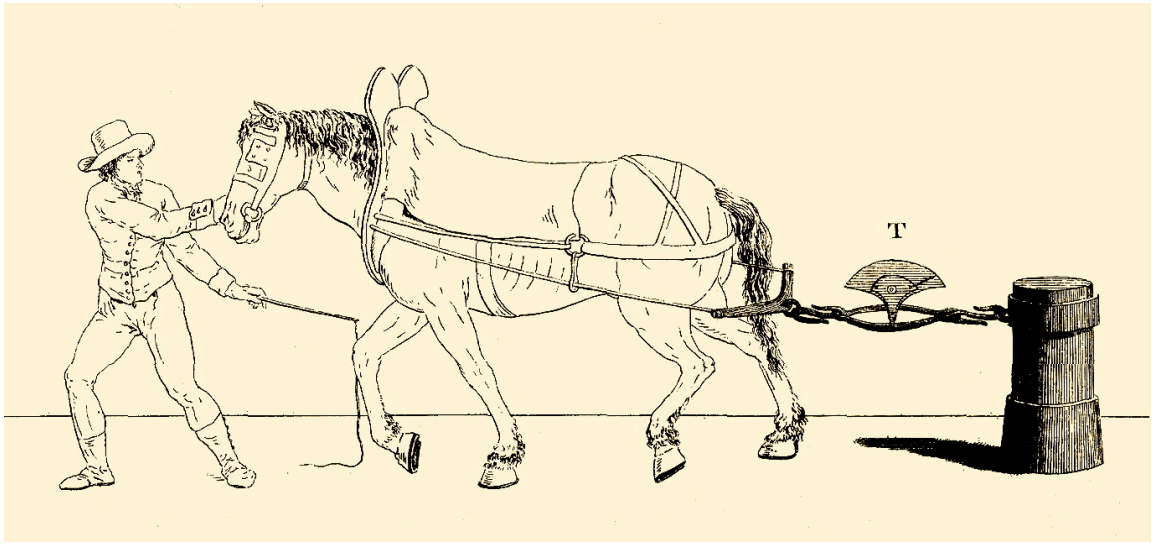
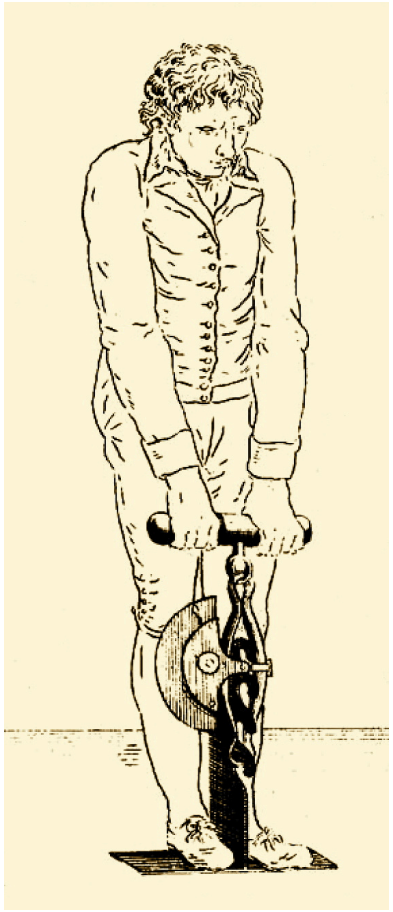
Force and Work Measurements: the Beginnings



Regnier's Dynamometer (1798)



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FÉDÉRALE DE LAUSANNE

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Abstract

Force and work measurements: the beginnings

The first practical, portable “dynamometer”, designed in 1798 by Regnier, was used to quantify the muscular strength of men and animals. It was promptly used by ethnologists to test the strength of the “savages”. A smaller improved model (Collin dynamometer) is still sold to medical and para-medical practitioners. With the development of agricultural and industrial machinery from the beginning of the 19th c., the need arose to measure not only the force between a motor and a load, but also the work done and the delivered power. Inventors and mechanics competed to combine heavy force-measuring machinery with newly invented delicate, precise graphic-recording apparatus and/or integrators and planimeters.

Before Regnier (I):

Spring balances based on Hooke's law

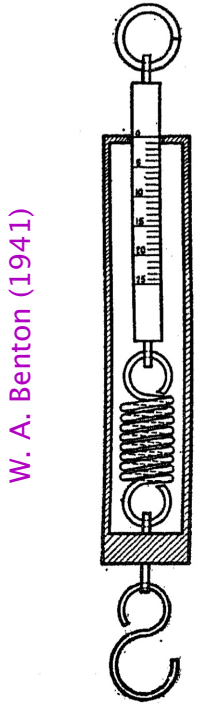
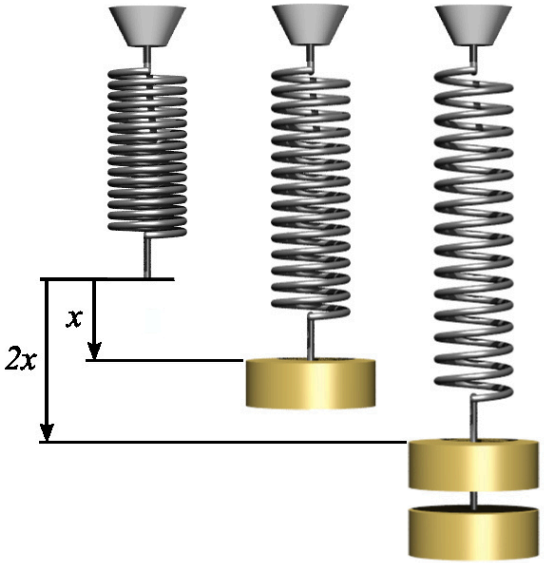


Fig. 30. Tension Spring Balance.



Deformation (strain)

∝

Stress (force or torque)

(as long as the elastic limit is not exceeded)

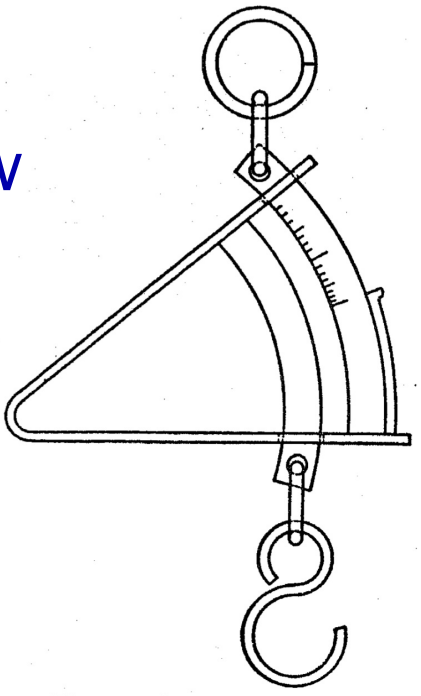


Fig. 32. Sector Spring Balance.

- 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.

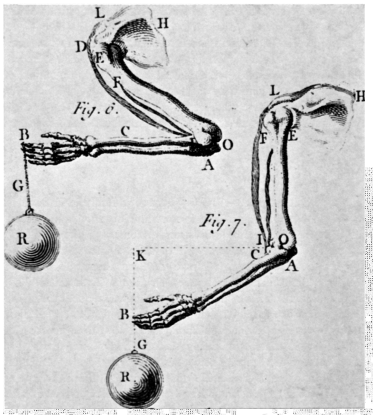
Before Regnier (II):

The best known of a few forerunners:

– 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!

