A generic model for inquiry-oriented labs in postsecondary introductory physics

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While many involved with college- and university-level introductory physics complains about "cookbook" labs, few do anything about it. There are a number of inquiry-oriented lab models for postsecondary physics currently available, but such models appear to depend strongly upon the presence of lab instructors who are highly dedicated to inquiry, are well informed about associated scientific processes, and integrate lectures and labs. While integrated lecture/labs are the ideal, not many institutions have the resources or opportunities to implement those models. The Illinois State University Physics Department – led by its teacher education coordinator, undergraduate PTE majors, and cooperating faculty and staff – has recently completed nearly two years of work developing and implementing a generic inquiry-oriented lab model that we believe can be employed by institutions using less expert lab instructors and labs separate from lectures. After experiences with 15 different inquiry-based labs, 8 undergraduate teaching assistants, and 240 students enrolled in calculus-based physics courses, we give an initial report on the nature of our inquiry labs, the development process, and general observations arising from using this approach.

Physics teacher education institutions that are accredited though their state boards of education and/or the National Council for Accreditation of Teacher Education (NCATE) must comply with a substantial number of standards at both the university and program levels. At the program level for NCATE institutions, the teacher preparation process must satisfy criteria established by the National Science Teachers Association (NSTA). The inquiry "cluster" in the NSTA's Standards for Science Teacher Preparation (NSTA, 2003) clearly indicates the need for teacher candidates to learn about the nature and processes of science by being actively involved in the process of scientific investigation. This call for active involvement in the creation of knowledge mirrors the concerns of the American Association of Physics Teachers (AAPT). In 1998, the AAPT promulgated a policy statement dealing with introductory physics laboratory goals. The goals were enunciated by the AAPT's Committee on Laboratories (Gerald Taylor, Jr., Chair), working in cooperation with the Apparatus Committee, the Two-Year College Committee, the Committee on Physics in Undergraduate Education, as well as others. The policy statement was approved on behalf of the AAPT by the Executive Board at its October 1997 meeting in College Park, Maryland. The policy statement was published shortly thereafter in the *American Journal of Physics* (AAPT, 1998). A summary of the goals can be found in Table 1.

A question now arises. Do traditional "cookbook" labs commonly used in teaching introductory physics courses satisfy these goals? If the distinction between traditional cookbook labs and inquiry-based labs expressed in Table 2 holds true (Wenning, 2005a), then this is highly unlikely. If the AAPT goals are to be achieved and NSTA preparation standards met, there must be a significant shift in the way conventional introductory postsecondary physics laboratory activities are conducted.

There are a number of excellent inquiry-based approaches to laboratory available that clearly and effectively address the AAPT's Introductory Physics Laboratory Goals. Among these approaches are the Activity Based Physics program developed by the Physics Education Group (2004) involving the University of Washington, the University of Maryland, and Dickinson College among others. As University of Washington's McDermott states

Summary of Introductory Physics Laboratory Goals

I. **The Art of Experimentation:** The introductory laboratory should engage each student in significant experiences with experimental processes, including some experience designing investigations.

II. **Experimental and Analytical Skills:** The laboratory should help the student develop a broad array of basic skills and tools of experimental physics and data analysis.

III. **Conceptual Learning:** The laboratory should help students master basic physics concepts.

IV. **Understanding the Basis of Knowledge in Physics:** The laboratory should help students to understand the role of direct observation in physics and to distinguish between inferences based on theory and on the outcomes of experiments.

V. **Developing Collaborative Learning Skills:** The laboratory should help students develop collaborative learning skills that are vital to success in many lifelong endeavors.

