THE UNIVERSITY OF CHICAGO

ENRICO FERMI INSTITUTE

# HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

## A STORY OF INVENTION AND DISCOVERY

## Additional Material

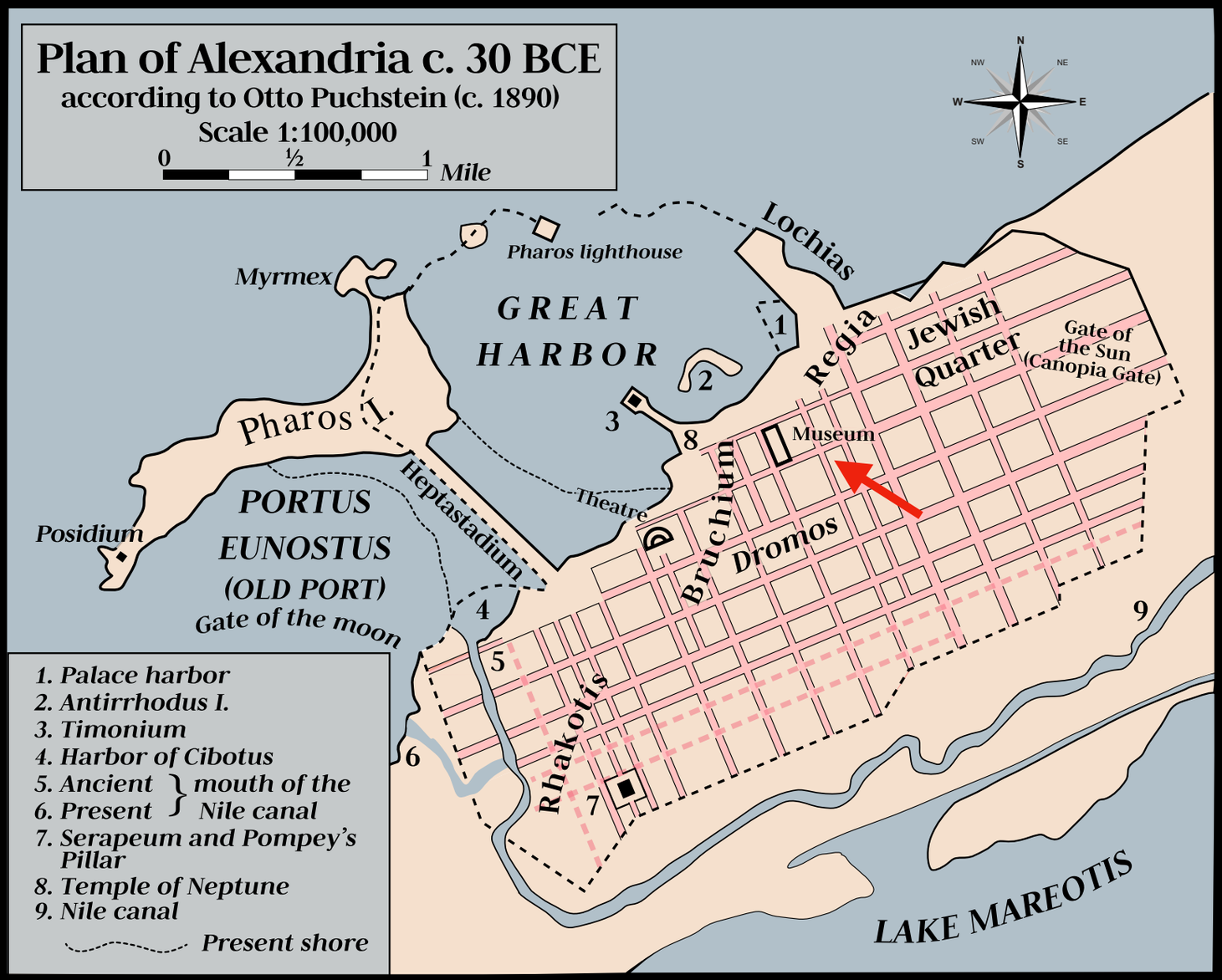
Philipp Windischhofer

*October 7, 2023*

Composite image created by combining representation of universe sphere by Pablo Carlos Budassi with human eye by Kamil Saitov (Google Commons).

# Hero of Alexandria (ca. 70 AD)

## Mathematician, physicist, engineer, teacher

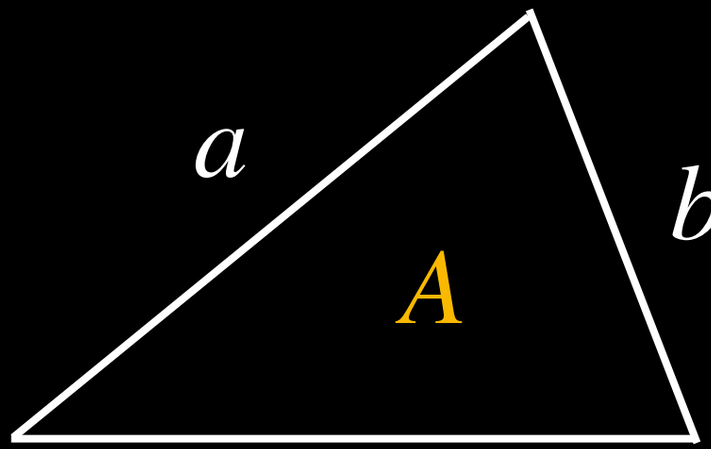



Mouseion of Alexandria

*"Seat of the muses"*

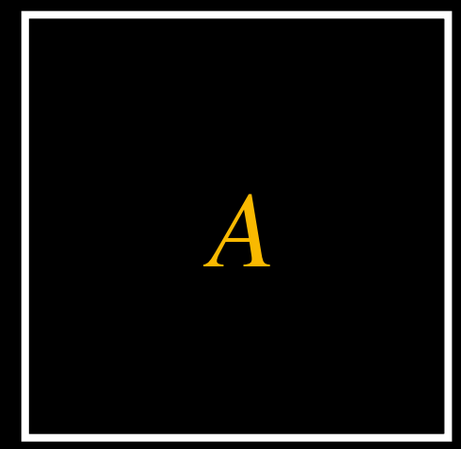
# Hero the mathematician

## “Hero’s formula”




$$A = \frac{1}{4}\sqrt{4a^2b^2 - (a^2 + b^2 - c^2)^2}$$

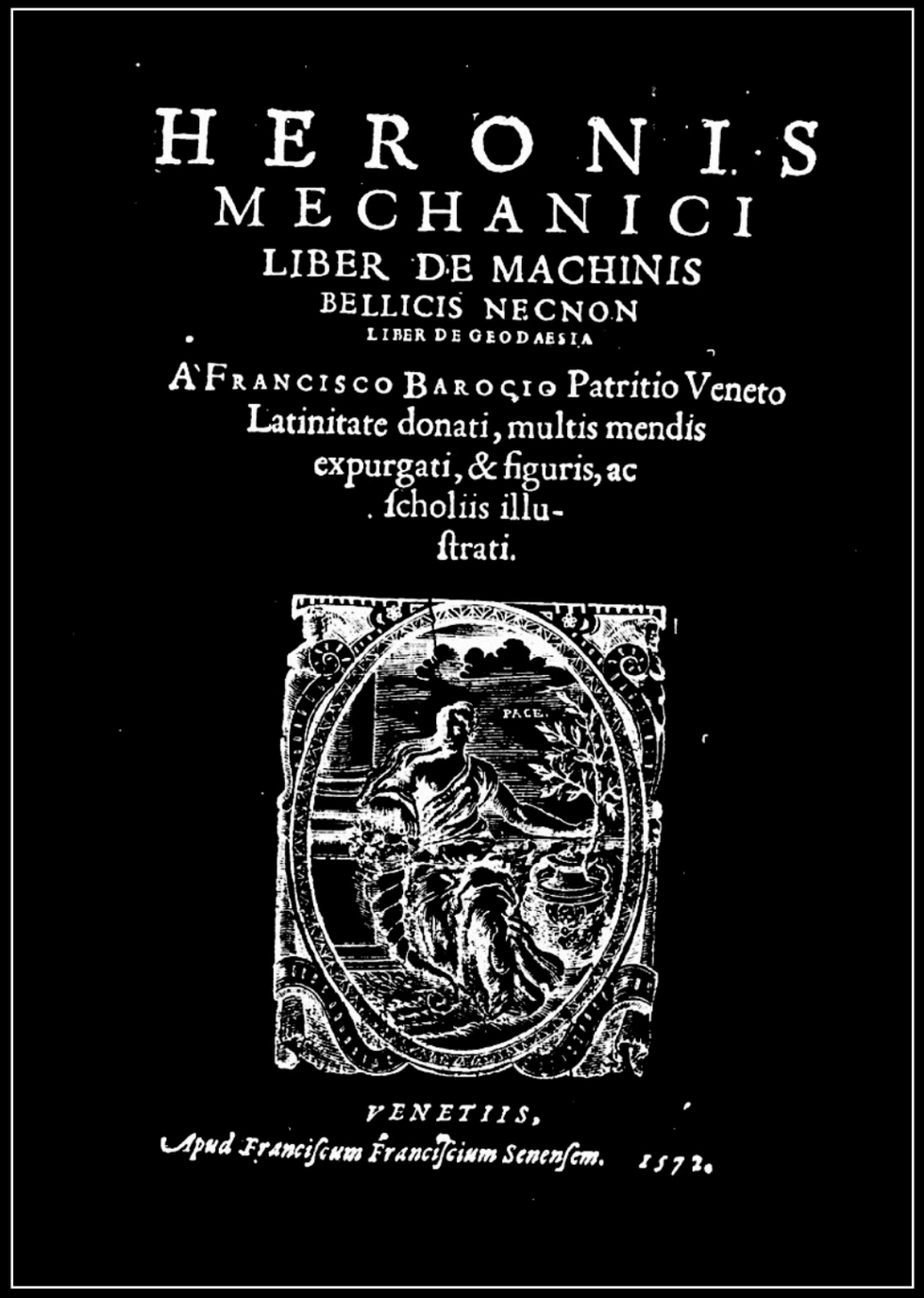
## “Hero’s method”




$$a_0 \approx a$$

$$a_1 = \frac{1}{2}\left(a_0 + \frac{A}{a_0}\right)$$

# Hero the engineer

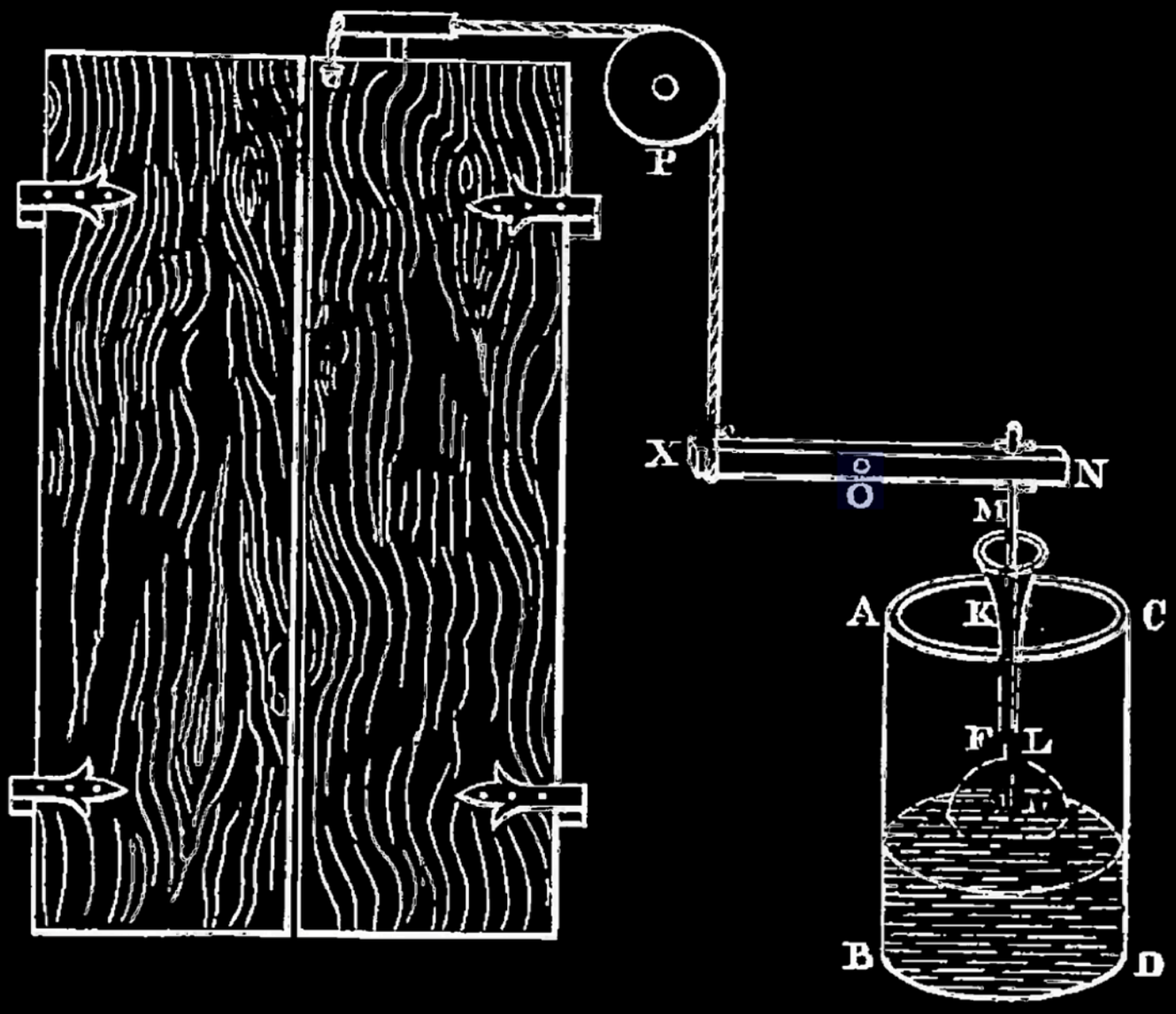

HERONIS
MECHANICI
LIBER DE MACHINIS
BELLICIS NECNON
LIBER DE GEODAESIA
A FRANCISCO BAROCIO Patritio Veneto
Latinitate donati, multis mendis
expurgati, & figuris, ac
scholiis illu-
ſtrati.
PACE.
VENETIIS,
Apud Franciſcum Franciſcium Senenſem. 1572.

Hero's "*mechanics*"

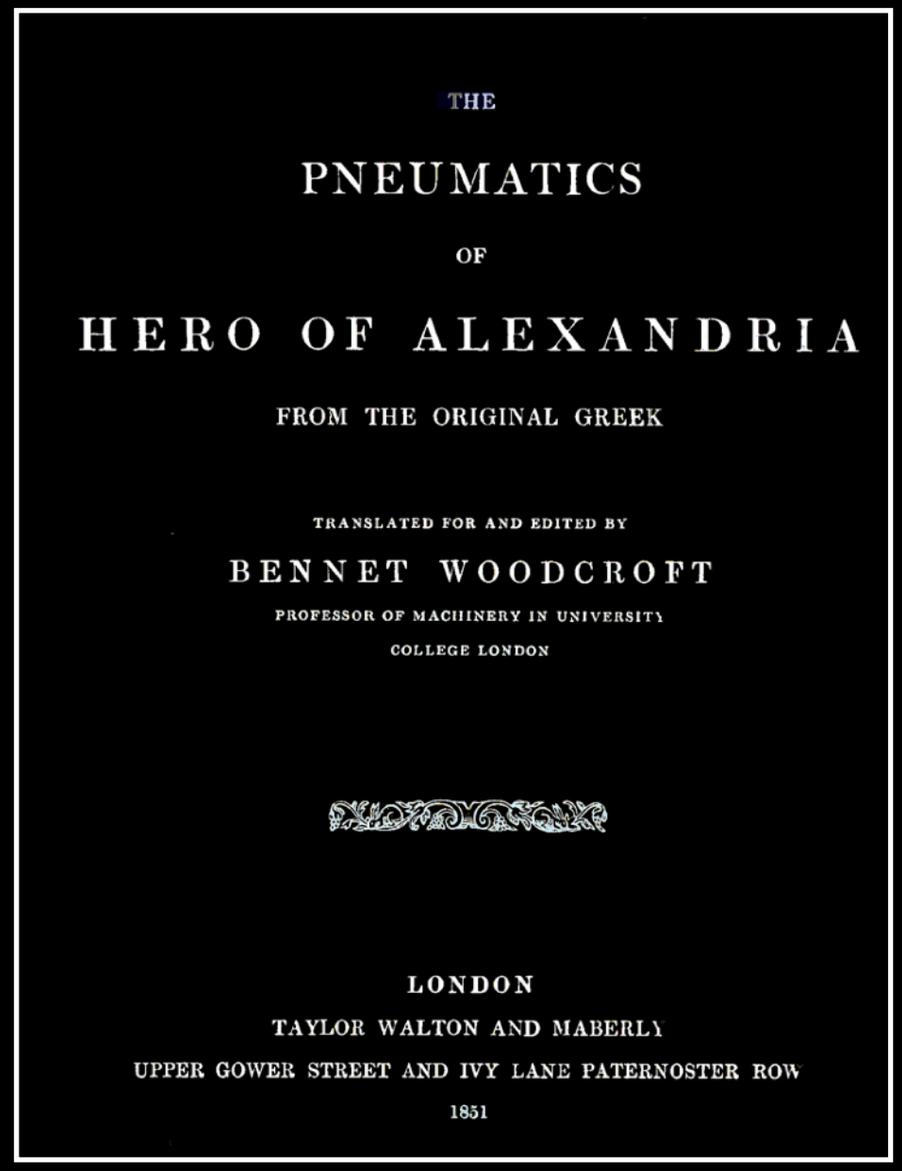
*Translation into Latin from Venice*

# Hero the engineer

***"Sounds produced on the opening of a Temple Door"***




"When the door is opened, the cord will be stretched and the vessel will descend into the water and give forth the sound of a trumpet by the expulsion of the air […]"


THE

PNEUMATICS

OF

HERO OF ALEXANDRIA

FROM THE ORIGINAL GREEK

TRANSLATED FOR AND EDITED BY

BENNET WOODCROFT

PROFESSOR OF MACHINERY IN UNIVERSITY

COLLEGE LONDON

LONDON

TAYLOR WALTON AND MABERLY

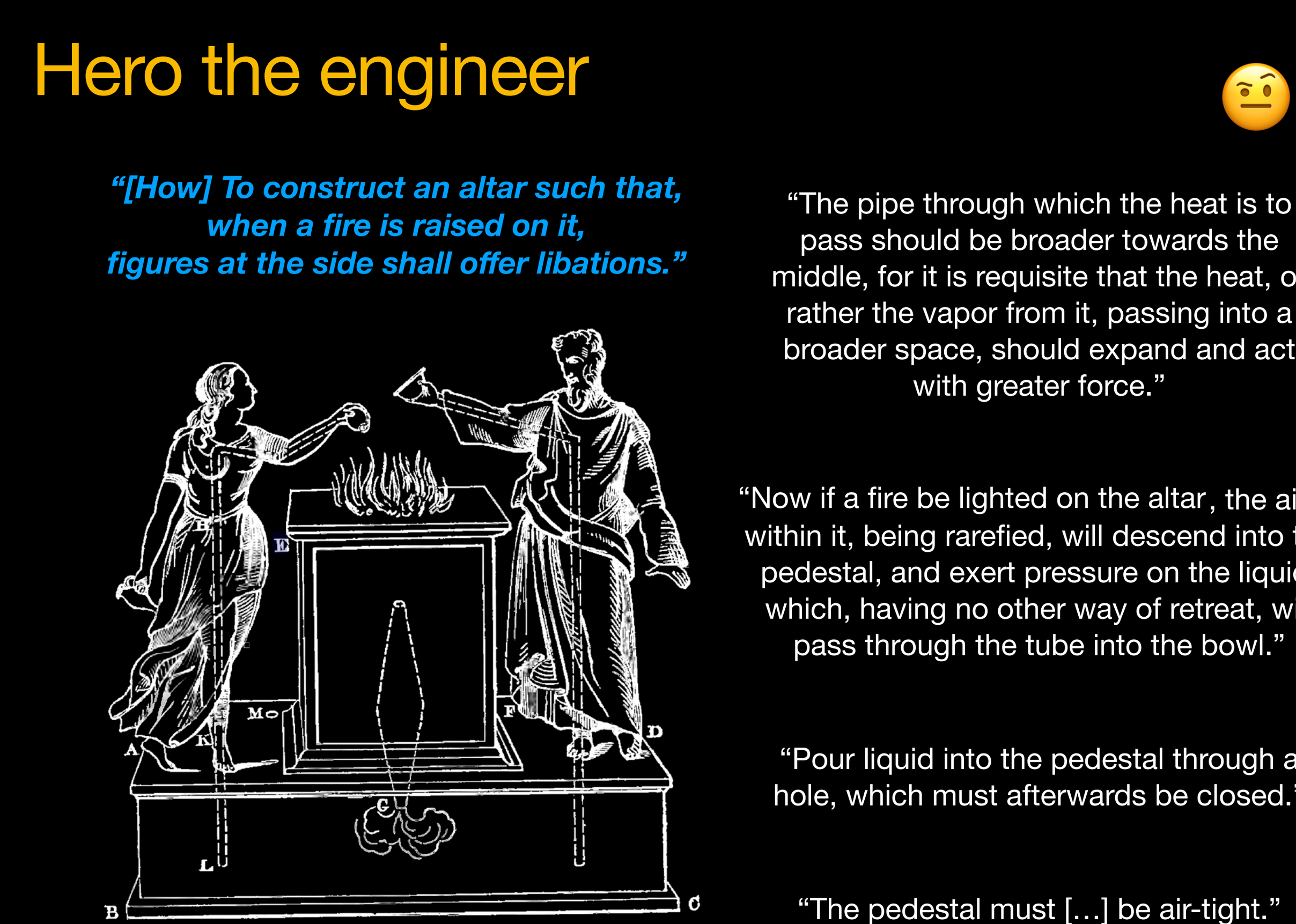
UPPER GOWER STREET AND IVY LANE PATERNOSTER ROW

1851

Hero's "*pneumatics*"

*Translation into English*

# Hero the engineer



***“[How] To construct an altar such that, when a fire is raised on it, figures at the side shall offer libations.”***

“The pipe through which the heat is to pass should be broader towards the middle, for it is requisite that the heat, or rather the vapor from it, passing into a broader space, should expand and act with greater force.”

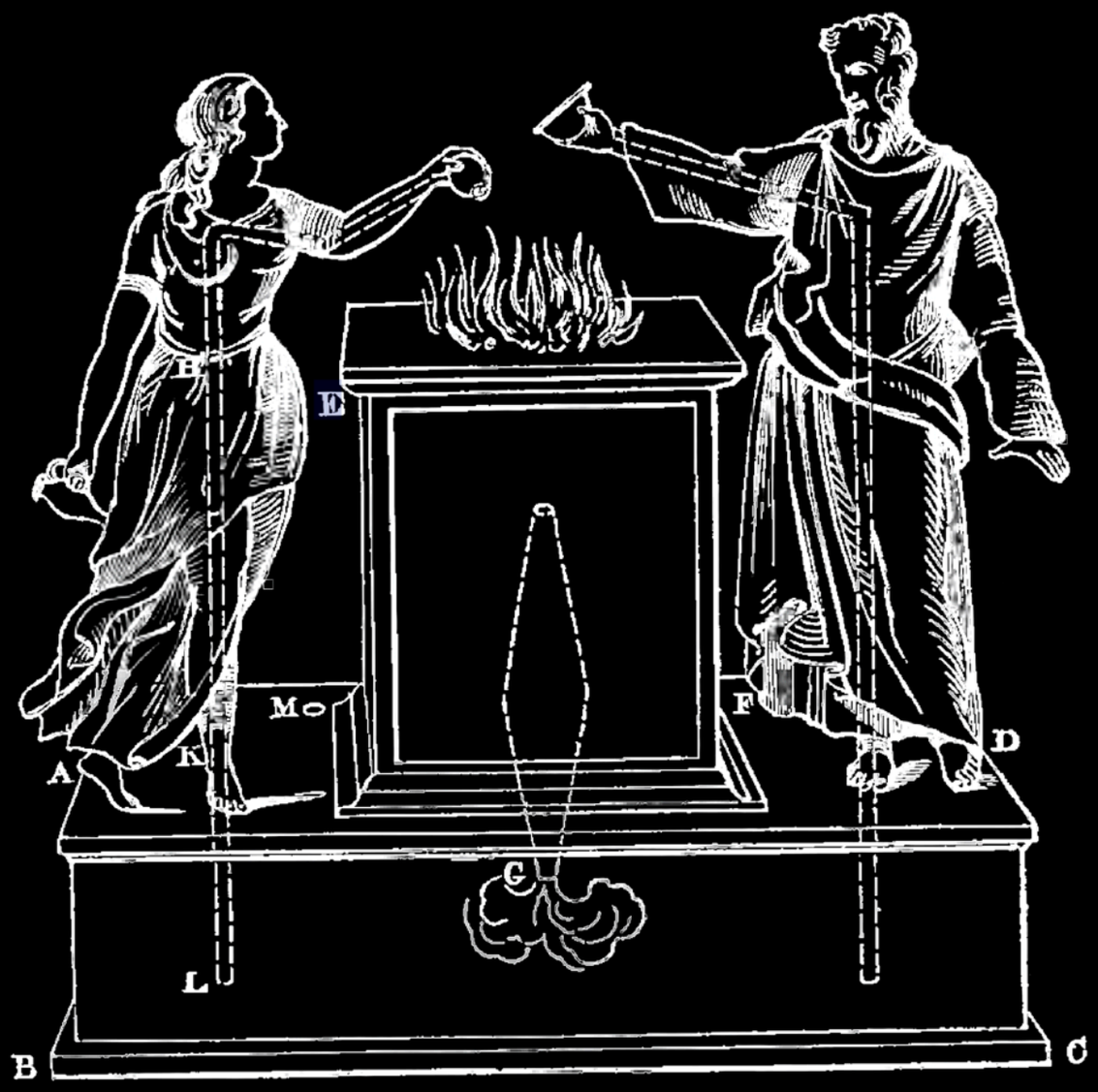
“Now if a fire be lighted on the altar, the air within it, being rarefied, will descend into the pedestal, and exert pressure on the liquid, which, having no other way of retreat, will pass through the tube into the bowl.”

