BALANÇA DE TORÇÃO
Relatório Final

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Resumo

Este projeto tem como objetivo a construção de uma balança de torção, similar a apresentada por Henry Cavendish no final do século XVIII. A principal finalidade é observar, através da Lei Da Gravitação Universal proposta por Newton, o fenômeno de atração entre corpos. Nossa montagem utiliza materiais simples, de fácil obtenção.

Palavras-chave: Constante Gravitacional, Atração Gravitacional, Balança de Torção.

1. Descrição

O aparato foi originalmente inventado por Rev. John Michel em 1975, para medir a densidade do planeta Terra. Foi modificado por Cavendish em 1798 para medir a constante G e subseqüentemente por Coulomb para ter medidas elétricas e magnéticas de atração e repulsão.

O experimento de Cavendish é o sexto entre os dez experimentos mais belos da física, de acordo com a pesquisa realizada pela revista *Physics World (ref. [6.]).*

Neste projeto propomos a montagem de um sistema composto por materiais relativamente simples, que trabalhe com os conceitos da Lei da Gravitação Universal levantados por Newton no inicio do século XVII. O trabalho pretende apresentar um aparato similar ao demonstrado por Henry Cavendish, que mais de um século depois propôs uma prova direta, em laboratório, dos conceitos que Newton havia colocado observando questões astronômicas.

Nosso objetivo é mostrar que existe uma força de atração entre corpos.

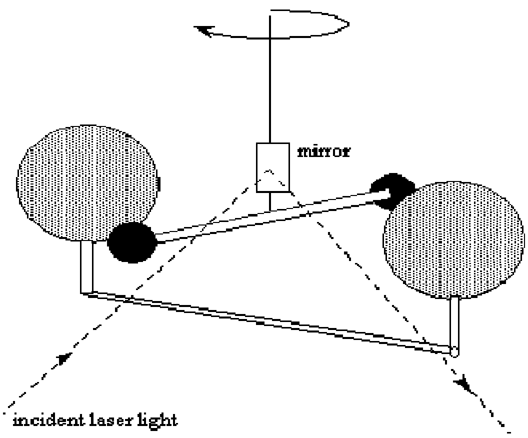
2. Importância Didática

O experimento tem como alvo alunos do ensino médio e universitário, partindo de um conceito que surgiu em estudos astronômicos alguns séculos atrás e generalizado a quaisquer corpos, ou seja, o objetivo é mostrar-lhes que existe atração gravitacional entre corpos de massas relativamente pequenas, que fazem parte do seu cotidiano.

3. Modelo Proposto

Duas pequenas massas são fixadas nas pontas de uma barra, o conjunto é suspenso em seu centro de massa por um fio, esta haste com pequenas massas pode se deslocar horizontalmente com a torção do fio. Duas outras massas maiores são mantidas fixas nas proximidades das massas menores. Inicialmente, existe uma distância entre as massas. A força de interação gravitacional provocará um deslocamento da massa menor em direção à massa maior. Este deslocamento causará uma torção no fio que sustenta a barra. A medida do ângulo de torção permite a determinação da constante da gravitação universal G, presente na Lei da Gravitação Universal de Newton.

Fig. 1 Ilustração lateral do experimento de Cavendish



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A velocidade com que a o fio pode responder ao movimento depende da constante de torção k, a qual pode ser calculada medindo o período de oscilação do fio por:

$$T = 2\pi\sqrt{\frac{I}{\kappa}}$$

onde T é o período, I é o momento de inércia e k é a constante de torção.

O torque aplicado pela atração gravitacional é $\tau = \kappa\theta$ onde θ é o Maximo ângulo de deflexão do ponto de luz. Neste ponto de máxima deflexão, a força entre a esfera maior e a esfera menor é:

$$F = \frac{GMm}{r^2}$$

Onde M e m, são as massas relacionadas, G é a constante gravitacional procurada, e r é a distância entre os centros de massa dos corpos.