– Charles Augustin de Coulomb (1736–1806):

Publishes in 1799 the results of his experiments on the “work”
you can get from a man, in many different activities.
No separation between the physiology and the mechanics.

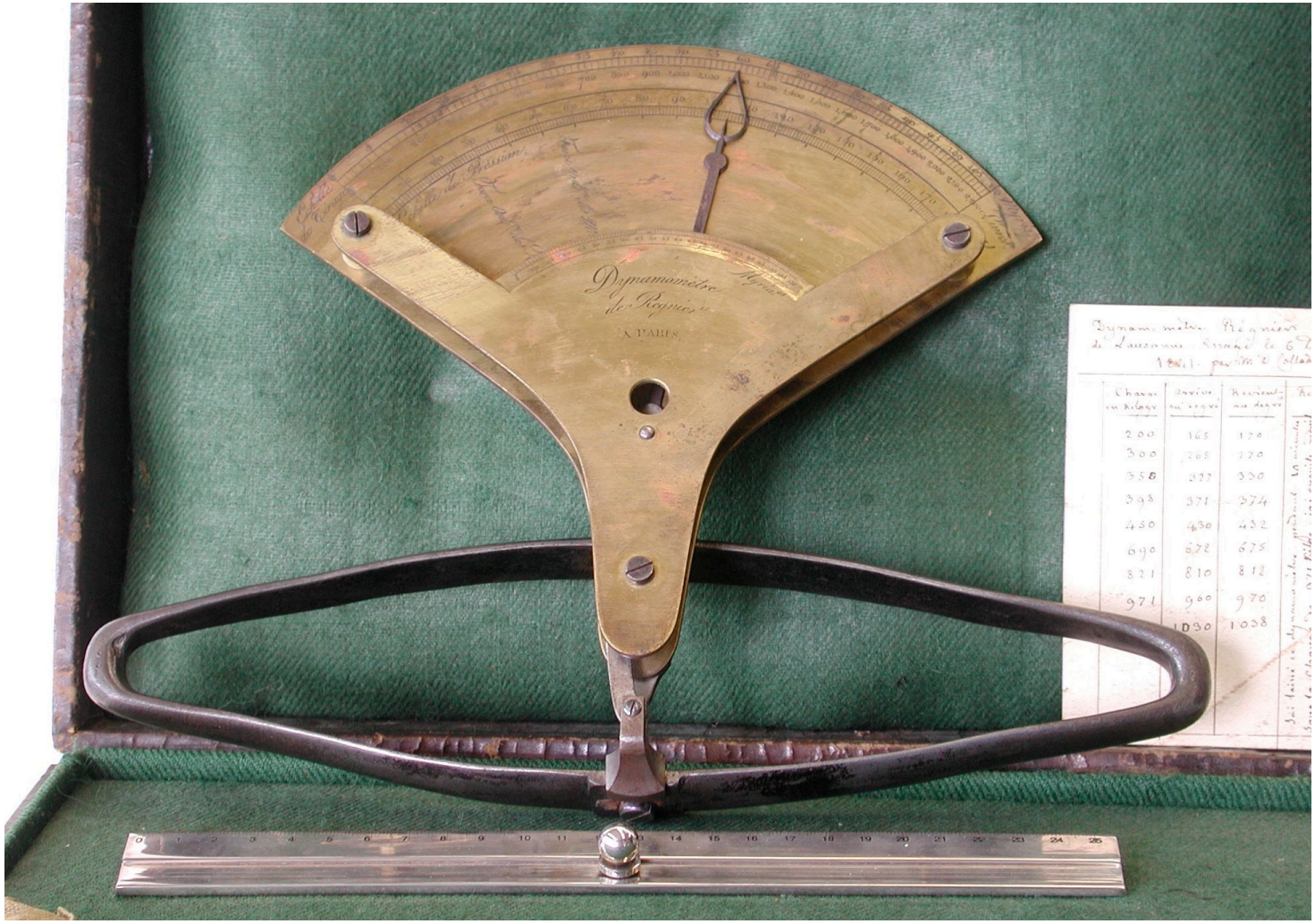
Carrying a load on a flat road is considered as work.

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

A simple, portable instrument to measure the strength of men and animals was needed !

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 (?) and the DYNAMOMETER



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

Regnier's "DYNAMOMÈTRE" (1798)

First portable, versatile, easy to use dynamometer

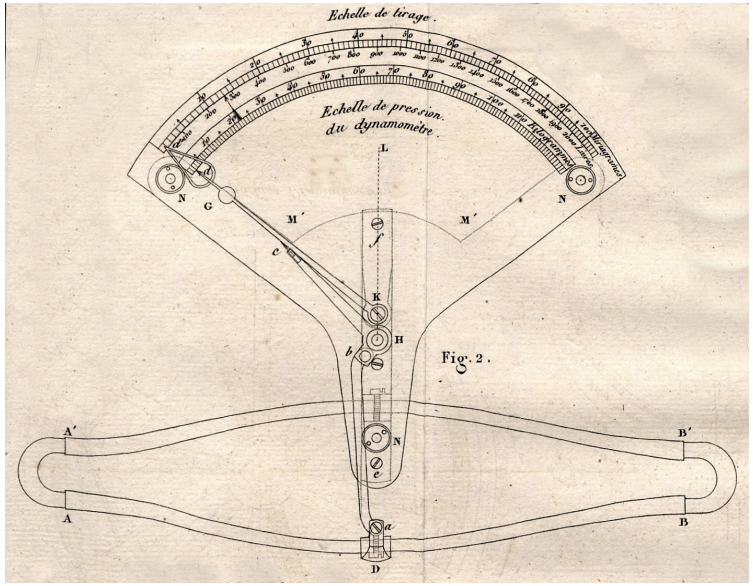
(first apparition of the word)

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

Oval/elliptical
one-piece closed spring

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

A pointer registers the
maximum of the force



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

Measures:
- strength of men ("force ordre des mains", "force ordre des reins")
- traction force of animals
- resistance to traction of carts (ammunition wagons, gun carriages,…)

But doesn't measure mechanical *work* !

Dynamometers evolved in two directions:

I. Anthropology, medicine and sport

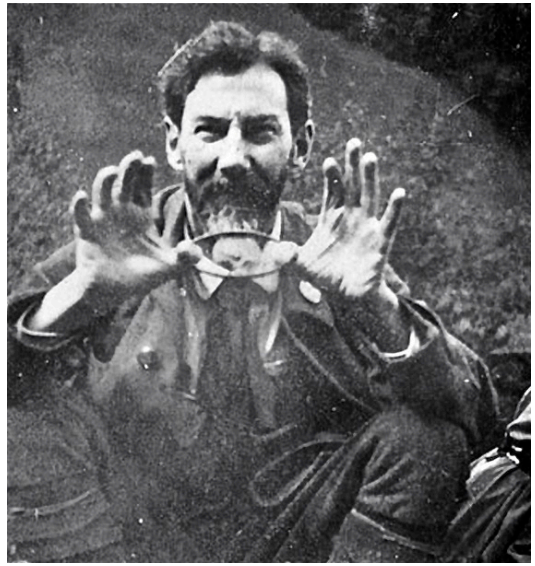
The Regnier Dynamometer was immediately adopted by anthropologists wanting to compare the strength of the European men and of the "Savages" they met during their exploration voyages around the globe.
The results didn't always agree with their expectations!
(Péron in 1807, Quetelet in 1846, the Austrian 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 (late XIXth c. - early XXth c.)

