Hands on STEM Learning at Home with 3D Printed Manipulatives

Abstract

This NSF-IUSE exploration and design project began in fall 2018 and features cross-disciplinary collaboration between engineering, math, and psychology faculty to develop learning activities with 3D-printed models, build the theoretical basis for how they support learning, and assess their effectiveness in the classroom. We are exploring how such models can scaffold spatial skills and support learners' development of conceptual understanding and representational competence in calculus and engineering statics. We are also exploring how to leverage the model-based activities to embed spatial skills training into these courses. The project's original focus was on group learning in classroom activities with shared manipulatives. After a year of development and pilot activities, we commenced data collection in classroom implementations of a relatively mature curriculum starting fall 2019. Data collection ended abruptly in March 2020 when we had to shift gears in the context of a shift to online learning amid the COVID-19 pandemic.

With uncertainty as to when the use of shared hands-on models in a collaborative in-person learning context would be feasible again, it was clear a change in approach would be necessary. We have since developed new versions of the models and associated curriculum designed for independent at-home use in the context of online learning. We implemented the new curricula in an online statics courses in fall 2020 and in multiple sections of online calculus courses in winter 2021. In this paper, we describe our strategies for implementing hands-on learning at home. We also present some example activities and compare the approach to the face-to-face versions. Finally, we compare student feedback results on the online activities to analogous feedback data from the classroom implementations and discuss implications for the anticipated return to face-to-face learning in the classroom.

Introduction

The EMARCS (Engaging with Modeling Activities for Representational Competence in STEM) project is in its third year of a three-year NSF-IUSE exploration and design tier grant. This project is a collaboration between math and engineering faculty at Whatcom Community College working with psychology faculty at Western Washington University, all located in Bellingham, WA. We are working to integrate hands-on learning activities in Integral Calculus and Engineering Statics instruction with emphasis on leveraging these activities to promote conceptual learning and embed spatial skills training. Integral to the work is research to understand how students use the models as learning aids with a goal of using these observations to develop general activity design principles that may be applicable to a wider array of STEM courses. We presented the project rationale, goals and research questions along with the overall research design in 2020 [1].

After a year of development and pilot activities, we commenced data collection in classroom implementations of a relatively mature curriculum starting fall 2019. Data collection ended in March 2020 when the onset of the COVID-19 pandemic forced an abrupt shift to online learning. Clearly, an educational intervention featuring group learning in classroom activities with shared manipulatives would need significant modification to continue the practice in an online modality. The project team worked quickly to adapt the models and associated activities for remote learning at home. This paper describes those modifications and some of the underlying reasoning before presenting some student feedback results comparing their perceptions of the face-to-face and online versions of the modeling curriculum.

Model Adaptation

The activities we developed during year 1 primarily use 3D printed models so that they are easily replicable for any instructor who has access to 3D printing. The curriculum anticipates groups of 3-4 students working together with an instructor present to answer questions. In fact, we designed some of the prompts in the activity worksheets with the explicit intention to promote student-student discussion and student-instructor interaction during class with the model nearby to serve as a teaching and communication aid. We describe many of the activities and present some data on student learning and feedback in prior work [2] [3] [4]. The models (STL files) and associated activity worksheets are publically available at two websites:

- Calculus models available at https://graspthemath.wordpress.com/integral-calculus/
- Statics models available at https://staticsmodelingkit.wordpress.com/

The first challenge we faced in transitioning to online instruction was a fourfold increase in the number of models we would need, significantly increasing the time and expense associated with model production. The classroom sets of models cost approximately $840 for statics (designed for six groups of four students each) and $144 for calculus (designed for 8 groups of 4 students each). We considered the following strategies to reduce the per-model cost and production time substantially in order to distribute one model kit per student.

- Reduction in number and size of modeling kit components
- Reduction in number and scope of modeling activities
- Redesign of activities to increase re-use of components across activities
- Shift from 3D printing to laser cut acrylic where possible

A mix of these approaches led to significant cost reductions for statics, and significant production time reductions for calculus.

Statics Model Modifications
The cost savings for the take-home version of the Statics kit come primarily from using fewer components by slightly reducing the scope of the activities and by redesigning for reuse of components. Together, these modifications reduced 3D printing filament needs from 600 grams per kit in the classroom version to 155 grams in the take home version. Total per kit materials cost decreased accordingly from \$140 to \$25 and per student cost decreased from \$35 to \$25.