“Pour liquid into the pedestal through a hole, which must afterwards be closed.”

“The pedestal must […] be air-tight.”

# Hero the engineer

***"[How] To construct an altar such that,***
***when a fire is raised on it,***
***figures at the side shall offer libations."***



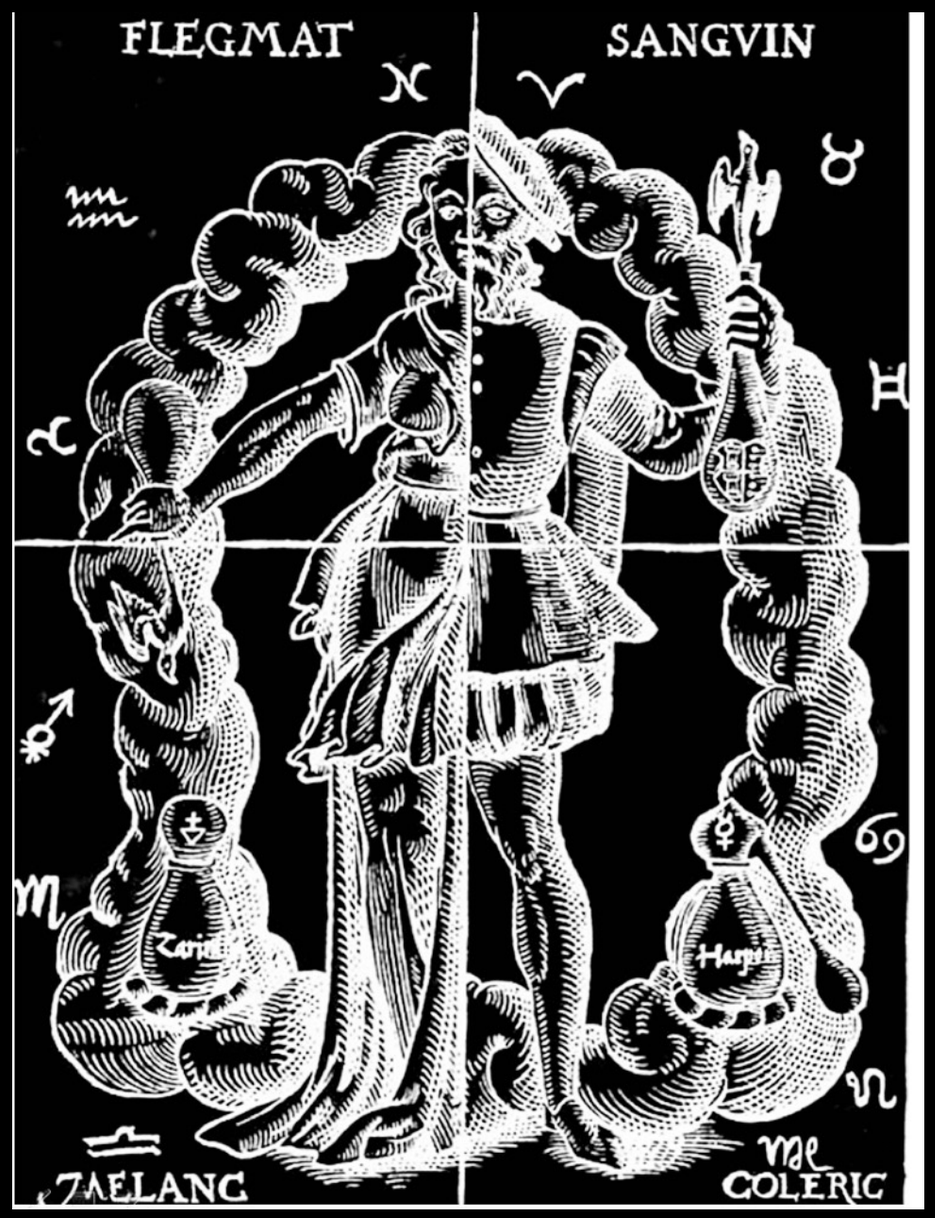

**Hot air expands**

# Galen of Pergamon (ca. 140 AD)

## Physician, surgeon, philosopher


**The four "humors"**

**Phlegm** **Blood**




**Black bile** **Yellow bile**

"The Human body contains blood, phlegm, yellow bile, and black bile."

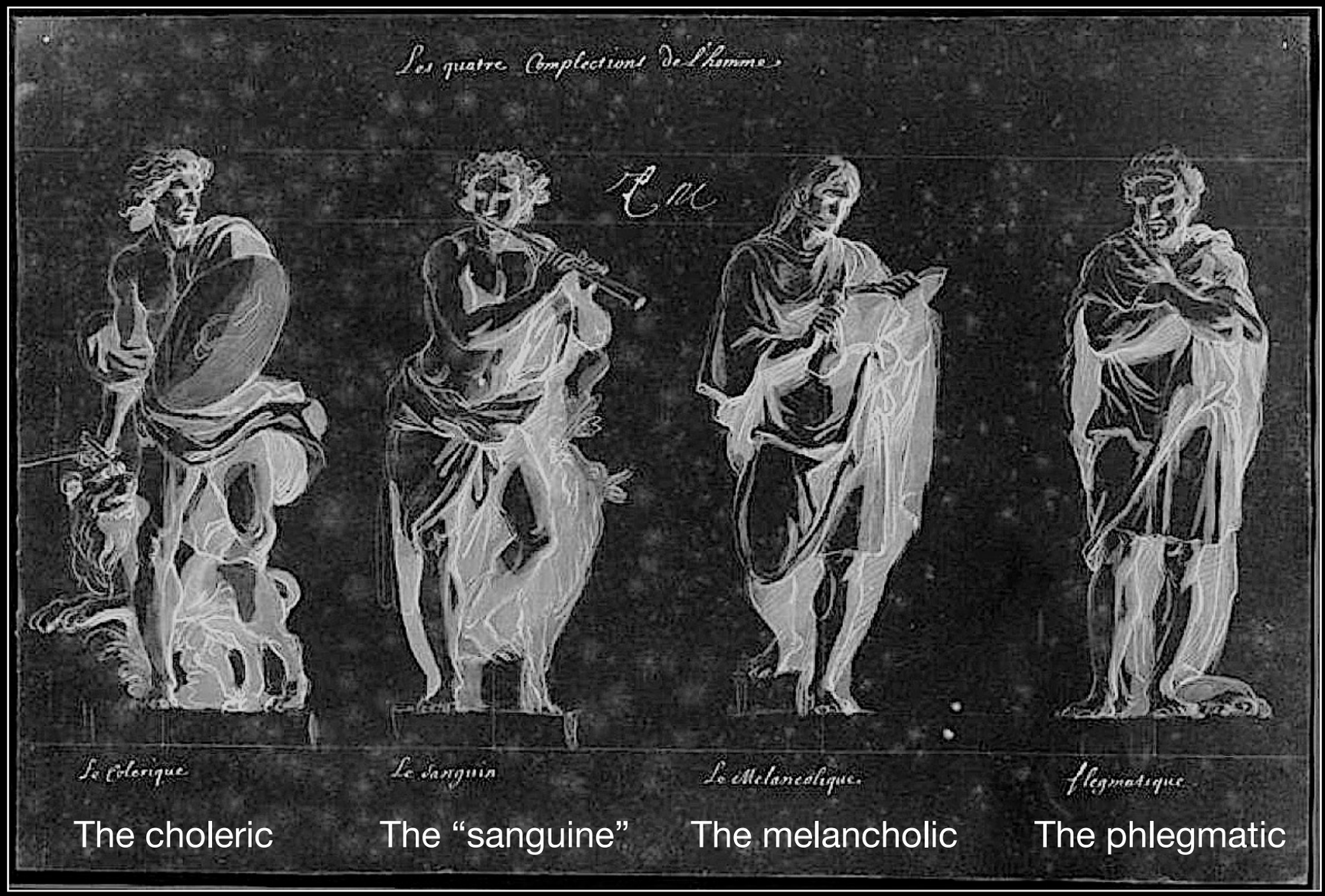
"Health is that state in which these constituent substances are in the correct proportion to each other, both in strength and quantity, and are well mixed."

"Having the right amount of humor is essential for health."

"Disease is consequently brought on by humor excesses and/or deficiencies."

# Galen: “On temperaments”

**The four “temperaments”**




The choleric | The “sanguine” | The melancholic | The phlegmatic

*“For in Celts and Germans […] the skin is cold and wet. However much innate heat there is has fled for refuge to the internal organs, along with the blood, which here is agitated, confined in narrow spaces and itself seething, rendering them high-spirited, rash, and quick to change their opinions.”*

# Galen’s temperature scale

**Heat picks up a scale!**

*“Proceeding from the hottest of all those coming to perception*
*(for example, either fire or boiling water)*

*to the very coldest of all things we know*
*(for example, either ice or snow),*

*and considering the separation between them, we divide this precisely in the middle.*

*In this way we shall discover conceptually the median (moderate)*
*which is equally removed from each of the extremes.*

*But we are also able to prepare this in a certain way*
*when we mix an equal mass of ice with boiling water.”*

**“Four degrees of cold”** **“Neutral”** **“Four degrees of hot”**

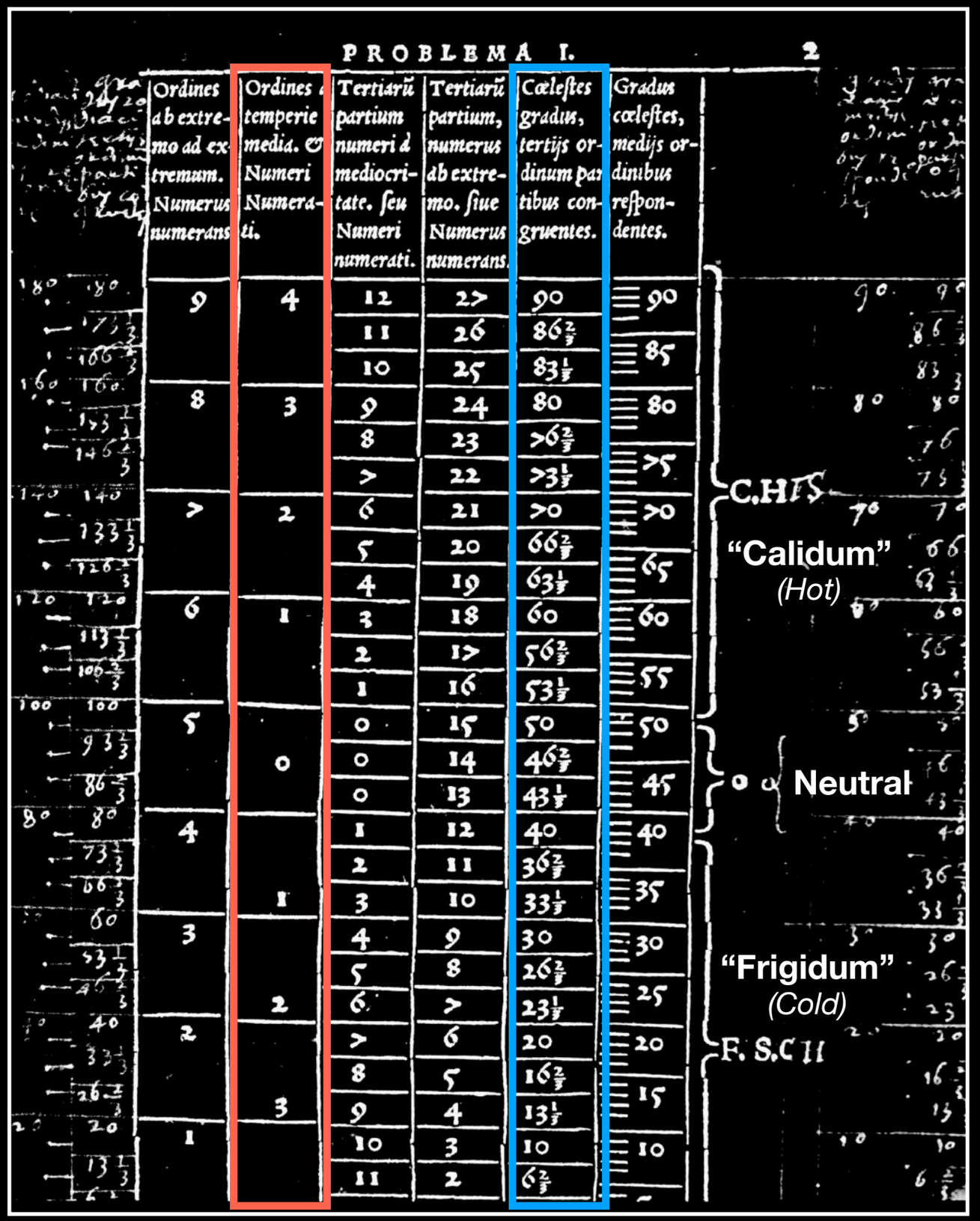
# Nothing much changed for 1500 years!

**Johannis Hasler of Berne:**
"Of medical practice" (1578)

Problem 1:
*"To find the natural degree of temperature of each man, as determined by his age, the time of year, the elevation of the pole, and other influences."*

**Relating Galen's temperature scale …**

**… to the latitude of the patient.**



# The first “thermoscopes”

**Letters from Giovanni Sagredo to Galileo:**

**Giovanni Francesco Sagredo**

Mathematician in Venice, diplomat and spy
in Syria, treasurer in Palmanova,
close friend of Galileo’s

# The first “thermoscopes”

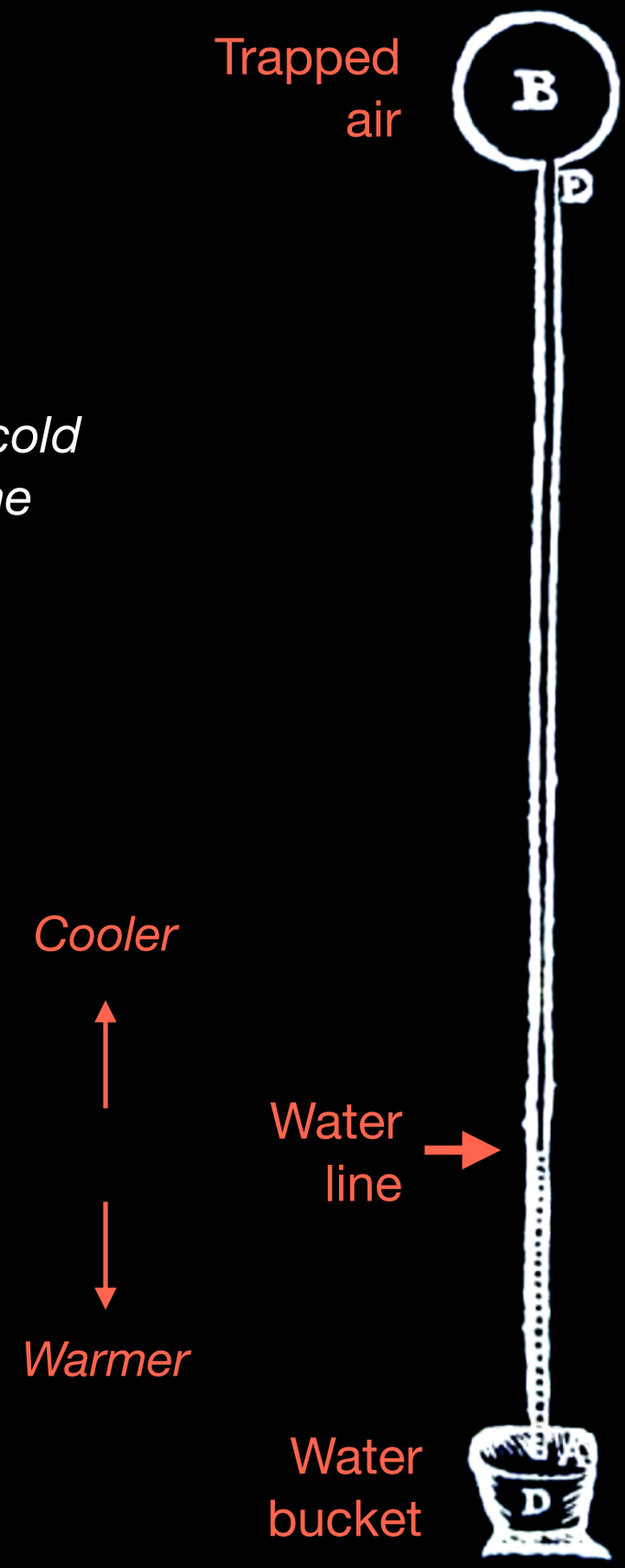
**Letters from Giovanni Sagredo to Galileo:**

June 30, 1612:

*“Signor Mula told me about an instrument of Santorio’s, with which cold and heat were measured by means of compasses; and finally let me know that this is a large glass bulb with a long neck.*

**In today’s terminology:**
“air thermometer”

**Trapped air expands when warmed, contracts when cooled**



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June 30, 1612:

*“Signor Mula told me about an instrument of Santorio’s, with which cold and heat were measured by means of compasses; and finally let me know that this is a large glass bulb with a long neck.*

*I immediately devoted myself to making some very fine and elegant ones.*

*I work so fast that in an hour I finish as many as ten of them.”*

May 9, 1613:

*“The instrument for measuring heat, invented by your excellent self, has been reduced to me to various very elegant and convenient forms.*

*With these, I have found various marvelous things, as, for example, that in winter the air may be colder than ice or snow; that the water just now appears colder than the air, and similar subtle matters.”*

# The first “thermoscopes”

**Letters from Giovanni Sagredo to Galileo:**

June 30, 1612:

*“Signor Mula told me about an instrument of Santorio’s, with which cold and heat were measured by means of compasses; and finally let me know that this is a large glass bulb with a long neck.*

*I immediately devoted myself to making some very fine and elegant ones.*

*I work so fast that in an hour I finish as many as ten of them.”*

May 9, 1613:

*“I have clearly seen that well-water is colder in winter than in summer, although our senses tell differently”*

# Measuring temperature

**Letters from Giovanni Sagredo to Galileo:**

February 7, 1615:

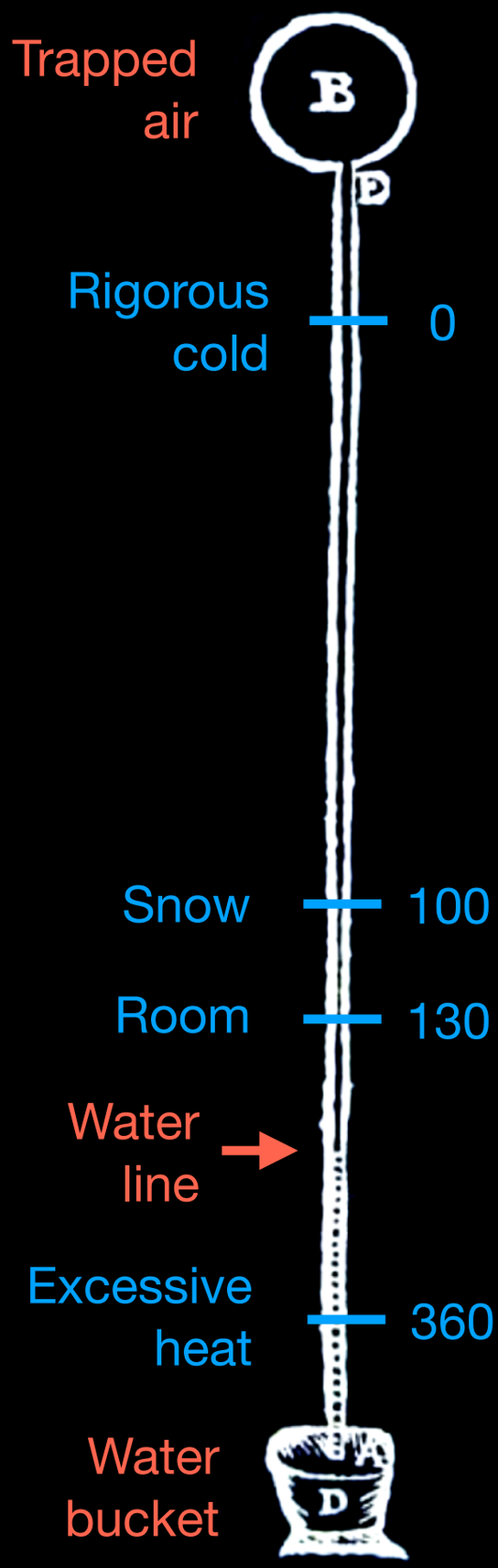
*“Two days ago it snowed.*

*Here in the room my instrument showed 130 degrees of heat more than there was two years ago at the time of the very rigorous and extraordinary cold; which instrument, immersed and buried in snow, showed 30 degrees fewer, that is to say only 100.*

*But then, immersed in snow mixed with salt, it showed another 100 fewer.*

*Thus, as the instrument had gone up to 360 degrees in the greatest heat of summer, it appears that salt combined with snow increases the cold by as much as amounts to a third of the difference between the excessive heat of summer and the excessive cold of winter*

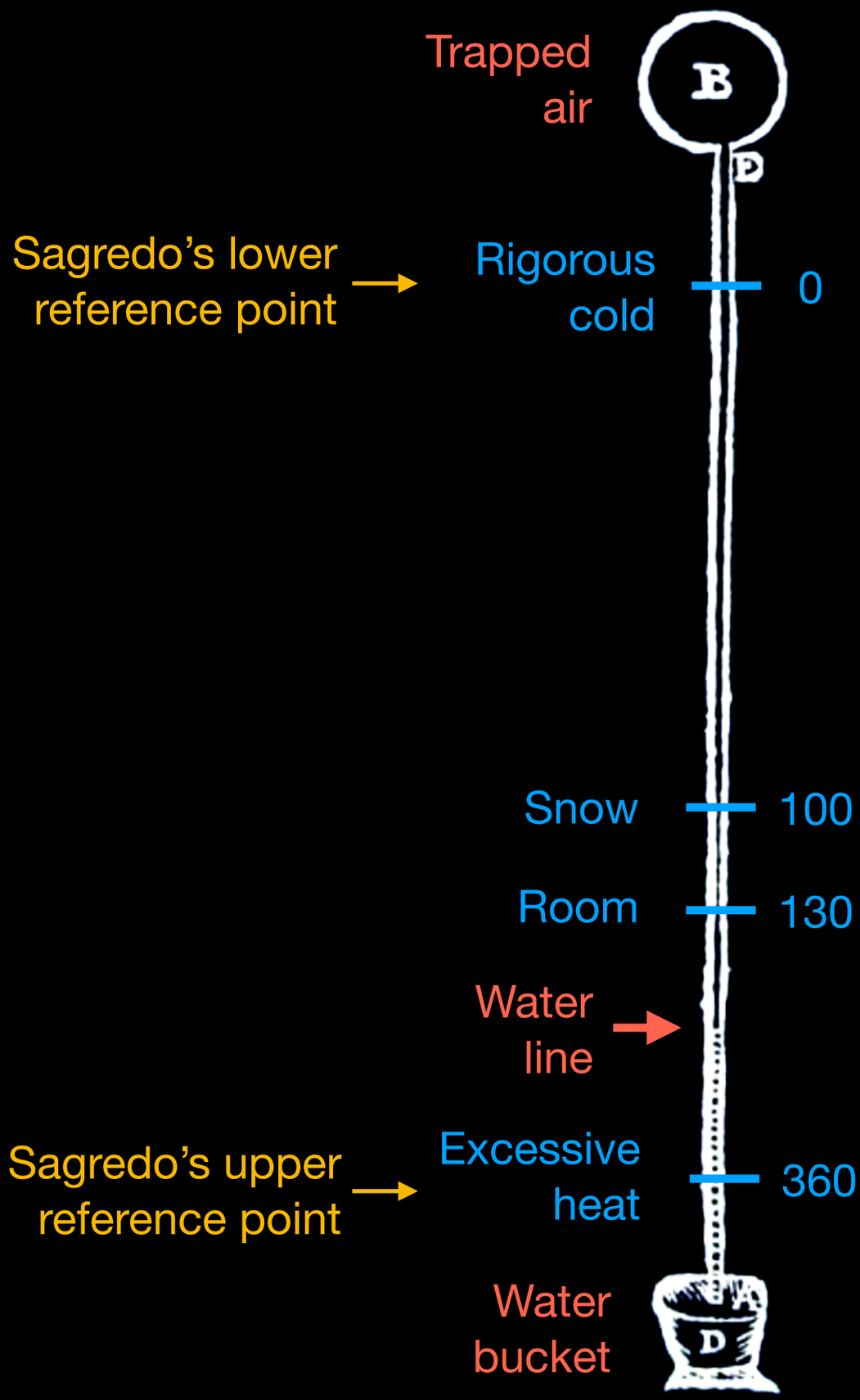
*—a thing so wonderful, that I can provide no credible reason for it.”*