Table 1. *The AAPT policy states that laboratory programs should be designed with these five fundamental goals in mind. A detailed explanation appears in the original AJP article.*

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Cookbook labs…	Inquiry labs…
• are driven with step-by-step instructions requiring minimum intellectual engagement of students thereby promoting robotic, rule-conforming behaviors. • commonly focus students' activities on verifying information previously communicated in class thereby moving from abstract toward concrete. • presume students will learn the nature of scientific inquiry by "experience" or implicitly; students execute imposed experimental designs that tell students which variables to hold constant, which to vary, which are independent, and which are dependent. • rarely allow students to confront and deal with uncertainty and misconceptions; do not allow students to experience blind alleys or dead ends. • employ procedures that are inconsistent with the scientific endeavor; show an unrealistic linear process.	• are driven by questions requiring ongoing engagement using higher-order thinking skills and independent thought and action. • focus students' activities on collecting and interpreting data to discover new concepts, principles, or laws thereby moving from concrete toward abstract. • require students to create their own controlled experimental designs; require students to independently identify, distinguish, and control pertinent independent and dependent variables; promote student understanding of the skills and nature of scientific inquiry. • commonly allow for students to learn from their mistakes and missteps; provide time and opportunity for students to make and recover from mistakes. • employ procedures that are much more consistent with authentic scientific practice; show the work of science to be recursive and self-correcting.

Table 2. *Fundamental distinctions between traditional cookbook and authentic inquiry-oriented lab activities* (Wenning, 2005a).

in *Physics By Inquiry,* "Through in-depth study of simple physical systems and their interactions, students gain direct experience with the processes of science. Starting from their observations, students develop basic physical concepts, use and interpret different forms of scientific representations, and construct explanatory models with predictive capability. All the modules have been explicitly designed to develop scientific reasoning skills and to provide practice in relating scientific concepts, representations, and models to real world phenomena." Richard Hake's *Socratic Dialogue Inducing Labs* (SDI) appears to do likewise. According to Hake (1992), "SDI labs emphasize hands-on experience with simple mechanics experiments and facilitate interactive engagement of students with course material. They are designed to promote students' mental construction of concepts through their (1) conceptual conflict, (2) kinesthetic involvement, (3) extensive verbal, written, pictorial, diagrammatic, graphical, and mathematical analysis of concrete Newtonian experiments, (4) repeated exposure to experiments at increasing levels of sophistication, (5) peer discussion, and (6) Socratic dialogue with instructors."

A generic model for inquiry-based labs

While the above forms of teaching introductory physics appear to approach the ideal of integrating physics instruction with laboratory activities, not all postsecondary institutions are willing and able to reformulate their course and lab formats and schedules to accommodate these types of instruction. This problem often stems from not having adequate preparation and/or release time for faculty, a necessity of using advanced undergraduate or graduate students to conduct lab activities, large sections in physics courses, inadequate lab space or materials, inflexibility of schedules, lack of financial resources, and so on. This conflict produces the need for a generic model for implementing inquiry-based labs under rather restrictive sets of conditions.

Illinois State University (ISU) historically has used the more traditional approach of separate lecture and lab. Still, there has been a growing desire among certain of the department's faculty members, the physics teacher education (PTE) coordinator, and the program's PTE majors to replace ISU's traditional cookbook labs with something that is more inquiry oriented. A way needed to be found to overcome the limitations imposed by working with lab instructors who have limited experiences with inquiry, courses with separate lab and lecture sections, and large enrollments with limited facilities. A decision was made during the spring of 2004 to create and pilot two inquiry labs that could be taught by the PTE major co-author who at that point was a highly experienced undergraduate lab instructor.

The first two inquiry labs developed dealt with the derivation of the ideal gas law, and the analysis of an RC circuit. Prior to writing these labs, the co-authors of this article defined the basic properties of inquiry labs in general. Inquiry labs would:

1) contain pre-lab activities including reading assignments and problems,
2) provide a detailed list of student performance objectives,
3) provide one or more tasks associated with each student performance objective,
4) include clear performance tasks but a minimum of instructions, and
5) be driven primarily by substantive, not trivial, questions.

