Measuring 10 gram masses in terms of electrical quantities using a LEGO-based Kibble balance

Stephan Schlamminger - stephan.schlamminger@nist.gov
Leon Chao- leon.chao@nist.gov

Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899

Abstract

In 2018, the International System of Units (SI) is expected to undergo a major revision. This presents a paradigm shift where the present SI, based on seven fundamental units, will evolve into a system based on seven fundamental constants. More specifically, the unit of mass, the kilogram, will no longer be defined by an artifact standard, but rather be derived from a fixed value of the Planck constant *h*. One possible means to realize the unit of mass from *h* is provided by the watt balance (or Kibble balance), invented in 1975 by Dr. Bryan Kibble (1938-2016). Since the advent of his concept, many national metrology institutes around the world have worked toward developing watt balances capable of realizing a kilogram mass with relative uncertainties of a few parts in 10^8. At the National Institute of Standards and Technology (NIST), located in the USA, we have developed a high-precision, full-sized watt balance as well as a fun, tabletop watt balance constructed from LEGO bricks capable of measuring gram-sized masses with a relative uncertainty of 1 %. This article presents the design, construction, and performance of the LEGO watt balance and its ability to measure a small mass.

Introduction

On May 20, 1875, seventeen countries signed a treaty entitled the “Meter Convention" to establish new international standards for length and mass. This agreement defined the unit of mass as the kilogram (kg). In 1879, a physical mass standard was fabricated from an alloy of platinum (90 %) and iridium (10%) and dubbed the “International Prototype Kilogram" (IPK), becoming the primary mass standard for the world. Many copies of the IPK were distributed to the participating countries to serve as secondary standards. At the National Institute of Standards and Technology (NIST) in the USA, the fourth (K4) and twentieth (K20) copies are stored[1]. Presently, the IPK is housed under three glass bells and locked inside of a metallic vault at the Bureau of Weights and Measures (BIPM) located in Sevres, France. Since its original conception, the IPK has only been taken out of the vault three times to update and assign new mass values for the working standards used at the BIPM and to copies distributed across the globe. May 20th has been designated as “world metrology day” and it could be the day in 2019, where the new definition of the kilogram goes into effect.

It is expected for the International System of Units (SI) to undergo a paradigm shift from a system of seven base units to a system of seven reference constants in 2018/19. In this new SI, after losing its status as the only mass on Earth defined with zero uncertainty, the IPK will be assigned an uncertainty of a few micro-grams. Therefore, the Planck constant *h,* which has a present relative uncertainty of 1.2 x 10^{-8}(and hopefully less by next year), will be fixed with no uncertainty. This fixed value of *h* will be used to bootstrap the unit of mass, the kilogram. Two different experimental approaches have been developed to create a link between macroscopic mass and quantum mechanical *h:* the Avogadro project and the watt balance. At NIST, we have chosen to pursue the watt balance experiment to realize the kilogram after the SI redefinition.

In the watt balance experiment, the weight of an object is balanced against an electromagnetic force generated by a current-carrying coil immersed in a magnetic field. By design, the watt balance toggles between two measurement modes and indirectly compares electrical power and mechanical power, measured in units of watts, hence the term “watt balance"[2]. It is essentially a force transducer that can be calibrated solely in terms of electrical, optical, and frequency measurements. Two watt balances around the world have demonstrated the capability of measuring 1 kg masses with a relative uncertainty of a few parts in 10^8 [6, 7].

The redefinition of the kilogram, or more specifically the watt balance, serves as an embodiment of Dr. Bryan Kibble's (1938-2016) legacy and monumental contributions to metrology. While at the National Physical Laboratory (NPL), Kibble led the watt balance project, creating two prototypes, Mark I and Mark II. The latter model was designed to operate in vacuum and was intended to measure the Planck constant with sufficient accuracy in aiding the redefinition movement[3]. In 2009, the Mark II was transferred to the National Research Council of Canada (NRC) and presently has measured the Planck constant with the smallest relative uncertainty of 1.9×10^{-8} [6]. When Kibble officially retired in 1998, he was still very active in metrology as a consultant and prolific writer. Unfortunately, Dr. Kibble will not be able to witness the 2018 redefinition of the SI, but he will forever be remembered as the father of the watt balance. To honor his contribution, Dr. Terry Quinn, the director emeritus of the BIPM, proposed to rename the watt balance as “Kibble balance” at the 22nd meeting of the consultative committee of units. This proposal was adopted.

Here in honor of Bryan Kibble and under the inspiration of Terry Quinn, we describe the construction of a tabletop LEGO Kibble balance capable of measuring gram-level masses with a much more modest relative standard uncertainty of 1% [8, 9]. For the instrument described here, the cost of parts sums to about $450. The largest portion of the cost is in the data acquisition system used to transfer the data to a computer. A recommended parts list is provided in Appendix A. We encourage readers to use this manuscript as general guidance for constructing such a device and by no means as a definitive prescription. There are many ways to build a watt balance, and we consider here a concept to highlight general considerations that are most important for success.

