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Supporting Nanoscale Innovators to Achieve Macro Impact: A Course on Innovation and Entrepreneurship in a Nanoscience Makerspace for Undergraduate Students

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Dr. Charleson S Bell, Vanderbilt University

Charleson Bell, PhD, overseeing the domain of Innovation, Enterprise, and Economic Development in the Vanderbilt Office of the Vice Provost of Research and Innovation, is a recognized leader administering the establishment of an innovation ecosystem across the Mid-South that will galvanize an innovation economy to impart shared prosperity across the region. Dr. Bell is the Hub Director of the NSF Mid-South I-Corps Hub and co-PI & State Director of the NIH Mid-South Research, Evaluation and Commercialization Hub, both led by Vanderbilt University. Dr. Bell is also the Director of the Coalition Responsible for Equitable Skills Training (CREST) & Pl of the NSF ExLENT workforce development award that launched the coalition. Dr. Bell, Research Assistant Professor of Biomedical Engineering, Associate Director of the Medical Innovators Development Program in the Vanderbilt School of Medicine, former Director of Entrepreneurship and Biomedical Innovation at the Wond'ry, Vanderbilt's Center for Innovation, is a parallel innovator, 3x serial entrepreneur, 10x published researcher, and 3x patented inventor with over a decade of experience launching ventures and developing new products. Dr. Bell is a 'triple-Dore', earning his undergraduate and graduate degrees in Biomedical Engineering from Vanderbilt University (BE'07, MS'09, PhD'15). The first graduate student at Vanderbilt to receive an investment of venture capital to launch a startup, Dr. Bell uses his innovative mind to combine his engineering knowledge to create novel technologies of great impact. He is a much-respected champion in the pursuit of shared prosperity, creating an innovation culture that cultivates a sense of kindred rapport for all instructors, innovators, participants, and founders. Most importantly, Dr. Bell is a staunch believer that the value and practice of convergent innovation is critical to optimize the way innovators empathize with humanity and ideate solutions that create positive change across the world via financially sustainable business models.

Mrs. Deanna Meador, Vanderbilt University

Deanna Meador is CEO of tech company Couture Technologies, as well as the co-founder of edtech company CHALK Coaching. She is also the lead instructor for the Mid-South I-Corps Hub at Vanderbilt University. Deanna was part of the founding team that started the Wond'ry, Vanderbilt University's Innovation Center. Through her role as the former Deputy Director, she taught over 17 cohorts of aspiring entrepreneurs and mentored over 600 teams as they evaluated new technologies and launched new ventures. She is a certified national instructor for the National Science Foundation's I-Corps program and in this role, she leads entrepreneurial training cohorts for teams from across the country. Deanna really enjoys working with creators, inventors, and entrepreneurs that dedicate their lives and talents to making a positive impact in the world.

Christopher Harris, Vanderbilt University

Chris Harris joined the Center for Technology Transfer and Commercialization (CTTC) in October 2011 and is responsible for leading all licensing activities. Prior to joining CTTC, Chris was the Associate Director for Licensing at the National Renewable Energy Laboratory in Golden, Colorado where he managed a team of licensing executives. He was also previously the Senior Licensing Manager at the University of Virginia Patent Foundation.

Chris received his doctorate in nuclear physics from the University of Virginia in 2001. In 2003, he became a registered U.S. Patent Agent and in 2008 he became a Certified Licensing Professional. He is also an active member of the Association of University Technology Managers and helped create and manage the AUTM TransACT database for deal comps. Chris also provides guest lectures for entrepreneurship classes at Vanderbilt.

Prior to his graduate school career, Chris worked as a software design engineer for Martin Marietta in King of Prussia, Pa. where he helped design command and control type software for a classified contract.

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Yiorgos is a Professor and Director of the Engineering Science and Management program in the School of Engineering at Vanderbilt University in Nashville, Tennessee. His background combines experience in the semiconductor industry, academic technology transfer, and scientific research. Over the course of his career, he has successfully launched numerous products in the semiconductor industry and led market expansion efforts for various product lines in global markets. He received his PhD from the University of Rochester and his MBA from Boston College.

Dr. Kevin Galloway, Vanderbilt University

Dr. Galloway is a Research Associate Professor in the Mechanical Engineering Department at Vanderbilt University, also holding the positions of Director of Making at the Wond'ry, Vanderbilt's innovation center, and serves on the Advisory and Leadership Council in Vanderbilt's Institute of National Security. He completed his B.S., M.S., and Ph.D. in Mechanical Engineering at the University of Pennsylvania.

Through extensive project involvement and collaborations, Dr. Galloway has cultivated a diverse skill set encompassing mechanical design, materials science, advanced manufacturing, bioinspired design, human-centered design, robotics (i.e., legged robotics, micro-flapping robotics, and soft robotics), and medical devices. His work has been funded by NSF, ARL, AFRL, DARPA, NAVSEA, and the National Geographic Society and has resulted in 17 patents and 8 technology licenses to date.

Dr. Philippe M. Fauchet, Vanderbilt University

Philippe Fauchet has more than 40 years of experience in silicon photonics, nanoscience and nanotechnology with silicon quantum dots, biosensors, electroluminescent materials and devices, and optical diagnostics. He is an elected Fellow of the Optical Society of America, the American Physical Society, the Materials Research Society, the Institute of Electrical and Electronic Engineering, the International Society for Optical Engineering (SPIE), the American Association for the Advancement of Science, the National Academy of Inventors. He served on various boards for industrial and governmental entities. Fauchet holds numerous patents and has founded one successful startup. He served as the dean of the Vanderbilt University School of Engineering from 2012 to 2023, as the chair of the ECE department at the University of Rochester for 8 years, and as the founding director of two large, multidisciplinary research centers. His degrees are from Faculte Polytechnique de Mons in Belgium, Brown University, and Stanford University. He taught at Stanford, Princeton, Rochester and now Vanderbilt.

Dr. David A. Owens, School of Engineering, Vanderbilt University

Dr. Owens serves as the Evans Family Executive Director of The Wond'ry, Vanderbilt's Innovation Center. He is Professor of the Practice of Innovation in Vanderbilt's School of Management and in the department of Engineering Management. Owens received his PhD in Management Science and Engineering at Stanford University where he also earned his BS in electrical engineering and MS in Mechanical Engineering / Product Design. A Registered Professional Electrical Engineer, Owens also has significant industry senior leadership experience. His academic work takes a cross-disciplinary perspective on the organizational behavior of innovation.

Dr. Sharon M. Weiss, Vanderbilt University

Sharon Weiss is a Cornelius Vanderbilt Chair in Engineering and Professor of Electrical and Computer Engineering, Physics, and Materials Science at Vanderbilt University. She also serves as Director of the Vanderbilt Institute of Nanoscale Science and Engineering. Her research group primarily focuses on silicon photonics for optical communication/datacom and optical biosensing.

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Introduction

The incorporation of the innovation mindset, along with an increased appreciation for design thinking, creativity, and problem-based learning opportunities sparked the university makerspace trend that began in the late 1990s. As this trend has continued to gain momentum, entrepreneurship and the role of making in entrepreneurial activities added further fuel to this movement. A census conducted in 2018 and 2019 of 784 public U.S. institutions of higher education found that 214 institutions had at least one makerspace and an additional 31 institutions were planning to build their first makerspace [1].

