A Student-Centered Active Learning Environment for Introductory Physics

Gerald Feldman (feldman@gwu.edu) and Larry Medsker (lrm@gwu.edu)
Department of Physics
George Washington University
Washington, DC 20052 USA

Nawal Benmouna (nawal.benmouna@montgomerycollege.edu)
Department of Physics, Engineering and Geosciences
Montgomery College
Rockville, MD 20850 USA

I. Introduction

Studies of undergraduate science education have shown that students need to be actively engaged in the learning process in order for it to be effective. Passive lecturing ("teaching by telling") is known to be ineffective in developing students' skills in critical thinking [1]. One of the first collaborative group-learning environments ("studio physics") was developed by Wilson [2] in the mid-1990's to address this issue — students worked together in small groups and the instructor served as a facilitator or "coach" instead of a lecturer. A critical aspect of the studio approach is the integration of laboratory activities into the classroom — in this manner, class time is filled with a seamless progression of activities, ranging from group problem-solving exercises to lab experiments to short demonstrations to mini-lectures. By merging the collaborative approach with the integration of various pedagogical activities, a dynamic collective learning environment is created.

A practical limitation of the studio method is the small class size — it is simply not possible to staff multiple sections of a course with limited faculty resources. Beichner at North Carolina State University has pioneered an extension of the studio approach, called SCALE-UP (Student-Centered Active Learning Environment for Undergraduate Programs), which adapts the method for larger class sizes (*e.g.*, up to 99 students) [3]. In this scheme, round tables accommodate 3 groups of 3 students (9 students per table) for all classroom activities. For a class of this size, one instructor and two Teaching Assistants are sufficient to handle the questions and to promote useful discussions among the students.

The SCALE-UP pedagogy has several basic characteristics: active learning, collaborative groups, integrated lecture/laboratory and technology assistance. In a SCALE-UP classroom, there is minimal lecturing in the conventional sense. The students are expected to prepare for class by reading the textbook in advance, and then most of the class time is spent enriching the material by engaging the students in a variety of hands-on and "minds-on" activities. In that regard, the activities are built around three fundamental pillars: (1) *ponderables* are problems to think about, both numerical and conceptual, that students work on together in their groups with portable white boards, (2) *tangibles* are hands-on activities, ranging from short 5-minute demonstrations to more lengthy laboratory experiments, and (3) *computer simulations* that help the students model physical trends and behavior, usually done using the VPython language [4].

There are over 50 institutions in the United States that have adopted the SCALE-UP pedagogy, and at present there are at least a dozen institutions in other countries implementing this approach as well. The SCALE-UP web site at North Carolina State University has a wealth of information about this collaborative approach and the results at various institutions [5].

II. Implementation

We have implemented the SCALE-UP approach at George Washington University (GWU) for our calculus-based introductory physics class and the first semester of our algebra-based class. We have redesigned a classroom with 6 round tables, able to accommodate a total of 54 students. Each group of 3 students shares a laptop computer and has a portable white board to facilitate their work together. The classroom walls have large white boards on which students can display their work, 4 large LCD screens for image projection, and storage cabinets for lab equipment. For a room of this size, one instructor and one Teaching Assistant can provide sufficient coverage for all students. A schematic drawing of our SCALE-UP classroom is shown in Fig. 1 below.

