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■ *Research Paper*

Humour Applied to STEM Education

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Humour has been shown to improve elements of the educational experience, but only under certain circumstances. We use Cognitive Load Theory to explain that these circumstances occur when humour does not overload the student's cognitive load. The problem-solving approach, typically used in science, technology, engineering and math (STEM) education, already increases the cognitive load, and the addition of humour can push STEM education past this overload point. Using examples from the literature and classroom experiences, we illustrate how to integrate humour in an effective manner. We pay particular attention to integrating humour with STEM problem-solving so as to avoid adding additional cognitive load. Copyright © 2016 John Wiley & Sons, Ltd.

Keywords humour; STEM; education; cognitive load

INTRODUCTION

Q: What did one Psychology miner say to the other when they discovered a deep idea?
A: Drop your pickaxe Caleb! Woo hoo! We just hit the Cognitive Lode!

Since the beginning of the 20th century, humour has been recommended as a valuable educational aid (Krause and Walter, 1917). Because humour is enjoyed by most of the population, it is tempting to believe that it can improve the typically dry experience of technical education in the fields of science, technology, engineering and math (STEM). While humour can improve STEM education, it must be applied in a particular manner that properly accounts for the interaction between human and the STEM education system. Psychologically, humour can have many benefits in the classroom, including reducing anxiety, decreasing stress, while enhancing self-esteem and motivation (Berk, 1996), (Berk, 2002). Humour can be important in creating a positive affective (social and emotional) environment in the classroom by forging a positive bridge between the instructor and students (Glenn, 2002). This improvement in the student–instructor relationship improves instructor immediacy (the psychological distance between communicating individuals as determined through speech and related communication cues), and humour has been shown to improve instructor immediacy (Aragon, 2003).

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Social Presence Theory finds that immediacy is important in effective educational interaction (Aragon, 2003; Mackey and Freyberg, 2010), which has been shown to improve educational satisfaction (Tu and McIsaac, 2002; Baker, 2004). In addition to educational outcomes, the addition of humour can also improve creativity (Ziv, 1983), and because creativity is part of STEM-based design, this is also an important educational consideration.

The system consisting of both humour and STEM education is a complex one where humour can either increase or decrease the aforementioned positive effects depending on the manner in which it is applied. This complex interaction depends on the total cognitive load of the two combined components. Excessive cognitive load can diminish the positive effects of humour. Cognitive Load Theory (CLT) (Sweller, 1988) helps illustrate the conditions under which humour is effective in STEM education, and we discuss these in the context of a few relevant examples later. CLT is also helpful in guiding our application of improvisational humour to improving technical innovation, which is an important aspect of STEM education.

THEORY

A good description of the interaction between humour and STEM education is provided by CLT. CLT categorizes the cognitive load associated with learning into the following three contributions (Figure 1a):

Germane cognitive load is devoted to the processing of information and construction of schemas that facilitate learning.
Intrinsic cognitive load is imposed by the learning task.
Extraneous cognitive load is the additional cognitive load imposed by the mode of the educational lesson.

Cognitive Load Theory suggests that learning is maximized when the majority of the cognitive load is devoted to permanent construction of knowledge schema (germane CL). STEM education is challenging because its intrinsic CL is already fairly high, given the complex nature of many math, science and engineering theories, and the STEM instructor's desire to teach via problem solving. Adding humour into the extraneous CL can exceed the maximum cognitive load for many students and disrupt the learning process. Many applications of CLT suggest that problem solving should be reduced to reduce the intrinsic CL so as to improve learning. CLT recommends reducing the amount of problem solving to maximize the germane CL through worked problems (Sweller and Cooper, 1985; Cooper and Sweller, 1987). STEM instruction typically uses significant amount of problem-solving that increases the overall CL by increasing the intrinsic CL associated with problem-solving. Also, if the humour is not conceptually integrated, the resulting effect may include the split attention effect, the result of poorly designed instruction derived from CLT (Chandler and Sweller, 1992). Here, the CL is increased because the student's attention is split between the humour and the educational lesson.

