



Scaling Up Education Reform

By Jon D.H. Gaffney, Evan Richards, Mary Bridget Kustus, Lin Ding, and Robert J. Beichner

Picture your favorite restaurant. Which aspects make it a relaxing, comfortable environment? What if you could take those aspects and apply them to a classroom? Imagine students seated at round tables, discussing physics while “waiters” (the course instructors) bounce around among the tables, asking questions. In fact, many such classrooms are now in operation across the country, and studies are showing major benefits over traditional lecture settings.

Over the years, quite a few pedagogical advances have been demonstrated to work effectively (see Figure 1). The common factor in most of them is interaction. However, economics at large universities simply require that classes have large enrollment to be sustainable. The SCALE-UP (Student-Centered Activities for Large Enrollment for Undergraduate Programs) project was developed to implement reforms designed for small classes into large physics classes.

Notwithstanding its specific initial motivation, the SCALE-UP learning environment is general in terms of both class size and discipline. Over 50 schools across the country, ranging from Wake Technical Community College to Massachusetts Institute of Technology (MIT), have adopted it for classes of various sizes. SCALE-

UP has also been employed in a variety of courses such as chemistry, biology, mathematics, engineering, and even comparative literature.

In this article, we will discuss the classroom design and teaching techniques that allow pedagogical advances to be used in large-enrollment classes. Should you want even more details of the implementation and research underpinnings, a more in-depth description can be found in Beichner et al. 2007.

Designing the classroom

Each school that implements SCALE-UP adapts it to meet the school’s needs (see Figure 2 for a possible layout; bear in mind that the design of the classroom was not accidental—several iterations were made before we found a large classroom design that would promote interactive learning). The tables are the most important technological presence in the classroom. Their 7-foot diameter is optimal, as larger tables are not conducive to conversation and smaller tables are too crowded. Around each table sit nine students in groups of three, denoted by the letters A, B, and C. This group structure is regularly used for in-class activities, where each group member has a specific role that changes for each activity (see Figure 3). The groups are also

intended as a support mechanism to help students outside of class and are periodically changed to ensure optimal effectiveness (Heller and Hollabaugh 1992).

In front of each student is a nametag, held in place with an aluminum name block (see Figure 4; later in this article we will describe an activity using these). The nametags are always prominently displayed so that no student can remain anonymous. In a SCALE-UP classroom, it is impossible for a student to hide; the design of the room prohibits students from choosing a seat in the middle of a row or in the back of the class. Students are accessible to the instructors and to each other, and any student can be asked to present work at any time. This promotes individual accountability while enhancing personal interaction among students and with the instructors (Johnson, Johnson, and Smith 1991).

Also shared by each group is a computer connected to the internet and loaded with course-relevant software. The instructor’s computer is able to observe and, if necessary, control students’ computers to prevent distraction. While computers are quite helpful if present, SCALE-UP can be run without them.

Located on all walls of the classroom are whiteboards; additional personal whiteboards are distributed as needed. These whiteboards are

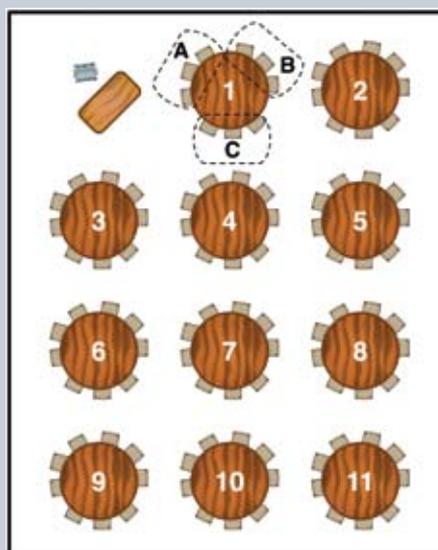
FIGURE 1**Pedagogical techniques and specific examples of reform implementation in the physics domain.**

Pedagogical technique	Example of implementation
Collaborative learning (Johnson, Johnson, and Smith 1991)	University of Minnesota Collaborative Groups (Heller and Hollabaugh 1992)
Learning by inquiry (Prince and Felder 2006)	Physics by inquiry (McDermott and University of Washington Physics Education Group 1995)
Problem solving (Evensen and Hmelo 2000)	Minnesota real-world problems (Heller and Hollabaugh 1992), computer modeling (Scherer, Dubois, and Sherwood 2000)
Social constructivism (Vygotsky 1978)	Peer instruction (Mazur 1997), polling questions (Judson and Sawada 2002)
Proximal development (Vygotsky 1978)	Just-in-time teaching (Novak, Patterson, and Gavrin 1999)
Communication (Rivard and Straw 2000)	Modeling method (Wells, Hestenes, and Swackhamer 1995)

essential for students to produce visible work. Group members are able to see and discuss what is written on the boards, while instructors are able to observe and comment. Some schools find that video cameras are a convenient aid for displaying student work (as well as demonstrations) to the entire class.

