University of Toronto Physics Practicals

A Proposal to the Student Experience Fund

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Introduction

Approximately 1600 students enrol in a first year Physics course with a laboratory component each year at the St. George Campus of the University of Toronto. Supporting the first year labs requires 50 TA's, 2.5 technical support staff, 1.5 full-time Lecturers and an annual maintenance budget of about $50K. An additional 35 TA's are required to run the tutorials. Roughly 1200 of these 1600 students are enrolled in our two largest first year courses, PHY110Y and PHY138Y, the majority of whom are life science students. Currently, students in both courses attend two or three hours of lectures and one hour of tutorials each week, along with a three-hour laboratory every second week.

The PHY110Y/138Y laboratory was designed over thirty years ago, for a different generation of students. For many years it was quite successful, but it has become apparent that the structure of the laboratory is no longer appropriate either for training in real-life experimentation or for our students. A number of issues have become apparent in recent years:

- For reasons more practical than pedagogical, the laboratory is effectively a separate course in experimental science, without explicit connections to the material in classes or tutorials. This frustrates students who often do not know the physics behind the experiment they are doing, and many have told us in course evaluations that they do not find the lab relevant. This is a missed opportunity – students need "hands-on" experience with physical systems to reinforce the lecture material, and studies show that such experience greatly enhances their comprehension of the material.
- There is currently a tremendous amount of choice available to students in the labs, with dozens of possible experiments to choose from. This has proven in many cases to be confusing for the students – a sequence of common, well-chosen experiments tied to the lecture material is more appropriate at this level. From a practical perspective, this is also problematic because the TA's (particularly inexperienced ones) do not have the time to become acquainted with all the experiments that are available.
- The laboratory equipment has become increasingly antiquated. In particular, the equipment in our laboratories does not make use of the revolution in data acquisition and process control that has occurred since the original design. In many cases the apparatus is not only older than our students, it is older than their parents. Students in 2007 expect to be using computers for data acquisition and analysis, and indeed this is an essential skill for modern experimental work.
- Traditional tutorials do not always foster a collaborative learning environment, and may easily turn into a mini-lecture by a TA, with rote copying of solutions by the students. Not only is this not an optimal pedagogical approach, it also represents another missed opportunity - given the pressures of enrolment numbers and the high student-faculty ratios at the University of Toronto, it is essential that the tutorials provide a meaningful "small-group experience."

In addition, the expectation that students now have easy access to computers means that we have new tools at our disposal. Much of the mathematics that proves a barrier to our students understanding the physics can be done numerically and visually on a computer. This opens up vast new regions of applicability – students are no longer restricted to simple, analytically solvable examples (i.e. constant acceleration, no friction, etc.).

Concerns about the structure of the undergraduate Physics labs have been reflected not only in student evaluations of the laboratories but also in a recent external review of the Department of Physics. Quoting directly from the review, “In the case of the lower division laboratories, it is extremely important to have new ways to teach laboratory sciences at this level, and the teaching faculty should be strongly encouraged to design such curricula.”

The University of Toronto is hardly unique in facing these issues. Over a decade of research into Physics Education has revolutionized the way introductory Physics is being taught at many of our peer institutions – including Berkeley, Illinois and M.I.T. – as well as small U.S. liberal arts colleges. Two key conclusions of this research are:

- Most students learn best in a social context, interacting with their peers in small groups, and
- The single most effective pedagogical technique uses conceptually based “guided discovery” activities involving actual apparatus.

Consequently, best practices in introductory Physics laboratory instruction have undergone major changes over the past ten years; our labs and tutorials have not evolved to reflect this.

In this document we propose an integrated laboratory and tutorial for our first-year non-specialist courses which addresses these issues.

Physics Practicals: The Proposal

We propose a fundamental redesign of the structure of the tutorials and laboratories in our first year non-specialist courses (currently PHY110Y and PHY138Y). Students currently attend one hour of tutorial every week, and a three-hour lab session every second week (starting in mid-October). We propose to eliminate the labs and tutorials, combining elements of both into weekly two-hour Physical Practical sessions. The format of the lectures will remain unchanged.

