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Teaching Manufacturing Processes Using a Flipped Classroom Model

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Abstract

Manufacturing processes is a key subject in undergraduate engineering curricula, and ideally blends theory with hands-on activities and exposure to manufacturing practice. Therewith, the emergence of scalable, versatile digital learning tools and techniques suggests that manufacturing courses should explore how to maximize the use and value of in-person teaching time. This paper describes the application of a flipped classroom model to undergraduate manufacturing processes courses at the Massachusetts Institute of Technology and the University of Michigan. In the flipped classroom approach, pre-recorded lecture videos are provided to students, and in-class time is used for hands-on activities and/or labs, thereby promoting discussion and interaction among students and staff. Together, the combination of online preparation and in-person learning is designed to: (1) study manufactured products, and relate observations to fundamental principles; (2) encourage formulation of questions based on open-ended topics; (3) practice written, verbal, and graphical communication skills; and (4) build a layered understanding of manufacturing as a complex system that connects process physics to overarching principles of rate, quality, cost, and flexibility. We also share our experiences teaching during the COVID-19 pandemic, which necessitated a balance of remote and in-person learning, and comment on emerging curriculum elements including use of augmented reality.

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1. Introduction

Many mechanical engineering and industrial engineering undergraduate programs offer core and/or elective courses on manufacturing processes. Course pedagogy and curriculum vary in different programs due to the tradition and priority of the department, local and national industry needs, expertise and focus of the instructors, and lab and equipment availability. Yet, the foundational content in lectures on manufacturing processes is similar among most programs. Key manufacturing processes such as machining, casting, metal forming, injection molding, joining, composite processing, and electronic manufacturing, are addressed from both a fundamental and practical perspective. The lectures are typically supplemented with hands-on laboratory exercises, ranging from demonstrations using machine tools to comprehensive team projects. Product disassembly exercises, and in-person factory visits are also invaluable experiences in student learning of manufacturing.

Moreover, manufacturing processes are relevant to all engineering disciplines [1]. Using aerospace engineering as an example, advanced manufacturing processes, such as composite layup, computer numerical control (CNC) machining, and additive manufacturing (AM), are driving the design and performance specifications of structure, propulsion, and other systems in modern aircraft and spacecraft. Yet, it is still uncommon to have a manufacturing course as the technical elective in most aerospace engineering curricula. Similarly, manufacturing provides essential knowledge for materials science and engineering, nuclear engineering, chemical engineering, and most engineering programs. It is advantageous to have modular course content in manufacturing processes that can be tailored to various disciplines while embracing key fundamental principles. Interests in modularity, as well as maximizing class time for hands-on activities and staff-student interaction motivate the use of digital learning to deliver traditional lecture content.

Advances in technology and ideology have unlocked the recent pedagogical innovation of the “flipped classroom” [2]. In a traditional classroom, the majority of classroom time is used for one-way transfer of knowledge through lectures. A flipped classroom employs asynchronous video and practice problems

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as homework prior to the lecture, consequently freeing up classroom time to enable two-way activities [3]. The flipped classroom increases student opportunities for active learning through a number of modes, such as active, group-based problem solving, and coaching at the moment students struggle. Active learning has been demonstrated to increase student performance [4], heightened motivation [5], and may engender greater curiosity and higher dopamine levels, which the science of learning now links to more effective learning [6]. This pedagogy is supported by constructivism, whereby knowledge is not transmitted from teacher to student but constructed within the individual's mind [7]; and social constructivist theory, whereby knowledge is constructed through interactions with others [8]. Thus the flipped classroom may afford the greatest opportunity for effective, relevant learning by incorporating problem-solving that is open-ended, real-world, and collaborative.

In the past year, the use of digital learning in combination with in-person instruction has been explored in teaching two manufacturing processes courses: "Design and Manufacturing II" (2.008) which is the core undergraduate manufacturing course in Mechanical Engineering at the Massachusetts Institute of Technology (MIT), and "Manufacturing Processes" (ME481) at the University of Michigan (U-M). The major goal of this paper is to share our lessons and observations in teaching 2.008 and ME481 in the flipped classroom format, both before and during the COVID-19 pandemic which has added new constraints and opportunities for delivery of online content. In what follows, we describe the flipped classroom pedagogy of MIT 2.008x (Sec. 2), the hybrid learning format of U-M ME481 (Sec. 3), and our reflections from these experiences.

