“I think I would better satisfy my desire by working on an English book on artillery”
Euler’s work on ballistics
(and its precursors)

June Barrow-Green

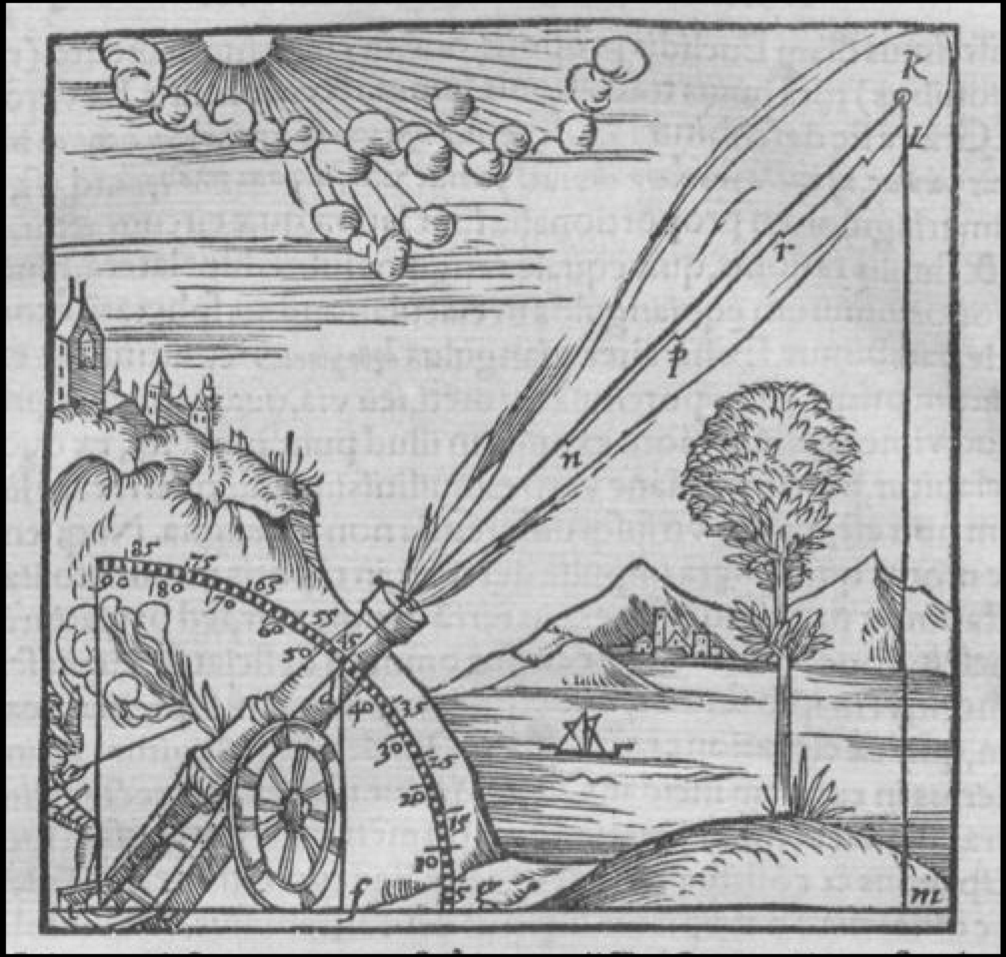
The Open University

‘Mathematics in War and Peace’
BSHM and Gresham College
24 October 2018

Aristotle's theory of projectile motion

A shot object (cannon ball) follows a straight line until it loses its impetus at which point it falls straight to the ground.

Daniel Santbech
Problematum Astronomicorum et Geometricorum Sectiones Septem
(1561)



Niccolò Fontana (1499–1577)
‘Tartaglia’ (the stammerer)

1512 Wounded by French soldier

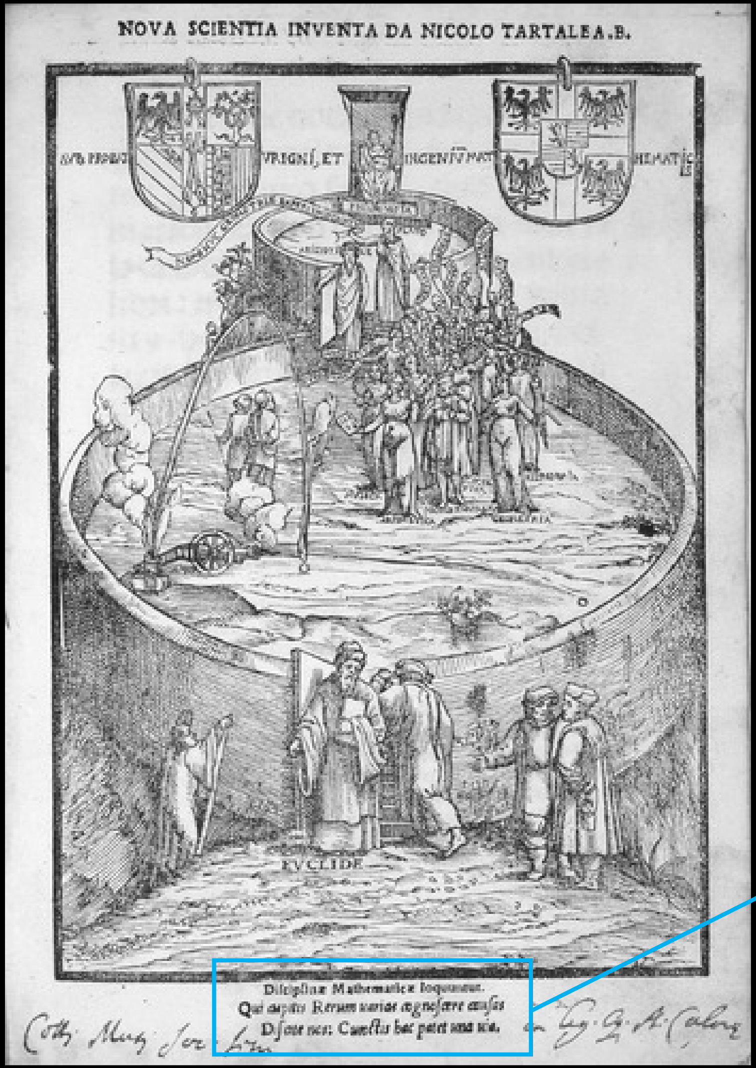
1535 Won a mathematics challenge by being able to solve two types of cubic equation

1537 *La nova scientia*

1543 First Italian edition of Euclid’s *Elements*

1556-60 *Trattato di numeri et misure,* 3 vol. “Treatise on Numbers and Measures”

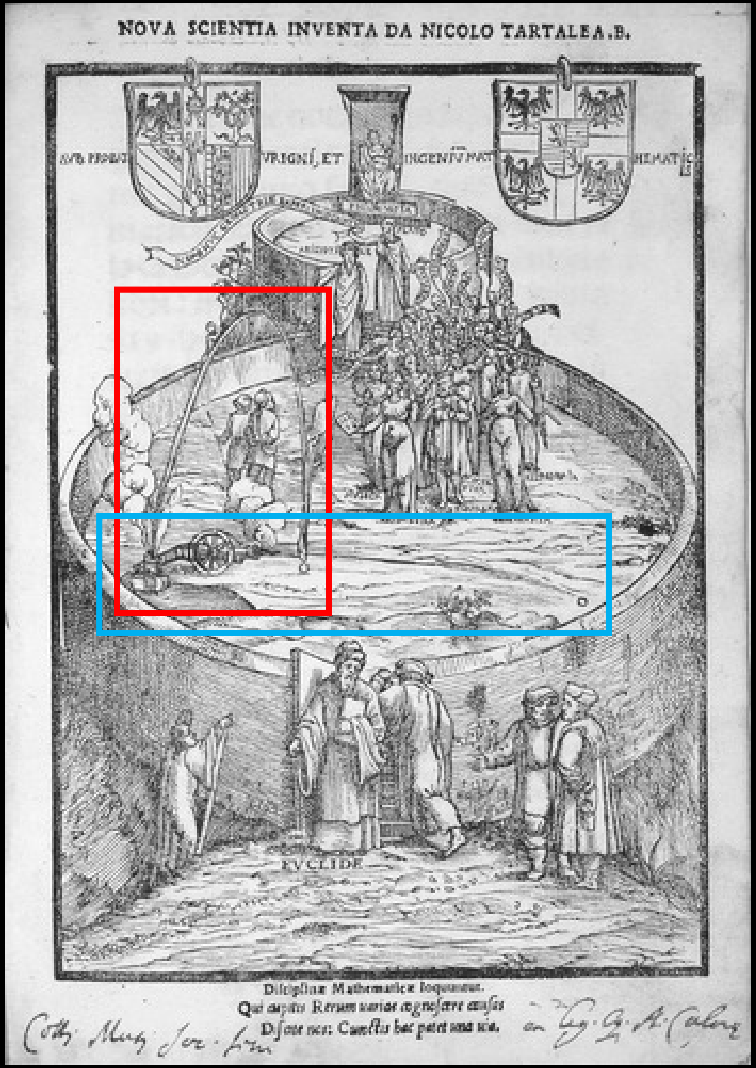
La nova scientia (1537)

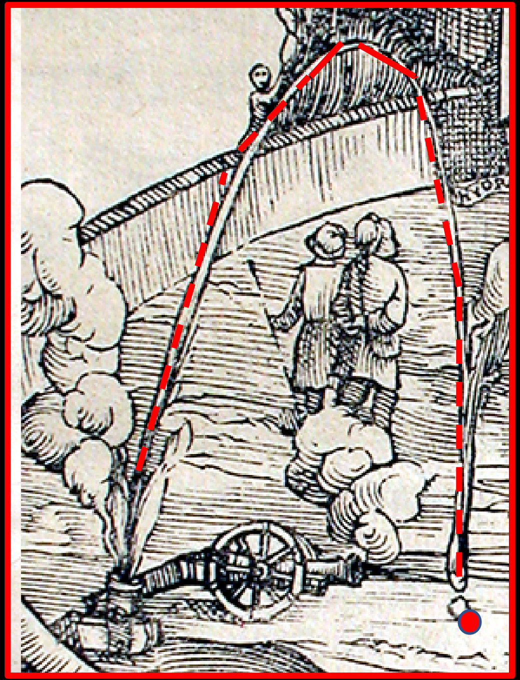


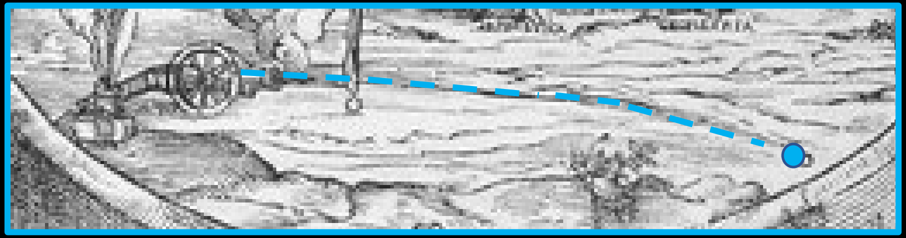
"The mathematical sciences speak:

> Who wishes to know the various causes of things, learn about us. The way is open to all."