Essa força é relacionada ao torque pela relação $\tau = F\ (L/2)$, onde L é o comprimento da haste onde está fixada as massas menores. Então a constante gravitacional pode ser calculada por:

$$G = \frac{\kappa\theta r^2}{MmL}$$

Enquanto o espelho gira por um ângulo θ, a luz refletida move por um ângulo $2\ \theta$.

Este modelo apresentado é uma forma bastante direta para atingirmos o objetivo, porém o andamento do projeto nos trouxe novas perspectivas de trabalhos, a fim de montarmos um sistema simples e funcional.

A montagem de um modelo similar ao apresentado era o objetivo do projeto, porem o andamento dos trabalhos mudaram o aparato

. Durante as atividades desenvolvidas no semestre pudemos perceber imensas dificuldades na montagem do aparato, principalmente pela falta de referências que nos auxiliassem a um resultado positivo.

A grande dificuldade era quanto aos materiais corretos, principalmente ao fio que deveria ser utilizado para manter a haste suspensa e livre para girar, as referências a que nos dedicamos durante vários meses diziam da utilização de um fio de quartzo, foi quando decidimos trabalhar com um fio de vidro, ou seja, um fio de fibra óptica sem proteção externa.

Este trabalho, como consta no relatório parcial, não nos trouxe resultados positivos para a montagem, apenas a certeza de que para que fosse possível a montagem com esse material precisaríamos de uma estrutura muito grande com, materiais sofisticados, específicos e ambiente adequado.

Ao aprofundarmos mais no assunto, da Lei da Gravitação Universal, percebemos que a constante *G* é das constantes universais, a que menos temos convicção do seu valor correto. Atualmente existem diversos trabalhos ao redor do mundo que buscam uma precisão maior deste valor que hoje temos como: $6{,}673 +/- 0{,}01 \times 10^{-11} N.\ m^2/Kg^2$.

Sendo essa constante muito pequena podemos imaginar a sensibilidade de um sistema que pretende observar a atração gravitacional entre corpos.

Depois de diversos trabalhos e tentativas, encontramos um artigo que faz referência a uma balança de torção como a que desejamos construir, porém usando apenas materiais caseiros *(ver ref. [8]).* Como cita o artigo, a idéia seria montar um aparato simples. Este trabalho nos trouxe novas perspectivas, afinal seria muito interessante se conseguíssemos provar que existe uma atração entre os corpos com materiais do dia-a-dia, ao invés de montarmos um aparato sofisticado, totalmente isolado, mesmo por que não vemos essa montagem como objetivo do curso.

Nosso objetivo, partindo desta nova visão, não tem como objetivo a constatação da constante gravitacional *G* e sim provar que existe atração entre corpos massivos.

4. Lista de Materiais

- Esferas de chumbo de 80g
- Esferas de Ferro de 2200g
- Fio de nylon com 0,2mm
- Haste de isopor 30x5x5cm
- Recipiente com água
- Chapa de alumínio 7x7cm
- Escada de metal
- Câmara de ar

5. Descrição dos Materiais

A montagem experimental utiliza apenas materiais caseiros, como podemos ver pela lista de materiais.

Para fazermos uma descrição mais detalhada dos materiais utilizados, podemos começar falando das esferas de chumbo, que foram compradas em uma casa de materiais para pesca. As esferas maiores, mais pesadas, foram o grande desafio desta montagem final, utilizamos um equipamento de musculação, um halter emborrachado, comprado em uma loja de materiais esportivos, no qual serramos a haste central nos dois cantos e retiramos as esferas maciças de ferro. O fio de nylon é uma linha utilizada para pesca, suporta até 4,08Kg, também comprada na loja de materiais para pesca. A haste foi feita a partir de uma placa de isopor, a chapa de alumínio é na verdade uma um quadrado cortado de uma lata de alumínio. A câmara de ar foi encontrada no laboratório de óptica, assim como a escada de metal. O recipiente para água utilizado, é um recipiente de plástico para alimentos.

