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Creating Scalable Reform in Engineering Education Through Low-Cost Intrinsic Motivation Course Conversions of Engineering Courses

Prof. Geoffrey L Herman, University of Illinois, Urbana-Champaign

Professor Geoffrey L. Herman is a visiting assistant professor with the Illinois Foundry for Innovation in Engineering Education at the University of Illinois at Urbana-Champaign. He earned his Ph.D. in Electrical and Computer Engineering at the University of Illinois and conducted postdoctoral research in the School of Engineering Education at Purdue University. He now serves as the Intrinsic Motivation Course Conversion project lead with the iFoundry and on the steering committee of the College of Engineering's Strategic Instructional Initiatives Program.

Kathryn F Trenshaw, University of Illinois, Urbana-Champaign
Prof. Michael C. Loui, University of Illinois, Urbana-Champaign

Michael C. Loui is a professor of Electrical and Computer Engineering and University Distinguished Teacher-Scholar at the University of Illinois at Urbana-Champaign. His interests include computational complexity theory, professional ethics, and the scholarship of teaching and learning. He serves as editor of the Journal of Engineering Education and as a member of the editorial boards of College Teaching and Accountability in Research. He is a Carnegie Scholar and an IEEE Fellow. Professor Loui was associate dean of the Graduate College at Illinois from 1996 to 2000. He directed the theory of computing program at the National Science Foundation from 1990 to 1991. He earned the Ph.D. at M.I.T. in 1980.

Mrs. Kerri Ann Green, University of Illinois, Urbana-Champaign
Dr. David E. Goldberg, ThreeJoy Associates, Inc. and the University of Illinois

Dr. David "Dave" Goldberg is president and founder of ThreeJoy Associates, Inc. and is a consultant, trainer, and coach to students, faculty, and administrators in higher education. Prior to founding ThreeJoy Associates, Dr. Goldberg was the Jerry S. Dobrovolny Distinguished Professor in Entrepreneurial Engineering at the University of Illinois at Urbana-Champaign, where he was known for his path-breaking research in genetic algorithms and evolutionary computation; for his role in co-founding ShareThis, Inc.; and for his work as co-founder and co-director of the Illinois Foundry for Innovation in Engineering Education, iFoundry. Dr. Goldberg authored The Entrepreneurial Engineer and Genetic Algorithms in Search, Optimization and Machine Learning, among other books. He has been a registered engineer in Pennsylvania and Alabama and holds a B.S. in Engineering, a M.S. in Engineering, and a Ph.D. in Civil Engineering from the University of Michigan and a Certificate in Leadership Coaching from Georgetown University. Together with Mark Somerville of Olin College, he recently co-founded the Big Beacon, a global movement for the transformation of engineering education.

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Abstract

We present our efforts to create a scalable engineering education reform process that has a low barrier to adoption by focusing primarily on promoting students' intrinsic motivation (IM) to learn. Students who are intrinsically motivated rather than extrinsically motivated to learn are more likely to persist in their learning and perform better. Despite major investments in, and promising innovations for, reforming engineering education, many instructors are slow to adopt these innovations because of prohibitive time, money, and training investments. In contrast, the intrinsic motivation (IM) course conversion project has three goals: (1) to redesign the classroom based on motivational theories, (2) to improve students' learning by promoting their intrinsic motivation to learn, and (3) to implement the reform through methods that require minimal or zero additional costs to the faculty. We initially piloted one such IM course conversion in a sophomore-level computer engineering course (ECE 290) during the Fall 2011 term with 37 students. This pilot was scaled to encompass the full course in Fall 2012 with 220 students.