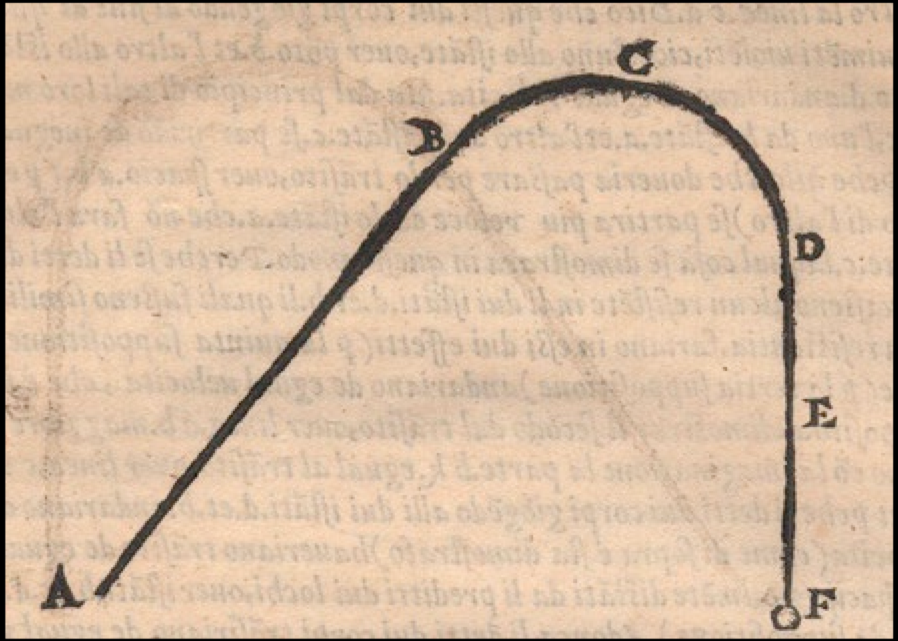
La nova scientia (1537)







La nova scientia (1537)



Trajectory composed of three segments:

Violent motion

(i) rectilinear segment

(ii) an arc of circumference

Natural motion

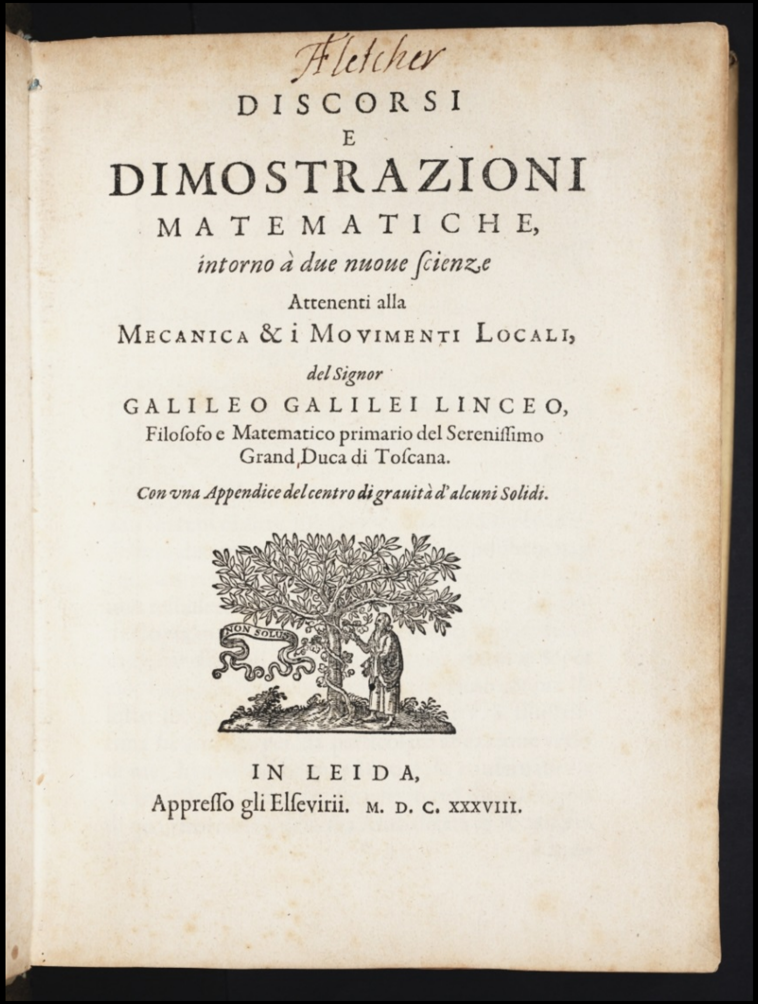
(iii) rectilinear segment turning towards the centre of the Earth.

Claimed maximum range is attained when angle of elevation is 45^{o}.

Galileo Galilei (1564–1642)

The Dialogues of the Two New Sciences (1638)

Includes inclined plane experiment to determine the path of a projectile



Fletcher

DISCORSI
E
DIMOSTRAZIONI
MATEMATICHE,
intorno à due nuoue ſcienze
Attenenti alla
MECANICA & i MOVIMENTI LOCALI,
del Signor
GALILEO GALILEI LINCEO,
Filoſofo e Matematico primario del Sereniſſimo
Grand Duca di Toſcana.
Con vna Appendice del centro di grauità d'alcuni Solidi.

NON SOLUS

IN LEIDA,
Appreſſo gli Elſevirii. M. D. C. XXXVIII.

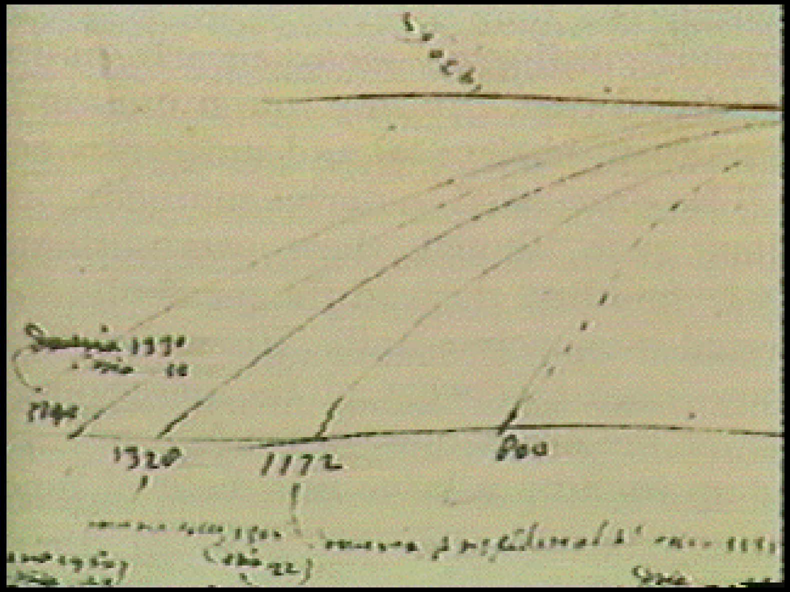
Galileo’s experiment to determine projectile motion

Galileo placed an inclined plane on a table and provided it with a curved piece at the bottom which deflected an inked bronze ball into a horizontal direction.

The accelerated ball rolled over the table-top with uniform motion and then fell off the edge of the table.

Where the ball hit the floor, it left a small mark. The mark allowed the horizontal and vertical distances travelled by the ball to be measured.

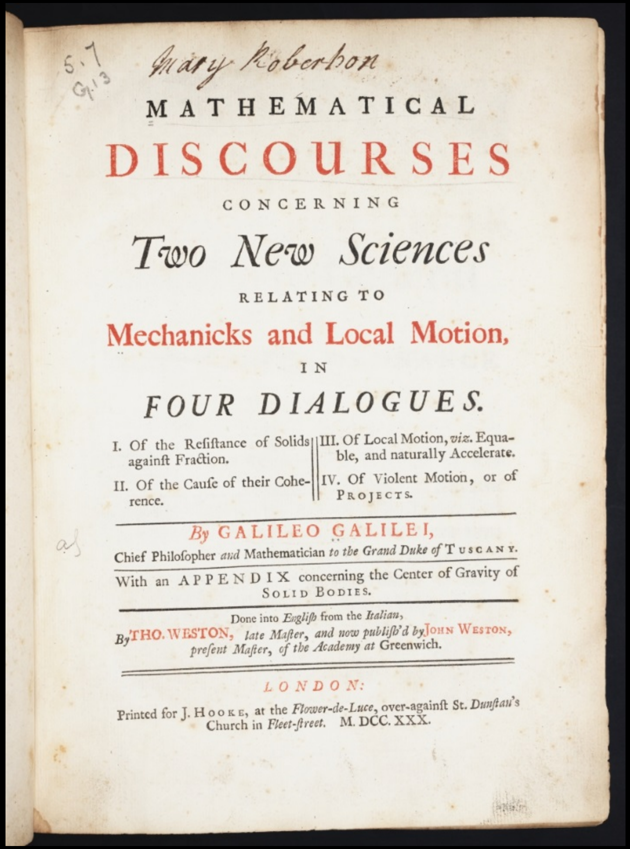
By varying the ball's horizontal velocity and vertical drop, Galileo determined that the path of a projectile is parabolic.