Fig.1. Halter e linha utilizados

6. Montagem Experimental

A idéia é ter um aparato que possa manter uma haste suspensa com pequenas massas e livre para girar. Para isso utilizamos uma escada de metal como suporte ao fio que liga a haste de isopor. A conexão do fio com a haste é feita através de fios metálicos finos e encapados, presos pelos cantos da barra, onde são colocadas as massas de chumbo. O sistema fica livre para girar indefinidamente.

Este aparato é montado e colocado sobre uma câmara de ar com suporte metálico a fim de diminuirmos as vibrações no sistema proveniente do solo.

Para que pudéssemos ter uma diminuição na amplitude de rotação da haste livre, e chegássemos a um estado de repouso, foi colocado uma chapa de alumínio na parte posterior da haste de isopor, como uma pá, que permanece durante todo o tempo com grande área imersa em água, um liquido viscoso, criando um amortecimento fraco no sistema oscilatório

Manter a haste com uma pá submersa a água é necessário para que possamos diminuir as oscilações provenientes das relaxações do fio, transferindo parte desta energia cinética a água.

Sistema inicial

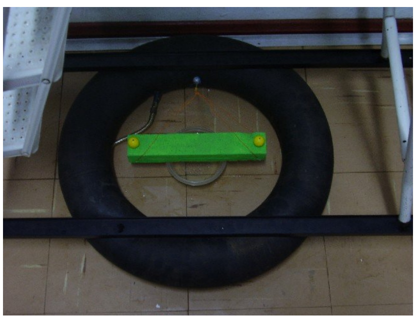

Fig 2. No centro, haste em verde com as massas nos cantos, em amarelo, no chão um recipiente com água e uma câmara de ar. Sobre a câmara de ar um suporte de metal que mantém a escada acima do solo.

Com o aparato apresentado em repouso por um tempo grande, sem interferências externas, chega-se a um ponto de equilíbrio, permanecendo assim imóvel a haste. Com bastante cuidado, aproximam-se duas massas grandes nos cantos opostos e em direções contrarias da haste, a fim de gerar forças que façam o sistema girar,ou seja, gere um torque que seja maior que o a resistência proposta pelo sistema fio-haste.

Com a colocação das massas maiores, tomando muito cuidado para não perturbar o sistema, deixa-se o local e aguarda respostas da haste.

Sistema final

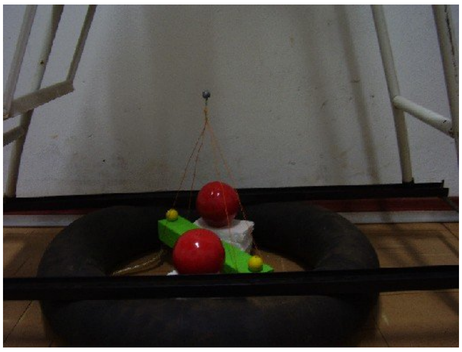

Fig.3. Sistema final montado, em vermelho as esferas com massas grandes.

7. Descrição das Atividades

Como pudemos perceber é um sistema simples. A montagem nos trazia sempre novos pontos a melhorar, e ainda nos traz, principalmente em relação a centralização, a nivelação e a maneira de acoplar cada peça. Ao chegarmos a esse modelo, o tempo para a finalização do projeto estava se esgotando, e as tentativas são extremamente sensíveis e demoradas. Pudemos perceber que qualquer vibração, ou fluxo inesperado de ar é capaz de alterar a estabilidade do sistema.

Durante algumas tentativas, com ambiente totalmente isolado, fomos capazes de observar movimentos leves, que se estendiam com o tempo, até praticamente encostarem as massas maiores. Retirando as massas, observamos que o sistema voltava ao equilíbrio em outro ponto. Porém foram tentativas impares em locais adequados.

Fig. 4. Sistema próximo ao equilíbrio.

As primeiras tentativas não utilizavam a câmara de ar sob o aparato, a colocação deste equipamento buscava a minimização das vibrações externas, para que conseguíssemos um sistema capaz de mostrar didaticamente a atração entre os corpos.