Physics Practicals will be small (up to 36 student) sessions, with students working in redesigned rooms in groups of three or four. The students will be working in TA-led sessions focusing on a common syllabus that encompasses both the conceptual and problem-solving aspects of the current tutorials along with experimental investigations to both reinforce the lecture material and introduce experimental techniques. There will be two types of Practicals:

- *Conceptual*: These will concentrate on the concepts that are the heart of what is currently being discussed in class. They will serve many of the roles of the current tutorials, with the important added feature that in addition to problem solving, the students will be obtaining hands-on familiarity with apparatus to reinforce the concepts introduced in lecture. The material will be closely integrated with the lecture material.
- *Discovery*: These will concentrate on experimental investigations of topics that may or may not be related to the topics of the class.

Each session will be led by two TA's, pairing experienced and inexperienced TA's to provide a significant mentoring and training experience for graduate students. This will provide a social learning environment both for the undergraduates working in teams, as well as the TA's practicing team-teaching.

We intend to achieve a number of goals with this format:

- The disconnect between the lecture material and the laboratory material will be eliminated.
- The Practicals will reinforce the material learned in lecture, by providing a "hands-on" approach to improve student understanding of the material.
- The setting will provide a meaningful small-group experience along with a collaborative learning environment.
- The students will be working with modern equipment, using computers for data acquisition, analysis and control.
- The situation for TA's will be greatly improved: training will be greatly increased, team-teaching will allow more experienced TA's to mentor less-experienced ones, and the new structure will obviate the need for an individual TA to be familiar with the huge variety of experiments currently available.
- Computer simulations will be introduced into the curriculum as a problem-solving technique, overcoming some of the mathematics shortcomings of our students, and allowing them to focus on the physics rather than the math. Even for the mathematically adept students, computer-based problem solving vastly increases the applicability of the material to previously intractable complex or non-linear problems.

The model we are proposing to adopt is based on material developed at a variety of institutions over the past decade, and in particular on the "Workshop Physics" project developed at Dickinson College in the U.S. Over the past 15 years or so, there has developed an extensive literature on the subject of Physics Education, and the educational effectiveness of a variety of pedagogical approaches has been measured. By administering pre- and post-course tests to their students, educators have been able to quantify not only the traditional problem-solving abilities of their students, but more importantly their conceptual understanding of the material. The "discovery-based" approach on which this proposal is based has been shown to be the single most effective means to improve student comprehension of the material.

When in place, by design the Physics Practicals will require comparable TA resources to our current tutorials and laboratories. The requirements for academic and non-academic staff to support the Practicals will also be unchanged from our current levels. We similarly predict that the steady-state maintenance costs of the Practicals will be about the same as our current laboratories.

Rooms and Pods

At the heart of this proposal are redesigned labs, with each room containing nine "pods" at which groups of three or four students work. Each pod will include

- a large hexagonal table and some square tables
- a computer, data acquisition interface, and various sensors and other apparatus
- a whiteboard.

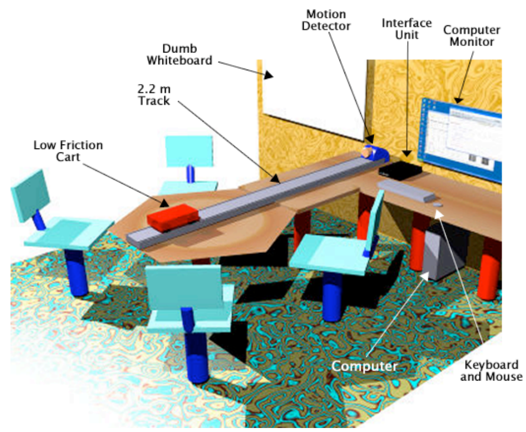


Figure 1: A typical pod layout

A typical pod setup is shown in Figure 1, while a typical room layout is shown in Figure 2. Our pod design is very similar to a design developed at Dickinson College, shown in the photo below. In addition to nine pods, each room will have:

- A work area at the front for the instructors (not shown in the FIgure).
- A large screen, projection system and computer for the instructors. With cameras mounted in front of each student whiteboard and networked computers, the instructor will be able to display what is on any of the computer monitors or whiteboards on the screen.

