Tinkering Tactics: A Guide to Incorporating Tinkering Into STEM Curricula

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Abstract

This guide synthesizes common recommendations from several different papers, most of which reviewed in the literature review article [1], into guidelines to incorporate when designing making and tinkering activities for undergraduate STEM students. While the central focus will be on engineering students, the concepts proposed in this guide are applicable in all STEM educational fields. This guide also discusses why incorporating making and tinkering would greatly benefit the students when implemented using these guidelines.

Index Terms: Education, Tinkering, Making, STEM, Engineering

1 Introduction

Traditional educational methods offer specific instructions and expected outcomes. Such concrete structures for thinking and learning may preempt the types of exploration and creativity that STEM students often need in order to tackle the important challenges posed by our society. Making can "engage people in personally compelling, creative investigations of the material and social world" [2], driving the learners to become personally invested in their research and education, which promotes better retention and comprehension of the learned material. Making and tinkering provides students with a way to learn that emphasizes exploratory ideals such as raising questions, reflection, and problem framing by applying them in projects that requires making design choices based upon predetermined and self-determined constraints [3]. These ideals are core aspects of the mindset required of STEM programs, especially engineering.

Not only do engineers need to have technical knowhow, they have to be adept at communicating the main concepts and issues to others. The ability to work in a team and problem solve is as important to an engineer as have the specific knowledge of the materials or concepts that are applicable. Applying traditional educational tactics in an engineering class has its largest pitfalls here. While traditional methods may be able to teach the students the technical knowledge, it provides very few chances to experience the teamwork and practical application sides necessary to engineers. As Mader et al. notes, "universities have recognized the shortcoming of engineering curricula and introduced new content to educate a different kind of engineer" [3]. Mader continues on, saying that many are turning towards Problem Based Learning (PBL) or other project centered approaches to fill this need, yet another solution to the issue can be applying making and tinkering into engineering curricula [3].

1.1 Defining Making and Tinkering

Making and tinkering are ambiguous terms. Papert et al. [4] describes that ambiguity as a necessity when applying them in a learning environment, though having some semblance of structure to the terms is required to create guidelines for the application of them. Making and tinkering are very similar, both employing the students to use the physical materials and conceptual resources available to them to accomplish the desired task. Making and tinkering also employs self-directed inquiry, social engagement, intentionality and fluid experiences. It supports learners to be decision-makers and values their exploration above the assembly of a final product, providing the student with intrinsic motivation, rather than extrinsic motivation typically seen from traditional educational methods. As summarized in the literature review [1], making and tinkering have a slight distinction between each other, noting that tinkering is more experimental while making allows for more creative expression. Kotsopoulos et al. describes tinkering as a subset of making, where it is based upon modifying existing devices to accomplish a purpose that the original device was not used for [5], yet they both accomplish identical goals, so we will refer to them synonymously as M&T to simplify.

There are several main objectives that an M&T centric curriculum should reinforce. It should promote the student's desire to explore the material, allowing the student's intrinsic motivation to be the driving force to obtain a deeper understanding of the taught material. M&T curriculum should allow the students to iteratively assess their designs and goals, and experiment with both traditional and non-traditional solutions to those goals that they set for the project. The aspects of M&T within the curriculum should foster these goals. The items in the following list are tinkering tactics, aspects that when implemented will promote M&T curriculum goals.

1. M&T Recommended Elements
   - Develop and Employ the Student's Utilities
   - Create a Seed for Each Activity
   - Setup the Environment to Facilitate Learning
   - Give Feedback
2. M&T Application Guidelines
   - Promote Ideas
   - Encourage Collaboration
   - Place Ideas in Context
   - Allow Students to Direct the Process

Below, these elements and guidelines are explored in greater detail.

2 Recommended M&T Curricula Elements

Several educational researchers have determined key elements that are useful when designing activities that incorporate making/tinkering [3, 6, 2, 7, 8]. These elements are key facets for the instructor to implement either prior to the M&T activities, during the activities, or after the activities to enhance the learner's understanding of the knowledge gained.

2.1 Develop and Employ the Student's Utilities

A student's utilities are the physical tools and the conceptual knowledge obtained from prior experiences. This includes their familiarity with how to use specific tools, their knowledge of mathematical and engineering topics, or other relevant knowledge they have. These materials and resources are also referred to as a part of the student's "toolbox" , as defined by Mader et al. [3]. For both tinkering and making, the student uses their toolbox to complete their desired goal in they way that they see fit. It is important to aid in the development of their utilities prior to a project that is designed to exercise those tools, so the student can explore those tools more in depth and bridge any gaps in understanding of the utilities.