1 Introduction and Background

Despite major investments in, and many promising and proven interventions for, reforming engineering education, many instructors are slow to adopt these proven pedagogies because of prohibitive time, money, and training investments[1]. Further, students often resist these newer pedagogies because they challenge students' expectations for successful or enjoyable learning. The low-cost intrinsic motivation (IM) course conversion project is an attempt to address both of these challenges to reform by focusing first on promoting students' intrinsic motivation to learn and helping faculty make strategic changes to support intrinsic motivation in their courses that require minimal or zero net costs[2]. We propose that this change of focus can lead to sustainable reform as intrinsically-motivated students learn more, want better education, and often invest in their courses to improve them[3]. After small investments by faculty and reformers, students rather than faculty can become the engine for long-term reform.

During the Fall 2011 term, we piloted our first IM course conversion with a sub-population of students (approximately 37 out of 225) in a sophomore-level computer engineering course (ECE 290). This pilot indicated that we could improve students' learning outcomes and create a learning climate that promotes students' intrinsic motivation to learn at no increased "cost" to the presiding course instructor [2]. We executed this course conversion by shifting the duties of two graduate teaching assistants from conducting discussion sections and grading homework to supporting students with structured autonomy over their learning[4]. During the Fall 2012 term, this pilot was scaled to include all ECE 290 students and graduate teaching assistants (TAs). We present our process to scale this pilot and present evidence for the effectiveness of this focus on students' intrinsic motivation to learn in large enrollment courses.

2 Background

2.1 Interactive Engagement pedagogies and the Goldberg-Laffer curve

Many efforts to reform engineering education document or encourage the adoption of Interactive Engagement (IE) pedagogies (also known as active learning pedagogies) that promote teacher-student and student-student interactions. These interactive engagement pedagogies leverage these interactions to develop "deep learning" that leads to expertise in a variety of engineering skills and knowledge rather than surface learning such as fact memorization or rote problem solving[5-11]. Although interactive engagement pedagogies are effective, faculty are often reluctant to adopt them because of the time, financial, and training costs are prohibitive[1].

Adapted from Arthur Laffer's taxation-revenue model from economics[12], The Goldberg-Laffer curve (Figure 1) hypothesizes that when we attempt to move from "sage-on-the-stage" lectures to "guide-on-the-side" IE pedagogies, we can increase student engagement, but only by increasing the time and energy costs to faculty[13]. It further hypothesizes that there is an "IM space jump" through which we could increase student engagement in the classroom with minimal or no cost to faculty. Instead of faculty-driven change, intrinsically-motivated students drive the change in the classroom and create pedagogical and educational reform. The IM course conversion project is an attempt to test the possibility of this jump.