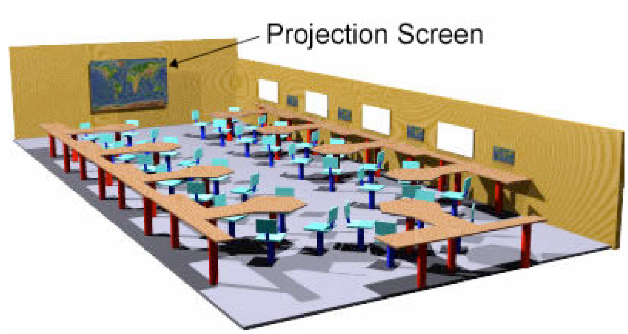


Figure 2: A typical room layout

•A storage area (not shown in the Figure).

The Physics Practicals will use a guided discovery-based teaching method, based on a series of Activities. Often the Activities will involve the students interacting with real physical apparatus, typically using modern computerized data acquisition and process control technology. There will also be some Activities that use video capture and analysis hardware and software. Other Activities will involve computer simulations, and some will be paper and pencil based.

At the beginning of the year, Conceptual activities will predominate. These are directly related to the material currently being discussed in lecture, and are intended to have the students confront the conceptual misunderstandings that we know most of them share. These activities will also begin introducing general principles of best practices in experimental science.

Later in the year we will introduce Discovery activities, which concentrate on experimental determinations of various aspects of the numerical description of the physical universe. Some of these may not be related to what is being discussed in lecture. These activities will be based on having students design and implement their own procedures to solve a given project.

Workshop Physics at Dickinson College

We also intend to have at least one activity concentrating on the writing of scientific reports.

While we will draw extensively on materials developed at other institutions, particularly from Dickinson College, there are a few areas in which we believe we can improve on them:

- The Discovery Practicals, concentrating on Projects on experimental science, are not part of the Workshop Physics suite.
- The software used by Workshop Physics is designed more for a High School level than a University context. We will build our Activities using different and more sophisticated LabView based software. We note here that Virginijus Barzda at UTM has been building materials using this base for over a year, sponsored in part by a grant from the Information Technology Courseware Development Fund. We intend to work closely with our UTM colleagues in the development of materials.
- The data acquisition system used by Workshop Physics has some serious limitations. We intend to use more sophisticated hardware.

Time-scale for Implementation

We plan to implement the Practicals in two stages: a pilot project in September 2007 and a full-scale rollout in September 2008. Because of the complexity of redesigning and developing materials for 1200 students all at once, we see the pilot project to be an essential step, allowing the material to be developed in the context of a smaller group of self-selected students, while giving both faculty and TA's experience with the new structure before full-scale implementation.

For the pilot project, we propose offering two or three sections, composing between about 70 and 110 students, of PHY138Y in the new format, with the remainder of the students operating in the traditional tutorial/laboratory mode. We plan to convert two smaller rooms currently used for the first-year labs into a single Practical room.

Full implementation of the Practicals in September 2008 will require four additional rooms, for a total of five. We anticipate holding up to two two-hour Practicals a day five days a week, plus one or two evening sections as needed. During the day we can accommodate a maximum of 1800 students, so the design allows for future increases in enrollment in the current target courses of PHY110Y and PHY138Y. This will also give us the capacity to use the rooms, if desired, for other courses such as PHY140Y for Physical and Mathematical Science students, or PHY205H ("Physics of Everyday Life") for Arts students.

We note that as a result of curriculum review processes currently occurring at both the Faculty and Departmental levels, it is quite possible that PHY110Y and PHY138Y will be radically revised or replaced in the next few years. While changes in the course content will have to be reflected in the Practicals, the structure and equipment required will be sufficiently general that it will be straightforward to make changes in the Practicals to meet the evolving needs of the curriculum.