Limiting the utilities available to a student forces the student to explore the tools available even further [3]. Engineers are meant to be a "Jack of All Trades", able to adeptly complete tasks within multiple educational realms, including but not limited to mathematics, physics, communications, and computer science as well as engineering. Exposure to multiple utilities forms an engineer with a broader and deeper knowledge of concepts, devices, and materials useful to an engineer.

While traditional lecture-styled class sessions will expose the students to many concepts, exploring uses for those concepts by working on projects is better for ingraining them into memory. Try implementing this by teaching the students about the main ideas of the concepts, devices, and materials that they are unfamiliar with prior to the M&T session that they will use them in. Short lectures that are focused directly on those key topics will give the students a base for which they can formulate their exploration of that topic upon.

2.2 Create a Seed for Each Activity

The seed is a concept introduced by Mader et al., but is a key component to all project based educational curriculum. The seed "has to work as a motivating factor or starting point" for the project [3]. It is what the M&T activity is based upon, and is what peaks the student's interest in the project in the first place. Examples of it can be unfamiliar technology or foundational concept that can be used in bottom-up tinkering [3].

The quality of the seed is critical to the success of the M&T activity. A bad seed can restrain the activity, making it more of a procedural lab than an exploratory opportunity. A good seed gives slight direction in where to start, but allows for the students to use their own ideas as guidance. The quality of the seed is directly affected by the quality of help provided during the M&T session. Even with a good seed, the session can fail if poor help is provided. More will be discussed about how to facilitate learning by providing quality help in the guidelines section below (Section 3).

The seed should be simple and direct, in line with the core concept(s) that the project should reinforce or explore. Make sure to allow the students to interpret things in a way they see fit first. Don't push a certain way of thinking onto them. Create the seed so that the students have to use their existing utilities to explore the topic.

2.3 Setup the Environment to Facilitate Learning

Setting up the environment is the last element done prior to the M&T activity. The English historian Thomas Fuller stressed the importance of the quality of the tools available to a worker by saying "no good workman without good tools". Even with an exceptional, innovative worker, the end result will always be limited by the quality of tools and materials accessible to the worker. This notion of a proper setup of the making environment goes hand in hand with the development of the learner's utilities. The environment should contain various tools and materials found in the student's utilities, as well as a good space to foster the creativity and ingenuity required for M&T projects.

Mader et al. posits that the environment must be flexible, allowing the learners to modify their work station to fit their needs, must stimulate adventure and exploration to foster the student's intrinsic motivation, and should be time bounded [3]. A time limit provides a sense of urgency, which increases productivity, as well as allowing a skilled facilitator to proctor the session. The proctor should have a mastery of the toolbox desired to be exercised during the tinkering session. He or she should also allow room for the students to try and fail, to scour their mind for their own ideas before coming to the facilitator for help.

2.4 Give Feedback

Even after the session is over, the work is not done. Following the completion of a session, feedback should be given quickly and with high quality. Feedback is even more imperative when the learners are novices, so that good habits and methods are built. Also, they may need to learn how to explore. Due to the way traditional education teaches, some students may learn only by being told what to to know. Traditional education does not allow for much exploration, so just thrusting students into an environment where exploration is the key to understanding the concepts will not aid them. They have to learn how to explore, and giving them feedback on ways they could do that are necessary.

The core concepts to address when giving feedback are more how to appropriately go about the process of exploration. "We have to hold ourselves back to not debug setups for the students and thus spoiling their learning moments" notes Mader et al. [3], telling that we should help them to identify new opportunities and seek new ways of thinking. If the teacher was to identify their issues for them, it would prevent the student from making faults, which is often the best way to learn in an M&T based curriculum.

When giving feedback, make it more of a question based process rather than just telling them what they did wrong or right. Just as the M&T learning process is about discovery and insight, so too should be the feedback process. Ask open ended questions pertaining to their choices. Ask them to reason out why they did something that specific way, because even if the got the "wrong answer", the most important aspect is that they can explain their reasoning behind their choices and try to deduce why they ended up not working. The ability to think critically about the problem, their solution, and the problem to their solution is much more valuable then following a procedure to get the correct answer.