# Measuring temperature

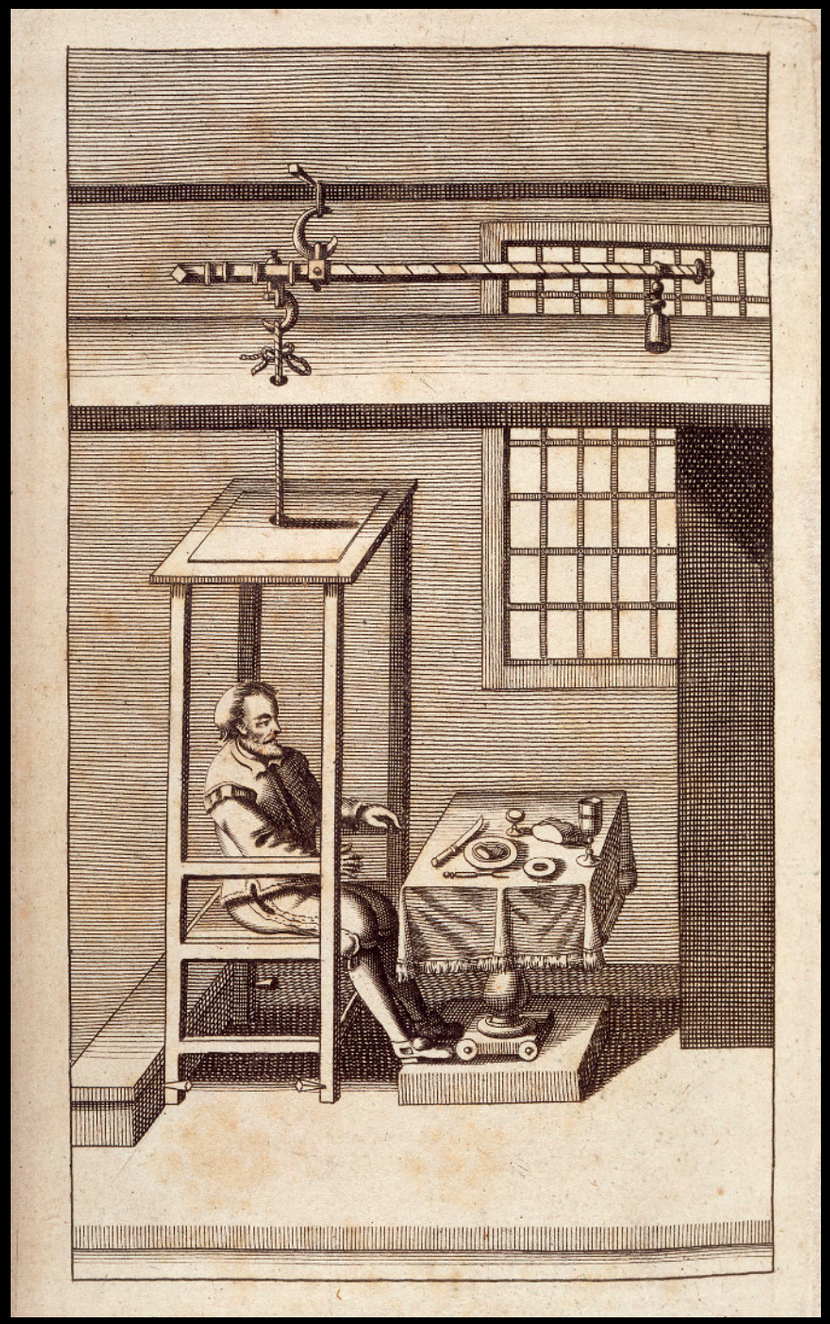
**This is how (most) temperature scales are defined even today!**

Pick two reference points, divide the space in between into an arbitrary number of “degrees”.



# Uses in medicine

Santorio Santorre: *Professor of Medicine at Padua*




← "Weighing chair" to study his own metabolism for 30 years!

**On thermometers:**

*"I wish to tell you about a marvelous way in which I am accustomed to measure, with a certain glass instrument, the cold and hot temperature of all parts of the body; and so exactly, that we can measure the degrees and ultimate limits of heat and cold at any time of day.*

*It is in our house at Padua and we show it very freely to all.*

*We promise that a book about medical instruments that are not well-known will shortly appear, in which we shall give an illustration of this instrument and describe its construction and use."*

# People are still confused

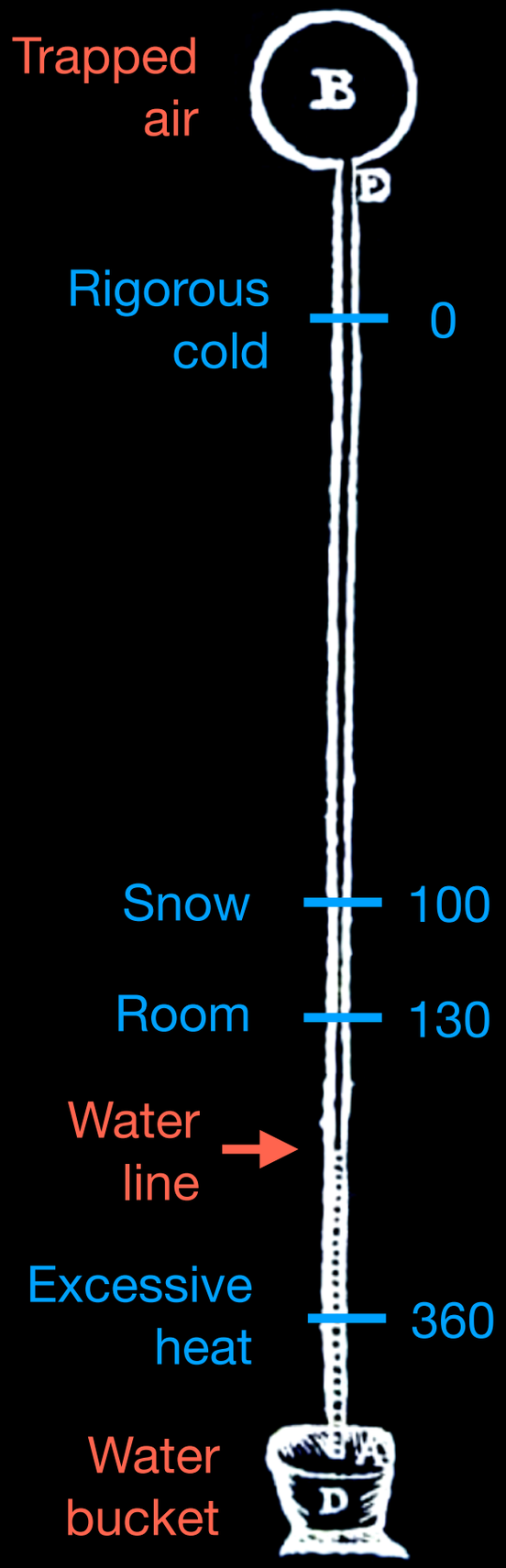
**Bartholomeo Telioux:** “Wonderful mathematics”

“I might explain that the water will rise or fall
according to how hot or cold it is.

Because, heat causing expansion,
the water needs more room and thus,
confined by the narrowness of the neck, rises.

Then, when the cold comes,
the expanded water condenses and,
desiring less room, descends.”

**He got everything backwards!**



# A more serious problem

## The air thermometer is also a barometer!

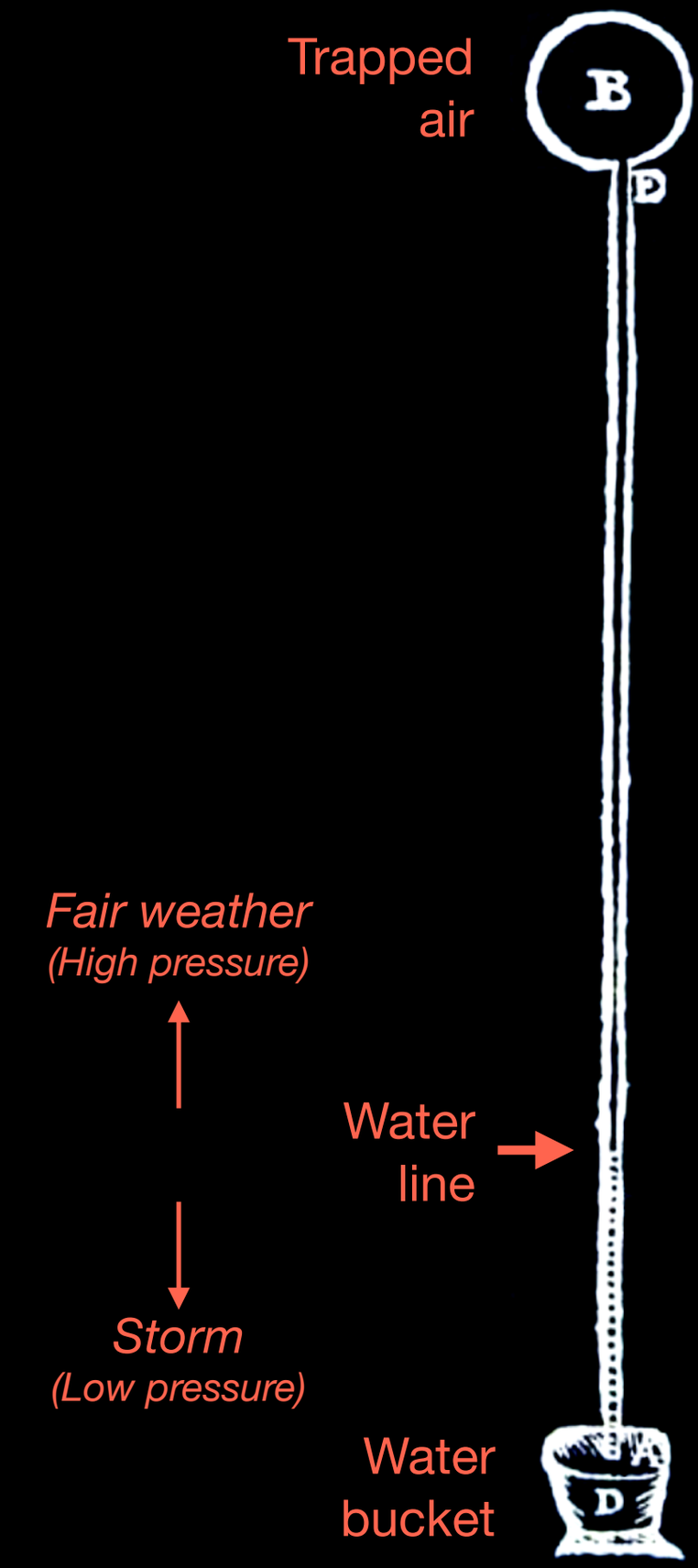
**The water bucket is open!**

*Atmospheric pressure also affects the water level, in the opposite direction that temperature does!*

**Blaise Pascal**
(1644, i.e. 29 years after Sagredo's last letter to Galilei):

*"From [my experiments] follow many consequences, such as the lack of certainty that is in the thermometer for indicating the degrees of heat (contrary to common sentiment).*

*Its water sometimes rises when the heat increases, and sometimes falls when the heat diminishes […]"*



# A side story: Blaise Pascal

Mathematician, physicist, inventor, philosopher, writer

Discovery of variations of atmospheric pressure

Mechanical calculator

# A silent inventor: Jean Rey

## A physician in the French countryside

**Marin Mersenne** (a monk from Paris) to Jean Rey:
*September 31, 1631*

*“Then the thermoscope, making the liquid descend by the rarefaction of its air, bears witness that heat makes air more subtle […]”*

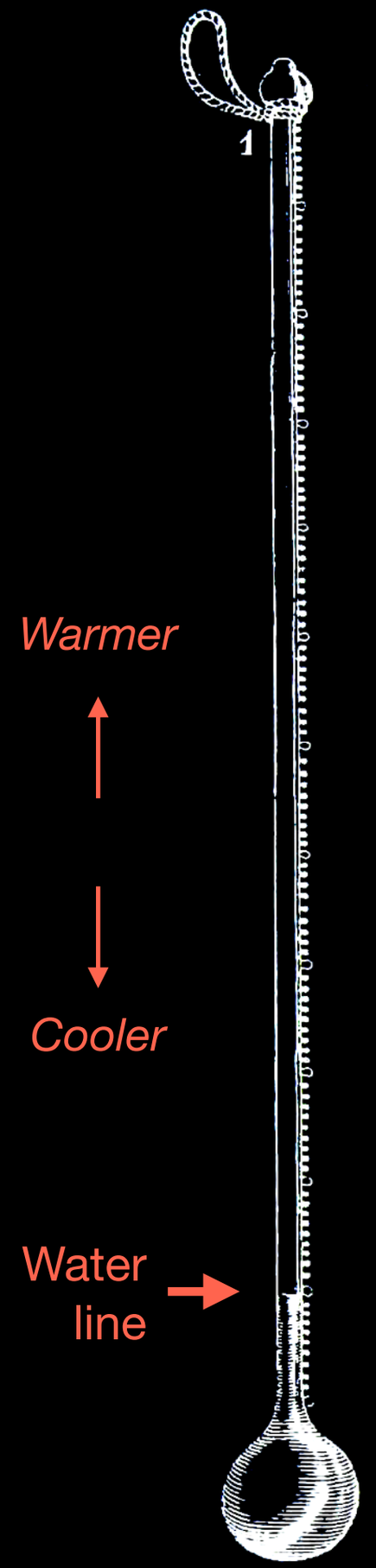
**Jean Rey**, in his reply:
January 1, 1632 (before Pascal!)

*“There are a variety of thermoscopes, or so it appears.*

*What you say cannot agree with mine, which is nothing more than a little round phial with a very long and slender neck.*

*To use it, I fill all but the neck with water.*

*The heat, expanding the water, makes it rise more or less according to whether the heat is great or small.”*



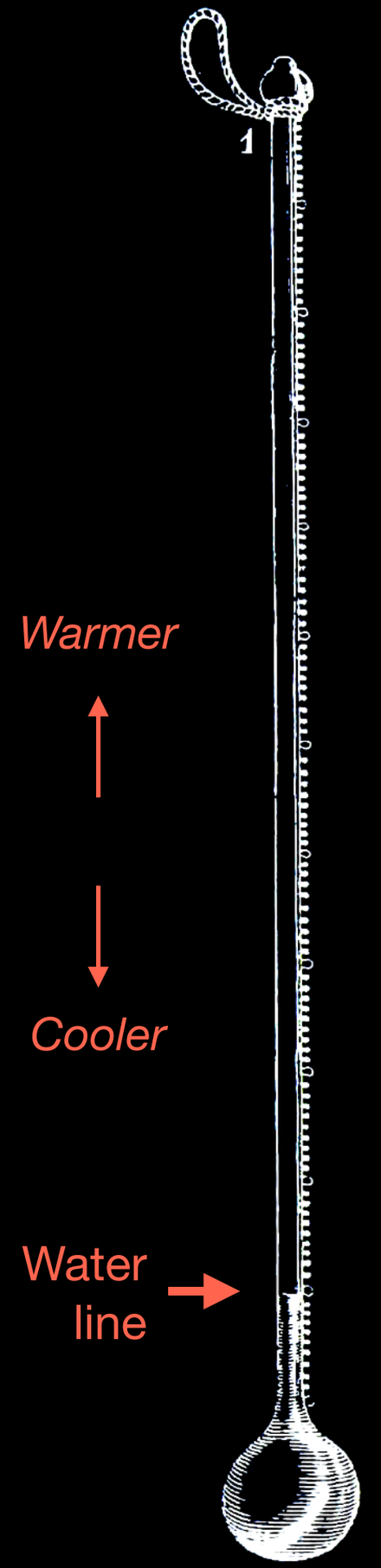
# A silent inventor: Jean Rey

## A physician in the French countryside

**Rey's thermometer is hermetically sealed**

**Changes in air pressure**
**<u>do not</u> affect the temperature reading**

He did not know of that advantage!

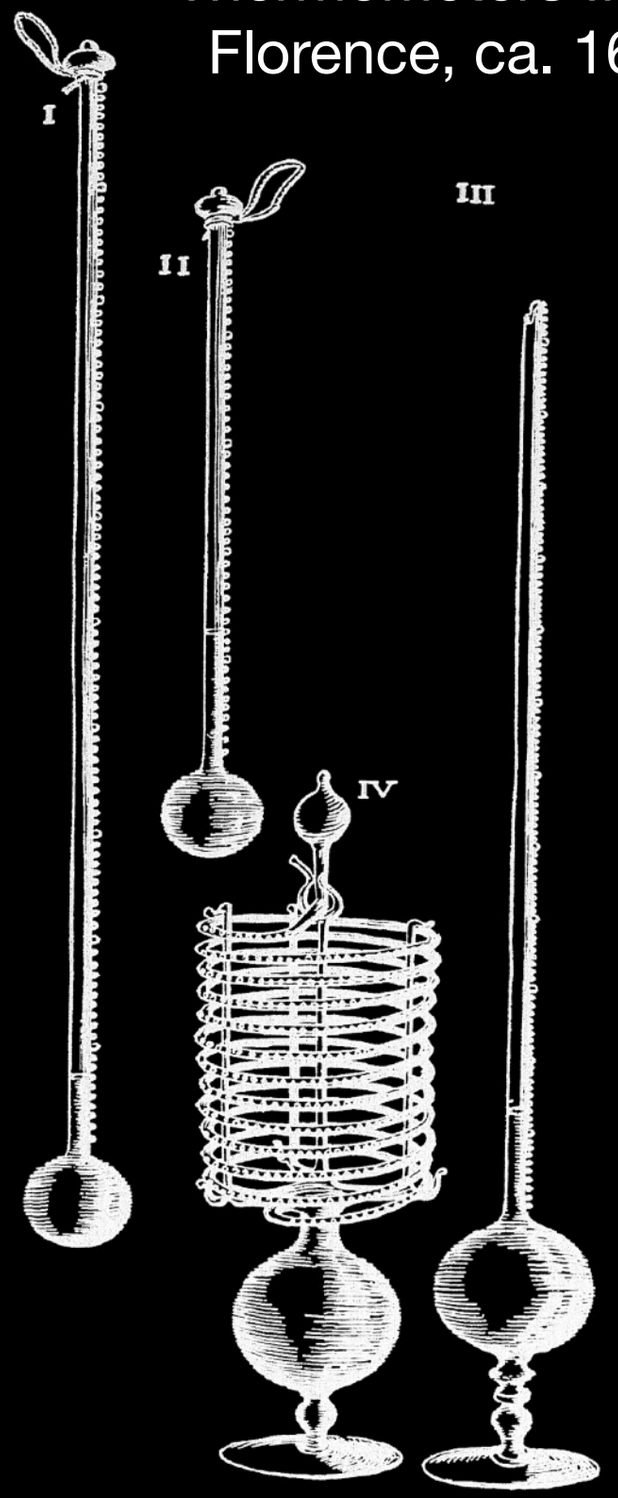


# Thermometry as a precision science

**But which scale and which reference points to use?**

| | | |
|---|---|---|
| **Florence** (~1660) | “The most severe winter cold” | “The greatest summer heat” |
| **Florence** (1669) | Melting snow | “The greatest summer heat” |
| **Dalencé** (1688) | Melting snow: -10 degrees | Melting butter: +10 degrees |
| **Renaldini** (1694) | Water freezing 0 degrees | Water boiling 12 degrees |
| **Rømer** (1702) | Ice + water 0 degrees | Water boiling *(at standard pressure)* 60 degrees |

Thermometers from Florence, ca. 1660



# Today's temperature scale

**Fahrenheit (March 1717):** 102 years after Sagredo

*"It will be necessary to say a few words about the thermometers that I have built for the observation of the weather, and the division of the scale they use.*

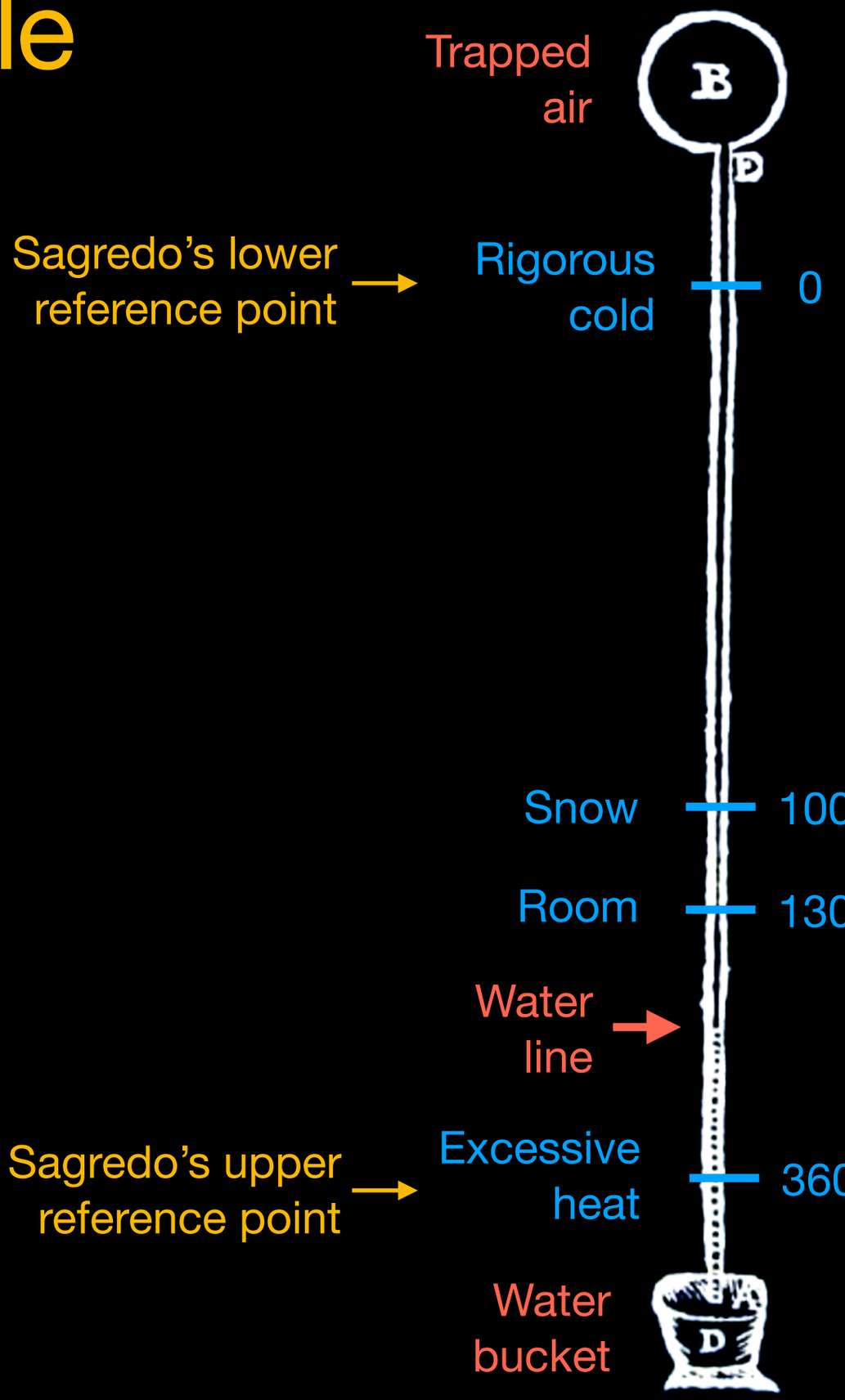
*The division of the scale depends on the fixed points, which can be determined in the following manner.*