Space Requirements

A plan of the first floor undergraduate wing of McLennan Physical Laboratories is shown in Figure 3. Currently, the

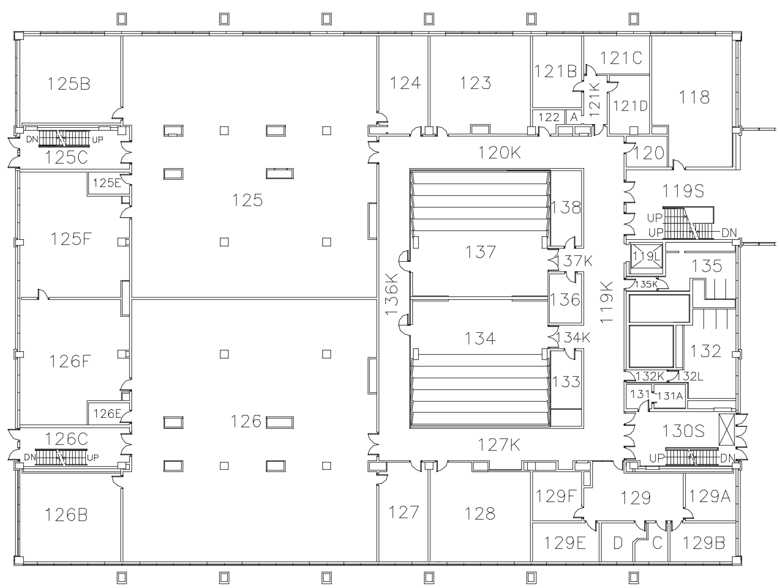


Figure 3: Undergraduate WIng of McLennan Physics Labs

laboratories are primarily located in MP125 and 126, with some specialized experiments located in the smaller rooms 125B, 125F, 126B and 126F. The undergraduate lab technologists and lab co-ordinator are housed in MP123, MP124, MP127 and MP128. MP118, MP134 and MP137 are classrooms, and the office suites MP121 and MP129 are offices for Teaching Faculty. The small rectangles shown in the Figure in MP125 and MP126 are pillars. Since these block lines of sight and cannot be moved, the locations of the pillars strongly affect the reconfiguration of the space.

The proposed modified layout of the undergraduate wing is shown in Figure 4. For the pilot project, MP125F and MP126F will be combined to form a single Practicals room with storage at either end, while the remaining rooms will continue to serve as the original first-year lab for the majority of students. In the full implementation, new lab rooms will be constructed along the outside walls of the building, and the technologists will be moved into a central area.

This arrangement will provide a more efficient use of the technologists' space than the current setup, and will also give them a central location. In turn, the laboratories will have a uniform design, with large floor-to-ceiling windows (except for the Pilot room), giving them ample natural light. By avoiding the pillars entirely, the laboratories will have uninterrupted lines of sight. We anticipate installing a number of windows on the inside walls of the laboratories, so that the activity inside will be easily visible from the corridors. This will both make the rooms brighter, more pleasant