2. Teaching Undergraduate Manufacturing Processes at MIT (2.008)

The MIT Mechanical Engineering course "Design and Manufacturing II" (2.008) focuses on the fundamentals of manufacturing processes, along with hands-on experience whereby the students work in teams to design and manufacture a custom yo-yo toy in quantities of 50-100. The goals of the course are expressed in the following statement from the 2.008 syllabus:

> *"Almost everything around us has been in a factory and was made possible (in part) by innovations in manufacturing processes. 2.008 introduces you to advanced manufacturing, with emphasis on the following intertwined themes: manufacturing processes, equipment and automation, variation and quality, design for manufacturing, and sustainability. We use the videos, examples, Challenges, labs, and deliverables (both individual and team) to build fundamental knowledge and hands-on experience on the methods and challenges of manufacturing, i.e., creating value at scale. A graduate of 2.008 should have the knowledge and confidence to enter an advanced factory and be able to understand its operations and make suggestions for improvement."*

2.008 is required for undergraduates taking the core mechanical engineering curriculum, and is optional for students in the department's flexible option (MIT course '2-A') which allows specialization by substituting some core courses with additional electives. 2.008 is typically taken in the second semester of the junior year, or in the senior year; for students in the core curriculum, it ideally precedes or is taken in parallel with the senior capstone product design course (2.009). 2.008 is a full-semester course with 12 credit units; 1 unit at MIT is nominally equivalent to one hour of time commitment to course-related activities per week. Typical enrollment is 50-70 students each semester, and 120 students each academic year (2 semesters).

Traditionally, 2.008 met twice weekly for lectures, delivered by a faculty member in a slide presentation and/or chalkboard format. In 2015, the course staff began to produce video lectures toward launching an open online course (2.008x in MITx) on edX, a massive online open course (MOOC) provider [9]. The online course was launched first in 2016, independently of the on-campus offering of 2.008, yet the in-person lecture materials (e.g., slides, examples, and assignments) were revised to incorporate new themes and content that were prepared for 2.008x. In preparation for the Fall 2018 semester, the 2.008 faculty decided to explore a flipped classroom format where the 2.008x videos would be published to the class during the week before the corresponding lecture meeting. Then, class time would be used for an in-person activity to be called a "Challenge", in the format discussed later in this paper. To accommodate the Challenge activity, the "lecture" portion of the class met once a week, for a three-hour session.

In addition to the lecture, the students meet (each assigned to one lab section) once weekly in the manufacturing machine shop for a three-hour session focused on the yo-yo project. Each lab session is led by a staff technical instructor and comprises one or two project teams (each 4-5 students). This time is used for hands-on tutorials on equipment, design reviews, and tooling or part production (in addition to the separately scheduled time as needed). The focus of this paper is the lecture and digital/in-person learning experience that is accompanied by the project, and therefore we will not describe the project in further detail here.

2.1. Schedule of the hybrid course

A representative list of weekly lecture/Challenge topics of 2.008 is given in Table 1. Regardless of the lecture format, 2.008 covers unit manufacturing operations as well as system-level considerations, and throughout the semester the topics are united by principles of rate, quality, cost, flexibility, and sustainability. As such, after addressing unit operations and then administering a quiz based on a product that encompasses many of the processes, the class transitions to the system-level topics, and concludes with guest lectures on emerging manufacturing topics and industry experiences. To accommodate the single lecture session per week, select topics were combined, and some were eliminated from the prior sequence. For instance, one week is devoted to sheet forming which includes sheet metal forming and thermoforming of plastics. Yet in the flipped format the videos amply cover equivalent lecture content while the in-class Challenges enable further emphasis of the key learning objectives for each topic. The order of topics is chosen to both build a progression of understanding and to support the lab (yo-yo) project. In this regard, the introductory lecture is followed by machining, and then injection molding; the role of machining in the production of injection mold tooling is emphasized by this sequence.

Table 1. A representative list of weekly topics for MIT 2.008

Week	Topic	Challenge item(s)
1	Process Planning	Hair dryer
2	Machining	iPhone 4 and 6 housings
3	Injection Molding	Fisher-Price Classic See 'n Say
4	Sheet Forming	Plastic coffee lids, aluminum beverage can top
5	Casting	Brass stop valve
6	Additive Manufacturing	Complex geometries made by FFF and SLA printing methods
7	Variation and Quality	Yo-yo body and snap ring made by injection molding
8	Quiz (written or oral)	-
9	Manufacturing Systems	Aluminum beverage cans
10	Robotics	Aluminum beverage cans
11	Sustainability	PVC stop valve
12	Cost	Amazon Fire tablet
13	Electronics	Fisher-Price Classic See 'n Say
14	Manufacturing scale-up	Guest lectures
15	Yo-yo expo	Team final presentations

In a semester with fewer weeks (as was the case in Fall 2020), the manufacturing systems and robotics topics can be combined, with a progression from measuring demand to optimizing production rate to adding automation. Likewise, extracting and evaluating the electronics from the See 'n Say or Amazon Fire tablet (see Table 1) during those lectures provides an avenue to incorporate electronics manufacturing and assembly topics earlier in the semester.

2.2. Recorded lecture videos

For the original 2.008x production, and ultimately in support of the flipped classroom version of 2.008, lecture videos were recorded in a professional studio. Each lecture was divided into 5-10 minute segments, and therefore each topic (week) comprised a series of segments totaling 45-90 minutes. Most videos were recorded in a lightboard style setup (Fig. 1), where the instructor speaks from behind a pane of high-quality glass. The instructor can write directly onto the glass using a fluorescent ink marker, such that the camera captures his/her notes in full view, albeit in mirror image. In post-production, the video is mirrored such that the writing is in plain view, and the instructor's likeness is mirrored. Examples are shown in Fig. 1. The videos are intended for repeated use, i.e., the same videos are distributed each semester. After the course was delivered for two years without changes to the videos, the staff seeks to maintain a routine practice of creating 1-2 new (or revised) lecture videos each semester, such that the content is fully refreshed every ~5 years.