*The first is determined by a mixture of ice, water and ammonium chloride or even sea salt.*

*If the thermometer is placed in this mixture, its liquid descends as far as the degree that is marked with a zero.*

*The second point is obtained if water and ice are mixed without the aforementioned salts.*

*When the thermometer is placed in this mixture, its liquid reaches the 32nd degree."*



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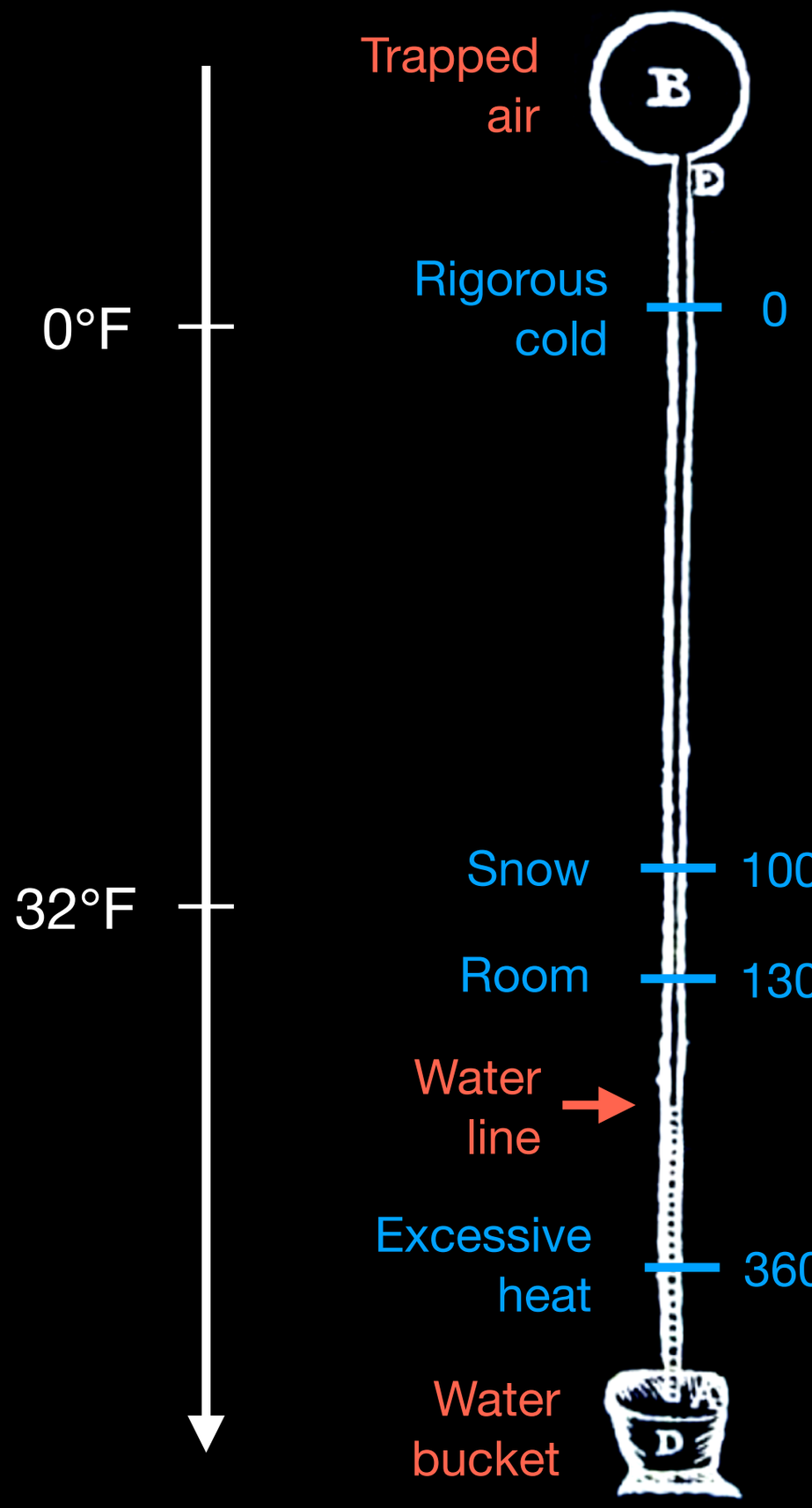
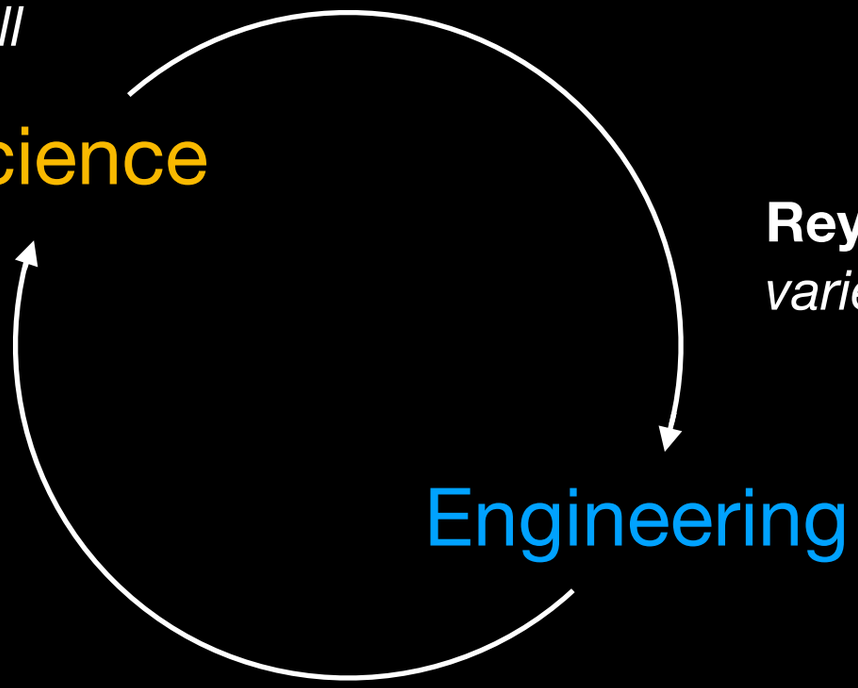


# The evolution of thermometry

**Sagredo:** *"[…] although our senses tell differently."*

**Pascal:** *"[…] lack of certainty in the thermometer for indicating the degrees of heat […]"*

**Galen:** *"[…] from the hottest of all to the very coldest of all things we know […]"*



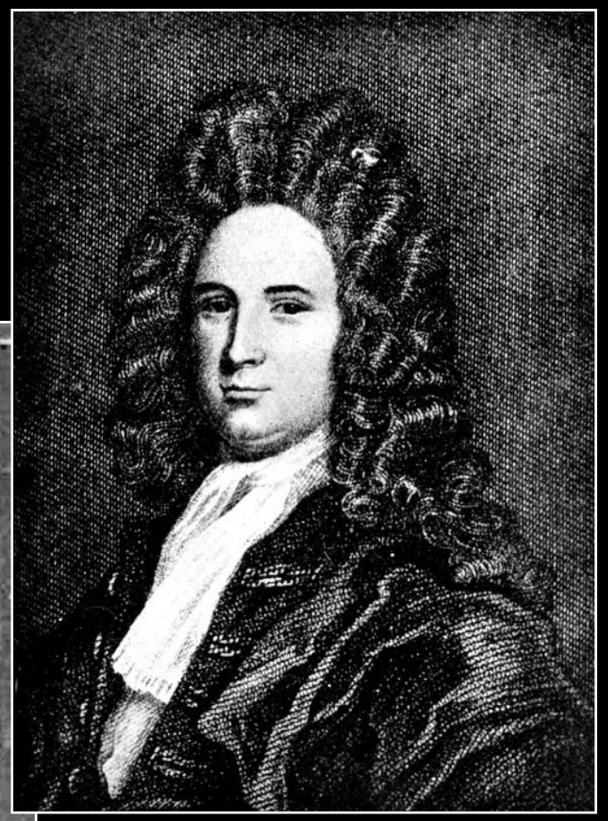

**Rey:** *"There are a variety of thermoscopes […]"*

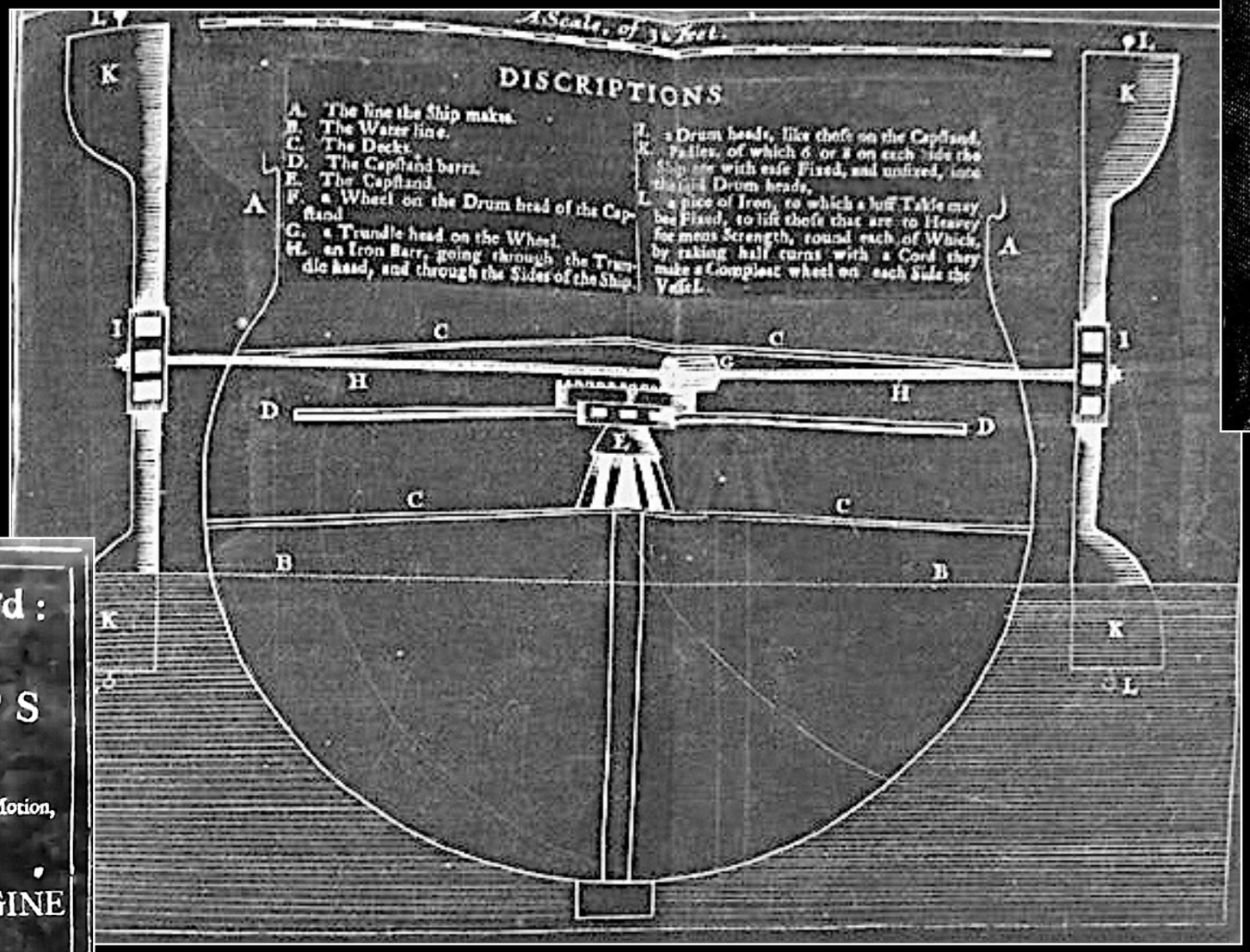
**Santorio:** *"A book about medical instruments that are not well-known […]"*

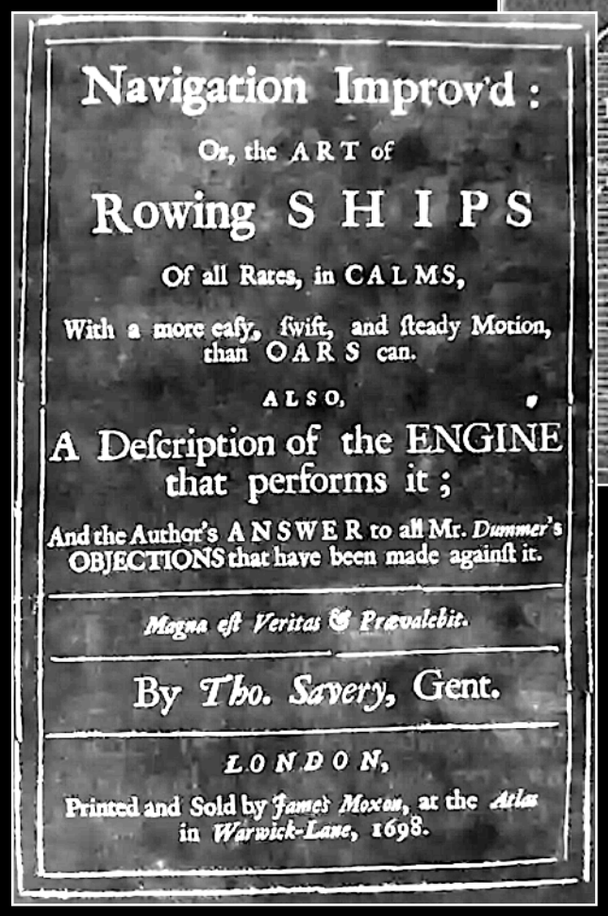
**Fahrenheit:** *"[…] the thermometers that I have built for the observation of the weather […]"*

# Captain Thomas Savery

## Military engineer, trench-master, hobbyist





Navigation Improv'd:
Or, the ART of
Rowing SHIPS
Of all Rates, in CALMS,
With a more easy, swift, and steady Motion, than OARS can.
ALSO,
A Description of the ENGINE that performs it;
And the Author's ANSWER to all Mr. *Dummer's* OBJECTIONS that have been made against it.
*Magna est Veritas & Prævalebit.*
By *Tho. Savery*, Gent.
*LONDON*,
Printed and Sold by *James Moxon*, at the *Atlas* in *Warwick-Lane*, 1698.

**Navigation improv'd:**
Or, the art of Rowing Ships of all Rates, in Calms, with a more easy, swift, and steady Motion than Oars can.

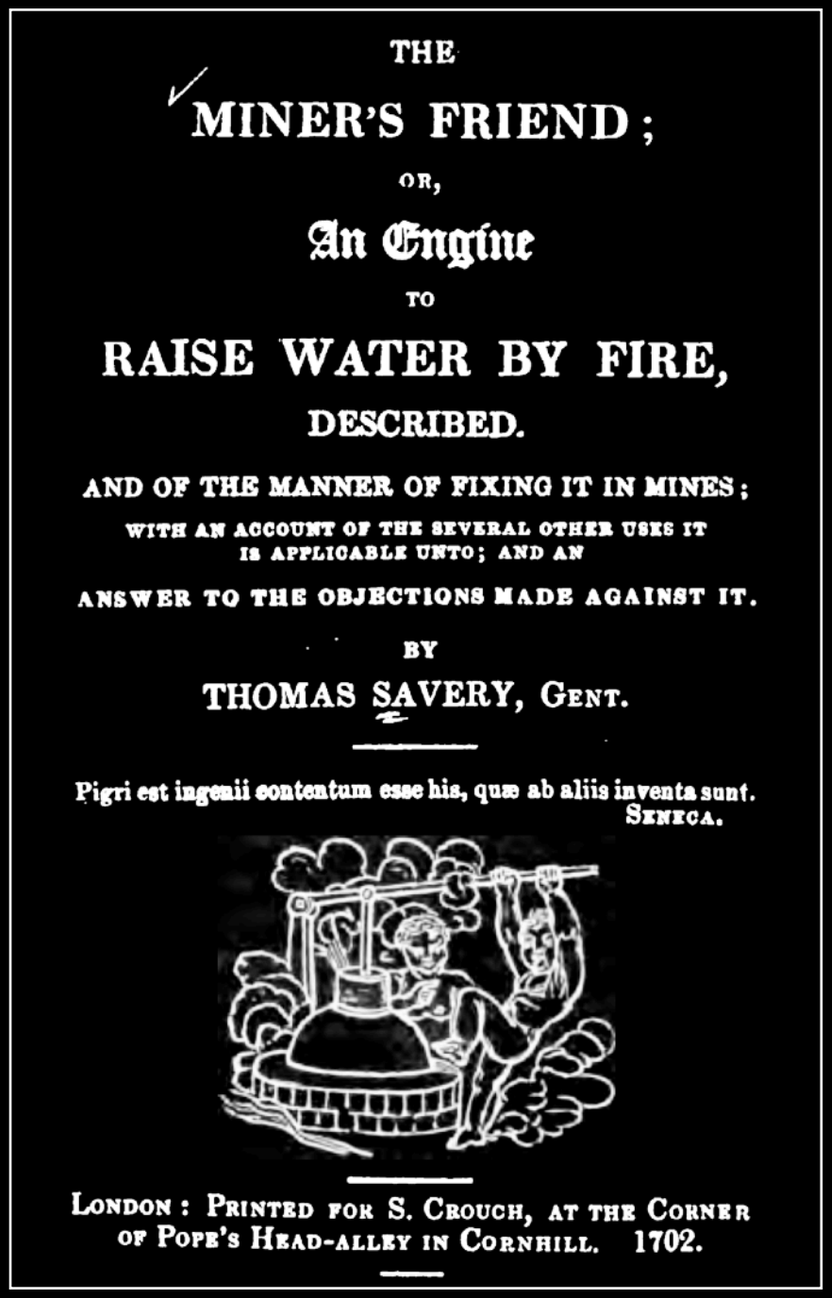
*Surveyor of the Royal British Navy: "And have interloping people, that have no concern with us, pretend to contrive or invent things for us?"*

# His second try: a steam pump

**Patented on 2 July 1698:**

*“A new Invention for Raiseing of Water and occasioning Motion to all Sorts of Mill Work by the Impellent Force of Fire, which will be of great use and Advantage for Drayning Mines, serveing Towns with Water, and for the Working of all Sorts of Mills where they have not the benefitt of Water nor constant Windes;*

*to hold for 14 years; with usual clauses”*



THE

MINER'S FRIEND;

OR,

An Engine

TO

RAISE WATER BY FIRE,

DESCRIBED.

AND OF THE MANNER OF FIXING IT IN MINES;

WITH AN ACCOUNT OF THE SEVERAL OTHER USES IT IS APPLICABLE UNTO; AND AN

ANSWER TO THE OBJECTIONS MADE AGAINST IT.

BY

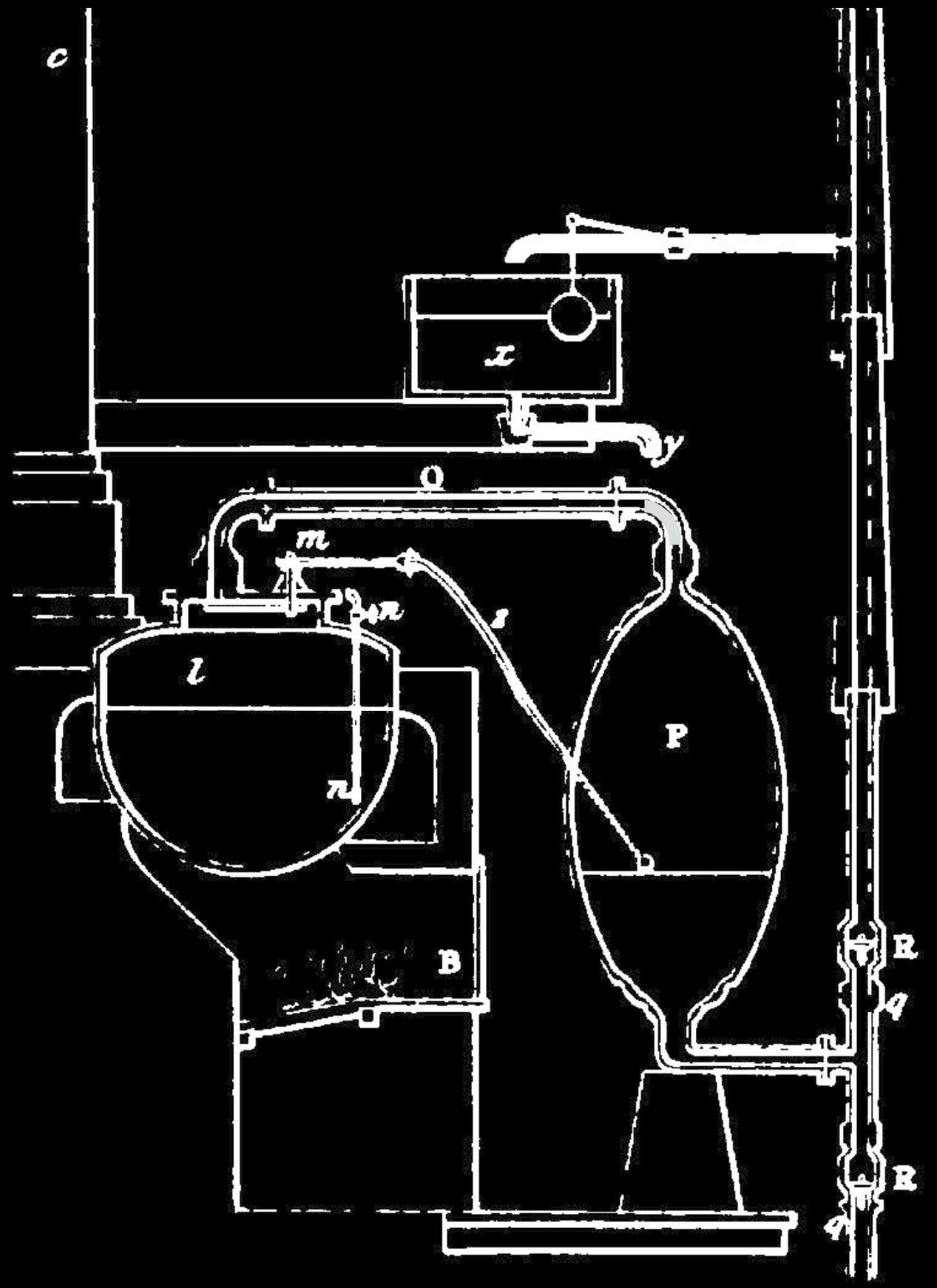
THOMAS SAVERY, GENT.

Pigri est ingenii contentum esse his, quæ ab aliis inventa sunt.
SENECA.

