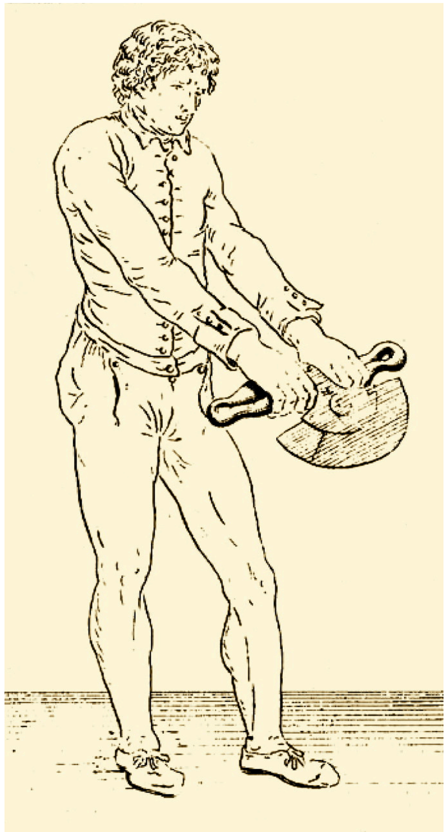
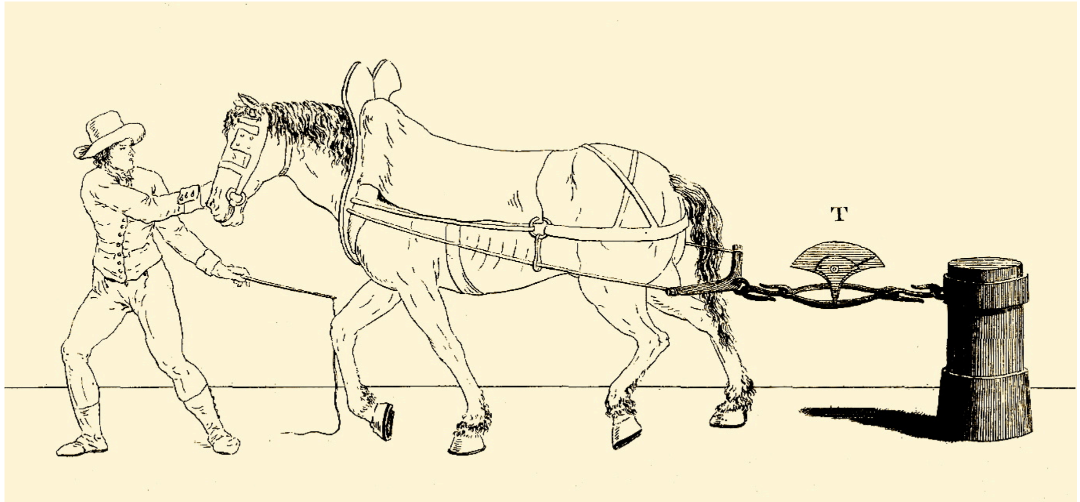
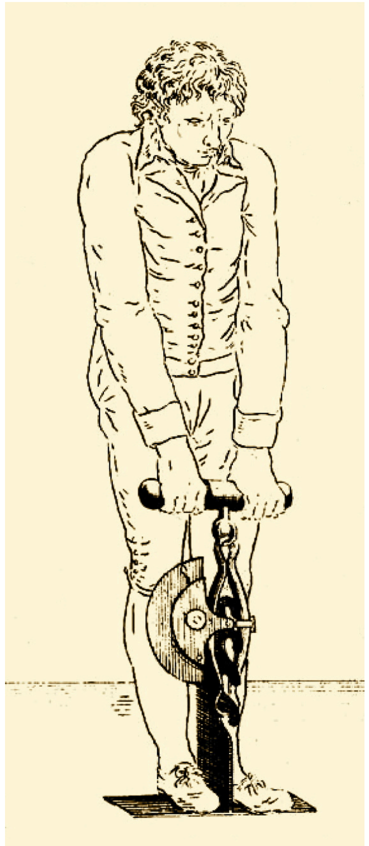
EARLY DYNAMOMETERS

(FROM MUSCLE TO STEAM POWER)





Regnier's Dynamometer (1798)



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Abstract

Early Dynamometers

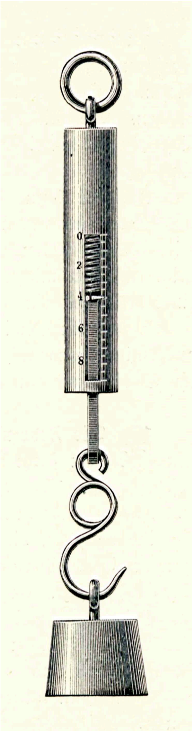
Spring balances, based on Hooke's law, have been used for weighing since the early 18th century.

At the end of the century, naturalists such as Buffon felt the need to quantify the muscular force of men (humans) and animals. The first practical, portable "dynamometer" was designed in 1798 by Regnier, in Paris, using for the first time an oval, closed spring and displaying the indication of the maximum force, tension ("loins") or compression ("hand"). It was promptly used by ethnologists to test the strength of "savages". A smaller improved model (Mathieu/Collin dynamometer) is still manufactured today and sold to medical and para-medical practitioners.

Used for measuring the rolling resistance of horse-driven wagons, the Regnier device is an example of a transmission dynamometer.

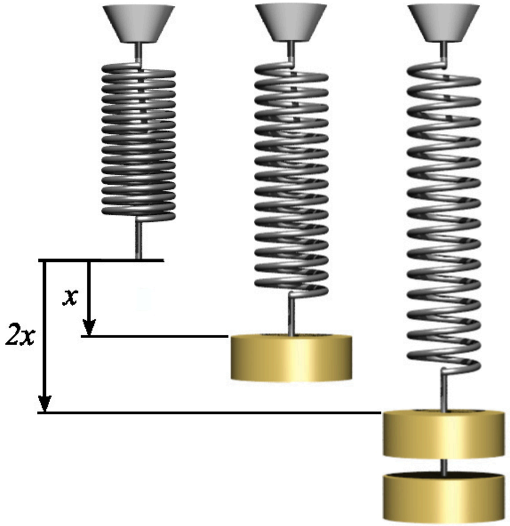
Since the early 19th century, the development of agricultural and industrial machinery resulted in the need to measure not only the force between the motor and the load, but also the work done and the delivered power. The name "dynamometer" came to be applied not only to force-measuring devices, but also to work-measuring ones (actually, they should have been called "ergometers"). Inventors and mechanics competed to combine heavy force-measuring machinery with newly invented delicate, precise graphic-recording apparatus and/or integrators and planimeters.

Focusing on transmission dynamometers, I will examine a few examples of either linear-motion ones or rotary-motion ones, as well as on the totalizing/integrating devices connected to them.



Before Regnier (I):

Spring balances[1] based on Hooke's law

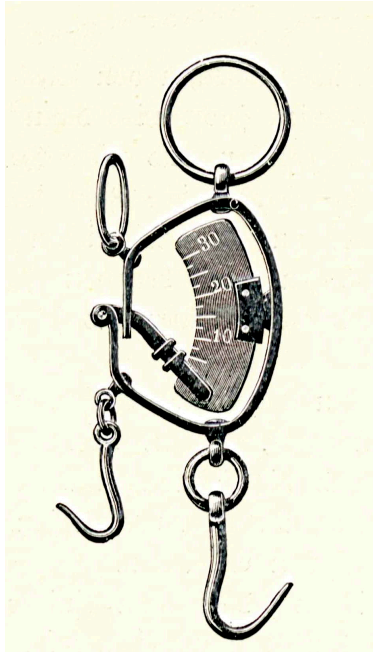


Deformation (strain)

$\propto$

Stress (force or torque)

(as long as the elastic limit
is not exceeded)



• Helical, spiral, V or C-shaped, …*open* spring balances known and used during all the XVIIIth c.
• Quick measurements, convenient to use,
but imprecise, limited dynamic range.
• In most countries, use for commercial transaction or taxation purpose (involving money) not allowed.

Used to measure amounts of matter (*i.e.* mass) through *g*, not forces.

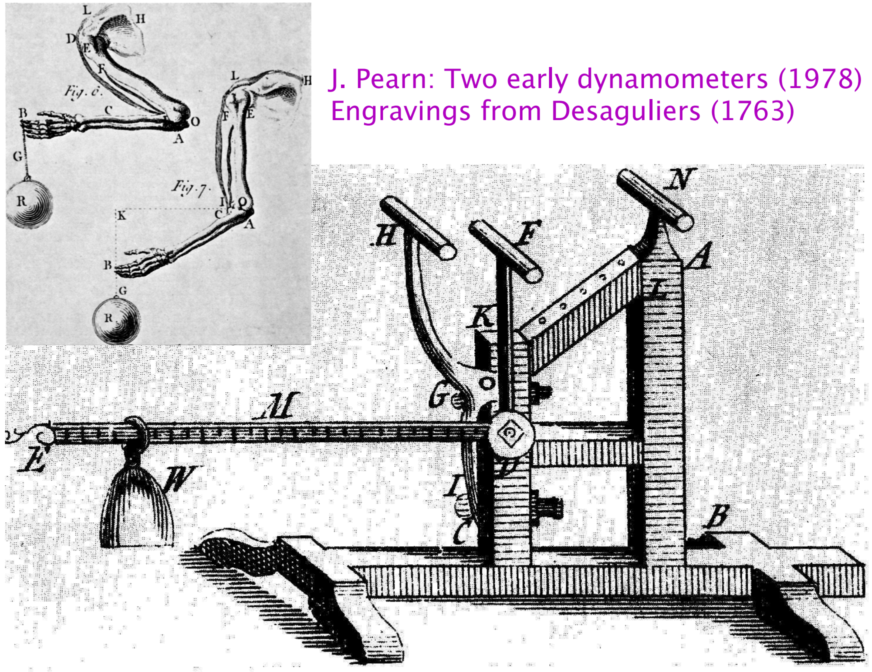
Before Regnier (II):

The best known of a few forerunners[2]:

- Graham-Desaguliers (1763)

Measures the *forearm strength* by lifting a weight.

Limited use. Not portable.



J. Pearn: Two early dynamometers (1978)
Engravings from Desaguliers (1763)

Early XIXth c. : most work still done by men and animals[3]!

- Citoyen Coulomb (1736-1806):

Publishes in 1799 the results of his experiments[4] on the useful “work” you can get from a man, in many different activities.
No separation between the physiology and the mechanics.
Carrying a load on a flat road is considered as work.