Present in the classroom with the lead instructor is a teaching assistant or two, depending on class size. A ratio in excess of one instructor to about fifty students is inadvisable. The responsibility for the class is generally shared among all instructors, who collaborate on the construction, implementation, and evaluation of activities and instruction. The instructors rarely sit, as they are continually interacting with students: answering and asking questions, distributing resources, and listening to what students are saying.

Much of the course is organized through an online homework submission program (we use WebAssign [www.webassign.net]) as the online homework system and platform for some in-class activities and polling questions; unlike most polling systems, WebAssign allows students to enter a justification for their answers). Such a resource greatly reduces the time required to grade homework, frees up the instructors for instruction, and can be used for in-class activities. Additionally, a class website is maintained that provides resources for

FIGURE 2

A possible SCALE-UP layout for a 40' x 50' room. The tables have a 7-foot diameter. The instructor station can go anywhere in the room; its location depends on doorways and teachers' preferences. Such a room can hold 99 students. Three groups of three students are at each table. There are three laptops at each table, and whiteboards surround the room.

students, including an electronic copy of any notes from class.

While the course contains the same content as its traditional counterpart, the flexible structure of SCALE-UP allows the class to spend more (or less) time on materials as necessary. Since the instructors are continually receiving feedback, they are in an excellent position to adjust lessons as dictated by the class's needs.

Designing the lessons

While the classroom layout is vital to the success of the program, SCALE-UP is fundamentally more than just a

redesigned room; rather, SCALE-UP is a heads-on and hands-on environment that is compatible with a myriad of educational activities.

Many of the activities run in SCALE-UP are classified as either "tangibles" or "ponderables." Tangibles, along with more formal laboratory experiments, are opportunities for students to use scientific or everyday equipment (such as racquetballs and transparent tape) in an inquiry-based setting (Prince and Felder 2006). Through tangibles, we guide students to enhance their estimation and conceptual skills, as well as provide some

FIGURE 3

Specific group roles for various activities in SCALE-UP.

	Recorder	Skeptic or Questioner	Manager or Organizer	Summarizer
“Ponderables” or whiteboard problems	<ul style="list-style-type: none"> Writes problem steps on the whiteboard Ensures all agree on each step of solution Verifies all members understand solution 	<ul style="list-style-type: none"> Ensures that all strategies are explored Suggests alternative approaches to problem Checks solution validity (reality, units, etc.) 	<ul style="list-style-type: none"> Provides sequence of steps in the problem Manages time and keeps group on task Ensures participation by each group member Reinforces the merits of everyone’s ideas 	<ul style="list-style-type: none"> Summarizes group discussion/solution Maintains group energy and enthusiasm Suggests new ideas when motivation is low
“Tangibles” or experiments	<ul style="list-style-type: none"> Monitors/records experimental data Ensures all agree on experimental results Verifies all members understand data/results Submits lab reports 	<ul style="list-style-type: none"> Ensures that data interpretation is correct Suggests alternate methods/interpretations Checks validity of experimental results Ensures questions/results fully explored 	<ul style="list-style-type: none"> Provides outline of experimental procedure Manages time and keeps group on task Ensures participation by each group member Reinforces the merits of everyone’s ideas 	<ul style="list-style-type: none"> Summarizes group plan/results Maintains group energy and enthusiasm Suggests new ideas when motivation is low
Computer programs	<ul style="list-style-type: none"> Types the code Ensures all agree on the typed code Verifies all members understand the code Submits programs 	<ul style="list-style-type: none"> Debugs the program Suggests alternative organization/expression Checks validity of program (reality check) 	<ul style="list-style-type: none"> Provides steps with pseudo code outline Manages time and keeps group on task Ensures participation by each group member Reinforces the merits of everyone’s ideas 	<ul style="list-style-type: none"> Summarizes group discussion/conclusions Maintains group energy and enthusiasm Suggests new ideas when motivation is low

The roles are based on the University of Minnesota group role definitions (www.co-operation.org). These roles are rotated through the group on a per-activity basis. To see examples of what the roles “sound like,” visit <http://scaleup.ncsu.edu>. Ideally, all students would be in a group of three and the role of summarizer would not be used. However, in most classes, the number is not evenly divisible by three, so occasionally students are placed into groups of four. Rather than having a second skeptic (which is one possible solution), we prefer to introduce a new role: the summarizer. Groups of four rotate among these four roles, but groups of three only use manager, recorder, and skeptic.

real-world connections and address scientific methodology.