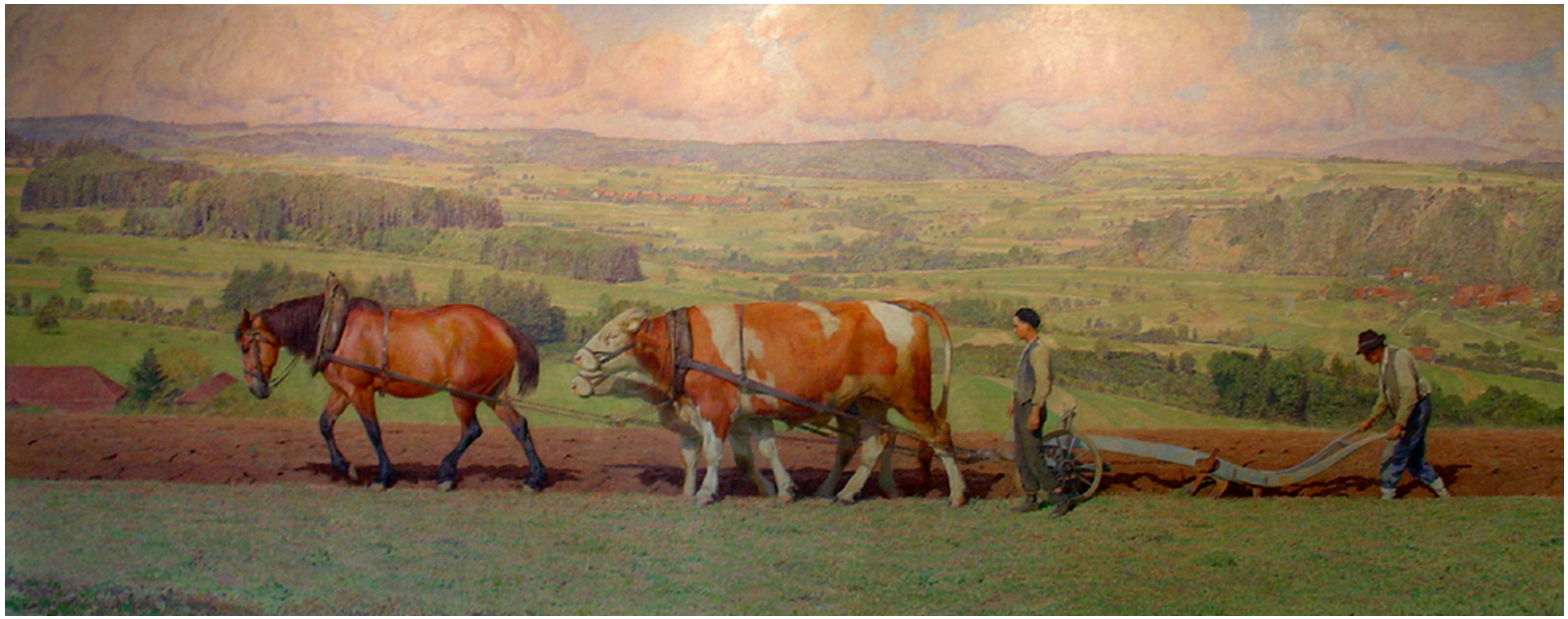
Mathieu/Collin dynamometers
Private collection of J.-F. Loude

From about 1860, Mathieu sold a smaller version for the Regnier's dynamometer, also made by Collin. Recommended by Hammond and Broca, it was widely adopted for medical and para-medical use. The "Collin dynamometer" is still available today (≈ EUR 125).

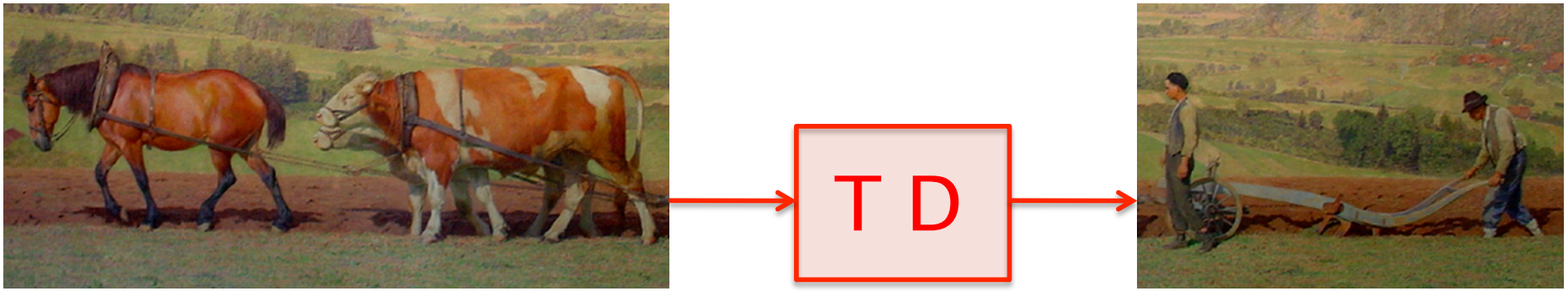


E. Claparède (1873-1940) in 1921
www.notrehistoire.ch

II. Mechanical work measurement



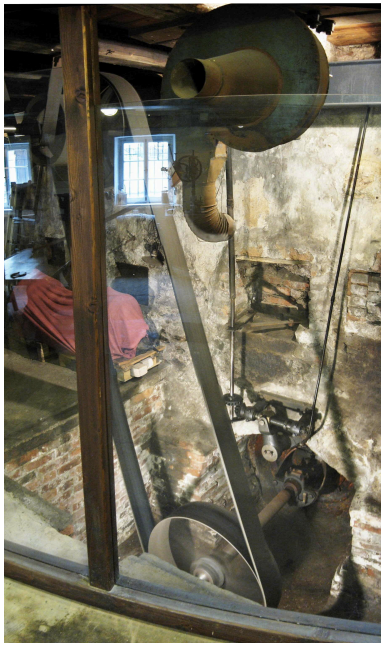
Eugène Burnand : Le Labour dans le Jorat (1916) — Musée Eugène Burnand, Moudon (Switzerland)



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



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)

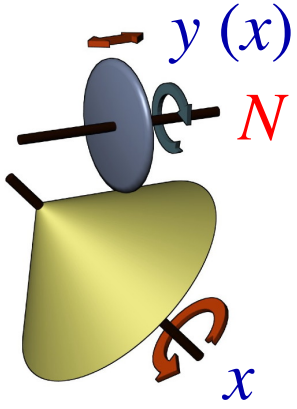
- Linear motion : work W is the product of force F by space x
- Rotary motion : work W is the product of torque τ by rotation angle ϑ
  power P is the product of torque τ by rotation rate ω

- 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 of Planimeters & Integrators

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

Adapted from Drechsler & Haeberlin (2011)



