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

SPS Chapter Research Award Proposal

Project Proposal Title	A LEGO Watt balance: an apparatus to determine the SI unit of kilogram using the fundamental Plank's constant
Name of School	The University of Tennessee - Chattanooga
SPS Chapter Number	7170
Total Amount Requested	**$1997.76**

Abstract

The University of Tennessee-Chattanooga SPS chapter will construct a LEGO-based model of the Kibble balance that redefines a SI unit of kilogram using the fundamental Plank's constant. It will measure macroscopic masses to 1% accuracy, and will be used for physics demonstrations, student recruitment, community inspiration, and outreach.

Proposal Statement

Overview of Proposed Project

The University of Tennessee-Chattanooga chapter of the Society of Physics Students (UTC-SPS) proposes to construct, calibrate, and put to action a LEGO-based model of the watt (Kibble) balance that redefines a System International (SI) unit of kilogram using one of the fundamental constants, the Plank's constant. The model will be able to measure gram-level masses with relative standard uncertainty of 1%. The detailed description of the project is presented in the next section.

We have chosen this project as our chapter 2021-22 academic year research project because:

- It will allow the UTC-SPS team members to learn about areas of physics and metrology that are usually not covered or covered very little in standard physics curriculum.
- The project is hands-on, so we will be able to apply and greatly improve our experimental skills.
- The project will require computer interfacing and learning LAB View applications, which is a very useful skill in today's workplace, but not covered in our physics classes.
- The project will promote teamwork and the SPS brotherhood. Our SPS chapter has been dormant for several years, and we believe that working together on such a fascinating project will help us to revive and grow our chapter.
- The final product, the LEGO watt balance, will be housed on display on the first floor of the Chemistry and Physics building, the Grote Hall, unless it is used for physics demonstrations and recruiting new physics majors and the local SPS chapter members and/or outreach events. To the best of our knowledge, such a model does not exist in the Southeast region of the United States, so we expect, it will draw a lot of interest.
- We will acknowledge that the model is constructed with the help of the SPS grant, which will increase students' awareness with local SPS chapter and the SPS National.
- This project combines high-level physics concepts with LEGOS, which is a synonym of fun for many people. We are looking forward to having a lot of fun (and learning) ourselves while working on this project. We believe that we can convince other people that physics can be fun. We believe that this LEGO model will inspire many physics enthusiasts from our university and a broader community.

Background for Proposed Project

Both science and technology rely on the measurement and units of measurements. The International System of Units (SI, abbreviated from the French *Système international (d'unités)*), the modern form of the metric system, is the most widely used system of measurement in the world. It consists of seven base units: meter, kilogram, second, ampere, kelvin, mole, and candela. Born with the French Revolution, SI used to rely on physical (material) standards such as prototypes of meter and kilogram, originally made with special material and kept at each country under special conditions. For example, the International Prototype of Kilogram (IPK) is one of three cylinders forged in 1879 of platinum (90%) - iridium (10%) alloy (Fig. 1). The IPK is the only mass on Earth with zero uncertainty. The stability of the IPK is crucial because the kilogram underpins much of SI system units as it is currently defined and structured. However, we know that the IPK changes with time.

Recently, a lot of effort has been made to redefine the SI units based on fundamental physical constants rather than material standards [1]. This means that the SI units can be defined by declaring that seven fundamental (defining) physical constants have certain exact numerical values when expressed in terms of their SI units. For example, the unit of length, the meter, has been defined based on the speed of light. The unit of time, the second, has been defined based on the hyperfine transition frequency of the caesium-133 atom (Caesium or atomic clock). On May 20th, 2019, The International Committee for Weights and Measurements approved a new definition of the kilogram by defining Planck's constant to be exactly 6.62607015 x 10^{-34} kg m^2/s [2], therefore eliminating the material standard for the kilogram.

To re-define the kilogram experimentally, the apparatus, known as the watt balance, or the Kibble balance, has been developed [3]. Named in honor of physicist Bryan Kibble who invented it in 1975, this device incidentally compares mechanical power to an equal amount of electrical power. More precisely, it measures the downward pull of a gravitational force on a mass by counteracting it with an upward electromagnetic force as schematically shown at Fig. 2. It toggles between two measurement modes and indirectly compares electrical power and mechanical power, hence the name “watt balance”. This design makes Kibble balances capable of ultra-precise mass measurements. Such a balance has been designed and constructed at the National Institute of Standards and Technology (NIST), in Gaithersburg, Maryland, USA. It can be used to realize the kilogram unit of mass within about three millionths of a percent. The machine (Fig 3) is unique, very complicated, is being kept under “clean room” conditions, and costs several millions of dollars.

