A TRIBUTE TO LORÁND EÖTVÖS

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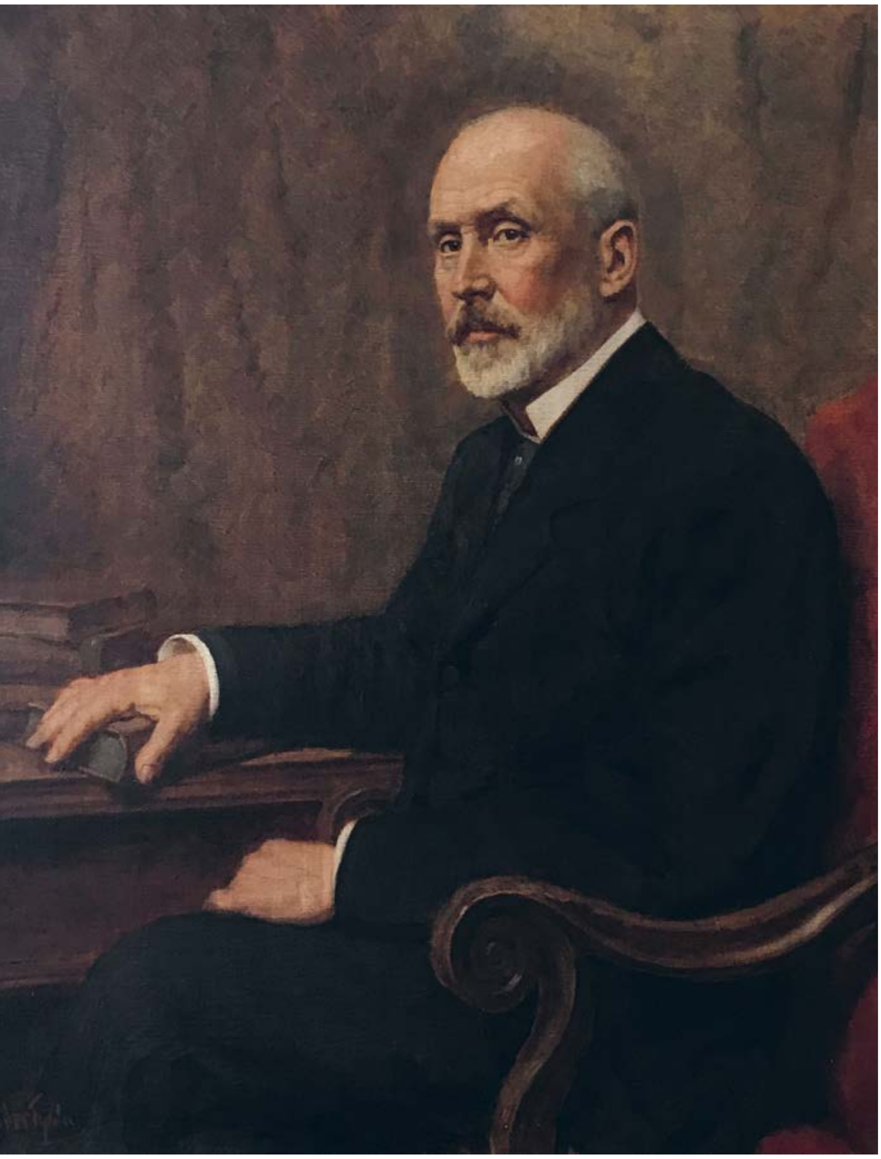
The last decades of the 19th century Hungary came to flourish as an independent part of the Austrian-Hungarian Monarchy; 1867 was a crucial year, a year of 'Ausgleich', 'Compromise'. József Eötvös, Hungary's leading intellectual and Cabinet Minister, reorganized science. He sent his son to Heidelberg, where junior learned physics from i.a. Bunsen, Helmholtz and Kirchhoff. What more could a youngster wish for? Roland Eötvös returned home with a predilection for fundamental matters, most of all for the nature of gravity and its relation to inertia. Geophysics, Hungary's pride, finally took centre stage.