Basic Watt Balance Theory

Before building a LEGO watt balance, it is helpful to understand the general principles behind the operation of a watt balance. Several laboratories have constructed watt balances and are presently pursuing ultra high-precision mass measurements. These watt balances can measure masses ranging from 500 g to 1 kg and obtain relative standard uncertainties as small as a few parts in 10^8, or about a million times smaller than that of the LEGO watt balance.

Even though a watt balance might appear functionally similar to an equal-arm balance, there is a fundamental difference. A traditional balance compares weight (mg) against another weight. In contrast, a watt balance compares weight to an electromagnetic force. The experiment involves two modes of operation, illustrated in Fig. 1: velocity mode and force mode. The basis of both modes is the principle of the Lorentz force (the force that a moving charge experiences in a magnetic field). In velocity mode, a coil (wire length L) is moved at a vertical velocity v through a uniformly distributed radial magnetic field (flux density B) so that a voltage V is induced. The induced voltage is related to the vertical velocity through the flux integral BL:

$$V = BLv. \tag{1}$$

In force mode, the weight mg of a mass m is counteracted by an upward electromagnetic force F generated by the now-current-carrying coil in a magnetic field:

$$F = BLI = mg, \tag{2}$$

where g is the local gravitational acceleration and I is the current in the coil.

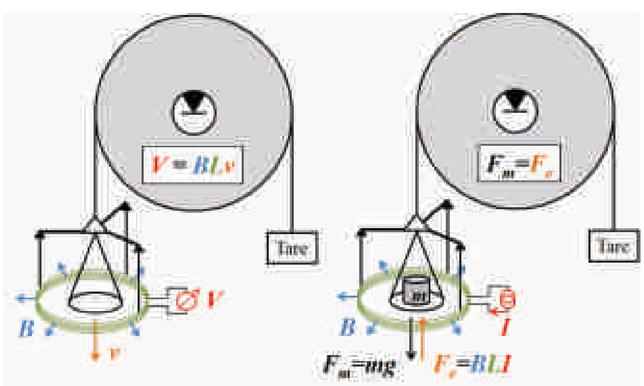

FIG. 1. Left: velocity mode. The coil moves vertically in a radial magnetic field and a voltage V is induced. Right: force mode. The upward electromagnetic force generated by the coil opposes the gravitational force exerted by m.

In principle, mass could be realized solely by operating in force mode if B and L could be measured accurately. Because both of these variables are difficult to measure precisely, velocity mode is necessary as a calibration technique. By combining Eqs. (1) and (2), canceling out the BL factor common to both equations, and rearranging the variables, expressions for electrical and mechanical power are equated and a solution for mass is obtained:

$$VI = mgv \Rightarrow \quad m = \frac{VI}{gv}. \tag{3}$$

The equation above relates mechanical power to electrical power and provides a means to relate mass to electrical quantities. More precisely, the relationship equates "virtual" power, in the sense that the factors of each product, V and I or mg and v, are not measured simultaneously, but separately in the two modes. The "power" only exists virtually, i.e., as a mathematical product. The practical significance of a "virtual" comparison is that the result is independent of several nonconservative elements, such as the mechanical friction during velocity mode or the electrical resistance of the coil wire.

In electrical metrology, the current I is difficult to measure precisely so we take advantage of Ohm's law by converting the current I to the voltage drop by running the current through a precise resistor. By comparing the electrical measurements V and R to two quantum devices, the Josephson voltage standard and the quantum Hall resistor, we are able to measure and derive electrical power from the Planck constant h [4].

The remaining two variables g and v are measured accurately with an absolute gravimeter and interferometric methods, respectively. For the LEGO watt balance, these ultra-high precision metrology approaches are unnecessary.

The local acceleration can be estimated by inputting one's geographical coordinates into the web page found in Ref. 10, or even measured experimentally with a simple pendulum in the laboratory. Velocity can be determined using a simple optical method that we describe in Sec. V.

However, do not be fooled by our toy. The LEGO watt balance is versatile and fully capable of measuring gram-level masses in terms of electrical quantities. A capable operator can perform a measurement with a relative uncertainty of 1% with the device described below.

LEGO Watt Balance Mechanics

We chose a symmetric design for the LEGO watt balance to appeal to the easily recognized notions of an equal-arm beam balance. Figure 2 shows a computer generated model of our balance. A weighing pan is suspended from each arm of the balance, which pivots about its center. Suspended below each weighing pan is a wire-wound coil immersed in a radial magnetic field.