As scientists and engineers work to solve societal grand challenges in energy, sustainability, and medicine, it has become increasingly clear that nanotechnology advances will be extremely important. From the recent developments in COVID-19 rapid diagnostic tests [2] to the promise of new technology emerging from the CHIPS and Science Act [3], nanotechnology is poised to continue playing a critical role in our lives. However, when it comes to training the workforce of the future to solve these global challenges, most universities are not providing makerspace and entrepreneurial experiences in nanotechnology. The typical makerspace has tools such as 3D printers, laser cutters, and soldering irons [1] while a nanotechnology makerspace requires specialized nanofabrication and characterization equipment that is typically found in a cleanroom, a space with very few airborne particulates. Despite more than 125 universities in the United States having a cleanroom [4], only a small fraction of the undergraduate population at these universities has the opportunity to work in a cleanroom for research or for a course, and almost none are given an opportunity to combine entrepreneurship and innovation with nanotechnology in the cleanroom.

We developed a team-taught undergraduate course, “Nanoscale Innovation and Making”, at Vanderbilt University to address the need to train students to be the next generation of innovators who are prepared to solve societal grand challenges by applying nanotechnology solutions. This course provides a unique opportunity for students to learn about the commercialization process while gaining access to a state-of-the-art cleanroom and additional nano-makerspace facilities. Here, we discuss a blueprint for “Nanoscale Innovation and Making” and share lessons learned.

Course Goals

In “Nanoscale Innovation and Making”, students learn and apply nanotechnology, entrepreneurship, and business strategy concepts and they work in a nano-makerspace that includes a research-grade cleanroom and nanoscience analytical laboratory. Students identify a pain point that nanotechnology can solve, use nano-makerspace tools to make a prototype with a specific customer segment in mind, articulate why their solution would add value to society, and deliver a product pitch to investors and entrepreneurs at the end of the course. The course goals are:

1) Students will gain an understanding of the impact of nano- and microtechnology on society.

2) Students will learn how to solve problems using nanotechnology and will build a prototype product using nanofabrication tools. Example prototypes are shown in Figure 1.
3) Students will learn how technologies transition from the research laboratory to the marketplace.

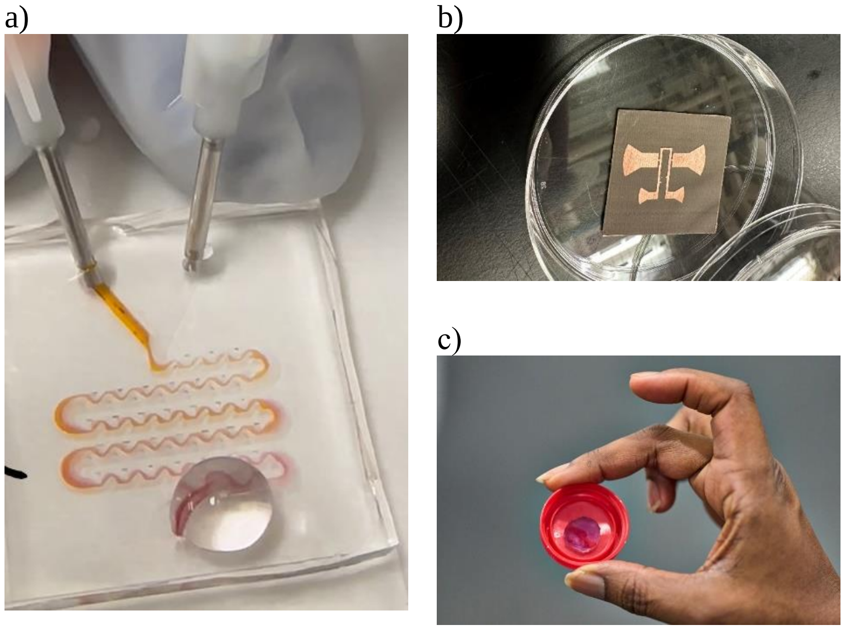

Figure 1: Subset of student project prototypes showing a) colorimetric detection of trace lead in drinking water, b) antennas to tag space junk for detection, and c) colorimetric food freshness sensor for raw milk.

Course Structure and Schedule

The current week-by-week course schedule is shown in Table 1. The course meets twice a week for two-hour sessions for a total of 14 weeks. This course has no prerequisite courses or restrictions on majors, with the only eligibility requirement is that students are sophomores or above. The course is capped at 15 students per offering to ensure an optimal student experience in the cleanroom portions of the course. Additional detail on this constraint is provided in the section “Facilities and Logistics” below. “This course was taught three times to date with 31 total students in engineering and non-engineering disciplines. The engineering disciplines include computer science, electrical and computer engineering, engineering science, mechanical engineering, and biomedical engineering. Students outside of engineering include areas such as: medicine health and society, cognitive studies, physics, applied math, chemistry, and piano. The gender breakdown to date is 32% women / 68% men. The class year breakdown to date is 42% sophomores / 42% juniors / 16% seniors.

Each class is taught by the member(s) of the instructional team with relevant experience. Content in the first six weeks is focused on a curated mix of introductory nano- and microtechnology, innovation, and entrepreneurship concepts as well as lab experiences to give the students the necessary base knowledge to ideate and assess the initial feasibility of team project ideas. The students choose teams and which project ideas to carry forward in week seven. In the second half of the course, students apply this knowledge and new content to their selected student-ideated projects. The course culminates in the students pitching their products with a prototype and pitch deck to investors and entrepreneurs associated with the Wond'ry, Vanderbilt University's innovation center.

Table 1: Weekly course schedule

Week #	Topics
1	Introduction to course and instructors, case study with nanoscience entrepreneur (I)
2	Overview of nano-makerspace and nano/micro fabrication, introduction to business model canvas (BMC) and customer discovery
3	Background on structured labs in nano-makerspace, intellectual property strategy
4	Structured lab in nano-makerspace (I), case study with nanoscience entrepreneur (II)
5	Structured lab in nano-makerspace (II), team management, project idea brainstorming
6	Structured lab in nano-makerspace (III), computer-aided design
7	Project selection, identifying project value proposition and customer segment, project BMC check-in, identifying project prototype fabrication approach
8	Market landscape and customer relationships for project, library databases and ChatGPT
9	Storytelling, project BMC check-in, student-led product prototyping in nano-makerspace (I)
10	Channels + key partners + key activities + key resources for project planning, student-led product prototyping in nano-makerspace (II)
11	Intellectual property workshop for project, student-led product prototyping in nano-makerspace (III)
12	Pitching, student-led product prototyping in nano-makerspace (IV)
13	Project progress check-in, practice product pitch
14	Finalize project and last questions, final group product pitches to entrepreneurs

The instructional team has modified the course schedule and content over the three iterations of the course to improve the student experience and deliver the most critical content towards the goals of the course at the times most useful for the students over the duration of the semester. We removed two of the initially four case studies and replaced these with an intellectual property (IP) workshop dedicated to IP for the students' projects as well as a class on library databases and ChatGPT as entrepreneurial research sources. This enabled the instructional team to teach more entrepreneurship and IP concepts earlier in the semester which yielded a better mix between nanoscience, case studies, and these concepts before project selection. We replaced one structured lab with specific class time for students to discuss their possible prototype fabrication approaches with the relevant members of the instructional team. We removed two of the initially three computer-aided design (CAD) classes, moved the remaining CAD class to when students were doing project design work, and replaced the classes with a full class period for practice pitches including instructor feedback and with BMC check-ins to better prepare the students for their final product pitches.