Fig. 1. The International Prototype of Kilogram (1879) [1].

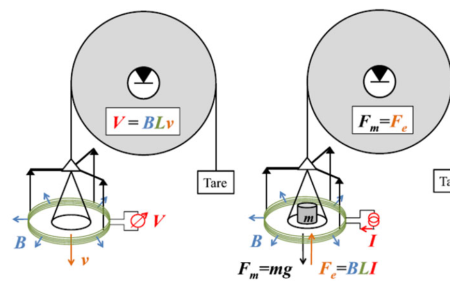

Fig. 2. Watt balance. Left: velocity mode. The coil moves vertically in a radial magnetic field, and a voltage V is induced. Right: force mode. The upward electromagnetic force generated by the coil opposes the gravitational force exerted on m. [4].

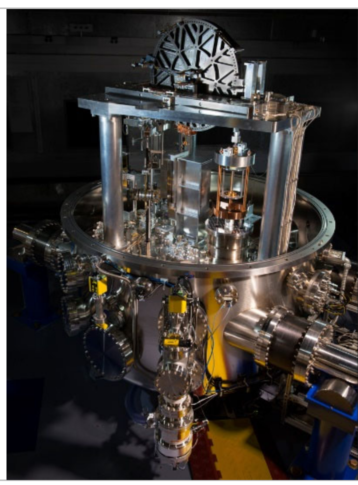

Fig. 3. The NIST-4 Kibble balance, https://www.nist.gov/si-redefinition/kilogram-kibble-balance

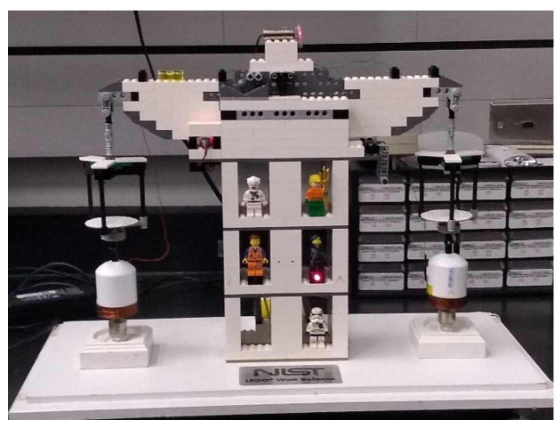

Fig. 4. The LEGO watt balance [4].

A LEGO-based model, a much simpler version of the watt balance (Fig.4) has been developed by the NIST researchers [4] to inspire interest in metrology in aspiring physicists and general public, and to increase outreach opportunities for the high-level physics research. It is within the ability of an undergraduate physics students to put it together and calibrate; it is very cost-effective and uses a NIST-developed LabView based computer software. It is capable of measuring gram-level masses using Plank’s constant with relative standard uncertainty of 1%. Our goal is to construct a replica of such model, which to the best of our knowledge does not exist in the South-Eastern region of the US. We believe that we as a team will gain invaluable experience constructing this model and will inspire many budding physicists while using it for demonstrations, recruiting and outreach in our area.

Expected Results

The expected results of this project will be constructed and calibrated LEGO-based watt balance apparatus capable of measuring the the gram-level masses to an uncertainty of 1% or less. We, as the UTC-SPS team, expect to gain invaluable theoretical knowledge and experimental experience constructing and testing this apparatus. We also expect that having such a LEGO-based watt balance will bring more attention and recognition to the Society of Physics Students chapter at our university and to the physics program as a whole. We believe that due to the fun construction of the device using LEGOS it will make a wonderful outreach tool to support physics education at local schools and museums. Also, the experience of having a serious, funded project will create interest among the students of our university allowing us to recruit more members and develop a larger presence on the University of Tennessee-Chattanooga campus.

Description of Proposed Research - Methods, Design, and Procedures

The UTC-SPS team will construct the tabletop, computer-controlled LEGO-based watt balance. We will follow the procedures suggested in [4]. We have chosen a symmetric design that follows the notions of an equal arm balance. Weighing pans are suspended from each arm of the balance which will pivot about the center. Two coils which are immersed in a radial magnetic field are each placed on opposites sides of the watt balance. One of the coils will function as the driving coil while the other will be used to read voltage changes as the balance beam moves. The radial magnetic field will be produced by two neodymium ring magnets (one per coil). No additional ferromagnetic material to guide the magnetic flux direction will be used.