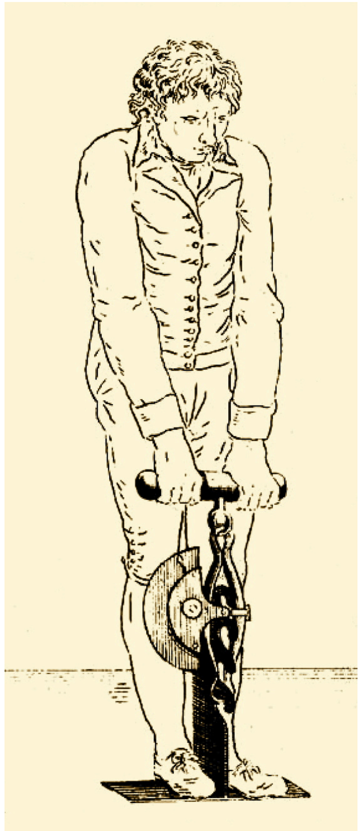
Cf. Hachette: Traité des machines (2e éd., 1819), Christian: Traité de mécanique (1822), Poncelet: Mécanique industrielle (1870), etc.

XIXth c. program: *measure* force, work and power
Build the instruments to do that!

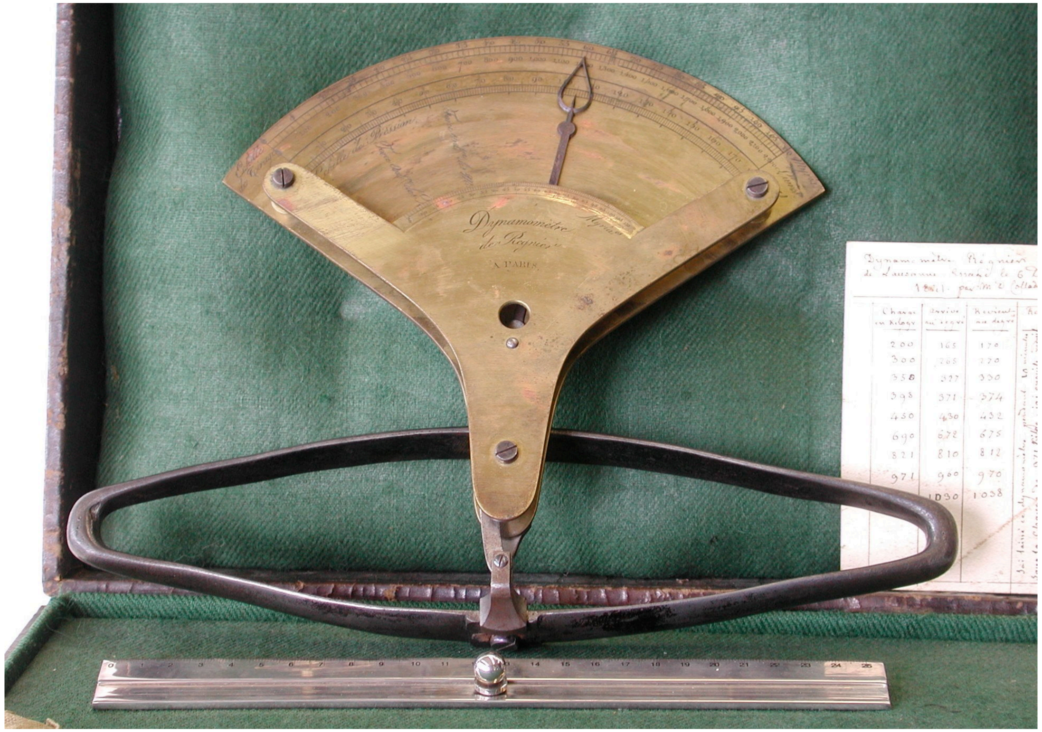
Regnier & his Dynamometer (1798)

Edme Regnier (1751–1825) works at Paris from 1789,
where he supervises the fabrication of weapons.
About 75 inventions, among them the secateur (?).

The best known is the “DYNAMOMÈTRE[5]” (first apparition of the word).
First published in 1798 in the *Journal de l’École polytechnique.*
English translation published the same year in the *Philosophical Magazine.*



Tension



Displayed at UNIL Physics Museum (Inv. 603.162);
tested by M. D. Colladon jr. in 1841. Photo JFL.

Compression

Regnier's DYNAMOMETER

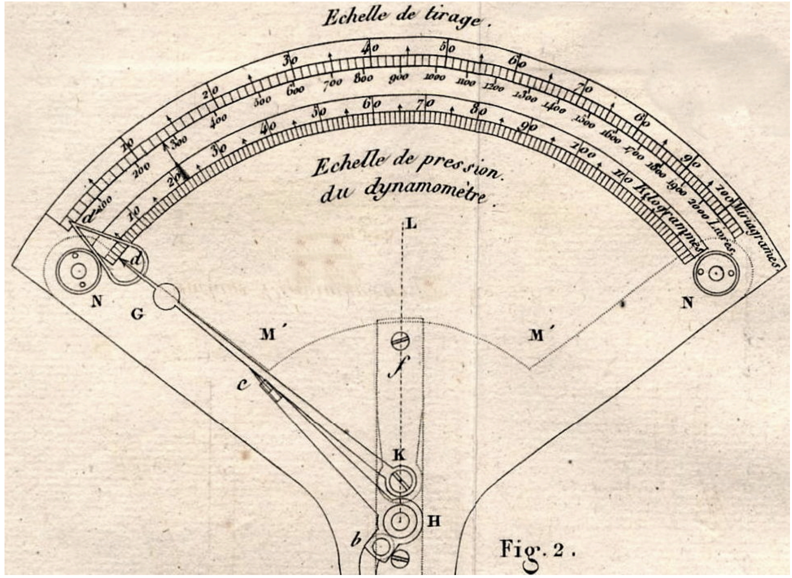
First portable, versatile, easy to use dynamometer

Dynamometer with accessories,
by Arnheiter, the mechanic
who had worked for Regnier.
Private collection of J.-F. Loude

Oval/elliptical
closed spring

Two scales:
- *compression* forces
- *tension* forces

A pointer registers
the *maximum*
of the force



The two scales.
From Hachette :
Traité élémentaire des machines (2e éd., 1819)

It has been used to measure:
- strength of men ("force ord^{re} des mains", "force ord^{re} des reins")
- traction force of animals
- resistance to traction of carts (ammunition wagons, gun carriages,…)

But it doesn't measure mechanical *work* !

Dynamometers evolved in two directions:

I. Anthropology, medicine and sport

The Regnier Dynamometer was immediately adopted by anthropologists wanting to compare the strength of the European men and of the "Savages" they met during their exploration voyages around the globe.
The results[6] didn't always agree with their expectations!
(Péron in 1807, Quetelet in 1846, the Austrian HMS Novara expedition (1857-59), etc.)

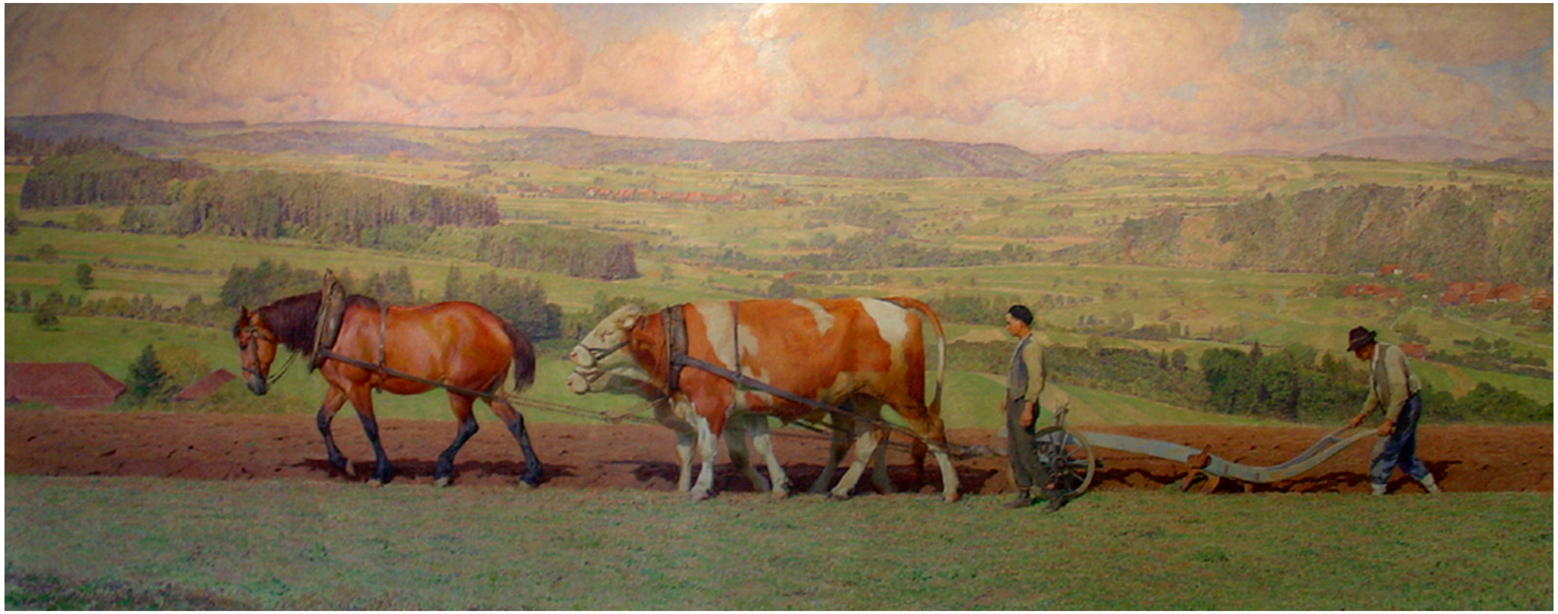
Similar oval-spring dynamometers were developed during the XIXth c., for testing human muscle strength (Tiemann in the USA, etc.)

Also used in strongmen championships[7] (late XIXth c. - early XXth c.)