Managing a Massively Co-taught Course

A key challenge and opportunity for this course is selecting and managing the instructional team. At our university, we taught the course with a lead instructor and seven co-instructors to minimize the time commitment of each co-instructor and maximize the overlap between each instructor's expertise and the class(es) they taught. Fewer co-instructors, each with more responsibility in the course, could also be used. At our university, only the lead instructor was a tenured faculty member and the co-authors were subject matter experts in the Vanderbilt Institute of Nanoscale Science and Engineering (VINSE), the Wond'ry, the Center for Technology Transfer (CTTC), the business library, and the engineering management program with enthusiasm for the course goals and working with undergraduates.

With many co-instructors, we found it helpful to start planning a detailed syllabus including a course schedule at least one semester before the first time the course was offered. We first determined together the most important content to convey in the 14-week course, balancing the nanoscience, innovation, and entrepreneurship content. With overarching content determined, we defined the topic and co-instructor(s) for every class during the semester. Setting the full calendar allows the co-instructors to assess the flow of the course and how they can "call back" to prior content presented by other co-instructors, check the location of semester breaks, and easily manage any needs to swap class order during the semester. The lead instructor balances (1) co-instructor autonomy by providing each person the autonomy to design and teach their content in a manner that they believe most effective and (2) curricular cohesiveness to ensure a high-quality student experience.

The emphasis on course continuity for the student experience is managed by the lead instructor. The lead instructor attends all classes to maintain overall knowledge of how the course is going and to gain an understanding of the students' experiences in the course. For classes where this is not feasible, which include the structured labs and prototyping sessions, the VINSE nano-makerspace co-instructor discusses with the lead instructor how each of these classes went. This provides the students with a sense of continuity for the course, helping to ensure that the students do not incorrectly perceive that the course comprises multiple individual instructors presenting their own content in isolation. In the same way, the consistent lead instructor helps the students identify the lead instructor as someone to whom they can address all questions related to the course. A lead instructor presence in most classes also enables them to take responsibility for ensuring that the course stays on track during the semester.

The responsibility of the lead instructor to maintain course continuity also extends to leading communication within the instructional team, so everyone can be kept current on what is happening in the course. One strategy employed by the lead instructor was sending weekly email updates summarizing activities and content covered during the week, sharing what did and didn't work well, and reminding co-instructors of the content for the classes the following two weeks and co-instructor for each class. The lead instructor also defines co-instructor responsibilities for assignments involving content and assessment from multiple co-instructors such as the students' final project reports and is responsible for ensuring that all portions of the report are graded and all co-instructor input is considered when assigning a final grade for each student. Lastly, we found it valuable to organize an instructors meeting after the semester to review course evaluations, celebrate aspects of the course that were successful, and brainstorm how to further improve the course for the next offering.

Teaching a Course with Broad Content and No Content Prerequisites

"Nanoscale Innovation and Making" has no content-specific prerequisites, and students enter the course with varying experience levels in nanoscience/nanotechnology, nano/microfabrication techniques, business strategy, IP, commercialization, and entrepreneurship. We used a variety of teaching strategies to manage the range of students' prior experience, including hands-on and experiential learning, strategic pre-class or post-class work to reinforce new concepts, and motivating new content through examples of its real-world relevance. Examples of these strategies are detailed in the subsections below.

First Classes of the Semester

During the first class, we give an online survey to determine students' self-assessed knowledge of (i) nanoscience, nanotechnology, nano/microfabrication techniques and (ii) business strategy, IP, commercialization, entrepreneurship, as well as whether they have participated in activities in VINSE and/or the Wond'ry. The survey also asks the students to share what topics or activities they are most interested in related to the theme of the course. This survey provides the instructional team with knowledge about the background and interests of the students. This information is helpful for setting lab groups for the instructional labs and for understanding the common baseline knowledge of the enrolled students. To motivate nanoscience early, we set an assignment during the first class and due the second day of class for the students to make one slide identifying a product that utilizes nanotechnology and present it to the class. This immediately engages the students in recognizing that there are already many products on the market that incorporate nanotechnology and many more in the research and development stage.

NanoMaking

For the first nanofabrication class, the focus was on teaching basic nanofabrication techniques and introducing cleanrooms at a very high level, using the appropriate defined terminology for each technique or concept so the students could begin to learn the vocabulary associated with nanofabrication. This class assumed no background knowledge. The class was taught in an interactive style that asked the students to think and contribute to the discussion based on their intuition and applying what they learned earlier in the class to understand a slightly more complicated nanofabrication example at the end of class. In an additional nanofabrication lecture one week later providing background information on the structured labs in the nano-makerspace, the specific nanofabrication methods to be used in the labs were discussed, giving the students another opportunity to reinforce what they previously were taught about nanofabrication terminology and techniques.

In designing the structured labs in the VINSE nano-makerspace, we break the learning experience into three parts. First, the students are given a pre-lab assignment that asks the students to consider the motivation and background information necessary to understand the theme of the lab (i.e., solar cells, brain-on-a-chip microfluidics, and a forensics lab applying nanoscience characterization to study commercial materials) and the relevant nanofabrication techniques that were initially introduced in the nanofabrication lectures. Videos are included as part of each pre-lab to provide another learning modality and lower the barrier for students with little nanoscience background. Second, the students are given the lab procedure. Since the structured labs in the nano-makerspace can appear to be complicated, with many steps needed, students less experienced with STEM labs may be initially intimidated. To mitigate this, we clearly state what the students will make/test, list what tools they will use to do it, and give a concise process flow diagram all on the first page of the lab procedure so the students can get a quick overview of the lab without getting overwhelmed by the details. Third, the students are given a post-lab that asks them to reflect back on the lab and apply the knowledge they learned to propose solutions to other challenges that may be addressed using the techniques they were exposed to in the lab. This serves the dual purpose of reinforcing the nanofabrication concepts and helping the students begin to brainstorm ideas for their projects carried out during the second half of the semester.

To combat differing experience levels with computer-aided design (CAD), we provide a pre-class step-by-step video tutorial to level-set. We connect the abstract of CAD to the tangible through designing a real-world object in the tutorial and real-world examples in the lecture. To account for large differences in pre-existing CAD knowledge, we also take an open-ended approach to a CAD assignment by providing minimal constraints so students can do the assignment quite simply or translate an elaborate idea in their head onto a screen and in the end to a physical object. Shifting from mandating a complex shape with prescribed part sizes to an assignment with minimal constraints resulted in CAD designs with fewer errors in student designed nanotechnology “stencils”.

Entrepreneurship and Innovation

For the entrepreneurship portion of the class, we employ other strategies to aid reaching students with such diverse backgrounds. As our students have a range of experience starting companies, we give students first-hand accounts of creating startups in the nanotech space with two to four guest lectures provided by entrepreneurs turned CEOs or CFO (often from the university’s own startup companies) who talk about their path from the lab to the company. CEOs or CFOs are encouraged to talk about all the ups and downs of that process and often focus on the struggles they had to overcome. Often the startups are in different stages of development, and have achieved different levels of relative success, giving the students different perspectives on what it takes to commercialize their innovations. Points raised in these guest lectures are typically echoed in the students’ pitches at the end of the semester.

Entrepreneurial training offered at the Wond’ry is developed specifically to support innovators that do not have experience in business nor commercialization. Training programs for entrepreneurship at the Wond’ry were established on the philosophy and programmatic approach of the National Science Foundation Innovation Corps (I-Corps) Program, which implements experiential learning using the customer discovery process. The innovation and entrepreneurship content provided by the Wond'ry during the course was adapted to a format better suited for a didactic environment while conserving experiential learning. This method generated content easily absorbed by the students and ready for immediate application. For example, the business model canvas was introduced didactically; thereafter, those concepts were explored during team-based workshops and evidence to support the business hypotheses generated during the workshops was validated during customer discovery interviews completed as experiential homework.

