Sandia National Laboratories

Redefining the Kilogram: A LEGO Kibble Balance

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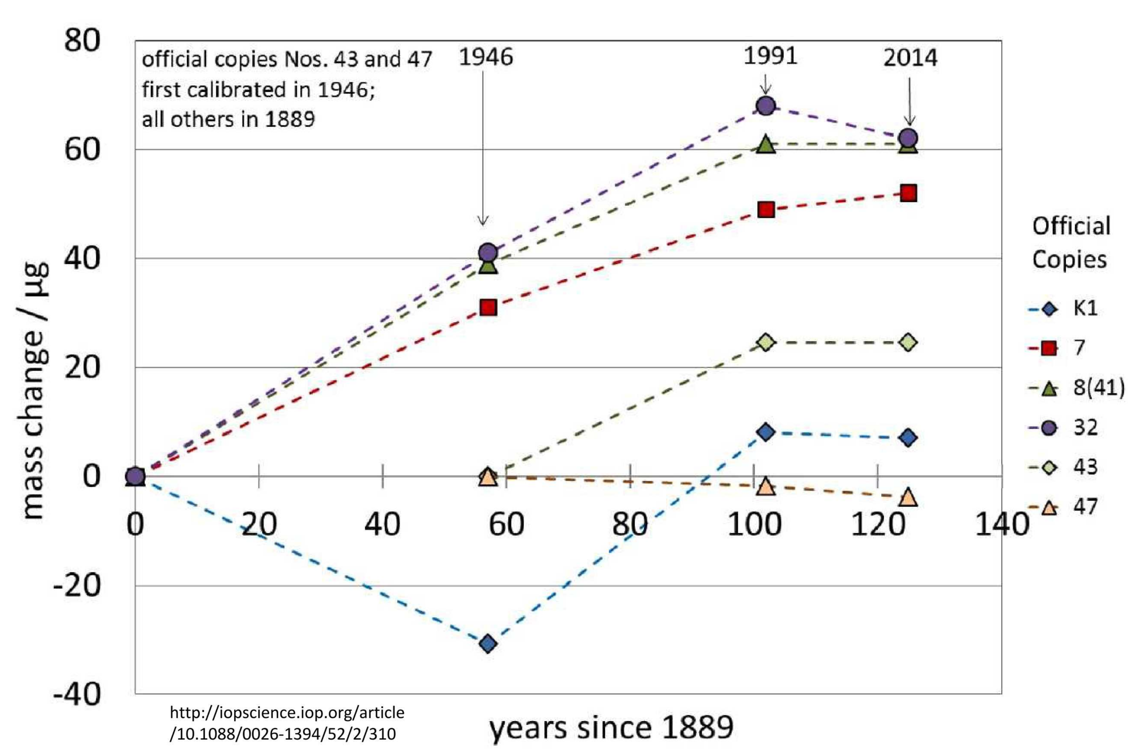
Kibble balance: Background

Currently, the kilogram is the only SI Unit (International System of Units) to be defined by a physical standard. This one kilogram standard, called the International Prototype Kilogram (IPK), was manufactured in the late 19th century out of a platinum iridium alloy. Drift in the mass of the standard means that the definition of the kilogram has not remained constant over time, an issue for scientists and **metrologists**.

In the late 1990s, scientists started considering the possibility of redefining the kilogram, such that it would no longer be based on a physical mass standard. One leading idea on how to accomplish this was through the use of a device called a Kibble balance. The advantage of a Kibble balance is that it eliminates the need for a physical standard, allowing scientists to decouple the definition of the kilogram from its realization – the IPK – instead allowing it to be defined in terms of **Planck's constant**.

Prototype of K20 at the NIST. https://insights.globalspec.com/article/3993/coming-in-2018-the-new-kilogram