For 2.008x, the staff also configured software enabling slides to be overlaid as translucent images on the video feed, such that the instructor could virtually gesture over the slide content. Further, a document camera accompanied the instructor, such that parts could be shown in detail during the presentation. With some practice, this setup enabled the instructor to both adapt the lecture content and format to the desired short video segments, while preserving key presentation elements from in-person lectures. Also, the computer system produced both individual video feeds from the main camera, document camera, and slide presentation, along with a single composite video feed with the mixed presentation (queued by a script that switched the video feed accordingly during the presentation). The availability of this composite feed significantly reduced video post-production.

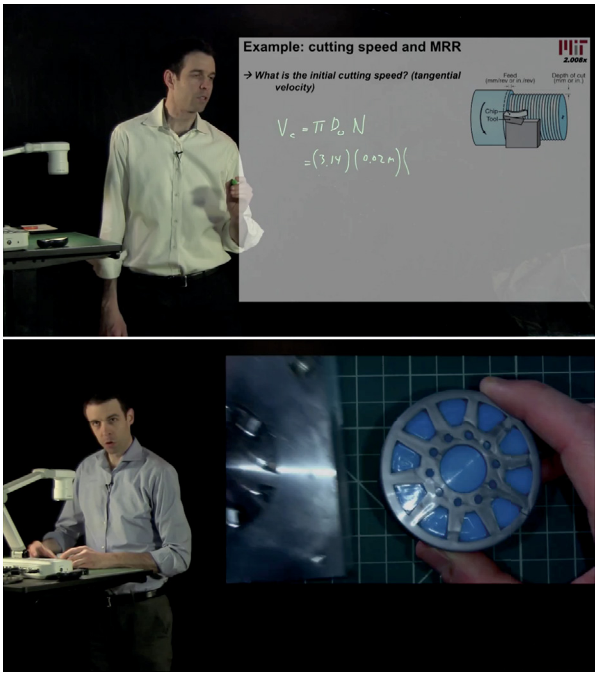

Fig. 1. Screenshots of 2.008x lecture videos taken in a lightboard studio at MIT, which captured real-time composite video feed including projection of slide content and/or part manipulation under document camera.

In addition to the videos, each week's online preparation includes introductory text about the topic, selected images, a list of learning objectives, and recommended readings/references. To demonstrate their understanding, students complete auto-graded "concept checks" after each video; these have been demonstrated in cognitive science to promote subsequent learning and long-term knowledge retention. The concept questions are multiple choice, based on presented text or image-based information that relates directly to points made in the foregoing video segment.

2.3 Flipped classroom "Challenges"

Due to the development of the recorded lecture videos, weekly class time was now available for more interactive activities. The goals were to maximize student engagement during this class period, giving students the most difficult technical questions while they would have easy access to course staff for assistance, and the opportunity to collaborate with one another. An additional goal was to spark students' curiosity about manufactured products and learn to connect the manufacturing processes from the class to real-life items that they encounter.

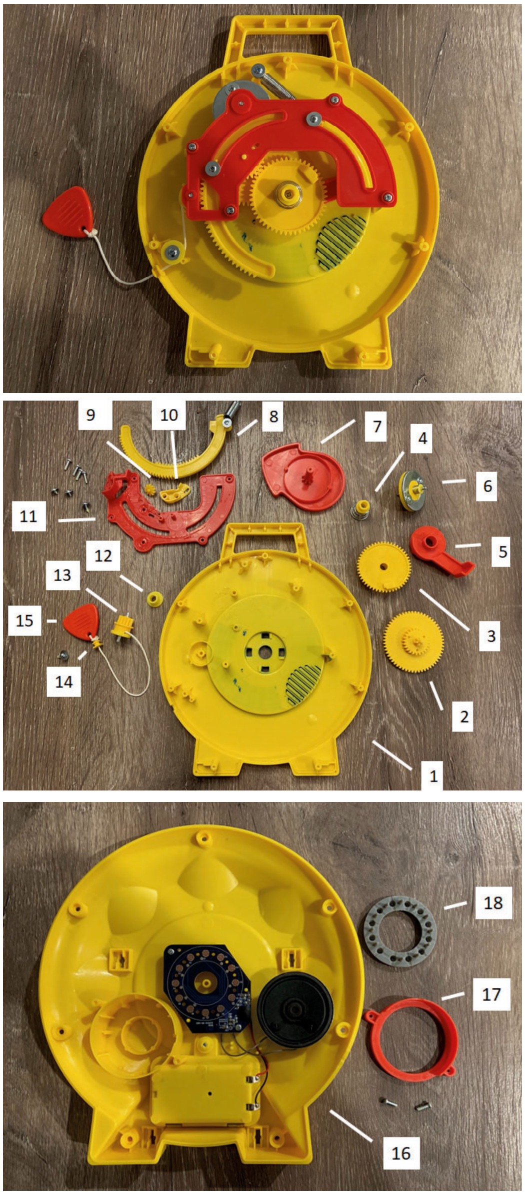

Fig. 2. Example teardown of the Classic See 'n Say by Fisher-Price used for the injection molding Challenge. Students disassemble the toy and analyze the components, and perform calculations on key process variables such as cooling time, injection pressure, and clamping force.

