SOCIETY OF PHYSICS STUDENTS
An organization of the American Institute of Physics

SPS Chapter Research Award Proposal

Project Proposal Title	Constructing a watt balance to redefine the kilogram
Name of School	University of Maryland, College Park
SPS Chapter Number	4155
Total Amount Requested	$1,999.66

Abstract

Physicists are working towards redefining the kilogram in terms of a natural physical constant through a watt balance, which measures mass by counteracting gravitational and electromagnetic forces. Here, we propose the construction of a high-precision watt balance using low-cost hardware, in collaboration with UMD Physics Makers.

Proposal Statement

Overview of Proposed Project

- **Research question:** Can we improve on the watt balance design presented in NIST's DIY LEGO Watt Balance paper, and to what precision can we make measurements of mass with respect to Planck's constant rather than to the way the unit of mass is currently standardized? [1]

- **Motivation:** The major motivation behind the construction of a watt balance lies in the power to redefine the standard unit of mass by referring only to other constant universal quantities. Currently, the kilogram is defined by a platinum-iridium block kept in France, which we will talk about more in the Background section. This is undesirable because this block is a physical object subject to contamination and change over time, and ideally our standard units are universal and are consistent with physical theory. Defining any unit of physical measurement in a precise manner is essential in modern research and technology, where high precision measurements are becoming a commonplace phenomenon.

- **Brief description:** The research project will include building an improved version of the NIST LEGO watt balance using cheaper materials in place of the LEGO structure and incorporate open-source hardware. After building the initial watt balance, we will attempt to improve the design of the hardware and software to increase precision and usability, and decrease cost to build.

- **Research goals of the project:** The goal of the project is to build a watt balance that can measure a mass of approximately 1 gram with an uncertainty of less than 1%. The 1% figure comes from NIST's LEGO watt balance, which had a relative uncertainty of 1%, and our goal is to construct an improved system that provides more accurate measurements for potentially less cost.

- **SPS connection:** Our project will help the local SPS chapter by creating opportunities for SPS students to gain experience in many areas: designing and milling printed circuit boards (PCBs), soldering, 3D computer-aided design (CAD), woodworking (which carries with it many similarities to machining), optics, electrodynamics, and software development. For the national organization, our project will result in a plan to build a cost effective watt balance to use for outreach and skill-building. We will release the plans to be used by other chapters in the organization.

Background for Proposed Project

The standardization of the base units—the second, ampere, meter, kilogram, kelvin, mole, and candela—is essential for every facet of modern industry and research. The kilogram, the base unit of mass, was first defined in 1795 as the mass of one liter of water at four degrees Celsius. Since 1889, the kilogram has been redefined according to the mass of a single cylinder block of platinum-iridium alloy called the international prototype kilogram (IPK), which is currently stored in Paris, France. Identical copies of the cylinder were made and distributed to labs and government agencies outside of Paris. This makes the kilogram unique among the seven base units, which are otherwise defined in terms of only the fundamental constants of nature. For this reason, combined with other factors such as the fluctuations in the weight of the IPK due to decades of cleaning the cylinder, has motivated efforts by physicists to redefine the kilogram according to the fundamental constants of nature. One of the leading proposals to do this has been to redefine the kilogram by measuring Planck's constant using a watt balance, which has been implemented in the United States by the National Institute of Standards and Technology (NIST).

The watt balance, invented by Bryan Kibble in 1975, is used to precisely determine the weight of a test mass through measurements of induced current via a Joseph junction and voltage via the quantum Hall effect [2]. The upward electromagnetic force produced by running a current through a coil in a magnetic field counterbalances the downward gravitational force acting on a test mass. Equating these forces, the force balance is given by:

$$mg = IBL \qquad (1)$$

Where B is the magnetic field strength, m is the mass of the test object, g is the gravitational acceleration, I is the current running through the coil, and L is the length of the wire in the coil.

$$Bl = \frac{V}{v} \qquad (2)$$

The BL is the flux integral, which is given in terms of the coil velocity v and the electromotive force voltage V induced in the coil. By substituting Eq. (2) into Eq. (1), we obtain that:

$$m = \frac{IV}{gv} \qquad (3)$$

The voltage, measured through a Josephson voltage system, depends on Planck's constant h, the elementary charge e, and the microwave frequency f of the electric field:

$$V = \frac{h}{2e}f \qquad (4)$$

Hence, the watt balance can be used to measure the mass from Planck's constant, a fundamental constant of nature. Two years ago, students collaborated with researchers at NIST to build a DIY LEGO Watt balance based on a proposal conceived by Terry Quinn [3]. We plan on improving their design by using less expensive materials and open-source hardware.

Expected Results

By the end of this project, we expect to have built an improved watt balance with greater precision than the NIST DIY watt balance. Our version will also be cheaper because LEGO is more expensive than the materials we will use, and we will replace the Labjack data acquisition device (DAQ) with a far less expensive and open-source Arduino microcontroller.

We also plan to release our Arduino software that we create, along with descriptive instructions to build our version. These materials will be available to others who want to build a similar device.

Description of Proposed Research - Methods, Design, and Procedures

At the start of the project, we will meet with all interested students and go over the project. We will determine roles based on interest, skill, and available time of the students. After this initial meeting, each team will meet once a week, providing minutes to the management team. The management team will meet every other week to assess progress and coordinate teams. The teams and their roles are listed below.