Cone and wheel integrator

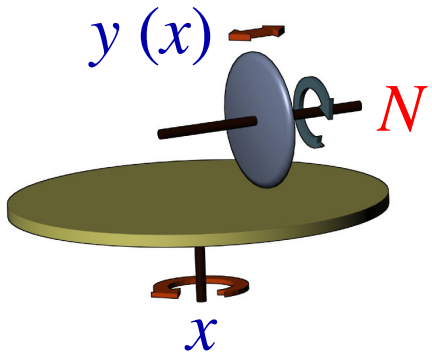
Count the number N of turns made by the sliding wheel :

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

Dynamometer :

$x \propto x$ or ϑ

$y \propto F$ or τ



Disk and wheel integrator

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

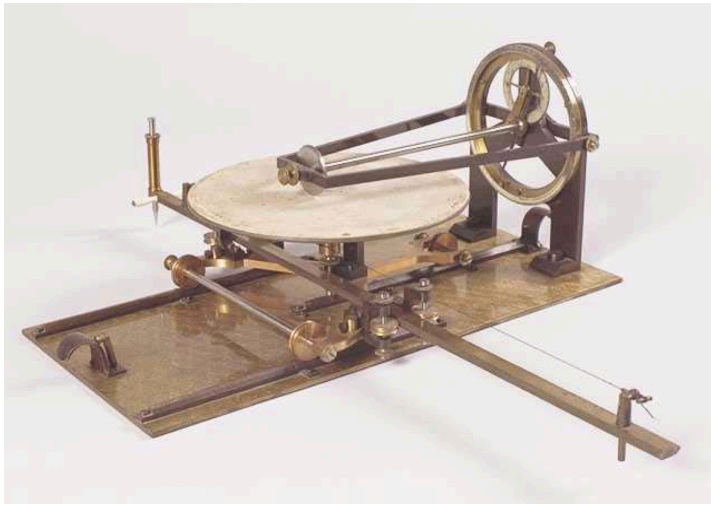
Cone and wheel planimeters were invented independently several times:

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)

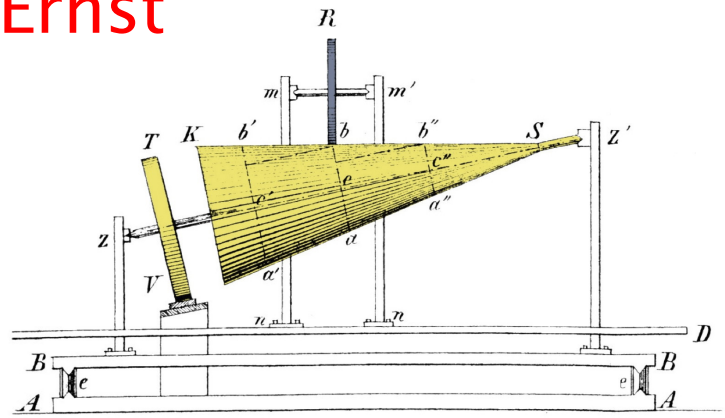


Uni Delft through Savoysky (2002)

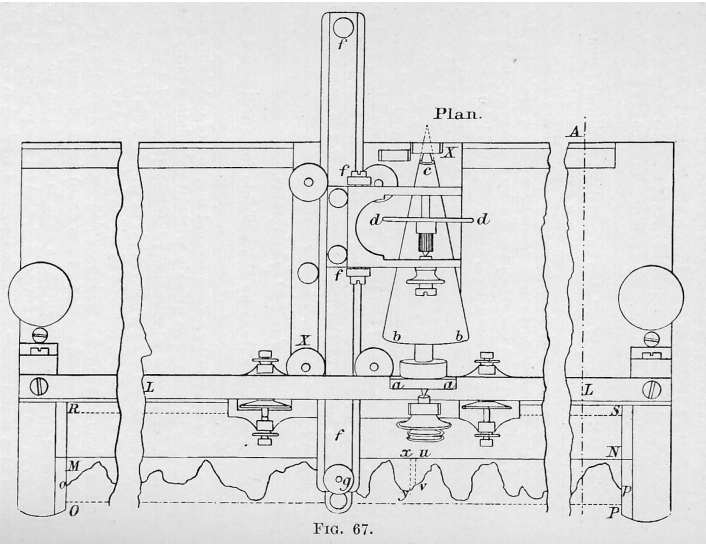
Ca. 1850 : First disk and wheel planimeter by C. Wetli in Switzerland

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.

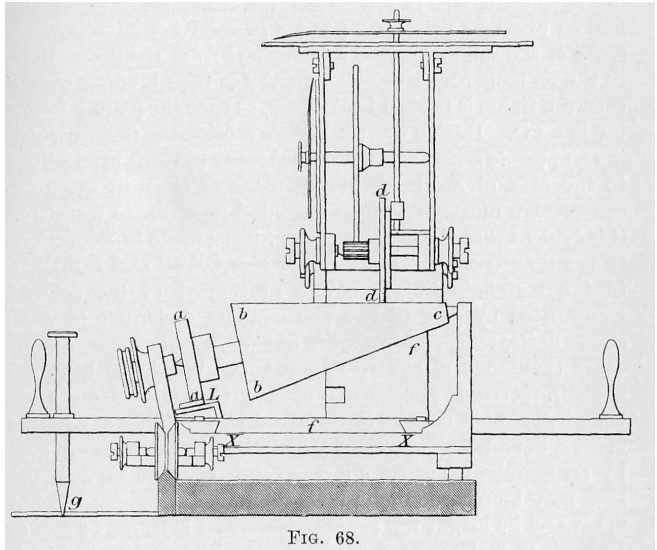


Drechsler & Haeberlin (2011) from Bauernfeind (1853)

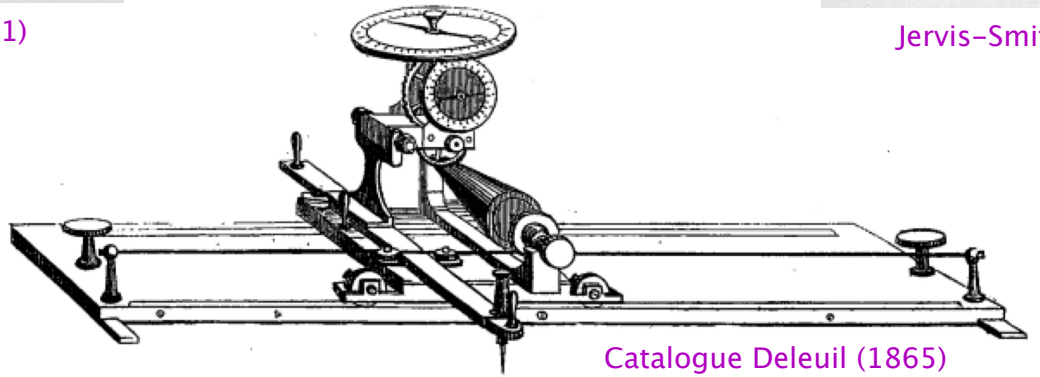


Jervis-Smith (1915) from Morin (1841)

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



Jervis-Smith (1915) from Morin (1841)