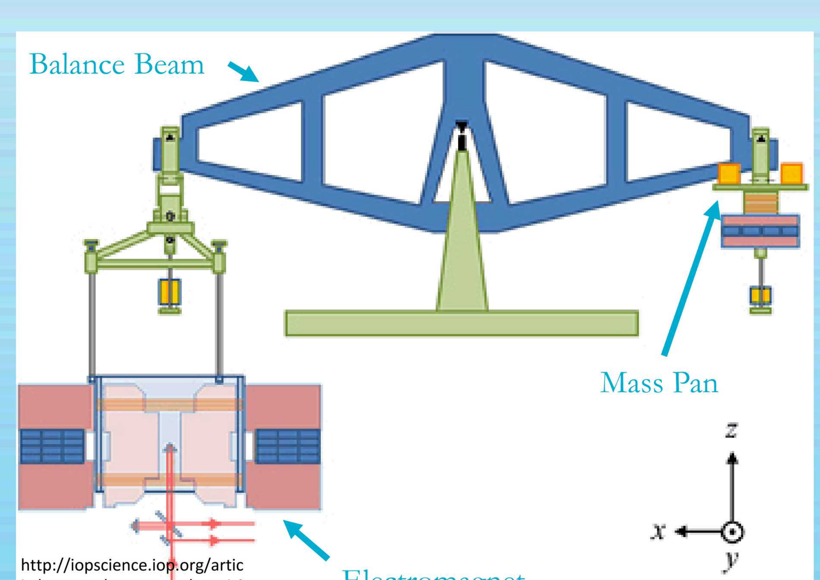


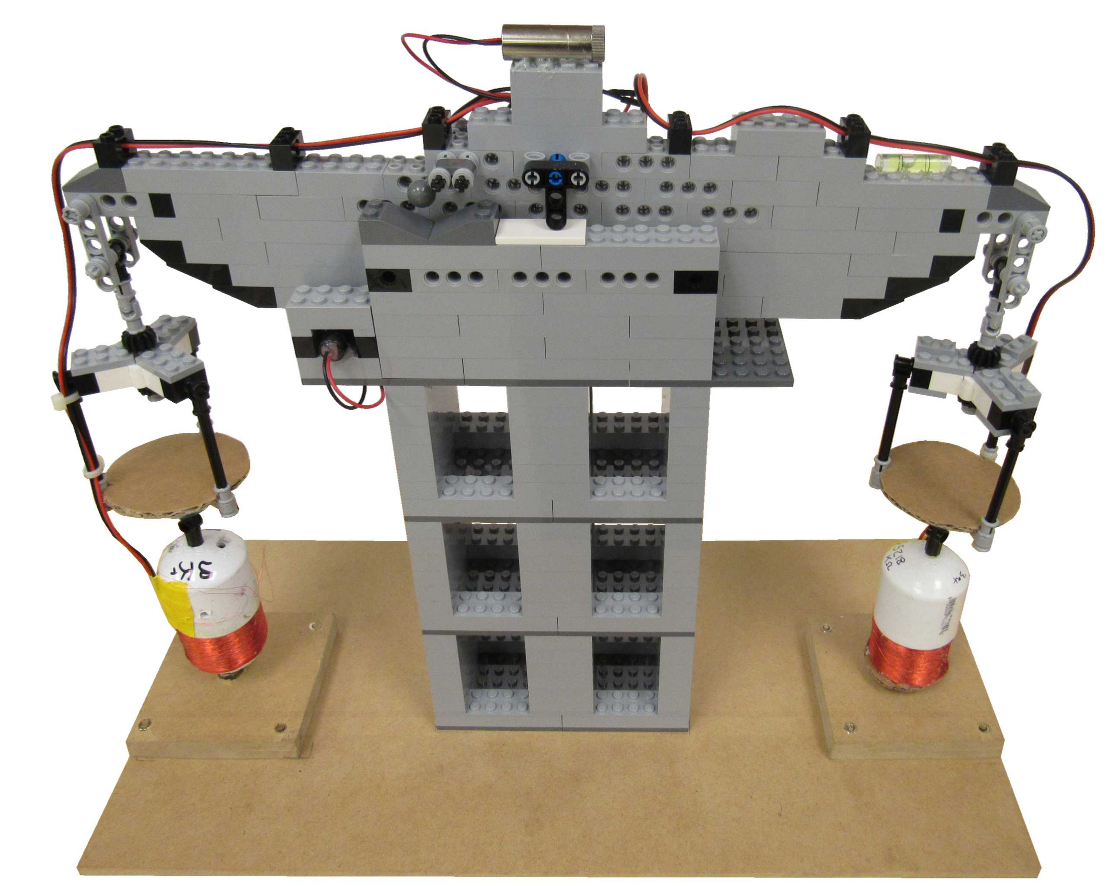
Kibble balance: Principles of Operation

Unlike a regular balance, which compares an unknown mass to a known standard, a Kibble balance compares an unknown amount of mechanical power to a known amount of electrical power. Typically, an unknown mass is placed on one end of the balance, and then a force is exerted from an electromagnet on the other end to return the balance to a state of equilibrium (shown below). The current required to hold the balance is used to determine the mass of the unknown, equating mechanical power with electrical power. The mass of an unknown can be determined by:

$$m = \frac{VI}{gv}$$

where V is the voltage, I is the current in the coil, g is the site gravity, and v is the velocity at the end of the balance beam.