The magnet system we chose to generate this radial magnetic field consists of a pair of neodymium (N48) ring magnets, one pair per coil. For simplicity, we recommend keeping the system an open field design, i.e., "yokeless" meaning no additional ferromagnetic material to guide the magnetic flux direction. The dimensions of the ring magnets were chosen such that they could fit inside the PVC pipe former with approximately 5 mm clearance all around. A brass threaded rod secured to a wooden base plate provides the vertical guide for each magnet system (see Fig. 3).

The magnets are oriented on the brass rod such that they repel each other, and two aluminum nuts on either side of the magnets constrain the repulsive force, also setting their separation distance. This design allows us to adjust the distance between the magnets and the geometrical center of the magnet assembly. By holding a needle by the thread close to the permanent magnets, the radial magnetic flux lines can be revealed (see Fig. 4).

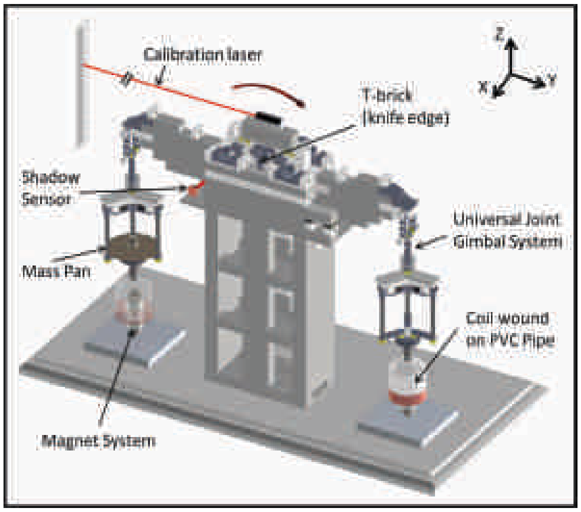

FIG. 2. Computer generated model of the LEGO watt balance. The balance pivots about the T-block as the fulcrum. Two PVC endcaps with copper windings hang from universal joints on either side of the balance beam. Coil A is on the left and Coil B is on the right. A small mass sits on the Coil A mass pan and each coil is concentric to its own magnet system. Two lasers are used to calibrate and measure the velocity of each coil.

Each coil former was made from a standard 1-inch PVC pipe with end caps glued to it. The coil was manually wound onto the PVC pipe using a very low-speed lathe spindle and each layer of wire was potted with epoxy. We chose to use AWG-36 wire with about 3000 windings. In our system, a current of 2.7 mA generated about 0.1 N of force. The total resistance of the wire was 450 Ω.

The coils can be constructed without a lathe by either hand-winding or by using a power drill. Using a lathe to turn down the PVC pipe is an optional step which we chose to execute because it allowed a deeper groove for more windings. Increasing the number of windings on the coil increases the vertical electromagnetic force generated for the same current by increasing the BL factor.

A small hole was drilled into each end cap top where a LEGO cross axle was attached vertically, allowing each to hang rigidly beneath their corresponding mass pan (see Fig. 3). The mass pan was suspended from three rigid rods linking to a LEGO universal joint (part no. 61903). This dual-gimbal system hangs from a set of two freely pivoting axles parallel to the central pivot (part no. 4208204) connecting to the balance arm. The central pivot (T-brick part no. 4211713) has a “knife edge" radius of approximately 3.1mm and rests on a smooth surface.

The whole balance measures approximately 43 cm x 36 cm x 10 cm and has a mass of 4 kg, including the wooden base board. Figure 10 shows a photograph of one of three balances we have constructed.

Electronics And Data Acquisition

We employ a National Instruments USB-6001 data acquisition (DAQ) to connect the LEGO watt balance to a laptop computer. The USB-6001 is used to measure the position of the beam balance, the induced voltage, and the current in each coil. We connect a seventh input to A I3+ to a hand held LEGO controller (potentiometer) that allows students to manually tare the balance, making a popular exhibit for explaining controller feedback principles. The DAQ sources 5V for the circuit and the analog output is connected to a double-throw, double-pole relay for energizing only one coil at a time. One coil serves as the sine-driven actuator while the other coil picks up an induced voltage. The relay allows toggling between the two coils, providing the operator with the option to select which coil is the driver.