A page from Galileo’s notebooks describing projectile motion

Parabolic trajectory sufficiently accurate for heavy mortar shells fired at low velocity

"This excessive *Impetus* of Projects, thrown with such Violence, may cause some Irregularity in the Path of the Project; by making the parabolic lines less inclin'd, or curv'd at its Beginning than at its End; but this can be of little or no Prejudice to our Author in practical Operations: Amongst which the Chief is the Composition of a Table of Ranges, which contains the Distances Balls are flung to at every different Elevation; and because such Projections or Shots are made with Mortars, by Help of a small Quantity of Powder; in these, the *Impetus* not being supernatural, the Projects describe their Paths exactly enough." **(p.390)**

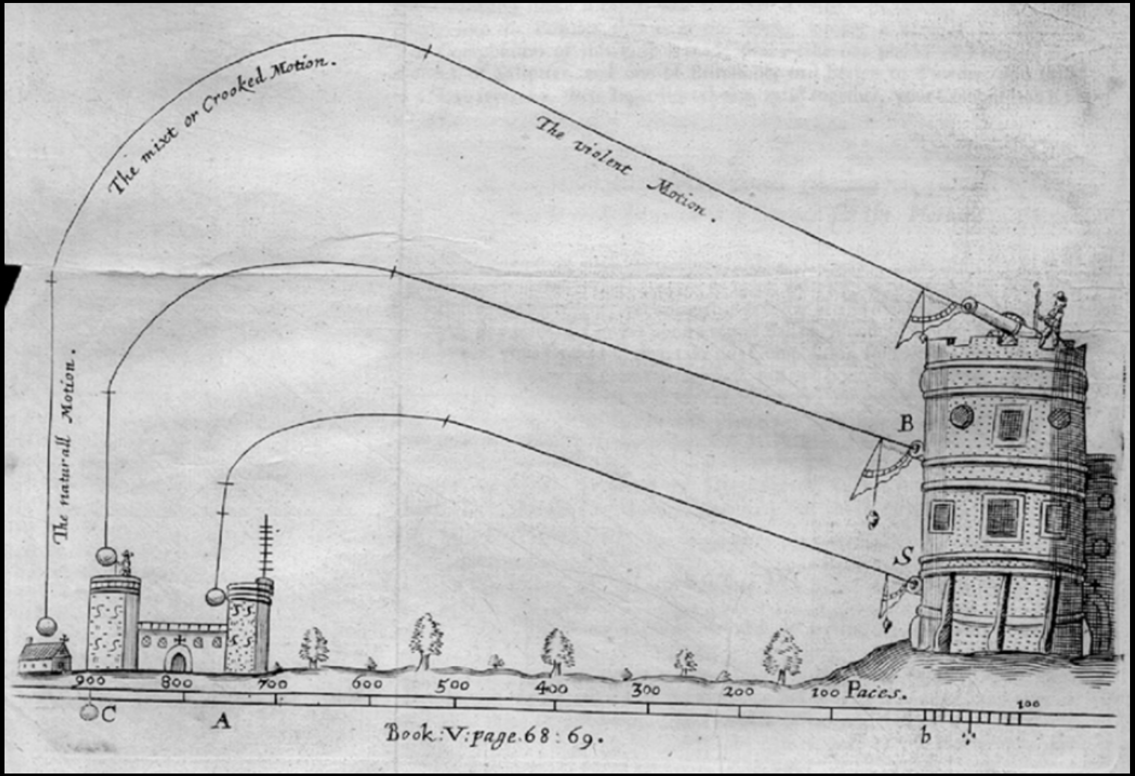


English translation (1730)

Galileo understood the effects of air resistance - deforms parabolic trajectory at high velocity but negligible at low velocity.

Samuel Sturmy *The Mariner's Magazine* (1669)

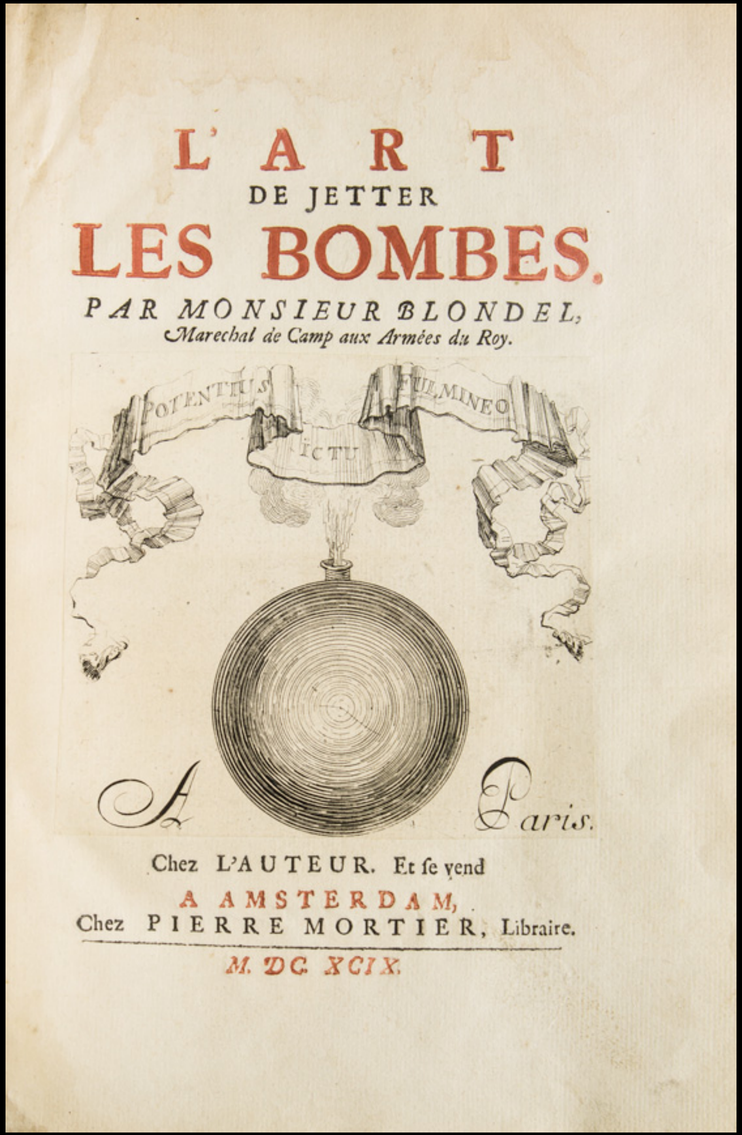
The concept of 3-part motion for a projectile moving through air persisted after Galileo.

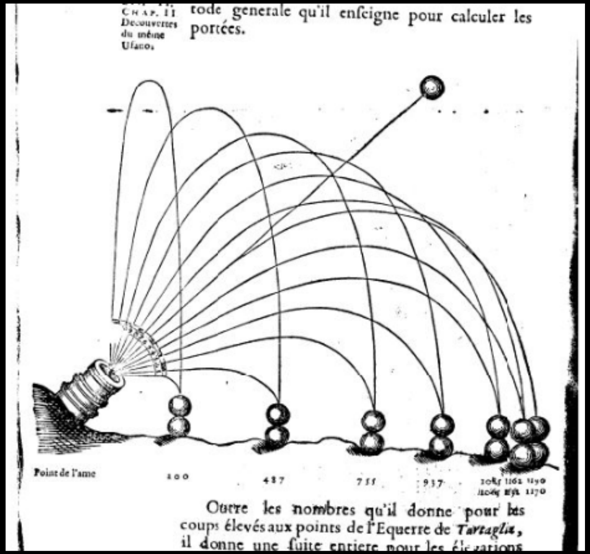


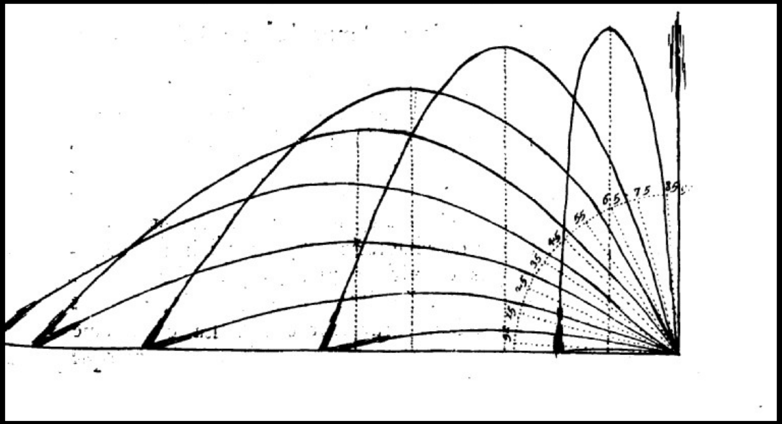
Incorporating the effects of air resistance on the motion of a projectile, with its observed trajectory, proved problematic.