Utilizamos também durante as tentativas, ao invés do fio de nylon, uma fibra óptica, com cerca de 0,2mm de diâmetro, com a capa protetora, diferentemente das utilizadas nas tentativas anteriores quando pretendíamos utilizar o fio de vidro. Os problemas encontrados na utilização da fibra foram à dificuldade de fixação do fio na haste e na escada, pois é um material que não podemos criar nós, e dificilmente se mantinham fixas as extremidades. Algumas tentativas obtiveram sucessos, porém a observação mostrou que o comportamento do sistema não era muito diferente do sistema com nylon, desta forma decidimos pelo fio mais simples.

Dentre as atividades que mais nos trouxe dificuldades foi, como citado na descrição dos materiais, a obtenção da esferas grandes, onde um longo tempo foi necessário para que serrássemos o halter, e retirássemos as esferas, porém foi bem sucedido o processo e acreditamos que a massa seja suficiente para que possamos perceber o efeito.

As montagens nos fizeram notar que é extremamente complicado ao menos prever a força de atração, pois não é simples escolhermos uma distância correta dos centros de massa das partículas pontuais, ou melhor, escolher pode ser até um procedimento simples, o difícil é atingirmos esse ponto, simétrico, sem perturbarmos o sistema.

Com todas essas considerações devemos de dizer que uma apresentação didática da balança de torção para constatação da atração gravitacional é uma atividade um tanto quanto complicada, requer muito tempo e muita precisão. Creio que não será possível uma visualização direta em uma apresentação da forma que se encontra o sistema, não que não seja possível verificarmos, os problemas são externos e difíceis de contornarmos. Pretendemos continuar nossos estudos e experimentações a cerca de deste trabalho, pudemos perceber, ao longo do projeto, a falta de informações e não existência de referencias nacionais da montagem deste experimento, o que nos leva a buscar novas expectativas.

8. Originalidade

O experimento de Cavendish, como já citado, foi considerado pela revista Physics World *(ref. [6.])* o sexto entre os dez experimentos mais belos da física. Pelas pesquisas realizadas notamos que é um experimento bastante difundido em todo mundo, inclusive reproduzido em aulas experimentais de cursos de graduação pelo mundo. O maior desafio deste trabalho, é experimentá-lo utilizando materiais simples.

Pudemos verificar pela Internet que este experimento já foi reproduzido por outro aluno do curso de F 809, relatório parcial *(ref. [7.])* porém, não obtive informações quanto aos resultados finais.

9. Referências

[1.] M.H.Shamos, Great Experiments in Physics, (Henry Holt & Co. New York 1959) p.75, contêm paper original de Cavendish's

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[6.] http://physicsweb.org/articles/world/15/9/2/1

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[9] Marion, J. B., Thornton, S. T. Classical Dynamics of Particles and Systems 5a ed., Thomson Brooks/Cole, 2005.

ANEXOS

Bending Spacetime in the Basement

One of the things I detested about being a little kid was that every time I thought of something really cool to do, I was invariably thwarted by my little brother shouting, "*Mom! Kelvin's mixing rocket fuel in the bathtub again!*" or "*Mom! Kelvin's making a submarine out of the old refrigerator!*". Well, middle age has its drawbacks, but at least you can undertake a project like this without fear of getting nipped in the bud at the cry, "*Mom! Kelvin's down in the basement bending spacetime!*". It's important to recall the distinction between "grownup" and "grown up". Let's us grownups head for the basement to bend some serious spacetime.

Matters of Gravity

Apart from rare and generally regrettable moments of free-fall, we spend our entire lives under the influence of the Earth's gravity, yet rarely, if ever, do we experience the *universal* nature of gravitation. It's a tremendous philosophical leap from "stuff falls" to "everything in the universe attracts everything else". That leap, made by Isaac Newton in the 17th century, not only allowed understanding the motion of the Moon and the planets, but inoculated in Western culture the idea that the universe as a whole was governed by laws humans could discover. This realisation fueled the Enlightenment and the subsequent development of science and technology.