▲ **FIG. 1:** Loránd Eötvös by Gyula Éder (oil on canvas; 89×73 cm; 1941), after a photograph made by Aladár Székely (1913). Courtesy: Eötvös University, Budapest.

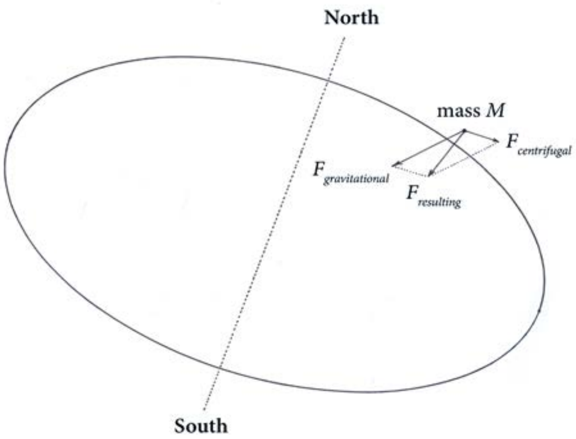
Politics, science, fundamental science

In order to be prepared for an eventual political career, like that of his father, Loránd Eötvös studied law at Budapest's University (1865-1867), before definitely switching to physics, mathematics and chemistry. On 7 July 1870, he passed the PhD under supervision of Gustav Kirchhoff in Heidelberg without a formal dissertation. In 1872 he was nominated Professor of Physics at the University of Budapest, the university which, since 1950, carries his name.

In the mid 1880s an interest in gravitation became apparent, in all probability initiated by the first results of the triangulation campaign of the territory of Austria-Hungary (1860-1913) with the European degree measurement in the background. Gravitation—or gravity, if you please—had been part of the physicist's subconsciousness since Newton, and every now and then it resurfaced, mostly in the context of a debate on conservation laws.

Instruments and their accuracy

Eötvös started by considering the instruments that would allow for an exact measurement of the gravitational constant (his γ, our g), or perhaps better: its 3D-variation. Among his new instruments featured the torsion balance of 1891. It consisted of two equal weights of about 30 g fixed at the ends of a horizontal beam of 25 cm, the beam being attached in the middle to a platinum wire carrying the whole. That wire also carried a small mirror such that the reflection of a ray of light, produced *e.g.* by a storm lantern, could be observed from a distance. It was affected by heavy masses like lead balls, so it worked indeed. With a brass sphere at the one end, the material at the other end could be varied (glass, cork, an empty glass sphere, ...). When the beam was put orthogonal to the local meridian, its behaviour was observed, first, when the brass



▸ **FIG. 2:** The earth as a rotating ellipsoid; for clarity's sake the ratios are exaggerated. A resting mass M at heigth h experiences two forces, $F_{gravitational}$ and $F_{centrifugal}$, whose resultant produces a net effect to the South.

sphere pointed to the East and, next, when it pointed to the West. Since the effect on both weights is the result of the centrifugal force combined with gravity, both experience a net force to the South (Fig.2). Any difference in gravitational mass, then, brings about a difference in that net force, producing a torque on the beam and hence a torsion. And it worked correspondingly, the answer being: "No, there is no difference."