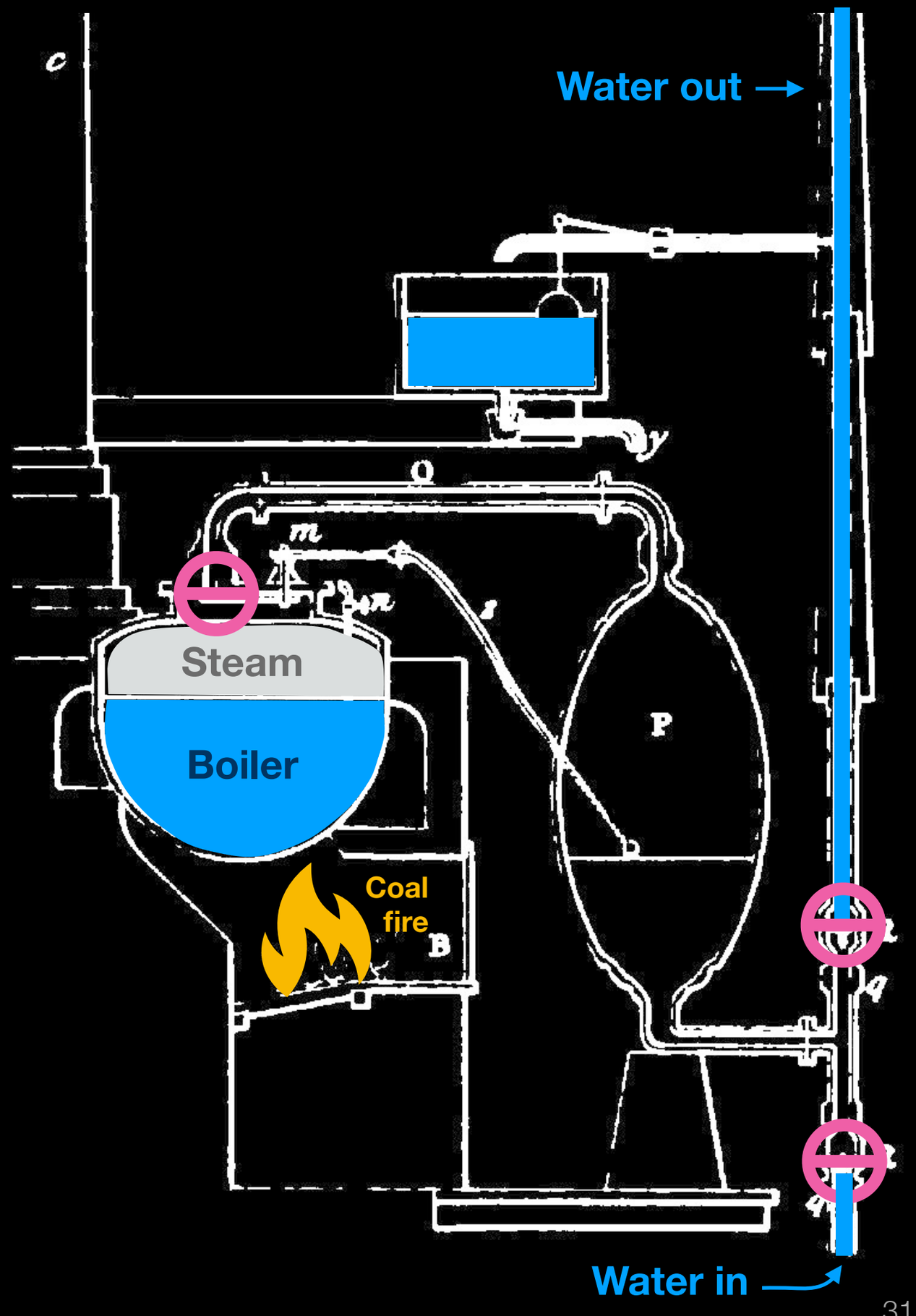


(Published right around Rømer’s proposal for his temperature scale)

# The “Savery Engine”



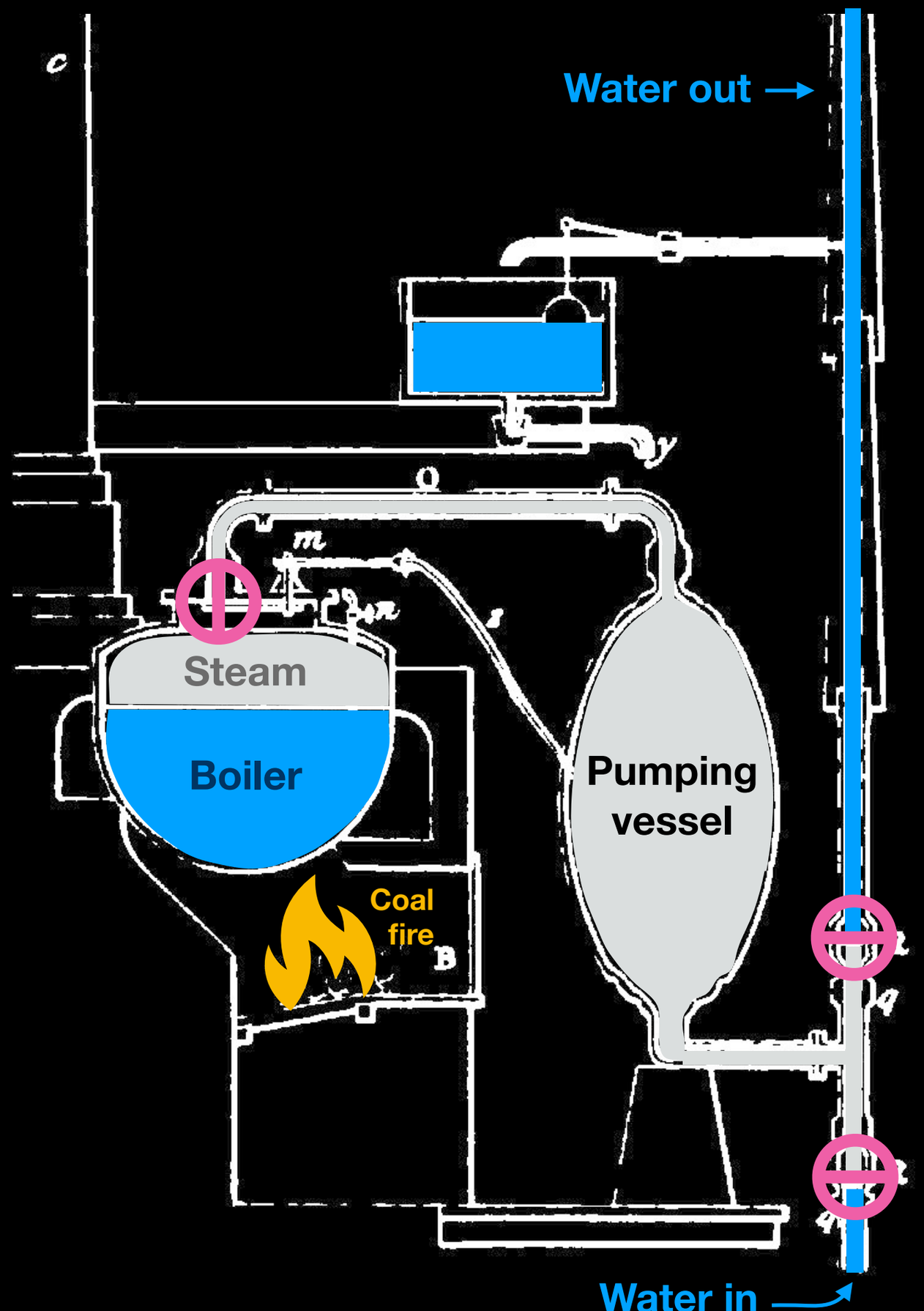
# The “Savery Engine”



# The “Savery Engine”

**Pumping cycle:**

**1.) Pumping vessel connected to boiler; filled with steam**

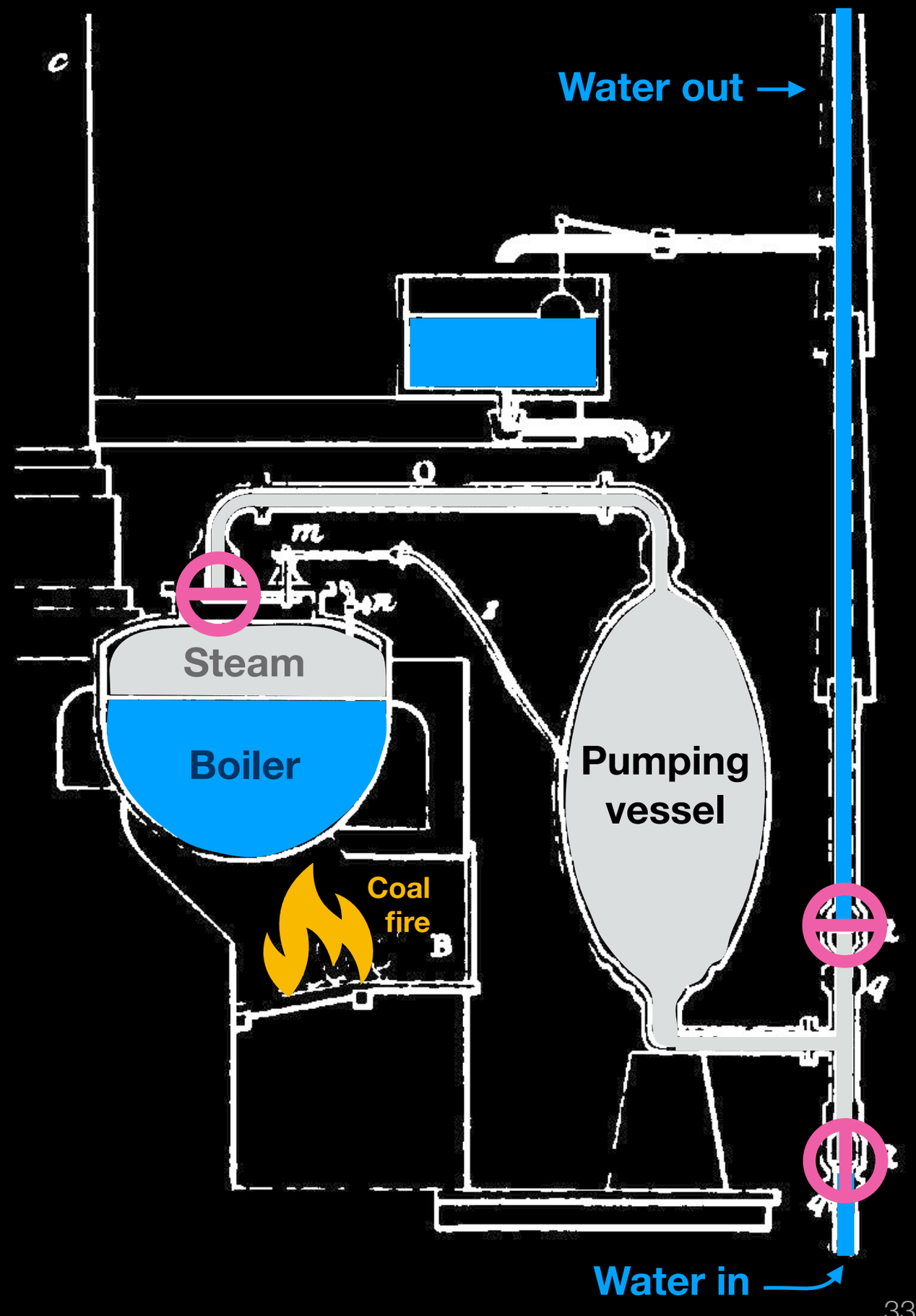


# The “Savery Engine”

**Pumping cycle:**

**1.) Pumping vessel connected to boiler; filled with steam**

**2.) Pumping vessel isolated from boiler; connected to intake**



# The “Savery Engine”

**Pumping cycle:**

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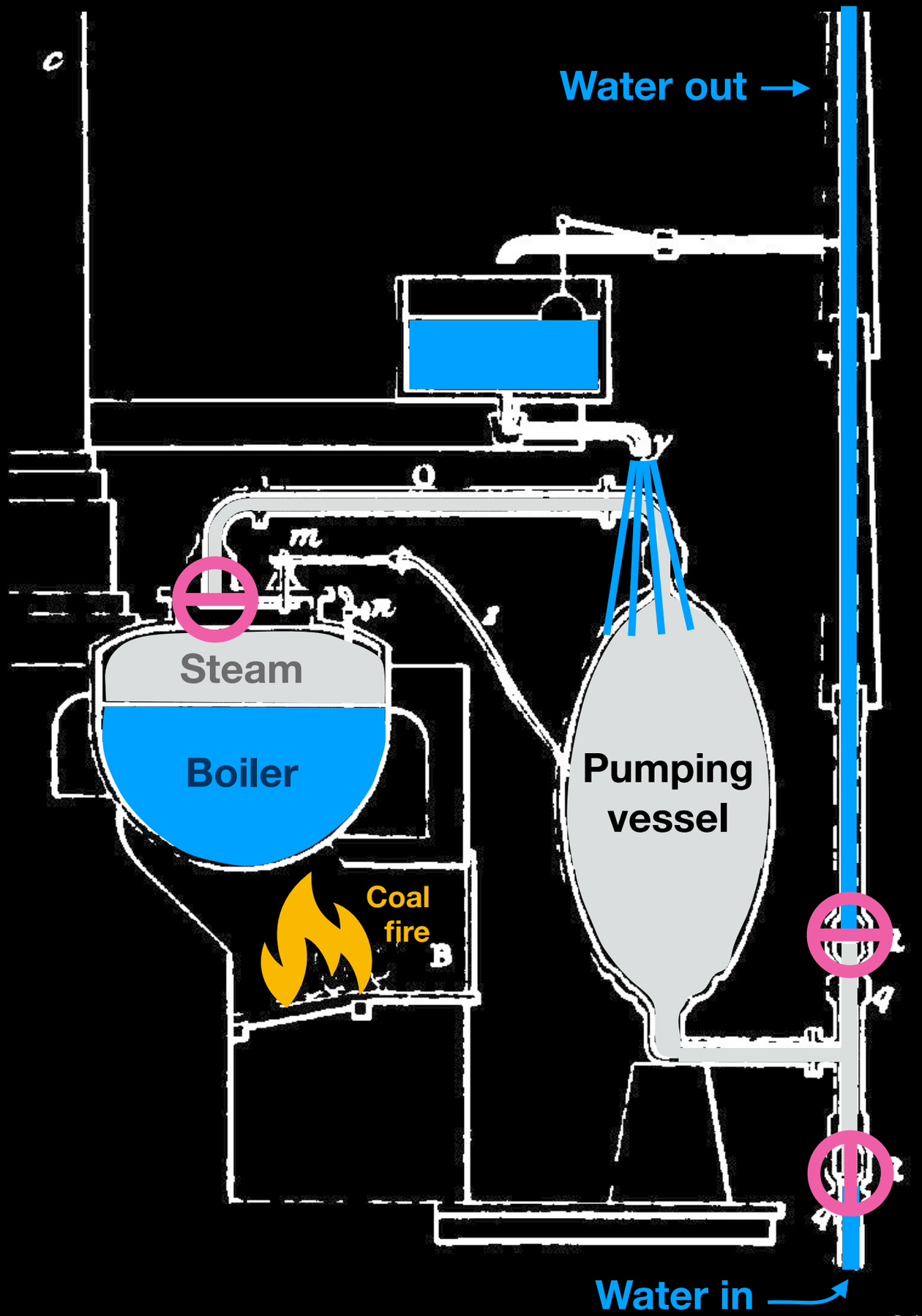
**3.) Pumping vessel doused with water and cooled down**



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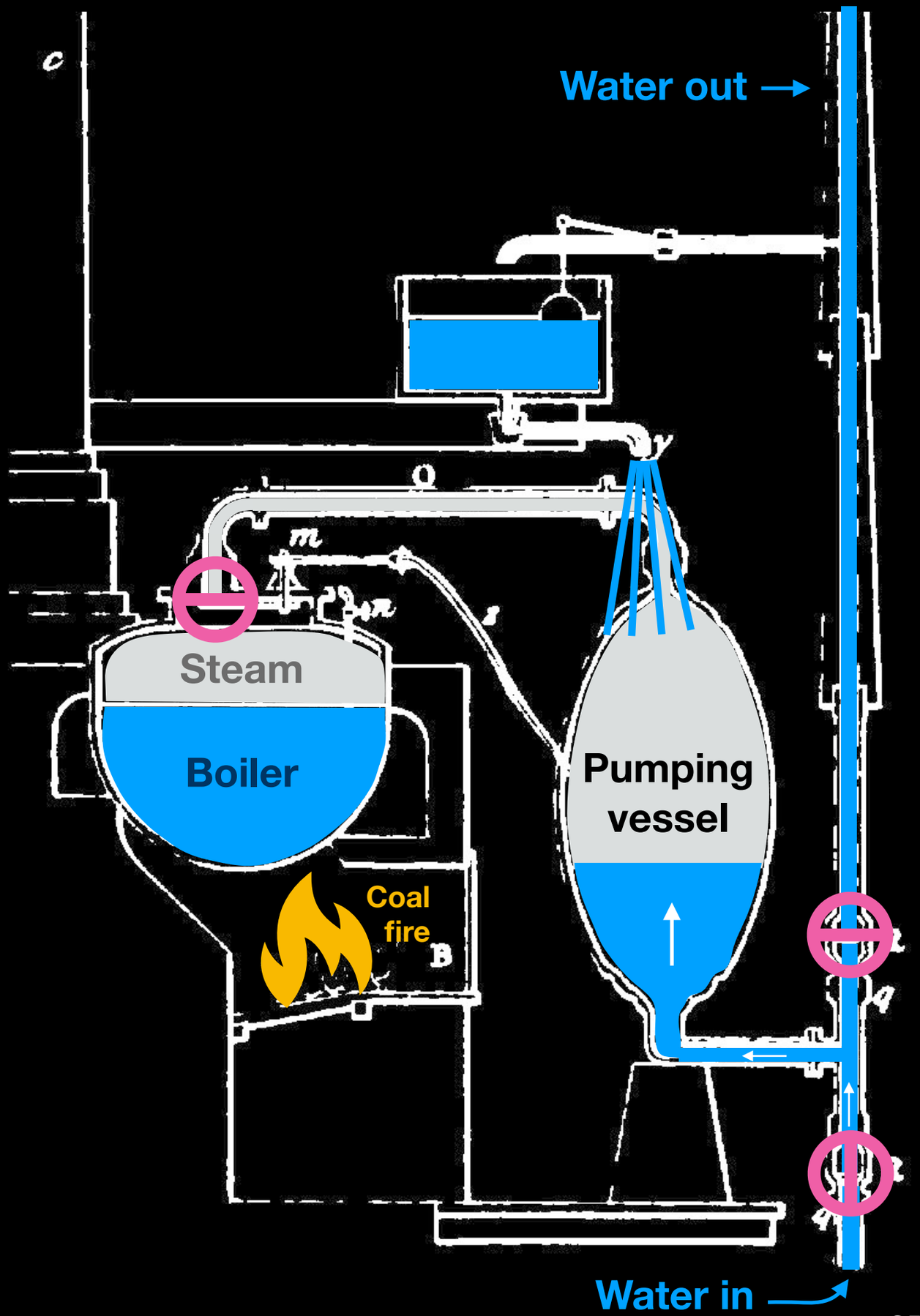

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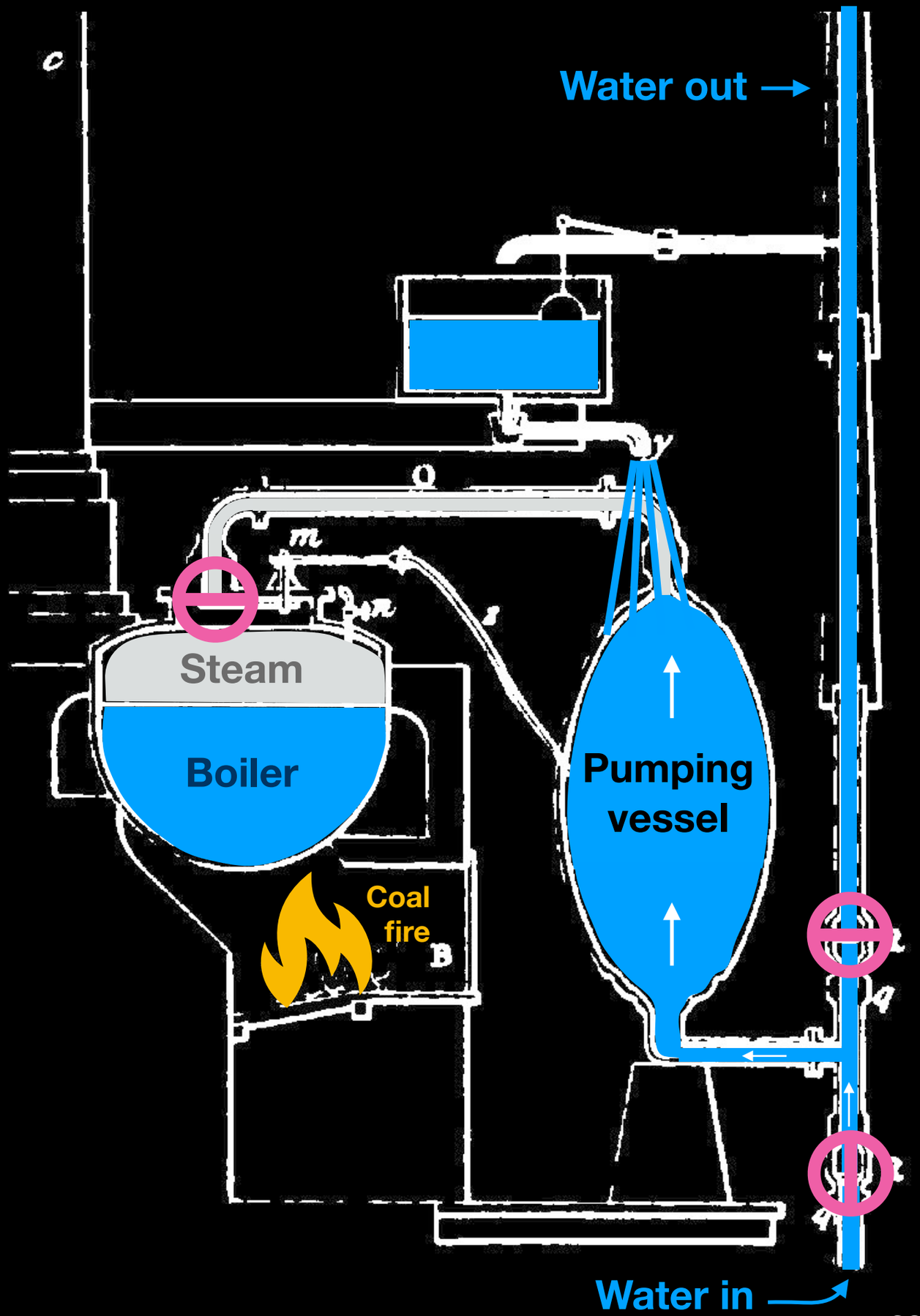

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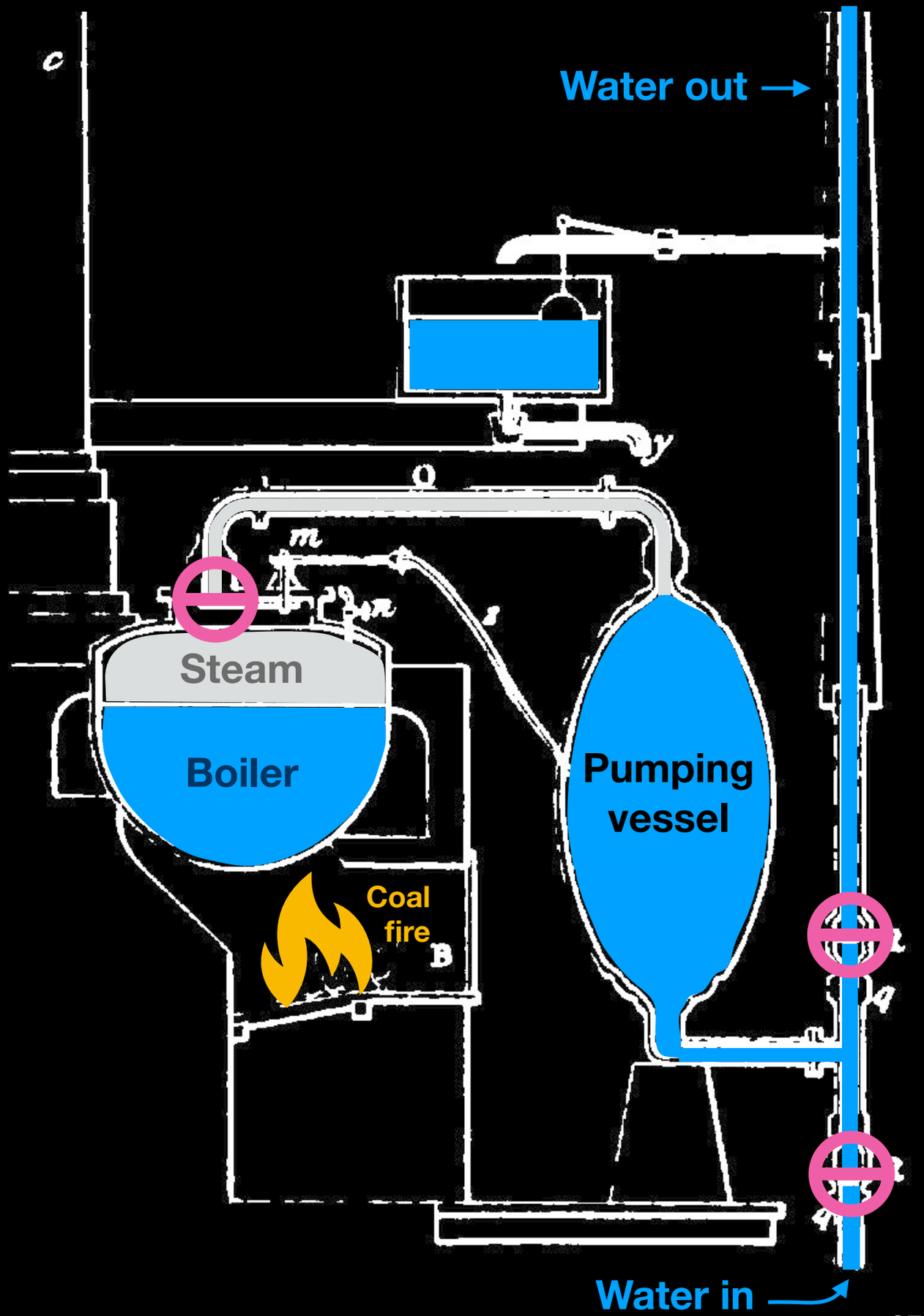