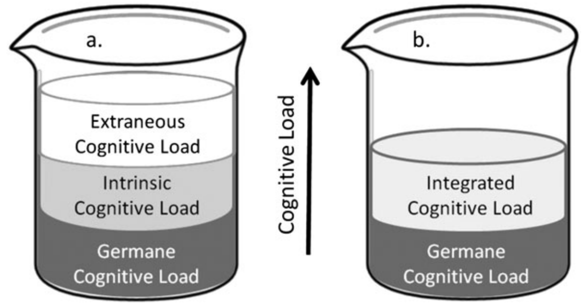

Figure 1 Schematic of the integrated humour approach to the total cognitive load. By choosing a problem topic that is already humorous, the humour is integrated into the intrinsic cognitive load of the problem (b.), rather than adding to the extraneous cognitive load (a.)

To avoid exceeding the acceptable CL, we suggest integrating humour into the educational concept so that most of the humour becomes part of the intrinsic CL and does not add significantly to the extraneous CL, as seen in Figure 1b. By picking an illustrated problem that is already humorous, we integrate the humour, which normally adds to the extraneous CL, in with intrinsic CL to reduce the overall CL (Figure 1b). A good illustration of this concept is seen in the addition of humour to the narrative of a planetarium

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show to improve learning outcomes (Fisher, 1997). In this study, humour was added to the show as part of the recorded narrative. For example, when the planetarium's pointer indicated Saturn, the humorous narrative said 'You won't see this arrow in the sky outside. Trust me.', but the non-humorous narrative was silent. After experiencing a humorous and non-humorous version of a planetarium show, adults were tested on 20 concepts. The non-humorous group had better learning outcomes. We contend this occurred because the humour was not conceptually integrated into the presentation. The humour was temporally integrated into the presentation, but this is actually more of a distraction because the cognitive processes must switch back and forth between the humour and educational tasks. A study by Vance and co-workers indicates that integrated humour may be less effective, but this study refers to the temporal, not the conceptual integration of humour (Vance, 1987). The temporal integration of humour means the humorous content is put in sequence with the desired information, typically before, after or in the middle of it. Vance found that humour temporally injected into the lesson was distracting, but humour presented before the lesson improved information retention. We suspect such delayed educational improvement from humour is related to the role of processing fluency in humour (Topolinski, 2014). This observed processing fluency phenomenon may be related to the concept of a call-back in stand-up comedy, in which the comedian illicit an additional humorous response by referring to a previous joke.

Conceptual integration of humour can be found in statistics education, where it improved learning outcomes because the humour was specifically focused on lessons in statistics fundamentals (Garner, 2006). Consider the metaphorical joke about a planned escape by one of two prisoners in a desert jail:

> The story finds one prisoner trying to escape after unsuccessfully persuading the other to go with him, only learning—after breaking out—that escape was futile as there was sand in every direction for hundreds of miles. After capture and return to the cell, the prisoner relates his story of the failed attempted escape. The other prisoner shares that he knew about the desert as he had also tried to escape a few years earlier. Incredulous, the first prisoner exclaimed, "You knew! Why didn't you tell me?" whereupon the other remarks, "Silly man, you should know that no one reports negative results."

In contrast, a text that used humorous puzzles to apply humour to statistics was ineffective because the humour and the statistics were not conceptually integrated (Pyrczak, 2009). The primary drawback to this approach is the challenge of writing topical humour for the lesson. A simpler approach, that does not require significant comedic talent in the instructor, is to choose a humorous example that also happens to be amenable to rigorous STEM analysis to produce the integrated CL seen in Figure 1b.

A review of the effect of humour in testing found no significant effects from using humour (McMorris *et al.*, 1997). We suspect this is due to the additional cognitive load associated with testing. Problem-based test questions naturally increase cognitive load because the test-taker must navigate what the test problem is really asking and avoid making the wrong assumptions. Such additional cognitive load is unavoidable because both tests and classwork in the STEM fields are composed mainly of problem solving.

Figure 2 shows a schematic of the qualitative relationship between the degree of humour integration and the cognitive load. Regions where humour can be used effectively are indicated qualitatively. This figure includes the Vance and Fisher studies as well as some recent popular examples of educational videos from Delta Airlines and the American Heart Association. These two videos teach topics involving low cognitive load: airline safety procedures (Delta Airlines Corporation, 2015) and the appropriate frequency of compressions for cardiopulmonary resuscitation (American Heart Association, 2011). The airline video alternates between a verbal announcement and a video illustration of the announced procedure. We presume Delta Airlines made the video humorous to engage the audience, without