Therefore, it was decided to center each week's manufacturing topic around a physical item or parts in class. During each class session, students are presented with a "Challenge" based around a product or parts. The Challenge is a document of questions similar in depth and length to the previously used homework assignments. However, unlike homework, students are placed in randomly-assigned pairs and given physical parts to solve the Challenge questions together during class. Each student writes up their answer, so the students don't have to agree on the solution that they submit, and can express answers in their own words and calculations. Students have the three-hour class session to work on the Challenge and it is due at the end of class. The students are encouraged to ask the course staff if they are confused or get stuck on a question. The staff seeks to mitigate student stress about answering the Challenge questions and are available in person for the duration of the session. The Challenges are designed, and expectations are set such that, grading is on an integer scale of 1-5. A grade of 4 points is considered full credit, and while there is a distribution of performance among the pairs of students, the staff intends for most students to earn full credit. These expectations, in the staff's experience, reduce the stress level on the students, and encourage them to collaborate and ask questions throughout the session.

The Challenge objects (Table 1) play a large role in the success of the flipped classroom model. Products start fully-assembled and students inspect, analyze, and/or disassemble them through the Challenge. Some examples of disassembled items are the Fisher-Price Classic See 'n Say (Fig. 2), and pipe stop valves (Fig. 3,4). Some of the items are provided to the students as received (enabling the students to disassemble, per the Challenge instructions), and others are modified by the staff (such as the brass ball valve, which is cut in half).

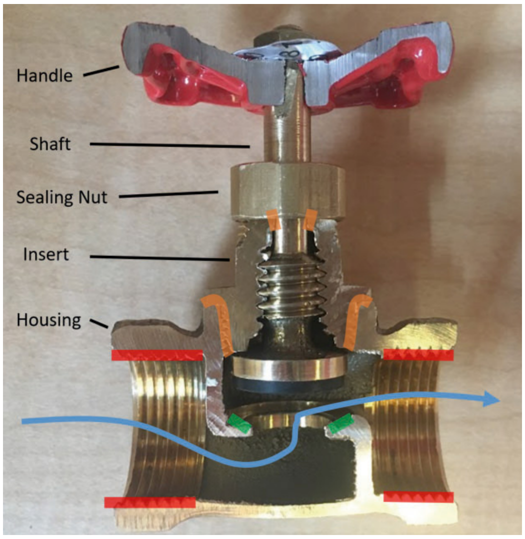

Fig. 3. Cross-sectioned brass valve provided to the students for the casting Challenge.

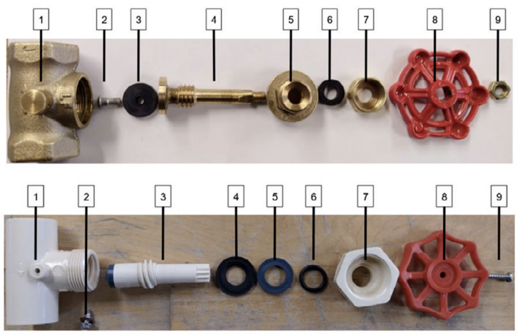

Fig. 4. Comparison of brass and polymer valves used for the sustainability Challenge.

The COVID-19 pandemic necessitated some changes to the Challenges in Fall 2020, namely that students could not share items and could not be physically together in the same classroom (as labs were in person, but lectures were remote regardless of the student's location). Therefore, packages of Challenge materials were shipped to each student at the start of the semester. The students were paired online in Zoom breakout rooms and course staff circulated through the breakout rooms to answer questions and discuss the Challenge with students.

2.4. Evaluation

The class is evaluated based on the pre-lecture questions (5% total), the in-class challenges (25% total), one quiz (15%), the yo-yo project (50%), and in-class participation (5%). The exam is given individually during a three-hour session, and typically relates to one or more manufactured products comprising components made by multiple processes studied in 2.008. While a statistical comparison of student performance is not straightforward due to the differences in assessments, student scores on the quiz during flipped classroom semesters are higher than prior semesters taught in the conventional lecture format. The students also provided very positive feedback on the flipped classroom format during end of semester evaluations; in Fig. 5 the aggregate responses from Fall 2018 are shown. Fall 2017 was the first flipped classroom semester of 2.008.