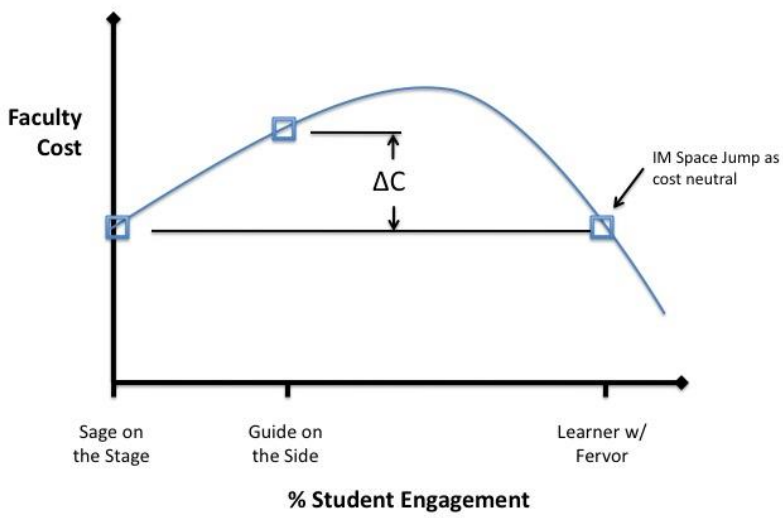

Figure 1: Goldberg-Laffer curve

2.2 Student motivation

Students' motivation to learn ranges on a continuum from amotivation through *extrinsic* motivation (receiving rewards such as grades, complying with rules) to *intrinsic* motivation (satisfying personal interests, or deriving from the inherent value of an activity)[14,15]. Students tend to learn more when they are intrinsically motivated to learn[16]. Intrinsic motivation is supported when students' needs for a sense of *competence* (*mastery*), *autonomy*, *relatedness*, and *purpose* are met[14,15,17]. Although intrinsic motivation can be supported by meeting any of these needs, supporting students' sense of autonomy is perhaps the most effective way of improving students' motivation[17]. Intrinsic motivation can be supported in any classroom or by any instructor regardless of the predominant teaching mode (i.e., traditional lecture versus interactive engagement pedagogies versus problem-based learning), but some learning environments foster autonomy better than others.

Despite the importance of motivation in learning, it seldom has served as the focal point of pedagogical change in engineering[18].

3 Design of the Pilot IM course conversion

We have previously described our pilot IM course conversion in detail[2-4]. We provide a brief synopsis of the pilot below and encourage interested readers to refer to our prior publications for more detail.

3.1 Description of the Intrinsic-Motivation pedagogy and pilot

ECE 290 is a large enrollment (about 200 students per semester), sophomore-level, digital logic and computer architecture course required for all electrical and computer engineering majors at the University of Illinois at Urbana-Champaign. Students first learn about logic gates, then state machines, and finally the von Neumann model of computer architectures. Traditionally, each week, students attend two lectures taught by a professor and one discussion section out of eight taught by TAs.

The pilot had two design constraints: (1) minimize faculty time and effort to increase chances of scalability and dissemination and (2) promote each student's sense of autonomy, competence, purpose, and relatedness. To minimize faculty time and effort, we made the discussion sections the locus of change. The presiding faculty members could teach their lectures as they normally would. The changes to the pedagogy were driven instead by the TAs who were in charge of the two experimental intrinsic motivation discussion sections. These TAs changed their teaching activities and grading activities to focus on supporting students' autonomy rather than any one particular learning outcome. Since these TAs also want to become faculty, this increased responsibility for the TAs created a secondary benefit of training these TAs to become agents of change in their future careers. The remaining six discussion sections were led by other TAs who used interactive engagement (IE) pedagogies. We considered these sections to be control sections for the sake of evaluation.

The course design was designed to support the four motivational constructs of relatedness, purpose, autonomy, and competence. Within these intrinsic motivation discussion sections, students were organized into learning teams (relatedness) based upon the students' stated purpose for taking ECE 290. Over the course of the semester, these learning teams negotiated a series of purpose-based learning agreements with the TA. In these learning agreements, students' were given autonomy over three elements of the course: (1) what elective topics they would study (topic selection), (2) how they would learn all mandatory and elective topics (practice selection), and (3) how they would demonstrate their mastery of the mandatory and elective topics (mastery selection). We supported the students' sense of competence in this new learning environment by giving the students fewer choices at the start of the semester, and gave them more autonomy as the semester progressed (See Figure 2 for a comparison of the control IE and experimental IM sections). We also communicated to the students that we believed that they could use this autonomy to do amazing things (competence).

On the first learning agreements, students were required to select topics, mastery options, and practice options from pre-approved menus. Students were given progressively more autonomy, so that on the final learning agreement, students were allowed to choose whatever topics they wanted to study and practice that topic in whatever way seemed best, as long as they could demonstrate mastery of a computer architecture. This final learning agreement gave the students autonomy that was comparable to that of a senior design course (see Figure 2).