Ponderables are problems that students discuss and solve, usually on whiteboards. These can range from simple calculations to complex paradoxes. Computer modeling (we use VPython [www.vpython.org]) and simulations are often included in more complicated problems to help students visualize abstract three-dimensional concepts (Scherer, Dubois, and Sherwood 2000; Beichner 2006). Along with tangibles, ponderables are designed to ensure that students who understand the material can encourage and aid those who do not.

Discussions, our term for informal lecture sessions, are typically limited to 15–20 minutes each, and are used to connect the activities, rather than the other way around. We introduce concepts as they are needed, after students have read the relevant sections in the book and usually after they have attempted homework.

Within our discussions, we often ask polling questions (Judson and Sawada 2002), which are multiple-choice questions that poll the entire class, or table questions. Table questions are open-ended questions that are meant for short deliberation at each table. A student at a random table is selected (us-

ing a 12-sided die) to present the table’s answer, and the instructor builds on that answer in the discussion.

No single approach or activity is able to accomplish all of the goals of our class; we therefore assemble activities specific to our needs. For example, if we are introducing a topic, we often choose tangibles to enhance real-world connections; if we want to encourage a problem-solving method, we often choose ponderables.

We use laboratory experiments in SCALE-UP, as well. However, students do not attend separate class and laboratory sections. Instead, SCALE-UP allows for the labora-

FIGURE 4

The name block used in the activity discussed in the paper.



Name-block activity

To illustrate how the SCALE-UP environment works, consider this example activity that is used in the introductory calculus-based physics class. We ask students to calculate the mass of a single atom of aluminum and to estimate the number of atoms that are located along an edge of their name block (see Figure 5 for calculations based on actual measurements; student estimates

are typically correct to one significant figure). The procedure we follow and the reasoning behind it are provided as an example of a beneficial activity that is easy to implement in a SCALE-UP class. Before beginning, we assign specific roles within each group. This can be done informally, by saying something like, “Whoever has the most exciting plans this weekend will be the recorder; whoever is planning on studying the most will be the skeptic.” We find that doing so allows for a moment of casual interaction that encourages a friendly classroom environment.

First, we ask students to estimate the mass and dimensions of the name block, using whatever means they wish (we do not provide them with rulers, but we do give them 100-gram masses to heft). This provides students with an opportunity to practice estimation, a useful skill for engineers and scientists.

Next, based on their estimates of mass and volume, students calculate the density of aluminum and record their work on whiteboards. After this, they are told to look up the density using the internet. At this point, an instructor asks a student to tell the class what value that student’s group found and why the internet site should be considered valid. Justification is important because so much information is available online; requiring it encourages skepticism, especially within the realm of technology.

After the class has agreed on a value for the density of aluminum, we ask students to estimate the number of moles, and therefore the number of atoms, of aluminum in the block. After allowing a few minutes of conversation, we synchronize the class and discuss the estimates. Students are encouraged to present and defend their estimates and to respectfully criticize others’. Once the class agrees, we guide students through the following, more complicated steps.

Since the name block’s shape is essentially two cubes stuck together, students are told to focus only on one cube at a time, dividing their “number of atoms” estimate in half. Next, we introduce to students the ball-and-spring model for solids and distribute small cubic models to the tables (see Figure 6). Students use these models to figure out how many atoms are on each edge of the cube, a task that requires sophisticated reasoning.

When we are sure that most of the groups have accomplished the task, an instructor rolls a 12-sided die to randomly select a table. A representative for one of the groups at that table (selected by rolling the die a second time) makes a short, informal presentation of that group’s results. Picking a random table promotes individual accountability, enforcing the notion that students are responsible for their own understanding. After the calculation of the number of atoms along each edge, the instructor presents a quick calculation to show how to determine the distance between neighboring atoms. Alternatively, students could calculate this by themselves or in their groups.