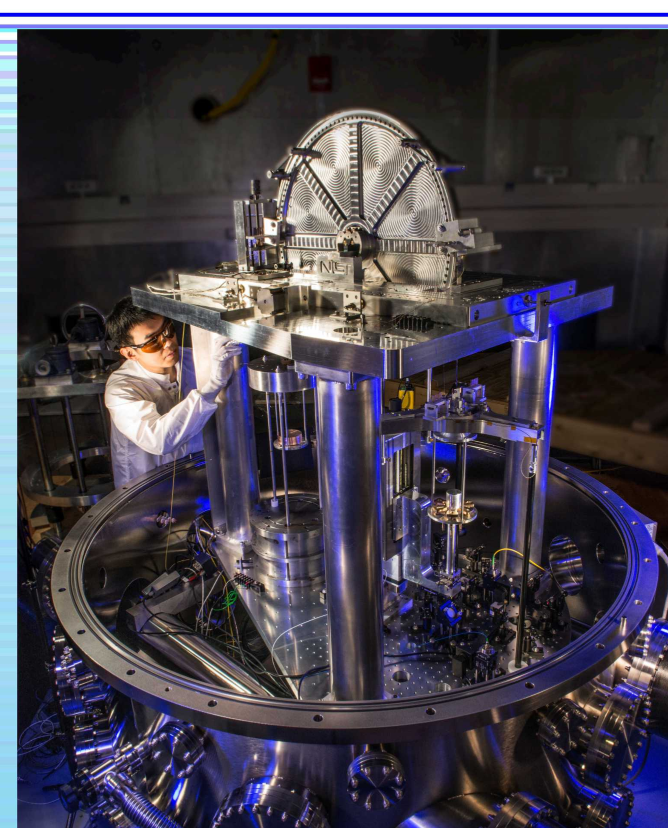




Redefinition Using Planck's constant

Interestingly enough, mass can actually be quantified in terms of energy, through **Planck's constant** (*h*). Using the Josephson effect and the Quantum Hall effect, the energy of the electrical current used to hold an unknown in equilibrium can be represented in terms of **Planck's constant**.

This raises another issue, though. Since the kilogram is soon to be based on **Planck's constant**, it is extremely important to get the best measurement possible with today's technology. That value was in part obtained through the use of a Josephson voltage standard and a quantum Hall resistance standard, in conjunction with the Kibble balance at the NIST (shown below). The measurement yields a result of $6.626070150 \times 10^{-34}$ J·s with no uncertainty. For now, this is the best value we have for **Planck's constant**.



Kibble balance at the NIST. https://www.nist.gov/news-events/news/2016/11/universes-constants-now-known-sufficient-certainty-completely-redefine

Acknowledgements

This project began in June as an exploration into **metrology** and the revision of SI. Both my mentors, Edward O'Brien, and Raegan Johnson, and my lab partner, Lorenzo Costanza were instrumental in the construction of the LEGO Kibble balance. Thank You.

Works Cited

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Definitions

1. **Metrology** – The study of measurement.
2. **Planck's constant** (h) – A physical constant ($6.626070150 \times 10^{-34}$ J·s), relating the frequency of a photon to its energy through $E = hf$.