We next discuss a representative example of some of the compromises we made in scaling down the statics kit. Figure 1 shows an example exercise for an introductory activity on the topic of 3D vectors in both the classroom version and the take home version. Students analyze this figure to learn about 3D position vectors and Cartesian component notation.

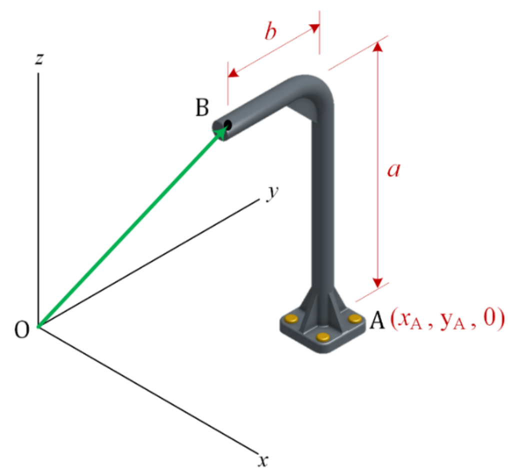

Figure 1. Problem figure for an introductory vector activity.

The photos in Figure 2 on the next page demonstrate some of the compromises we made in scaling down the kit. One task in this activity has students build a model of a 3D position vector describing the relative positions of points O and B in Figure 1. Students use elastic cord to represent this vector (modeled by the green cord in the photos) as the vector sum of its Cartesian components (modeled by the three red cords in the photos). The in-class model uses the L-shaped flange-mounted post to create a direct concrete representation of the problem figure, with the inside corner of the three pegboard panels representing the origin of the coordinate system. We removed this post component from the take-home kit to reduce overall 3D printing filament and associated cost and production time. The at-home version instead uses the “cross piece” of a two-part object also used later for activities on 3D moments and 3D rigid body equilibrium as shown in Figure 3. This change renders this first model more abstract, asking students to use a little imagination to see how the edge of the pegboard and the cross piece represent the post and locate point B (from the problem figure) in space.

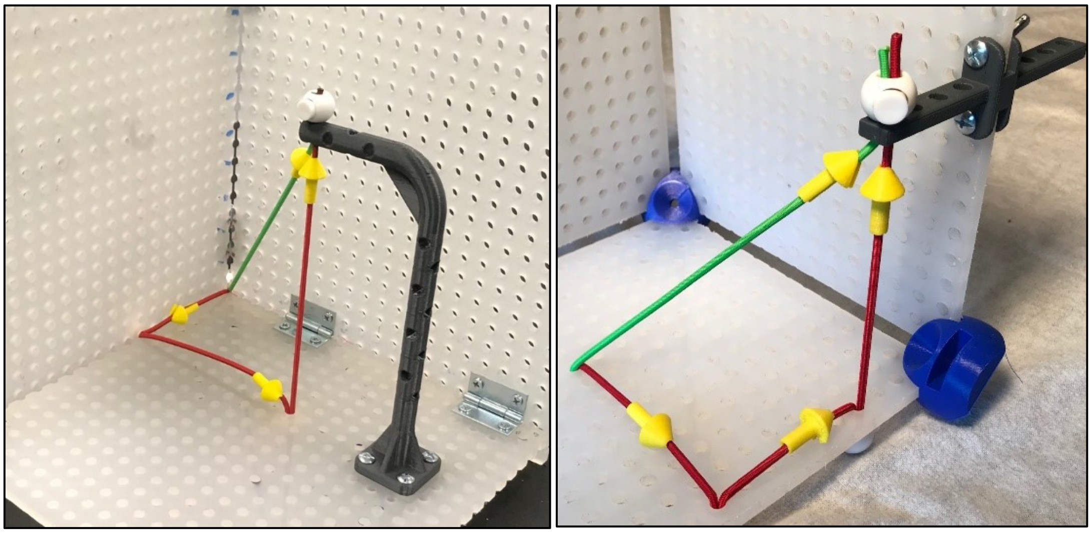

Figure 2. Modifications to a vector activity to increase component reuse.