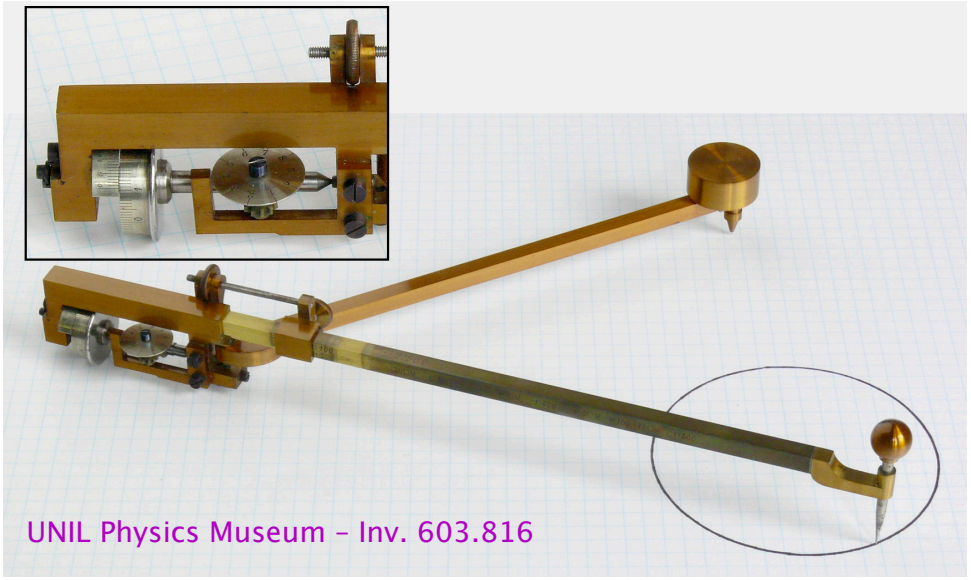


Catalogue Deleuil (1865)

Planimeters & Integrators (after 1851)

1851 : The Great Exhibition at Crystal Palace (London)

First opportunity to compare the instruments and machines off all countries

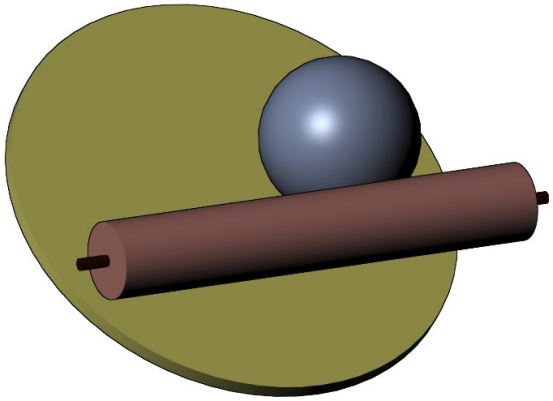


1854 : Jakob Amsler's Polar planimeter : simple, "cheap", for every surveyor and engineer.

Hugely successful!

An improved version is still manufactured.

The sliding motion of the wheel limits the precision. How to suppress it ?

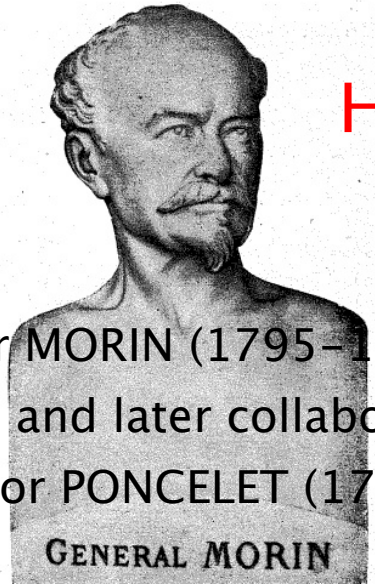


Drechsler & Haeberlin (2011)

1875 : James Thomson (brother of William) invents the Disk, Ball and Cylinder integrator.

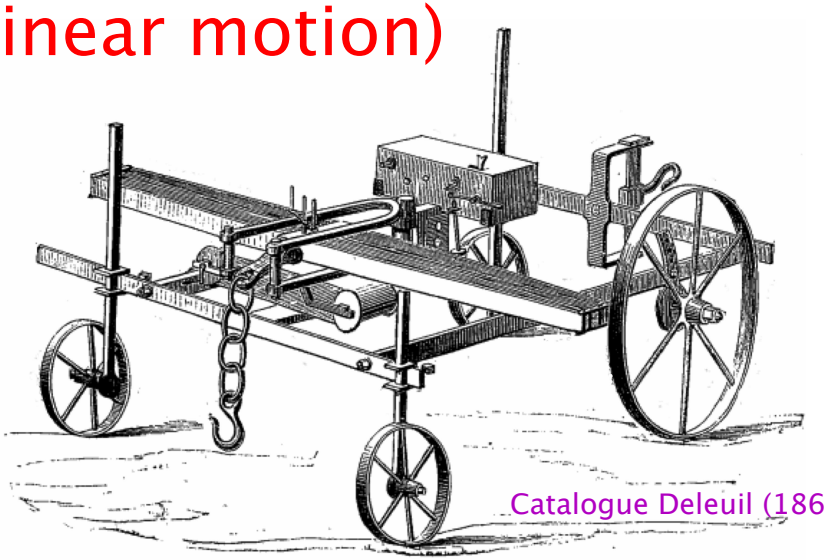
It opens the way to scientific analog computers.

Back to dynamometers:
Horse & Plough (linear motion)



Arthur MORIN (1795–1880) :
student, and later collaborator, of
Jean-Victor PONCELET (1788–1867)

CNAM (1905) – Mécanique



Catalogue Deleuil (1865)

He adopts the "Poncelet Dynamometer",
with 2 plano-parabolic steel strips

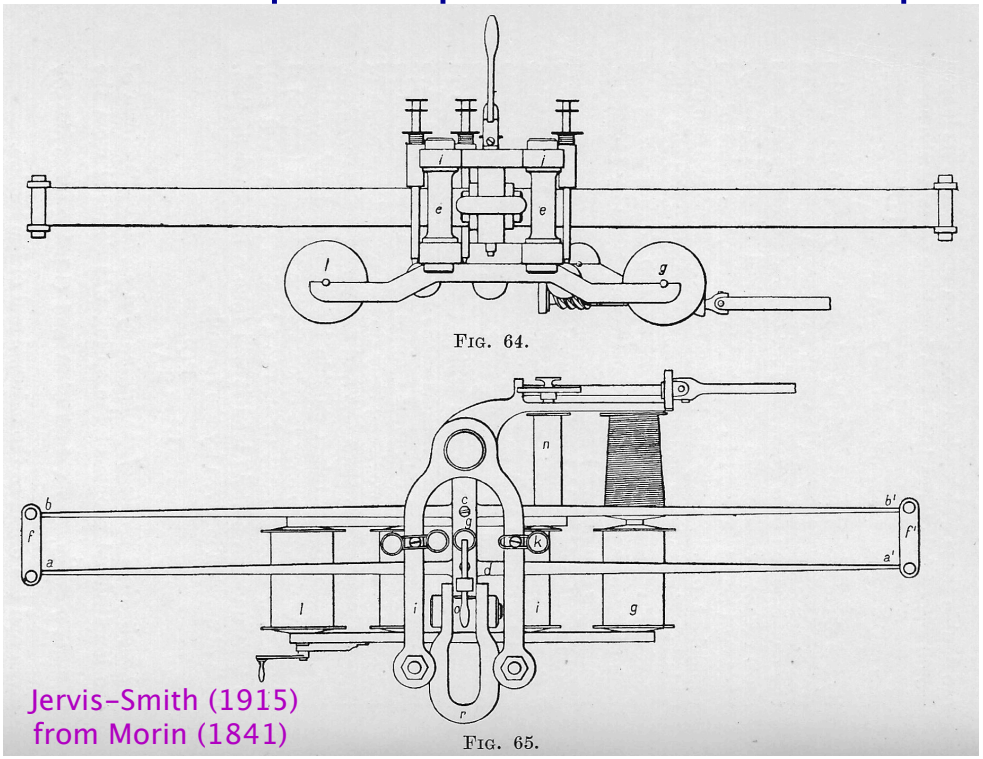
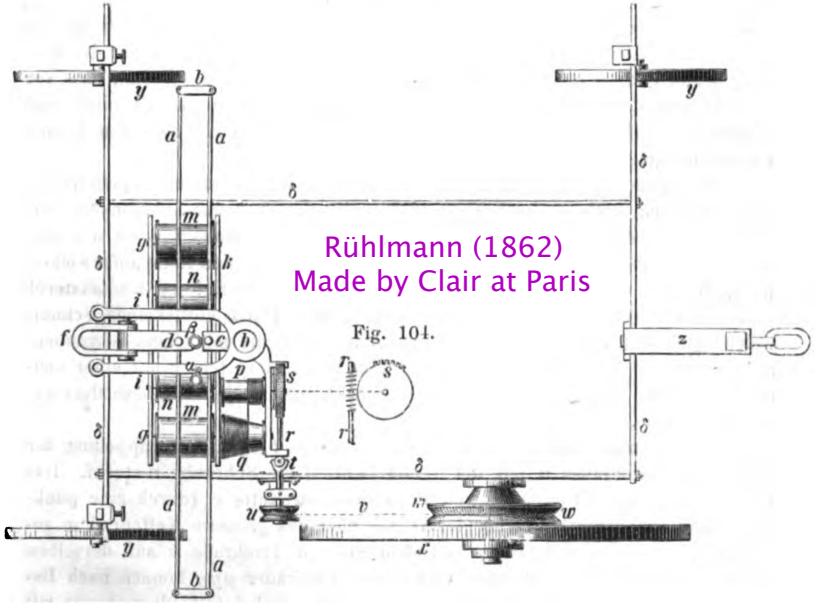