Nicholas François Blondel

L'art de jetter les bombes (1669)







Benjamin Robins (1707-1751)

'transformed ballistics into a Newtonian science'

1707 b. Bath

c.1725 Moved to London to study with Henry Pemberton

1727 Fellow of the Royal Society

1742 *New Principles of Gunnery*

1746 Royal Society Copley Medal

On account of his curious Experiments for showing the resistance of the Air, and his rules for establishing his doctrine thereon for the motion of Projectiles

1749 Appointed Engineer General of the East India Company

1750 Arrived Fort David, India

1751 d. India

Pemberton edited 3rd edition of Newton's *Principia* (1726)

New Principles of Gunnery (1742)

"A beautiful example of the scientific method"

Preface (57 pp)
Cites many earlier authors including Tartaglia, Galileo …

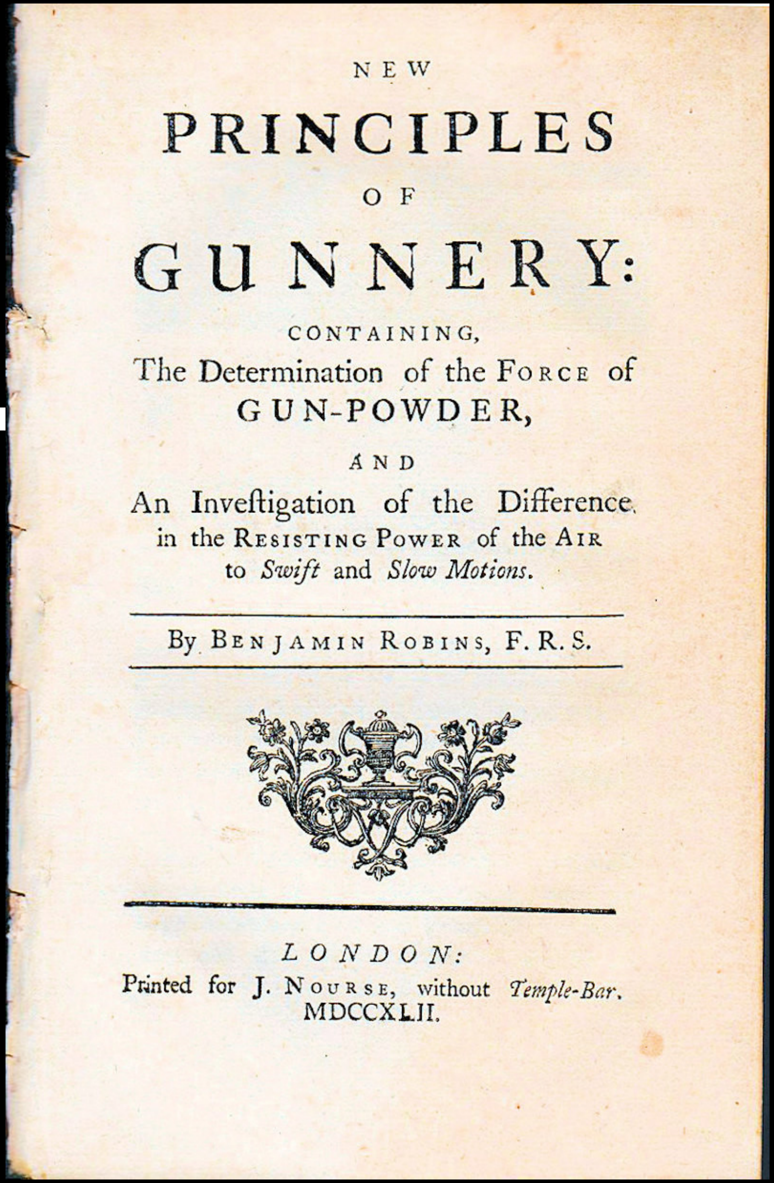
1. *On the Force of Gunpowder* (65 pp)

   [Interior Ballistics]

2. *Of the Resistance of the Air, and of the Track described by the Flight of Shot and Shells* (30 pp)

   [Exterior Ballistics]

Gives a series of propositions which form a model for ballistic theory; tests the model's predictions against experiment.



NEW
PRINCIPLES
OF
GUNNERY:
CONTAINING,
The Determination of the FORCE of
GUN-POWDER,
AND
An Inveſtigation of the Difference
in the RESISTING POWER of the AIR
to *Swift* and *Slow Motions*.

By BENJAMIN ROBINS, F.R.S.

LONDON:
Printed for J. NOURSE, without *Temple-Bar*.
MDCCXLII.

The need to understand air resistance

PROP. VI.

The Track described by the Flight of Shot or Shells is neither a Parabola, nor nearly a Parabola, unless they are projected with small Velocities.

FOR we have determined, in the fourth proposition of the present chapter, that a musket-ball $\frac{3}{4}$ of an inch in diameter, fired with half its weight of powder, from a piece 45 inches long, moves with a velocity of near 1700 feet in 1″. Now, if this ball flew in the curve of a parabola, its horizontal range at 45° would be found, by the fifth postulate, to be about 17 miles. Now all the practical writers assure us, that this range is really short of half a mile. *Diego Ufano* assigns to an

For a particular shot, parabolic theory predicts range of ‘about 17 miles’; actual range ‘short of half a mile’

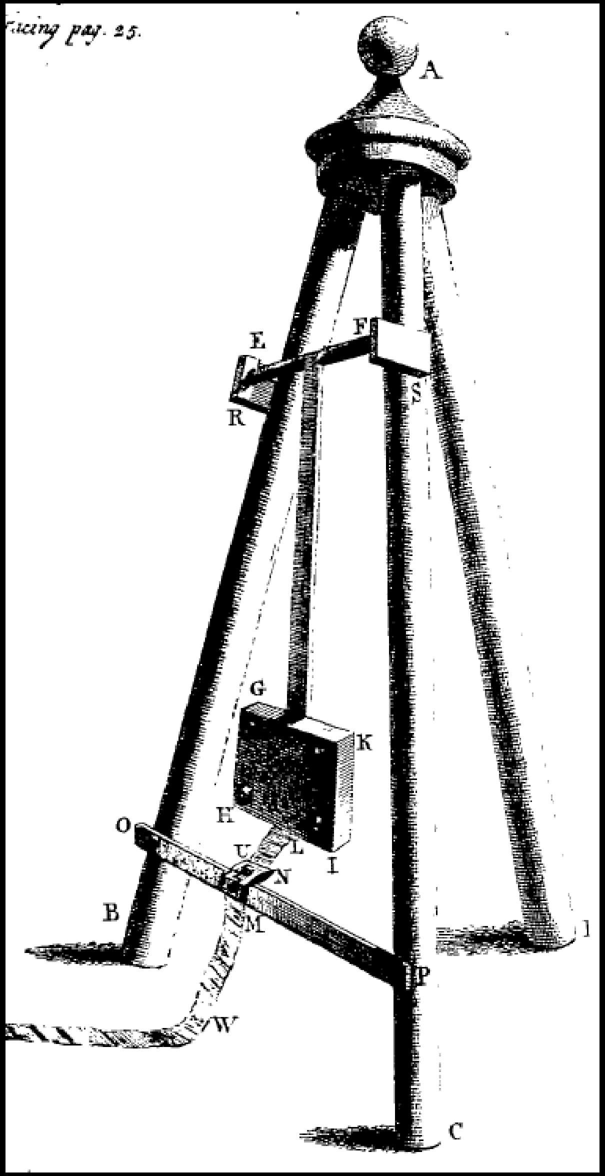
Robins’ Ballistics Pendulum

Uses Newton’s mechanics & Huygens theory of the pendulum to:

- Calculate initial velocity of projectile
- Measure air resistance

“[Robins’s] method of finding the velocity of a ball by experiment is, without doubt, one of the most ingenious and useful discoveries in artillery. Whatever had been delivered on that subject before him, was not only uncertain but erroneous.”

Leonhard Euler

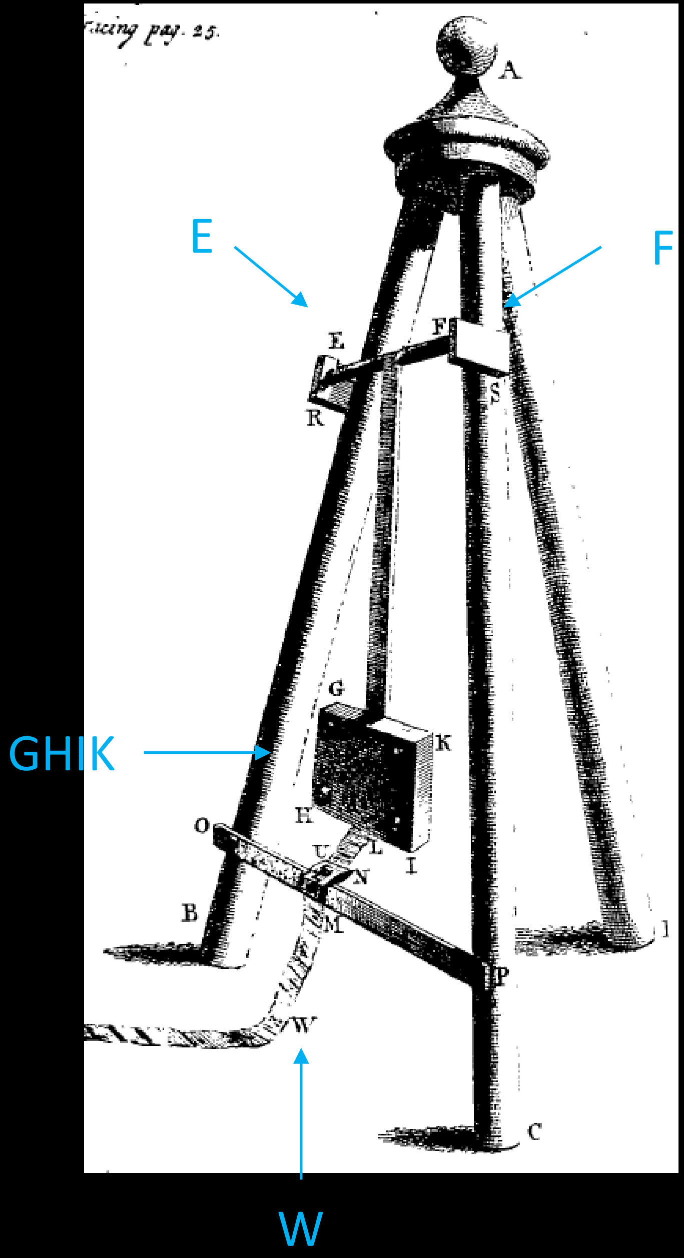


Robins’ Ballistics Pendulum

Projectiles are fired horizontally so that they strike the plate of wood GHIK causing it to swing back in an arc around the pivot EF

As the plate swings, it pulls a ribbon W through a slot in the mounting; the length of ribbon is equal to the length of the arc through which the plate swings.