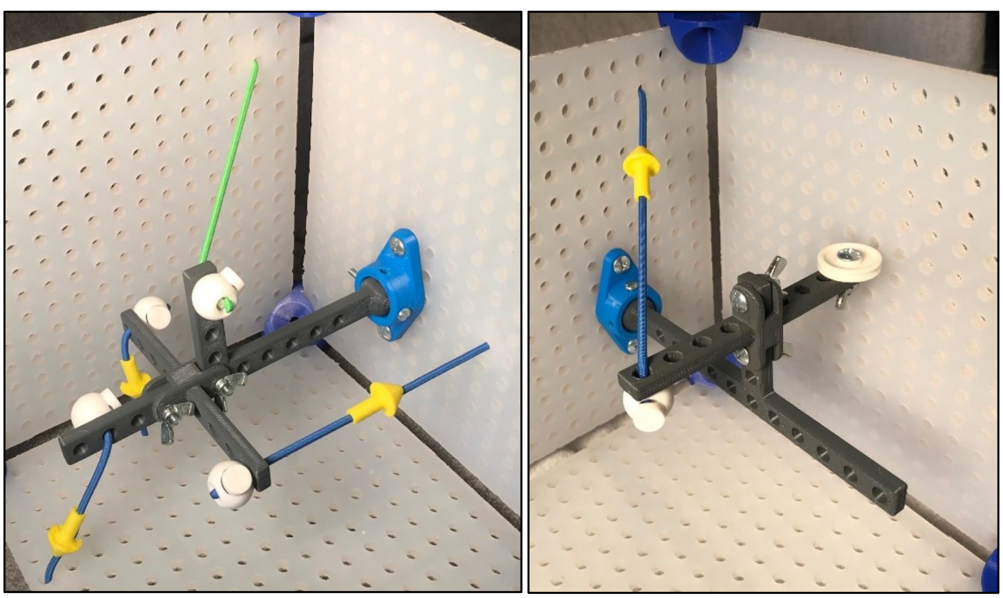

Figure 3. Photos demonstrating repeated use of the “cross piece” in later activities.

Calculus Model Modifications

The per-student cost for the volume of revolution models in the Calculus classes was essentially the same since we made a 60% reduction in size and used foam instead of flexible filament for the "slices" in the volumes. We redesigned the balance beams used in centroid activities to use washers instead of pennies (due to the coin shortage) and to reduce filament need substantially. Figure 4 shows both versions of the balance beam. The left photo shows the original design for pairs of students in class that required about 52 grams of filament (total is 780 grams for 1 beam per pair of students for a class of 30 students). The right photo shows the revised design for the take home version that requires 7.5 grams (total is 225 grams of filament at 1 beam per student for a class of 30 students).

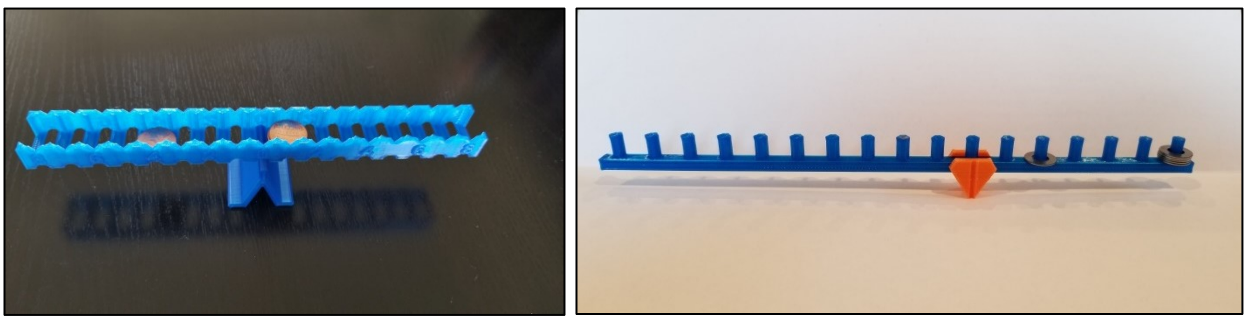

Figure 4. Revisions to the balance beam design for the 1D centroid activity.

There was an increase in cost for the lamina used for the 2D centroid activity in the individual kits, mainly due to higher cost of acrylic compared to 3D printing filament. The switch from 3D printed shapes to acrylic was a response to a need for rafts by a new bank of 3D printers we used for the increase production volume, significantly increasing the cost to print. Laser cut acrylic proved faster and less expensive. The lamina shapes were updated so that there were more models in the centroid composition handout, and smaller shapes were used to save on cost. Overall, the acrylic shapes are easier to use since they can be marked on with a dry erase marker and then erased for reuse by other students. Figure 5 shows examples of the take home version of the centroid activities.