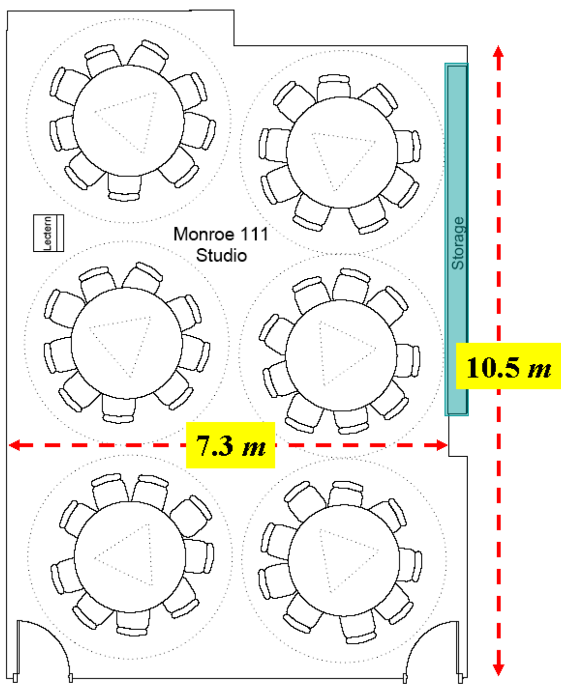

Fig. 1: Schematic view of the SCALE-UP classroom. The instructor station is mobile and can be located anywhere in the room. The storage cabinets for equipment and laptop computers are located on the right-hand wall.

We instituted SCALE-UP in Spring 2008, and at this point, we now have 5 semesters of experience. While most of our efforts have focused on the introductory calculus-based class that is typically taken by science majors and engineers (Phys 21 and 22), we have also tried out the collaborative approach in our algebra-based physics course (Phys 11) and also our astronomy class (Astr 1). A timeline of the development of SCALE-UP at our institution is given below:

- Spring 2008 – calculus-based Phys 21 and Phys 21 (bio-focused)
- Fall 2008 – calculus-based Phys 21, algebra-based Astr 1
- Spring 2009 – calculus-based Phys 21, Phys 22 and Phys 21 (bio-focused)
- Fall 2009 – calculus-based Phys 21
- Spring 2010 – calculus-based Phys 21 and Phys 22, and algebra-based Phys 11
- Fall 2010 – calculus-based Phys 21 and Phys 22, and algebra-based Astr 1

In our "usual" configuration, the class meets 3 times a week — 2 hours on Monday and Wednesday and 1 hour on Friday — with a weekly 15-minute quiz every Friday. Groups are carefully arranged by the instructor, and guidelines are clearly outlined in a "group contract" that is prepared by each group. The group assignments are switched at the mid-point of the academic semester — that is, the students are reorganized into different groups so as to keep the group interactions fresh and vigorous. In class, students work collaboratively on conceptual questions and numerical problems (*ponderables*) using their portable white boards, in addition to short hands-on activities and longer laboratory experiments (*tangibles*) using real-time data acquisition. It is necessary to point out that so far we have not yet included the computer simulations using VPython, primarily due to lack of time.

Homeworks are delivered via a web-based online system called *MasteringPhysics* [6] which is available through Pearson Higher Education, who is the publisher of the textbook that we use (*Physics for Scientists and Engineers: A Strategic Approach* by Randall Knight [7]). We typically assign 14 problems per week, with an additional 2 problems being available for extra credit. These assignments generally take about 3-4 hours to complete. Since lecture is reduced to a minimum, class preparation is an important consideration for students. To gauge their understanding and to motivate their preparation for class, pre-class "Warmups" are available online for students, also through the *MasteringPhysics* system. These consist mostly of about 10 multiple-choice conceptual questions related to the material to be covered in class on that day. The "Warmups" are expected to require about 30-40 minutes for completion and are presented to the students twice a week, before the Monday and Wednesday two-hour classes.

Tangibles are highly beneficial, and it is often a challenge to devise short demonstration exercises that take only 10 minutes or so. One example of a simple tangible is to drop a meter stick between the fingers of a student (see Fig. 2) to measure her reaction time using free fall. The distance that the meter stick falls before the student catches it can be converted into a time interval which is a rough estimate of the student's ability to react to the dropped meter stick.

Fig. 2: Example of a "tangible" to measure human reaction time. By dropping the meter stick from a fixed position, the time needed to catch the falling stick can be deduced by a direct measurement of the free-fall distance.

Another tangible actually begins with a ponderable, in which students calculate the angle at which a rough surface must be tilted in order to make a metallic block overcome static friction and slide down the plane. This exercise yields the usual $\mu_s = \tan\theta$ result with which we are all familiar. After the calculation, the students try the exercise themselves, using the rough cardboard backing of their own white boards as the inclined plane. Each group member takes a turn slowly tilting the white board until the metal block just begins to slide — then the other group members take length measurements that enable them to determine the angle of the board. After all three group members have tried this, the measurements are averaged and an overall average value of μ_s

is obtained. While the actual answer is unknown, the fact that 75% of the groups come up with a value within ±10% of $\mu_s = 0.35$ seems convincing that a consensus value has been reached.