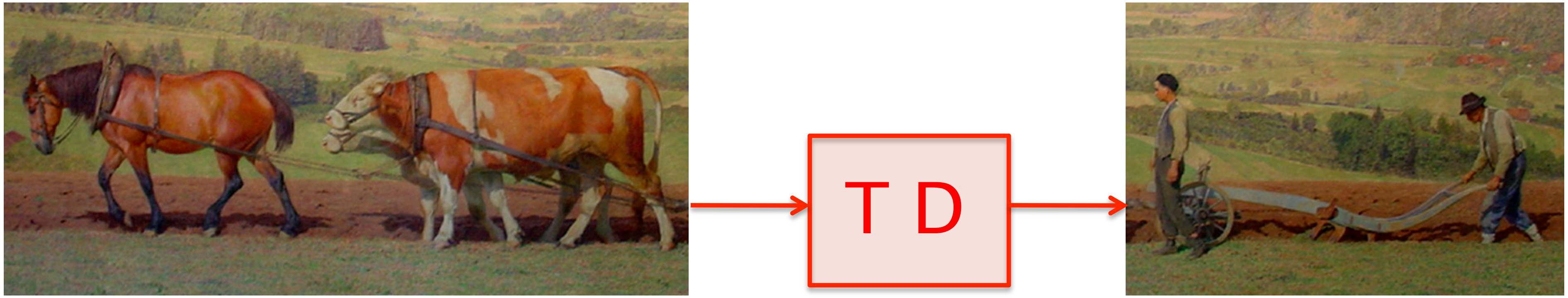
From about 1860, Mathieu sold a smaller version[8] for the Regnier's dynamometer, for compression only. Also made by Collin, it was widely adopted for medical and para-medical use. The "Collin dynamometer" is still available today (≈ EUR 125).

Mathieu/Collin dynamometers
Private collection of J.-F. Loude

II. Mechanical work measurement



Eugène Burnand : Le Labour dans le Jorat (1916) — Musée Eugène Burnand, Moudon (Switzerland)



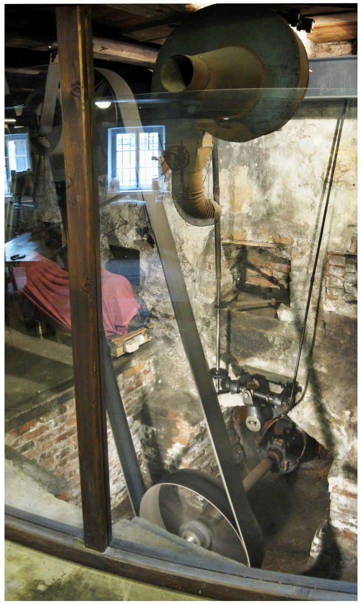
TD : Transmission Dynamometer,

inserted between *motor* (animal, steam engine, etc.)

and *pulled load* (plough, cart, railway carriage, boat, etc.).

Transmission Dynamometers:

- Measure *mechanical work*, should be called Ergometers[9]



Wikimedia - Commons
(Lokilech)

- Different models:
  - for *linear* motion
  - or for *rotary* motion, either:
    - Man turning a crank
    - Pulley and Belt transmission (←)
    - Drive-Shaft transmission (→)

Wikimedia - Commons
(Ad Meskens)

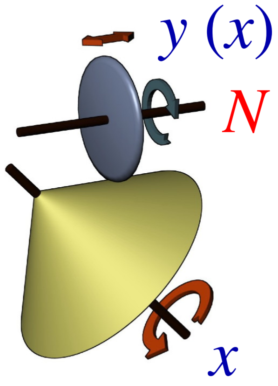
- Linear motion : work W is the product of force F by space x
- Rotary motion : work W is the product of torque τ by rotation angle ϑ
  power P is the product of torque τ by rotation rate ω

- Combine *heavy machinery* (strong spring to measure force or torque) and a *precision, delicate apparatus* (integrator or curve tracer), normally made for office or laboratory work. Field work difficult!

Short digression about the history[10] of Planimeters & Integrators

Early XIXth c. : need to measure the areas on cadastral plans (taxation!)

Adapted from Drechsler & Haeberlin (2011)

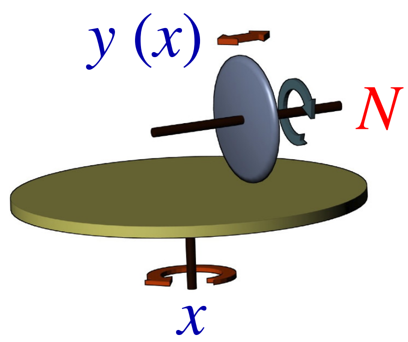


Cone and wheel integrator

Count the number N of turns made by the sliding wheel :

$$N \propto \int y(x)\, \mathrm{d}x$$

Dynamometer :
$x \propto x$ or ϑ
$y \propto F$ or τ



Disk and wheel integrator

Cone and wheel planimeters were invented several times, independently :

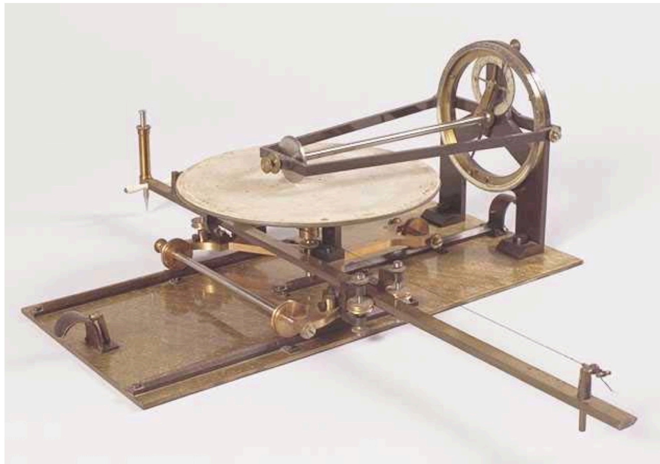
1814 : First one by
Johann Martin Hermann (Bavaria)
No publication, scrapped, forgotten until 1855

1816 : Tito Gonella (Tuscany)

1826 : Johannes Oppikofer (Switzerland)

1851 (!) : John Sang (Scotland)

1837 : Disk and wheel integrator used by Morin in his traction and rotary "totalizing" dynamometers



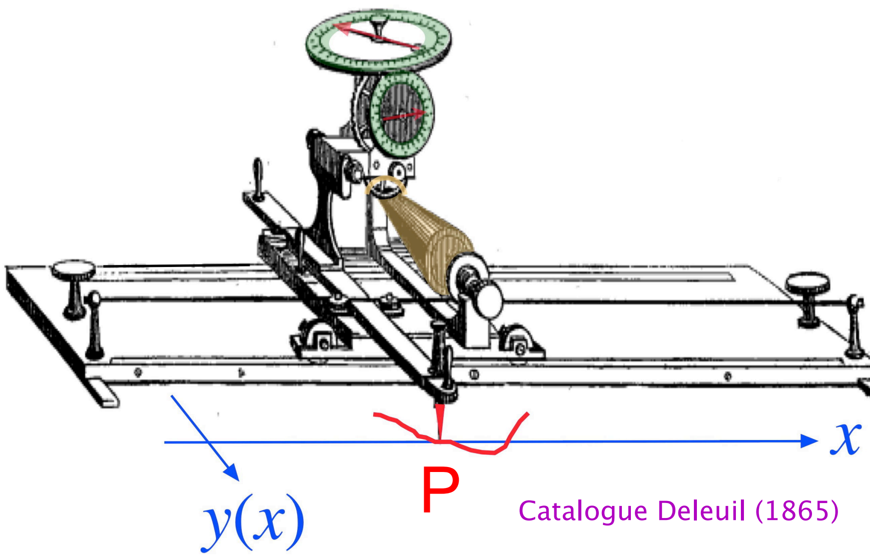
Uni Delft through Savoysky (2002)

Ca. 1850 : First disk and wheel planimeter by C. Wetli in Switzerland

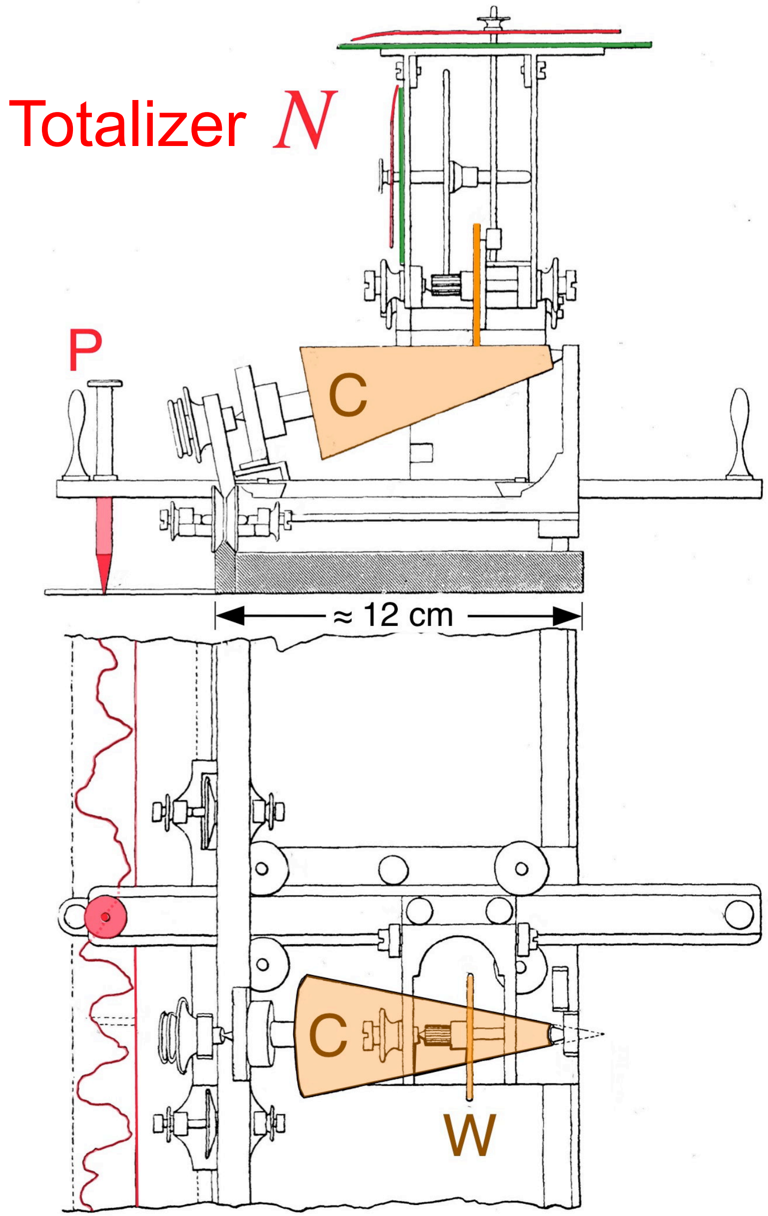
Planimeters & Integrators: Oppikofer-Ernst

The Swiss J. Oppikofer designs in 1826 the first successful cone-and-wheel planimeter, later made by Ernst at Paris, much used by surveyors.