Its also important to allow the students time to give themselves feedback, promoting them to step back and reflect on the process and decision they just made [6]. Students need the opportunity to understand why they made the decisions they did, so they can integrate their new understandings into their process.

3 Guidelines for Applying M&T Curricula

These are guidelines to follow when applying the M&T elements previously discussed into the curriculum. It is imperative to follow these guidelines when using M&T elements so that the learner not only is exposed to a project with M&T elements, but that the environment, help available, and structure of the project is created in a way that facilitates the process and reinforces the desired outcomes of M&T based curriculum.

3.1 Promote Ideas, but Don't Define Outcomes

A tinkering activity can provide the opportunity for students to wrestle with particular concepts without explicitly stating the goal of their explorations [6]. For example, students learning about transmission of sound across distance can be given tools to transmit and measure sound (musical instruments, electronic speakers, microphone, analytical tools), and the information that sound travels differently across different media (through metal, through air, through water).

Throughout this process, the instructor is encouraged to pose questions instead of giving answers [6]. An activity can be guided by questions such as: Does the received volume of sound transmission vary according to frequency? How would you design a device to communicate with dolphins? How does the waveform of recorded sound look different across different media?

However, a tinkering-based activity would likely not set out specific steps to be followed in order to "transmit sound properly". Further, students engaged in a tinkering-based activity would likely not have similar creations, since there is no one guiding principle to the exploration of the transmission of sound. Students can share discoveries with each other as they find particularly interesting ways of using sound. In this way, a tinkering activity emphasizes process over product [6].

While this approach encourages the instructor to emphasize questions over explanations, many M&T contexts effectively combine such inquiry-based educational setups with more traditional models that recognizes a crucial role for the instructor to offer information as needed to support the thought development of the students in the class [7].

3.2 Encourage Collaboration, but Challenge Defined Relationships

Students working together can increase their understanding by learning from each other, which is known as "social scaffolding" [2]. Researchers recommend creating a supportive community of learners such that each person can bring their skills and interests to reaching a common goal [7]. Tinkering brings to mind the idea of having an interaction with relevant materials. However, researchers also recommend designing tinkering activities that encourage engagement with people, not just materials [6].

A crucial accompaniment to paired work is pair rotation, where students are assigned to different work partners throughout a class term. Most students prefer pair rotation over a fixed pairing. Further, pair rotation benefits instructors by breaking up of dysfunctional pairs without administrative time dedicated to intervention, and by providing a context for peer evaluation [9].

Setting up an environment that encourages collaboration allows for social scaffolding. This happens as students request or offer help in solving problems, inspire new ideas or approaches, and physically connect to each others work [2].

As both students and instructors engage activities, it can be useful to recognize the roles of expert and novice as fluid. While students in a classroom have certain arenas in which they know less than the instructor, there are also ways that students can learn from each other in surprising configurations, and ways that instructors can learn from students [7].

3.3 Place Ideas in Context, but Allow Them to Move

Several researchers codify the notion of contextualizing STEM concepts and practices in meaningful activity as a cornerstone for M&T activities [8, 7]. As many educators understand intuitively, the best place to learn about how something works is by experiencing the process directly. According to Blikstein, "abstract ideas such as friction and momentum become meaningful and concrete when they are needed to accomplish a task within a project" [8]. So, rather than teaching the abstract concept of a sinusoid, its more effective to teach about sinusoids by granting it a compelling context, such as graphical representations of alternating current or birdsong.

One radical step a tinkering education path can take is to change the context of the core concept. Instead of talking about sinusoids in a purely mathematical format, what if it was put into a context that was more relatable to the learner. What if recorded birdsong could be the code to unlocking a door? What would birdsong sound like at frequency ranges producible by humans? We can rearrange or relocate ideas in order to unlock new possibilities. Further, we can arrange a learning environment so that the materials and tools used can also be rearranged and relocated, a type of tinkering with space that reinforces the notion of appropriately setting up the environment to foster learning [6, 3].

In the previous section, engaging with people was shown to be a core component of M&T. Further, engaging with people with different knowledge or specializations allows for a greater diversity of ideas. The interdisciplinarity of making is seen as a core component of its effectiveness [7]. These interdisciplinary projects increase the richness of the learning experience [8]. This cross pollination of ideas is a form of a changing context, internally restructuring the way a student approaches new problems and ideas. Instead of seeing the problem from only one viewpoint, a learner with diversity in knowledge can step between various academic perspectives to find the best solution to the problem, shifting the context of the problems to fit the academic lenses they are looking at it with.