Laboratory experiments also fall into the category of tangibles. For our real-time data acquisition, we use probes and software from Vernier [8]. While these exercises are not so different from a conventional lecture/lab course, the guidelines for conducting the experiments are "streamlined" to leave the exercise a bit more open-ended. Some of the experiments conducted in our SCALE-UP class include:

- using motion sensors to measure the acceleration of carts on an inclined plane (along with video analysis of similar motion)
- using motion sensors to analyze elastic and inelastic collisions of carts (along with video analysis of similar motion)
- measuring the moment of inertia of a uniform cylinder by wrapping it with a string attached to a mass and letting the mass fall, unwinding the string as it falls
- determining the mass of an automobile by measuring tire pressure and contact area
- determining the density of air by floating helium balloons
- measuring the specific heat of an unknown metal sample
- investigating the "coffee and cream" problem to ascertain whether cool cream should be added to hot coffee right away or after a waiting period

It is important for the students to have a means by which they can gauge their overall progress at regular intervals. Since homework assignments are often collaborative efforts (it is entirely acceptable and even encouraged for students to help each other in these assignments) and since exams are too infrequent and are often high-stakes (and high-stress) events, we have opted to give a quiz every Friday at the beginning of our one-hour class. The quiz lasts 15 minutes and contains one conceptual and one numerical problem (possibly with multiple parts). The main idea is to simulate an exam-like environment so that the students can get a sense of how they are doing on a weekly basis, thus enabling them to take the necessary steps if they feel that they are struggling with the conceptual or the problem-solving aspects of the course. The Friday quizzes have proven to be an excellent predictor of exam performance, as evidenced by the plots shown below in Fig. 3 from the Spring 2008 and Spring 2009 semesters.

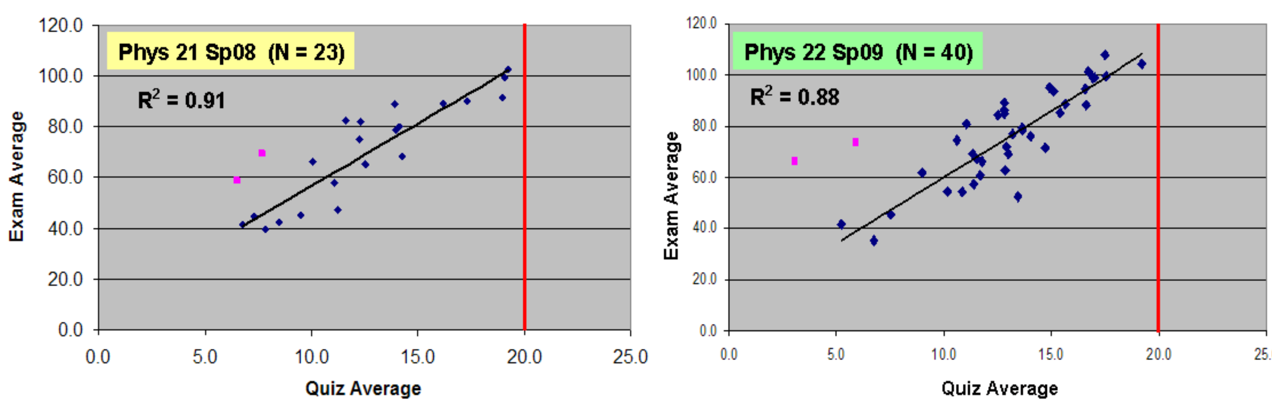

Fig. 3: Correlation between quiz grades and exam grades in the Phys 21 and Phys 22 classes. The maximum score on each weekly quiz is 20 points (indicated by the red marker). The pink data points were omitted from the linear fit, due to a large number of quiz absences for those students.