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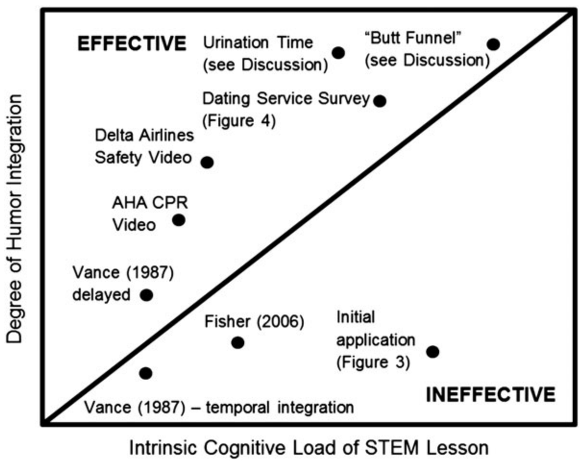

Figure 2 Qualitative schematic of the effectiveness of humour interventions as a function of cognitive load and integration into the educational lesson. The higher the cognitive load, the higher the level of integration required to produce an effective educational outcome. Note: this figure is designed to illustrate the ideas. Any increase in educational outcomes is anecdotal

increasing the CL. The American Heart Association produced a humorous video (American Heart Association, 2011) in which physician/actor/comedian Ken Jeong humorously imitates the main character from the movie 'Saturday Night Fever' to the movie theme song 'Stayin Alive'. The integration occurs because the beat of this well-known theme song matches chest compression frequency teaching students to follow the song rather than remember a specific compression frequency. Even more humorous is the fact that any song whose rhythm conforms to and American Heart Association recommendation of at least 100 beats per minute is acceptable. There are many songs in this category including the appropriately-titled 'Stayin Alive' by the Bee Gees, to the inappropriately titled 'Another One Bites the Dust' by John Deacon of the group 'Queen' (Disco Revival Helps Revive Patients, 2008).

We present Figure 2 to qualitatively illustrate these ideas. Any increase in educational outcomes (e.g. for the American Heart Association or Delta videos) is anecdotal to our knowledge, and investigations of learning outcomes from these videos have yet to be reported. The remaining points in Figure 1 are discussed later.

The CLT recommendation that problem-solving be minimized to maximize learning is rarely used by STEM educators. This is because at the college level, problem-solving is often the educational goal in STEM fields. College-level STEM instructors often attempt to use a realistic problem to make the materials more engaging. Failure to integrate these realistic details into the problem causes a similar excess CL. Adding details that are not particularly germane can confuse the student. This phenomenon reduces learning by increasing the extraneous CL and is often described as the seductive detail effect (Harp and Mayer, 1998).

Humour improves creativity in STEM because it increases divergent thinking (Ziv, 1983). As with humour effects on education, the effectiveness of humour in improving creativity depends on the manner in which it is applied. A study in which humour was applied to adolescents using the Torrence Test of Creative Thinking (TTCT) showed that humour decreased creativity (Boyle and Stack, 2014). In this study, the control group observed animated cartoons, while humorous narration was added to the cartoons for the experimental intervention. It is possible the dialogue focused the students to think in a particular area, thereby reducing their creativity. The group exposed to humor tested low on the "Resistance to Premature Closure" dimension of the TTCT, which measures the degree of openness of the subject. Successful applications of humour to increase creativity must result in a clear increase in divergent thinking.

As in the educational arena, the application of divergent thinking must be balanced against the unreasonable increase in cognitive load. Kolfschoten explains the variation of cognitive load within the task of Brainstorming (Kolfschoten, 2011). Elements of brainstorming, such as those that emerge from group interaction, can increase the cognitive load. Any effective ideation or brainstorming exercise must manage the cognitive load properly (Kolfschoten, 2011). The Cognitive Network Model of creativity indicates that diversity of stimuli, and the associated disparity among the elements suggested by the diverse stimuli, improve creativity (Santanen and De Vreede, 2004). Divergent thinking helps

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to increase the diversity of stimuli, but it can also increase the cognitive load because innovative ideas are derived from combining these disparate elements to produce creative solutions. Balancing these two elements (disparity among elements and the economy of combining elements) is required for effective ideation (Santanen and De Vreede, 2004).