LEGO Kibble balance Construction and Operation

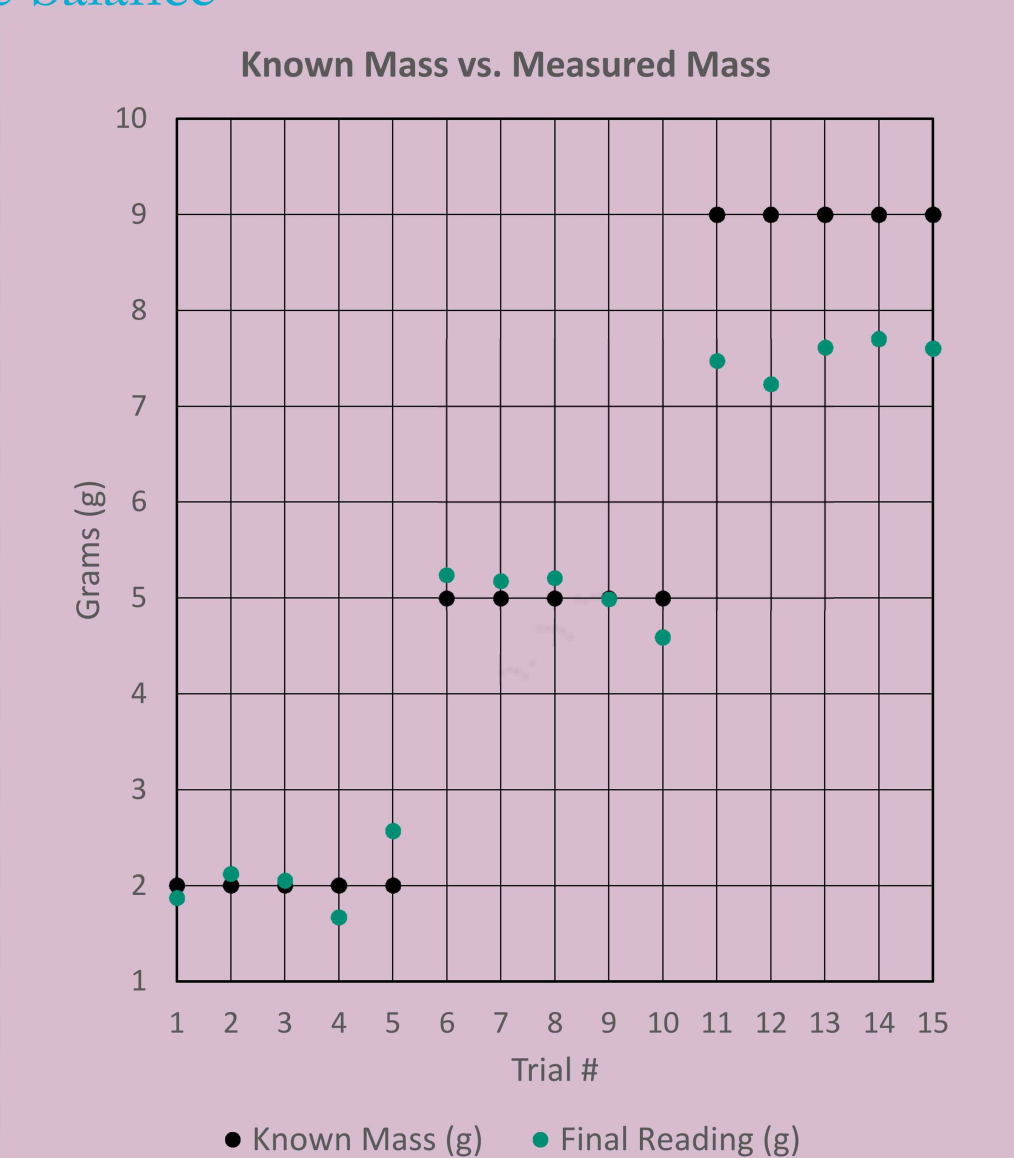
The design for the LEGO Kibble balance was sourced from the American Journal of Physics, A LEGO Watt Balance, designed originally by the National Institute of Standards and Technology (NIST) to demonstrate the principles behind a Kibble balance, and as an educational tool. A LabVIEW program for the LEGO Kibble balance is used to interface with the device.

A typical Kibble balance uses one mass pan and one electromagnet. The LEGO Kibble balance utilizes a symmetrical design with electromagnets and mass pans on both sides of the balance.

Before a mass can be measured, a set of calibrations needs to be performed. Once the laser inclinometer has been zeroed, and the flux integral of both coils is obtained, the mass of an unknown can be measured.

Data – My LEGO Kibble balance

Known Mass (g)	Final Reading (g)	% Error
2	1.87	6.50%
2	2.12	-6.00%
2	2.05	-2.50%
2	1.67	16.50%
2	2.57	-28.50%
Avg:	**2.0560**	
Stdev:	**0.3006**	
Avg % Error:		**-2.80%**
5	5.24	-4.80%
5	5.18	-3.60%
5	5.21	-4.20%
5	4.99	0.20%
5	4.59	8.20%
Avg:	**5.0420**	
Stdev:	**0.2423**	
Avg % Error:		**-0.84%**
9	7.47	17.00%
9	7.23	19.67%
9	7.61	15.44%
9	7.70	14.44%
9	7.60	15.56%
Avg:	**7.5220**	
Stdev:	**0.1634**	
Avg % Error:		**16.42%**



Concluding Remarks – My LEGO Kibble balance

While the LEGO Kibble balance is not nearly accurate nor precise enough to be used in a professional setting, it is a great demonstration tool, because the principles on which a full scale Kibble balance functions are the same as the LEGO Kibble balance. If I was to continue working on this project, I would make a few changes in an attempt to improve the performance of the balance. The first step in this process would be to wind new coils. In the current design, the coils were wound by hand, and are not optimized for this application. A shorter, more tightly wound coil would likely improve the performance of the LEGO Kibble balance.

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