The librarian used the Research Out, Knowledge In (ROKI) model [5] to deliver a workshop that provided maximum choice and engagement for students in the library databases and ChatGPT class. The ROKI model invites students to learn by 'doing and reflecting' among peers and more experienced practitioners. Here, students work through one of four activity sheets, in groups, to explore library resources such as Pitchbook, BCC Research, Statista, and IBISWorld. Each activity sheet provides prompts that guide students in navigating specific features and key content pieces that might be useful for their project. Students then share back reflections and any questions they have with each other and with the librarian based on their versions of the activity. Questions such as "where does this information come from" and "what are the advantages and risks in using ChatGPT alongside these sources" are derived from direct experience with the resources instead of abstract concepts. This style puts experience first and supports peer learning by helping students to create a shared experience and language for conducting business research. This is important in the context of an entrepreneurial course that is driven by students' unique interests and executed in a team of students with varied curricular backgrounds with no common content prerequisite. With each group exploring different research questions that are common to innovation processes, students experience 'just enough' practice with a new resource, yet walk away with robust insights about a suite of options.

One specific strategy to get the students thinking like entrepreneurs involves discussing a concept which is not intuitive to students new to the area in their first class. The goal is to impart the counterintuitive idea that "keeping all your options open" may not be the best approach when trying to decide which direction to take a new technology with possible application in many fields. The instructor emphasizes that the students are likely to do a poor job with all the applications they are considering if they try to pursue each one instead of deciding on one application and focusing their energy on that application. From here, the instructor guides the students in applying this concept to their projects. Each team informally presents what market they are thinking of going after and receive feedback from the other students. To provide a foundation to teams for assessing the suitability of their selected markets, the instructor discusses with the students a mini case study of a technology from MIT (SensAble Technologies) and uses the 6 criteria from Bill Aulet's Disciplined Entrepreneurship [6] with the students to test the market selected by each team.

Although students enter the course with widely varying experiences, no prior exposure to intellectual property is expected and a primer lecture on intellectual property is provided to level set the entire class. Basics of the primary areas of intellectual property – patents, copyrights, trademarks, and trade secrets – are provided in a brief lecture, with additional emphasis placed on patent rights due to their relevance to the course. Students are taught about the elements of patent, the rights conferred by a patent, the process of patent prosecution, and the requirements for patentability. "Patentability" is differentiated from "freedom-to-operate" and a homework assignment requires the students to each evaluate the patentability of their own inventions in a "prior art search" carried out before project selection. A separate workshop is delivered weeks later after project selection to provide practical tips on how to conduct this search for all experience levels of students, giving the teams an early start on their homework assignment, and underscoring the differences between patentability and freedom-to-operate in a hands-on activity. In many instances, students discovered prior art that covered the exact innovation they wanted to pursue, causing the teams to pivot to a new idea or focus on more unique aspects of their innovations - exactly what the patent system was designed to do.

Facilities and Logistics

Structured labs and project prototyping are carried out in potions of Vanderbilt University's Vanderbilt Institute of Nanoscale Science and Engineering (VINSE) nano-makerspace comprised of a cleanroom (shown in Figure 2) and analytical laboratory. For scale, there are approximately 100 individual current users utilizing the cleanroom to carry out research as of the end of 2024 using the over 40 tools in the cleanroom. The cleanroom and analytical laboratory portions of the VINSE nano-makerspace are staffed by five full-time technical staff members including an author of this work. Independent nano-makerspace access and equipment usage requires university safety training, nano-makerspace training, and specific training for each tool. In short, the nano-makerspace differs significantly from the average introductory STEM teaching laboratory and requires specific strategies and planning for successful implementation of structured labs and prototyping sessions.

a) b)

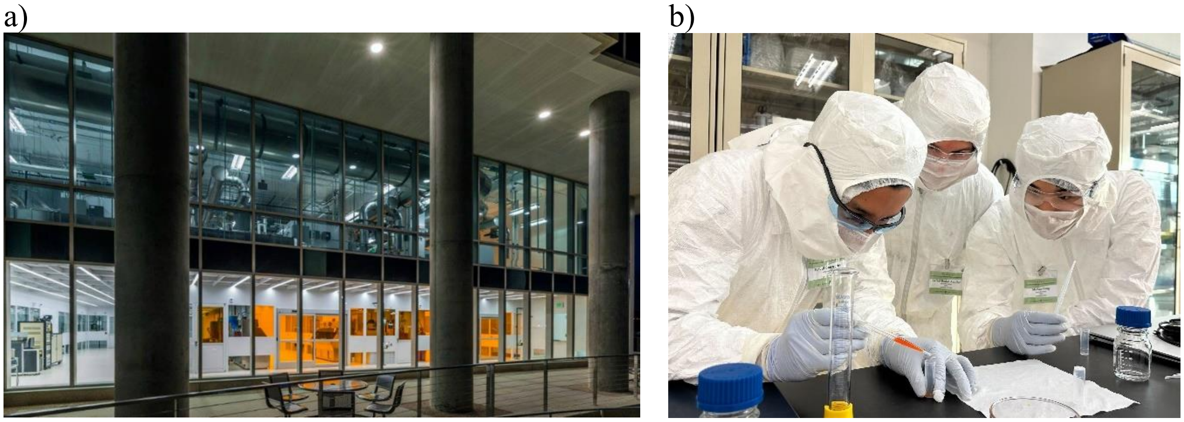

Figure 2: a) Cleanroom portion of nano-makerspace and b) coursework students inside Vanderbilt Institute of Nanoscale Science and Engineering cleanroom.

The overarching goal of the structured labs and prototyping sessions is that the students solve problems using nanotechnology and build their own prototypes in the VINSE nano-makerspace which is a shared user facility. To that end, we design these components to give the students as much hands-on experience and familiarity with equipment as possible. We additionally design to minimize training time and waiting time in the nano-makerspace. To minimize student safety and equipment training time while retaining a safe nano-makerspace environment, students are escorted by a trained user of the facility approved by VINSE nano-makerspace technical staff – in this case a specially-trained nano-makerspace teaching assistant (TA). This removes the need for time-intensive student trainings. We train TAs both for familiarity with equipment operation and to emphasize student "doing/making" with TA guidance. In this way, the students follow procedures with oversight and carry out nearly all of the procedure steps unless a step is particularly hazardous. This decreases the risk of equipment damage; important since nearly no VINSE nano-makerspace equipment is duplicated and is also used by many researchers. We reserve all nano-makerspace equipment needed for student time in the space at least a week ahead on a calendar accessible to and used by all makers with independent access to that equipment as well as communicate in advance to all makers carrying out research in the nano-makerspace when coursework students will be in the nano-makerspace. This ensures that students in this course complete their labs or prototyping in the allotted time with minimal unexpected impact to research users. Strategies/considerations specific to the structured labs and prototyping sessions are discussed in the following paragraphs.

In the current iteration of the course, the three structured labs are solar cell fabrication and testing, microfluidic device fabrication and testing, and analysis of nanoscience properties of commercial products. For the structured labs, primary considerations include the lack of duplicate equipment, the duration of inactive time during processes or while using equipment, and methods for training TAs.