A. Morin[11], in 1841, describes the Ernst planimeter in his "Notice sur divers appareils dynamométriques"



Catalogue Deleuil (1865)



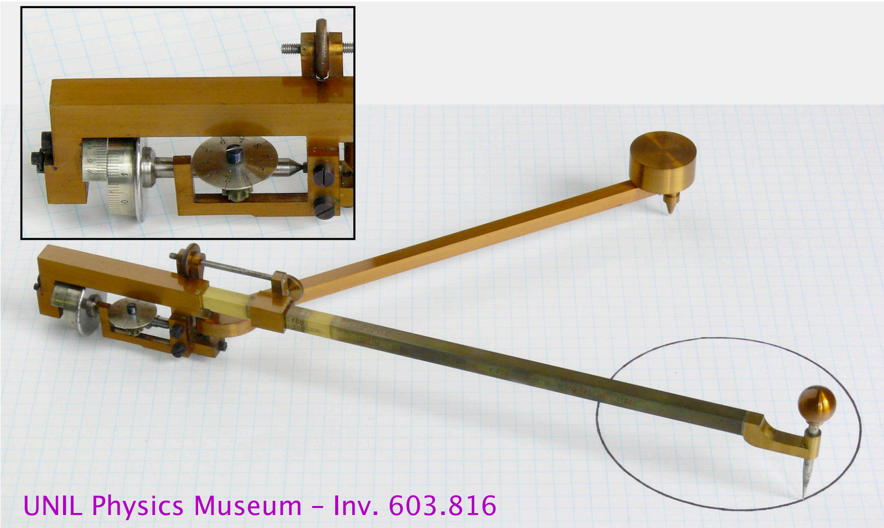
Jervis-Smith (1915) from Morin (1841)

W wheel rolling and sliding on wooden cone C

Planimeters & Integrators (after 1851)

1851 : The Great Exhibition at Crystal Palace (London)

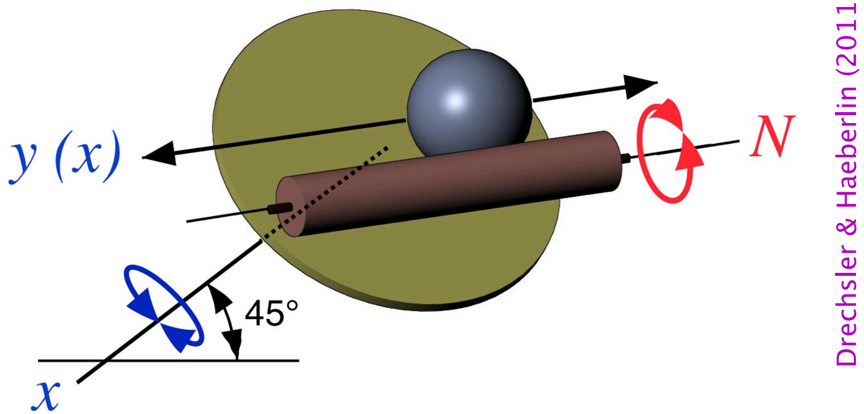
First opportunity to compare the instruments and machines off all countries



1854 : Jakob Amsler's Polar planimeter : simple, "cheap", for every surveyor and engineer. Hugely successful!

Copied, improved (Coradi's Compensating Planimeter"), still manufactured today.

How to suppress the sliding motion of the wheel ?

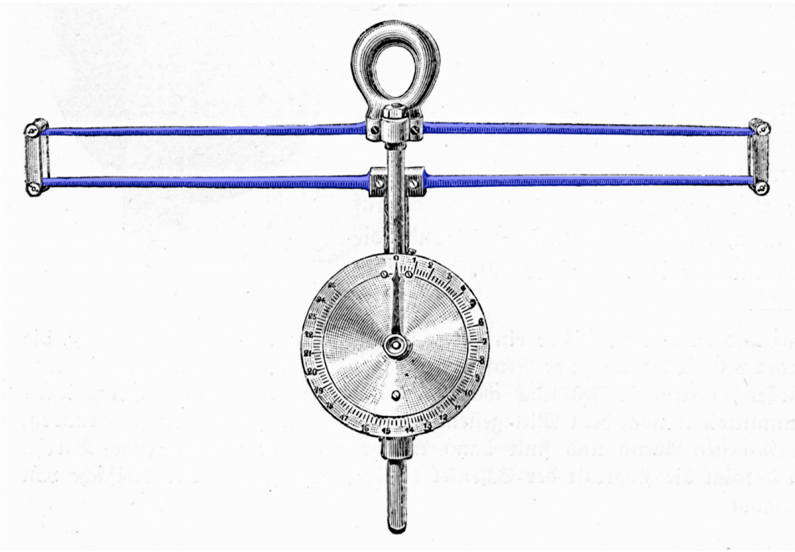


1875 : James Thomson[12]

The Disk, Ball and Cylinder integrator opens the way to scientific analog computers

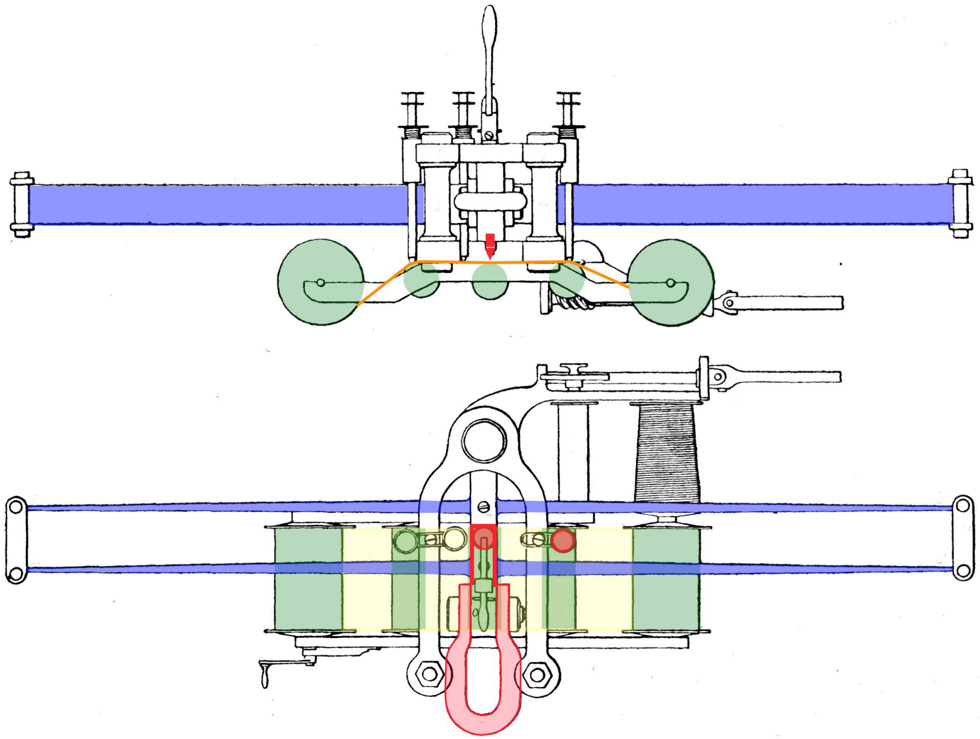
Back to dynamometers:
Poncelet and Morin

Jean-Victor PONCELET (1788-1867):
makes the first dynamometer based on sound scientific principles, with two spring blades articulated at both ends.
For tension only.



Frick-Lehmann I.2 (1905) p. 662

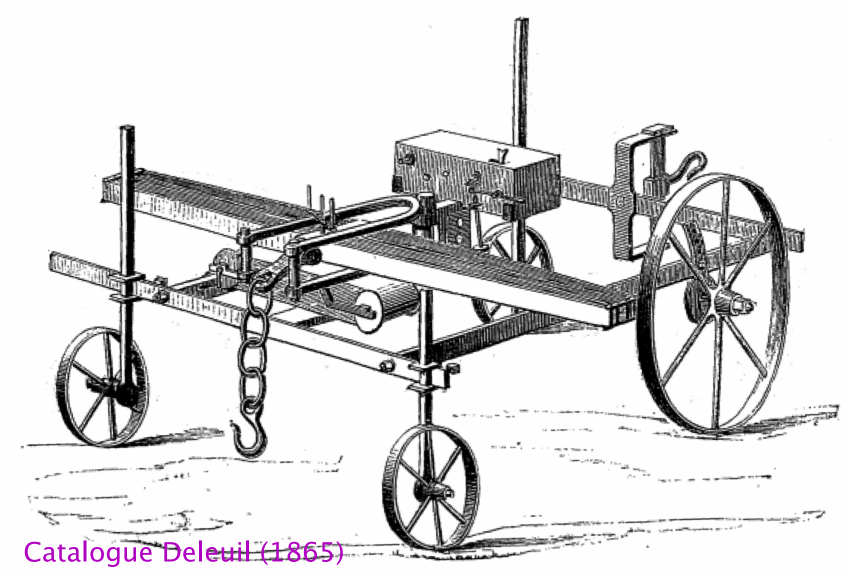
Arthur MORIN (1795-1880) :
student of Poncelet at Metz, later his collaborator, improves the dynamometer of his “maître et ami”, using 2 *plano-parabolic* steel blades[13] and adding a *chart recorder*, with a *pen or pencil* writing on a *paper band* moving proportionnally to the linear displacement.

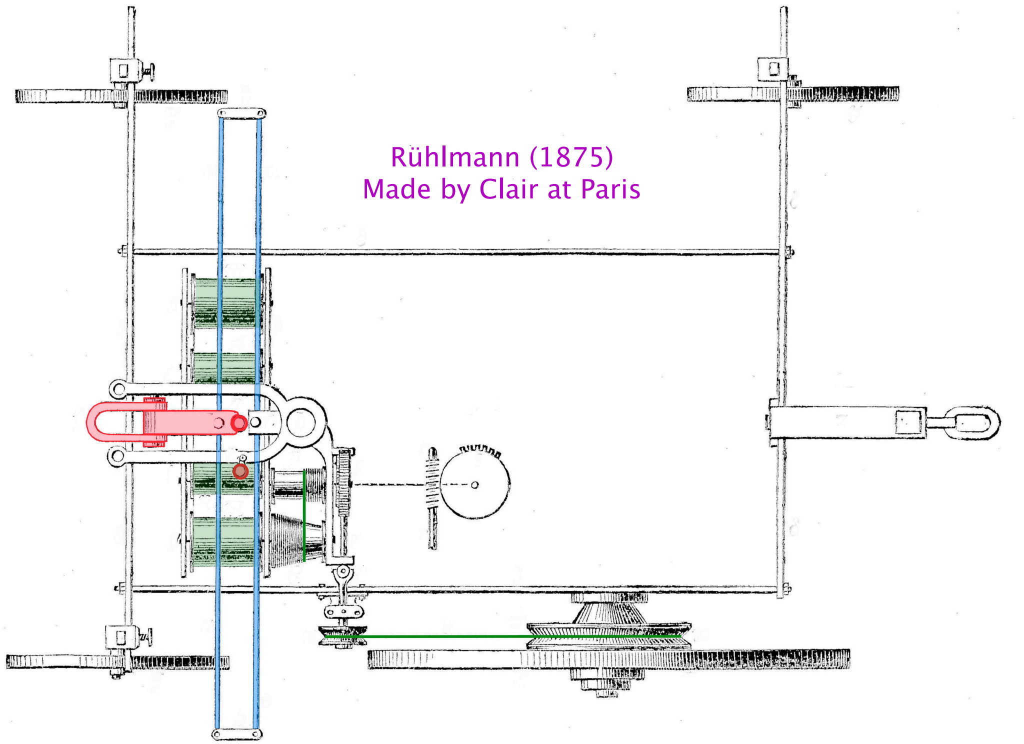


Jervis-Smith (1915) from Morin (1841)

Horse & Plough dynamometer (linear motion)

Morin, around 1840, using his improved recording dynamometer, designs an instrument for measuring the *work* made by an animal pulling a plough.