We will use two USB devices, a U6 from Labjack and a voltage output from Phidget to connect the device to a laptop computer. There will be a LEGO handheld controller in order to manually tare the balance and provide easy interaction during outreach events. We will design the circuit to keep the part count minimal, for simplicity. Only seven resistors, one relay, and one voltage regulator will be used.

To control the watt balance we will use the LABVIEW-based software. Dr. Darine El Haddad, a scientist at NIST, has agreed to provide us with a free version of the software as well as to help us with any questions regarding the computer control while constructing and testing the apparatus.

We will calibrate and align the LEGO watt balance before starting the measurements. The angular position of the balance will be monitored using a shadow sensor which is composed of a laser pointer and a photodiode near the lower edge of one arm of the balance. A second laser pointer mounted on top of the balance serves as an optical lever for calibrating the shadow sensor. Once the balance is properly calibrated and aligned, a determination of a mass or the value of the Planck constant can begin. One will be able to see the relationship between a physical macroscopic mass and the Planck constant, a natural constant found in quantum mechanics, and will be able to determine the absolute mass of a small object without needing any comparison to reference mass standards, and with a great accuracy of 1%.

Plan for Carrying Out Proposed Project

The project will be carried out by all current members of the UTC-SPS (currently five members). The project leaders are Ivy Cartwright (UTC-SPS President) and Gaige Benkert (UTC-SPS Treasurer). When the parts/materials are obtained, we will divide responsibilities between the members (construction, assembly, circuitry, calibration, etc.) and hold regular working meetings. We will enlist help from our faculty advisor, Dr. Allen, regarding general questions, and from Dr. Darine El Haddad from NIST regarding the LabVew code. The Department is very supportive of the project and will provide research space on the second floor of the Grote Hall (Advanced Physics Lab and/or Physics Study room) as well as necessary additional resources, such as measurement equipment, etc. not covered by this grant.

Project Timeline (2022)

January: Order the parts, divide responsibilities between the team members, create work schedule.
February-May: Construct and beging calibration of the LEGO watt balance.
5/31/2022 Submit the Interim Report.
August: Complete the calibration. Create a short video explaning how the apparatus works. Present the LEGO watt balance at the UTC student organizations promotion day to promote the UTS-SPS.
September-November: The LEGO watt balance will be displayed at the lobby of the Grote Hall along with a running video explaining how it works. It will also be used as a demonstration apparatus by the SPS members for Physics recruitment (Departamental and UTC Open House events) and outreach events at the local Creative Discovery Museum and local schools.
September-November: Submit the abstract and present our project at the South Eastern Section of the American Physical Society 2022 Meeting.
12/31/2022 Submit the Final Report

Budget Justification

To construct the LEGO-based watt balance we request the following equipment:

Lego parts according to the list specified in [4], 416 parts total, from the LEGO web site and other sources.	$ 83.20
Data acquisition hardware: Lab Jack DAQ w/ USB	$345.00
Voltage output: Phidget Analog 4	$ 85.00
Photo-electronic components: laser components, photodiodes, resistors, linear voltage regulator, copper wire, magnets, etc.	$152.25
Construction components: 2x4 lumber, brass rod, PVC pipes and fittings	$ 38.80
Subtotal (parts) = $704.25	
Shipping and handling (estimated at 12% of the parts)	$ 84.51
Dell Latitude 5520 laptop computer to control the apparatus	$1209.00
LabView code (from NIST)	free
Total	**$1997.76**

Bibliography

1. Ketterle, W.; Jamison, A. O. "An atomic physics perspective on the kilogram's new definition". *Physics Today*. **73** (5): 32–38. (1 May 2020). doi:10.1063/PT.3.4472.
2. International Bureau of Weights and Measures (20 May 2019), The International System of Units (SI) (PDF) (9th ed.), ISBN 978-92-822-2272-0, archived from the original on 12 November 2021.
3. Robinson, I A.; Schlamminger, S. "The watt or Kibble balance: A technique for implementing the new SI definition of the unit of mass". Metrologia. **53** (5): A46–A74 (2016). doi:10.1088/0026-1394/53/5/A46.
4. Chao L.S., Schlamminger S., Newell D.B., Pratt J.R., Seifert F., Zhang X., Sineriz G., Liu M., and Haddad D., American Journal of Physics 83, 913 (2015); doi: 10.1119/1.4929898