DISCUSSION

Cognitive Load Theory suggests that any application of humour should be fully integrated into the STEM educational lesson or associated problem solving exercise. This integration prevents an increase in the extraneous CL, which in turn pushes the total CL beyond an acceptable level and a reduction in educational effectiveness as illustrated in Figure 1. We recommend choosing a humorous example from daily life that is amenable to analysis using STEM techniques appropriate for the particular course. Such topic selection achieves automatic integration of the humour and STEM topic. The alternative is to write humour specific to the technical concept, which is more challenging (Garner, 2006). When using humour to improve creativity, the humour must be applied in a way to foster divergent thinking without increasing the cognitive load beyond an acceptable level. Later, we describe applications of these recommendations.

Humorous Problems in a Numerical Methods Class

Under a grant from the National Science Foundation, we are investigating the application of humour to problems in a sophomore-level numerical methods class in the School of Chemical and Biomolecular Engineering at Georgia Institute of Technology. Our initial application of humour lacked the required integration and produced negative results. By temporally integrating humour into one class relative to the control class, we found that there was no statistically significant difference in learning outcomes, nor any difference in perception of humour in the two classes, based on a question from an instructor immediacy survey. A question about the instructor's use of humour in the class was asked, and the results are shown in Figure 3. Admittedly, part of this difference could be due to the class times (8 AM for the experimental intervention and 9:30 AM for the control group). However, the fact that the instructor, Pete Ludovice, who also works as a professional comedian, could not produce a difference in the perceived humour content illustrates a potential drawback of temporally-integrated humour.

More recently, this same course had one of its traditional chemical engineering projects replaced by one with integrated humour. The project was to write computer code to carry out multiple linear regressions on a set of data and make conclusions about the meaning of this regression analysis. The course was the second course for chemical engineering students and is challenging to teach. Teaching students to analyze data from more advanced chemical engineering phenomena must rely on significant scaffolding to explain these advanced concepts. Teaching this scaffolding increases the intrinsic

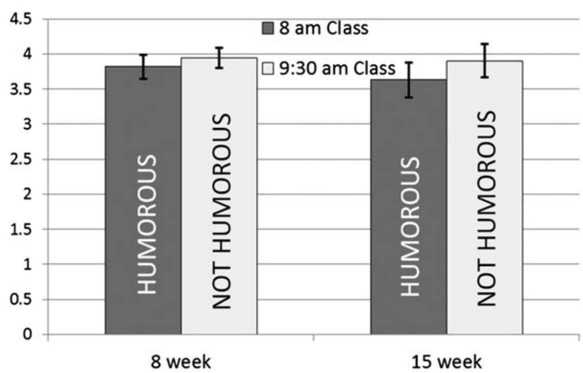

Figure 3 Average score (1 = never, 2 = occasionally, 3 = often, 4 = very often) for the 'Uses humour in class' question on the instructor immediacy behavior survey in week 8 for the 8 and 9:30 AM classes ($N = 22$ and $N = 32$, respectively), and for week 15 for the 8 and 9:30 AM classes ($N = 19$ and $N = 30$, respectively). Error bars are the 90% confidence intervals about the mean, and the critical significance for difference between the 8 and 9:30 AM classes are $p < 0.2444$ and $p < 0.0768$ for the 8- and 15-week application, respectively. The 8 AM class was the experimental class with humour, and the 9:30 AM control class had no additional humour

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and extraneous CL, which reduces the effectiveness of the problem-solving activity. Furthermore, students hesitate to make substantive conclusions about the meaning of the data analysis. The students fear their lack of knowledge about advanced engineering topics, which renders them incapable of interpreting the results relative to the instructor/expert. This fear about their lack of knowledge can be circumvented with humour. If a funny example from everyday life is used for the analysis, the students then see the instructor as no more of an expert than they are. In particular, we designed a class project involving the regression of data from a questionnaire typical of online dating services. The students were assigned to analyze trends in this data and make conclusions about the survey population. Students were shown the patent for the algorithm used by Eharmony.com, an online dating service that began operation in 2000 (Buckwater *et al.*, 2004). The dating service uses the very same analysis techniques that students use in the assignment. The grades on this assignment (project 9 in Figure 4) were the only ones statistically different from the mean of the other projects given that semester ($p < 0.05$). The mean scores for the assignments that semester are given in Figure 4. In Figure 4, only project 9 used a humorous example in the lesson. We suspect the students found it easier to make substantive conclusions because the results were interpretable through common experience.