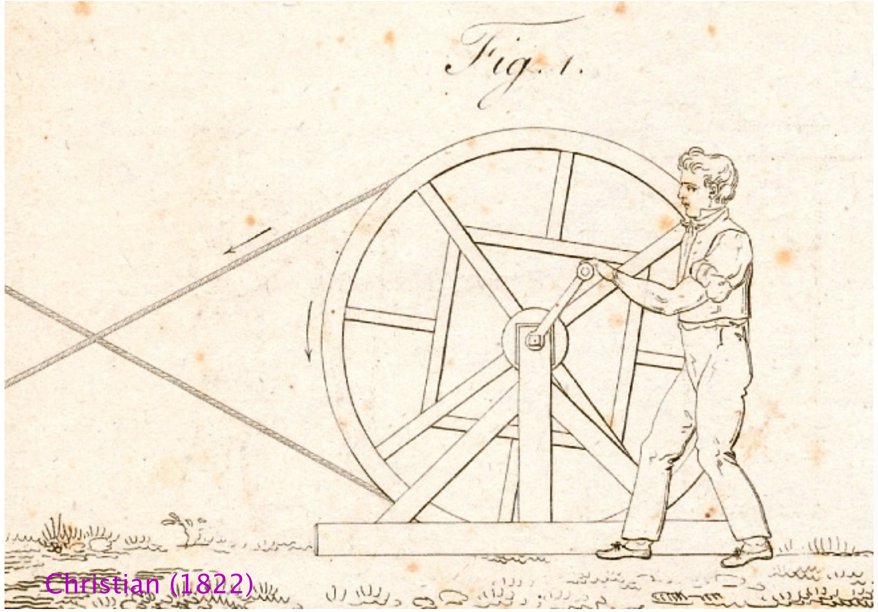


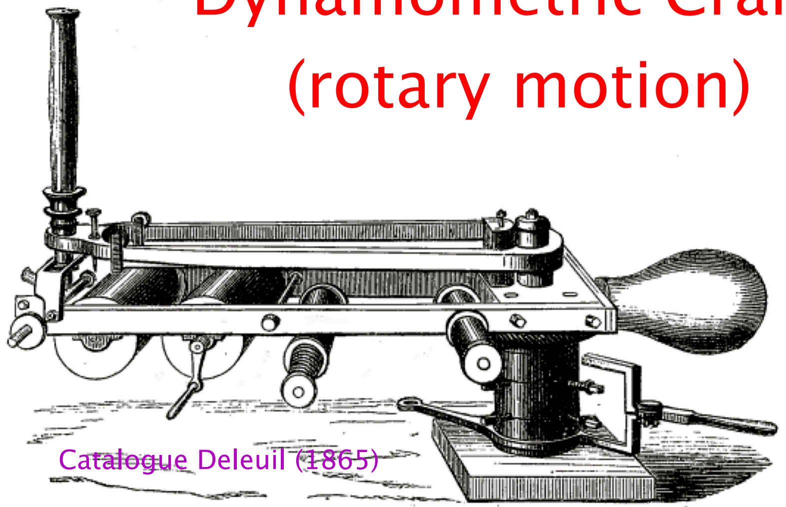
F vs. x : pen recording on a paper roll ⇒ W : integration by Ernst planimeter

Similar machines actually used in the fields
by agronomists such as Poirot de Valcourt (1841).

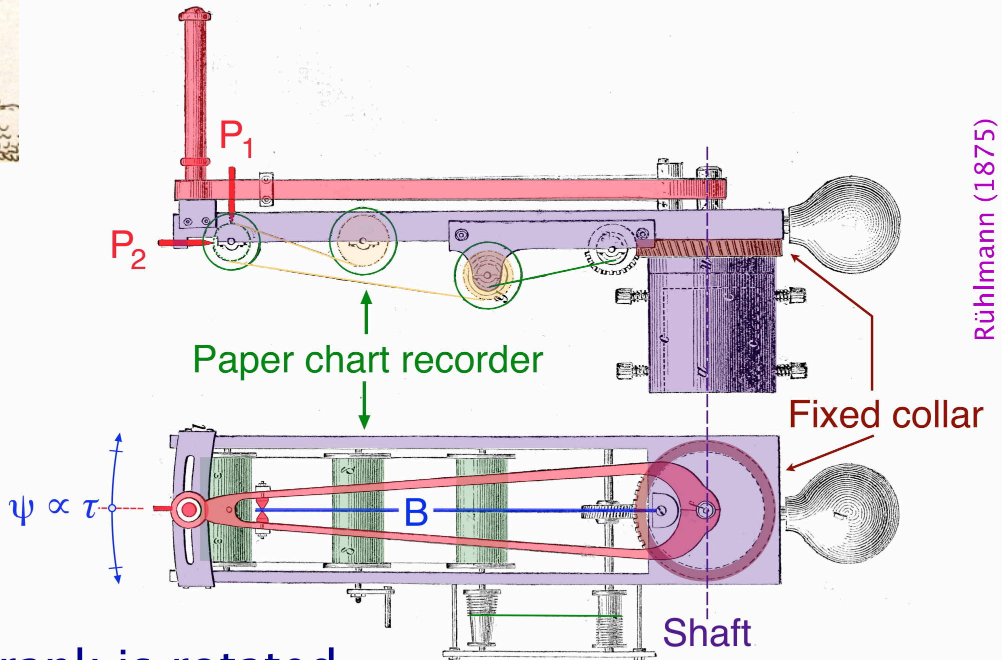
What is the mechanical work done by a man turning a crank[14] ?

Dynamometric Crank (rotary motion)



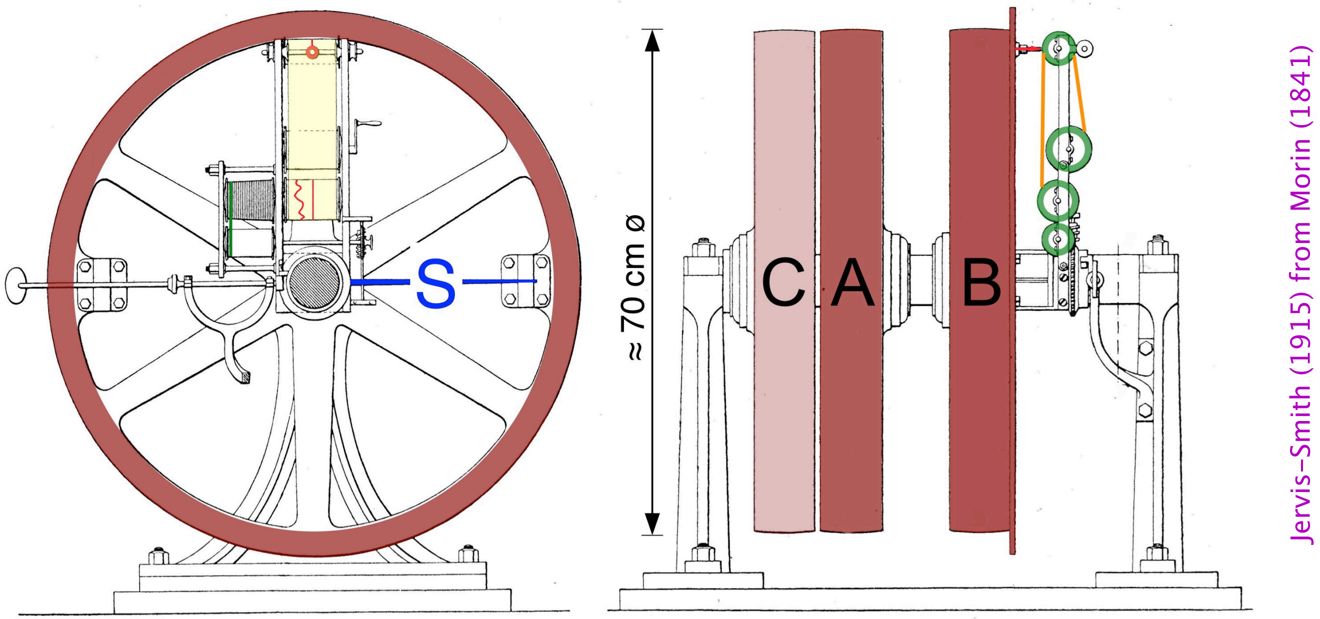


E. Regnier is credited with the invention of the "Manivelle dynamométrique", later improved by Morin and manufactured by the mechanic Clair, at Paris.



The paper moves forward when the crank is rotated. Pen P_1 draws a line showing the flexion of the spring B, relatively to the straight line drawn by the fixed pen P_2.

Belt and Pulley drive (rotary motion) — I. MORIN (ca. 1840)

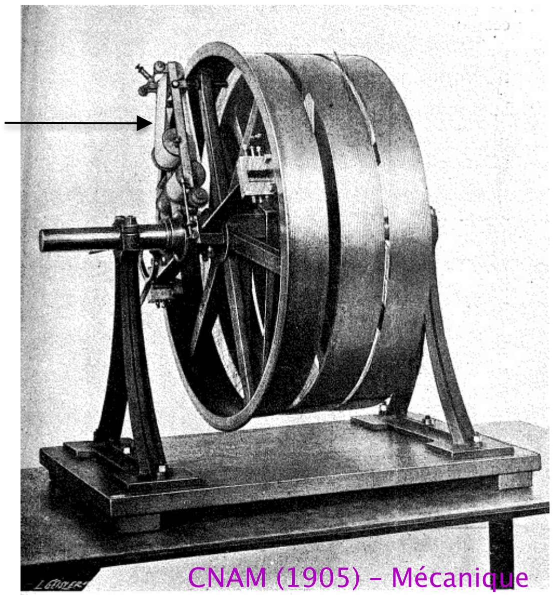


Pulley *A* receives the leather belt coming from the motor, pulley *B* drives the machinery under test through a second belt.