This page presents a "basement science" experiment which reveals the universality of gravitation by demonstrating the gravitational attraction between palpable objects on the human scale. The experiment deliberately uses only the crudest and most commonplace materials, permitting anybody who's so inclined to perform it. Einstein's 1915 theory of General Relativity explains gravitation as spacetime curvature created by matter and energy.

So, by demonstrating how every object in the universe attracts everything else, we're *bending spacetime in the basement*.

But, if gravitation is ubiquitous, why was it not discovered millennia before Newton's 1687 *Philosophiæ naturalis principia mathematica*? The reason lies in the extraordinary *weakness* of the gravitational force.

Feeble Attraction

Now you might say, "What do you mean, weak! I fell down a flight of stairs a couple of years ago, and gravity sure didn't feel weak to me!". And yet, of the four forces of nature known to physics, gravitation is the weakest, by the mindboggling factor of 4.17×10^{42} (4 followed by 42 zeroes) times weaker than the electromagnetic force.

The stark difference in the strength of the electromagnetic and gravitational forces is evident in the picture to the left. The bright square in the jaws of the pliers is a 4 mm cubical magnet. It is lifting a spherical steel pétanque (a lawn bowling game popular in southern France and Switzerland) ball which weighs 550 grams. Consider this picture in the following way: we're pitting our valiant little magnet, with a volume of 0.064 cubic centimetres, weighing less than one gram, pulling **up** with the electromagnetic force, against the entire Earth, pulling **down** with gravity. And the winner is...the magnet. A one gram magnet (I'm being generous: I don't have a scale on which its weight reads other than zero) out-pulls the Earth, which weighs 5.9736×10^{27} grams and has a volume of more than 10^{27} cubic centimetres.

(The apparent discrepancy between the ratio of masses of the Earth and the magnet and the 4.17×10^{42} strength ratio of electromagnetism and gravitation is due to the fact that only an infinitesimal fraction of the mass of the magnet contributes to the [electro]magnetic attraction on the ball, while every gram of the Earth's mass exerts gravitational force. To obtain the correct ratio of force strengths, one must compare the gravitational attraction between two electrons at a given distance with the electromagnetic repulsion resulting from their charge. This calculation arrives at the correct strength ratio for the two forces.)

If gravity were not so weak compared to the electromagnetic force, you wouldn't be reading this page; it's only because the electromagnetic force that bonds the atoms in your body together so easily defeats the Earth's gravity that you, along with all other solid objects, don't slump into a puddle and eventually merge into a perfectly spherical (actually, slightly ellipsoidal thanks to rotation) planet.

Do the Twist!

Even though the force of gravity between objects of modest mass is palpable compared to the weight of objects one can see, detecting such a tiny force seems a daunting, if not hopeless, endeavour for the basement tinkerer. Certainly, painstakingly designed and constructed laboratory apparatus has allowed measuring the gravitational constant to great precision and verifying the equivalence of gravitational and inertial mass, and precision gravitometers are routinely used in oil and gas exploration and mineral prospecting, but we're trying to see if we can experience the universal attraction of gravity without any high tech, high budget gear.

Measuring tiny gravitational forces would be easy if we were in deep space, far from any massive bodies. The only forces on objects in our space laboratory, then, would be those entirely under our control. As long as we made sure none of the objects we were experimenting with were magnetic or electrically charged (easily arranged, assuming they are conductive, simply by bringing them into contact so all excess charges equilibrate), the only force remaining between objects would be gravity, so however weak it be, we need only be sufficiently patient to observe its effects. (The other two forces, the strong and weak nuclear interactions, are limited in range to distances on the order of the size of an atomic nucleus and can be neglected on the human scale.)

What we'd like to do, then, is *cancel* the Earth's gravity so that the much smaller gravitational forces between objects that fit in the basement become evident. Fortunately, we don't need a 25th century WarpMan to accomplish this, only a modest helping of 18th century technology.