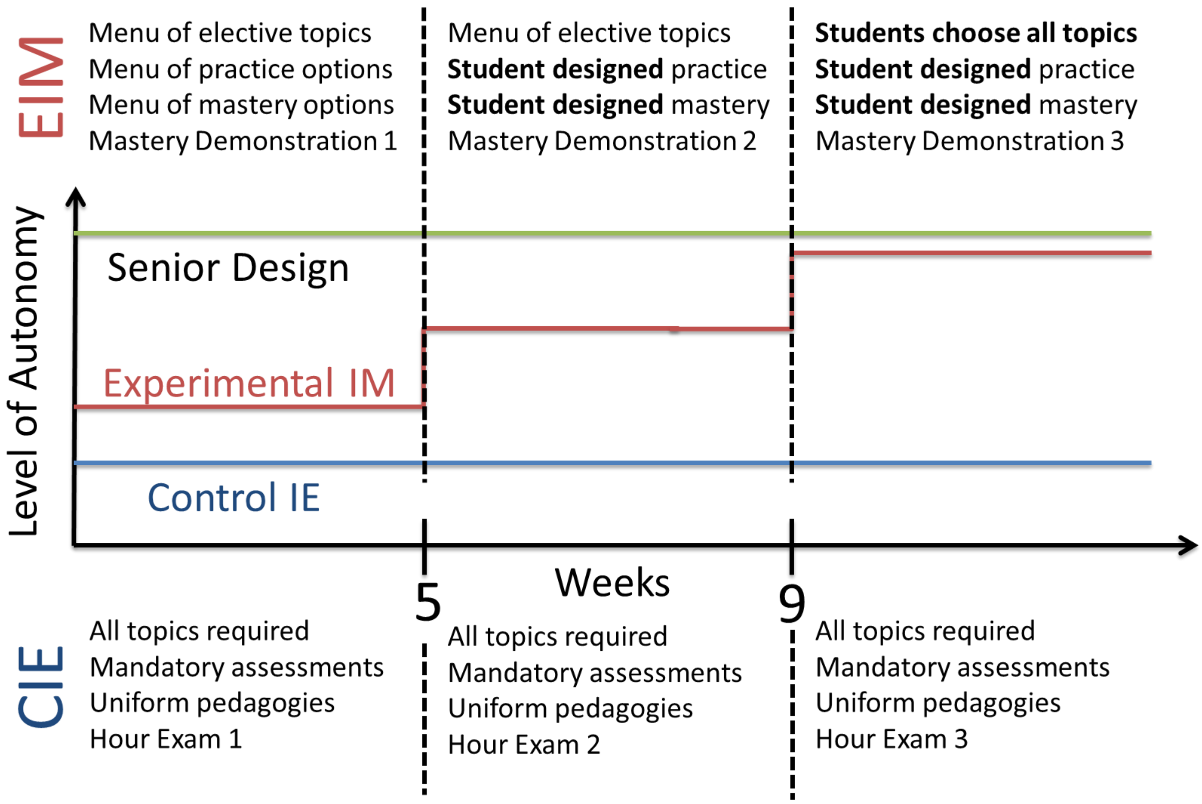

Figure 2: Comparison of learning activities for the Control IE and Experimental IM sections.

Increased levels of choice and autonomy in the Experimental IM sections are highlighted in bold. The level of autonomy in a Senior Design course is included for reference.

3.2 Intrinsic Motivation Course Design Procedure

To create this autonomy-supportive environment, we followed a four step design process: (1) Identify the strategic core, (2) determine negotiable elements, (3) create course structures, and (4) train teaching assistants. These four steps are based on our four goals of promoting autonomy, competence, purpose, and relatedness respectively (See Table 1).

Table 1: Design steps and the intrinsic motivation attributes that they promote

Step	Autonomy	Competence	Purpose	Relatedness
1. Identify strategic core		X	X	
2. Determine negotiable elements	X	X	X	
3. Create course structures	X	X	X	X
4. Train teaching assistants	X	X	X	X

3.2.1 Identify a strategic core

We collaborated with the course instructors to determine a list of "need-to-know" topics and "nice-to-know" topics. The strategic core[19] of need-to-know topics was composed of learning outcomes that are considered indispensable for future learning and would be tested on the final exam. The identification of the strategic core supports students' competence and purpose by giving them greater clarity for the goals and relevance of the course.

3.2.2 Determine negotiable elements

After identifying the strategic core, we discussed what topics and activities students could choose. The *negotiable elements* reinforced the strategic core, but give students autonomy to pursue personal interests (purpose) and competencies. For example, students could choose to take the hour exams that the interactive engagement students took or they could choose to create design projects or educational resources.