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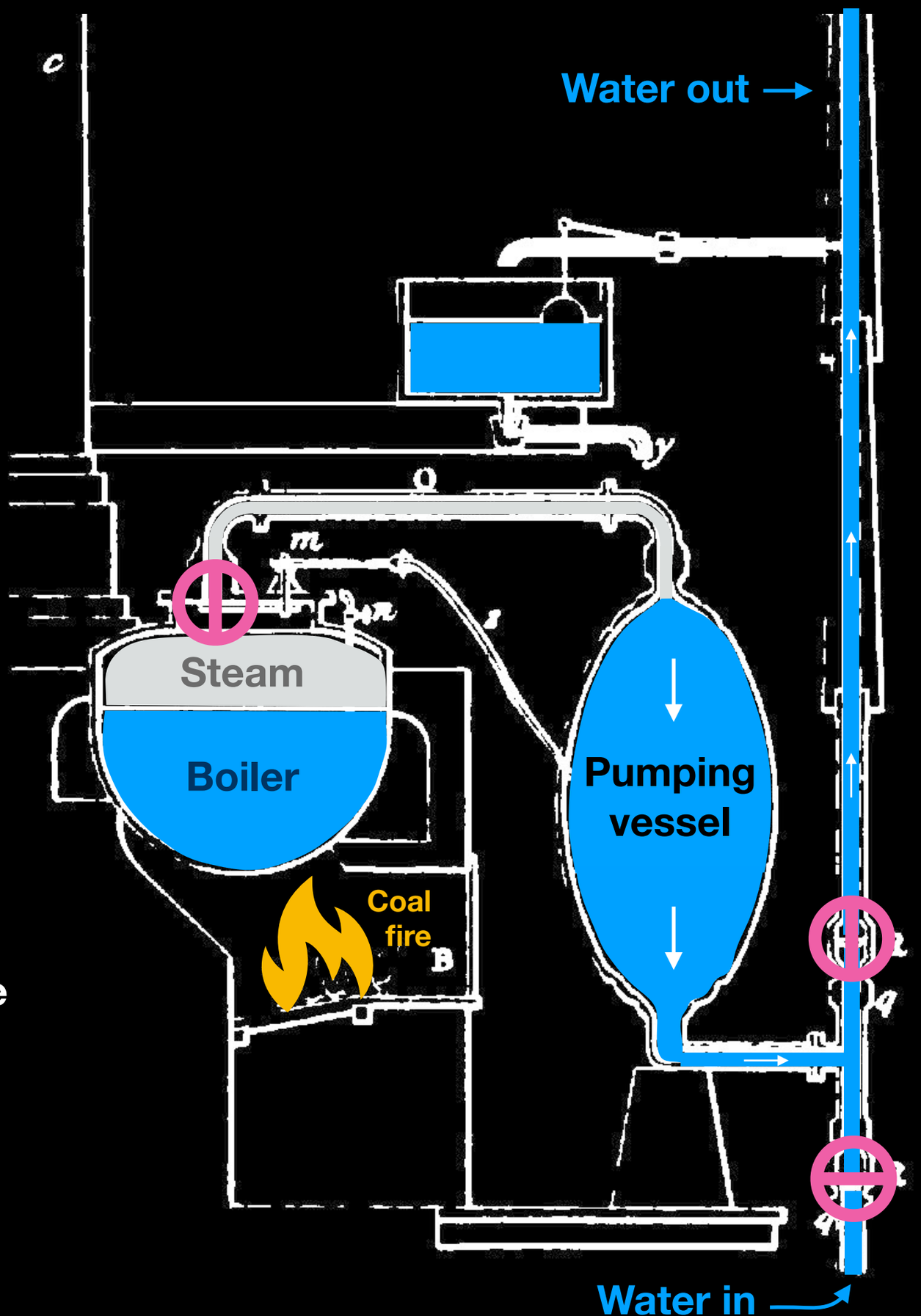

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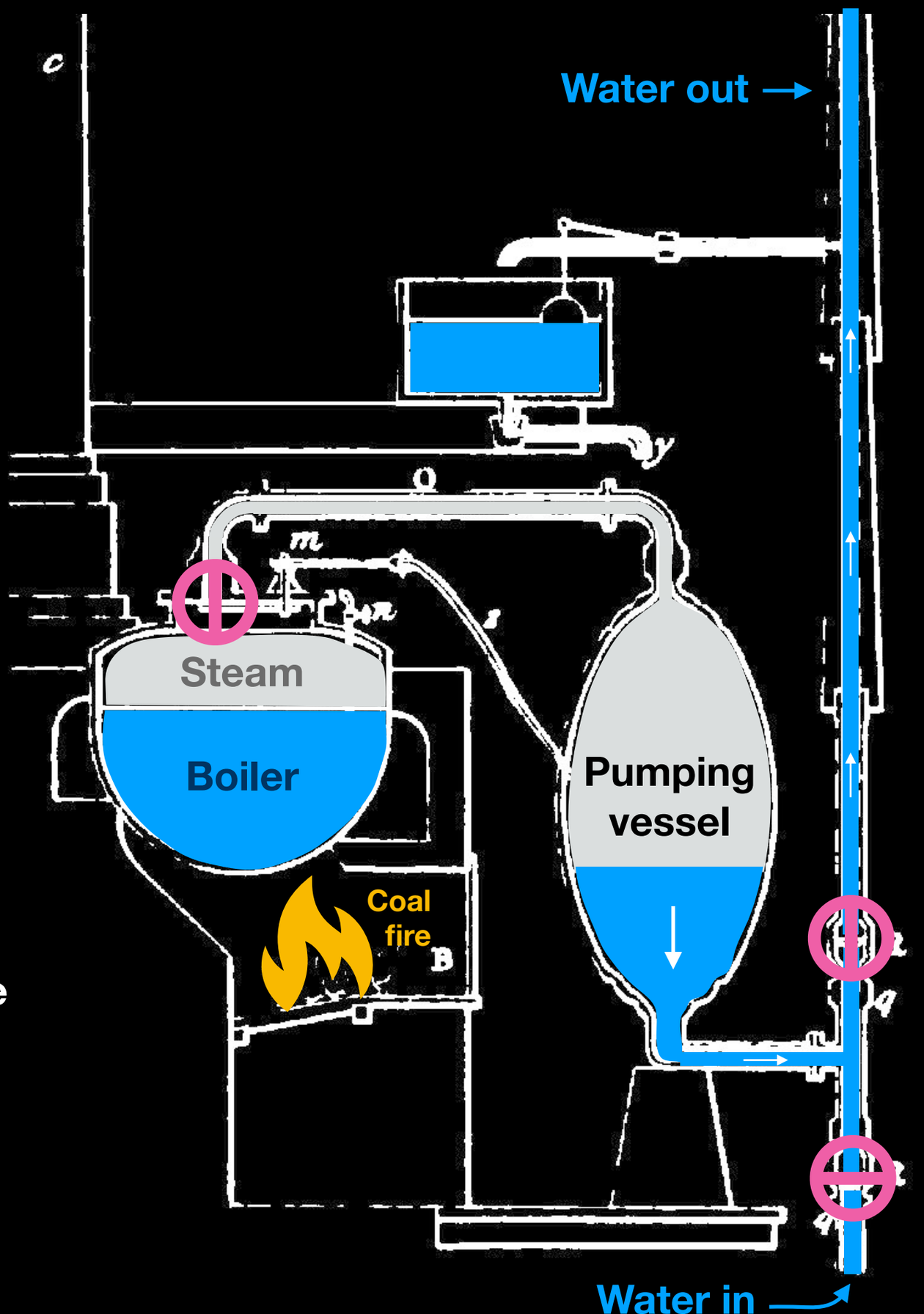

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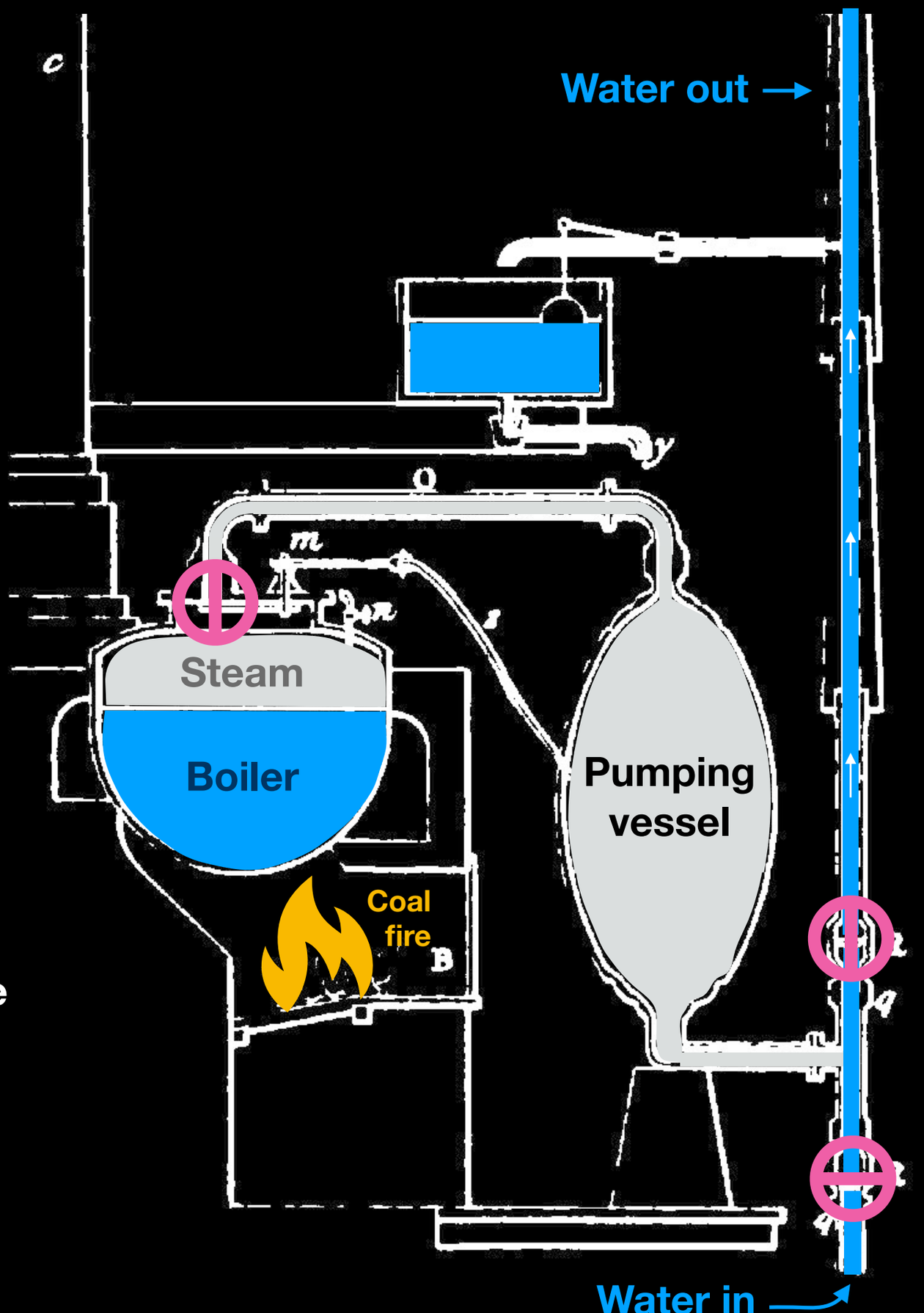
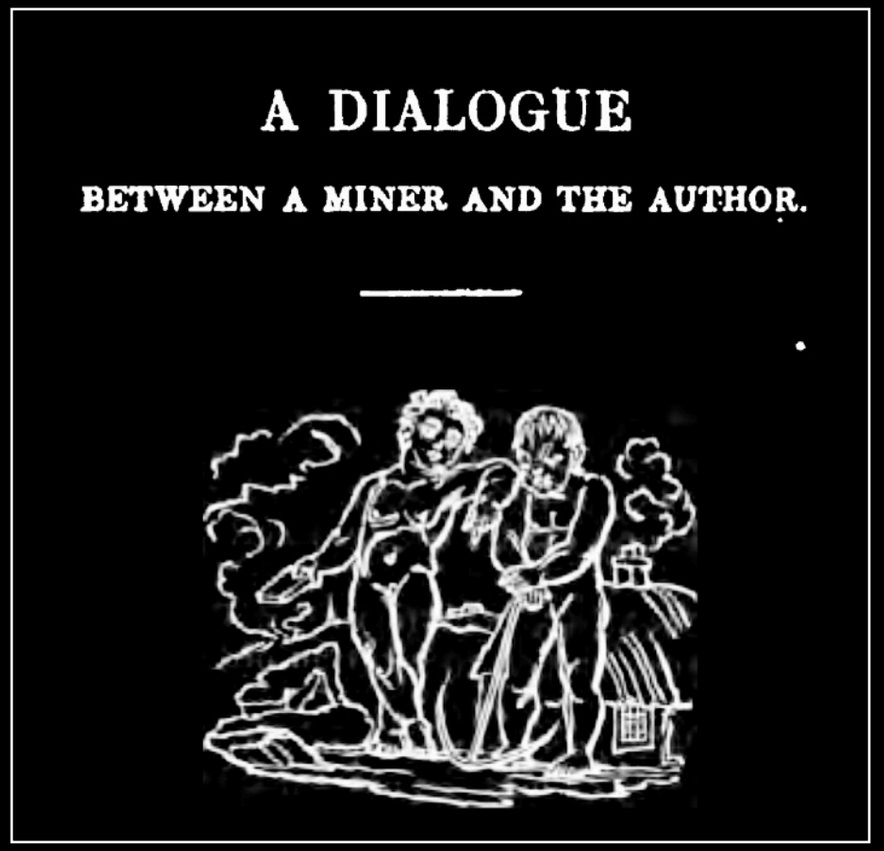


# Savery the salesman

**Miner:** *"Sir, having been some time concerned in the engines now used for drawing water out of our mines, and hearing so much talk of this wonderful invention of yours, of raising water by fire, I was very desirous to enter into some discourse with you concerning the nature […] of your engine, so strangely different from all other engines ever yet invented for our works. […]"*


A DIALOGUE

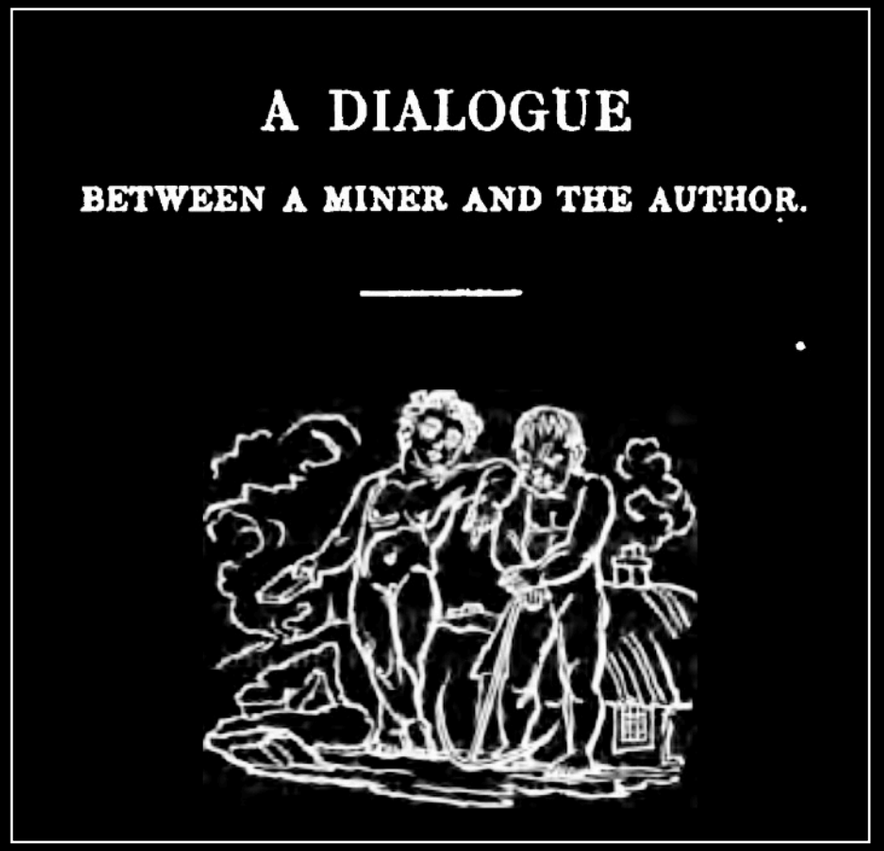
BETWEEN A MINER AND THE AUTHOR.

(From Savery's "A Miner's friend")

# Savery the salesman

**Miner:** *“Dear Sir, if sixty, seventy, or eighty feet be the determinate height or raising of water by your engine, how shall we use your engine in a mine or pit that requires water to be raised three times eighty feet, as you know some of our works do.“*

**Author:** *“I heartily thank you, sir, for this last proposal, because I have now an opportunity to acquaint you, that the force used in my engine is in a matter infinite and unlimited, and will raise your water five hundred or one thousand feet high, were any pit so deep; and that you could find us a way to procure strength enough to support such an immense weight, as a pillar of water a thousand feet high must certainly produce.”*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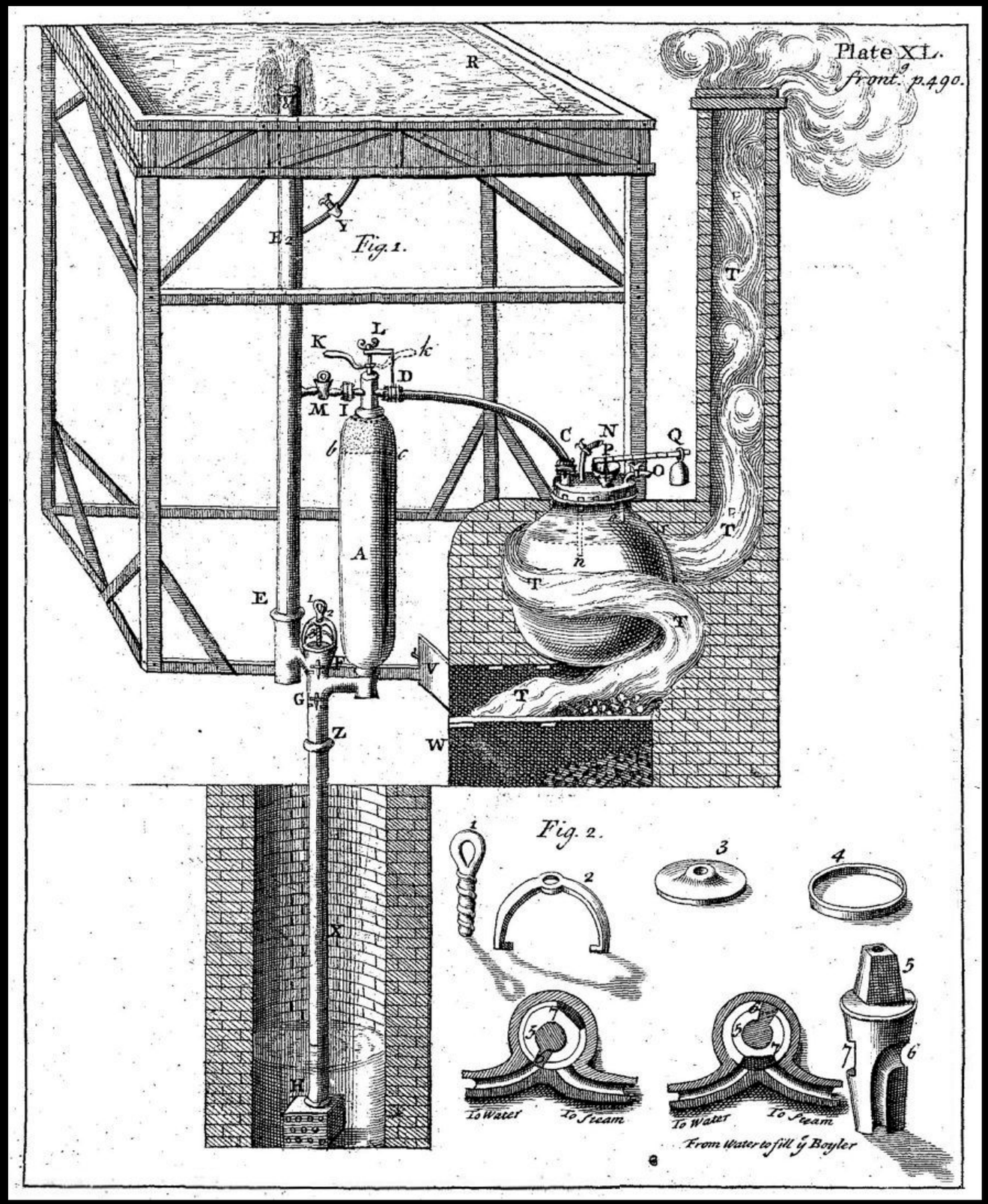
**In reality: high-pressure steam led to boiler explosions!**

# The Savery Engine in action

**Never became the “Miner’s friend”**

Used in two London waterworks



# Thomas Newcomen

## Ironmonger in Devonshire, phantom

*“Now it happened that a man from Dartmouth, named Thomas Newcomen, without any knowledge whatever of the speculations of Captain Savery, had at the same time also made up his mind, in conjunction with his assistant, a plumber by the name of Calley, to invent a fire-machine for drawing water from the mines.*

*He was induced to undertake this by considering the heavy cost of lifting water by means of horses, which Mr. Newcomen found existing in the English tin mines.*

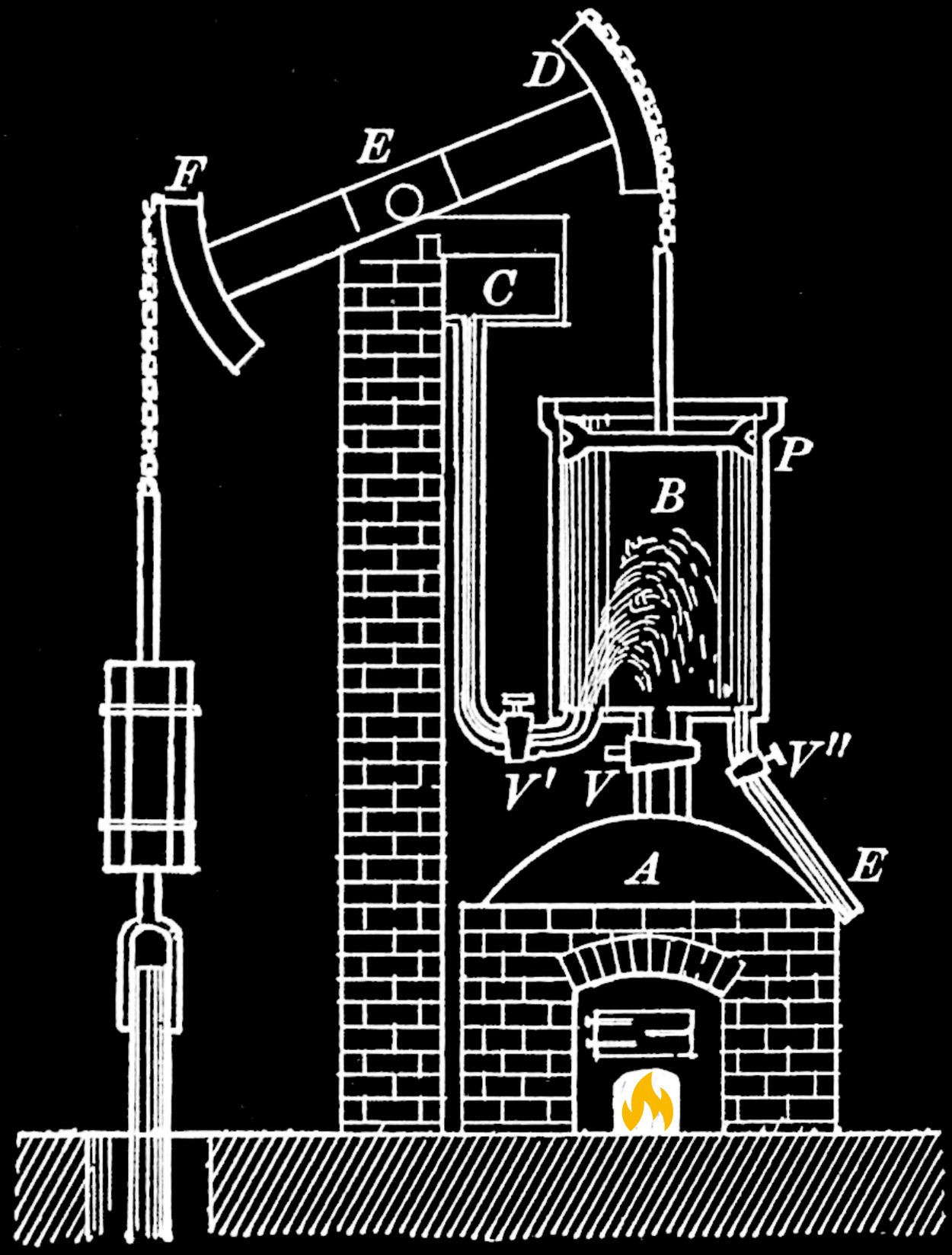
*These mines Mr. Newcomen often visited in the capacity of a dealer in iron tools with which he used to furnish many of the tin mines.”*