Differential Cleverness

One of the great all-purpose sledgehammers in the toolbox of physicists and engineers is *differential measurement*; in other words, don't worry about the absolute value of something, but only the *difference* between things you can measure. For example, it is common practice for linemen repairing high-voltage power transmission lines to work on them, without cutting power, from insulated baskets raised by a crane. As long as the lineman is insulated from the ground, only the voltage difference between his hands and the line he's working on matters; after attaching the basket to the line, this is zero, so he might as well be repairing a grounded conductor. Now if, while working on a conductor at, say, 200,000 volts above Earth potential, he should happen to touch the tower, grounded to Earth, that would make for a really bad day. The trick is keeping the *difference* small; you can live your entire life at 1 million volts, and as long as everything around you is near that value, there is no way, even in principle, you could discover the absolute potential. This is the consequence of all the forces of physics being *gauge invariant*: absolute values don't exist--only differences matter.

The Torsion Balance

What we're looking for, then, is a device which responds only to differences in gravitational attraction, canceling out the much stronger constant gravitational attraction of the Earth. We need look no further than a slightly modified version of the same device Henry Cavendish used in 1798 to first measure the gravitational constant, G in the equations above. Ever since, the *torsion balance* has been the primary tool used both for measuring the gravitational constant and testing the *equivalence principle*, which states that all bodies experience the same gravitational force regardless of composition; Einstein's General Relativity showed this to be a fundamental consequence of the structure of space and time.

State of the art torsion balances have measured the gravitational constant to better than one part per million and confirmed the equivalence principle to more than 11 decimal places. This requires extraordinarily refined and delicate laboratory apparatus and experimental design, in which a multitude of subtle effects must be compensated for or canceled out. We, however, aren't going to *measure* anything--we're only interested in *observing* universal gravitation. This allows simplifying the torsion balance to something we can set up in the basement.

The principle of the torsion balance is extremely simple. Suspend a horizontal *balance arm* from a vertical elastic fibre. At each end of the balance arm are masses, much denser than material of the arm, which respond to the gravitational force. Once the suspending fibre, balance arm, and weights are set up and brought into balance, the downward force of gravitation acts equally on every component. The balance arm is then free to rotate without any hindrance from the Earth's gravity. It is constrained only by air friction and the *torsional strength* of the support fibre--its resistance to being twisted. We can then place *test masses* near the ends of the balance arm and observe whether the gravitational attraction between them and the masses on the arm causes the balance arm to move. When measuring the gravitational constant one must precisely calibrate the torsional strength of the fibre, but to simply observe gravitation we need only make sure the fibre is sufficiently limp to allow the gravitational force to overcome its resistance to twisting.

In practice, the balance arm is *so* free to move that once any force sets it into motion, it oscillates for a long period, spinning round and round if free or bouncing back and forth off the stops if constrained. To avoid this we need to *damp* the system so kinetic energy acquired by the bar is more rapidly dissipated. Well, nothing's more damp than water, so we add a *water brake* to the arm which turns in a fixed reservoir. The resulting drag as the balance arm moves is much greater than air resistance and frictional losses in the fibre, and reduces the oscillations to a tolerable degree.

The Gravitational Balance

"The time has come," the Hacker said,
   "To talk of many things:
Of plastic foam--and tuna cans--
   Of chunks of lead--and string
And how the force of gravity—
   Will make the balance swing ."