FIG. 64.

FIG. 65.

Jervis-Smith (1915)
from Morin (1841)



Rühlmann (1862)
Made by Clair at Paris

Fig. 104.

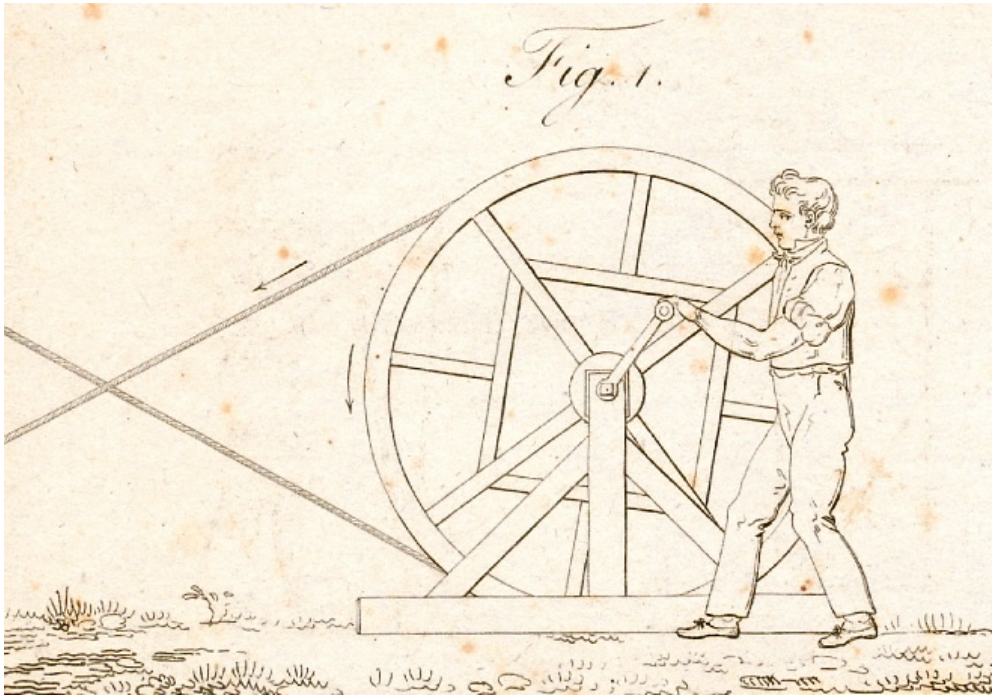
F vs. x : pen recording on a paper roll

$\Rightarrow$

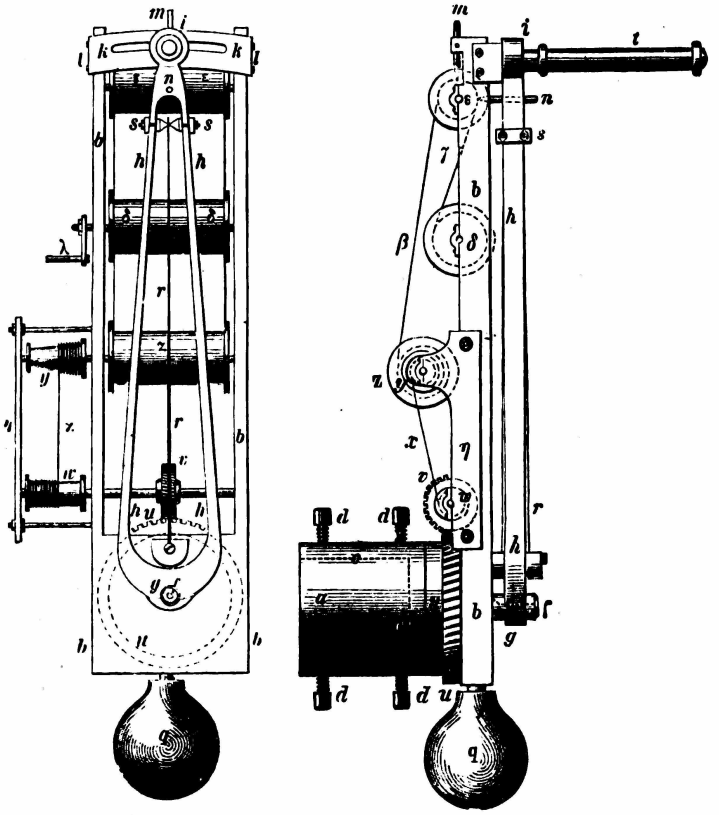
W : integration by Ernst planimeter

Dynamometric Crank (rotary motion)

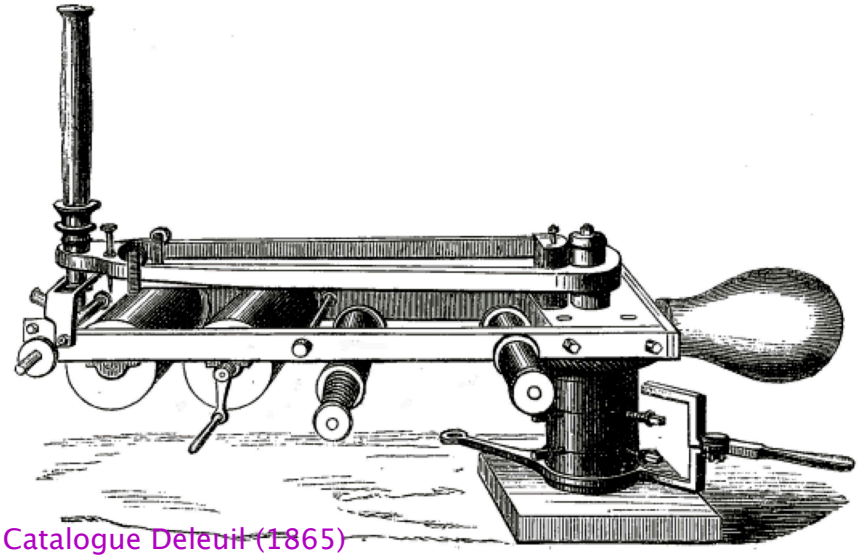
What is the mechanical work done by a man turning a crank ?