There is only one copy of nearly any piece of equipment in the VINSE nano-makerspace, so structured labs are designed to account for this. We first consider the largest number of students that can be together in a lab group while retaining (1) sufficient hands-on equipment use per student and (2) visibility of process steps while an individual student is not the group member carrying out the specific step. These help the students understand the fabrication process and more easily create and implement a prototype fabrication process plan in the second half of the course. We empirically found five students to be the maximum with three to four students as the optimal group size. Thus, the structured labs have a maximum of five students per group and the project groups typically have three to four students. Of the three structured labs, two labs are in the cleanroom and the third is in the analytical laboratory section of the nano-makerspace. To efficiently use instructional time, the labs are taught by TAs using a 'round robin' approach where lab groups rotate to a different structured lab each week. The VINSE nano-makerspace typically has three to five TAs and one VINSE technical staff member who is a co-instructor for the course. The number of structured labs, maximum viable lab group size, and number of available TAs and technical staff dictate the maximum class size for the course; 15 students for this course. Each structured lab being taught during each structured lab period also requires strategic lab design to ensure that no two labs will need to use the same equipment at the same time in a lab period. For an example, with a tool that transfers a pattern to a liquid plastic used by two labs, we altered one lab to use a far thinner version of the liquid plastic to ensure that the group doing this lab would be finished with the tool before the second group arrived at the tool.

Some laboratory procedures which are foundational nano-makerspace techniques cannot be completed in their entirety in a single two-hour period and have long stretches of waiting such as the 25-minute vacuum chamber evacuation before depositing a thin film of metal. Just as a live cooking show has a chef put a cake into the oven and immediately take out a pre-prepared fully baked version of that cake instead of showing the cake baking, we design the labs with "cooking show magic" to remove large blocks of downtime. For the above example from the solar cell lab, this manifests as a TA mounting samples and deposition material, starting the vacuum pump before the lab, showing the students the inside of a similar vacuum chamber to orient them to the components of the system the students will use, and then the TA teaching the students to deposit the film in the already-prepared vacuum chamber, saving 25 minutes in a two-hour lab block. We previously used structured lab downtime to have the students skip to parts of the process further into the lab with premade samples and come back later to their initial samples so students would do more of the total procedure steps. This out-of-order making process proved confusing for students and was abandoned based on student feedback in favor of not showing certain steps in certain lab procedures but discussing these steps verbally instead. We also shifted mindsets to view the structured labs where the ultimate goal is to expose the students to a range of techniques instead of having students see all steps of each lab and rushing through such that student understanding of procedures and processes suffered. This helped inform when to use cooking show magic to shorten processes. As an example, the solar cell lab originally had two instances of spinning a liquid plastic onto a sample for different scientific reasons. Carrying out both coating steps did not introduce students to new nano-makerspace techniques, so we removed the first instance and used pre-made samples at that step instead.

TA trainings in the context of structured labs in the VINSE nano-makerspace are discussed. For structured labs, TAs are trained for familiarity with the lab structure and explaining to students how to use equipment in addition to TA familiarity with equipment. Guiding students through use of research-grade nano-makerspace equipment in a manner which is both time-efficient and effective is a distinct skill from knowledge of and ability to use that piece of equipment. After a TA is trained and assessed for independent use on a piece of equipment in the nano-makerspace, they practice the lab two times with a "test student" before the lab period so the TA understands lab flow, what strategies work to explain equipment use to another person, and ensure that the TA can teach the lab in the two-hour lab period. TAs are students with limited time allotted for TA duties. We have found multiple practice runs on a subset of labs a more efficient use of TA time than training each TA to carry out each lab. We note that TAs selected for the course are graduate students who are either current VINSE nano-makerspace users or are anticipated to be nano-makerspace users during their educational careers. Hence, despite being a relatively heavy TA load, there is clear value added for the TAs, and their feedback has indicated that they find the course to be a tremendously positive experience for them.

For successful student-driven product prototyping sessions culminating in a device successfully exhibiting at minimum an aspect of the full desired product, strategy centers on preparation. Two of three postlabs for the structured labs require students to answer questions on an excerpt from a nanoscience paper including how the nanoscience device is made, giving students practice reading methods sections before they need this skill to identify fabrication strategies in papers for their product prototypes. For students to efficiently use the first project prototyping session in the VINSE nano-makerspace, dedicated class time with the VINSE nano-makerspace co-instructor and TAs is set aside in week seven to vet student-generated prototype fabrication plans and provide guidance so all parties know the first session's plan. The project prototype fabrication strategy class is placed two weeks before the first prototype fabrication session to provide time for instructors to purchase supplies and reserve equipment. In weeks eight through twelve, we additionally provide dedicated fabrication office hours with the relevant instructor and TAs where students can solicit feedback on student-proposed fabrication approaches for upcoming prototype fabrication sessions. In the first prototyping session, a TA is placed with each project team and stays with these students through the sessions for continuity of prototyping plan and safety. To maintain efficient use of prototyping sessions in the VINSE nano-makerspace, the relevant instructor solicits a detailed prototyping plan at the end of each session.

Managing Student-Driven Project Ideas and Making Strategies

An emphasis for this course is that the nanoscience-based products which the students prototype and pitch come from student ideas about unfilled needs, student ideas on how to fill those needs, student entrepreneurial strategies, and student prototype fabrication strategies based on nanofabrication concepts they learned in lectures and implemented in the structured labs. Instructors provide guidance and suggestions and TAs help students bring their prototype ideas to fruition, but we find it is important that the students are the primary drivers of these projects from start to finish. This increases student buy-in, the feeling of ownership of the project, and better mimics the experience of nanoscale innovation and making in a non-classroom setting. The emphasis on student ideation also means that the students can come up with a vast range of nanoscience-based product ideas, from the achievable to the outlandish, with only a rough idea of how to fabricate that product prototype based on knowledge acquired during the structured labs in the VINSE nano-makerspace and the nanofabrication lectures. The open-ended student ideation, which is great for students, can induce instructor stress because we want to see our students succeed and have some sort of physical product prototypes to show at the end of the course when they pitch their product. The uncharted fabrication territory and team formation induces stress, but also excitement of seeing how our students will manage to grow and succeed when we as instructors give them the lead. We have developed strategies to mitigate the stress and increase the odds of student success with the order and manner of introducing content, support structures, and semi-invisible guardrails.

A first challenge when handling student-driven project ideas is getting enough student ideas. The students didactically learn about customer discovery and the interviewing process and are asked to do secondary market research and subsequently interview potential customers in an industry of their choosing outside of class, to learn about some of the biggest challenges. The resultant interview findings are discussed during class and potential topics areas and themes around customer pain points start to form organically. Additionally, dedicating time at the end of lecture classes in the first half of the course for project ideation, scheduling a project brainstorming class with instructor guidance in week five, and incorporating a question into postlabs where students state how they would use a tool or technique they saw in that week's lab to solve a problem they experience in their life all increase the number of ideas the students bring to the project selection class in week seven. On project team formation and decision day, the instructors facilitate a discussion to capture all possible ideas using an innovation ideation process called "bad ideas only" to create an environment that project ideas may be provided in a psychologically-safe environment without judgement. These ideas lead to the generation of stronger project ideas that are added to the list of student ideas from postlab questions.

A second challenge, once students generate a list of project ideas, is team formation and project selection. The instructors guide all students to vote on any ideas they are interested in. The ideas with the highest number of votes advance to the next round of discussion. For this, instructors from different disciplines are onsite to help the students think about what is feasible, who (the potential customers) they should interview going forward to do additional customer discovery, what materials they would need, and what a prototype would potentially look like. From here, students self-assemble into teams with the instructors supporting as needed to ensure heterogeneity of the teams from a declared major and classification standpoint. Instructors strive to place three to four students on each team while seeking to ensure that team members are interested and cognitively invested in the project they have chosen.