2.008 SPECIAL QUESTIONS — Rating Scale: 1=Strongly Disagree, 7=Strongly Agree, N/A=Not Applicable (7 is best)

	AVG	1 2 3 4 5 6 7	RESPONSES	MEDIAN	STDEV
Compared to traditional class format (lecture follwed by at-home problem sets), I preferred this semester's format of 2.008	6.4		39	7.0	1.21
Compared to a traditional class format, I spent less time doing the pre-lecture material (videos and questions) than I would have expected to spend on problem sets and class preparation (combined).	6.3		39	7.0	0.99
Compared to a traditional class format, I felt there was more time to ask questions in this semester's format.	6.3		39	7.0	1.15
I felt comfortable asking questions during the challanges.	6.7		39	7.0	0.58
I learned important real-world manufacturing details from the challanges.	6.4		39	7.0	0.93
The videos and pre-class questions prepared me well to complete the in-class challenges.	5.8		38	6.0	1.55
The time spent on challenges in class could have been better spent on more lecture content.	2.8		39	3.0	1.7

Fig. 5. End-of-term student responses to course evaluation questions comparing flipped classroom format to traditional lecture format. Note that the students did not participate in the traditional lecture format, so comparisons are hypothetical, and/or based on experiences in other lecture-based courses.

2.5 Augmented and Virtual Reality Enhanced Learning

Manufactured products of pedagogical interest may not be available for students due to practical issues of availability, size, safety, distance, or costs. For example, it would be difficult or prohibitive to carry out a Challenge activity for windmill turbine blades, a radioactive part in a nuclear reactor, or a Macbook pro. Educational contexts such as COVID-forced distance education or a MOOC also limit or prevent the delivery of physical products to students. To address this, an Augmented Reality (AR) application is being developed to disassemble and examine any manufactured product in virtual space. The app enables the measurement and disassembly of 3D photo-realistic reconstructions of products such as a consumer electronics tablet (Fig. 6). In addition, virtual reality tours are being developed to offer the manufacturing students an immersive and educational experience when it is not possible to tour factories in person.

Fig. 6. MIT-developed augmented reality (AR) app enables measurement and disassembly of 3D photo-realistic reconstructions of products such as a consumer electronics tablet.

3. U-M ME481 Manufacturing Processes

Three key elements of the three credit-hour ME481 course at the University of Michigan are the lecture, project, and lab. The typical enrollment of ME481 is about 50 students. These elements are interwoven and complement one another to enhance the student learning of manufacturing processes.

3.1. Lecture: topics, delivery, quiz, homework, and discussion

Lectures provide fundamental knowledge and define the scope of manufacturing processes in ME481. The required and supplemental lectures for U-M ME481 as well as the duration of each lecture are listed in Table 2. In Winter 2021, ME481 is designed to have 12 required lectures. All lectures have a set of slide presentations and are recorded in advance. Students need to watch the lecture and take a quiz before the 80 min discussion/activity session during the scheduled class time. Each lecture also has an associated homework. An 80 min help session is designated for each homework, which is due at the end of this help session. A teaching assistant (TA) is staffed in every homework help session to assist students who may have questions working on the homework. This homework help session is designed for two purposes. First, it gives students dedicated time (with TA assistance) to focus on their homework and learning of the lecture material. Second, it alleviates the perception of overloading in online courses. Many students have completed the homework before the scheduled class time and do not need to attend the homework help session. Compared to past offerings of ME481, lectures in machine tools, and manufacturing of integrated circuits (IC), microelectromechanical systems (MEMS), and printed circuit boards (PCB) have been added. Coverage of additive manufacturing has been expanded. Manufacturing of gears, Li-ion batteries, and electric motors and generators have been added as optional lectures. Casting processes were not covered but will be added in the future.

Table 2. Lectures and duration in U-M ME481

Lecture	Topic	Min
Required		
1	Course overview and advanced manufacturing processes for competitiveness and national security	80
2	Work-materials	160
3	Tool-materials	80
4	Machine tools	160

5	Programming of computer numerical control machines and industrial robots and the simulation	80
6-1	Machining I – Turning, milling	160
6-2	Machining II – Drilling, grinding, nontraditional	160
7	IC, MEMS, and PCB manufacturing	200
8	Plastic and composite manufacturing	160
9	Metal forming	160
10	Additive manufacturing	240
11	Joining	160
12	Tour of Protomatic (a local manufacturing shop at Dexter, MI)	60
Supplemental – Advanced products		
1	Gear manufacturing	80
2	Li-ion battery manufacturing	40
3	Electric motor and generator manufacturing	40
4	IoT in manufacturing processes in production	40
5	Medical device manufacturing	--
Supplemental – Processes		
6	Casting	--
7	Powder material processing	--
8	Automation in manufacturing processes	--

As such, the ME481 class is scheduled to have two 80 min sessions every week. Typically, in each week one 80 min session will be the discussion/activity of a lecture topic and the other 80 min will be the homework help session from the topic of the previous week. This gives students time to study and work on the homework after the discussion/activity session. The lecture slides, quizzes, lecture recordings, homework, and slides from the discussion/activity sessions are available to manufacturing instructors at other institutions by contacting the UMich authors.