**From the records of Marten Triewald**

# Newcomen’s “atmospheric engine”

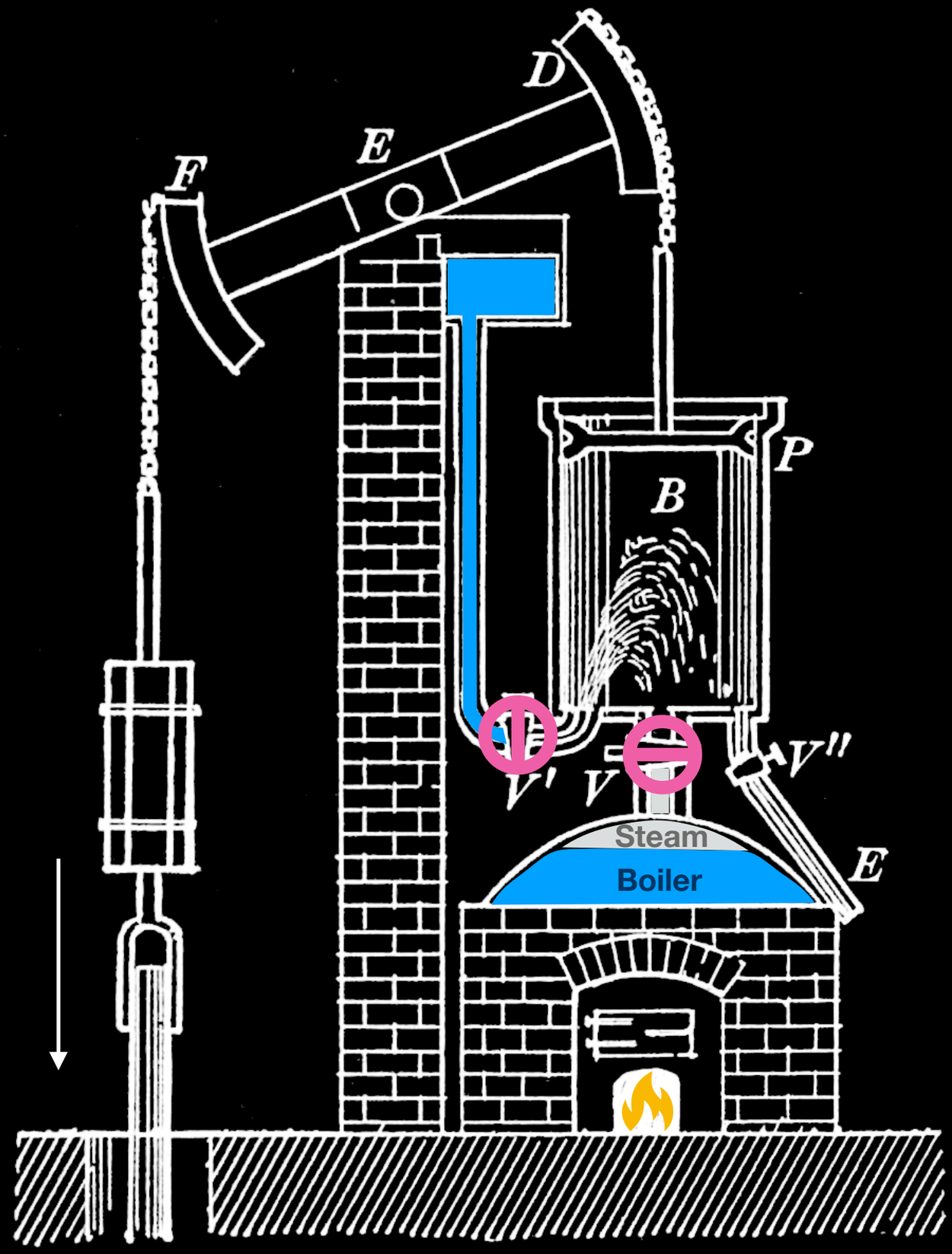
“For ten consecutive years Mr. Newcomen worked at this fire-machine …”

**Marten Triewald**



# Newcomen's "atmospheric engine"

**Pumping cycle:**

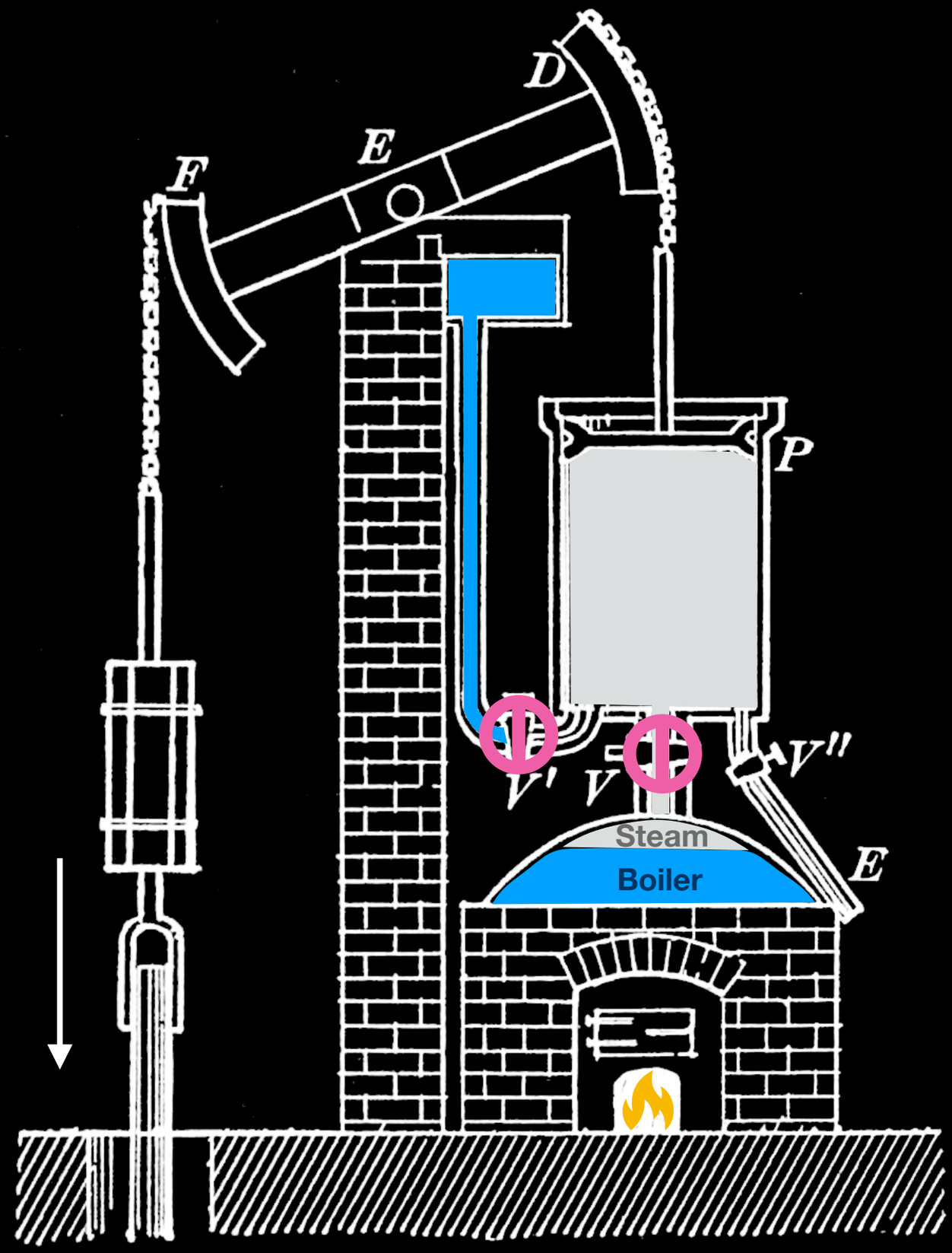


# Newcomen's "atmospheric engine"

**Pumping cycle:**

**1.) Piston connected with boiler, filled with steam**

**→ Piston extends, counterweight is lowered**



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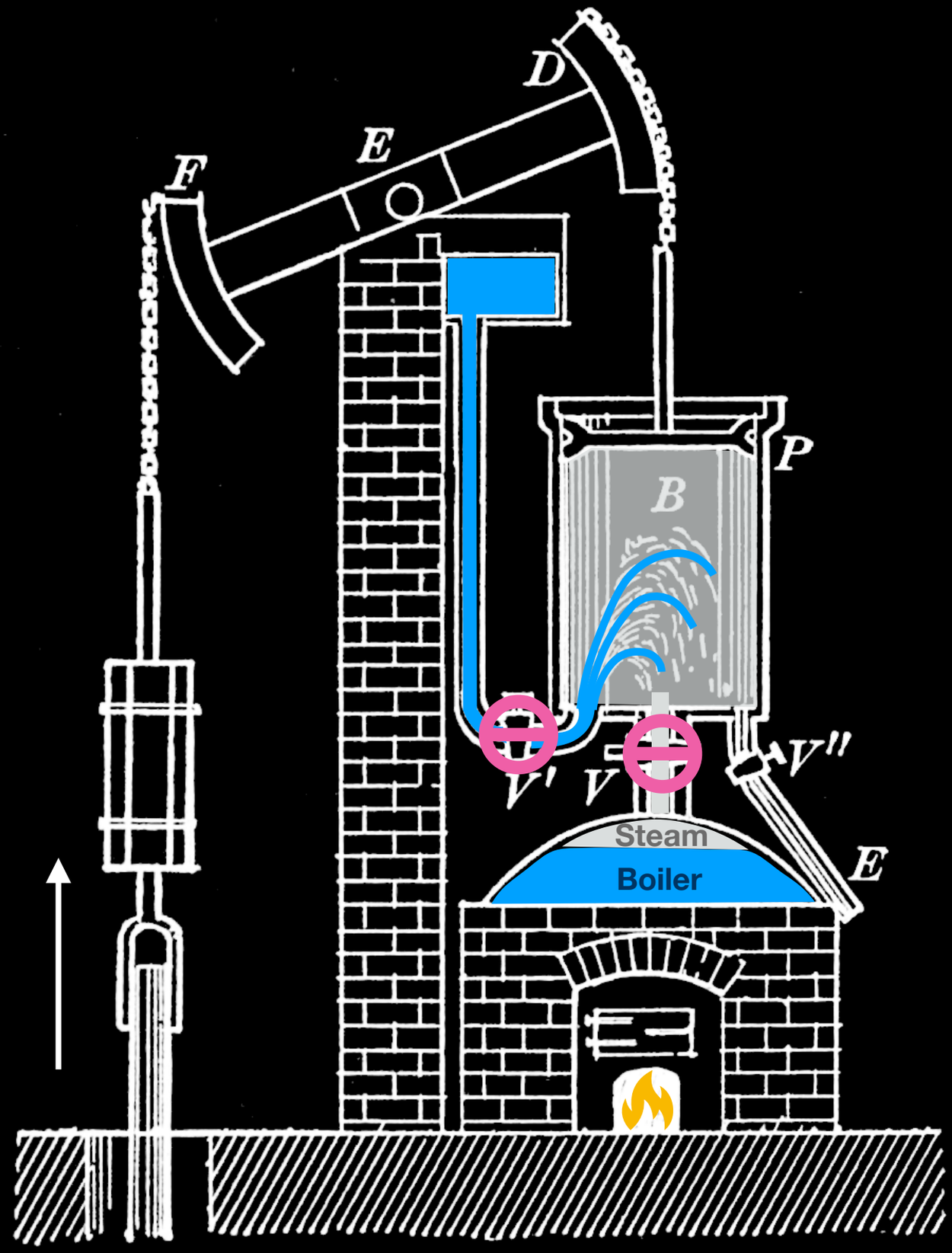
**→ Steam condenses, atmospheric pressure pushes piston back in, counterweight is raised**



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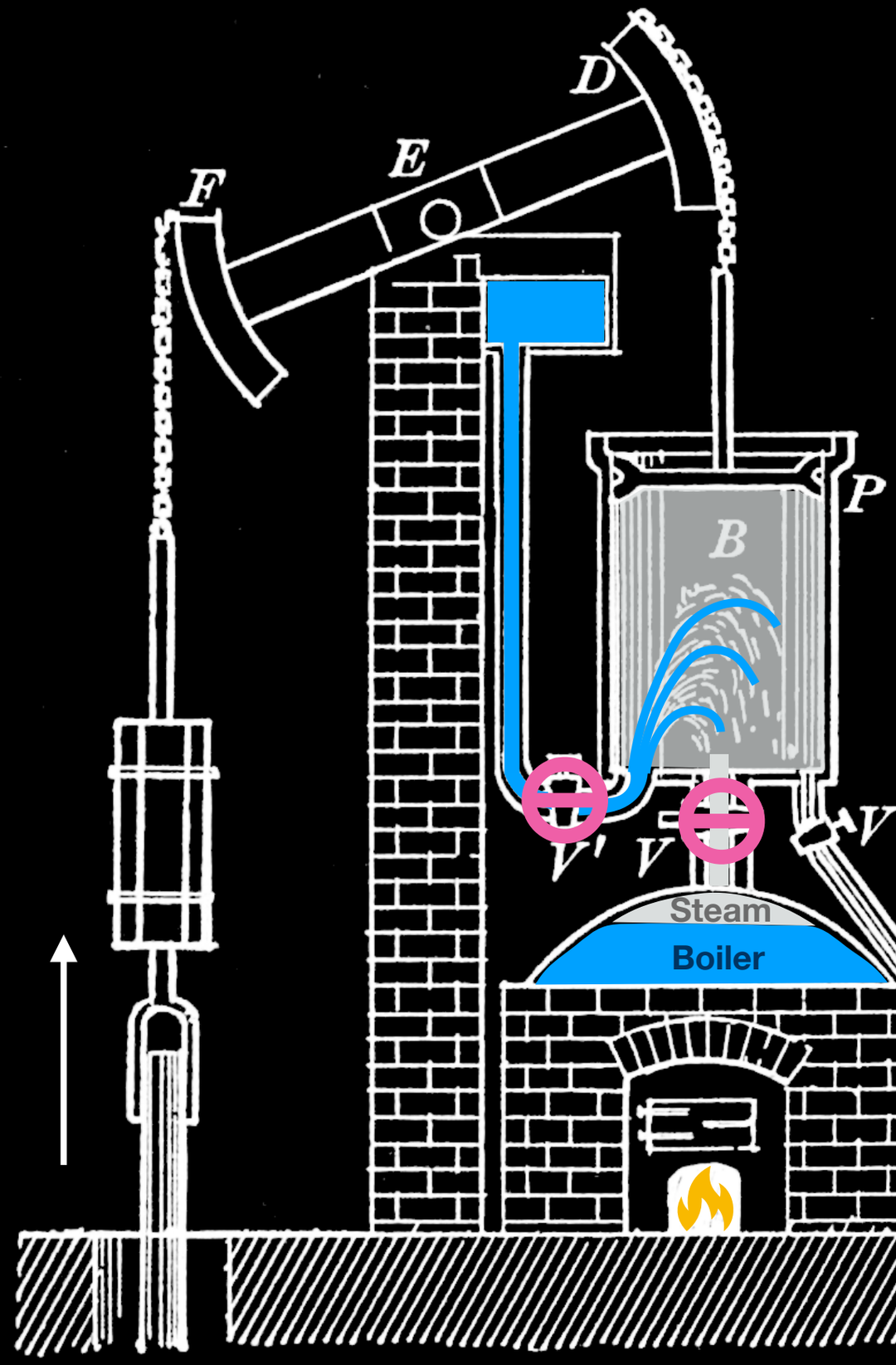
**Up- and downward movement of shaft drives pump**

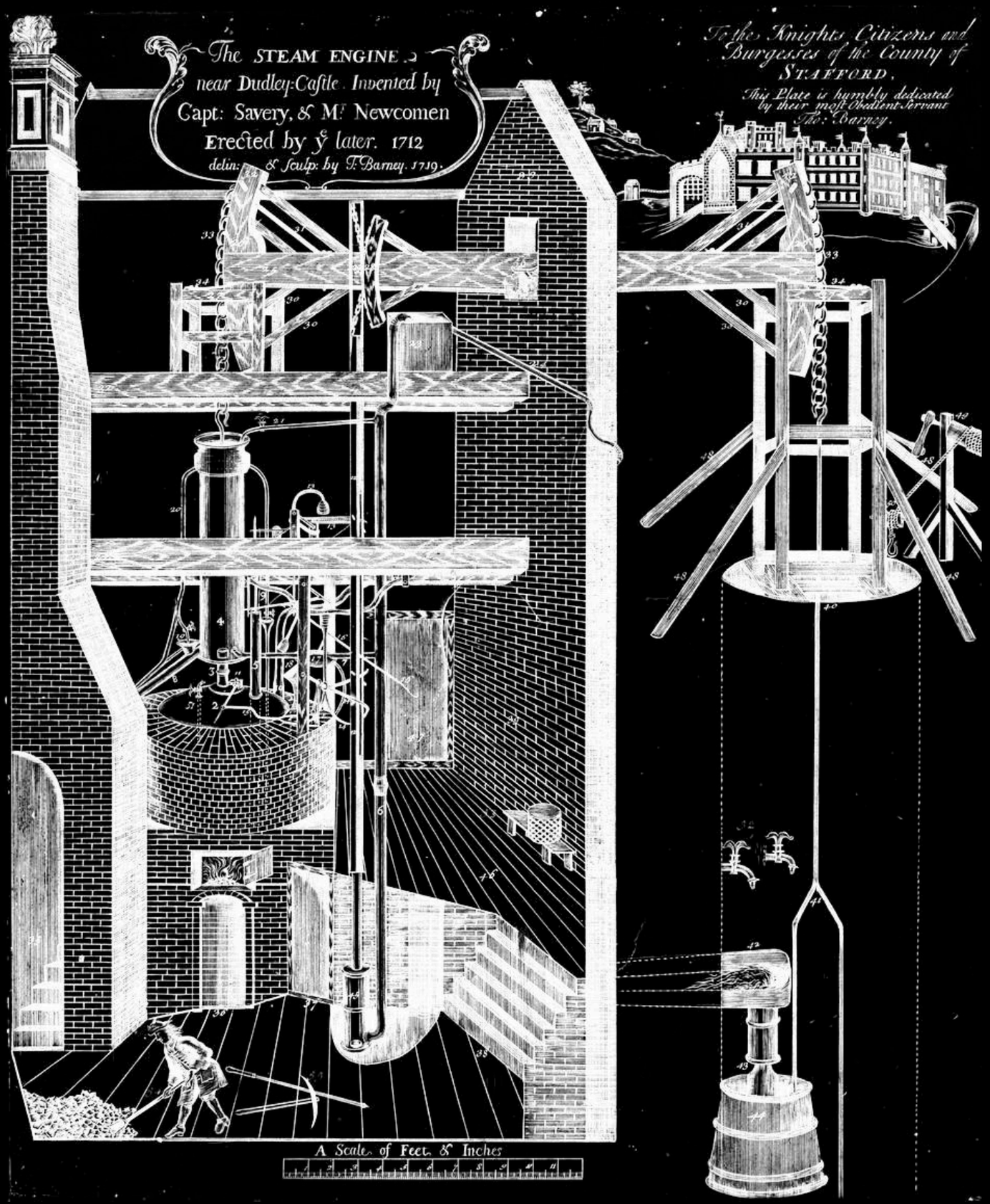
No need for high-pressure steam
→ more reliable



# The first Newcomen engine in operation

*“The steam engine near Dudley castle.*

*Invented by Capt. Savery & Mr. Newcomen, Erected by ye later 1712”*



# The Newcomen engine spreads …

… under Savery's patent!

**Announcement in the *London Gazette,* 11-14 August 1716**

by

*The Proprietors of the Invention for Raising Water by Fire*

*"Whereas the invention of raising water by fire, authorized by parliament, is lately brought to the greatest perfection, and all sorts of mines, &c, may be thereby drained, and water raised to any height with more ease and less charge than by the other methods hitherto used, as is sufficiently demonstrated by diverse engines of this invention now at work in the several counties of Stafford, Warwick, Cornwall and Flint.*

*These are therefore to give notice that if any person shall be desirous to treat with the Proprietors for such engines, accordance will be given for that purpose every Wednesday, at Sword-Blade Coffee-House in Birchin Lane, London from 3 to 5 of the clock; and if any letters be directed thither to be left for Mr Elliot, the parties shall receive all fitting satisfaction and dispatch."*

# The Newcomen engine spreads …

… under Savery's patent!