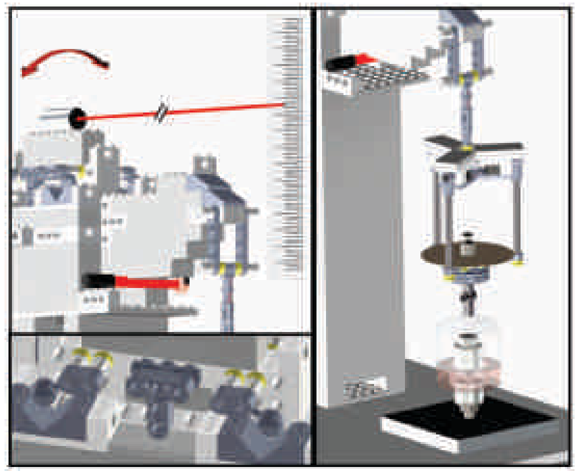

FIG. 3. Top left: The calibration laser projects onto a ruler a few meters away. The shadow sensor detects angular motions of the balance and outputs an oscillatory voltage signature. Right: A transparent view of the PVC coil assembly shows its concentricity to the magnet assembly. A stainless steel 10 g mass sits centered on the mass pan and the gimbal system above the mass pan is shown. Bottom left: LEGO T-block serving as the central pivot with balls and V-blocks for kinematic realignment. An identical set exists on the opposing face of the balance.

FIG. 4. By holding a needle by the thread, the radial magnetic field flux lines can be revealed.

We designed the circuit to keep the part count low (four resistors, one relay, one diode, one transistor), to allow for easy construction. Fig.5 shows the circuit diagram.

The 5 V obtained from the USB data acquisition board powers the two laser diodes (see Sec. V for functions of the optical system). The photo current produced in the photodiode is proportional to the balance position. The photo current flows through R5, the 5 kΩ resistor and the changing voltage drop is calibrated in terms of physical displacement of the coil.

A custom executable program has been designed to control the LEGO watt balance. If interested in obtaining the free executable and CAD files, please visit the American Journal of Physics Electronics Archive found in Ref. 11. A screenshot of the main interface is shown in Fig. 6.

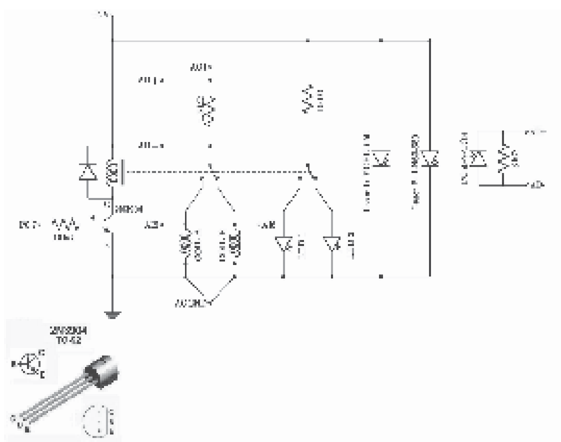

FIG. 5. Circuit diagram for the LEGO watt balance. We included an optional set of light emitting diodes (LEDs) wired to the relay as an indicator of which coil is active.

FIG. 6. The front panel of the LEGO watt balance control software. It allows the operator to calibrate the system and weigh small masses

Measurement

Like a professional watt balance, the LEGO watt balance must undergo a series of alignments and calibrations prior to starting the experiment, detailed in the following four-step procedure. We measure the balance's angular position using a shadow sensor. The system consists of a vertically oriented line laser pointer and a photodiode near the lower edge of one arm of the balance. When the balance moves, it gradually obstructs the optical path of the laser, thereby changing the intensity of light hitting the photo detector. A second laser pointer mounted on top of the balance serves as an optical lever for calibrating the shadow sensor, as we will describe shortly.

Once these prerequisites have been achieved, a complete determination of a mass can begin using a common A-B-A measurement technique. This repetition method is used to cancel the time-dependent drift associated with measurements. For instance, one can interleave velocity mode, then force mode, then velocity mode again. Ideally, these measurements are done such that the instrument undergoes as little change as possible, or by performing the measurements in quick succession, neither moving nor tinkering with the balance in between measurements. For reference, our experienced operators could perform the following alignment, calibration, and measurement procedure in about 10 minutes.

A. Calibrating the shadow sensor

The shadow sensor is the method we implemented for measuring the angular displacement of the balance beam and is calibrated using an optical lever. The angular displacement is then used to calculate the vertical velocity v of the coil needed for velocity mode.

1. Place the LEGO watt balance on a flat, level surface located a few meters from a wall or vertical structure.

2. Shine the laser pointer mounted on top of the balance at a wall a few meters away as in Fig. 3. Ideally, a ruler or grid paper is taped to the wall where the laser spot is located. Measure the distance d from the fulcrum of the balance to the wall.

3. Align the balance beam to its support tower. Ensure that the balance is not rotated around the y and z axes (the coordinate system is shown in Fig. 2). Looking from the top, the clearances between the beam and the support tower should be evenly spaced on each side. Our version of the balance has several auxiliary parts, i.e., balls that engage in V-grooves and a swivel bracket that aid in the balance alignment. However, it is also possible to perform alignment without these parts. Also, it is good practice to check if the balance is fairly leveled when absent of masses.