Table 3. Summary of seven class discussion and activity sessions and homework in U-M ME481

Lec.	Topic for Class Discussions and Activities	Homework
1	Manufacturing and national security: The failure of US manufacturing in 2020 coronavirus pandemic on the shortage of N95 respirator	Watch the testimony of Mike Bowen on the Coronavirus pandemic response in a US House Subcommittee.
2 and 3	Work- and tool-materials: Tesla's Giga Press – the large aluminum die casting machine – and structural battery for Model Y production.	Reverse engineering to find the work- and tool-materials for Tesla's aluminum die casting and structural battery in new Model Y chassis manufacturing.
4	Machine tools: DJI drone as a machine with structure/base, bearing, sensor, motor, computer control, cooling, etc.	Identify and photo six key elements of machine tools (base, guideway, drive, sensor, spindle, and fluid delivery/tooling) in three machines in the lab.
5	Industrial robots: The evolution of automation and simulation of industry robot toolpath	ABB IRB140 programming: Simulation of the toolpath to draw a block "M" logo.
6-1	Machining I – Turning, milling: Large telescope lens manufacturing. Active optics and machining of advanced surface for telescope lens.	Single point turning, face milling, and end milling model-based process analysis and design.
6-2	Machining II: Gear manufacturing and powertrain of electric vehicles.	Drilling and grinding model-based process analysis and design.
7	IC, MEMS, and PCB manufacturing: Intel dilemma and the importance of IC manufacturing in the US.	IC, MEMS, and PCB manufacturing model-based process analysis and design.
8	Plastic and composite manufacturing: Thermoplastic carbon fiber composite for aerospace.	Plastic manufacturing model-based process analysis and design.
9	Metal forming: Ford F150 aluminum frame and high strength steel chassis light-weighting.	Metal forming model-based process analysis and design.
10	AM: Myths in AM and why there is no AM component in DJI drones.	AM model-based process analysis and design.
11	Joining: SpaceX stainless steel welding for the Starship.	Joining model-based process analysis and design.

The lecture topics and sequences are selected based on the project (DJI drone disassembly and reverse engineering) and the lab schedule. These 12 lectures can be divided into two categories: foundation and unit process. Six foundation topics are: advanced manufacturing processes for competitiveness and national security, work- material, tool-materials, machine tools, programming of computer numerical control (CNC) machines, and tour of the manufacturing factory (Lectures 1-5 and 12). The six-unit processes covered are: 1) machining; 2) integrated circuit (IC), microelectromechanical system (MEMS), and printed circuit board (PCB) manufacturing; 3) plastic and composite manufacturing, 4) metal forming, 5) additive manufacturing, and 6) joining.

Four supplemental lectures on advanced products have been prepared for students to gain knowledge in advanced manufacturing of key components of the DJI drone for their project. These four advanced product lectures are in gear manufacturing, Li-ion battery manufacturing, electrical motor and generator manufacturing, and Internet-of-Things (IoT) in manufacturing processes in production.

This list of lectures is not complete and will be expanded and refined. The ME481 staff plans to add lectures on three-unit processes: casting, powder material processing (including metal, ceramic and plastic powders), and integration of automation in manufacturing processes. A medical device manufacturing lecture will be added for a future project on medical devices.

The topic of eight discussion/activity sessions during the lecture and the related homework are listed in Table 3. An advanced or recent topic related to the corresponding manufacturing process is presented and discussed during the discussion/activity session. For online discussion sessions, we have learned that the "break out" room is critical. Students are more open and engaged in small 4-5 student breakout rooms for a 10-15 min discussion. All small groups then reconvene to report to the whole class. The selection of these topics is important to spur the discussion and show the impact and application of a specific manufacturing process.

Fig. 6. Screenshots of ME481 lecture video with the instructor demonstrating physical parts.

Video enriched pedagogy [10] has been utilized throughout all lectures to enhance the student learning in manufacturing processes. The video library has been shared with manufacturing instructors from several other universities and is available by contacting the authors.

Students have good feedback on the Panopto video platform (Seattle, WA) for viewing lecture recordings. Two screenshots of the lecture recording with the instructor showing an Apple MacBook Pro aluminum keyboard case machined using the multi-point cutting are illustrated in Fig. 7. Students can see the video and the camera view of the instructor. A close-up view of the part is available from the overhead video camera to focus on details of the part for better illustration. It is also common that students will watch the lecture recording at 1.5 times the regular speed to save time.

3.2. Lab

ME481 has three in-person labs:

- Lab #1: Disassembly and assembly of a DJI Spark quadcopter drone (as part of the term project);
- Lab #2: identifying key machine tool components (as part of Homework 4 on machine tools); and
- Lab #3: programming the ABB IRB 140 robot to draw a block M logo.

Due to COVID-19, the in-person lab was minimized. Students came to the lab as a team (with 4 to 5 students per team) and completed all three labs in about 2 to 3 hours. This was the only in-person meeting throughout the whole semester. The session was scheduled after Lecture #5 (Programming of computer numerical control machines and industrial robots and simulation). The lab time was arranged to avoid overcrowding. All students in the lab were required to practice social distancing, wear a mask, wash their hands before the lab, and disinfect all contact surfaces after use.