III. Results

We have several semesters of data for the Phys 21 class to assess the effectiveness of the SCALE-UP pedagogy at GWU. We have acquired data on the Force Concept Inventory (FCI) [9], as well as the Colorado Learning Attitudes about Science Survey (CLASS) [10] to examine student attitudes. In the first semester of our SCALE-UP deployment (Spring 2008), we had a large (concurrent) conventional lecture section take the same assessments for comparison purposes, including common in-class exams. The results of the in-class exams are shown in the table below.

	Exam #1	Exam #2	Final Exam
Standard Lecture (Sec. 10 — N = 50)	63.0	62.4	55.0
Bio-focused SCALE-UP (Sec. 11 — N = 14)	81.0	70.5	60.3
SCALE-UP (Sec. 12 — N = 23)	70.0	72.9	64.0

Both of the SCALE-UP classes (Secs. 11 and 12) exceeded the exam performance of the conventional lecture section (Sec. 10). While the bio-focused class (aimed primarily at biomedical engineers and biophysics majors) had additional biological content in the course and in their exams, a more direct comparison can be made between Secs. 10 and 12. It can be seen that the SCALE-UP section had an exam average about 9 points higher than the corresponding lecture section.

The Force Concept Inventory (FCI) [9] has been given to the Phys 21 classes in each semester. The composite FCI results over all five semesters are shown in Fig. 4 below.

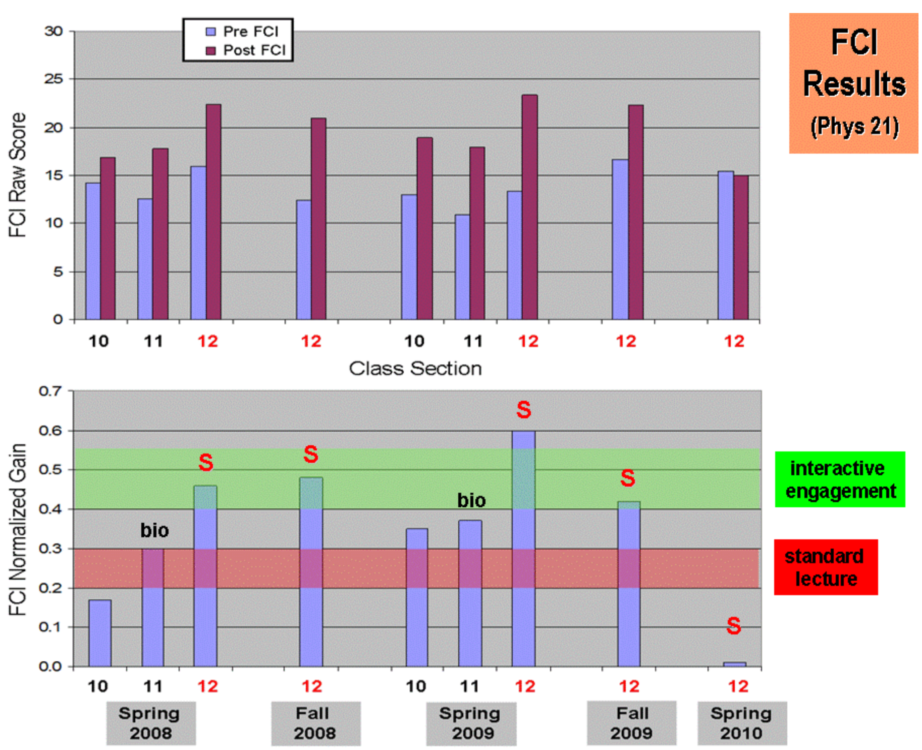

Fig. 4: Results from the FCI for the five semesters of Phys 21. The top panel shows the pre/post test scores; in the bottom panel, the normalized gain is displayed. SCALE-UP sections are indicated by a red "S"; bio-focused sections are indicated by "bio".

The top panel shows the pre- and post-test scores, where the maximum score is 30. The bottom panel shows the normalized gain $\langle g \rangle$ defined by Hake [11], such that $\langle g \rangle = \frac{post - pre}{30 - pre}$. Also shown is Hake's estimate of a range indicative of interactive engagement classes (the green band, for $\langle g \rangle$ = 0.40-0.55) as compared to conventional lecture classes (the red band, for $\langle g \rangle$ = 0.20-0.30). It is evident that the SCALE-UP classes (marked with a red "S") are performing very well, although the bio-focused SCALE-UP classes (marked by "bio") are only marginally outperforming the regular lecture classes (Sec. 10). All of the SCALE-UP classes are showing gains well into the interactive engagement domain (green band), with the exception of Spring 2010 when the delivery of the FCI post-test was somehow compromised by time constraints.