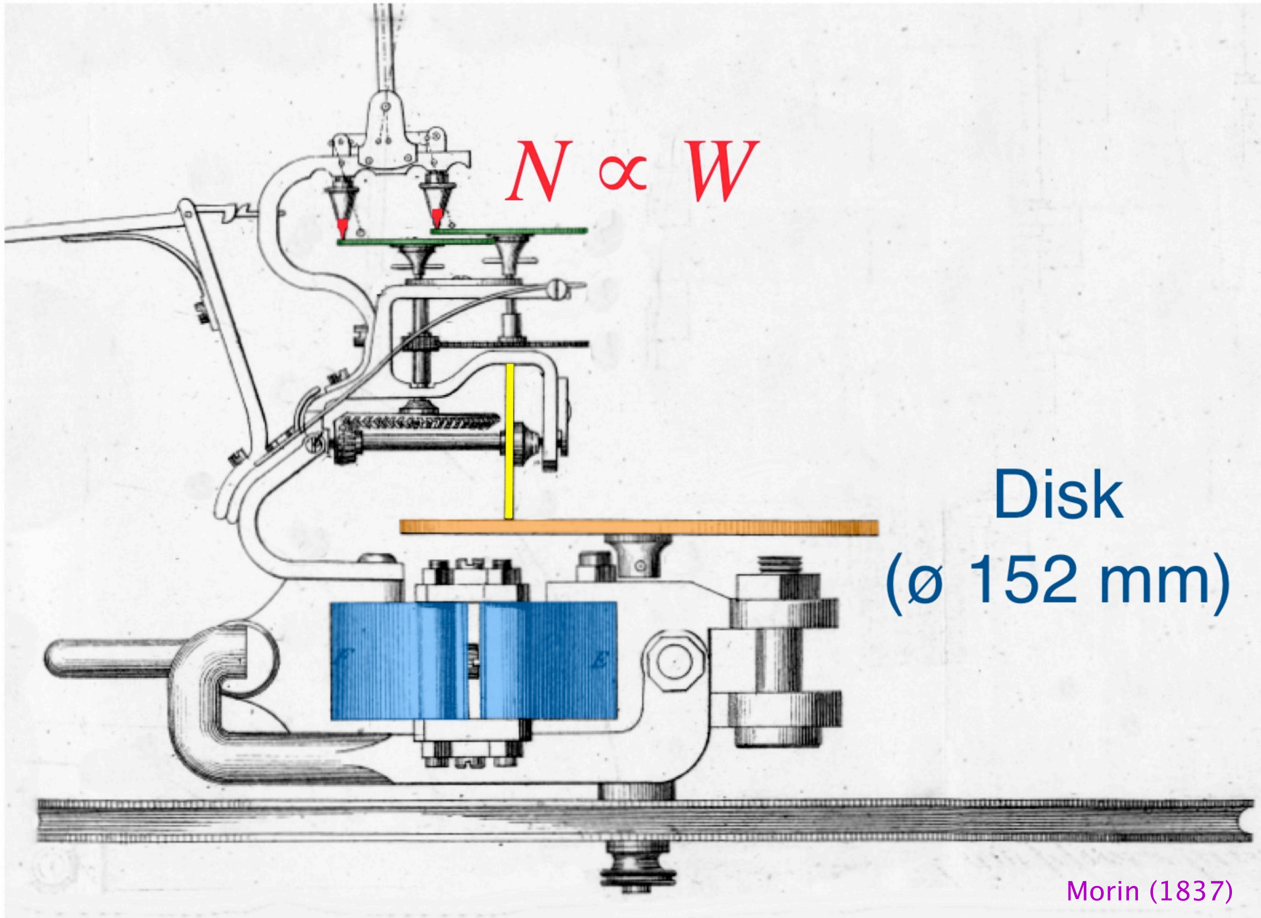
A spring blade *S*, inserted between pulley *B* and the shaft, bends (angle ψ) proportionally to the torque τ.

C is a loose pulley, for start and stop.

Paper strip recorder (τ vs. ϑ)



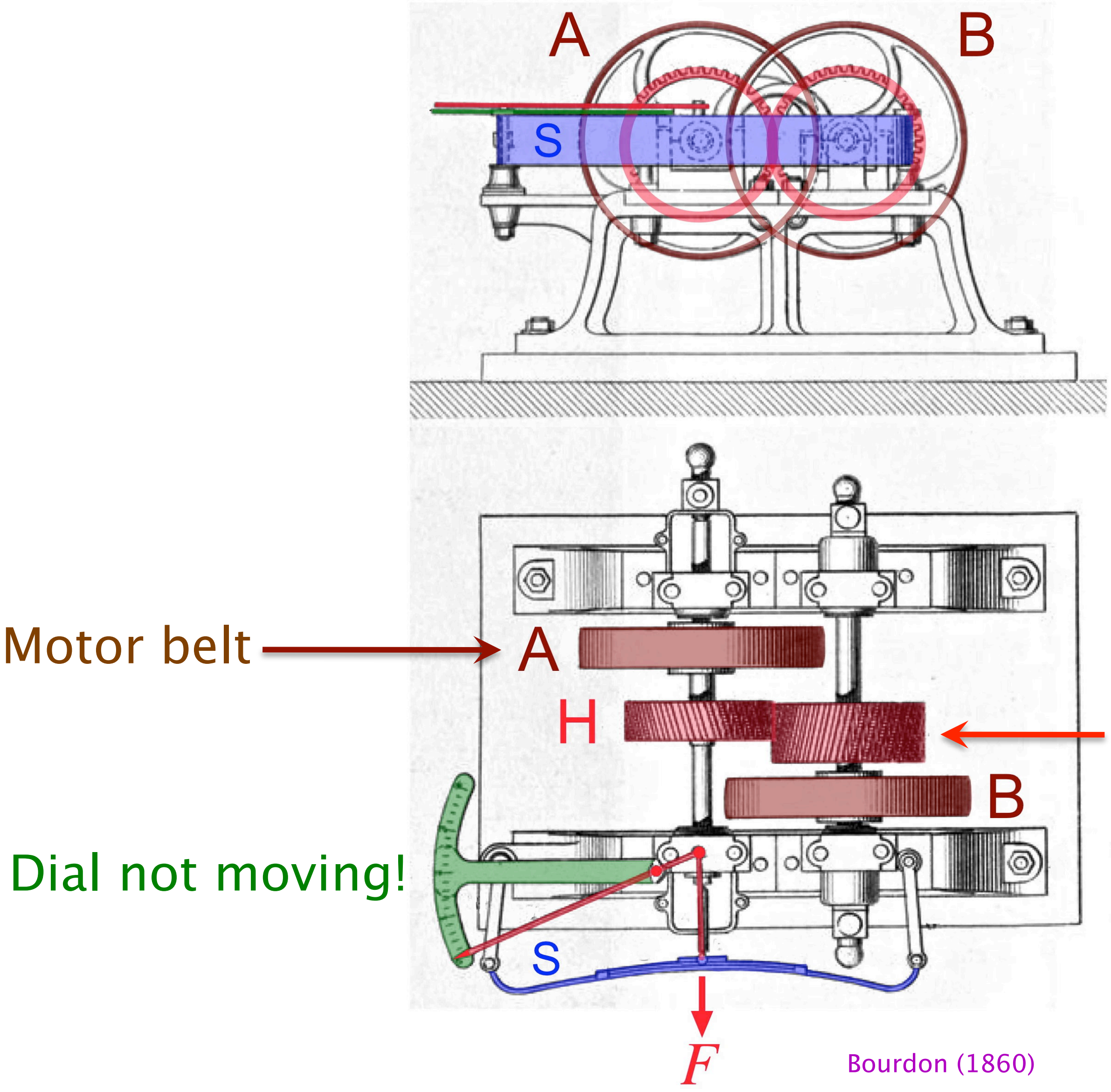
The *chart recorder* can be replaced by a *disk-and-wheel integrator* [15], that directly totalizes the work done during the test.



In the case of Morin's dynamometric crank and belt dynamometer, the recording device / totalizer is rotating!

Belt and Pulley drive — II. Further developments (1)

A curiosity[16]: the Bourdon dynamometer (1860)

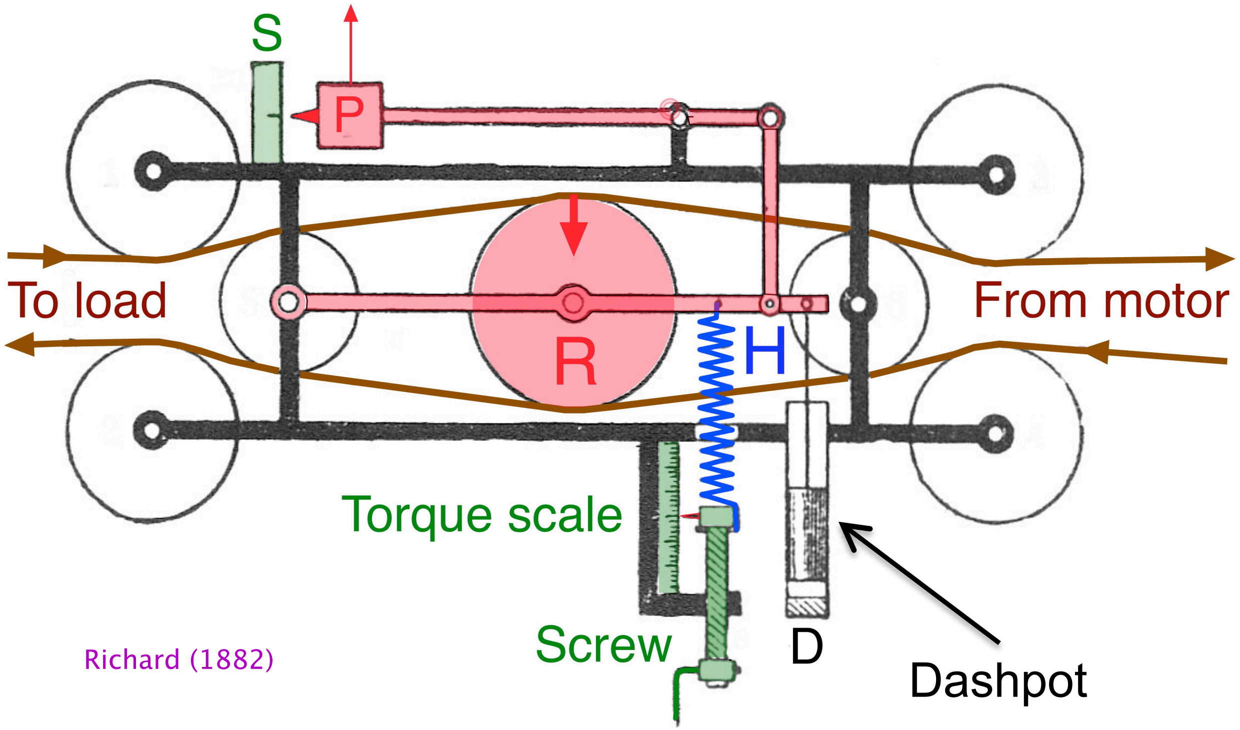


Bourdon (1860)

Helical gears H generate an *axial force* F proportional to the transmitted torque. F bends the spring S.