4. Concentrically align each magnet system to its corresponding coil by adjusting the X-Y location of the wooden base of each magnet.

After these four alignment steps, the instrument is ready for calibration. Employing the software's "SS Calibration Mode," the balance is servoed to a few different angles, which causes the shadow sensor to detect differing light intensities and convert them into voltages V_i. For each voltage, the position x_i

of the light spot on the ruler is measured. In addition to these points, we note the position x_0 of the light when the balance is horizontal. Using the small angle approximation, the balance angle is then determined as $\theta_i = (x_i - x_0)/d$ and the coil height is calculated by multiplying the balance angle by the effective radius or $z_i = r_{\text{eff}}\theta_i$. The effective radius is found by measuring the distance from the knife edge to the mass pan universal joint. For the balance described here, $r_{\text{eff}} = 175$ mm.

Within a reasonable range, the voltage produced by the shadow sensor is a linear function of the coil height. Hence the coil height can be obtained as $z(V) = b(V - V_o)$. A best fit line to the data (z_i, V_i) yields b and V_o. Fig. 7 shows an example of such a calibration.

B. Velocity mode measurement

As stated before, velocity mode measurement (*BL*) is the key for characterizing the electromagnetic properties of the balance. Our chosen method was to use the information from our calibrated optical displacement sensor and simply take its time derivative to calculate velocity. Velocity mode is activated by clicking the "Measure BL" button on the front panel of the software.

We arbitrarily chose to perform the watt balance experiment using Coil A so Coil B was used to drive the balance in a sinusoidal motion and we will continue this nomenclature for consistency and clarity; see Fig. 2. Using the language of control theory, Coil B was the input driven with an open-loop sinusoidal voltage, and the output balance position was detected by the shadow sensor.

A sinusoidal driving signal resulting in a 1mm coil displacement and a period of 1.5 s seemed to be a good starting point for our balance. We sampled the DAQ at a rate of $\Delta = 1$ and obtained values for the induced voltage on Coil A $V(i\Delta)$, and the shadow sensor voltage $V_{SS}(i\Delta)$, where *i* is the sample number. The coil position $z(i\Delta)$ was

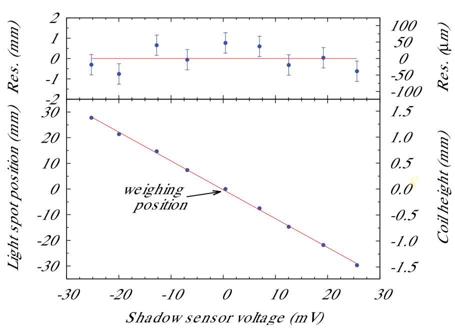

FIG. 7. Calibration of the shadow sensor. The balance is servoed to 9 different shadow sensor voltages. For each voltage, the position of the light spot on the wall, in this case 3489 mm away, is measured. The relationship between the position of the light spot on the wall and the shadow sensor voltage is almost linear. The solid line indicates the best fit to the data. The upper graph shows the residuals between the fit line and the measured data points. We attributed an uncertainty of 0.5 mm (represented by the error bars) to the position measurement of the light spot. Judging from the residuals, that seems reasonable. Then extracted from the shadow sensor voltage. The sampled data were filtered and the coil velocity was obtained by taking the numerical derivative:

$$v(i\Delta) = \frac{z((i+1)\Delta) - z((i-1)\Delta)}{2\Delta}$$

For the pairs of voltages and velocities, a best-fit line was calculated whose slope was *BL*. For simplicity, we assumed that *BL* did not vary significantly along the coil's trajectory. Since the coil moved only 2 mm, this seems like a reasonable assumption.

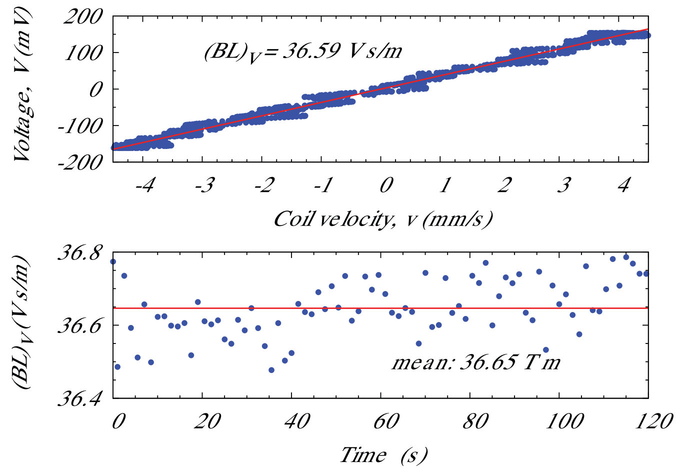

FIG. 8. The top graph shows the measured voltages and velocities of the coil for one period, i.e., 1.5 s. The slope of the solid line which is the best linear fit to the data gives the measured flux density, BL. The bottom graph shows the result of 80 such determinations. The relative standard deviation of the data is 0.2 %. For a possible explanation of the small drift see the main text.