In the Spring 2008 semester, the Colorado Learning Attitudes about Science Survey (CLASS) [10] was given to all three sections of Phys 21. The results for the overall CLASS score are shown below in Fig. 5, where higher scores indicate more expert-like attitudes towards science.

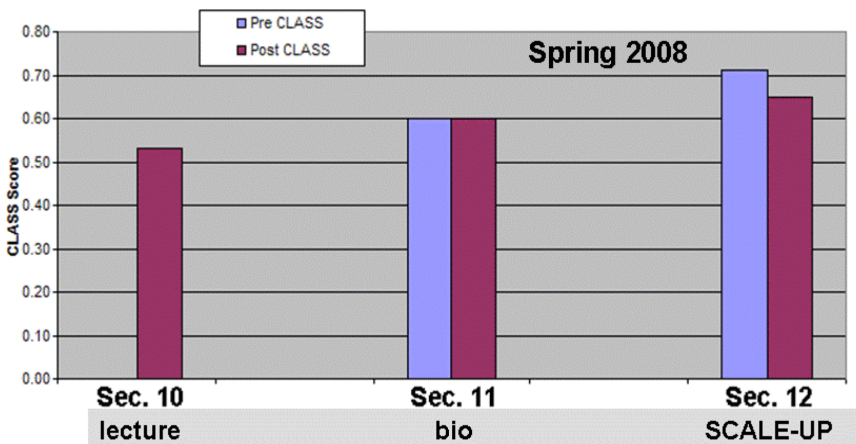

Fig. 5: Results for the pre- and post-tests from the CLASS survey for the Spring 2008 semester of Phys 21. There was no pre-test given at the start of the semester in the regular lecture class.

The main point of the CLASS survey is to observe the change in the students' attitudes from the beginning to the end of the semester. In this regard, the results do not look very impressive — none of the sections showed a gain (and in fact, Sec. 10 had not administered the pre-survey). This result is typical of calculus-based classes that have been surveyed, that is, the students actually show a deterioration of their attitudes after the semester.

Since there was no pre-survey for Sec. 10, it is interesting to look in more detail at the post-only results for all three sections. These results are shown below in Fig. 6, broken down into the 8 categories that are identified for the CLASS questions. The red arrows highlight specific categories in which the SCALE-UP section (Sec. 12) showed a significantly higher score in the post-survey. Note that these categories relate to problem solving and conceptual understanding. It is noteworthy, however, that the bio-focused section (Sec. 11) came out slightly ahead in the "Real World Connection" category (indicated by the blue arrow), possibly due to the emphasis on biological applications of physics principles.