The student author of this paper, with guidance and assistance of the PTE coordinator, wrote these first two inquiry labs using a guided inquiry approach (Wenning, 2005a). The labs were then conducted with two calculus-based lab groups containing approximately 20 students each. The inquiry labs incorporated for the first time computer-based lab sensors and a new graphing program. Subsequent to these labs, a debriefing session was held with the students who participated in the lab activities. Student reactions to using the inquiry approach were mixed. Some liked the approach; others preferred to "be told what to do," and still others indicated a desire to see a mix of inquiry and traditional lab activities. Students felt somewhat unprepared to perform some of the more advanced activities such as error propagation and dimensional analysis, and were unfamiliar with the sensors and computer programs. Most felt it was too much too fast, "sort of like drinking out of a fire hose." An end-of-semester survey was then conducted among these students. The most challenging labs were the inquiry labs; the inquiry labs were the least "fun." Students also felt that the inquiry labs were least beneficial as far as learning was concerned. Student concerns resulted primarily from our too rapid introduction of technology and computer programs, and their limited understanding of how to derive relationships from graphs. Our experiences with students showed that there are other specific problem areas that students failed to identify: graph creation and interpretation, understanding the meaning of a "physical fit" or "physical model", interpreting the meaning of constants, linear regression, data analysis, propagation of error, error assessment, and dimensional analysis to name but a few. Even with these expressions of student and instructor "concerns," we felt that if these obstacles could be overcome, the benefits of inquiry would be clear to our students.

Despite student concerns and even resistance to inquiry, it was agreed that the inquiry route was the best way for the Department to go given the extensive case that can be made for inquiry (NRC, 2000). During the summer of 2004, a "Lab Writing Group" was established within the ISU Physics Department that created and piloted with small groups of students about 10 new inquiry labs. The following accommodations were made to provide for identified concerns:

1) We started with a simple, sensor-free paradigm lab incorporating the use of a graphing program. This lab consisted of finding relationships between circumference and diameter of a set of aluminum disks, the relationship between a series of equal–area rectangles, and the relationship between air temperature and the rate of cricket chirps.
2) We followed the first lab with a second that oriented students to the use of sensors. A paradigm lab dealing with the factors that possibly could influence the period of a pendulum (length, amplitude, mass) was conducted. The relationship between period and length was worked out for small amplitude.
3) We conducted climate setting starting early and continuing on a somewhat regular basis thereby providing students with an explanation about why the inquiry approach is being used and how students will benefit from it.
4) We wrote a *Student Lab Handbook* containing critical background readings, made it available on-line (http://phy.ilstu.edu/slh/), and integrated it into pre-lab activities.

During the summer of 2005, the faculty and staff of the ISU Physics Department revised first-edition inquiry labs, wrote new inquiry labs, and revised several older lab activities for calculus-based introductory physics courses.

Student Lab Handbook

The *Student Lab Handbook* readings are considered essential to student growth as scientific experimentalists. It is most appropriate for all science students to become familiar with the knowledge base provided in these readings. Students benefit significantly from reading these articles prior to beginning the lab experiences. Knowledge of this information is often crucial for completing lab reports accurately. Most readings are typically 1 to 2 pages in length. All articles are written in simple, even "pedestrian" language, and include multiple examples. The writing focuses on student learning, not on scholarly elocution. All documents are available in "portable document format" (PDF). The titles currently contained within the *Student Lab Handbook* are the following:

- Absolute and Relative Error
- Chi-Square Test for Goodness of Fit
- Common Graph Forms in Physics
- Conversion Factors
- Deriving Relationships from Graphs
- Dimensional Analysis
- Error Propagation
- Generic Experimental Design
- Glossary of Technical Terms and Concepts
- Interpreting Slopes, Areas, and Intercepts of Graphs
- Lab Expectations and Policies
- Lab Goals (Position Statement of AAPT)
- Percent Difference and Percent Error
- Physical Interpretations and Graphical Analysis
- Preparing Graphs
- Quick Reference Guide for DataStudio
- Quick Reference Guide for Graphical Analysis
- Scientific Values
- Significant Figures
- Uncertainty in Measurement