Robins used this arc length to compute the vertical distance through which the plate had moved, and so compute the change in its gravitational potential energy.



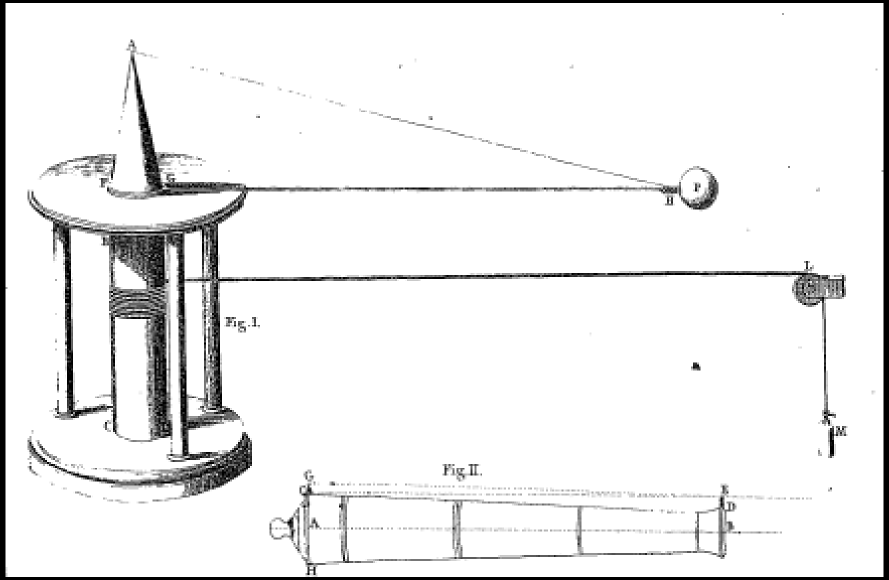
Robins' Whirling Arm (1746)

Different shaped objects mounted on the tip of the arm and spun in different directions.

The shape of the object affected the air resistance, or drag, even though equal total areas were being spun and exposed to the airstream.

Newton's theories did not adequately describe the complex relationship between drag, the shape and orientation of the object, and air velocity.

Experiments limited by speed of whirling arm (a few feet p/s).



The whirling arm was widely used in aeronautical research until the development of the wind tunnel towards the end of the 19th century.

Air resistance

CHAP. II.

Of the Resistance of the Air, and of the Track described by the Flight of Shot and Shells.

BEFORE I more minutely discuss the subject of this chapter, it is necessary to premise, that the greatest part of authors have established it as a certain rule, that whilst the same body moves in the same medium, it is always resisted in the duplicate proportion of its velocity; that is, if the resisted body move in one part of its track with three times the velocity, with which it moved in some other part, then its resistance to the greater velocity will be nine times the resistance to the lesser. If the velocity in one place be four times the velocity in another, the resistance to the greater velocity will be sixteen times the resistance to the lesser, and so on. This rule, though excessively erroneous, (as we shall hereafter shew) when taken in a general sense, is yet undoubtedly very near the truth, when confined within certain limits;

"Greatest part of authors" have established that air resistance is "in the duplicate proportion of its velocity" but Robins will show that this is "excessively erroneous" except "when confined within certain limits".

Robins identifies the ‘Magnus effect’

PROP. VII.

Bullets in their Flight are not only depressed beneath their original Direction by the Action of Gravity, but are also frequently driven to the right or left of that Direction by the Action of some other Force.

Today this is known as the Magnus effect after the German physicist Gustav Magnus (1802–1870) who investigated aerodynamic forces on spinning spheres in 1852.

Leonhard Euler (1707-1783)

1707 b. Basel
1721 University of Basel

1727 St Petersburg Academy
1733 Chair of Mathematics

1741 Berlin Academy

1766 St Petersburg
1783 d. St Petersburg

Euler's works: Theory of numbers; musical harmony; infinite series; logarithms; complex numbers; calculus, mechanics; astronomy; lunar theory; wave motion; stability of sailing ships; ballistics, ...

Euler's works on ballistics

1727 'Meditatio in experimenta explosione tormentorum nuper instituta'
[Meditation on experiments made recently on the firing of a canon]

1745 *Neue Grundsätze der Artillerie*

1753 'Recherches sur la véritable courbe que décrivent les corps jetés dans l'air, ou dans un autre fluide quelconque'

‘Meditatio in experimenta explosione tormentorum nuper instituta’ (1727)

[Meditation on experiments made recently on the firing of a canon]

Although not published until 1862, famous for being the first paper to employ ‘e’ to represent base of natural logs.

Written at the end of 1727 or beginning of 1728, when Euler was just 21 years old. Describes seven experiments performed 21 August - 2 September 1727 (probably performed by Daniel Bernoulli).

Aim was to measure accurately the speeds, as transmitted through the air, of the flash and sound of cannon shot.

Scribatur pro numero cujus logarithmus est unitas, e, qui est 2,7182817... cujus logarithmus secundum Vlacq. est 0,4342944. Indicat porro N numerum graduum arcus, cujus tangens est:

$$\sqrt{e^{\frac{3nx}{4mc}} - 1}$$

existente sinu toto $= 1$. Altitudo quesita x, ex hac aequatione erui debet:

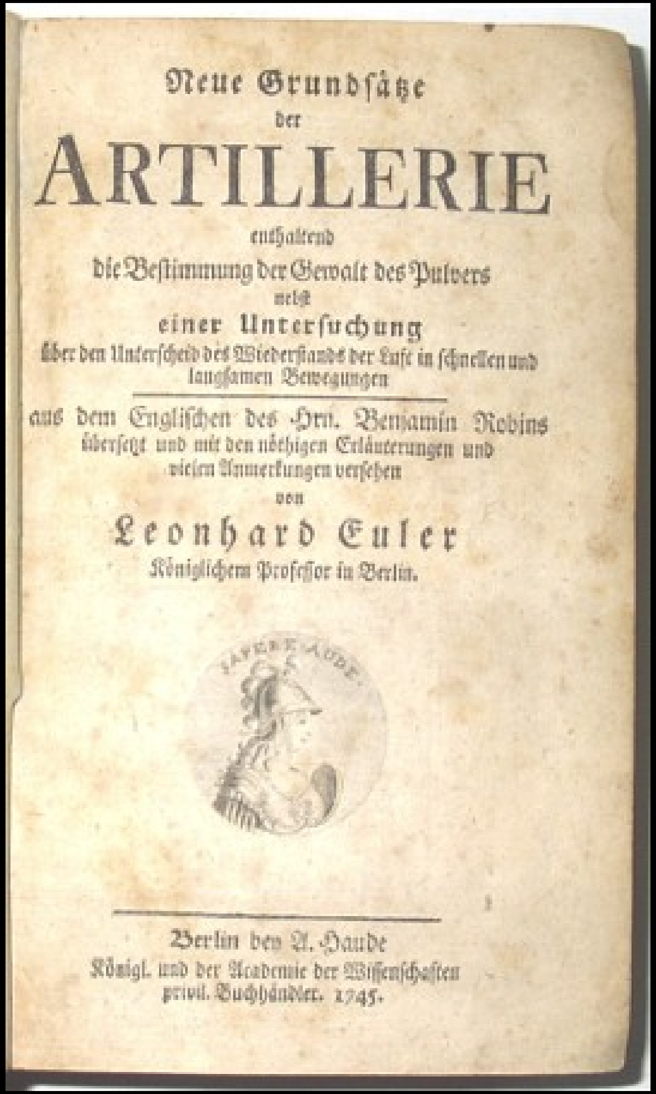
$$t = \frac{m\sqrt{c}}{447650\sqrt{3n(m-n)}}\left(125N - 7162\log.\left(\sqrt{e^{\frac{3nx}{4mc}}} - \sqrt{e^{\frac{3nx}{4mc}} - 1}\right)\right).$$

Letter from Euler to Frederick the Great (1744)

"My infinite desire to serve Your Majesty has made me want to apply my strength to a science which could have some important utility for the service of Your Majesty. But as the research requires a lot of experiments and I do not find myself in a position to undertake such work, I think I would better satisfy my desire by working on an English book on artillery, which has recently appeared. The author, who is called Robins, having made a large number of experiments, has fortunately deduced … how much the true velocity with which shells are fired and their motion are altered by air resistance.

Since this research can contribute much to the perfection of artillery, especially if one took the trouble to develop it better, and illuminate it fully, I judge that the public would be able to profit rather considerably, if I were to undertake to translate this work …"

Euler's *Neue Grundsätze der Artillerie* (1745)



Neue Grundsätze
der
ARTILLERIE
enthaltend
die Bestimmung der Gewalt des Pulvers
nebst
einer Untersuchung
über den Unterschied des Wiederstands der Luft in schnellen und langsamen Bewegungen
aus dem Englischen des Hrn. Benjamin Robins
übersetzt und mit den nöthigen Erläuterungen und vielen Anmerkungen versehen
von
Leonhard Euler
Königlichem Professor in Berlin.

SAPERE AUDE

Berlin bey A. Haude
Königl. und der Academie der Wissenschaften privil. Buchhändler. 1745.

- Euler received advice from Johann Bernoulli I and from Count von Schmettau.
- Written in German [supposedly] to be accessible to lower military officers.
- Five times as many pages as Robins' text!