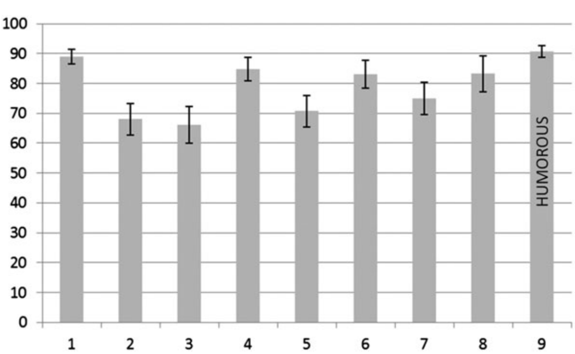

Figure 4 Average Project Scores from the Spring semester for both the 8 and 9:30 AM *classes. Error bars are the 90% confidence intervals about the mean project scores. An ANOVA test of the difference in scores for project 9 (humorous intervention) relative to the mean of the other projects were statistically different ($p < 0.05$).* All other projects showed no statistical difference between the mean of the other projects

Other funny examples from everyday life are amenable to technical analysis. Previously, we observed that students are more willing to make broad conclusions about the analysis of trends in movie box office data, relative to manufacturing quality data. Many common phenomena, such as the time variation of people at a party, can be modelled with sets of coupled differential equations. A system of two coupled ordinary differential equations describing the number of people and the amount of beverages at a party provides a fun but rigorous analysis that clearly illustrates the concept of over-specified models. Popular culture can be a source of other examples. The reality television series 'Bar Rescue' stars John Taffer, a food and beverage industry consultant, who uses 'Bar Science' to improve the performance of failing bars. While it seems hilarious to talk about bar science, the examples are indeed amenable to STEM analysis. For example, Taffer suggests placing a bar rail to limit access for people traversing between the main bar area and the dance floor, which he humorously calls a 'Butt Funnel'. Limiting the flow rate of people generates more interaction between patrons as they are forced to turn sideways and verbally interact to traverse the narrow passage between the bar and the dance floor. This design is analogous to the use of supported catalysts to force various reactants and catalyst components to interact, which can be modelled with systems of partial differential equations.

Using Urination to Humorously Teach Engineering and Biology

The aforementioned philosophy of integrating humorous phenomena with science amenable to rigorous study is embodied by the Ig Nobel Prize, which, since 1991, has honoured achievements in science, medicine and technology that make you 'Laugh, then think' (www.improbable.com). Our next multidisciplinary example in engineering and biology is based on the 2015 Ig Nobel prize in physics and teaches students

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several important skills for scientific and engineering inquiry and problem solving.

The example is derived from one of the author's (Hu) Ig Nobel-prize-winning paper on the fact that most animals urinate for approximately the same duration (21 s on average) (Yang *et al.,* 2014). The research was motivated by a rather unfortunate experience of the author changing his son's diapers. This initial observation challenged the assumptions that adults should urinate longer than infants. The ensuing study at the Atlanta Zoo by a few highly motivated undergraduate students confirmed that the duration of urination is relatively constant. The study illustrates the importance of simple observations in everyday life in motivating modern research. Experienced researchers are aware of this, but students rarely get this experience in the classroom. The example is so compelling that, when first exposed to this study, most people find themselves counting during urination. Other examples of everyday science include housewife Anne Pockel's discovery of a method for measuring surface tension while she was washing dishes, and the invention of Velcro by Georges de Mestral, a swiss engineer who noticed burrs were sticking to his dog when they went for a walk in the Swiss Alps.

One can easily calculate urination duration using back-of-the-envelope, or order-of-magnitude, estimates. Hydraulic models, such as Torricelli's Law or Bernouli's equation, allow a reasonable mathematical exploration of the variable space and forces of the students to address the appropriate question for the study at hand. As with most STEM investigations, this question evolves as more is learned about the system. In this case, the question evolves from 'How do animals urinate?' to 'What is the duration of their urination?' In contrast to the velocity, this duration metric is much more accessible experimentally. This teaches students to ask the relevant question, which is one of the most important concepts in STEM.