General Observations

The main objective of most new inquiry-oriented introductory physics labs employed at Illinois State University is to have students design and conduct experiments that allow them to derive mathematical models of a relationship. These labs are taught by faculty members, administrative/professionals, and undergraduate physics majors. Having taught a variety of inquiry labs since 2004, we are able to make the following observations:

1) Nearly everyone involved with teaching inquiry labs for the first time is in need of some sort of "refresher" to help them deal with the complexities of the approach. Even those who

have taught cookbook versions of these labs for several years need to carefully re-think some of the processes so that they can help their students learn using the inquiry-based approach. We have found that it is best to have small groups of lab instructors meet each week to discuss and conduct inquiry labs that are new to them. During initial experiences with inquiry labs and new technology, we have found that it takes about 2-3 hours per lab to prepare adequately.

2) Lab instructors must resist the urge to provide answers to students about how to perform an experiment. Instead of providing answers, they should be prepared to respond to student inquiries with an appropriate line of focusing questions. Simple questions that do no relate to actually developing and performing the inquiry lab activity – such a how to use a caliper or how to use a particular component of a computer program – may be quickly answered.
3) Inquiry labs are best prefaced with pre-lab assignments that are due in lab at the beginning of the period. Pre-labs should focus on prerequisite knowledge, predictions, and the planning required to carry out a lab. Pre-labs engage students in pre-thinking the processes required to complete the lab successfully. They require students to learn critical skills and sometimes develop a "theory base" for designing and carrying out an activity. Making repeated reference to our *Student Lab Handbook* has proven a valuable means of getting students to understand such things as experimental design and error propagation that are often overlooked in the rush to complete a lab. In order to drive home the importance of the pre-lab content and references, it is important that this information be addressed in class and as part of tests.
4) Inquiry labs are hard work for students and instructors alike. In comparison to following a set of cookbook instructions, inquiry processes are intellectually demanding. Still, given the benefits of inquiry, such extra work as will be required to complete a lab activity is well worth it. In order to help students value the work of inquiry labs, it is our belief that inquiry labs should constitute a significant part of the grade in a given course.
5) Instructors should assess via testing what students were expected to learn in lab and pre-lab. The lab itself, with its requisite skills and intellectual processes, should be the subject of regular assessment. By holding students to a greater accountability, they will better learn the skills outlined in the AAPT position statement.
6) Course instructors should consider giving students a lab practical shortly after the beginning of the semester. This can serve as another type of assessment that can help ensure greater accountability.
7) Because most students (and some lab instructors) will not have had experiences with inquiry, it is imperative that students start with simpler paradigm labs before moving on to the more complex labs. For instance, it is relatively easy to conduct the pendulum experiment, and much more difficult to conduct an experiment dealing with deriving Newton's second law or the general form of the moment of inertia. Students can only develop the more complex skills required for more advanced inquiry by ramping up through a series of increasingly more challenging labs.
8) When introducing inquiry labs, it is important to conduct climate setting (Wenning, 2005b) so that students understand the benefits of the inquiry approach. We have found that students who understand the value of the inquiry process tend not to make negative comments concerning the approach.
9) Students report that they prefer to complete a lab and turn in their lab results at the conclusion of the lab session. Our approach avoids having students write and turn in "formal" lab reports. Using the short answer approach incorporated in our inquiry labs, students know exactly what they are supposed to get out of a lab experiences, and gone is the disconnect between lab activities and reports that so often results in poor student work.
10) The shift from traditional cookbook labs to inquiry-based labs can be a gradual process, with one or two inquiry-oriented labs being added to the line-up each year. Labs such as those noted in this article can be used as is or adapted as needed, or new labs can be written by those most familiar with and committed to introducing inquiry processes into labs.

Addressing Teacher Preparation Standards

NSTA program accreditation requirements drove our lab revision process. The NSTA clusters dealing with content (Standard 1), inquiry (Standard 2), and nature of science (Standard 3) were central to our efforts at revising the way we conduct our introductory physics labs. Starting with the 1998 NSTA standards, we thought for several years about how to meet these requirements, but didn't really start making program modifications until we were able to develop a generic model for inquiry labs. We propose this generic model for inquiry labs in postsecondary introductory physics to other teacher educators who share our concerns and interests.