The top graph in Fig. 8 shows the measured values of the induced voltage versus the calculated coil velocity. The data shown were taken during one period of a sinusoidal motion of the coil. The slope is 36.59 Vs/m [12]. The bottom graph shows 80 of these measurements for a total of 120 s. A value of the flux integral is determined every motion period. From this data we obtained a mean value

$$BL = 36.65 \text{ Vs/m}. \tag{5}$$

The relative standard deviation of the data was 0.21 %. A small relative drift of $3 \times 10^{-5}\,\text{s}^{-1}$ data. This drift can be explained by small temperature changes of the magnet. The remanent field of NdFeB magnet changes relatively by about $-1\text{x}10^{-3}\,\text{K}^{-1}$ drift in the *BL*. Here, we ignore the observed drift of the *BL* and assign the mean value.

C. Force mode measurement

Finally, a force mode measurement sequence was conducted for determining the mass of a small weight. To operate force mode, the "Weigh Mass" option must be activated on the front panel of the software. This measurement mode operates by automatically changing the magnitude of electrical current *I* flowing through Coil A (varying the amplitude of electromagnetic force) until the balance beam becomes leveled (when the calibrated shadow sensor indicates the zero position has been reached).

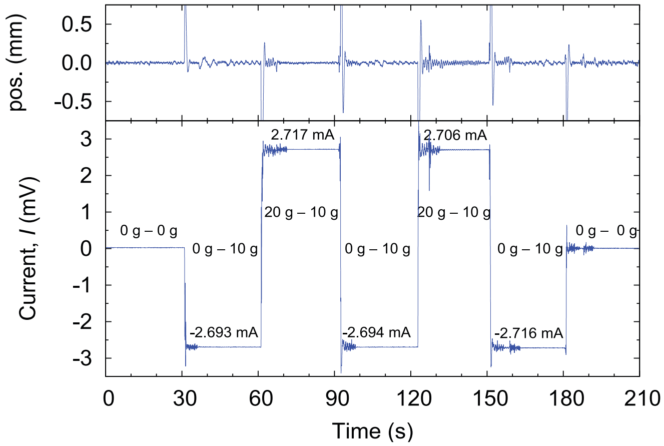

FIG. 9. Force mode in the time domain. The lower graph shows the current required to maintain the balance at a nominal position for seven altemating load states. The load states are abbreviated by differences. The minuend denotes the mass on the mass pan above Coil A and the subtrahend the mass on the mass pan above Coil B. The mass difference multiplied by the local gravitational acceleration is equal to the force produced by the coil. The software PID controller that is used to servo the balance employs two different gain settings. The change in noise in the measured current occurs when the gain is switched. The top graph shows the position of the coil as a proxy of the balance angle. Adding and removing a mass leads to a spike in position up to 2 mm. The servo quickly reestablishes the nominal weighing position.

We operated force mode in a similar fashion as our professional watt balance by placing our test mass on Side A and another mass equal to half that of the test mass on Side B.

Fig. 9 shows the measurement sequence in force mode. In this example, the measurement was performed in seven steps, each lasting 30 s. The steps were:

1. Both balance pans are empty and the current required to hold the balance at its weighing position is small.
2. A tare mass m_T=10 g is added to the pan above Coil B. The exact mass is irrelevant as it will drop out in the final equation. The current I_1 = -2.693 mA necessary to maintain the balance position. The current is given by

$$I_1 BL = -m_T g. \tag{6}$$

3. The calibrated mass, here m = 20.20 g, is added to the pan above Coil A. This time a positive current, I_2=2.717 mA, is required to servo the balance. The equation

$$I_2 BL - mg = -m_T g \tag{7}$$

describes this weighing. Subtracting Eq. 7 from Eq. 6 is sufficient to get an estimate of BL,

$$mg = (I_2 - I_1)BL \Longrightarrow BL = \frac{mg}{I_2 - I_1}. \tag{8}$$

However, to cancel out drift and to get an idea how big the drift is, it is always a good idea to perform a couple more weighings.

4. Another weighing with the Coil A calibrated mass removed determines

$$I_3 BL = -m_T g. \tag{9}$$

5. A second weighing with the Coil A calibrated mass added to the pan yields

$$I_4 BL - mg = -m_T g. \tag{10}$$

6. A third weighing with the Coil A calibrated mass removed yields

$$I_5 BL = -m_T g. \tag{11}$$

7. We finally remove both masses and check if the balance is back at the nominal position and if the current to servo the balance with no weights on either pan has remained stable.