Overall, the cost of the calculus kits increased from \$4.50 per student to \$6.00 per student, and from \$144 to \$192 per class (for a 32 person class), with the main increase coming from the acrylic lamina shapes used in the kit.

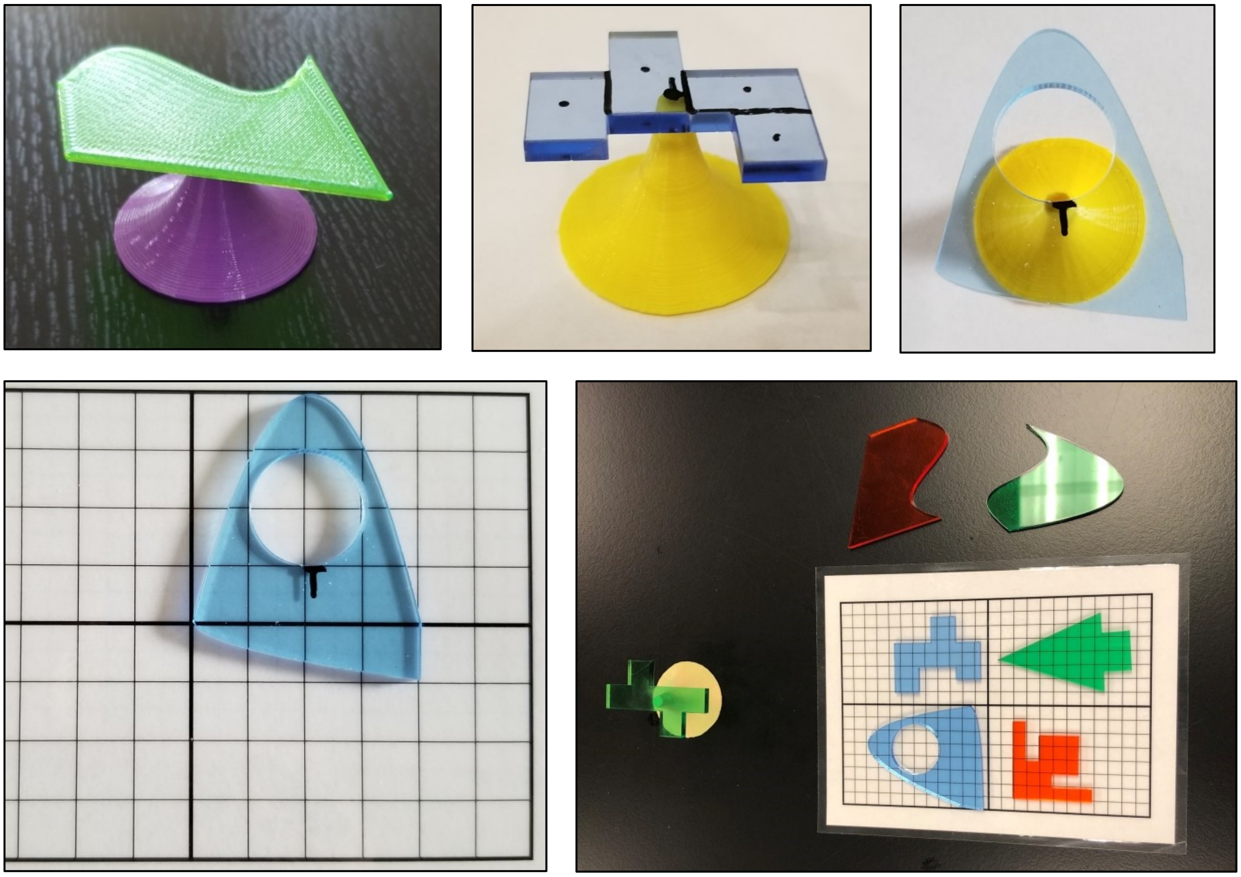

Figure 5. Example lamina shapes for 2D centroid avtivities.