In a project that introduced students to a laser cutter by asking them to create keychains, the facilitator was disappointed to learn that the students didnt extrapolate the possible uses of the laser cutter beyond making keychains [8]. By highlighting diverse examples of sample projects, facilitators can prevent students from having a narrow view of possible outcomes of their tinkering exploration [6]. Furthermore, connecting existing learning and interests with new tools can give a facilitator an opportunity to highlight projects that may be of interest to different genders and cultural backgrounds [7].

3.4 Allow Students to Direct the Process

The most radical shift offered by a M&T perspective is to put students in charge of their own experience. For many researchers, the element of engagement is the most significant aspect of M&T [2, 8]. Engagement is shown as students spend time in tinkering activities and show their motivation and interest in projects through their behavior [2]. This time spent directly relates to emotional involvement, as students who experience multiple design cycles feel the ups and downs of success and temporary defeat [8]. All of these core learning moments arrive when the student is allowed to be their own pathfinder.

A self guided activity allows them to make their own design choices, perpetuating the importance of critical thinking and discerning the most vital aspects of the project. The students will experience victories and defeats throughout this experience, and will be invested in the outcome a great deal more if they were pigeonholed into a specific project or activity that isn't appealing to them. This doesn't mean that they can be allowed to have complete control over all aspects. Providing a reasonable scope for them to work in is vital so they have a focused direction rather than a free-for-all.

4 Examples of Implementing M&T Activities

This section will provide several different examples of M&T activities that have been accumulated from multiple sources. These examples will be dissected into each of the elements and guidelines previously discussed. The information here will be mostly qualitative when addressing how effective the activity was. As discussed in the literature review [1], most of the literature don't provide examples, and even when they do they rarely give quantitative analysis of the results. Due to this, we will discuss mostly how the activities use these element and guidelines discussed previously.

4.1 Programming 1 & 3 [3]

This paper describes an example of M&T being implemented in conjunction with two separate programming classes. It combined classic lecture based classes with M&T assignments. The lectures are meant to supply the student with ample utilities for them to explore through the assignments. The main utilities were elements of programming languages and algorithms for each course respectively. Their seed was an assignment for each class. The first class had to animate a self chosen piece of art. The second class had to create a coherent application using algorithms. A key driving element to both of these seeds are the self appointed nature of the topics. Each assignment allowed the student to pick art or ideas that interested them, creating more intrinsic motivation within each student. Also employed were similar teaching tactics as discussed in the guidelines section. Students were allowed to move the core idea around to fit their ideas, which acts as self promotion to explore their own ideas.

The results were mixed, either mediocre or extremely successful. The successfulness were reported to be from "students that were driven by enthusiasm" [3], intrinsically motivated learners that cared about their project.

4.2 Computational Thinking For Girls (CT4G) [10]

CT4G applied M&T pedagogies into a hands-on seminar in order to engage a historically underrepresented population in computing. Outside the introduction of girls to this field of study, the main goal was to highlight the broad applicability the ideas formulated throughout the class, especially stressing the connection between computer science (CS) and computational thinking. The main activity highlighted was a programmable badge that the student would end up using as for a simulation of communication lines.

The main roles in this simulation that were meant to be explored were network endpoints, data packets, and routers. The endpoints played the role of the users of the communication application, and has the task of choosing the recipient and establishing a data link to the student playing the role of the data packet. The data packet role consists of the student entering the network and proceeding to the nearest router upon receiving the data link from the endpoint. If the router that the packet contacted does not know the physical address to the other endpoint, it can refer the data packet to a router that does know it. The router role is the director of the system, directing the packets to the correct endpoint.