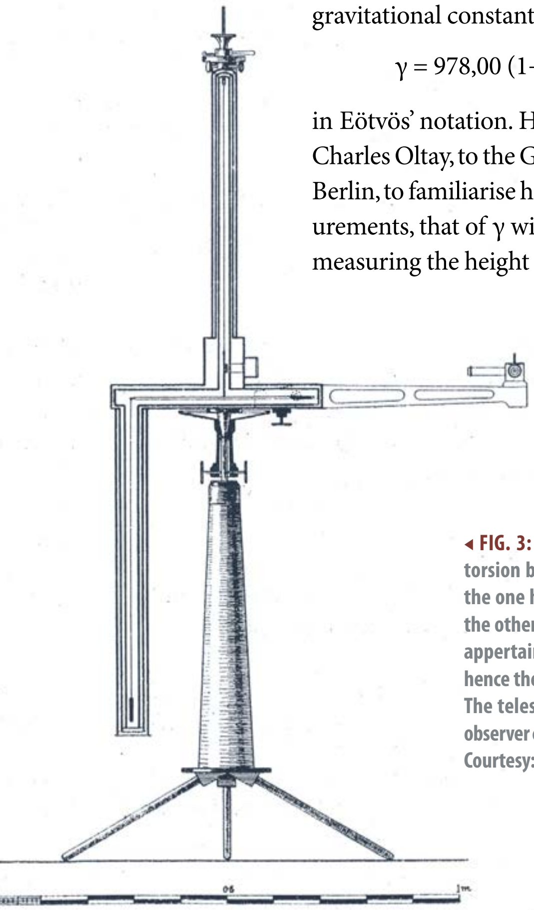
Chartering the earth; geophysics on the move

The state of the art in geophysics was defined by data from Friedrich Bessel (Kaliningrad; 1841) and Friedrich Helmert (Aachen; 1884). Bessel had calculated the dimensions of an idealized earth as an ellipsoid with half axes of 635.607.895 cm and 637.739.716 cm, Helmert contributed a formula for the interdependence of the gravitational constant, γ, and latitude, φ:

$$\gamma = 978{,}00\,(1+0{,}00531\sin^2\varphi)\ \mathrm{cm}\cdot\mathrm{sec}^{-2},$$

in Eötvös' notation. He, then, sent one of his assistants, Charles Oltay, to the Geodetic Institute in Potsdam, near Berlin, to familiarise himself with the two relevant measurements, that of γ with the pendulum and that of φ by measuring the height of Polaris. The idea was to charter interesting terrains using the data obtained for Potsdam and Budapest as gaugepoints. With pendulums borrowed from Potsdam, the local value of the gravitational constant, γ, could be measured and, subsequently, its spatial variation with the torsion balance. Imagine, then, such a torsion balance, equipped with equal brass spheres, above the surface of a perfectly horizontal, homogeneous underground, or above a homogeneous sphere of infinite radius: nothing will happen, since the common equipotential surface is (almost) perfectly flat. However, as soon as there are deviations, *e.g.* in case of an earth-like sphere featuring a mountain ridge, a torsion balance put on top of the ridge starts turning: the beam with its counterweights experiences a torque tending to turn it in line with the ridge, the torsion effect dictating the outcome.

This may be checked in advance. By turning subsequently the balance as a whole in the direction of the ridge the deflection angle tends to vanish. On moving the torsion balance along the ridge the deflection remains nill, γ being virtually constant; on moving the balance sidewards, however, down along the slope, the beam will remain in place though γ will change. Hence the possibility of charting a landscape in terms of lines of equal γ, *isogammic* lines in Eötvös' terminology: from each observation point, then, a gradient can be constructed, a kind of vector indicating the intensity of the γ-variation and its direction. Importantly, the same effect will show up in case of *invisible* mountain ridges on the bottom of a deep lake—think of Lake Balaton—or on mainland, *e.g.* under the pastures of the Great Hungarian Plain, roughly the South-Eastern part of the country. However, when the subsurface is of a less outspoken relief, no regularities show up. In such cases the sensitivity of the balance could be increased by exchanging one of the counterweights by a platinum thread carrying a similar counter-weight: the new version was called a 'horizontal variometer', later known as the one and only 'Eötvös torsion balance' (Fig.3). With respect to the earth the two weights now occupy different equipotential surfaces, so that any difference in the form of those surfaces will bring about a torque on the beam causing it to turn. Given the possibility to charter the subsurface in terms of density variations, that is: by systematically scanning the area, the interest of Eötvös' ideas for geology and mineralogy was obvious. Indeed, within a decade geophysics—the term was introduced by Julius Fröbel (1834)—became booming science.