Johann Bernoulli I

Artillery field marshal
Count Samuel von Schmettau

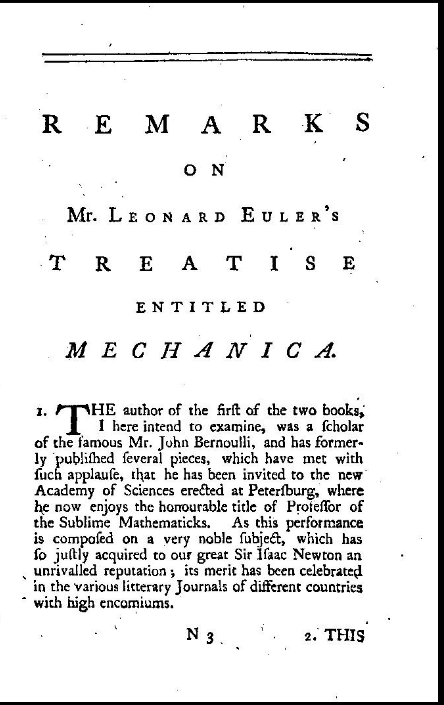
Robins’ critique of Euler and Euler’s critique of Robins

Robins (1739)

Robins unsparingly criticises Euler, e.g.

- “… [Euler] has unfortunately followed the principles of his calculus with so little caution, as even to contradict Euclide himself.”
- “The fourth chapter has affixed to it a very pompous title.”

And so on ….



REMARKS

ON

Mr. LEONARD EULER’S

TREATISE

ENTITLED

MECHANICA.

1. THE author of the firſt of the two books, I here intend to examine, was a ſcholar of the famous Mr. John Bernoulli, and has formerly publiſhed ſeveral pieces, which have met with ſuch applauſe, that he has been invited to the new Academy of Sciences erected at Peterſburg, where he now enjoys the honourable title of Profeſſor of the Sublime Mathematicks. As this performance is compoſed on a very noble ſubject, which has ſo juſtly acquired to our great Sir Iſaac Newton an unrivalled reputation; its merit has been celebrated in the various litterary Journals of different countries with high encomiums.

N 3 2. THIS

Euler (1745)

Euler critiques Robins (as well as praising him), e.g.

“[Robins’ account] appears to be so well grounded and conformable to the truth as not to admit of the least objection. But he must be either unacquainted with several books on the theory of artillery … or else he must have purposely passed over them in silence, in order to exalt the merit of his own discoveries.”

Euler endorses the use of fluxions for artillery purposes

"Some are of the opinion that fluxions are applicable only in such subtle speculations and can be of no practical use; or, at most, whatever conclusions can be obtained by them are owing to the well known lower parts of mathematics; but what has just been said of artillery is sufficient to remove this prejudice. It may be affirmed, that many things which depend on mathematics cannot be explained in all their circumstances without the help of fluxions ..."

Euler *Preface*

Euler acknowledges the difficulty of finding the true path of a cannon ball

“Here, again, Mr. Robins gives us farther expectations of discovering the real track of a cannon ball. It is some years since his book was published, and nothing more that I know of has appeared on the subject. This enquiry is so difficult, that the author was in the right to require a longer time to complete it.”

Euler *Chapter 2*

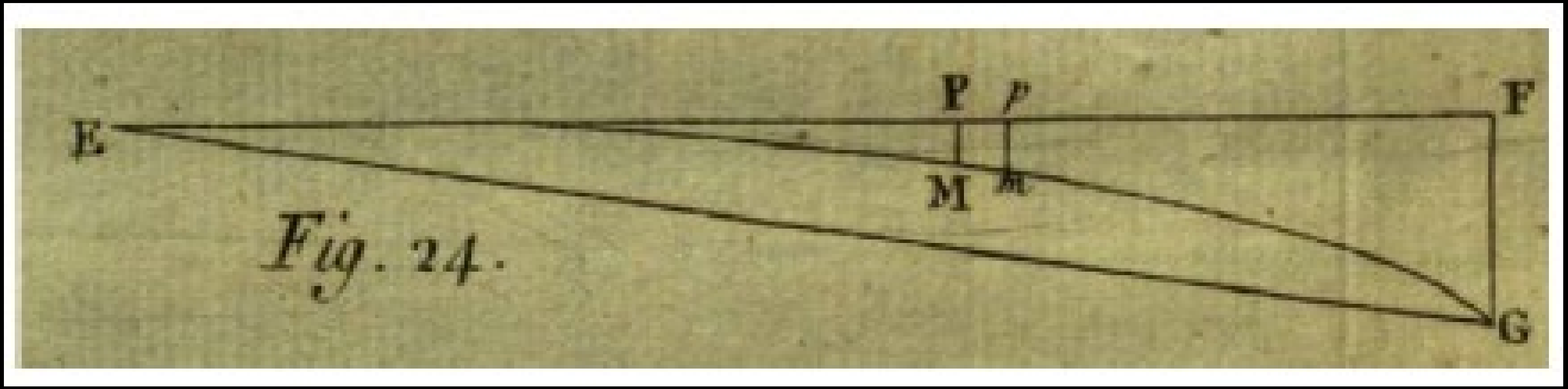
Euler's additions to Robins

Takes each of Robins' principles and erects on them his own new principles

- Corrects Robins' errors and criticises some of his assumptions, eg:
  - E thinks R's theorem for determining the velocity of the ball leaving the gun is "not … at all accurate". E additionally considers things such as gun length.
  - R originally assumed the blow of the ball against the pendulum passes through the centre of gravity of the board – this rarely happens.
    (*R corrected this in 1743 in Phil Trans RS but unknown to E*)

- Investigates several new topics, eg:
  - the theoretical strength of a gun barrel (early analysis of a pressure vessel)
  - the metal for gun barrels
  - structure of the cannon, the gun carriage platform and recoil
  - quality of gunpowder

Horizontal fire



Ball fired horizontally from E to F, where distance is not too great.

Ball falls to G, angle FEG very small.

Consider point P on EF and point M directly below it, to which the ball will fall as it moves from E towards P.

Want to find the time to reach point P; the angle through which the ball has fallen; and the velocity of the shot at P.

Euler's (eventual) solutions

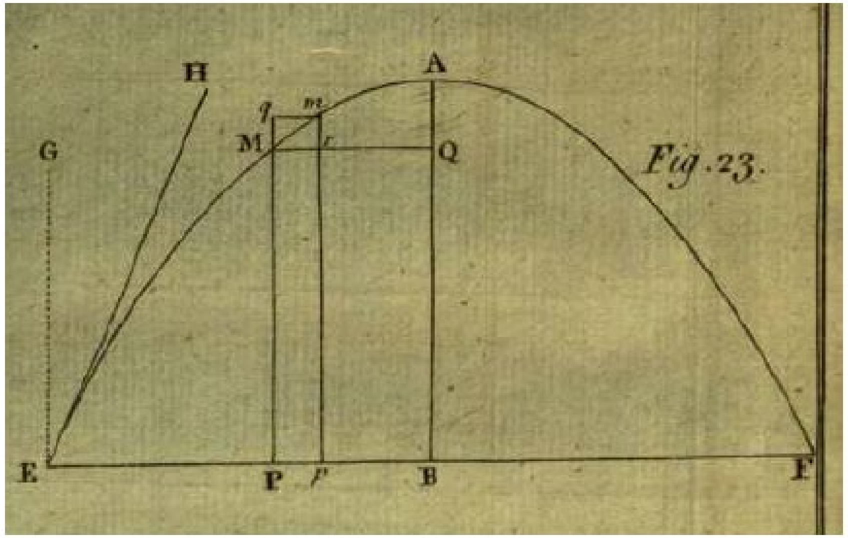
$$t = \frac{x}{\sqrt{b}} + \frac{3(b+h)xx}{16nch\sqrt{b}} + \frac{3(hh-bb)x^3}{128nncchh\sqrt{b}}$$

$$\text{Angle } PEM = A.tang.\left(\frac{x}{4b} + \frac{3(b+h)xx}{32ncbh}\right)$$

$$v = b - \frac{3b(b+h)x}{4nch} + \frac{9b(b+h)(2b+h)xx}{32n^2c^2hh}$$

b - height from which body must fall to acquire velocity with which body is projected from E
c - diameter of the ball
n - is ratio of density of ball to density of air
$\sqrt{v}$ - velocity of ball
$x = EP$

Shot fired at an oblique angle to the horizon



$$y = x \text{ tang. } \theta - \frac{gxx}{4b \cos.\theta^2} - \frac{gx^3}{12bk \cos.\theta^3} + \frac{ggx^4 \sin.\theta}{96bbk \cos.\theta^4}$$

$$- \frac{x^3}{6fk \cos.\theta^3} + \frac{gx^4 \sin.\theta}{16bfk \cos.\theta^4} - \frac{gx^4}{48bkk \cos.\theta^4} - \frac{x^4}{24fkk \cos.\theta^4} \pm \text{etc.}^{2)}$$

$$EF = 2b \sin. 2\theta \left(1 - \frac{b(b+h)\sin.\theta}{nch}\right),$$

Euler's results

- The range at any given angle of elevation will be less than that of the case with no air resistance. As the angle of elevation increases, so will the difference between the actual range and the range in the non-resistance case.

- The greatest range will occur at some angle less than 45°, and if $nc >> b$, ie shot is large and/or very heavy and moving at slow speed, an estimate for the angle that gives maximum range is

$$\sin. \theta = \frac{1}{\sqrt{2}} - \frac{b(b+h)}{8nch}.$$

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- Euler (incorrectly) denied the existence of what is now called the 'Magnus' effect – argued instead for imperfections in the bullet's curvature.

- Euler expressed D'Alembert's paradox for fluid flow (published by D'Alembert only in 1752).