Belt and Pulley drive — II. Further developments (2)

A success[17] : von Hefner-Alteneck (Siemens) dynamometer (ca. 1880)



Richard (1882)

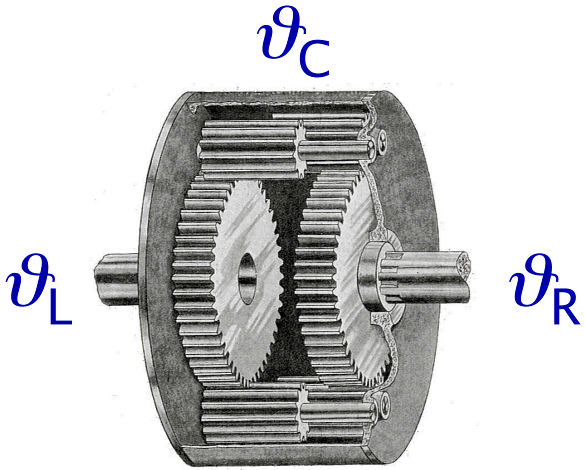
It measures the *difference between the tensions* on the leading side and on the trailing one of the belt. The pressure on the roller *R* is compensated by the helical spring *H*. The pointer *P* is set to 0 on scale *S* by the screw.

Only one belt !

Shaft drive (rotary motion)

How to transmit the torque exerted on a rapidly rotating shaft to a *stationary* measuring/recording device ?

Cut the shaft and insert a *spring* between the two parts, or use the *shaft* itself as a torsion spring,



en.wikimedia – Differential

and use some form of differential !

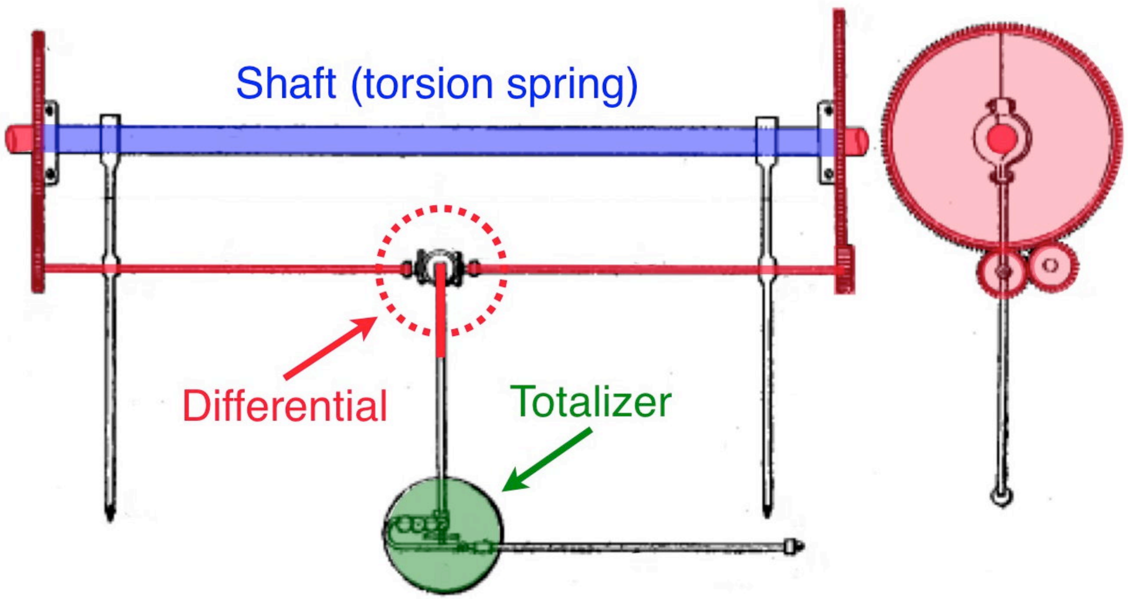
$$\vartheta_C = \tfrac{1}{2}\,(\vartheta_L + \vartheta_R)$$

(if $\omega_L = -\omega_R$, then $\omega_C = 0$: the casing doesn't rotate)

Example :

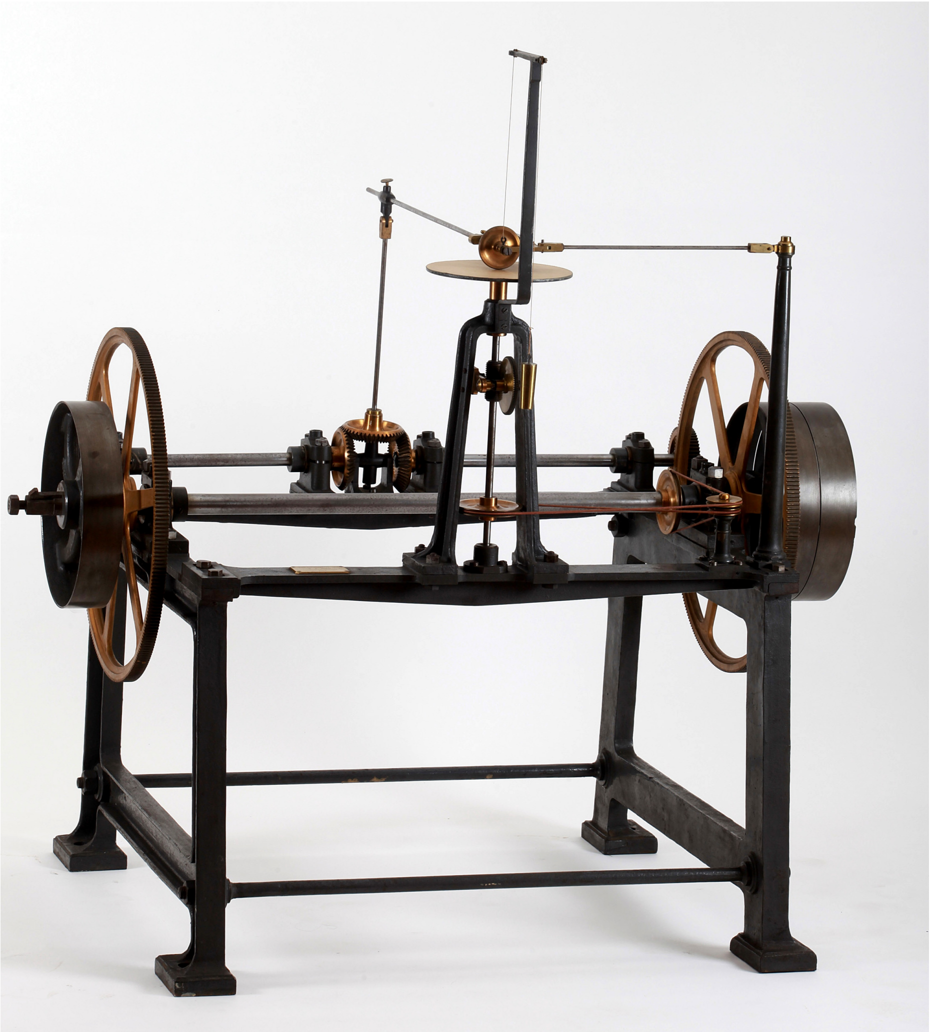
"Pandynamomètre[18]"

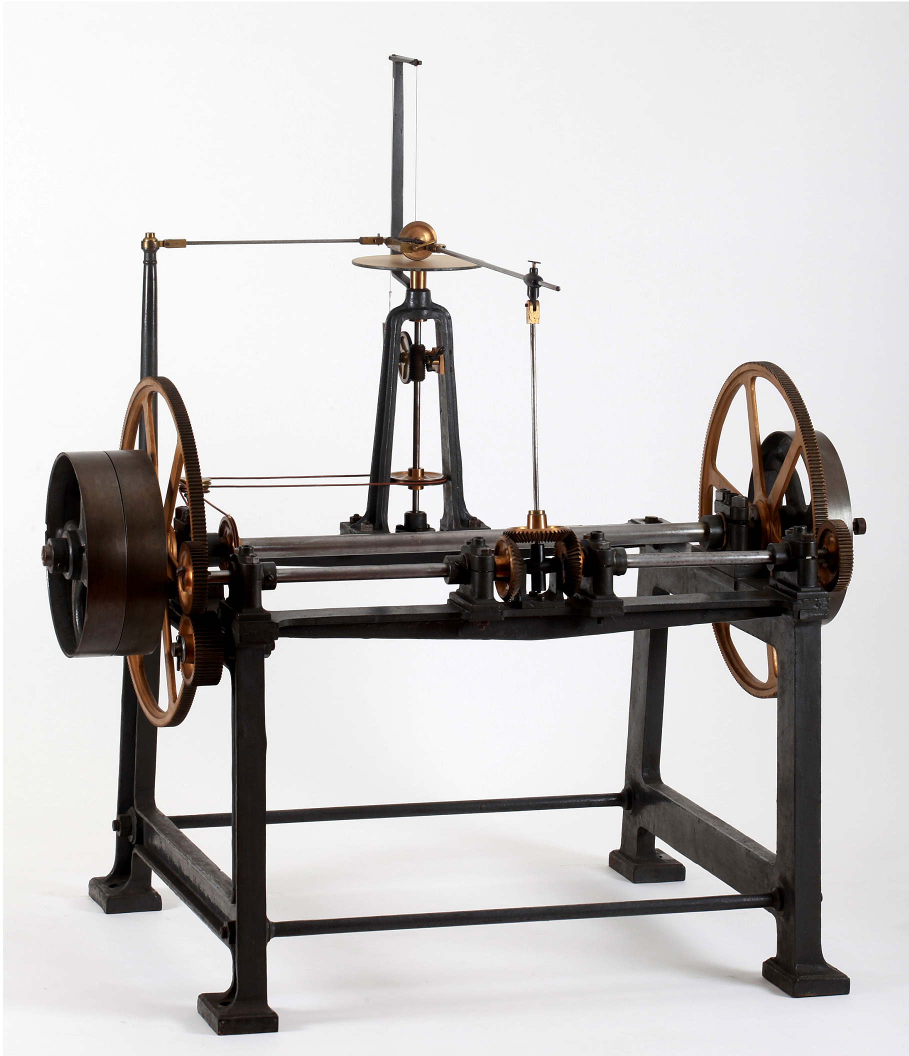
de G. A. Hirn (1876)



Richard (1882)

Hirn's differential Pandynamometer[19]





CONCLUSIONS

From ca. 1820 to 1840, Arthur Morin, designed the first traction dynamometers (what is the best plough?) and the first rotary ones, for belt drive.