Using the above observations, the following number can be calculated [13]:

$$I = -\frac{1}{3}(I_1 + I_3 + I_5) + \frac{1}{2}(I_2 + I_4) = 5.4125\,\mathrm{mA}. \tag{12}$$

In order to calculate the mass, one needs to know their local acceleration of gravity. Your local gravitational acceleration can be obtained from a website provided by the National Oceanic and Atmospheric Administration. [10]

For our geographical coordinates at NIST Gaithersburg (Latt: 39.1261°N, Long: 77.2211°W, Elevation: 124.304 m), the website yielded g = 9.80103 m/s^2 with a relative uncertainty of 2×10^{-6}. This is uncertainly was well below what we needed for a 1%-level measurement.

With the above values, our calibrated 20.20 g mass was determined to be:

$$m = \frac{BLI}{g} = \frac{36.65\ \mathrm{V\,s/m} \cdot 5.4125\ \mathrm{mA}}{9.80103\,\mathrm{m/s^2}} = 20.24\,\mathrm{g} \tag{13}$$

Summary

In 2014 we built three LEGO watt balances. These balances were demonstrated and received with enthusiastic responses in science fairs, classrooms, and with visitors coming to NIST. Our initial publication in the American Journal of Physics inspired dozens of makers and tinkerers around the world to construct their very own LEGO watt balances [4]. What will building and operating such a device accomplish?

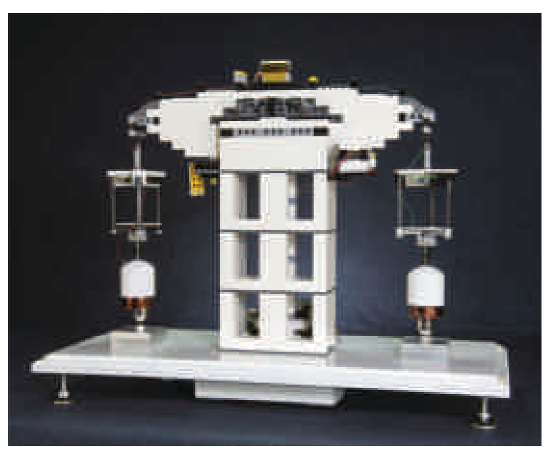

FIG. 10. Image of the NIST LEGO watt balance.

In the new SI, the kilogram will be defined via fixing the Planck constant through a procedure that is not apparent to most people. The LEGO watt balance takes the initial step in demonstrating the connection between mechanical units to electrical units. From here, it is easy to explain how a mechanical force can be measured solely in electrical quantities. The next step of abstraction is to explain how electrical power can be measured as the product of two frequencies and the Planck constant h. For this explanation one has to invoke the Josephson and the quantum Hall effect. On a technical level these two effects are difficult to understand. To help the audience to understand the redefinition on an abstract level, it helps to draw the parallel to the redefinition of the meter. Originally, the meter was defined as the distance between two fine scratch marks on a platinum iridium bar. In 1983 the meter was redefined via a constant of

Appendix A : List of parts

Part Name	Part No.	Quantity	Total Price ($)
Custom LEGO Watt Balance Software		1	Free
Brick 2x4	300101	75	22.50
Brick 2x8	6033776	75	37.50
Brick 1x2 with cross hole	4233487	6	2.10
T-Beam 3x3 w/hole	4552347	2	0.60
Technic Brick 1x2	370026	18	2.70
Technic Brick 1x4	4211441	66	16.50
Technic Brick 1x5 Thin	32017	4	0.80
Plate 8x8	4210802	9	9.90
Plate 1x2	4211398	14	1.40
Plate 1x4	4211445	3	0.45
Plate 2x3	4211396	6	1.20
Cross Axle 2M w/ Groove	4109810	8	0.80
Cross Axle 3M	4211815	2	0.20
Cross Axle 5M	4211639	6	1.20
Cross Axle 8M	370726	8	1.60
Bush for Cross Axle	4211622	14	2.10
1/2 Bush for Cross Axle	4211573	32	3.20
Double Bush 3M	4560175	4	0.80
Roof Tile 2x2/45 deg Inv.	366026	2	0.40
Roof Tile 2x3/25 deg	4211106	6	1.20
Roof Tile 2X3/25 deg Inv.	374726	4	0.80
Connector Peg W. Friction 3M	4514553	8	2.00
Connector Peg/Cross Axle	4666579	6	0.60
Catch w. Cross Hole	4107081	8	1.60
Flat Tile 2x4	4560178	2	0.60
Hinge 1x2 Lower Part	383101	6	1.50
Hinge 1x2 Upper Part	6011456	6	1.50
Double Conical Wheel Z12 1M	4177431	4	1.20
Angle Element, 180 Degrees [2]	4107783	2	0.40
Technic Beam 1 x 4 x 0.5 with Boss	2825 / 32006	6	0.30
Technic Beam 2 Beam w/ Angled Ball Joint	50923 / 59141	2	0.13
Wedge Belt Wheel	2786 / 4185	4	1.00
Gear with 8 Teeth (Narrow)	3647	2	0.20
Universal Joint	61903	2	0.94
N48 grade - 3/4(OD) x 1/4(ID) x 1/2 in. ring magnet	NR011-0	4	15.96
National Instruments DAQ	USB-6001	1	189.00
Focus Line Red Laser Module <1mW	YCHG-650	1	15.00
Line Laser Module (650nm) <1mW	LN60-650	1	15.00
Transistor	2N3904 TO-92	1	0.10
Photodiode 7.98mm Dia Area	PC50-7-TO8	1	61.63
Low signal Relay	TXS2-4.5V	1	4.58
Resistor 150 Ohms		1	0.10
Resistor 1500 Ohms		1	0.10
Resistor 5000 Ohms		1	0.10
Resistor 10000 Ohms		1	0.10
Brass Threaded Rod - 1/4"-20 Thread, 1' length		1	2.65
White PVC Pipe Fitting		2	1.00
White PVC Unthreaded Pipe		1	5.27
Total			$430.51