3.2.3 Create course structures

To present the strategic core and the negotiable elements in a way that supported students' sense of competence, we required students to create three learning agreements that replaced the normal course syllabus. These learning agreements would be completed in purpose-based learning teams to foster students' sense of relatedness. For example, students who wanted to learn about computer architectures were placed in one team and students who wanted to learn about sustainability were placed in a different team. Additionally, the learning agreements scaffolded students into increasing levels of autonomy.

3.2.4 Train teaching assistants

To reinforce the three previous design steps, we trained the TAs on team management skills[20] and autonomy-supportive behavior[20-23]. We also had the TAs work through exercises to help them identify the central purposes of the course and the goals of each learning team.

4 Assessment Procedures

We conducted preliminary assessments of the quality of our IM course conversions with two validated and reliable instruments: the Digital Logic Concept Inventory[24] (DLCI; Section 4.1) to measure students' learning gains and the Learning Climate Questionnaire [25-26] (LCQ; Section 4.2) to assess how much the learning environment supported students' intrinsic motivation to learn. The results of these assessments are reported below. Qualitative assessments are ongoing and will be reported later.

4.1 Digital Logic Concept Inventory

The DLCI has been used in ECE 290 as a pre-/post-assessment since 2008 to measure the effectiveness of different pedagogies in promoting students' conceptual learning of digital logic concepts. The normalized gain g compares concept inventory scores from different student populations to evaluate the effectiveness of different pedagogies[27]. The normalized gain is calculated by using the average pre-test and post-test scores of each course offering with the following equation

$$g = \frac{posttest - pretest}{100\% - pretest}.$$

4.2 Learning Climate Questionnaire

The LCQ measures the IM-supportiveness of a learning environment. The LCQ uses 15, seven-point Likert scale item to provide a single numerical rating of the learning climate. These items assess the instructor's support of students' decisions (autonomy), affirmation of students' ability (competence), approachability (relatedness), and communication of purpose (purpose).

5 Scaling the IM course conversion

We scaled the IM course conversion approach in the Fall 2012 offering of ECE 290. The course had two instructors: one was a member of the IM course conversion team and one was a neutral instructor who was willing to let us make changes to the course. It also had six TAs, none of which had taught with the intrinsic motivation pedagogy before and only one had any prior teaching experience. The course initially had 220 students enrolled and 216 of them finished the course.

To scale the IM course conversion, we maintained the core of the IM course conversion design process. We kept the same strategic core as the pilot, the instructors still lectured as they normally would, and students developed a series of learning agreements in learning teams. Similar to the pilot, a change in the TAs' duties represented the primary change to the course pedagogies. The course instructors also reduced some of their general purpose office hours and grading commitments to meet with individual learning teams during weekly consultation meetings (to be described later).

Evaluation of the pilot revealed four main shortcomings that we attempted to remedy with our initial scale-up effort. They were (1) choice paralysis during the first learning agreement, (2) lack of clear expectations for unfamiliar choices, (3) students regretted not choosing to do traditional written homework, and (4) TAs spent too much time grading.

1) During the pilot, we learned that we had offered the students too many choices. Because they had so many choices, students experienced a form of *choice paralysis*. Paralysis of choice is a problem in sales in which customers become overwhelmed when presented with too many brands or choices for a product and consequently choose not to choose and do not buy a product[28]. For example, if a customer wants to buy peanut butter and is presented with several brands, they are less likely to buy peanut butter than if they were presented with only two choices (including if their

desired brand was not for sale). During the negotiation of the first learning agreement, many teams saw so many choices that they chose to not choose and asked the TA to decide for them or they became overwhelmed with the choices and quickly retreated to the traditional course design.