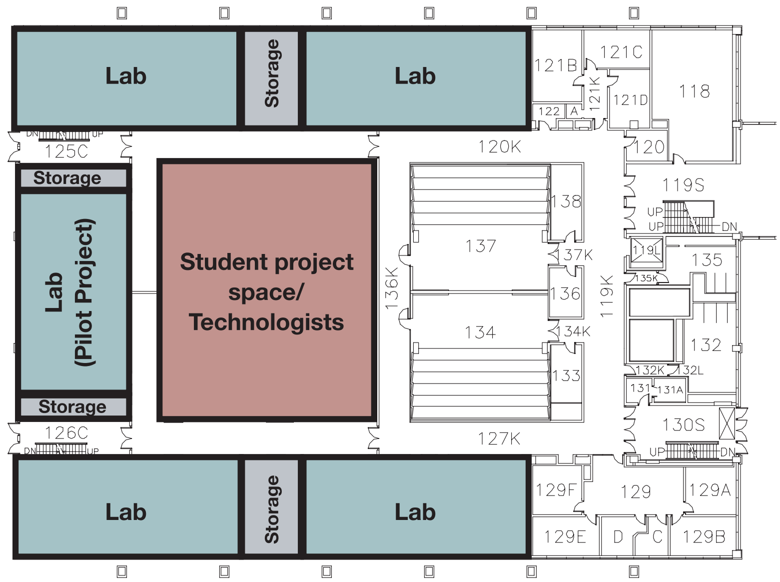


Figure 4: Planned Redesign of Undergraduate WIng of McLennan Physics Labs

spaces, and allow them to serve as a "showcase" for the Practicals.

The technologists will only need about half of the central area. There are several possibilities for the other half of the space:

- "Student Project Space": a sixth lab may be set up here, either for use by PHY110Y/138Y students for special Discovery projects later in the course, or by other courses such as PHY140Y/180Y.
- Study space: The space could be supplied with carrels, blackboards, couches, chairs and tables to form attractive and much-needed student study space. This would fit well with our general philosophy of using the labs to provide an interactive and pleasant academic environment that will serve the needs of our students.

Estimated Costs

Implementation of the Practicals will require four major categories of expenditure:

- Renovation of the existing space,
- Apparatus, sensors and computers,
- Furniture,
- Development of the curriculum, including TA training materials.

We may also divide the financial costs into three phases:

- One set of equipment for development between now and the beginning of the pilot in September 2007.
- 10 additional sets of equipment for use in the pilot itself. Some of this must be in place by the beginning of the pilot in September, and other components will be purchased as the pilot proceeds. This includes one spare set.
- 45 additional setups for full deployment in September 2008. With a few exceptions, noted below, this will allow a setup for each pod plus four spares.

The operating costs for the Practicals after they are developed will be about the same as our current tutorials and laboratories. This section discusses the funds and human resources necessary for the development of the Practicals. All costs are in Canadian dollars, and do not include taxes.

Physical Plant

The costs of the physical plant renovations and audio/visual requirements are being prepared by the Office of Planning and Information Technology in the Faculty of Arts and Science.

Apparatus, Sensors and Computers

For Each Pod:

Each pod will have a computer, data acquisition hardware and software, and in the course of the year a variety of apparatus and sensors will be used. Our baseline costing for this equipment is developed from the Comprehensive Physics Complete System from Pasco Scientific and the Workshop Physics suite developed at Dickinson College. Because of our experience with data acquisition (DAQ) systems at St. George and UTM, we plan to use National Instruments DAQ modules instead of those offered by Pasco. The precise experimental apparatus will undoubtedly change as we develop our pilot project in detail, but our initial physics equipment list for each pod is given in Appendix A. The total baseline cost of the experimental apparatus is $19,043 per pod. Each pod will also have a Windows computer, including special software such a Videopoint Capture for video capture and motion analysis, costing about $1,700. The total cost of the equipment for each pod is **$20,743**.

For Each Room:

Each room will require:

- 10 sets of physics equipment for 9 student pods plus the instructor station, for a total cost of **$207,430**
- A dedicated printer. A suitable color laser printer costs about **$800**.
- A tablet computer or equivalent, projector, and large resolution screen at about **$7,600**.
- A digital camcorder to be used for high resolution and remote motion analysis, including a tripod and computer interface card: **$750**.

Total equipment costs for each room are **$216,578**, or **$1.1M** for all 5 rooms.

Additional:

The campus backbone fiber runs into room MP126. We will need to tap into the switch to provide networking for each of the pods, smart board, printer, etc.

We will require a Windows server with sufficient capacity to serve all the computers and printers, with a cost of **$4,000**

Furniture

We are designing each edge of a table to be 2 feet wide. Each pod will consist of:

- Two hexagonal tables each 4 feet x 1.8 feet, which will be combined into a regular hexagonal table 4 feet by 3.6 feet.
- 2 rectangular tables each 2 feet by 4 feet.
- A steel whiteboard.
- 1 rectangular table 1 foot by 4 feet. This will be under the whiteboard.
- 4 chairs on rollers.