In Lab #1, five DJI Spark drones were available in five separate working stations with social distancing for each member of the student team to disassemble and assemble. Each student had a drone and needed to follow an instructional video to disassemble the drone. Together as a team, each member identified a drone component and applied what they learned in ME481 to study the manufacturing processes and supply chain (to be discussed in the following section). Every student needed to reassemble the drone following the instructional video.

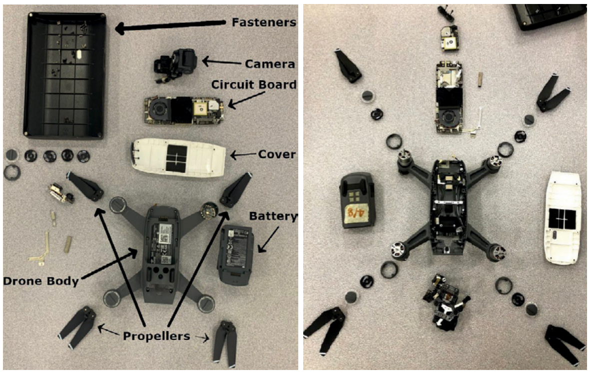

Fig. 8. (a) The disassembled DJI Spark drone and key components; (b) DJI Spark disassembly with exploded view.

The DJI Spark drone was selected because it has all the key components covered in lectures (with the exception of additive manufacturing). As shown in Fig. 8, the DJI Spark drone has four permanent magnet DC brushless motors, four plastic propellers, a camera with a gimbal to control the orientation, a light-emitting diode, a lot of plastic injection moulded parts, a Li-polymer battery, metal brackets, and fasteners for fixation, and a compact well-designed PCB with many IC chips (for computing, control, GPS, communication, etc.), and cooling fans for thermal management. These components made of metal, plastic, ceramic, and composite work-materials provide a great learning opportunity for students in this lab and in their term project.

Most students taking ME481 have performed well academically but previously did not have the opportunity nor experience for this type of hands-on lab to disassemble an expensive (about $350) and complex machine like the DJI Spark drone. This lab gave engineering students not only the opportunity but also the courage and confidence in the future to perform this type of hands-on exploration of a machine.

In Lab #2, students identify and photograph six elements (base, guideway, actuator/drive, sensor/control, spindle/workhead, and fluid delivery/tooling) of three machine tools in the lab. This lab allows students to practically see and identify real machine tool elements and apply what they learned in the lecture.

In Lab #3, students program an industrial robot (ABB IRB 140) to use a pen at the tip of the 6-axis robot to draw a block "M" logo (representing the University of Michigan) as shown in Fig. 9. The student team learns the programming of the ABB robot as well as the basic use of simulation software called RobotStudio (a free download from ABB). Before coming to the lab, each student team is required to test their toolpath using RobotStudio and show their results to the TA. During the lab, the student team loads their program, calibrates the ABB robot, and runs the program.

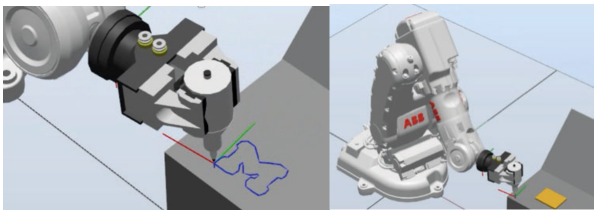

Fig. 9. (a) Simulation of the robot motion; (b) close-up view of the simulation to draw a block M before Lab #3.

(a) Overview of the DJI Spark drone and four selected parts

(b) Propeller blade

(c) Camera glass cover

(d) Propeller mounting plate

(e) LED cover mount

Fig. 10. The DJI drone and four selected components.

3.3. Project

A term project is assigned for each student team to select a part in the DJI Spark quadcopter drone and reverse engineer to identify manufacturing processes across the supply chain of this drone component. In Lab #1, the team members work together to select different components, one for each team member, for reverse engineering. For example, as shown in Fig. 10, four team members selected four components, the propeller blade, camera glass cover, propeller mounting plate, and LED cover mount.

For each selected component, students need to apply the reverse engineering technique to identify: 1) most-likely work-materials of the component and explain why this material is selected, 2) manufacturing processes for Tier 1, Tier 2, Tier 3, … suppliers (trace as deep as possible), and 3) tool-materials used in manufacturing processes in Tier 1, Tier 2, Tier 3, … suppliers. Students are allowed to help each other and learn together as a team. However, each student is responsible for one component. During the semester, the instructor meets with each team to review their preliminary findings and advise the possible work- and tool-materials and supply chain. Each team submits a report at the end of the semester.

3.4. Evaluation

The class is evaluated based on two mid-term exams (25% each), homework (25%), project (15%), and quizzes and participation (10%). Two 80 min mid-term exams were delivered online with five versions of the exam problem set – a different version for each team member. Each version of the exam arranged exam problems in a different order and slightly adjusted the number of exam problems. This exam set was prepared to deter students from cheating in online exams by communicating and exchanging the solution with each other.