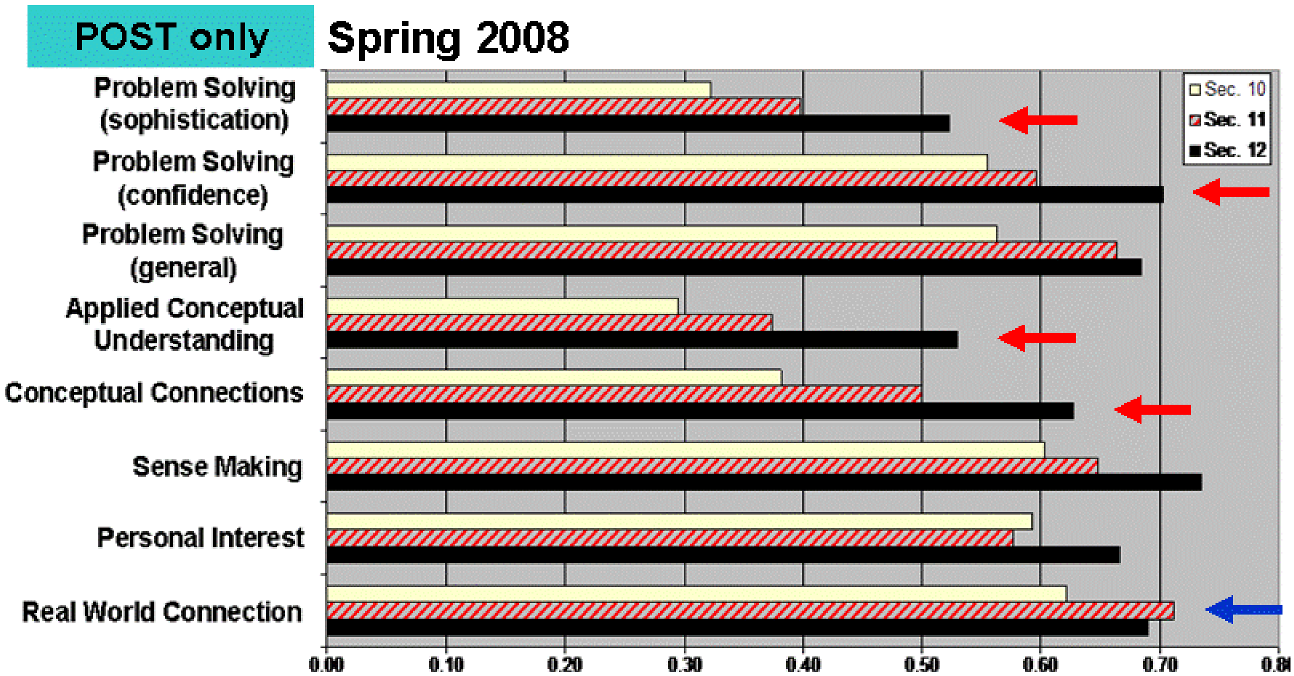

Fig. 6: Post-survey results only for the CLASS survey in the Spring 2008 semester of Phys 21, broken down into the individual component categories for science and attitudinal characteristics.

While most of the data that we have obtained thus far (as reported above) pertains to the Phys 21 class, we also have two semesters of experience with the second semester course, Phys 22. In this case, the standardized assessment that we used is the Conceptual Survey of Electricity and Magnetism (CSEM) developed by Maloney *et al.* [12]. Our results are compared to those of other institutions in Fig. 7 below — our data have been added to the plot from Ref. [12] as the filled green circles. The pre-test and post-test scores are plotted on the x and y axes, and lines corresponding to various values of the normalized gain $\langle g \rangle$ are shown. Note that the two GWU semesters are fairly consistent with each other (two different years and two different instructors) and that the gain values of 41% and 44% are among the highest values compared to other institutions.