A third challenge when handling student-driven project ideas is the students' tendency to overestimate what they can make in four two-hour sessions in the VINSE nano-makerspace. To ensure realistic planning, we remind students early in the prototype fabrication planning that they are making a prototype and have a limited number of hours in the nano-makerspace to create it. Around the third product prototyping session, we remind the students as needed that they are making prototypes and not expected to have products ready for stores. We find this is the time where some teams become concerned or disappointed upon realizing that their ambitious prototype fabrication plan for during the course might not be fully achievable in the remaining prototyping sessions. Depending on student interest, we also introduce students to possible routes for continuing the fabrication portion of their projects and continuing fabrication in the VINSE nano-makerspace in general, discussed in detail in the section "Student Options to Continue Nanoscience, Entrepreneurship, and IP After the Course".

A fourth challenge is that undergraduate students in a course with no content prerequisites will have a wide range of ideas due to their wide range of experiences from previous courses, internships and summer research, and outside interests, so unexpected ideas will inevitably be chosen by students. By tuning what is discussed in the first six weeks of the course, we strive to shape the types of ideas the students are likely to create. Specifically, we are strategic with what tools, techniques, and problems are shown to students in the structured labs and what areas and types of devices are discussed in the case studies. We try not to fully say no to any idea from the students. If making or testing the device in the way proposed by the students would be too hazardous or take far beyond the time available to the students, we suggest or assist them in finding safer and easier methods. If the product making takes a long time and the product has multiple parts, we guide the students in breaking down the product into components and selecting a subset of those components to create during the course. If making strategies are outside the area(s) of expertise of the VINSE nano-makerspace co-instructor, we reach out to relevant faculty and national lab colleagues and encourage students to do this as well.

Student Options to Continue Nanoscience, Entrepreneurship, and IP After the Course

If a student becomes interested in creating value through the creation of a financially-sustainable business connected or unconnected to their "Nanoscale Innovation and Making" project, the Wond'ry (Vanderbilt University's innovation center) offers a continuum of entrepreneurial supports and resources to guide these innovators on their journey. The Wond'ry provides an array of programs available to innovators including former students in "Nanoscale Innovation and Making" that build a bridge over the startup valley of death, notably: Ideator, Builder, and Founder. The Wond'ry's Ideator program teaches an evidence-based approach to idea evaluation, helping university innovators determine if their idea has potential. The program can make innovators eligible for the National I-Corps Program. The Wond'ry's Builder program provides a step-by-step guide for aspiring entrepreneurs to launch a new venture and offers both microgrants and eligibility for the National I-Corps Program. The Wond'ry's Founder program provides ongoing resources, connections, mentorship, and funding opportunities for entrepreneurs who have completed in-depth customer discovery, found product-solution fit and product-market fit, and launched a venture.

For a project concept that is truly novel, students may also utilize the Center for Technology Transfer (CTTC) to help protect and commercialize it. Students are not required to assign their innovations to the university but may choose to do so to have CTTC engage with outside patent law firms to protect the innovations. In such instances, CTTC would bear all costs of patenting and licensing, and the students would be treated the same as other university inventors, including receiving the plurality of licensing revenues under university policy.

If a student becomes enamored of nanoscale making during the course, the Vanderbilt Institute of Nanoscale Science and Engineering (VINSE) which manages the nano-makerspace offers both coursework and non-coursework options for the student to continue in nanoscience. In addition to the course "Nanoscale Innovation and Making", VINSE supports a range of nanoscience-related coursework with immersive experiences in the cleanroom, analytical laboratory, and/or advanced imaging portions of the nano-makerspace. The immersive coursework in the nano-makerspace forms a portion of the undergraduate Nanoscience and Nanotechnology Minor. For students seeking a non-coursework route to continue nanoscience making in the nano-makerspace, VINSE has the Technical Crew (Tech Crew) program for both school-year employment and ten-week summer fellowships. The Tech Crew program provides undergraduates an opportunity to work in the nano-makerspace (cleanroom, analytical laboratory, and advanced imaging suite) directly with technical staff, giving students technical skills and experience that few undergraduate students at any institution receive, such as independent usage of and process development for complex state-of-the-art instrumentation as well as maintenance of research-grade lab equipment.

Students can continue the making component of their course project after the completion of the course. To enable this, the VINSE nano-makerspace instructor has previously secured funding based on expressed student interest through a grant to faculty from the university provost's office to support immersive experiences. With this grant funding, students can carry out additional fabrication and testing of their prototypes in the VINSE nano-makerspace with nano-makerspace co-instructor guidance.

Selected Student Project Case Studies

In this case study, we demonstrate that a course combining nanoscale making with innovation and entrepreneurship does not prevent students from carrying out notable entrepreneurship based on their product ideas and prototype. In the first year of the course, a team of two students designed a wearable microfluidic-based glucose detection and insulin delivery system. This product included microfluidics and a microneedle patch for delivery to the body. The microfluidics portion of the product leveraged cleanroom techniques used in the structured labs, but the microneedles required the students to learn nanofabrication techniques beyond those taught in class which they did by bringing a range of possible ideas to making procedures to macro- and nano-makerspace staff. Impressively, the team had an initial microneedle prototype ready for their product pitch. By then, one student was hooked and set out to develop their prototype further as well as form their own startup to pursue it commercially. The student formed a new team and immediately participated in the Wond'ry's South by Southwest Ideator Program (Spring 2023), went on to the Builder Program (Fall 2023), informed the Wond'ry of the need for an on-campus bio-makerspace to support their further product development which was subsequently created, and sought to craft Small Business Innovation Research (SBIR). The team submitted an invention disclosure form to CTTC which subsequently filed a patent application to protect a key microfluidic pumping innovation. The new team continued startup development for two years, even beyond graduation from the university, and periodically contacted the VINSE nano-makerspace course instructor with fabrication questions until the research experiments yielded null results and they gave up. We consider this a positive outcome and a demonstration that combining nanoscale making with innovation can yield strong entrepreneurship and innovation from students in the context of a nano-based product.

In the second year of the course, a team of three students who were particularly passionate about nanofabrication aimed to design a product to continuously detect trace amounts of lead in drinking water using a microfluidic sampling device. The team initially planned to create this device or self-healing bike tires or a wearable dehydration sensor, and they needed time and guidance from the instructional team in searching for prior art as well as fabrication strategies to commit to a specific project. Once they did, the students committed to project design through outside reading, questions of their research advisors or previous instructors, and fabrication feasibility questions of the VINSE nano-makerspace co-instructor whenever the students saw them. The nano-makerspace instructor has since added dedicated prototype fabrication process office hours. After conversations around the VINSE nano-makerspace between the co-instructor, students, and other staff with chemistry expertise on suitable non-toxic chemical indicators for lead detection, we ordered the chemical. The students used their first prototyping session to test the limits of commercially available detection kits for drinking water and designing their device in CAD while waiting for their chemical indicator to arrive for the second session. With their chemical in hand, the team stayed 30-60 minutes after the end of each prototyping session discussing fabrication ideas with their TA and continuing to test their device because they were invested in getting their prototype working, which they did and showed in a video demonstration during their pitch. Two of the students expressed that the course should have an optional second semester for students who wanted to optimize fabrication of their prototypes, so the VINSE nano-makerspace co-instructor applied for and won a grant to faculty from the university provost's office to support this immersive experience. The two students worked with the nano-makerspace co-instructor to hone their fabrication, presented updated work at the end of the spring after they completed the course (Spring 2024), and plan to continue prototyping in Spring 2025.