nature, the speed of light. Thus, by precisely fixing the speed of light with zero uncertainty, one meter equals exactly the distance that light travels in 1/299 792 458 s.

The LEGO watt balance has been demonstrated at numerous fairs and exhibits since its inception. The pre-programmed "manual feedback" mode has been proven successful with audiences of all ages. In this mode, a human operator is substituted for the computer's automated controls and must rotate a potentiometer to try and null the balance. Most people who find it hard to control the balance then develop an appreciation for how seemingly effortless the PID controller achieves the task. This provides an excellent introduction into control theory.

We have created a Facebook page showing diagrams and photographs of the LEGO watt balance [14]. We would like to cultivate a community for enthusiasts to share their building experiences and exchange insights. It is our dream to see others construct their own instrument, improve on our design, and even surpass 1% relative uncertainty! Furthermore, we have an entertaining YouTube video which one may find useful as supplementary instructions [15]. Don't forget to “Like” our page! The LEGO watt balance combines three important things: science, technology, and fun.

Finally, in 2013 during an NPL interview, Dr. Bryan Kibble said, “In the world of metrology, if you attempt these very difficult measurements, you become very skilled at making easier measurements and there is a dissemination of knowledge as well as units down to the industrial laboratories" [16]. Coincidentally, or perhaps not, the NIST LEGO watt balance project gained traction around the same time. We believe the LEGO balance serves as a tremendous stepping stone toward devising a more accurate tabletop instrument in aiding Dr. Kibble's vision of one day enabling realization and dissemination of units directly on the factory floor.

Appendix A : List of parts

The Appendix A table shows the majority of the components we used to build our LEGO watt balance. Each LEGO engineer or scientist is encouraged to explore other building materials and components to create an even more optimized and personalized instrument. The prices are accurate as of 2014 and do not include shipping and handling.

In addition to the parts listed below, a wooden base, wires to connect the electrical circuits, and a spool of wire to wind the coil are required and can be purchased from a variety of vendors.

Construction and commissioning a LEGO watt balance can be a lot of fun. Such a project is suitable for small teams at school or a private person at home. We hope to encourage many enthusiasts to build a LEGO watt balance and have fun toying with the science of measurement, metrology.

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[9] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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[12] We deliberately use Vs/m as units for (BL)V, to emphasize that V is a conventional unit, while m and s are SI units. With the unit of Tm we would have lost this distinction. Analogously, we use the unit N/A for the quantity (BL)F.

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The Authors

Stephan Schlamminger was born in Kelheim, Germany. He received the Diploma degree in physics from the University of Regensburg, Regensburg, Germany, in 1998, and the Ph.D. degree in experimental physics from the University of Zürich, Zürich, Switzerland, in 2002. He was with the University of Washington, Seattle, WA, USA, where he was involved in the experimental test of the equivalence principle from 2002 to 2010. He is currently the Group Leader of the Fundamental Electrical Measurements Group at the National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, where he is involved with both the professional and LEGO watt balances.

Leon Chao joined the National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA in 2012 and serves as a mechanical engineer for the NIST-4 and LEGO watt balances. Recently, he began as a part-time mechanical engineering graduate student at the University of Maryland, College Park, MD, USA under the supervision of Dr. Balachandran.