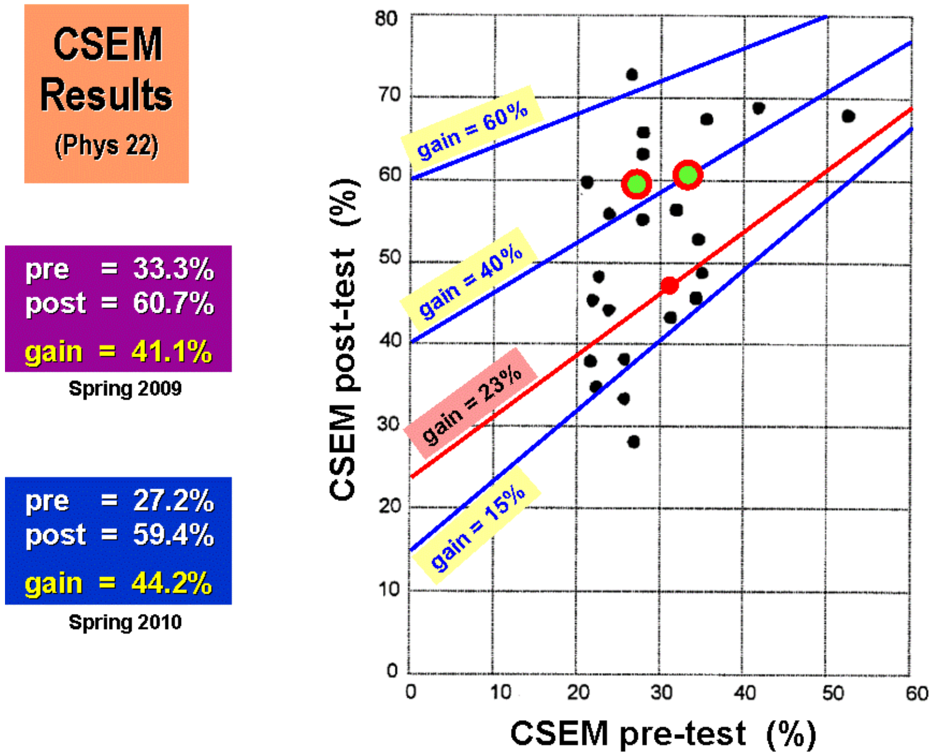

Fig. 7: Results from the CSEM for the two semesters of Phys 22, compared to the results from other institutions [12]. The specific pre- and post-test scores (with the corresponding normalized gains) are shown on the left, and these results are plotted as the two green data points. Different gain values are shown as lines of constant slope.

IV. Extensions

At GWU, we are working to extend the SCALE-UP environment by modifying one of our introductory laboratory rooms (smaller than our existing SCALE-UP room). The modular trapezoidal tables shown in Fig. 8 below can be formed into hexagons, allowing us to arrange 24 students into 4 tables of six students each. This is shown in the left-hand panel of the figure. While this lab room is not used for the full deployment of SCALE-UP, the configuration of the room does at least enhance the collaborative nature of the introductory lab sessions which are associated with the conventional lecture courses. In this manner, we are able to offer labs in a “mini SCALE-UP” format that is more conducive to group learning.

The modularity of the trapezoidal tables permits easy rearrangement into other configurations. One alternate example, a standard classroom with parallel rows of desks, is shown in the right-hand panel of the figure. Other configurations are also possible, such as a single large circular conference table for meetings. Thus, this smaller SCALE-UP room has a built-in flexibility which makes it extremely versatile for a variety of academic or administrative functions.

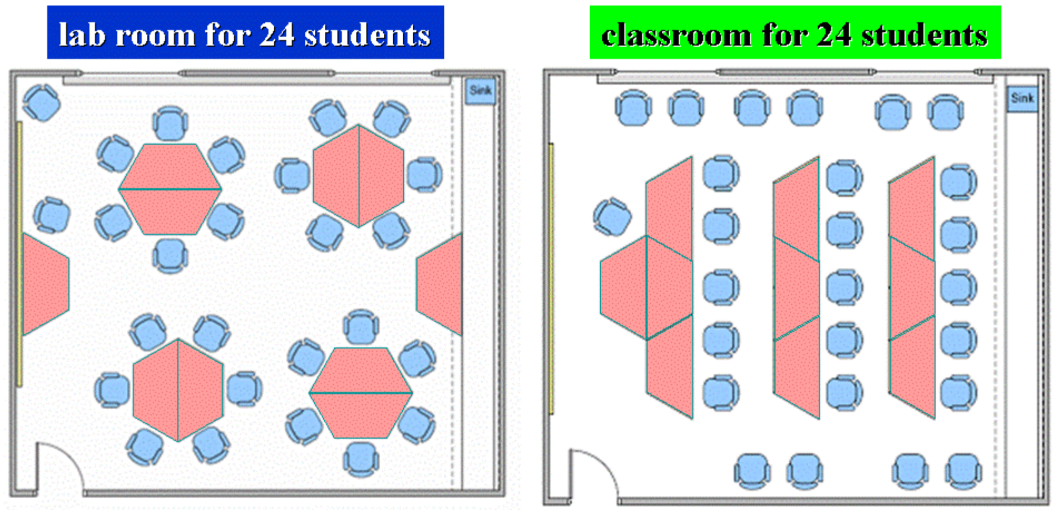

Fig. 8: Schematic view of a remodeled laboratory room using modular trapezoidal tables. The primary intention was to provide a "mini SCALE-UP" environment for lab sessions (left panel). The room can be reconfigured into a standard classroom arrangement, if needed (right panel).