It is our hope and expectation that all students – including physics teacher candidates – will have a better understanding of the nature of science and its attendant inquiry processes from their experiences with inquiry-oriented lab activities. If indeed students teach the way they are taught, then there is some hope that our PTE program graduates will use suitable inquiry lab processes in their own high school classrooms patterned after what they have learned through introductory lab experiences while at ISU. So important are inquiry labs to the understanding of physics, that PTE majors now focus attention on the lab as a form of instruction in the teacher preparation process. Physics 302 – *Computer Applications for High School Physics* – has been revised to take into account this new emphasis.

Several of our inquiry labs are currently available for inspection through the Physics 302 course syllabus – *Computer Applications for High School Physics* (http://phy.ilstu.edu/pte/302.html). The labs available through this Web page include: Graphical Analysis, Introduction to DataStudio, Free Fall, Resistance Relationships, Projectile Motion, and Moment of Inertia. The last lab follow this article as an appendix.

As a result of our two-year lab renewal odyssey, we have shifted from all traditional cookbook labs to mostly inquiry-oriented labs in calculus-based physics. We have been able to implement significant changes in the way labs are taught in a traditional university setting that still includes separate lectures and labs, and undergraduate teaching assistants. We have shown our faculty the need for and utility of introducing inquiry practices in the lab as a way of helping our students more fully grasp an understanding of both scientific processes and the nature of science. We have shown the way to address many of the problems associated with lab work such as getting students to understand the roles of graphical analysis and error determination. As proof of the worth of this process, our lab writing team has been asked by faculty members within the Department to prepare inquiry labs for use in algebra-based and even some lower-level general education courses in physics.

References

Activity Based Physics Group (1994). See: http://physics.dickinson.edu/~abp_web/abp_homepage.html

American Association of Physics Teachers (1998). Goals of the Introductory Physics Laboratory. *American Journal of Physics, 66*(6), 483-485.

Hake, R.R. (1992). Socratic pedagogy in the introductory physics laboratory. *The Physics Teacher, 30,* 546 - 552.

National Research Council (2000). *Inquiry and the National Science Education Standards.* Washington, DC: Author

National Science Teachers Association (2003). *Standards for Science Teacher Preparation.* Accessed 3/20/2006 http://www.nsta.org/main/pdfs/NSTAstandards2003.pdf

Wenning, C.J. (2005a). Levels of inquiry: Hierarchies of pedagogical practices and inquiry processes. *Journal of Physics Teacher Education Online, 2*(3), 3-11. Available: http://phy.ilstu.edu/pte/publications/levels_of_inquiry.pdf

Wenning, C.J. (2005b). Minimizing resistance to inquiry-oriented instruction: The importance of climate setting. *Journal of Physics Teacher Education Online, 3*(2), 10-15. Available: http://phy.ilstu.edu/pte/publications/minimizing_resistance.pdf

Name: ____ Date: ____________________

Moment of Inertia PreLab

Instructions: Provide correct answers to the following questions. Complete this PreLab and turn it in to your lab instructor upon arrival in lab.

Review the Glossary in the *Student Lab Handbook* for important terms associated with this lab.

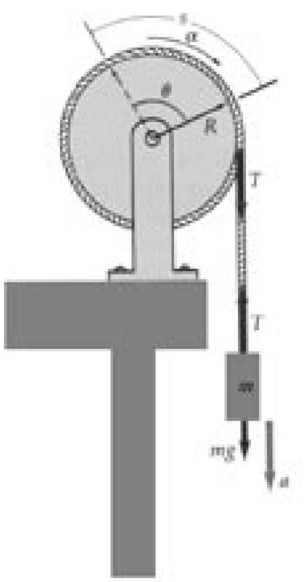
1) Sta□
mass.

$I_{dumbbell} =$ $I_{thin\ ring} =$ $I_{disk} =$

2) State the parallel axis theorem for moments of inertia.