This activity has two folds to it. The programmable badge itself is an M&T activity where the badge must be programmed effectively to act as the given role. This was more of a guided portion, with the majority of the badge's functionality being preprogrammed for the later activity. That activity had the students find a way to complete the aforementioned roles. Having the students understand the importance of each role allows them to think of new ideas for accomplishing these roles. The activity very directly follows the last guideline discussed, challenging students to see themselves in a different light than the societal norm. Girls have always been unrepresented in STEM subjects, so activities directed specifically to these type of minority groups must also rebuke the stereotypes established by convention and inspire their learners to actively pursue knowledge in subjects they are not typically associated with. The activity as a whole produced a positive trend towards girl's perception of CS and their interest in the subject. Brady et al. conducted a quantitative analysis pre- and post-administration which also resulted in a continued positive trend following the second year of this program [10]. The activity also employs a collaborative setting, having three different roles where the students need to work together in order to complete the activity. The communication skills gained from these social interactions are indispensable, providing the students with an opportunity to practice their communication skills in a setting akin to a business environment. Learning how to work together effectively to produce a desired outcome is vital to all business, so having this experience to demonstrate their existing utilities gives the students more knowledge and practice in an area of study often overlooked and undervalued.

4.3 Case Study - Katrina's Learning Trajectory [11]

Instead of observing a specific M&T activity here and how it is accomplished, we look at the effects of M&T pedagogies applied through an afterschool program on a youth student, referred to as Katrina. The case study specifically looks at “how these teaching decisions have led to learning outcomes related to learning outcomes related to the development learning dispositions, capacities for creative problem solving, and STEM understanding.” [11]. Katrina started with little to no familiarity circuitry, the main utility used for the first project. This project was to create a paper circuit, using LEDs and copper tape to create the circuitry. Katrina and the other students were briefly taught what circuits are and how they work. They were then allowed to create a circuit that they designed. The first paper circuit showed developing the ideas taught from the brief lesson about circuitry, seeing them as being similar to bridges and connect-the-dots, and with the assistance of a helper. The next circuit she decided to make the design more complicated by adding a paper switch that powers the circuit. Katrina sketched the new circuit completely on her own, even though she was relatively unfamiliar with the concept of a switch. After this project, she continued to explore concepts through the paper circuit medium. She applied the switch circuitry utilities obtained from the previous problems along with a new utility of soldering to create a three switch circuit that controlled several LEDs to light up a tiny theater she created.

Analyzing the afterschool making course as a whole shows the progression of Katrina’s knowledge. She came in with little experience to the topic at hand. Early on the assistant worked closer with the student, but not giving them the answers directly. The assistant allowed the student to dictate where the project was headed, and gave ideas of utilities that could be used but let Katrina choose if and how she wanted to implement them. This allowed Katrina to develop intrinsic motivation and to develop her own ideas and strategies when utilizing her utilities. The following projects increased in difficulty, requiring her to dive deeper and discover more utilities that she could use. She discovered the paper switch by seeing one already made in the makerspace. The way the environment was setup led directly to her gaining a broader knowledge of the overarching seed, showing that the setup of the environment can have a direct impact to the student’s knowledge. Eventually, she even taught some of what she learned to another student, showing that a M&T approach to learning can propagate positivity and a good attitude towards learning academic subjects, even ones that are typically disliked by youth such as most STEM subjects.

5 Conclusion: Apply These Tinkering Tactics to Develop Your Own Curricula

These tactics for integrating M&T philosophy offer a good foundational approach to incorporating the philosophy within an educational context. In keeping with this philosophy, educators will have to consider each particular context and how to apply these tools to a learning situation. Note that these ideas are typically most effective when designing activities from scratch, because that will allow for the fluidity of incorporating the more surprising or pedagogically radical of the ideas. However, it should also be quite effective to apply these principles to an existing exercise or curriculum, and tweak the experience so that it highlights some of these principles. Regardless, both the elements and guidelines provide general tactics that can be used to promote this philosophy.

Developing a student's utilities exposes them to several different concepts and tools, allowing them to draw connections and differences between the utilities and their uses. The seed acts as the main director to the activity. It is what provides the direction to a seemingly undirected process, and what focuses the learner's attention towards a general topic. The environment almost subconsciously affects the students. Often providing the inspirations for their solutions, setting up the environment appropriately can lead to the students exploring different avenue based upon their own interests. Feedback is the best tool for the students to develop the sort of meta-cognition required for them to understand how they learn and what drives their interests. Once this form of cognition is reached, they will be able to dissect most problems into a way that makes sense to them and one that they can research and discover solutions to. All of the guidelines express key qualities in the activity's design and the people implementing the activity that will foster the core goals of M&T projects. Applying these can produce results similar to the examples, which overall saw success in the implementation. As Peppler puts it, M&T activities mesh career practices with STEM and art, creating elegant solutions to practical problems found in STEM industries [12].

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