Pedagogy Considerations

Given institutional guidance to rely primarily on asynchronous online instruction, some of the worksheet prompts that we designed to promote student-to-student and student-to-instructor discussion would need re-examining. When instruction is face-to-face, students can work on problems, get stuck, struggle, and get help from other students or the instructor, an idea known as productive struggle. When instruction is online, prompts designed to promote productive struggle can result in just plain struggle. The just-in-time help is not available and students get easily frustrated at critical points in their efforts to learn a new concept or solve a difficult problem. We did not try much in the statics course to address this issue and probably underestimated the importance of providing more scaffolding and support. We removed some of the most challenging prompts from the activity worksheets, encouraged students to work together, and invited students to bring their models to virtual office hours, all with mixed success.

The winter quarter calculus implementation had the benefit of learning from the statics experience. In calculus, we created videos to help walk students through the worksheets, though not through every problem listed. Students were encouraged to pause the video at key points to think about questions or work through a specific part of a problem. Although it is impossible to tell if students utilize these "pause and think" parts of the video, the main ideas targeted by each worksheet are reinforced in the video. Students were also encouraged to post solutions or questions on the worksheet problems not covered in the video to the weekly discussion forum used for class.

Student Feedback

We collected student feedback after each set of activities using the same prompts we used previously in face-to-face implementation. Tables 1 and 2 present the feedback prompts and associated results for the statics activities. Tables 3 and 4 present the feedback prompts and associated results for the calculus activities. The survey uses a six-point Likert scale of 1 = Completely Disagree, 2 = Somewhat Disagree, 3 = Slightly Disagree, 4 = Slightly Agree, 5 = Somewhat Agree, and 6 = Completely Agree. We administer the survey as a Google form that students access through a link in the course learning management system. Students earn a negligible number of participation points as incentive for completion.

Table 1. Comparison of statics activities feedback survey results for Face-to-Face (F2F) and Online (OL) versions of activities relating to vectors and moments.

Survey Prompt	F19 + W20 F2F (N = 27)	F20 OL (N=20)
1. I understood what I was being asked to do.	5.41	5.05
2. The learning goals for each activity were clear.	5.48	5.15
3. The models helped me communicate with my classmates.	5.44	4.20^{**}
4. The activities helped me clarify the material we are learning.	5.52	4.90
5. The models helped me visualize vector concepts (e.g. unit vectors, direction angles, cross product).	5.71^{+}	4.95^{*}
6. The follow-up questions on Concept Warehouse helped me test my understanding.	4.89	4.75
7. The activities helped me connect different representations of the concepts (i.e. figures, diagrams, graphs, notation, equations, written descriptions, etc.)	5.41	5.00
8. The models helped me visualize and interpret the figures and diagrams on the worksheets.	5.52	4.95
9. Working with the models helps me visualize and interpret other figures and diagrams in the reading and problem sets.	5.31	4.35*

* $p < 0.05$, ** $p < 0.001$, (two-tailed t-test), $^{+}$N = 14 because question added in W20

Table 2. Comparison of statics activities feedback survey results for Face-to-Face (F2F) and Online (OL) versions of activities relating to rigid body equilibrium.

Survey Prompt	F19 + W20 F2F (N = 29)	F20 OL (N=20)
1. I understood what I was being asked to do.	5.31	4.85
2. The learning goals for each activity were clear.	5.52	5.10
3. The models helped me communicate with my classmates.	5.69	4.05**
4. The activities helped me clarify the material we are learning.	5.34	4.60*
5. The models helped me feel the forces and moments in the problems.	5.52	4.90*
6. The follow-up questions on Concept Warehouse helped me test my understanding.	5.17	4.35*
7. The activities helped me connect different representations of the concepts (i.e. figures, diagrams, graphs, notation, equations, written descriptions, etc.)	5.38	4.70*
8. The models helped me visualize and interpret the figures and diagrams on the worksheets.	5.69	4.90*
9. Working with the models helps me visualize and interpret other figures and diagrams in the reading and problem sets.	5.45	4.50*

* $p < 0.05$, ** $p < 0.001$, (two-tailed t-test)

Table 3. Comparison of calculus activities feedback survey results for Face-to-Face (F2F) and Online (OL) versions of activities relating to centroids.