3) Consider a disk that is free to spin about a horizontal axis attached to a weighted string (see figure). The string is wrapped around the outer rim of the disk and connected to a weight of mass *m* suspended over the edge of the level surface with a pulley. The disk has a moment of inertia *I*, and a radius *R.* The force of tension, *T*, arising from the disk, opposes the acceleration of the suspended weight. On the basis of Newton's second law one can conclude that $-T + mg = ma$ where *a* represents the linear acceleration of the weight. Given this relationship and assuming the definitions of torque, $\tau = TR$, angular acceleration, α, the relationship between them, $\tau = I\alpha$, and the relationship between linear acceleration and angular acceleration, $a = R\alpha$, show that the moment of inertia of the disk can be found using the following relationship:

$$I = mR^2\left(\frac{g}{a} - 1\right)$$



Name: ____ Date: ____________________

Moment of Inertia Lab Guidelines

Objectives: As a result of this lab, the student will:

- demonstrate a conceptual understanding of the phrase "moment of inertia."
- state a qualitative relationship between moment of inertia and amount and distribution of mass in a system.
- find the relationship between the moment of inertia and the amount of mass in a dumbbell system.
- find the relationship between the moment of inertia and the distribution of mass in a dumbbell system.
- verify the moment of inertia for a cylindrical ring with interior and exterior radii of R_1 and $R_{2,}$ and rotated around its central axis.

Task 1. Demonstrate a conceptual understanding of the phrase "moment of inertia."

a. The moment of inertia is to rotational motion as mass is to linear motion. In a linear system, the mass can be thought of as a "measure of resistance to linear acceleration." In a rotational system, the moment of inertia can be thought of as a "measure of resistance to rotational acceleration." The parallels between the force and torque relationships are clearly evident: $F = ma$ and $\tau = I\alpha$. As force is responsible for linear acceleration, so torque is responsible for angular acceleration.

b. Conduct a qualitative controlled experiment to determine the affect of the amount of mass at a fixed distance on the perceived moment of inertia of a weighted meter stick. Hold the meter stick at the 50*cm* position, and quickly rotate the meter stick back and forth with changing amounts of mass located at the same position each time. Note any changes in the resistance to rotational acceleration.

Q1. How does the amount of mass affect the perceived moment of inertia in this system?

b. Conduct another qualitative controlled experiment to determine the affect of the location of mass on the perceived moment of inertia. Use the same amount of mass each time. Again, hold the meter stick at the 50*cm* position, and quickly rotate the meter stick back and forth with changing mass distribution. Note any changing resistance to rotational acceleration.

Q2. How does the location of mass affect the perceived moment of inertia in this system?

Q3. Given the above system of meter stick and masses, what other pertinent variable(s) beside mass and location of those masses exist that might affect the perceived moment of inertia?

Task 2. Predict the dependence of moment of inertia on the amount and location of mass.

a. From the first task, it should be clearly evident that the moment of inertia of two equal units of mass placed at an equal distance from the axis of gyration is a function of both the total mass, m, and the distance of the two masses, r, from the axis of gyration. That is, $I = f(m, r)$. Perform a dimensional analysis to determine the expected form of this relationship. Keep in mind that because $\tau = I\alpha$, the units of I should be those of τ/α.

Q4. How did you perform your dimensional analysis? Show all work.

Task 3. Determine the moment of inertia of the test apparatus.

a. In order to conduct this experiment, you'll need to use a rotary motion sensor and accessories along with the associated software. Using the equation derived in the PreLab

$$I = mR^2\left(\frac{g}{a} - 1\right)$$

experimentally determine the moment of inertia for the test apparatus. The test apparatus should consist of the base assembly, the three-wheel axel mechanism directly attached to it, and the black metal rod. Be certain to average the results of three or four test runs.