So here's the sophisticated, high-tech, big science apparatus we'll use to observe the subtle curvature of spacetime. An aluminium ladder serves as the support from which the balance arm is suspended. Nylon monofilament fishing line, as shown above, is knotted to the middle of the third cross-beam at the back of the ladder, one above the brace bearing the little white box, about which more later. Using a ladder or similar movable support frame allows setting up the balance in the middle of the room. This is important because we *are* bending spacetime in the basement, in this case an underground storage room at Fourmilab. Ground level is about even with the ceiling of this room, about 45 cm above the top of the ventilation window at the upper right of the picture. An underground room is ideal because it minimises temperature variations and vibration which might perturb the balance arm. Both walls shown in this picture are sunk into solid limestone rock--if you set up the balance near one of these walls, the gravitational field from all that rock will mask that of the test masses, and the balance will assume a "gravity gradient" position with one of the ends of the bar pointing toward the wall, and will budge only slightly under the influence of the test masses. With the bar in the middle of the room, the tidal influence of the mass of the wall and the rock behind it is reduced to a negligible value. The pipe on the wall at the right is part of the serpentine pressurised hot water heating system; it was disabled to prevent air currents from disrupting the balance arm. In fact, since the room is underground, the heating system is rarely engaged, and only in the depths of winter, never in June.

The Balance Arm and Cradle

The balance arm is a 5 × 5 × 30 cm bar of plastic foam, hacked from a 5 cm thick slab of packing material with a Swiss Army knife. The bar is suspended in a cradle made of insulated telephone wire. The bar is held in its cradle by friction and the indentation made in the soft plastic foam due to the weights at either end of the bar; it's easier to adjust the bar for proper alignment this way than if it were glued to the cradle.

The Support Fibre

The nylon monofilament that suspends the cradle is barely visible at the top of the picture--it is fastened by a knot to a loop formed into the cradle wires by twisting them. The monofilament is a very fine "six pound test" (about 3 kg capacity) fishing line manufactured in Japan; a 300 metre spool of it costs about US$9. The masses which cause the bar to turn when a gravitational force acts upon them are lead "sinkers" used by fishermen, each weighing 169 grams. Two are placed on each end of the balance beam, giving it a total weight of 676 grams. Be sure to place the weights on both ends of the beam simultaneously so it doesn't topple, then adjust the placement so the beam is horizontal. Nylon monofilament is very elastic: when you put the weights on the beam the support line will stretch and the beam will end up closer to the ground. You may have to adjust the attachment of the line to the ladder (or other support) or, as I did, twist the cradle wires to restore the beam to the desired height. Finally, when you first hang the beam, it may take some time to release stresses in the fibre remaining from the manufacturing process and from its having been rolled onto a spool. It's best to let the arm hang for a couple of days, free to turn, to allow these initial stresses to equalise before attempting any experiments with gravitation.

The Water Brake

The height of the beam is important because of the need for it to fit properly with the water brake. If the beam is allowed to swing freely, it will be terribly underdamped--once it starts to swing, only air friction and the minuscule losses in the fibre will act to stop it. This causes the beam to bounce around incessantly, masking the steady influence of gravitation. The water brake dissipates the energy of these unwanted oscillations precisely as an automotive shock absorber does; the flap's motion does work on a viscous fluid, water in this case, and deposits its energy in heating it.

The water brake consists of a flap which projects downward from the balance arm (in this case, a piece of aluminium cut with scissors from the tray of a "heat and eat" meal, fixed with white glue into a slot cut into the bottom of the balance beam). The flap projects into a reservoir (a tuna fish can) filled with water. A more viscous fluid such as salad oil would provide greater damping and less bouncing than water, but I opted for water since it's less icky to clean up when the inevitable spill occurs and can be disposed of when the experiment's done without a visit to the village recycling barrel.

If I were rebuilding the balance beam, I would use a longer and narrower flap and/or a larger and deeper water reservoir. If the flap is only slightly smaller than the inside diameter of the reservoir, you have to be very careful that the flap and reservoir are centred on the beam. Otherwise, the flap will touch the edge of the reservoir and freeze the beam in place, as that frictional force is many orders of magnitude greater than the gravitational force we wish the beam to respond to. The water reservoir can be as large as you like, as long as it doesn't interfere with placing the test masses; the larger it is, the less you have to worry about its being precisely centred.

Test Masses and Supports

Blocks of plastic foam support the test masses so their centre of gravity is at the same height as the masses at the ends of the balance beam, maximising the attraction. The foam also keeps the balls from tending to roll away. The black rectangle, actually an inverted mouse pad, serves as a background for the time display superimposed by the video camera, rendering it more readable when images are reduced in scale so movies download more rapidly.