Survey Prompt	F19 F2F (N = 42)	W21+Sp21 OL (N=34)
1. The learning goals for each activity were clear.	5.24	5.26
2. The handouts helped me document the main ideas from the lesson.	5.57	4.91*
3. The models helped me communicate with my classmates/professor.	5.48	4.68*
4. The activities helped me clarify the material on moments and center of mass (centroids).	5.40	4.94
5. The models helped me internalize the ideas of moments and center of mass.	5.52	4.79**
6. The "Concept Check" questions helped me test my conceptual understanding.	5.33	4.94
7. The activity handouts helped me connect different representations of the concepts (i.e. figures, diagrams, graphs, notation, equations, written descriptions, etc.)	5.38	5.03
8. The models helped me connect different representations of the concepts (i.e. figures, diagrams, graphs, notation, equations, written descriptions, etc.)	5.50	5.03*
9. Working with the models helps me visualize and interpret other descriptions, figures, and diagrams in the book, quizzes, or problem sets.	5.52	5.00*

* $p < 0.05$, ** $p < 0.001$, (two-tailed t-test)

Table 4. Comparison of calculus activities feedback survey results for Face-to-Face (F2F) and Online (OL) versions of activities relating to volumes (revolution and similar cross-section).

Survey Prompt	F19 F2F (N = 40)	W21 OL (N=15)
1. The learning goals for each activity were clear.	5.5	5.13
2. The handouts helped me document the main ideas from the lesson.	5.68	4.80^{**}
3. The models helped me communicate with my classmates/professor.	5.58	4.73^{*}
4. The activities helped me clarify the material on volumes of revolution or similar cross-sections.	5.48	4.87^{*}
5. The models helped me internalize the ideas of volumes of revolution or similar cross-sections.	5.6	4.67^{*}
6. The "Concept Check" questions helped me test my conceptual understanding.	5.25	4.60
7. The activity handouts helped me connect different representations of the concepts (i.e. figures, diagrams, graphs, notation, equations, written descriptions, etc.)	5.6	5.07^{*}
8. The models helped me connect different representations of the concepts (i.e. figures, diagrams, graphs, notation, equations, written descriptions, etc.)	5.68	4.53^{**}
9. Working with the models helps me visualize and interpret other descriptions, figures, and diagrams in the book, quizzes, or problem sets.	5.6	4.87^{*}

* $p < 0.05$, ** $p < 0.001$, (two-tailed t-test)

We see the same general trend in all four tables. The student reception of the modeling curriculum was generally positive, but less so compared to prior face-to-face implementation with statistically significant differences on three items in the first statics survey (Table 1), seven items on the second statics survey (Table 2), five items in the first calculus survey (Table 3) and seven items in the second calculus survey (Table 4). This difference may be attributable to the general state of stress and dissatisfaction in students trying to learn during the COVID-19 pandemic in general. Some of the difference could also be because students were not generally collaborating in real time and engaged less in productive struggle to internalize the necessary information. There may also be a perceived sense that the models and activities are less useful with less dependence on the models, classmates, and instructor during the initial learning experience as compared to face-to-face implementation practice. Ultimately, the main takeaway from these results is that we likely did not successfully adapt the approach to the online learning environment due to both time constraints and incomplete understanding of what modifications are important.

Conclusions and Recommendation

In conclusions, we reported efforts to adapt parallel curricula using hands-on models in calculus and statics instruction for online learning in the context of the COVID-19 pandemic. We found significant cost reductions in adapting the models that made the approach economically feasible in both courses. Student reception of the models seems to be less positive than it had been in prior implementations in face-to-face courses. The authors see many opportunities to modify the online version to provide more support and scaffolding.

References

[1] E. Davishahl, T. Haskell and L. Singleton, "Engaging STEM Learners with Hands-on Models to Build Representational Competence," in *127th ASEE Annual Conference and Exposition*, Virtual Online, 2020.

[2] E. Davishahl, R. Pearce, T. R. Haskell and K. J. Clarks, "Statics Modeling Kit: Hands-On Learning in the Flipped Classroom," in *2018 ASEE Annual Conference & Exposition*, Salt Lake City, UT, 2018.

[3] E. Davishahl, T. Haskell and L. Singleton, "Feel the Force! An Inquiry-Based Approach to Teaching Free-body Diagrams for Rigid Body Analysis," in *127th ASEE Annual Conference and Exposition*, Virtual Online, 2020.

[4] L. Singleton, E. Davishahl and T. Haskell, "Getting Your Hands Dirty in Integral Calculus," in *127th ASEE Annual Conference and Exposition*, Virtual Online, 2020.