Finally, we have the intention of expanding our current SCALE-UP room (the one shown in Fig. 1) by knocking down the wall into an adjacent classroom, effectively doubling the size of the classroom space. The schematic of this proposed classroom is shown in Fig. 9 below. This would enable us to offer SCALE-UP classes to 108 or 72 students, depending upon whether we place 9 or 6 students at each table. For a room of this size, one instructor would have to be assisted by two Teaching Assistants in order to provide sufficient coverage for the 12 tables in the room. We hope that this expansion will take place in the Spring 2011 semester, or at the latest, in Fall 2011.

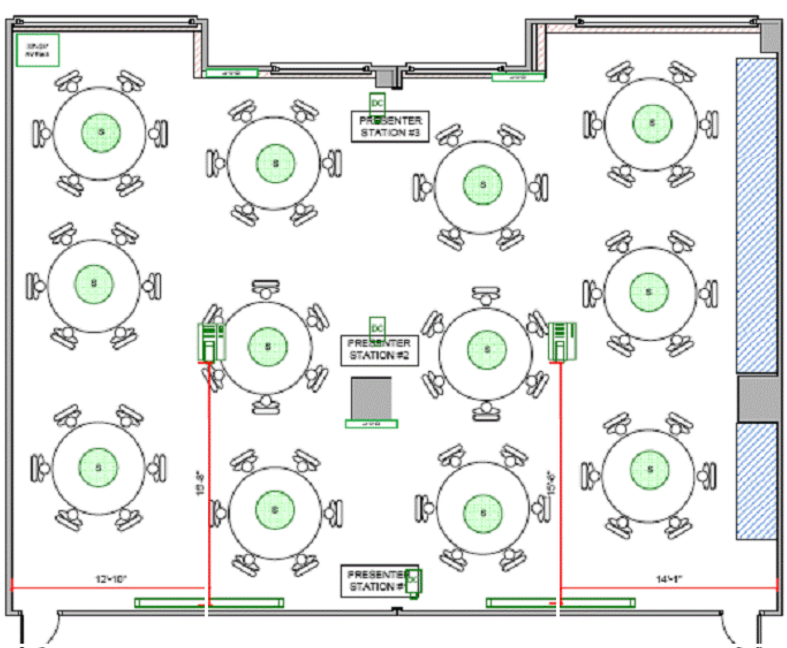

Fig. 9: Schematic view of a proposed plan for expansion of our SCALE-UP room to double its size (compare to Fig. 1 for current size). The expanded room will have 12 round tables, each holding either 6 students (as shown) or 9 students, giving a total of 72-108 students.

V. Summary

We have been using the SCALE-UP collaborative group-learning pedagogy for five full semesters at GWU, which includes five semesters of Phys 21 and two semesters of Phys 22. Both of these classes are continuing in the current Fall 2010 semester. While our data are not exhaustive, we have evidence that students are performing better in the SCALE-UP class than in a conventional lecture class. Student engagement is high in the SCALE-UP environment, and it seems that students gain a greater facility with the physics material in this collaborative mode compared to less interactive approaches.

Educational trends favoring more interactive engagement techniques have been gaining momentum in colleges and universities in the United States over the past decade. This sentiment concerning the shortcomings of the conventional lecture style of science education has recently been echoed by Eric Mazur in a short and incisive article appearing in a more mainstream forum, namely *Science* magazine [13].

In closing, it is worthwhile to share some "impressions" from our direct experience in teaching the introductory physics classes utilizing the SCALE-UP pedagogy. Admittedly, the following comments are purely anecdotal, but at some level, the observations and intuition of the instructor have some validity in judging the effectiveness of an educational experience.

- SCALE-UP really squeezes the best out of students
- students work harder, but for greater rewards
- the student working groups actually gel into cohesive units
- the classroom atmosphere is much more dynamic
- the instructor gets to know the students better
  (and the students get to know each other better)

In the end, there is one final comment — it is considerably more satisfying to be a "coach" rather than a lecturer, and the SCALE-UP pedagogy definitely affords that opportunity. Ultimately, this is much better for the instructor and certainly it is more beneficial for the students.

References

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