In the third year of the course, a team of four students was designing a compact, passive device to detect neutron radiation. The initial reaction of the VINSE nano-makerspace co-instructor, which was confirmed by researchers at a national laboratory and the radiation effects group at the university was that there are not good, safe, quick, and "easy" ways to make detectors for radioactive neutrons where the students could realistically prototype. This was confirmed when initial student fabrication plans included layers of toxic material not permitted in most nano-makerspaces, a procedure a national lab contact described as a ten-week summer project, or a layer of a less toxic material requiring over $10,000 in supplies to deposit. Instead of saying no outright, the nano-makerspace co-instructor helped the students break down the problem and realize that many radiation detectors convert radiation to light to electricity and that they could focus on the light to electricity part to optimize their detection aspects for the project while investigating other ways to deposit the less toxic material to convert radiation to electricity. From this point, a team representative attended fabrication office hours each week to discuss fabrication strategies for the upcoming prototyping session created by the team based on the tools they saw in the structured labs and new ways of using these tools described by the nano-makerspace co-instructor. Using these strategies, the students optimized the light-electricity conversion material through experiments in the VINSE nano-makerspace and demonstrated a successful light-to-electricity portion of a radiation-to-light-to-electricity detector with an Arduino-controlled indicator for real-time relative light intensity, which in the full design would be the relative neutron radiation intensity. They additionally proposed a way to deposit the less toxic material in a nanoparticle form instead of in a slab, which will be their next step if they choose to continue this project after the completion of the course.

Student Assessment of Course and Student Outcomes

We developed an end-of-semester anonymous student questionnaire on the online learning platform Brightspace to gather student feedback. Our student response rate was around 70% for each of the three cohorts, with responses from 4 of 6 students Fall 2022, 11 of 15 in Fall 2023, and 7 of 10 in Fall 2024. Four questions were based on a five-point Likert scale ranging from strongly disagree to strongly agree, with responses shown in Figure 3.

1) This course met my expectations for content and how much I learned.
2) The team project, including putting together a product pitch and having the opportunity to start making a prototype of the product, was a great way to bring together all the main concepts taught during the semester.
3) The instructional team worked well together and provided a broad background of knowledge that enriched the class.
4) There was an appropriate balance between the "innovation" and "making" aspects of the class.

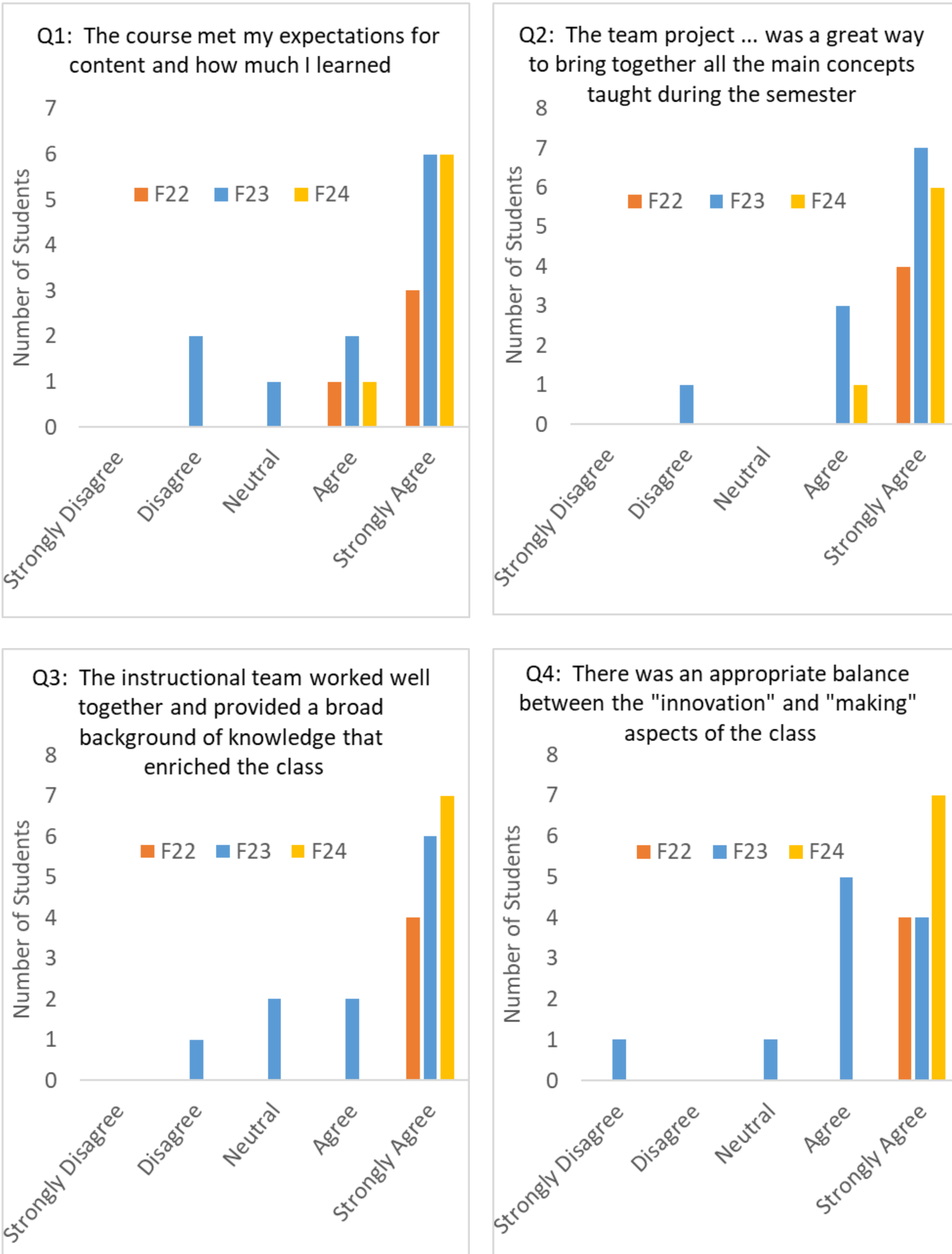

Figure 3: Student end-of-semester anonymous Brightspace questionnaire results from questions asked on a five-point Likert scale. F22, F23, and F24 represent responses from students who took the course in Fall of 2022, Fall of 2023, and Fall of 2024, respectively.

Overall, the course was well-received by the respondents in each of the three cohorts. The course met most of their expectations for what and how much content they learned. Most respondents liked the balance of innovation and making aspects, liked the team projects, and thought the large instructional team worked well and enriched the course.

Additional space on the questionnaire was provided for students to provide further feedback on the following free response prompts:

5) Please provide additional feedback on the above 'relative level of agreement questions' here or write N/A if you have no additional comments to share.
6) The best parts of this class were...
7) If I could change one thing about this class, I would...
8) We would appreciate any other comments you would like to share about the class that would help us make the class even more impactful and valuable for future students. Thanks!

We provide sample student responses on what the students liked about the course, including responses given in questions 5) and 6) in Table 2. We selected these sample responses from a larger pool to illustrate the themes we observed in responses from multiple students including the instructors' interest in working with students, the hands-on nature of the course, projects, making in the cleanroom, and the good mix of nanoscience and entrepreneurship.

Table 2: Sample student responses to free response questions on an anonymous Brightspace questionnaire describing what they liked about the course.