Finally, we ask students to find the mass of an atom of aluminum. Some students are able to immediately calculate the mass of a single atom, but many students need help. We attend to individual groups as needed, and students who are able to do the calculations on their own are asked to assist other groups. This promotes community and communication.

Following the investigation, we present the summarized results that

tory experiments to occur naturally as the material calls for them. We utilize the laboratory experiments to introduce the topic, to provide a real-world example of physics concepts discussed previously, or to provide a platform for student inquiry. The laboratory reports can be used as an opportunity to practice scientific communication. When a group is responsible for a report, they collaborate and learn about sharing responsibility for authorship within the scientific community. Additionally, because of the presence of computers within the classroom, the laboratories can be integrated with computer modeling, providing an additional dimension to visualization. Computer simulations, computer programming, and other visualization programs also blend easily into lessons.

As a dynamic project, we continue to develop new activities and adopt helpful tools. For example, in future iterations of SCALE-UP, we plan to implement homework journals. Homework journals will allow us to periodically grade each student’s ability to organize and solve complex problems (since online-submission grading programs only grade final answers), provide feedback about specific difficulties, and track the improvement of each student’s problem-solving skills throughout the course. They will also help students study, since the homework will be consolidated.

FIGURE 5

Calculations for the name-block activity, using measurements.

a.

Find your name block's density.

$$V_{\text{block} + \text{slot}} = (3.78 \text{ cm})(1.92 \text{ cm})(1.92 \text{ cm}) = 13.9 \text{ cm}^3$$

$$V_{\text{slot}} = (0.1 \text{ cm})(1.1 \text{ cm})(1.9 \text{ cm}) = 0.2 \text{ cm}^3$$

$$V_{\text{block}} = 13.7 \text{ cm}^3$$

$$m = 36.3 \text{ g}$$

$$\rho = \frac{m}{V_{\text{block}}} = \frac{36.3 \text{ g}}{13.7 \text{ cm}^3} = 2.6 \frac{\text{g}}{\text{cm}^3}$$

One mole of aluminum has a mass of 27 g, so how many moles are in your block?

$$\frac{36.3 \text{ g}}{27 \text{ g/mole}} = 1.3 \text{ moles}$$

How many atoms are in your block?

$$1.3 \text{ moles} (6 \times 10^{23} \frac{\text{atoms}}{\text{mole}}) = 7.8 \times 10^{23} \text{ atoms}$$

Your block is roughly two cubes, each with 3.9×10^{23} atoms. How many atoms per side of that cube?

$$\sqrt[3]{3.9 \times 10^{23}} = 73 \times 10^6 \text{ atoms on a side}$$

So the block is roughly 73 by 73 by 150 million atoms.

How far apart are the atoms? This is approximately the diameter of an atom.

$$d_{\text{atom}} = \frac{0.0192 \text{ m}}{73 \times 10^6 \text{ atoms}} = 2.6 \times 10^{-10} \frac{\text{m}}{\text{atom}} = 2.6 \text{ \AA}$$

What is the mass of a single atom?

$$m_{\text{atom}} = \frac{36.3 \text{ g}}{7.8 \times 10^{23} \text{ atoms}} = 4.7 \times 10^{-23} \frac{\text{g}}{\text{atom}} = 4.7 \times 10^{-26} \frac{\text{kg}}{\text{atom}}$$

Note that there is a direct way to calculate that value without referring to a specimen:

$$m_{\text{atom}} = \frac{27 \frac{\text{g}}{\text{mole}}}{6 \times 10^{23} \frac{\text{atoms}}{\text{mole}}} = \frac{M}{N_{\text{Avogadro}}}$$

$$m_{\text{atom}} = 4.5 \times 10^{-23} \frac{\text{g}}{\text{atom}} = 4.5 \times 10^{-26} \frac{\text{kg}}{\text{atom}} \text{ (dimensional analysis)}$$

Also, there is a direct way to calculate distance between atoms:

$$\rho_{\text{micro}} = \frac{m_{\text{atom}}}{V_{\text{atom}}} = \frac{m_{\text{atom}}}{d_{\text{atom}}^3} = \frac{N_{\text{atoms}} m_{\text{atom}}}{N_{\text{atoms}} d_{\text{atom}}^3} = \rho_{\text{macro}}$$

b.