Important Warnings: *Be very careful in your use of the above equation; don't confuse the mass of the suspended weight – m in the above equation – with the mass of the weights added to the rotational motion sensor. Don't confuse the radius arm – R in the above equation – with the radius of gyration of the masses added to the rotational motion sensor. Also, be certain to calibrate your rotational motion sensor so that the pulley wheel selected (radii of 5mm for small, 14.5mm for medium, and 24mm for large) is the same as the pulley about which you will wrap your string. Lastly, determine the linear acceleration of the falling weight, a, by taking the slope of a velocity-time graph. Direct measurements of acceleration have proven to be somewhat imprecise using the provided rotational motion sensor.*

Q5. What is the moment of inertia of the specified test apparatus? Be certain to show your work and include units in your answer.

Task 4. Conduct a controlled experiment to determine how the amount of mass affects the moment of inertia.

a. Controlling for radius of gyration, perform an experiment using the test apparatus with identical masses set atop the test apparatus to determine what affect the mass of these objects has upon the measured moment of inertia. <u>Make certain that all masses are centered over the axis of gyration at all times.</u>

b. Create a graph of moment of inertia versus mass. If the graph is not linear, appropriately modify the way you graph the data in order to linearize the graph.

Q6. Does the regression line pass through the origin? Why or why not?

Q7. If there is a non-zero y-intercept in the above graph, what does the y-intercept represent?

c. Correct your data for the above factor by using a column formula if necessary.

Q8. What does this say about the nature of combination of moments of inertia? (Is the total moment of inertia a product, sum, difference, product or some other combination of individual moments?)

d. Give the linear regression a physical interpretation (e.g., Must the modified graph's regression line pass through the origin after the data are corrected for the moment of inertia of the test apparatus? Adjust your best-fit relationship so that you end up with a physical interpretation of the data.) Label this graph *Moment of Inertia versus Mass.* Print the graph and include it with your lab report.

Q9. What is the nature of the dependence of the moment of inertia, *I*, on the total mass, *M*, of this system? (e.g., $I \propto m$, $I \propto m^3$, $I \propto 1/m$)

Task 5. For two equal masses placed equidistant from the axis of gyration, conduct a controlled experiment to determine how the location of mass affects the moment of inertia.

a. Controlling for mass, perform an experiment using the test apparatus with two equal movable masses to determine what affect the distance of these masses from axis of gyration has upon the measured moment of inertia. Be certain to adjust the moment of inertia of your experimental system by the amount equal to the moment of inertia of the test apparatus. Make certain that both masses are equidistant from the axis of gyration at all times.

Q10. Note that the masses on the rod are not point sources. From "where to where" does one *correctly* measure the distance used to derive this relationship?

b. Create a graph of radius versus moment of inertia. If the graph is not linear, appropriately modify the way you graph the data in order to linearize the graph. Give the linear regression a physical interpretation (e.g., Must the regression line pass through the origin? Adjust your best-fit relationship so that you end up with a physical interpretation of the data.). Label this graph *Moment of Inertia versus Radius.* Print the graph and include it with your lab report.

Q11. What is the nature of the dependence of the moment of inertia, *I*, on radius of gyration, *r*, in this system? (e.g., $I \propto r$, $I \propto r^3$, $I \propto 1/r$)

c. It should be clear from the analysis that a series of "point" sources distributed in a variety of ways (disks, rings, rods, etc.) and the fact that moments of inertia about the same axis of gyration are additive, that a more complete definition of moment of inertia can be based upon the following formula:

$$I = \sum_{i=1}^{n} m_i r_i^2$$

Task 6. Verify the moment of inertia for a ring.

a. Integral calculus can be used to show that the moment of inertia of a cylindrical ring of mass M (with inner radius R_1 and outer radius R_2) rotated about its central axis is given by the following relationship:

$$I = \frac{1}{2} M (R_1^2 + R_2^2)$$

b. Calculate and then experimentally verify the moment of inertia for the cylindrical ring provided.

Q12. What values did you get for theoretical an experimental values of the moment of inertia? Clearly distinguish your answers, one from the other. Include units.

Q13. What is the percent error given these two values? Show the initial formula and calculation.

Q14. What experimental error might account for the difference between these two values?