Student	Answer
Student 1	"The faculty engament *[sic]*, all the instructors seemed to want to be there, to help us accomplish the course goal, and enjoyed coming along for the process. This made an enviorment *[sic]* were *[sic]* engaging in the class and with the project feel rewarding and positve *[sic]*."
Student 2	"This course was so hands–on and every lesson had such practical implications that I was able to directly see how these concepts would translate outside of a classroom setting."
Student 3	The best part of the class was: "Creative freedom on the project with a presentation at the end giving it real stakes"
Student 4	"I loved working in the cleanroom! I thought the initial labs were great, especially with help from the TAs. I also really enjoyed that we had the autonomy to pick our own projects and work to develop them."
Student 5	"I love how it combined both innovation and making. I learned a lot not only about the science behind how nanofabrication worked, but also how to make a product and sell it: the process and the steps needed for a start up."

Student responses on what the students wanted to change, including responses given in questions 5), 7), and 8) can be grouped into a few categories. Students wanted to pick projects and evaluate feasibility earlier so 1) they would have more time to think about their final project and so 2) each entrepreneurship activity and assignment would apply to their final project. Students also wanted more of everything including a second course to delve deeper into content and project prototyping as well as introduce more tools and techniques, more time in the VINSE nano-makerspace, and more time on business elements. Student responses from the first two cohorts led to modifications in the course schedule as well as lab materials and lab design.

We additionally developed an end-of-semester anonymous student questionnaire specific to the immersive VINSE nano-makerspace portions of the course on Google Forms in Fall 2023 to gather student feedback. Our student response rate was 5 of 15 students in Fall 2023 and 5 of 10 in Fall 2024. Two questions on the content and the value of this content were based on a five point numerical scale with "1" as poor and "5" as excellent and a five point Likert scale ranging from strongly disagree to strongly agree, respectively. Responses are shown in Figure 4.

NANO_1) Overall, my experience with the VINSE immersion component of this course was:

NANO_2) The instructional labs in the VINSE were a valuable part of the course, exposing me to nano- and micro-fabrication techniques and preparing me to fabricate the prototype for my project.

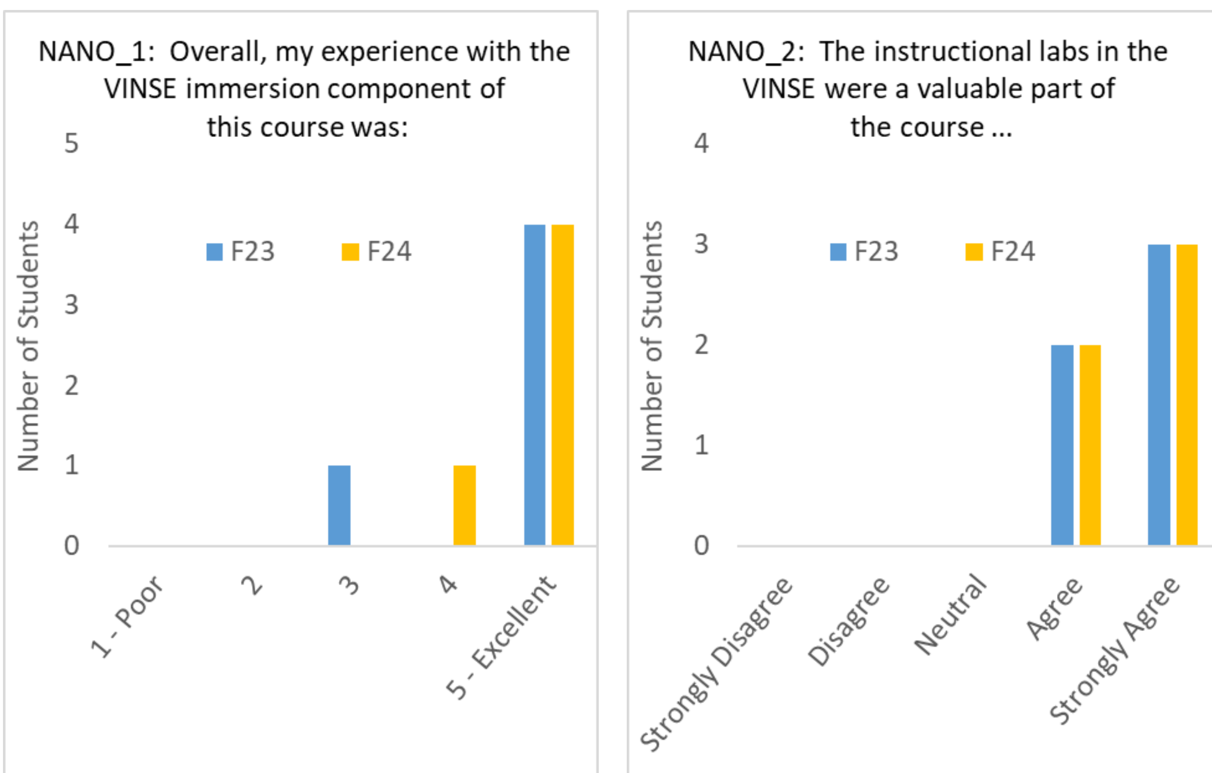

Figure 4: Student end-of-semester anonymous Google Forms questionnaire results from questions asked on a five-point scale. F23 and F24 represent responses from students who took the course in Fall of 2023 and Fall of 2024, respectively.

The nano-makerspace component comprising the structured labs and prototyping sessions was well-received by the respondents in the Fall 2023 and Fall 2024 cohorts, with 80% of students listing their experience as “Excellent”. All respondents either agreed or strongly agreed that the structured labs in the VINSE nano-makerspace exposed them to nano- and micro-fabrication techniques and prepared them fabricate their product prototypes based on knowledge of those techniques.

This course continues to impact students after completion of the course. At this time, it is too early to know how the three teams from cohort three will continue to engage after completing the course in Fall 2024. Thus, we discuss the 21 students from cohorts one and two. Six students from four of the seven total teams in cohorts one and two have continued working on their products in some capacity after completing the course. Details of some continuing work are described in the section “Selected Student Project Case Studies”, with an additional two students enrolling in Ideator in Fall 2024 with the technology from their Fall 2022 class prototype idea. For nanoscale making unrelated to course projects, multiple students took additional immersive nanoscience-related coursework, one declared a Nanoscience and Nanotechnology Minor, and one joined Tech Crew. Two students were already part of Tech Crew when they took the course. Five students participated in Wond’ry programs not related to the course projects, including seven programs on making in the macro-makerspace, two lectures and courses, and one bootcamp on social innovation.

To better understand the specific value added from combining nanoscale making and innovation, we have additionally identified standard undergraduate entrepreneurship courses to serve as possible points of comparison with our course. In future offerings of the course, we plan to integrate more rigorous assessment methods to examine the usefulness of the nanofabrication context in an entrepreneurship course.

Conclusions

We co-teach a 14-week course, “Nanoscale Innovation and Making”, to three cohorts of undergraduate students from different majors over three years to date. This course aims to fulfill the need to train students to become future innovators, prepared to solve societal grand challenges by creating nanotechnology solutions. The course meets twice per week for two hours per class. Students learn a mix of nanoscience, innovation, and entrepreneurship, and apply this knowledge in groups to create prototypes based on nanoscience with accompanying product pitches to fill a need which the students identify. We discuss a blueprint for teaching such a course, including initial course design, implementation, options for further student involvement in topics of interest, student project examples, and student feedback on the course. Overall, the course has been well-received by students. The instructional team continues to evolve lecture, lab, and workshop content for future years as well as work with the students interested in continuing in these areas after completion of the course.

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