Finally, this case study illustrates the comparative biology approach by deriving a funny and simple grand scaling law in biology. This relatively constant duration can be verified by measuring the bladder volume as well as diameter and length of animal urethras. Assuming negligible friction and flow driven by gravity, the urination duration can be calculated from the geometry of the urinary system. The evolutionary ramifications of this scaling law might also be explored. Did the 21-s average duration evolve to help animals avoid being eaten while they pee? Additionally, the limits in the application of this constant duration law can be explored: small rodents urinate in a series of drops, and aquatic animals are susceptible to buoyancy effects.

The inherent humour of this case was successfully used to engage audiences in a number of venues from classes to print to radio interviews. Various approaches to the humorous presentation, such as referring to this scaling law as the 'Golden Rule' enhance the engagement effect. The use of videos in the presentation includes funny slow motion videos of animal urination, and an illustrative physical model, comparing the biological proportions of a dog, a human and a rhino seen in Figure 5. Admittedly, urination humour may not have been an appropriate choice several decades ago, but time and the Internet may have eased restrictions on certain taboos and their application to humour. This is

Figure 5 Image from a video illustrating the relatively constant duration of animal urination regardless of the animal size. The containers on the right contain the bladders volumes of a rhino, human and dog. Long pipes representing urethras of the appropriate dimension are installed beneath the bladder. These pipes enable the containers of vastly varying volume to empty in the same duration

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seen in the popularity of the study. The paper, as of November 2015, has been downloaded 75 000 times and is ranked number 50 of all 37 000 articles in the *Proceedings of the National Academy of Sciences* (PNAS) in terms of impact, according to Altmetric. Moreover, the work received a great deal of media attention, including discussion on Science Friday, Discovery Channel and other venues for science education. The work is now being incorporated into science education modules, including MIT Blossoms (2016) and Georgia Tech's CEISMC programme. Despite the popularity, care must be taken in choosing edgy humour topics, particularly for the Millenniel Generation. While many studies suggest that this generation enjoys humour in class, edgy humour may offend their sensibilities.

This urination study is a good example of the integration of humour into the intrinsic CL of a STEM educational lesson that teaches students valuable skills including the following: (i) the importance of simple observations, (ii) order-of-magnitude analysis, (iii) the value of asking the right question and (iv) the comparative biology approach. Further, the record of Ig Nobel prizes, and articles that also embody the science that makes you 'laugh then think' in the associated Journal of Improbable Research are examples of this humour integration discussed earlier. These resources serve as a library of integrated humour to be used directly in STEM education or to inspire new examples of integrated humour.

Humorous Improvisation to Catalyze Technical Innovation

Humour can improve creativity in the educational environment by enhancing divergent thinking. However, any application of humour that constrains divergent thinking as seen in the creativity study by Boyle and Stack is ineffective in increasing creativity (Boyle and Stack, 2014). To this end, we apply humorous improvisation as a divergent thinking application to enhance creativity in the STEM field. While a divergent step is most important for artistic creativity, STEM creativity has additional requirements that must narrow the original divergent idea to something that is feasible. On the other hand, divergent thinking alone can produce infeasible ideas suitable for artistic and marketing ideas. For this reason, improvisation has been used by marketing firms to generate new ideas. One can imagine humorous improvisation producing the successful advertising campaigns based on talking lizards ('Geico Gecko' auto insurance commercials). Unlike commercials, technical design is highly constrained by numerous principles of physical science, so the original divergent ideas must then be filtered or constrained to those that are physically feasible in STEM. For example, a talking lizard is a great marketing tool for car insurance, but obviously, lizards do not speak, especially with an adorable English accent. Similarly, solutions to STEM problems are constrained by physical laws like conservation of energy.

To address this, we have formulated a three-step ideation method that begins with (i) a purely divergent step employing humorous improvisation, followed by (ii) convergent and (iii) emergent steps that constrain the result to the relevant STEM design challenge (Ludovice *et al.,* 2010, 2013). In practice, the first step is accomplished through a typical short-form improvisation game/session that is led by a facilitator. As the improvisation session proceeds, the workshop audience records any and all divergent ideas related to the improvisation.

Adjacent to this list of random ideas, the participants record any additional ideas inspired by the random ideas that might provide a potential, albeit impractical, solution to the technical design challenge being considered (Figure 6). The second list represents the convergent step towards a solution, a dual association between the divergent idea from the improvisation and the engineering design challenge. This list is discussed and explored for possible feasible design solutions by the entire group in the third emergent step that produces the design solutions. The three-stage process has been described in detail in earlier work by one of the authors (Ludovice *et al.,* 2010, 2013).