This implies that each pod will require 10 feet of wall space. However providing access to the corners of the room means more wall space than this will actually be required.

Although some modifications of the above numbers for the furniture are possible, we are constrained that the distance from the wall to the far edge of the hexagonal table must be no less than 2.2 m = 7.22 feet.

In addition each room will require:

- Two tables each about 3 feet by 5 feet. These are the size of our existing laboratory tables.
- At least two chairs on rollers.

Human Resources

Two of the authors of this proposal (JH and DMH) have already been relieved of some of their teaching assignments to free time for development of this project. There is also a larger group of about 15 academic and non-academic staff attending regular meetings and who provide particular expertise as needed. We have earlier discussed our collaboration with Virginijus Barzda at UTM, who has been developing software for their undergraduate Physics laboratories similar to what we wish to implement.

On the St. George campus we have a great deal of expertise in the software platform, LabVIEW, to be used. This software is already used for some upper year undergraduate experiments and in many research labs. Three of our Undergraduate Laboratory Technologists have considerable training by the vendor. A member of Physics Technical Services is a certified trainer for this software. We anticipate hiring several students to help with development of particular software modules.

We intend to use the staff of Physics Computing Services for configuration, deployment, and maintenance of the Windows server and network.

Appendix A: Pod Equipment List

Model#	Description	Price (Can$)	Number	Total Price
PASCO				
CI-6503	Voltage Sensor	$14.90	2	$30
CI-6504A	Light Sensor	$89.00	1	$89
CI-6506B	Sound Sensor	$74.00	1	$74
CI-6514A	Thermodynamics Kit	$89.00	1	$89
CI-6520A	Magnetic Field Sensor	$239.00	1	$239
CI-6532A	Absolute Pressure Sensor	$149.00	1	$149
CI-6537	force sensor	$300.00	1	$300
CI-6538	Rotary Motion Sensor	$300.00	1	$300
CI-6545	Accessory Bracket with Bumpers	$120.00	1	$120
CI-6552A	Power Amp II	$527.00	1	$527
CI-6555	Charge Sensor	$149.00	1	$149
CI-6556	Current Sensor	$68.00	1	$68
CI-6558	Acceleration Sensor	$166.00	1	$166
CI-6605	Temperature Sensors	$59.00	2	$118
CI-6691	Rotational Accessory	$239.00	1	$239
CI-6692	Dynamics Track Mount	$60.00	1	$60
CI-6742	Motion Sensor II	$135.00	2	$270
CI-6746	Economy Force Sensor	$179.00	2	$358
EM-6711	2 Field 200-turn Field Coils	$158.00	2	$316
EM-6715	Helmholtz Coil Base	$94.00	1	$94
EM-8620	Alnico Bar Magnets (set of 2)	$40.20	1	$40
EM-8622	basic electricity kit	$286.00	1	$286
EM-8641	variable gap magnet	$335.00	1	$335
EM-8656	AC/DC Electronics Laboratory	$286.00	1	$286
ES-9042A	Faraday Ice Pail	$127.00	1	$127
ES-9043	variable capacitor	$604.00	1	$604
ES-9057B	Charge Producers/Proof Plane	$45.90	1	$46
ES-9059B	Conductive Spheres	$142.00	1	$142
ES-9060	charge, equipot, field mapper	$221.00	1	$221
ES-9077	Electrostatics Voltage Source	$302.00	1	$302
ET-8771	Energy Transfer - Generator	$237.00	1	$237
ME-6755	Compact Cart Masses	$15.80	3	$47
ME-6821	Photogate Mounting Bracket for Projectile Launcher	$40.20	1	$40
ME-6825A	Mini Launcher	$253.00	1	$253
ME-6830	projectile launcher	$986.00	1	$986
ME-6838	Photogate/Pulley System	$114.00	1	$114
ME-8574	Discover Friction Accessory	$55.00	1	$55
ME-8735	Large Rod Stands	$127.00	2	$254
ME-8736	45 cm Steel Rod	$28.70	1	$29
ME-8738	90 cm Steel Rod	$31.60	1	$32
ME-8752	Photogate Pendulum Set	$62.00	1	$62
ME-8950A	Complete Rotational System	$1,241.00	1	$1,241