Project management team

- Consists of team leaders from all other teams
- Put together purchase orders
- Coordinate teams and keep project on track

- Write paper/poster upon completion

Optics and electromagnetism team

- This team will study the optical lever and shadow sensor mechanisms. They will look for improvements and ways to automate calibration and measurement.
- The team will also build the solenoids and magnet supports.
- Upon completion of the initial watt balance, this team will take data from the device and begin analysis to determine our accuracy and precision. This analysis will be updated with each improvement to show our progress.

Electronics hardware team

- This team will begin by studying the electronics plans given by NIST and designing and milling PCBs
- After building the initial watt balance, this team will re-work their designs to replace the Labjack DAQ with an Arduino, and look for other improvements.
- This team will work very closely with the optics and software teams for much of the project.

Software team

- This team will initially try to get source code from NIST and if possible, attempt to refine the software.
- Later, the team will work to write supplemental software for calibration and for running the Arduino.

CAD team

- This team will work to design the structure of the watt balance and the electronics enclosures
- The main goal in designing the structure is to make it simple to build. This is especially necessary given our limited access to tools, and supports our mission to reduce the cost of building a watt balance.
- Smaller parts will be made on campus using a 3D printer.

Construction team

- This team will work closely with the CAD team to ensure that the design accounts for the tools we have.
- Once the CAD is complete, this team will build the main structure for the watt balance

Upon completion of the project, the CAD team will produce design files and documentation, with build notes provided by the construction team. The software team will produce Arduino code and supplemental Python code with documentation. The electronics team will produce design files for the PCBs they design, along with build notes. The optics and electromagnetism team will produce documentation for design improvements and a build guide. They will also provide data and analysis of our accuracy and precision. All of this information will be posted on GitHub where anyone can access our work to replicate or improve on it. Once all of this is complete, the project management team, along with any other interested students, will write a paper or poster (depending on advice from faculty members) to finalize the project.

Plan for Carrying Out Proposed Project

- **Personnel**
    - 15 members of UMD Physics Makers, 12 of which are UMD SPS members, will be participating in the construction of the watt balance
- **Expertise**
    - John Evans and Elliott Hall have both taken machine shop courses in the Department of Mechanical Engineering at UMD. John also has been a woodworker for 12 years. Peter Zhou has had experience in

3D CAD and printed circuit board (PCB) design and milling. Many of the members of UMD Physics Makers have had experience soldering and working with electronics.

- **Research Space**
  - There will be multiple spaces available, including the UMD Physics Makers space, Vortex
  - Access to lecture demonstration area, workshop
- **Contributions of faculty advisors or the department**
  - The makerspace area will be provided by the UMD Physics Department, as well as access to the shop and any tools that we might need during our construction

Project Timeline

1/25/2018	- Assign team members based on skills and interest and time available
2/2/2018	- Purchase tools and electronics components - Begin design of structure - Begin design of PCBs
2/16/2018	- Finalize structure design - Purchase materials for structure - Finalize PCB design - Mill test PCB
3/2/2018	- Begin building structure
3/16/2018	- Test completed watt balance - Make changes to structure and electronics as necessary
3/23/2018	- Calibrate watt balance and begin testing possible hardware improvements
4/1/2018	- Begin interim report - Continue testing possible hardware improvements
4/29/2018	- Complete interim report draft - Begin combing through provided NIST software for ways to improve
5/15/2018	- Finalize and submit interim report with improvements found, and future possible improvements - Break for summer
9/10/2018	- Reconvene and recalibrate the watt balance - Begin attempt to replace the Labjack DAQ with an Arduino to reduce costs
10/10/2018	- Test watt balance with both the Labjack DAQ and the Arduino to compare their performance - Determine if the Arduino is a viable replacement - Test any further improvements
10/20/2018	- Begin poster/presentation/paper based on findings - Begin final report
11/12/2018	- Complete poster/presentation/paper based on findings - Complete final report, ideally before the kilogram is official redefined in terms of Planck's constant in November

Budget Justification

The cost associated with this project comes largely from the software and hardware required for the design, constructing, and operating the watt balance. Arduino microcontrollers must be purchased for acquiring the data. The router is needed in order to create mortises and roundovers in the main structure and to build the enclosure for the electronics. Another cost that contributes to the budget is due to our need for a drill press, which is required due to the fact that holes must be accurately drilled into the structure to ensure that our measurements can be made as accurately as possible. A reciprocating saw is needed to cut metal parts, and an impact driver is also required to drive screws and bolts. A portable drill will be used for tasks that cannot be accomplished with the drill press, and a bench plane will be used to joint and smooth all of the wooden components that make up the prototype structure. Finally, clamps and a portable workbench are needed to secure the pieces while we work on them.

Bibliography

[1] L. S. Chao *et al.*, "A LEGO Watt balance: An apparatus to determine a mass based on the new SI," *American Journal of Physics*, vol. 83, no. 11, pp. 913–922, Oct. 2015.

[2] D. Haddad, L. S. Chao, F. Seifert, D. B. Newell, J. R. Pratt, and S. Schlamminger, "First mass measurements with the NIST-4 watt balance," in *2016 Conference on Precision Electromagnetic Measurements (CPEM 2016)*, 2016, pp. 1–2.

[3] T. Quinn, L. Quinn and R. Davis, "A simple watt balance for the absolute determination of mass," *Physics Education*, vol. 48, no. 5, pp. 601–606, 2013.