The student evaluation of the flipped classroom was generally positive. Figure 11 shows the responses by 11 students who filled out the U-M standard at the end of the semester. The score is generally better than the U-M university-wide median on key questions. Students also provide some constructive comments. One positive comment was: "I feel that I don't typically learn well in online learning, but this class was an exception, I feel that I learned a lot in this course." The other comment was: "In-person format with discussions worked much better for me than the online portions. There were times when watching 2–3 hours of lecture was required before a class when I did not have that time to devote. I would have preferred a more spread-out approach to quizzing …" Thus, there is still room for improvement, such as spreading the quiz questions as well as improving student participation in ME481.

	SA	A	N	D	SD	N/A	Your Median	Univ-wide Median	School/College Median
This course advanced my understanding of the subject matter. (Q1631)	7	3	0	0	0	0	4.8	4.6	4.5
My interest in the subject has increased because of this course. (Q1632)	5	5	1	0	0	0	4.4	4.2	4.2
I knew what was expected of me in this course.(Q1633)	6	3	2	0	0	0	4.6	4.5	4.4
Overall, this was an excellent course.(Q1)	9	0	1	0	0	0	4.9	4.4	4.3
I had a strong desire to take this course.(Q4)	5	4	2	0	0	0	4.4	4.1	4.1
As compared with other courses of equal credit, the workload for this course was (SA=Much Lighter, A=Lighter, N=Typical, D=Heavier, SD=Much Heavier). (Q891)	0	3	7	1	0	0	3.1	2.9	2.8
How did you participate in this course? (Q1854)	4	5	0	2	0	0	4.2	4.7	4.5

Fig. 11. Student evaluation responses to the U-M University-wide questions about ME481.

4. Modifications for Remote Learning during COVID-19

In MIT 2.008, the flipped classroom architecture enabled fast response when COVID-19 moved most education online in Spring 2020. Within just one week, the staff collected all upcoming parts for Challenge into boxed kits that were mailed to each remote student (Fig. 12). Careful tracking of each part ensured a record throughout the rest of the semester that maintained customization for each student's experience.

The flipped classroom also allows staff to monitor the level of preparation and engagement from each student both before and during the lecture. Panopto video analytics show the level of engagement throughout the lecture video along with when students exited or rewatched, enabling a feedback loop for continuous improvement. This can be helpful to diagnose issues before they become systemic or identify students that need extra support. Also, the staff take notes based on their conversations with students in the online breakout rooms, and combine their feedback to refine the Challenges. As the students collaborate with a new partner each week, it is possible to assess individual contributions both from direct discussion and based on the Challenge scores.

The flipped classroom also lends itself well to merging the undergraduate and graduate manufacturing curriculum. This was taken as an experiment in Fall 2020. Graduate students were asked to complete an extension of the Challenge (after class time), which is typically centered around manipulating a spreadsheet to perform additional analysis. This approach enables interested graduate students to go above and beyond the prompts and test their intuition quickly if desired, especially if they have a particular interest or expertise in that subject. One difficulty with combining undergraduate and graduate students though is the standardization of grades and workload, especially when some weeks are less exhaustive in undergraduate preparation material than others. A further goal for the teaching staff for the upcoming semesters is to use CAD models of each Challenge item and relevant software (Moldflow Advisor, Fusion, MasterCam, PreForm) to incorporate simulation results into the Challenges, to complement first-order calculations that the students performed in lecture.

Fig. 12. Sets of injection molded yo-yo components made for each student upon interruption of the Spring 2020 semester, and boxes with items for Challenges ready for shipment to students at the beginning of Fall 2020.

At U-M, learning from the flipped classroom experience and lecture materials of MIT 2.008, ME481 was converted to a flipped classroom in the Winter 2020 term with all online lectures, one in-person three-hour section for three labs, and discussion sessions during the class time. The approach was successful with positive feedback from both on-campus and online students. The in-person labs were safe for all attendees. Students who could not attend the lab had a good online learning experience with the help and mutual learning with teammates. Such interaction with teammates is critical for the online students' learning experience. It also alleviates the burden on course instructors to teach the lab to each online student. More importantly, this collaboration between MIT and U-M demonstrated the benefits of manufacturing education partnership.

5. Conclusions

This paper summarized the flipped classroom pedagogy in two courses on manufacturing processes at MIT and U-M. The flipped classroom pedagogy can be adapted to classes of different sizes and budgets. Moreover, when a class has a very large number of students and/or heavily limited resources, the requirements for the project can be reduced and digital materials (which have almost no variable cost) can be used to scale the interactive experience. The manufactured items used in the MIT Challenges and U-M projects can be chosen based on cost constraints, or even discarded products and components could be selected by individual students. The modular lecture materials, video of the lecture, and design and content of the challenges in MIT 2.008 and discussion session in U-M ME481 are available to any manufacturing instructors upon request. We also are exploring the possibility of publishing an electronic textbook to accompany our course materials and broaden access to manufacturing fundamentals.

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