ME-9348	Mass and Hanger Set (5g resolution)	$104.00	1	$104
ME-9376B	Universal Table Clamp	$68.00	2	$136
ME-9377A	Large Picket Fence	$27.10	1	$27
ME-9453	2.2 m track	$316.00	1	$316
ME-9454	collision cart	$125.00	2	$250
ME-9471A	Photogates and Fences - IDS	$216.00	1	$216
ME-9491	Fan Accessory	$89.00	1	$89
ME-9781	Variable Speed Motorized Cart	$206.00	1	$206
ME-9803	IDS - Harmonic Spring (set of 3)	$24.40	1	$24
ME-9821	Centripetal Force Pendulum	$127.00	1	$127
ME-9873	Double Rod Clamp (3 Pack)	$28.70	1	$29
PK-9023	Field Mapper Kit	$158.00	1	$158
SE-7342	Tuning Fork Set of 8	$111.00	1	$111
SE-7347	No Bounce Pad	$48.80	1	$49
SE-8050	Braided Physics String	$31.60	1	$32
SE-8604	bar magnets (2 pack)	$66.00	1	$66
SE-8653	Primary/Secondary Coils	$94.00	1	$94
SE-8702B	Digital Stopwatch	$25.90	1	$26
SE-8716	3 spring scales 5 N	$37.30	3	$112
SE-8717	Spring scale 10 Newton	$37.30	1	$37
SE-8718	3 spring scales 20 N	$37.30	3	$112
SE-8746	2-D kinesthetics cart	$507.00	1	$507
SE-8747	kinesthetics cart	$912.00	1	$912
SE-8749	Hooke's Law Spring Set	$48.80	1	$49
SE-8760	Double Length Slinky	$25.90	1	$26
SE-8767	Hot Plate	$236.00	1	$236
SE-9081	Chime Set	$43.10	1	$43
SE-9084A	glass thermometer	$15.80	1	$16
SE-9443	Pendulum Clamp	$31.60	1	$32
SE-9638	e/m Apparatus	$2,283.00	1	$2,283
SE-9750	Patch Cords	$31.60	1	$32
SE-9751	Patch Cords	$31.60	1	$32
SE-9756	Alligator Clip Leads	$30.20	1	$30
SN-9794	1 microCi Co-60 source	$111.00	1	$111
SN-9795	Cs-137 source	$111.00	1	$111
SN-7970A	G-M Probe with Sample Holder	$540.00	1	$540
TD-8553	radiation sensor	$349.00	1	$349
TD-8557	Basic Calorimetry Set	$127.00	1	$127
WA-7334	Demonstration Wave Spring	$31.60	1	$32
WA-9495	Economy Resonance Tube	$87.00	1	$87
WA-9857	String Vibrator	$108.00	1	$108
WA-9900	Open Speaker	$102.00	1	$102