Euler’s 1753 paper

Recherches sur la véritable courbe que décrivent les corps jetés dans l’air, ou dans un autre fluide quelconque

- Provided first complete analysis of the equations for ballistic motion in a resisting medium
- Assumed projectile’s air resistance was proportional to velocity squared
- Numerically integrated equations representing the trajectory’s range, altitude, time and velocity using the trapezoidal rule.
- Provided ballistics tables which could determine velocity, range, maximum altitude and flight time, for a projectile fired at certain muzzle velocities and angles of elevation.*

* Robins presented ballistic tables for his analysis to the Royal Society in 1746 but they were not published until 1761 when James Wilson published *Mathematical Tracts of the Late Benjamin Robins.*

Letter from ARJ Turgot to Louis XVI
23 August 1774

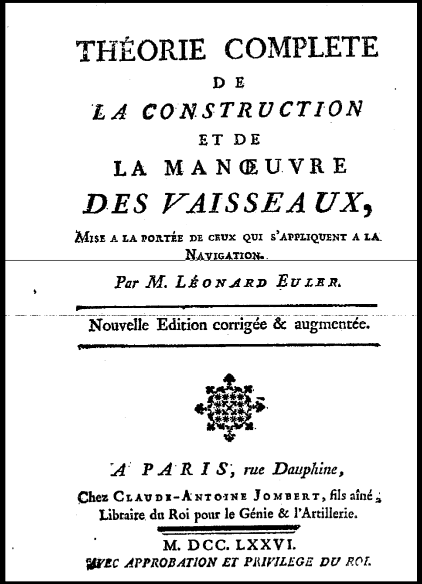
"The famous Leonhard Euler, one of the greatest mathematicians of Europe, has written two works which could be very useful to the schools of the navy and the Artillery. One is a *Treatise on the Construction and Manœver of Vessels*; the other is a commentary of the principles of artillery of Robins … I propose that Your Majesty order these to be printed. ... It is to be noted that an edition made thus without the consent of the author injures somewhat the kind of ownership he has of his work. But it is easy to recompense him in a manner very flattering for him and glorious to Your Majesty. The means would be that Your Majesty would vouchsafe to authorize me to write on Your Majesty's part to the lord Euler and to cause him to receive a gratification equivalent to what he could gain from the edition of his book, which would be about 5,000 francs. This sum will be paid from the secret accounts of the Navy. "

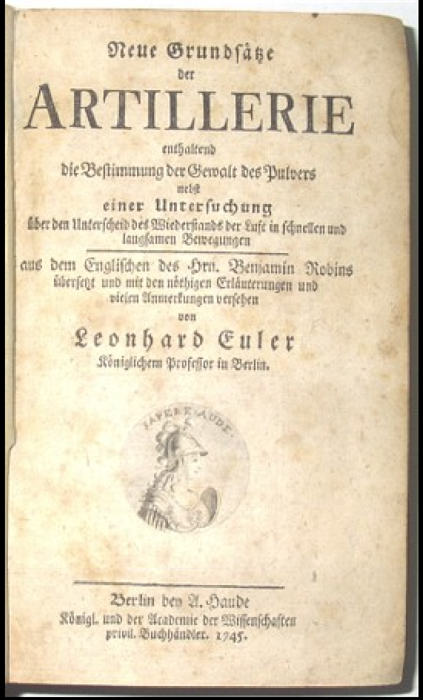
ARJ Turgot (1727-1781)
Minister of the Navy
Controller-General of Finances

Letter from ARJ Turgot to Euler 1775

"When I was in charge of the Navy I thought that I could do nothing better for the young men at the Naval and Gunnery Schools than to get them to study the books that you have written on these two branches of mathematics. Consequently, I proposed to the King to print, under his authority, your treatise on the construction and properties of vessels, and a French translation of your commentary on the principles of gunnery of Robins.

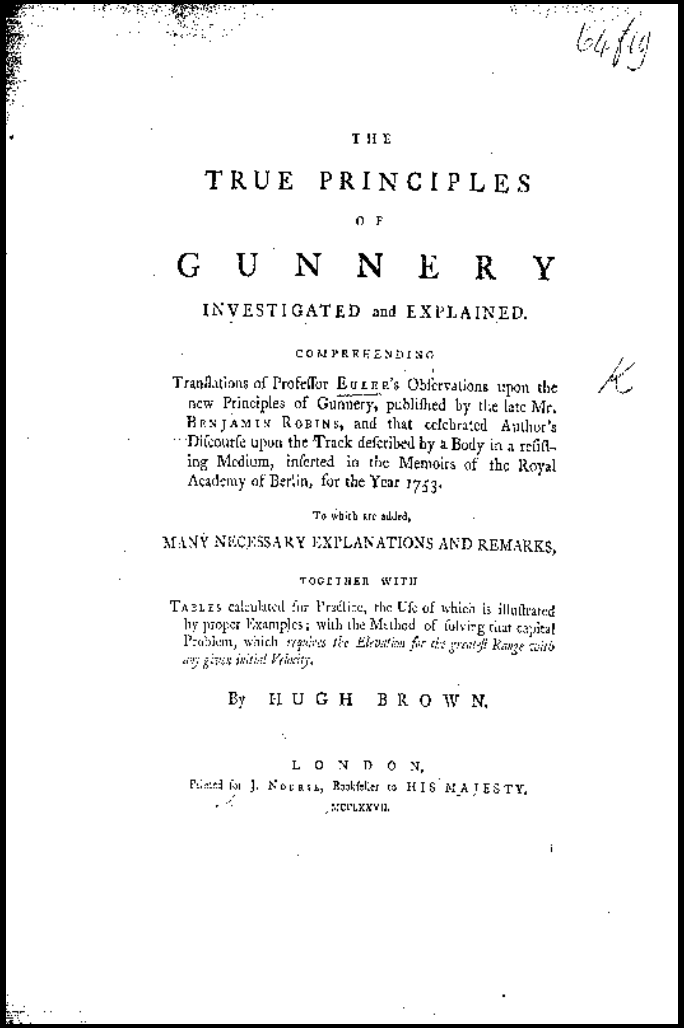
If I had been able to reach you, I would have asked your consent before using your books but I knew that the King would compensate you for this appropriation of your property. His Majesty has authorised me to pay you 1,000 Roubles as evidence of the esteem in which he holds your works … "


THÉORIE COMPLETE
DE
LA CONSTRUCTION
ET DE
LA MANŒUVRE
DES VAISSEAUX,
MISE A LA PORTÉE DE CEUX QUI S'APPLIQUENT A LA NAVIGATION.
Par M. LÉONARD EULER.
Nouvelle Edition corrigée & augmentée.
A PARIS, rue Dauphine,
Chez CLAUDE-ANTOINE JOMBERT, fils aîné, Libraire du Roi pour le Génie & l'Artillerie.
M. DCC. LXXVI.
AVEC APPROBATION ET PRIVILEGE DU ROI.


Neue Grundsätze
der
ARTILLERIE
enthaltend
die Bestimmung der Gewalt des Pulvers
nebst
einer Untersuchung
über den Unterscheid des Wiederstands der Luft in schnellen und langsamen Bewegungen
aus dem Englischen des Hrn. Benjamin Robins
übersetzt und mit den nöthigen Erläuterungen und vielen Anmerkungen versehen
von
Leonhard Euler
Königlichem Professor in Berlin.

Berlin bey A. Haude
Königl. und der Academie der Wissenschaften privil. Buchhändler. 1745.

Hugh Brown's translation of Euler's *Neue Grundsätze* (1777)



THE

TRUE PRINCIPLES

OF

GUNNERY

INVESTIGATED and EXPLAINED.

COMPREHENDING

Translations of Professor EULER's Observations upon the new Principles of Gunnery, published by the late Mr. BENJAMIN ROBINS, and that celebrated Author's Discourse upon the Track described by a Body in a resisting Medium, inserted in the Memoirs of the Royal Academy of Berlin, for the Year 1753.

To which are added,

MANY NECESSARY EXPLANATIONS AND REMARKS,

TOGETHER WITH

TABLES calculated for Practice, the Use of which is illustrated by proper Examples; with the Method of solving that capital Problem, which *requires the Elevation for the greatest Range with any given initial Velocity.*

By HUGH BROWN.

LONDON,

Printed for J. NOURSE, Bookseller to HIS MAJESTY.

MDCCLXXVII.

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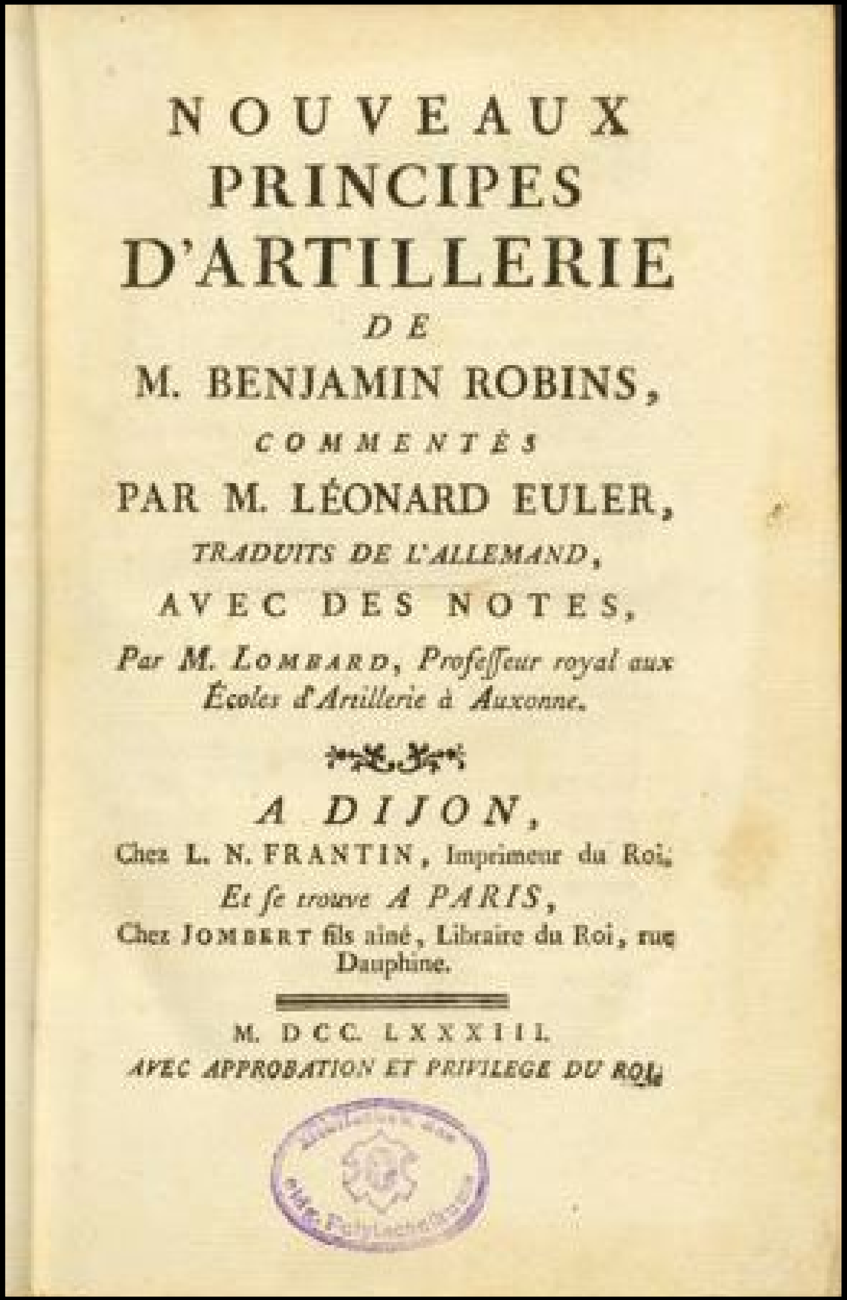
Lombard's translation of Euler (1783)