According to Christian (1822–25), one of the 9 ways to get rotary work from a man



Rühlmann (1862)



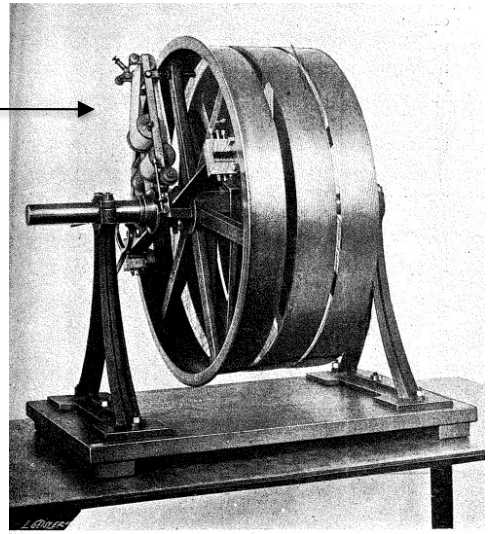
Catalogue Deleuil (1865)

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

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

Pulley *A* receives the belt coming from the motor, pulley *B* drives the machinery under test through a second belt. A spring is inserted between pulley *B* and the shaft. *C* is an loose pulley, for start and stop.

Paper strip recorder (τ vs. ϑ)



CNAM (1905) – Mécanique

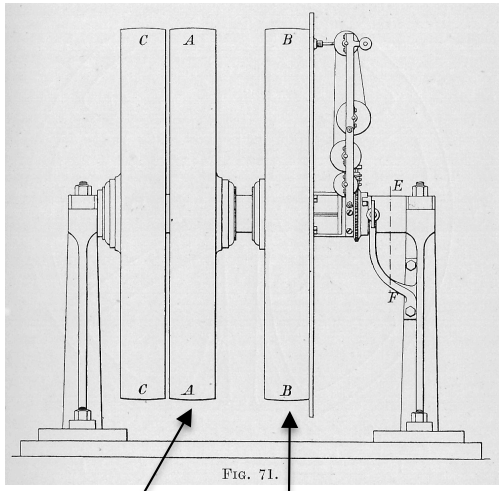


Fig. 71.

Motor belt

Load belt

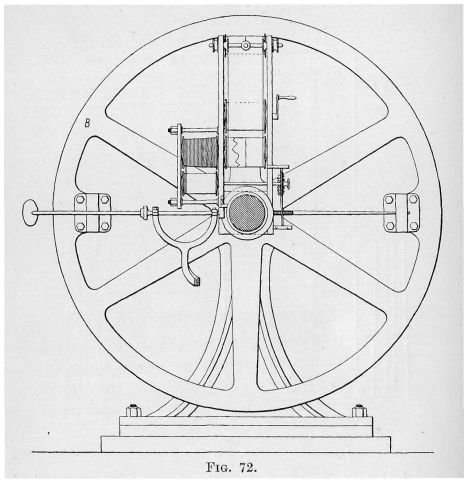
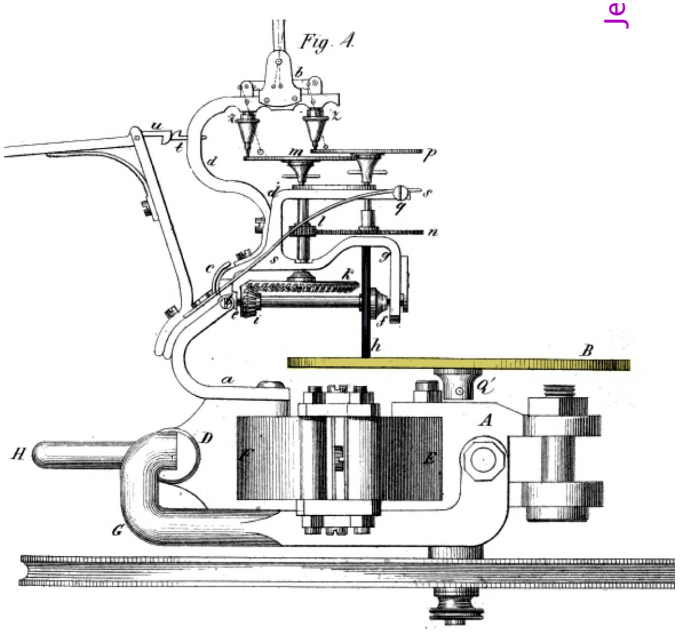


Fig. 72.

Jervis-Smith (1915) from Morin (1841)

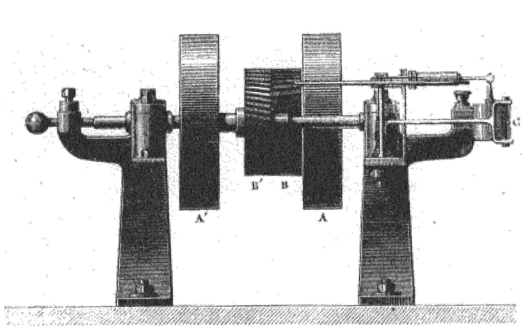


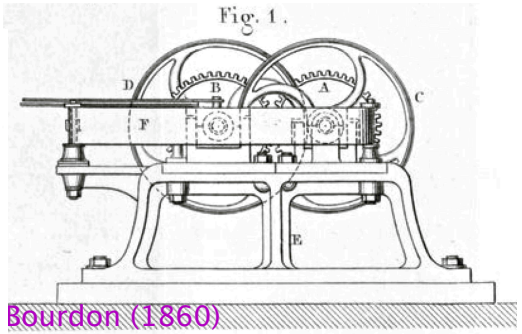
Drechsler & Haeberlin (2011) from Morin (1837)

The *paper strip pen recorder* can be replaced by a *disk-and-wheel integrator*, that directly totalizes the work done during the test.

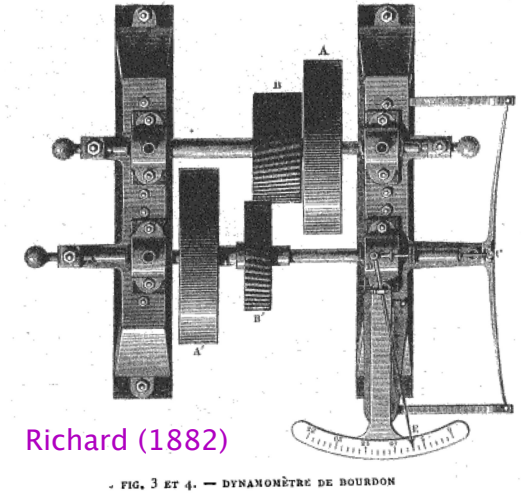
In both case the recording device / totalizer is rotating with the pulleys!