Use the densest objects you can obtain for the ends of the balance beam and as test masses: lead sinkers, steel balls, plutonium hemispheres, etc. Density is important because the gravitational force varies as the inverse square of the distance *between the centres of mass* of two objects. With a dense substance, the centre of mass is closer to the surface, so you can get the centres of mass closer together and enhance the gravitational force. For example, consider two pairs of one-kilogram spheres, the first made of lead (density 11.3 g/cm³), the second of pine wood (density about 0.43 g/cm³), placed so the surfaces of each pair of spheres are 1 cm apart. A one kilogram lead sphere has a radius of 2.76 cm, so the centres of mass are separated by 1+2.76×2, or 6.52 cm. A one kilogram sphere of pine has a radius of 8.22 cm, by comparison, so the centres of mass of the two pine spheres are 1+8.22×2 = 17.44 cm apart. Taking the square of the ratio of these distances shows that the gravitational force between the lead spheres is more than 7 times that of the pine spheres. Since attraction is linear by mass but inverse square in distance, you're better off with a modest mass of high-density material than a large mass of a substance with lesser density.

It's best to use a nonmagnetic material like lead for the weights on the ends of the balance arm. The forces we're working with are so small that if you use, for example, steel ball bearings on the arms, you may end up accidentally reinventing the compass instead of detecting the force of gravity.

The Spy Cam

"So what's the little white box on the back of the ladder?", you ask. Okay.... It's a BSR Model 500 surveillance camera which lets me observe the state of the experiment as it runs. The Sony camcorder I use to make movies doesn't generate video output while recording, so I can't use its video feed to monitor what's happening. Popping into the room where the experiment's running is a no-no--air currents from opening and closing the door, not to mention walking around in the room could seriously disrupt things. The BSR camera and accompanying 13 cm (diagonal) monitor allows keeping tabs on what's happening in a non-intrusive manner. I made a custom interface of the BSR camera/monitor cable to Fourmilab's ubiquitous RJ-45 cabling, so I can place two BSR cameras anywhere on the site and monitor either from anywhere else. At the right is an image from the surveillance camera taken at the end of an experiment, confirming that the balance beam has come to a stop against the foam block supporting the mass at the top. The camera is sensitive to infrared and includes infrared LEDs to illuminate nearby objects, and has a microphone linked to a speaker in the monitor. This makes it ideal for anxious parents who wish to monitor their sleeping baby; spacetime hackers can use the infrared illumination to view the balance beam without the thermal disruption of incandescent lamps or direct sunlight. The storage room where I ran this experiment has fluorescent strip lighting on the ceiling, and I observed no detrimental effects from its being illuminated. Of course, if the room you're using is equipped with that low-tech miracle called a window, you can dispense with all this complexity.

Gravitation in Action

The following time-lapse movies (about 30 seconds per frame) show the torsion balance responding to the gravitational field generated by two 740 gram competition pétanque balls. The picture at left shows the camera angle employed in both movies. In each, the movie begins with the bar stationary, in contact with one of the balls or the foam supporting it. The balls are then shifted to the opposite corners, where they attract the lead weights on the ends of the bar. The bar then turns, slowly at first and then with increasing speed as it is accelerated by the gravitational force growing as the inverse square of the decreasing distance between the masses. The bar bounces when it hits the stop on the other end, and finally, after a series of smaller and smaller bounces as the water brake dissipates its kinetic energy, comes to rest in contact with the closer ball or support. This is the lowest energy state, at which the bar will always arrive at the end of the experiment.

There is, at this writing, no movie format supported by all Web browsers and computer systems. The movies are furnished in three different forms, in the hope one will prove compatible with your equipment and software. The links below the movie posters download the movie in the various formats. Each gives the size of the movie file, which varies dramatically depending on the format. If your browser supports MPEG, that's the best choice, since the files are much smaller than the other alternatives. After the movie plays, use your browser's "Back" button to return to this document.