2) The vast majority of students chose to complete original design projects for their mastery options. Further, during exit interviews with students from the pilot, those who chose to do non-project mastery options expressed regret in those choices and wished that they would have done design projects instead. We believe that some of this lack of satisfaction came from the TAs' lack of clear expectations for what students could do for the other choices.
3) Students expressed the greatest satisfaction when they chose to complete the normal written homework assignments for their practice options. Students who chose other options similarly expressed regret for not doing the written homework assignments during exit interviews.
4) The TAs expressed frustration with the time commitments needed to both grade homework and supporting students' autonomy. A survey of the TAs revealed that most were spending close to 80% of their work time grading students' homework.

Given these lessons from the pilot, we modified the full-scale IM course conversion. First, we required all students to complete design projects for their mastery components. To continue supporting students' autonomy, though, students were given a list of six design projects that they could complete for the first learning agreement. Students rated each of the projects based on their interest in that project, and learning teams of five to six students were formed based on students' ratings of those projects. Each team worked on one design project per learning agreement. On the second and third learning agreements, students still completed projects, but they were encouraged to propose their own project ideas.

Second, we required all students to complete the written homework. However, we moved to a nuanced completion-based grading policy to further support students' sense of competency and relatedness and to reduce the TAs' time spent grading. Rather than have students turn in their homework and wait for TAs to grade and return the homework, each learning team scheduled a one hour weekly consultation meeting with one of the TAs or one of the instructors who became their "team leader." Students were expected to bring their completed homework assignments to the weekly consultation meeting. During this weekly consultation meeting, the team leader and learning team discussed the problems through a mixture of oral quizzes and group discussions. Students received credit for completing the written homework if they made meaningful contributions to the group discussions; meaningful contributions were defined broadly to include simply bringing questions indicating what they did not understand. Any remaining time during the weekly consultation meeting was used to help students make progress in their projects. These weekly consultation meetings gave the students more time with the course staff and their peers, increasing their sense of relatedness, and allowed them to receive more personalized and faster feedback than the previous model of grading, increasing their sense of competence. By trading grading hours for weekly consultation hours, we also did not increase the TAs' time commitment in teaching the course.

To further support students' autonomy, we also developed a formal petition process through which students could petition to change <u>any</u> component of the course. A few learning teams took advantage of this process. For example, one learning team petitioned to have only two learning agreements so that they could undertake larger projects for each learning agreement. Some students similarly petitioned to not take the final examination so that they could try to complete ambitious projects that would not have been possible if they had to complete them during the standard time frame.

The primary cost of the course conversion came from the development and refinement of the grading rubrics for these open ended projects. In the smaller pilot, we could provide more direct training to each of the TAs to help them learn how to grade open ended projects. However, with the increased scale and number of TAs, we could no longer offer this level of training. The initial rubrics we designed proved to be too ambiguous for the TAs. As a result, a surprisingly large number of learning teams received full points for the first project despite a wide range in quality in the projects and students' demonstrated learning. Further negotiation and training of the TAs helped to clarify expectations, but refinement of the rubrics mid-semester created an unexpected time cost in the reform process. However, we believe that the time cost of creating future rubrics will be lower now that we have begun to identify some of the pitfalls of grading different projects.

6 Student Contributions

The scale-up effort was also further supported by intrinsically motivated students. Four students from the pilot IM course conversion volunteered to serve as peer mentors. These peer mentors acted as team leaders for three learning teams during their weekly consultation meetings to help reduce the teaching load of the TAs. These students volunteered because they had had a positive experience in the pilot course and they recognized an opportunity to learn team management skills which they hoped would be helpful later in their careers as engineers. We expect that more students from the scaled IM course conversion will similarly wish to return as peer mentors. If sufficient numbers of students volunteer as peer mentors, we could potentially even lower the financial cost of the IM course conversion by reducing the number of TAs required to run the course.

