excuse for students to dismiss STEM in its entirely. The flow of the didactic and interactive problem-solving portion is shown below.

DIDACTIC LESSONS

1. Fundamental concepts
2. Relevant applications
3. Mathematical analysis
4. Stepwise problem solving example – LEVEL 1
5. LEVEL 2 – Auxiliary Concepts
6. LEVEL 2 – Math analysis
7. LEVEL 2 – Stepwise example
8. LEVEL 3 – Deeper Concepts
9. LEVEL 3 – Math analysis
10. LEVEL 3 – Stepwise example
11. Practice problem – LEVEL 1
    a. Help at each step – keep track of help used.
12. Practice problem – LEVEL 2 (student can skip if desired)

    a. Help at each step – keep track
13. Practice problem – LEVEL 3 (student can skip if desired)
    a. Help at each step – keep track

Evaluation

At this point, the student is ready to be tested. Cheating must be discouraged, so tests will be accessed with passwords (for Phase I), or preferably, biometric identification (Phase II). Order of test questions will be randomized for each test given, so even if students feel compelled to get answers from other students, they must at least read (and therefore be exposed to) the correct answer. All students answer Level 1 questions, even if they have already attained proficiency in this field through other modules. Students assessed at Level 1 and who successfully complete the Level 1 testing, are queried if they would like to take the Level 2 test; likewise for Level 2 students wanting to advance to Level 3. Upon successful completion, the color bar is updated to a rainbow color and the lesson is complete.

Upon completion of the module, at whatever level, the student-learner is presented with several options for further investigation. This is best illustrated with a brief narrative.

> *The student-learner may navigate away from the module in one of 3 ways, or may go deeper in one of 2 ways. Navigation can be "up", allowing her to pursue a related module in the sub-topic. Navigation can be "home" to investigate an entirely different topic ("Ew! Guts are gross! I'll try Computers"). Navigation can be through a "worm hole" to a module un-related in topic but which has similar basic principles that may have caught her fancy (e.g. fluidized bed reactors).*

Following these threads, the student proceeds to modules of interest, and that interest may begin to expand either through incidental knowledge gained, or through following of a wormhole. Juniper Tree does not impose a fixed endpoint, although the filling of colors at progressively more challenging levels provides milestones for internal goal-setting. In this way it is different from game-based learning. The student may quit at any time, but also, as will be explained in the next section, there is no limit to the involvement a student might choose. As W.B. Yeats wrote: "Education is not the filling of a pail, but the lighting of a fire." We might add: "or the planting of a tree."

Cultural Adaptability

A key function of the Juniper Tree seed kit software is a module creation tool (MCT) which guides the educator (or proficient student) through creation of a new module which will snap neatly into the architecture. It is this aspect of Juniper Tree which becomes culturally-adaptive over time. The white squares on the color palette are completed by either a community outreach event, or by creating a new module with the MCT. Of course, the administrator of the local Juniper Tree must provide approval for the student to receive credit for these activities. A suitable outreach event may be to demonstrate Juniper Tree to other student populations in the area, or it may involve helping to organize a County Science Fair, or a very wide range of other activities with the expressed goal of attracting and retaining interest in STEM fields. Alternatively, Level 2 or Level 3 students may voluntarily create their own training module to earn a white square. Juniper Tree provides no guidelines on the topics – only on their architecture. Thus, while newly-created modules will reflect the passions and thinking-process of the individual, a growing collection of such modules will begin to reflect the cultural identity within which they are created. Not immediately, but over time, each Juniper Tree installation will begin to adapt to the culture and time period of the community.