◂ **FIG. 3:** The 'horizontal variometer' or 'Eötvös torsion balance'. The beam carries two weights, the one hanging down fixed to a platinum wire, the other directly fixed to the beam. Each weight appertains to an equipotential plane of its own, hence the appearance of a horizontal component. The telescope on the right carries the scale; the observer carries *e.g.* a storm lamp as light source [4]. Courtesy: Hungarian Academy of Sciences.

Gravitation and inertia

In 1896 Eötvös summarized his research on gravitation and earth magnetism in a widely read paper in the *Annalen der Physik* [2]. In due course he became keynote speaker at various trendsetting conferences. So it happened also that in 1906 a prize-contest was launched by the University of Göttingen, inviting the community to address Eötvös' work. The question asked was: the medium between *charges*—the dielectricum—does it, or does it not, play the same role as the medium between *masses* like two molecules, the one in the Sun, the other in the Earth? The question was an acute one, since it had recently been demonstrated that charge carriers—the new 'electrons'—indeed behaved like tiny masses. Maxwell, moreover, had shown that electromagnetic phenomena propagate with the speed of light and the question now was: did gravitation propagate instantaneously—that is: with an infinite speed—or with a finite speed? One Albert Einstein (Bern), as yet unaware of Eötvös' activities, even pondered on the *varying* mass of objects in motion… Eötvös and his collaborators Dezsö Pekár and Jenö Fekete interpreted the Göttingen challenge as an instigation to reconsider the relation between gravity and inertia. Slightly adapted their argument runs as follows [3].

According to Newton's first law two masses M_1 and M_2 at a distance r attract each other with a force

$$F_{gravity} = f\frac{M_1 M_2}{r^2},$$

f being a constant, such that mass M_2—let's say, one of the spheres of a torsion balance—experiences a gravitational acceleration γ with respect to the Earth, M_1, of

$$\gamma = f\frac{M_1}{r^2},$$

If equal masses of different materials indeed feature different gravities this reduces to saying that their constant f varies, which may be expressed as follows:

$$f' = f(1+x)$$

In their paper, Eötvös *et al.* claim that Newton's experiments with pendulums had shown that $x < 10^{-3}$ and those of Bessel that $x < 5 \cdot 10^{-4}$; in both cases the estimate had been based on the presumed accuracy of the weighing procedures of Newton and Bessel. The new experiments, then, further narrowed down x to $< 2 \cdot 10^{-7}$. In a way typical for the problem at stake Eötvös *et al.* reason backwards: given the presumed equivalence or identity of gravitational and inertial mass, as demonstrated by Newton and Bessel, the task is to increase the numerical accuracy of that proposition. So they started from the smallest possible observable deviation on the screen and argued backwards: what is the smallest possible observable change in the ratio $F_{gravitational}/F_{centrifugal}$? The experiments proper were conducted with the aforementioned torsion balance (Fig.3) and a doubled version, featuring two parallel balances in opposite directions (Fig.4); the latter balance allowed for two measurements at the same time. Broadly speaking the equivalence or identity of gravitational and inertial mass was confirmed once and for all with a new record-accuracy. Though, properly speaking, slightly at odds with the intentions of the contest, the essay submitted by Eötvös, Pekár and Fekete was nonetheless awarded the 1909 prize because of the fundamental physics involved. ■

◂ **FIG. 4:** Double torsion balance in brass. The two telescopes are mounted with prisms to facilitate the observations. Courtesy: Eötvös Museum, Mining and Geological Survey of Hungary, Budapest.

Acknowledgments

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About the author

Henk Kubbinga (University of Groningen) is a member of the EPS-History of Physics Group. Actually he is finishing the fifth and last volume of *The collected papers of Frits Zernike (1888-1966)*.

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