From ca. 1830 to the end of the XIXth c., tens of models of transmission dynamometers have been invented, mainly to measure the work and power delivered to machinery.

Only a few examples have been shown.

Many more are described by Rühlmann (1862 and 1875), Guerout (1881), Richard (1882 to 1891), Flather (1892), Jervis-Smith (1915), …

Many dynamometers of all times and types are stored at the "Musée du CNAM", near Paris[20].

What I didn't speak about :

Absorption Dynamometers, that measure the power of a motor: put a *brake* and measure the *torque* or *convert* the power into something measurable (such as heat).

Notes & Comments (1):

1. See Frick-Lehmann (Bd. I.2, 1905, S. 661) und Benton (1941).
2. See Pearn (1978).
3. "*Moteurs animés*", as they were called in French.
4. Coulomb had also worked as an engineer, building fortifications. He had made many observations and experiments on the work one can get from a man. In his publication, the word "work" applies to the common use of the term. His results, somewhat improved, are reproduced in many mechanics treatises, until the end of the 19th c.
5. See also the english translation published in The Philosophical Magazine 1 (1798) 399, the booklet *Mémoire explicatif du dynamomètre et autres machines inventées par le citoyen Regnier* (Imprimerie de la République, Brumaire an 7 [22.10-20.11.1798]), others papers by Regnier and others in Journal des mines, No 97, Vendémiaire an XIII (1804-1805) 51, Journal des mines, No 132, décembre 1807, Bull. de la Société d'Encouragement pour l'Industrie Nationale No 156 (Juin 1817) 133 and the article by Pearn (1978). Dynamometers very similar to the original one by Regnier were still shown in the catalogues of physics instrument makers until the beginning of the XXth c.
6. François Péron, a Parisian doctor, had been sent by Buffon to Australia to make comparative studies of the strength of the native people. He found, in agreement with his preconceptions on the superiority of the white man, that South Seas natives were indeed not as strong as white European men (Bull. de la Société d'Encouragement… p. 143). Later, the beauty and great strength of Native North American men filled Quetelet (1846) with admiration.
7. D. Horne and E. Talbot: *The History of the Régnier Dynamometer*, in Iron Grip magazine, vol. 2 #3, July 2002.
8. In 1868, William Hammond (1828-1900), an American neurologist, promoted the use of the small dynamometer designed by Mathieu (Lanska 2000). Mathieu and Collin were both Parisian makers of chirurgical instruments. See also Hirschmüller (1997). The Mathieu dynamometer was also considered by Broca (1879) as an essential anthropological tool.
9. Etymologically, a *dynamometer* measures a force, not work or power. The term *ergometer,* more correct, was proposed but not adopted (Jervis-Smith 1915, p. 4). Both words are derived from the Greek words « dynamis » and « ergon », with the suffix *meter* derived from « metron », measuring instrument.
10. An early description of the first planimeters has been given by Bauernfeind (1853 and 1855). The development of integrators and planimeters is well summarized by Drechsler & Haeberlin (2011). The first planimeters used a cone-and-wheel integrator. It was later realized that the cone may be flattened to a disk, allowing integration of negative values of *y*. The small wheel rolls and *slides* on the cone or disk. The sliding motion is a source of errors. The *Planimeter* is an invention answering a perceived need, made independently and almost simultaneously in 3 countries : Bavaria, Tuscany, Switzerland. The Wetli Disk-and-Wheel *planimeter* was later improved by Peter Andreas Hansen in Gotha (Germany).
11. The Cone-and-Wheel Ernst planimeter is described in details by Morin (1841). The pointer *P*, guided by the hand, follows the registered curve. *C* is a cone made of wood. The small wheel *W* rolls and slides on it, making a number of turns *N* counted by the totalizer.
12. James Thomson (1824-1907), the younger brother of William Thomson, later Lord Kelvin (1822-1892), invented the Disk-Ball-and-Cylinder integrator. The disk being inclined by 45° relatively to the horizontal, the ball presses by its weight on the cylinder. This integrator was used by William Thomson in his well-known Harmonic Analysers. After a few improvements, it was possible to cascade several integrators, opening the way to scientific analog computers.

Notes & Comments (2) :

13. The plano-parabolic spring introduced by Morin provides twice as much flexion as a flat strip, for the same rupture load.
14. According to the mechanician Christian, the crank is one of the nine ways to get rotary work from a man, very common, but not the most efficient one. Rühlmann ascerts in his book that Morin invented the Dynamometric Crank, later improved by Morin.
15. It seems that Morin used a Disk-and-Wheel totalizer in his rotation dynamometer in 1837 already, well before the first Disk-and-Wheel planimeter was designed by Wetli, around 1850. The rotation of the recording device is a very serious drawback, making impossible to ascertain whether the recording device had been working properly before the end of a test. This defect was eliminated in later designs.
16. After Morin, the progress of mechanization stimulated many inventors to design more practical devices. I will show only two examples of later dynamometers for belt and pulley transmission. The first one, from Bourdon at Paris (1860), still needs 2 different belts on pulleys *A* and *B*. The spring *S* is pushed by the axial force generated by helical gears. Eugène Bourdon (1808-1884) is the inventor of a well-known pressure/vacuum gauge.
17. Friedrich von Hefner-Alteneck (1845-1904), working at this time for Siemens at Berlin, is better remembered for his photometric standard light source, the "Hefner Candle". His successful dynamometer can be inserted directly on the belt going from the motor to the load. The screw is adjusted until the pointer *P* returns to zero – it works best for a constant load! *D* is a pneumatic shock absorber.
18. Gustave-Adolphe Hirn (Colmar, Alsace, 1815-1890) was a French physicist and engineer. He was the first to design a dynamometer using the torsion of the shaft transmitting the power between the motor and the load as a measurement of the torque: *Le Pandynamomètre* (Annales des Mines, 6ème série, t. XI, 1867, p. 167-184). He proposed several versions of it. The differential model shown is described in details in the booklet published in 1876.
19. An exemplar of Hirn's differential Pandynamometer, adapted for belt transmission, can be found in the collections of the Fondazione Scienza E Tecnica/Istituto Tecnico Toscano of Florence (Italy). The photographs are shown with the kind permission of Paolo Brenni.
20. A search in the CNAM collections (data base "Objets", "Dynamomètre"):
    http://www.arts-et-metiers.net/musee/recherche-sur-les-collections
    identify 59 objects and graphic documents. Without, in most cases, any image, it is not possible to establish any relationship with the objects formerly shown in the CNAM 1905 Catalogue (Mécanique).

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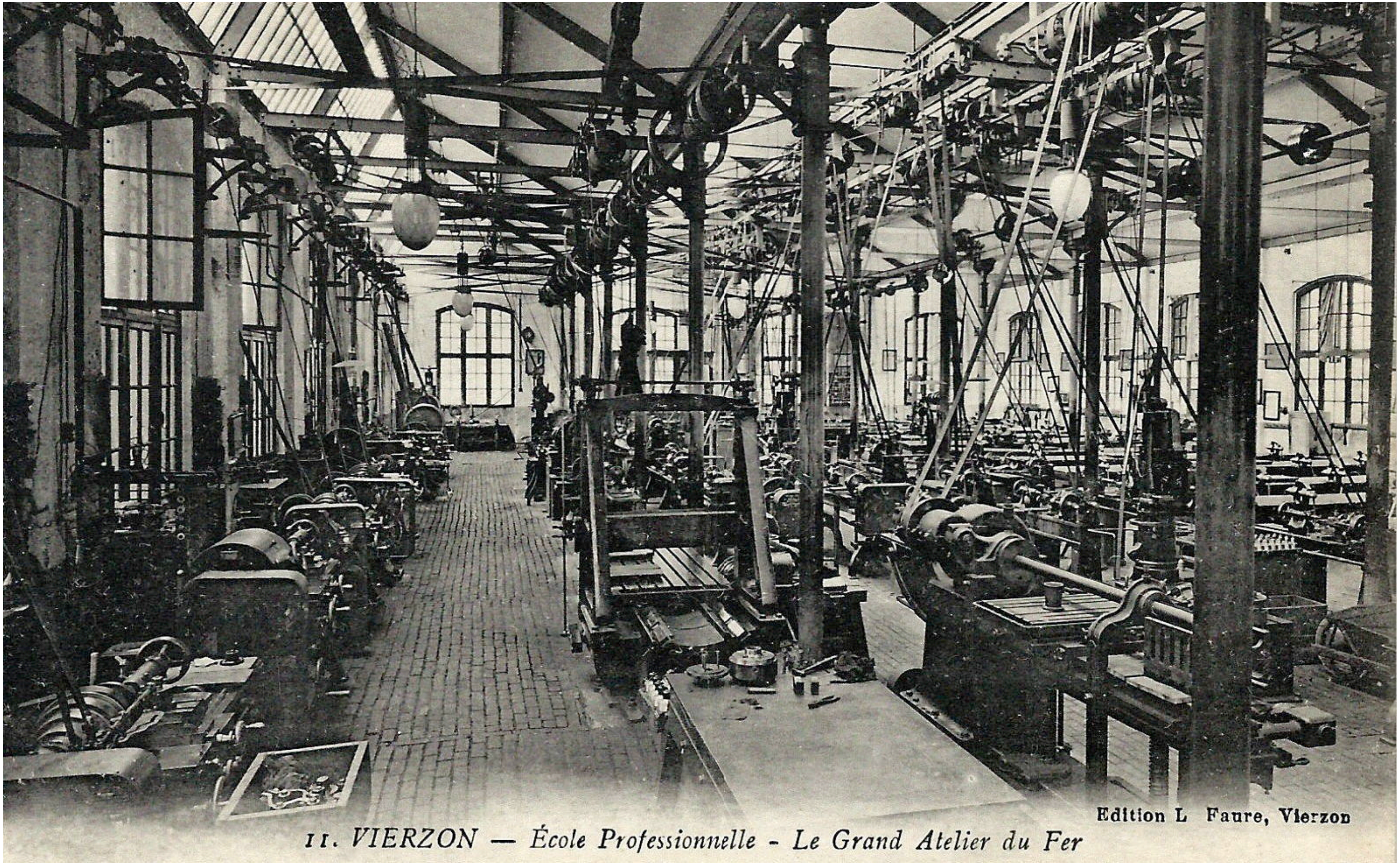
Belt transmission in a workshop



(Early XXth c.)