$$d_{\text{atom}} = \sqrt[3]{\frac{m_{\text{atom}}}{\rho_{\text{macro}}}} = \sqrt[3]{\frac{M/N_{\text{Avogadro}}}{\rho_{\text{macro}}}}$$

$$\rho_{\text{macro}} = \left(2.7 \frac{\text{g}}{\text{cm}^3}\right) \left(\frac{1 \text{ kg}}{1000 \text{ g}}\right) \left(\frac{100 \text{ cm}}{1 \text{ m}}\right)^3 = 2.7 \times 10^3 \frac{\text{kg}}{\text{m}^3}$$

$$d_{\text{atom}} = \sqrt[3]{\frac{4.5 \times 10^{-26} \frac{\text{kg}}{\text{atom}}}{2.7 \times 10^3 \frac{\text{kg}}{\text{m}^3}}}$$

$$d_{\text{atom}} = 2.6 \times 10^{-10} \text{ m}$$

Group A, find the mass and diameter of gold atoms.

$$\rho = 19.3 \frac{\text{g}}{\text{cm}^3}, M = 197 \frac{\text{g}}{\text{mole}}$$

$$m_{\text{atom}} = 3.3 \times 10^{-25} \frac{\text{kg}}{\text{atom}}, d = 2.6 \times 10^{-10} \text{ m}$$

Group B, find the mass and diameter of lead atoms.

$$\rho = 11.4 \frac{\text{g}}{\text{cm}^3}, M = 207 \frac{\text{g}}{\text{mole}}$$

$$m_{\text{atom}} = 3.5 \times 10^{-25} \frac{\text{kg}}{\text{atom}}, d = 3.1 \times 10^{-10} \text{ m}$$

Group C, find the mass and diameter of copper atoms.

$$\rho = 8.23 \frac{\text{g}}{\text{cm}^3}, M = 64 \frac{\text{g}}{\text{mole}}$$

$$m_{\text{atom}} = 1.1 \times 10^{-25} \frac{\text{kg}}{\text{atom}}, d = 2.4 \times 10^{-10} \text{ m}$$

the class developed, emphasizing that an actual specimen like the name block is not needed. A follow-up task is then assigned to each of the A, B, and C groups. Each letter group is told to find the mass and distance between neighboring atoms for a different metal. Again, at the end, random students are called on to present their results. The class takes note of which values are similar and which are different across the various metals.

Immediately following the activity, we have students hand their notebooks to the student on their right (which is easy to do when seated at a round table) and record in that notebook the main points of the activity. This is a structured form of reflection, allowing students a few moments to synthesize the activity and to contribute to another student's understanding.

Impact on students

Based on data that we have collected, we have reason to believe that every student can benefit from the SCALE-UP environment. Below are some highlights of a relevant study conducted by Beichner and his colleagues (2007).

Failure rates of women and minority students are dramatically reduced to as little as a fifth of the rate of traditional classes. Failure rates of "at-risk" students in later classes are also reduced by more than half.

Across the board, conceptual learning is improved as can be seen from impressive gains on the Force Concept Inventory (FCI) (Hestenes, Wells, and Swackhamer 1992). At our university (as well as other institutions), the normalized gain on the FCI was double that of a traditional lecture course. Moreover, the best students showed the largest gain on standardized conceptual tests, showing that stronger students have already learned most of what can be gleaned from lecture, but that they still have more to learn, especially when they have the opportunity to teach others. Studies like these, involving a wide array

FIGURE 6

The ball-and-spring model used in the name-block activity.



of concept assessments and other measures of learning, show that a SCALE-UP environment provides students with the opportunity to learn more, not only in terms of their conceptual gains, but also in their problem-solving abilities. As noted earlier, detailed research results are available elsewhere (Beichner et al. 2007).

Building a “restaurant” classroom of your own

SCALE-UP is dynamic and continues to improve. Dissemination is an ongoing project, and over 50 locations have already adapted our model to suit their objectives. While there are challenges involved in transforming a traditional lecture class to a SCALE-UP environment, colleagues from our university and other locations have experience and are willing to help in the process. If you are interested in learning more or want guidance in starting your own “restaurant,” contact us or one of the many adopters listed at <http://scaleup.ncsu.edu>.

The vision to enhance student understanding by allowing students to learn collaboratively no longer needs to be constrained by the limitations of a large class. SCALE-UP provides a way to overcome that barrier and deliver an interactive

community to all students regardless of class size. ■

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