The highest potential for increasing cognitive load occurs in step one because of truly unconstrained nature. Improvisation creates very

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Figure 6 Authors Pete Ludovice (left) and Lew Lefton (right) carry out the three-step improvisation exercise with a participant at the 2011 National Meeting of the American Society of Engineering Education. The two columns on the recorded list contain divergent and convergent ideas

diverse stimuli and with that, highly disparate elements, which are both associated with increased creativity. However, to create a feasible solution, these disparate elements must be associated with other ideas to produce a creative solution. CNM suggests that the more disparate these original ideas, the higher the associated cognitive load. Therefore, we carefully limit the cognitive load by adding two additional steps, the equivalent of two locks in a canal that lower us from the improbable space of humorous improvisation. Rather than expecting a feasible design from the first divergent step, we only attempt to find any association between the silly improvisation-inspired and the engineering challenge that produces a feasible or non-feasible solution. We wait until the third step to discuss whether this association could produce a feasible solution. We believe these additional two steps reduce the cognitive load required by associating ideas to produce a feasible solution without an excessive cognitive load.

The logic behind this methodology was illustrated in an example in which chemical engineering capstone design students designed a novel reactor for battery electrolyte production. This example was awarded the award for 'most novel design' by the battery company that sponsored the problem, and its details are described elsewhere (Ludovice *et al.*, 2013).

The application of unconstrained divergent thinking, required to improve creativity, is accomplished through an unconstrained step of humorous improvisation. This humorous improvisation is then used to inspire a potential solution to the STEM design challenge at hand. Because there is no constraint of the initial divergent improvisation step, we avoid constraining creative thought as seen in the Boyle and Stack study earlier. Santanen indicates that problem solvers often overlook 80% of the solution space (Santanen and De Vreede, 2004).

The application of this humorous improvisation to improve creativity is important for design components of STEM classes. Such design components are most important in capstone design experiences in engineering and computer science courses of study where the students must solve realistic problems that are ill-posed. Often these problems are inspired, or even funded by a corporation, government agency or non-profit organization. While many college engineering students are well-prepared to design components and systems for a well-defined engineering problem, the ideation required for such ill-posed, open-ended problems is not commonly taught.

To supplement ideation education in the engineering curriculum, we present these improvisation/innovation workshops for various classes at our institution, for participants in our

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institution's InVenture Prize Competition, and at other professional conferences both on and off campus. Early student feedback stressed the importance of facilitating these activities. This is likely due to the reluctance of STEM students to participate in a humorous improvisation exercises. We therefore suggest easing students into the exercise slowly by beginning with some warm-up exercises followed by simple short-form games.

The use of humour to catalyze technical innovation fits naturally into the cognitive load framework under consideration. The improvisational techniques described earlier suggest that humour might help people to search for more solutions and more fully sample the 'idea space'. This may indirectly reduce intrinsic cognitive load that arises in any brainstorming session. Brainstorming may increase cognitive load because of the stress of not knowing a solution, yet being put under the expectation of finding a solution after a short exercise.

CONCLUSIONS

Although humour brings some inherent advantages to education, it can also increase the overall cognitive load to the point where educational effectiveness is reduced. CLT describes when humour may be effective in STEM education. In this study, we assert that the addition of humour adds to the extraneous component of the cognitive load. STEM education commonly employs problem-solving exercises that contribute significantly to the intrinsic portion of the cognitive load. Therefore, the addition of humour to STEM education can push learners beyond the critical cognitive load and reduce learning effectiveness. We used CLT to rationalize the use of humour in both previous work and in an engineering numerical methods class we taught. We suggest that the effective use of humour in STEM education should involve the integration of humour into the STEM educational lesson and the associated problem solving exercises. This integration adds the benefits of humour without significantly increasing the cognitive load. This integration can be accomplished by choosing humorous phenomena amenable to analysis using STEM techniques. Further, humour's capacity to improve creativity hinges on its ability to enhance divergent thinking. Any application of humour that reduces divergent thinking will not enhance creativity. However, highly divergent initial ideas may impose an unreasonable cognitive load when attempting to build associations between these ideas to produce a creative design solution that is also feasible. We discuss an ideation scheme that employs humorous improvisation along with an additional convergent and emergent step to balance diversity of ideas with the cognitive challenge of associating these ideas to produce a design solution.

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