non-PASCO

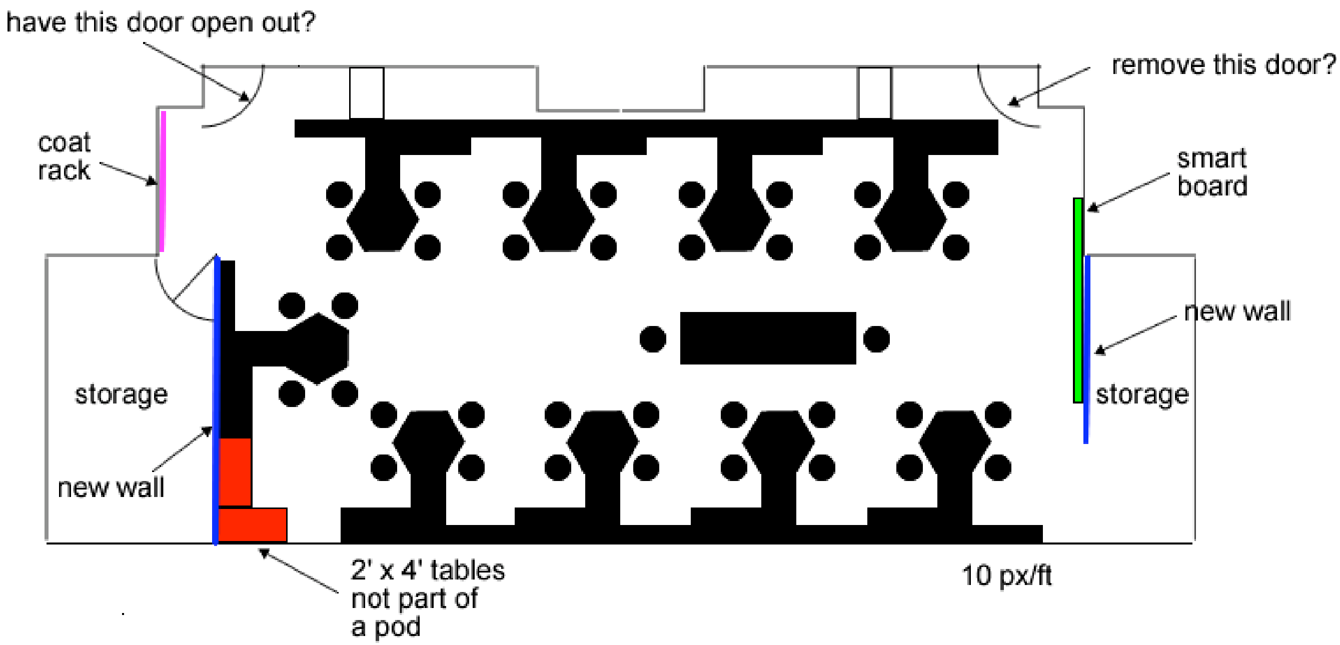
15XP	WavTek MeterMan Compact Multimeter	$72.39	1	$72
4010A	B.& K. 2 MHz Function Generator	$338.33	1	$338
	2 spring scales 200 N	$25.00	2	$50
	Logitech 1.3MP Webcam and tripod	$130.00	2	$130
	Data acquisition connector and switch box	$500.00	1	$500

NI USB-6259	National Instruments High-Speed USB M Series Multifunction DAQ	$2,365.00	1	$2,365
TDS1012B	Tektronix Oscilloscope (100MHz, 2 channel, USB, Mono).	$1,240.00	1	$1,240
				$22,403
	Vendor Discount	15%		-$3,360
	Total			**$19,043**

Appendix B: The Pilot Project Room

A sketch of the planned pilot project room is shown here. The pilot project room will be made by removing the wall separating MP125F and MP126F to create a single long and narrow room. The bizarre shape of the room, with many offsets and pillars, drove much of the layout.

In the figure, North is to the bottom.



Appendix C: The Final Layout

The final layout of the lab area, showing the location of pods, is sketched here. The locations of windows, radiators and pillars, which constrain much of the layout, are shown. Some remaining issues are:

- Do we require emergency exits in place of the 3 ½ foot wide floor-to-ceiling windows in the North-East and North-West corners?
- The details of the central block, marked Technologists/Student Projects in the drawing, needs further design in consultation with our technologists.
- There are numerous radiators and floor-to-ceiling windows on the East and West walls. We do not know how they constrain the placement of the new walls indicated in the drawing.
- What are the heating/ventilation/air conditioning requirements for the central block? All of the radiators are on the outer walls.
- It appears that recently some of the old radiators in MP129, almost 3 feet high, were replaced with units closer to 2 feet high. Is that a viable thing for us to do?