Computer programs are, in general, poor teachers. The human element which is so essential to elementary school learning is still important at the middle school level. For this reason, we have investigated possibilities for a champion, spokesperson or mascot for Juniper Tree. The Astronaut Office of the NASA Johnson Space Center was contacted on the possibility for a female, African-American or Hispanic astronaut to endorse Juniper Tree. However, USC sections 203 and 205 prohibit civil servants from endorsing commercial products. Several leading female figures holding advanced degrees in engineering have been, and are being, queried for support of Juniper Tree. Yet, those involved with not-for-profit organizations appear to be prohibited from this type of involvement. While the search continues for a nationally-recognized champion, an alternative is to use either local figures in the community or an on-line mascot. There are many challenges and risks associated with finding a suitable local champion. Informal queries of female students in high school suggest the use of an animated mascot personality. The present design concept for Juniper Tree is to provide “stubs” where an animated mascot can be inserted into the program, however, the creation of the mascot should be left to interested participants in the using community.

Self-Sustaining

Money motivates many people. An education program with the potential for earning money provides extrinsic motivation, which can be a powerful adjunct to the intrinsic motivation and curiosity we intend to evoke. Income monies may, in some cases, be a critical factor in a student’s decision to attend college, and their choice of major. Students who earn money through Juniper Tree are expected to be more likely to remain interested in STEM careers.

A number of US corporations are now posting engineering challenges on their websites and offering cash rewards for successful solutions[20]. These same companies need a fresh, talented workforce to fuel growth, offset attrition and to make up for retirements, often attracting them to high schools[21]. Juniper Tree merges these two dynamics. It must be realized that middle school or high school students are ill-equipped to solve most problems that a business cannot solve on its own. There are two answers to this dilemma. First, it is possible that, through the learning gained from Juniper Tree and associated references, a student (or team of students) may provide a key insight that leads to a breakthrough in the posted problem, and earn at least a portion of the bounty. Second, local businesses can be encouraged to post problems that are age-appropriate and culturally relevant (for example: “design a plastic louver for HVAC vents which evens-out the temperature in our VFW hall”). Motivation for the business is three-fold: (i) provide philanthropic “give-back” to their community, which is tax deductible; (ii) identify promising young people who may become future hires; and (iii) create a means by which their employees can relate to the local community through on-site visits, invited lectures, and other involvement in the administration of Juniper Tree. Anecdotally, several executives of large corporations or foundations have been approached with this idea and have given favorable feedback.

Bounties earned by students, or teams of students, using Juniper Tree can be appropriated to enhance the ability of the program to sustain itself financially. After a tithe has been returned to the licensor (as an incentive to keep the up-front costs as affordable as possible, and to continue providing upgrades and improvements), the remaining proceeds can be divided three ways, as follows:

30% to the student, or team of students, solving the problem

30% for Juniper Tree administration, with any surplus going over to the school budget

30% to participating students *other* than the problem-solvers

Putting money back into the school program eases budget concerns, and can allow the program to grow – adding new computers, or paying for the footwork to attract new business problem submissions. Putting money in the hands of the problem solvers (through their parents) not only demonstrates convincingly the lucrative possibilities of STEM work, but can also be the start of a savings account for college expenses. By sharing money with the other students in the program, those children who did not solve the problem are motivated in three ways: (i) they are encouraged to stay in the program to continue receiving a share of the bounty; (ii) they learn by example what may lay ahead for them if they continue to advance to higher levels; and (iii) they are encouraged to team with other, successful, students in order to receive even larger shares, thereby encouraging teamwork. These are powerful motivators for certain socio-economic demographics commonly associated with those groups we wish to encourage.

Summary

Juniper Tree is a work-in-progress still in the design phase, but ready to move into implementation. While not a traditional game-based learning approach, this meta-learning concept integrates interactive simulations, historical relevance and step-wise didactic delivery with both Socratic and problem-solving assessment. A facile means to add new modules provides the ability for Juniper Tree to become culturally-adaptive, making it amenable to all human settlements over any time frame. By engaging businesses interested in fostering the development of local talent, bounties exchanged for solutions to technical problems provides the opportunity for the project to fund itself, and to attract increasing numbers of students interested to share in the rewards. These features make Juniper Tree an exciting new means to attract and retain a wide demographic range of student to STEM fields. Growth of, and greater diversity of, our regional technical workforce can positively impact job creation and community prosperity.

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