Students within the course also made contributions to improve the course and aid future efforts to improve scaling the course. For example, one team opted to write online simulation tools to demonstrate and teach key concepts of the course as part of their learning agreement. Similarly, four learning teams decided to produce online video lectures to help the course move towards a "flipped classroom" model in which students would watch online video lectures so that all class time could be used to support students' autonomy and to give students feedback on their learning. By creating a library of online video lectures, we expect to further reduce the time cost of the instructor.

7 Preliminary Evaluation

7.1 Results from the Digital Logic Concept Inventory (DLCI)

Table 2 presents the results from the historic and new administrations of the DLCI. The historical data was collected from previous offerings of ECE 290 when the course was taught with three lectures per week with little or no interactive engagement pedagogies. The table also shows the gains of the interactive-engagement-based offerings of ECE 290, the pilot IM course conversion, and the scaled IM course conversion. The literature shows that 0.1 to 0.3 normalized gains (low gain) on concept inventories are typical for lecture-based courses and 0.4 to 0.6 normalized gains (medium gain) are typical for interactive-engagement-based courses[24,27,29].

As expected from the literature, the normalized gains of the interactive engagement pedagogy, pilot intrinsic motivation pedagogy, and scaled intrinsic motivation pedagogy are all statistically significantly higher than the normalized gains of the lecture-based pedagogy of the course when using Welch's t-test ($p < 0.01$). Surprisingly, the scaled intrinsic motivation pedagogy achieved statistically significantly higher gain than the pilot intrinsic motivation pedagogy and the interactive engagement pedagogy.

Table 2: Pre-test and post-test scores (out of a range of 0-24) for different offerings of ECE 290 along with calculated normal gains. Both the interactive engagement and intrinsic motivation pedagogies improved learning.

	Term(s)	N	Pre-test	Post-test	Normalized Gain
Aggregate Lecture Based	2008-2010	688	9.65	13.26	0.25
Interactive Engagement	Fall 2011	128	9.67	17.11	0.52
Pilot Intrinsic Motivation	Fall 2011	37	9.56	16.94	0.51
Scaled Intrinsic Motivation	Fall 2012	220	8.74	18.64	0.65

7.2 Results from the Learning Climate Questionnaire (LCQ)

Table 3 displays the students' learning-climate ratings from the LCQ.

Table 3: Climate scores for ECE 290 when taught with interactive engagement pedagogies, pilot intrinsic motivation pedagogies, and scaled intrinsic motivation pedagogies

	N	Climate Score
Interactive Engagement	122	5.3
Pilot Intrinsic Motivation	24	6.0
Scaled Intrinsic Motivation	148	5.9

The LCQ results revealed significant differences ($p < 0.01$) in students' perceptions of the learning climate in both intrinsic motivation pedagogies as compared to the interactive engagement pedagogies. The effect size (Cohen's d) for the difference was moderate ($d = 0.5$) in both cases. These results indicate that students perceived greater support of the four intrinsic motivation constructs of autonomy, competence, purpose, and relatedness.

8 Conclusions

We believe that this initial scale-up effort of the IM course conversion project provides evidence for our theory that we can drive education reform by focusing on improving students' intrinsic motivation to learn while making adjustments that are low-cost to the instructing faculty. By creating a strategic core, we can focus students' learning and instructional decisions. By giving students structured choices, we can promote their sense of autonomy and their intrinsic motivation to learn as long as we do not present them with so many choices that they suffer from choice paralysis. By swapping the time cost of grading to spend more time with students, we can also further promote students' intrinsic motivation to learn. While we have found that these techniques are some useful ways to provide students with an IM-supportive learning environment at large scale, we do not believe that this list of techniques is exhaustive and may not include the most effective techniques. We hope that future research and future IM course conversions will help us develop models for IM course conversions that are adoptable in other courses in other disciplines and other schools.

We also believe that this initial scale-up has provided evidence for the hope that students can also become part of the engine that drives education reform. As students experience positive learning experiences, they often want to enable other students to experience it. The role of peer mentors in supporting students' autonomy and competence and online content generation are promising ways in which intrinsically motivated students can lower the costs of reform and promote better learning[30,31].

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