Jean-Louis Lombard (1723-1794)

Professor of Mathematics at the Royal School of Artillery at Auxonne.

Teacher of Napoléon.



NOUVEAUX
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DE
M. BENJAMIN ROBINS,
COMMENTÉS
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A DIJON,
Chez L. N. FRANTIN, Imprimeur du Roi;
Et se trouve A PARIS,
Chez JOMBERT fils aîné, Libraire du Roi, rue Dauphine.

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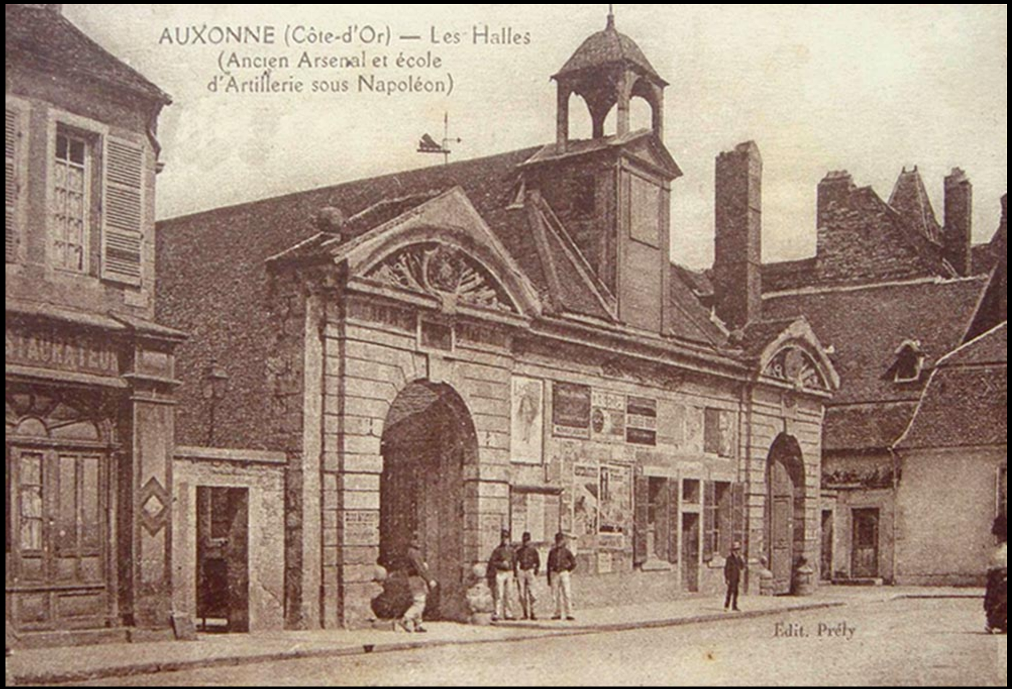
Napoléon and Robins-Euler

Napoléon studied Lombard's translation of Euler while at Royal School of Artillery at Auxonne (1788-1791)

Principes d'Artillerie - 12 page summary of Robins' work written in 1788

Napoléon inconnu, papiers inédits (1895)



The spread of Robins' and Euler's work on ballistics

1751 Robins' text translated into French by Jean Baptiste Le Roy for the Academy of Sciences in Paris.

1761 James Wilson publishes *Mathematical Tracts of Benjamin Robins*

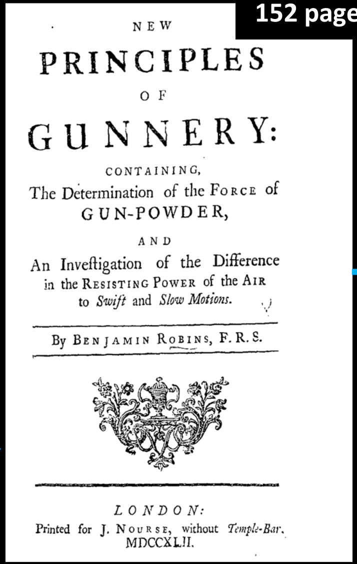
1764 HF Graevenitz, a German infantry officer, provided a complete set of ballistics tables using Euler's method

1777 Euler's text (with additions) translated into French by Hugh Brown

1781 GF Tempelhoff, director of Prussian Military Academy
Le bombardier prussien
Built on Robins' and Euler's analysis

1783 Euler's text translated into French by Jean-Louis Lombard
Studied by Napoléon while at the artillery school at Auxonne

1805 Charles Hutton edited a new edition of Robins' collected works for use at RMA Woolwich (including *New Principles of Gunnery*)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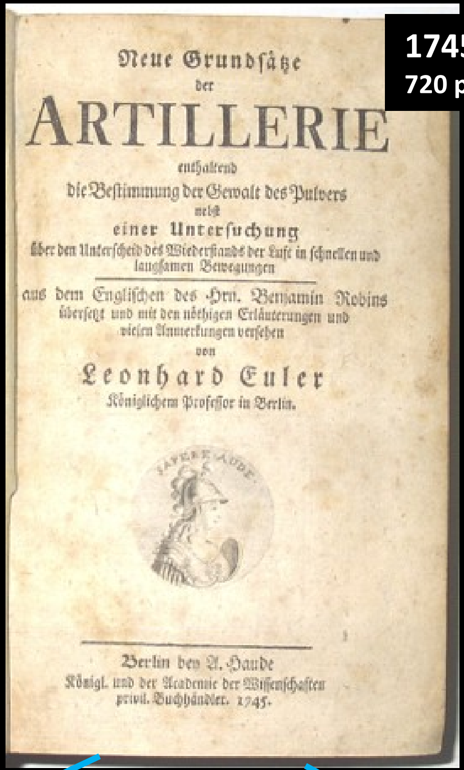
to *Swift* and *Slow Motions.*

By Benjamin Robins, F.R.S.

LONDON:
Printed for J. Nourse, without *Temple-Bar.*
MDCCXLII.

1742
152 pages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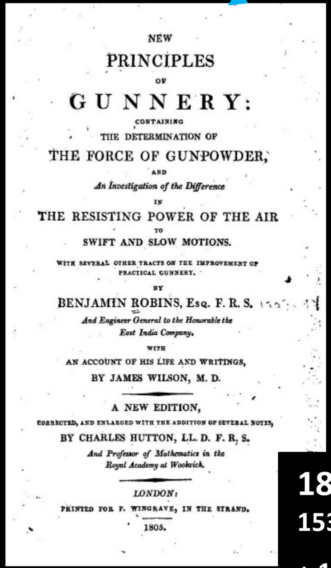
1745
720 pages

Jean-Baptiste
Le Roy
French
translation of
Robins
1751
(unpublished)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And Engineer General to the Honorable the
East India Company,
WITH
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BY JAMES WILSON, M. D.
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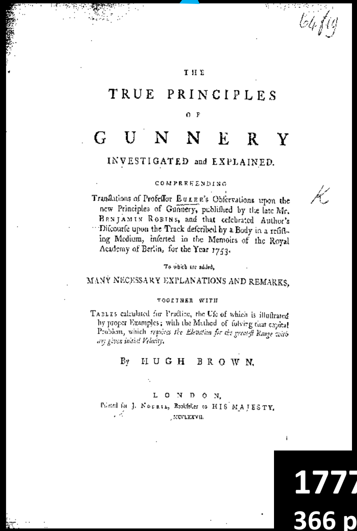
BY CHARLES HUTTON, LL. D. F. R. S.
And Professor of Mathematics in the
Royal Academy at Woolwich.
LONDON:
PRINTED FOR F. WINGRAVE, IN THE STRAND.
1805.

1805
153 pages
+ 185 pages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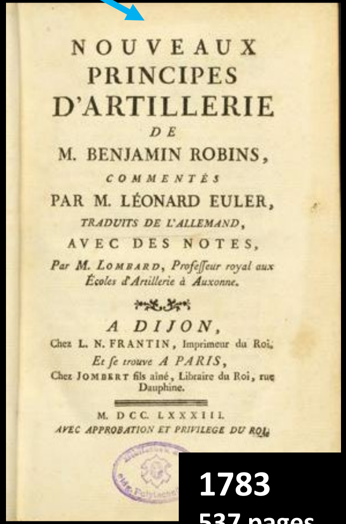
1777
366 pages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1783
537 pages