Belt and Pulley drive — II. Further developments



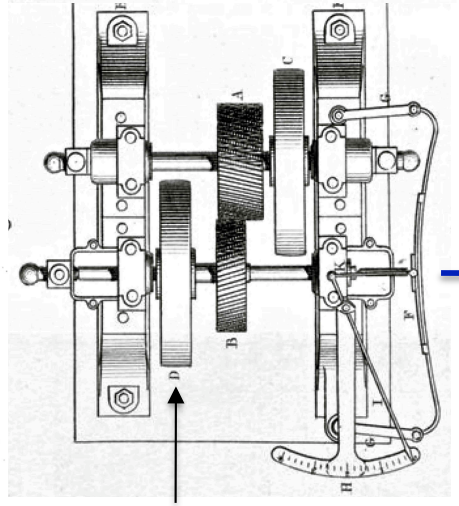


Bourdon (1860)



Richard (1882)

FIG. 3 ET 4. — DYNAMOMÈTRE DE BOURDON



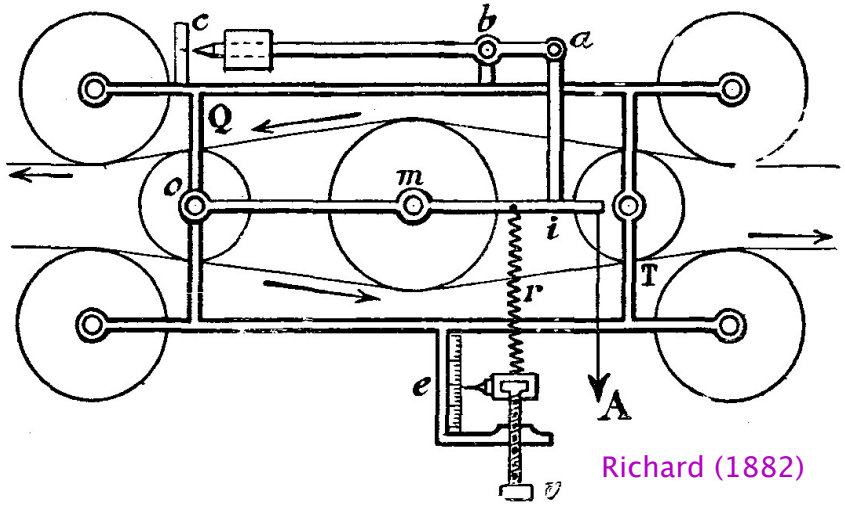
$\rightarrow F$

Motor belt

Bourdon dynamometer (1860):
Helical gears generate
an *axial force* F proportional to
the transmitted torque.
Dial not moving!

Von Hefner-Alteneck (Siemens)
dynamometer (ca. 1880) measures the
difference between the tensions on the
leading side and on the trailing one of
the belt.

Only one belt !



Richard (1882)

Shaft drive (rotary motion)

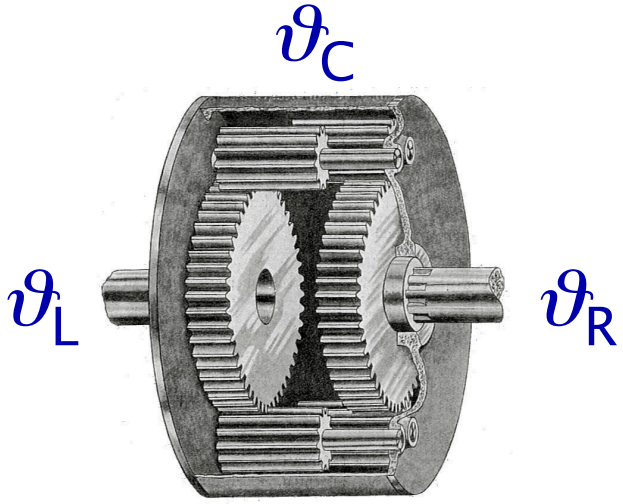
How to transmit the torque exerted on a rapidly rotating shaft to a *stationary* measuring/recording device ?

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

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)

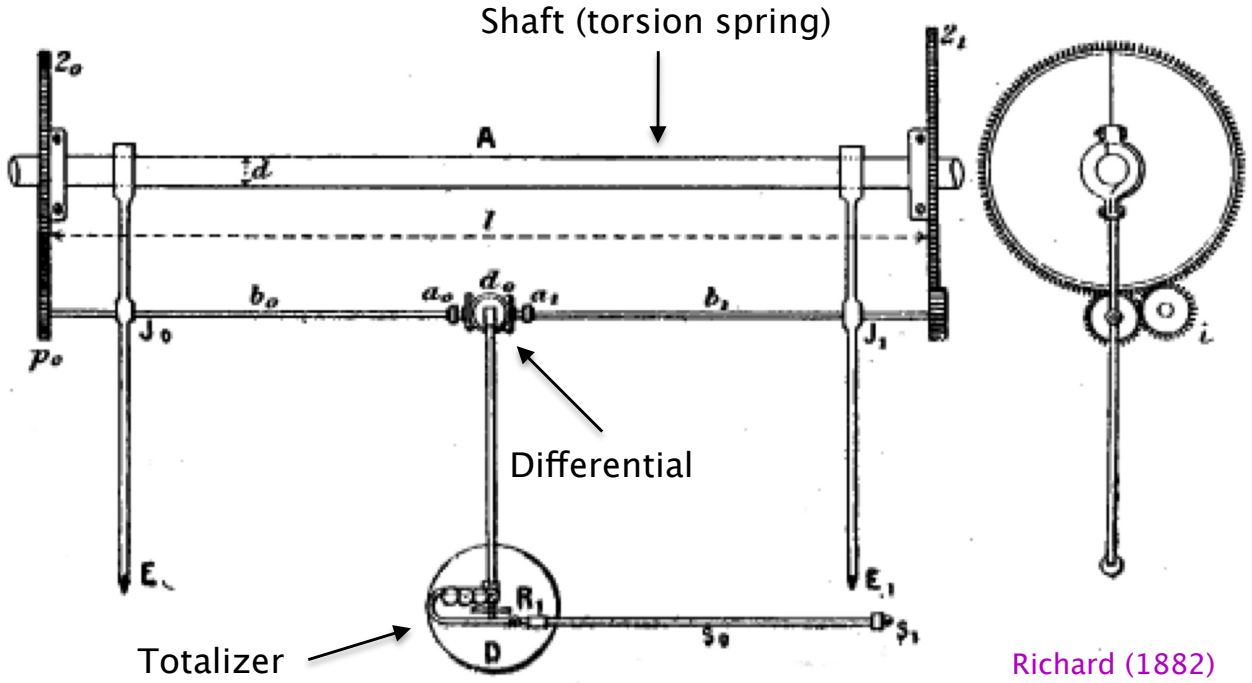


en.wikimedia – Differential

Example :

"Pandynamomètre"

de G. A. Hirn (1867)



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), Jervis-Smith (1915), …

More than 50 dynamometers of all times and types are stored at the "Musée du CNAM", near Paris. No images are available…

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 (heat).

¡ Thank you for your attention !

Mise en œuvre d'un dynamomètre de Régnier

Aquarelle exécutée pour le Conservatoire par Dronord [46,5 cm x 63 cm]; vers 1798

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