Bernissart, Belgium
(built 1781)

Landgoed Groenendaal,
Netherlands
(shown in 1780s)

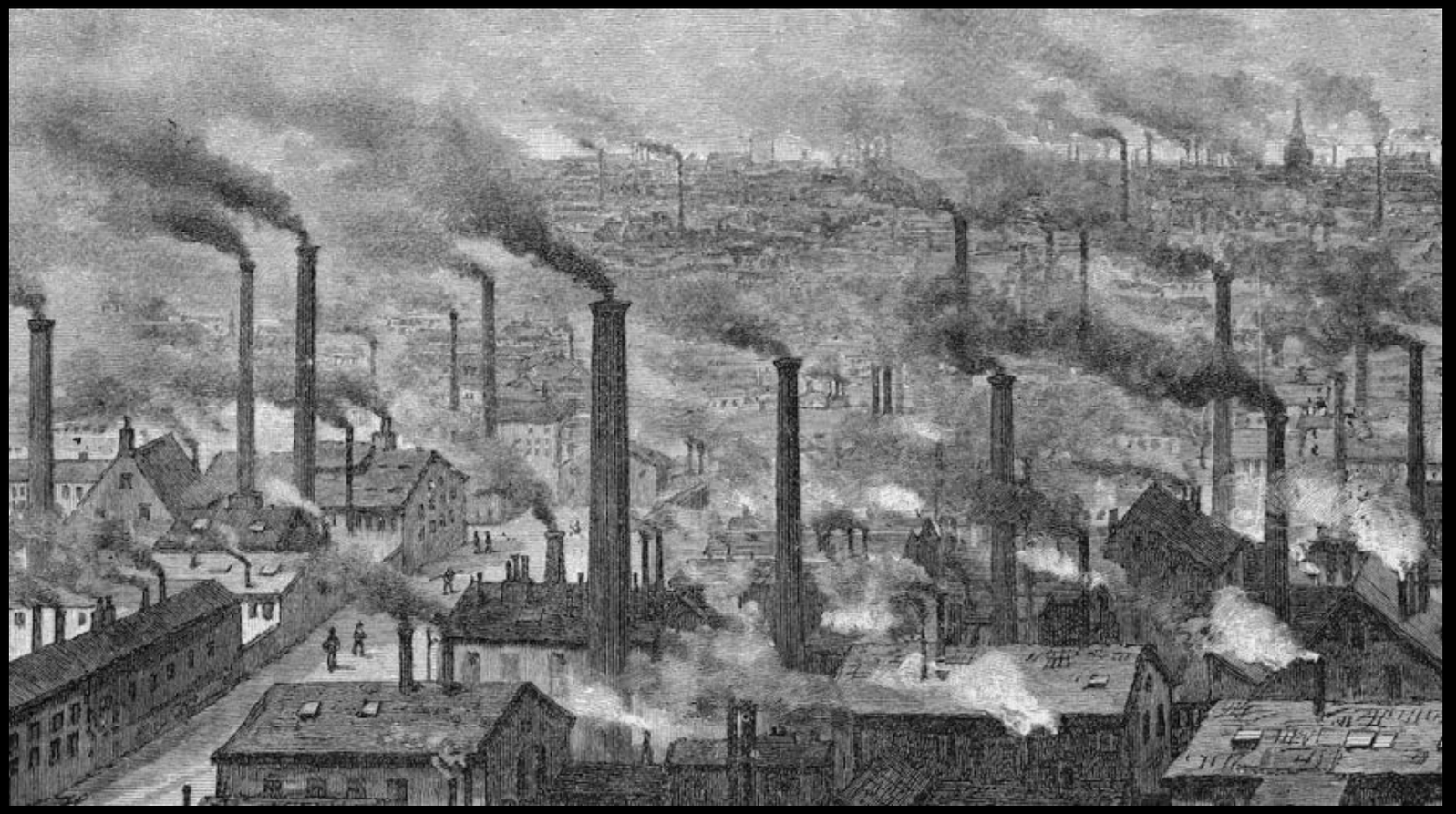
"Fairbottom Bobs" at a coal mine in
Lancashire, England
(operating 1760-1827)

Now at Henry Ford museum in Dearborn, MI

**~1500 Newcomen engines had been built by 1800**

# The Newcomen engine spreads …

**Extremely inefficient workhorse of the early industrial revolution:**
deep coal mines, blast furnaces, …

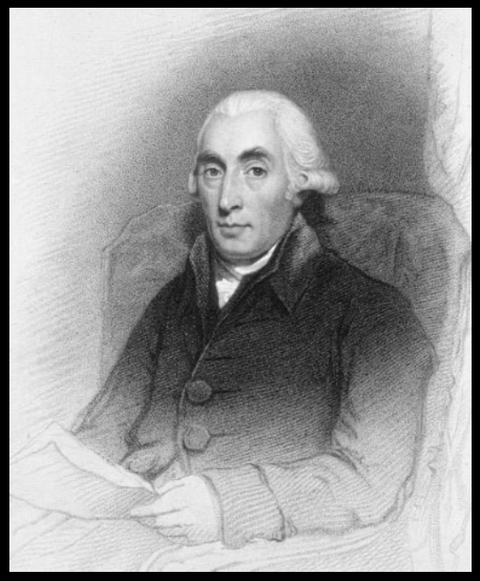


*And did the Countenance Divine,*
*Shine forth upon our clouded hills?*
*And was Jerusalem builded here,*
*Among these dark Satanic Mills?*

"And did those feet in ancient time",
William Blake, 1804

# Joseph Black

Professor of anatomy and chemistry in Glasgow



University of Glasgow (1756–1766)

*Newcomen's machine already well-established!*

**John Robison:**

*"Dr. Black had no wish to form a medical school which should be distinguished by some all-comprehending doctrine.*

*He contented himself with giving a clear and systematic account of as much of physiology as he thought founded on good principles, and a short sketch of such general doctrines as were maintained by eminent authors, but perhaps on a less firm foundation. Without this, he said that his students could not read their writings, which, in other respects, were highly valuable."*

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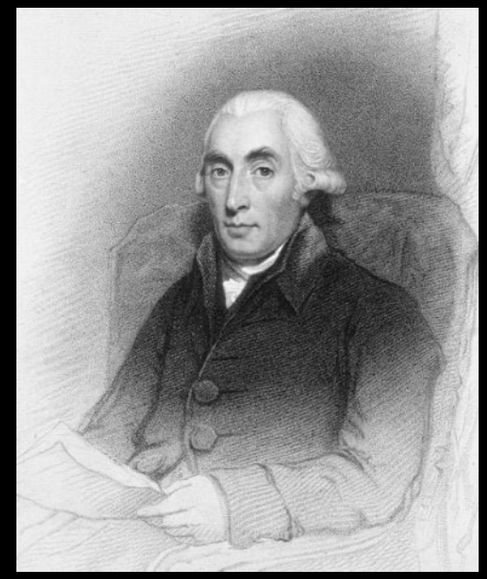


University of Glasgow (1756–1766)

*Newcomen's machine already well-established!*

**Letter to his father, September 20, 1763**

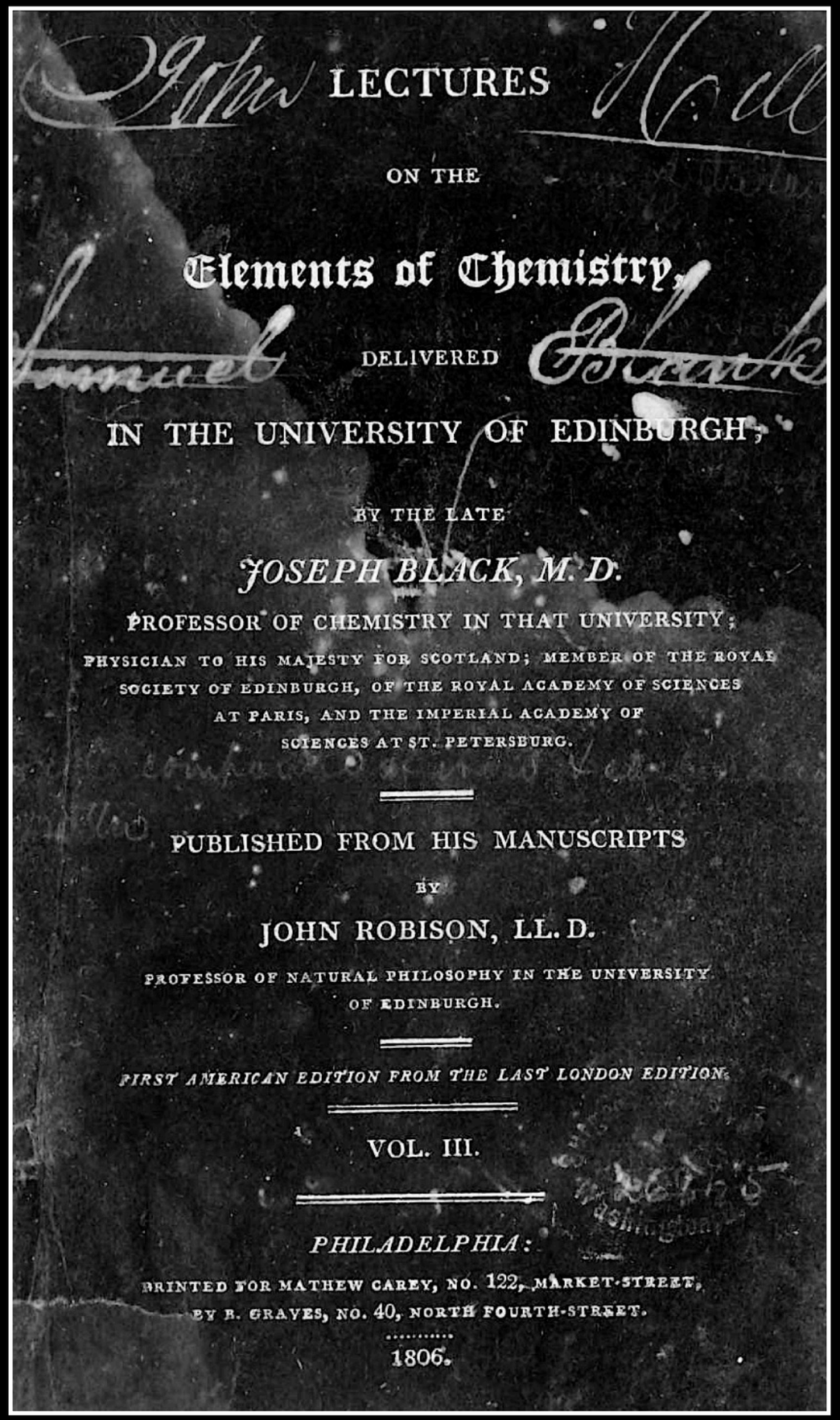
*"Dearest Sir,*
*I cannot reflect without blushing up not long time I have been in your debt for many of the kindest and most agreeable letters that ever son received from a father […]*

*My business as a member of the College & the moderate share of Practice I have in town & country, tho they would be very little trouble to others who have more spirits and activity, is yet enough to give me constantly some care and employment & seldom leaves me in that state of ease & good humor in which one would wish to write to their friends."*

# Black's lecture notes

**Published posthumously by John Robison from Black's notes and those of his students:**

*"Black's heavy duties, ill health, lack of initiative, and almost morbid horror of generalization prevented him from going further than forming a plan for a book"*


LECTURES

ON THE

Elements of Chemistry,

DELIVERED

IN THE UNIVERSITY OF EDINBURGH;

BY THE LATE

JOSEPH BLACK, M. D.

PROFESSOR OF CHEMISTRY IN THAT UNIVERSITY;

PHYSICIAN TO HIS MAJESTY FOR SCOTLAND; MEMBER OF THE ROYAL SOCIETY OF EDINBURGH, OF THE ROYAL ACADEMY OF SCIENCES AT PARIS, AND THE IMPERIAL ACADEMY OF SCIENCES AT ST. PETERSBURG.

PUBLISHED FROM HIS MANUSCRIPTS

BY

JOHN ROBISON, LL. D.

PROFESSOR OF NATURAL PHILOSOPHY IN THE UNIVERSITY OF EDINBURGH.

FIRST AMERICAN EDITION FROM THE LAST LONDON EDITION.

VOL. III.

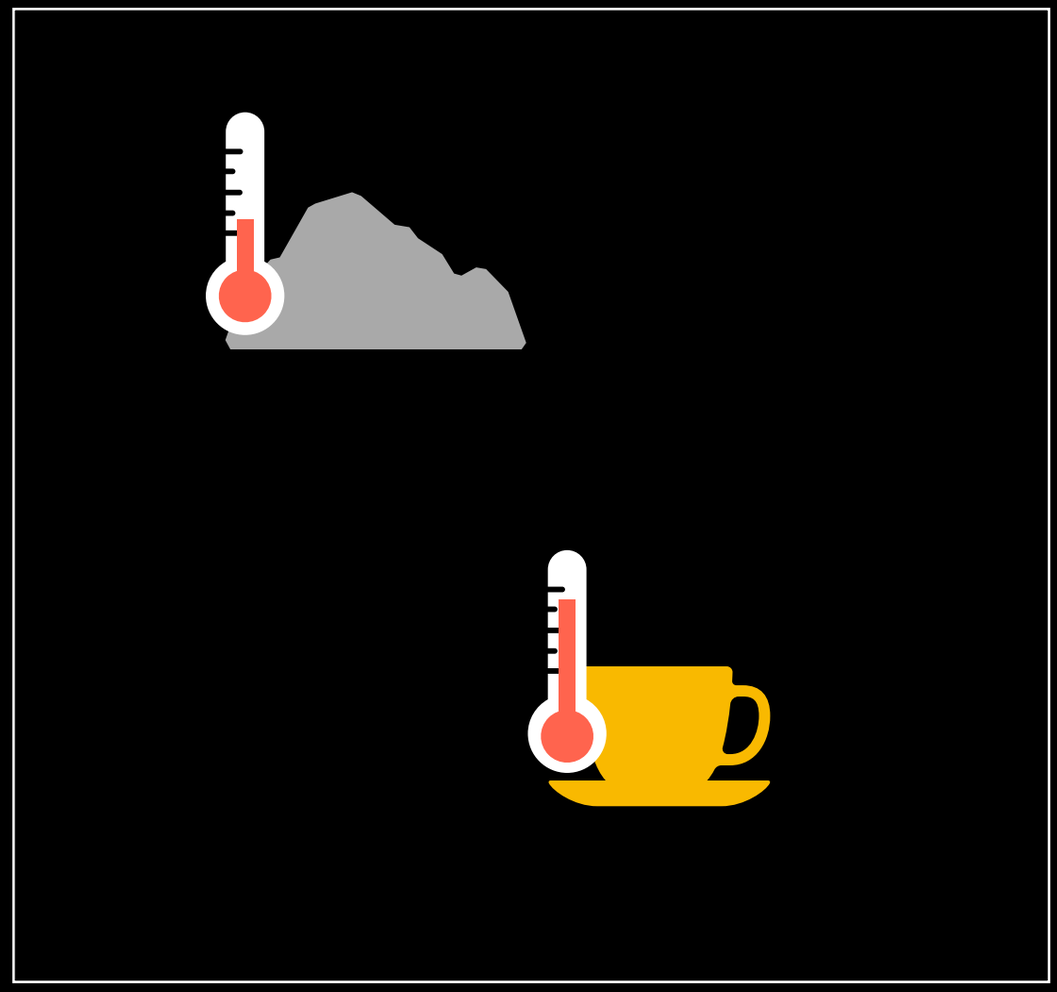
PHILADELPHIA:

PRINTED FOR MATHEW CAREY, NO. 122, MARKET-STREET, BY R. GRAVES, NO. 40, NORTH FOURTH-STREET.

1806.

# Black's "equilibrium"

*"By the use of thermometers we have learned that, if we take a thousand, or more, different kinds of matter —metals, stones, salts, woods, cork, feathers, wool, water and a variety of other fluids— although they be all at first of different temperatures, and if we put them together in a room without a fire, and into which the sun does not shine, the heat will be communicated from the hotter of these bodies to the colder,*



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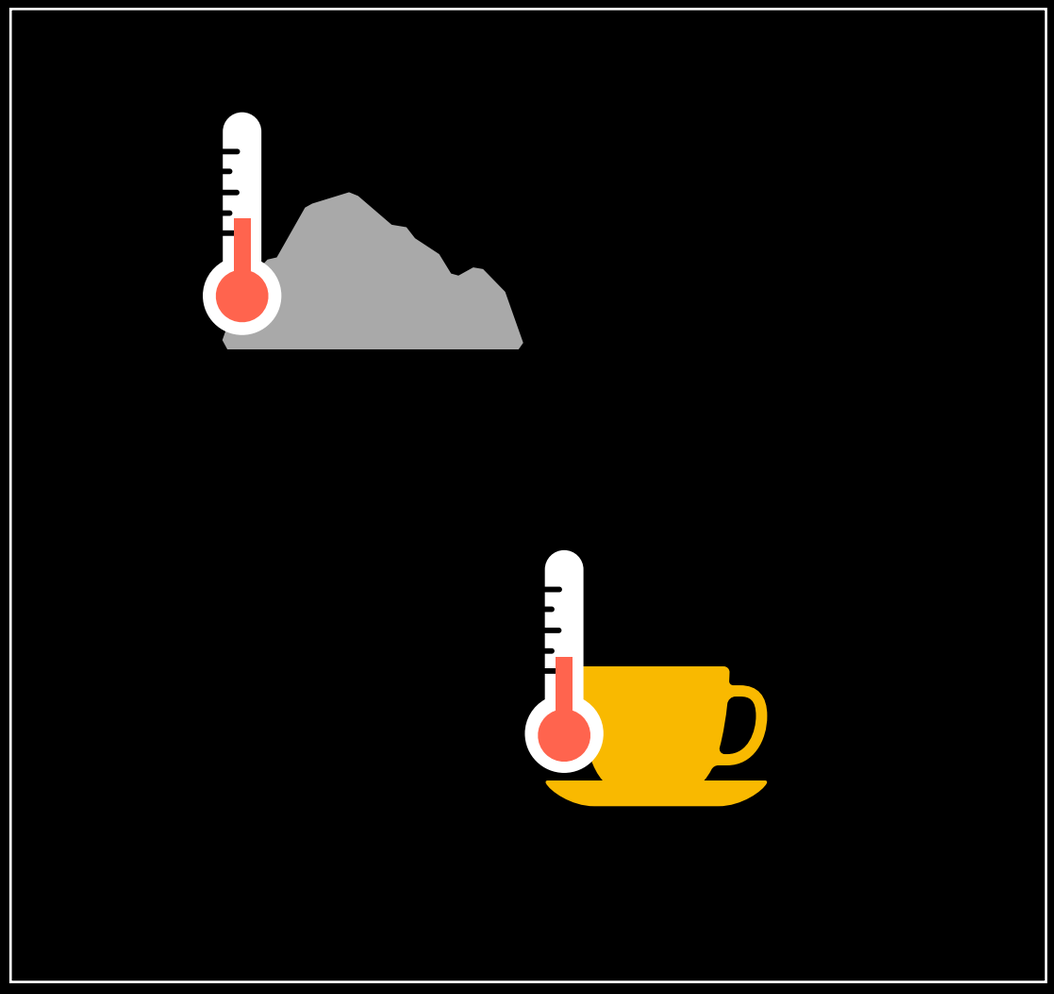


**The thermometer has been critical for this observation to be made!**

*A piece of metal and feathers at the same temperature feel very different*

**Sagredo**: *"[…] although our senses tell differently"*

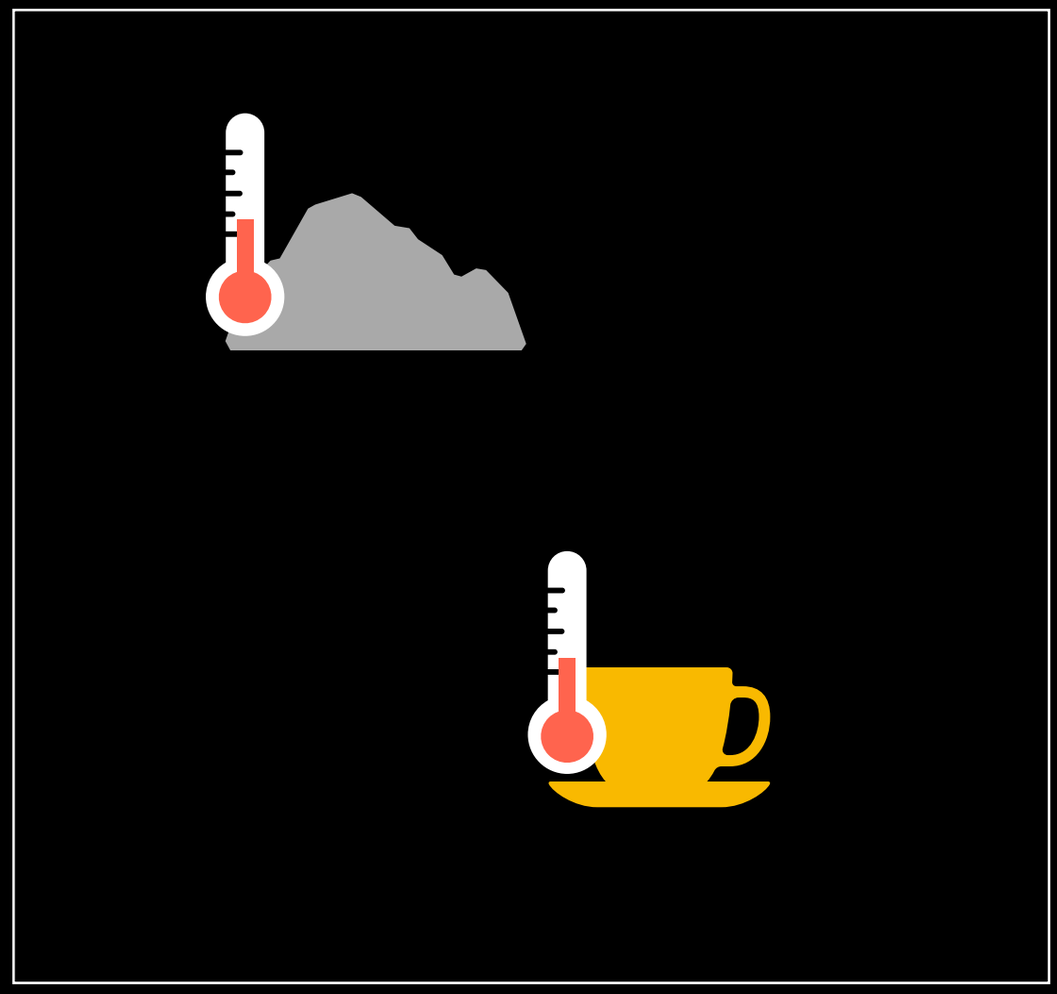
# Black's "equilibrium"

*"I call it the equilibrium of heat.*

*The nature of the equilibrium was not well understood until I pointed out a method of investigating it.*

*Dr. Boerhaave imagined that when it obtains, there is an equal quantity of heat in every equal volume of space, however filled up with different bodies.*

*The reason he gives for this opinion is that, to whichever of these bodies the thermometer be applied, it gives the same reading."*



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**Herman Boerhaave**

Dutch physician, chemist, and botanist (1668–1738)

"Father of physiology" together with Santorio

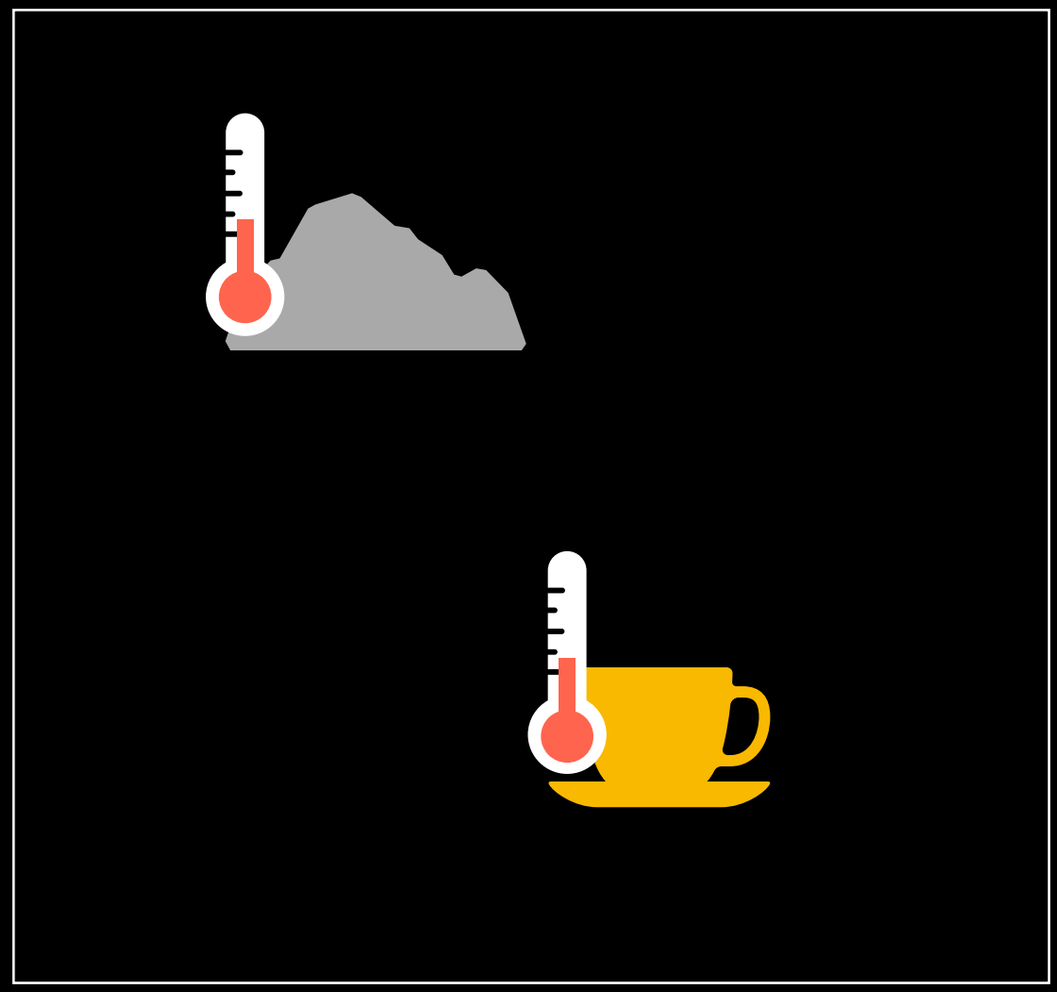
**The thermometer has been critical for this observation to be made!**
*A piece of metal and feathers at the same temperature feel very different*

**Sagredo**: *"[…] although our senses tell differently"*

# Black's "equilibrium"

*"But [Boerhaave] is taking a very hasty view of the subject.*

*[He] is confounding the quantity of heat in different bodies with its intensity [temperature], though it is plain that these are two different things, and should always be distinguished, when we are thinking of the distribution of heat."*



**Is it really "plain"?**

***Temperature*** is measured by a thermometer, but ***heat*** flows between bodies.

# Interpreting second-hand experiments

*"It was formerly a common supposition that the quantities of heat required to increase the temperatures of different bodies by an equal number of degrees were directly proportional to the quantities of matter in them.*

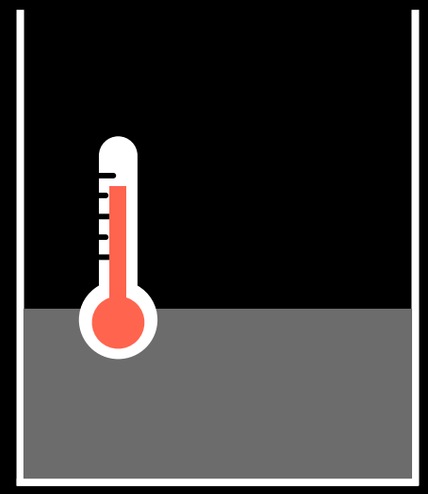
*Very soon after I began to think on this subject (in 1760), I perceived that this opinion was a mistake, and that the quantities of heat which different kinds of matter must receive to raise their temperatures by an equal number of degrees are not in proportion to the quantity of matter in each,*
*but in proportions widely different from this, and for which no general principle or reason could yet be assigned."*

**Black: "Boerhaave is wrong!"**

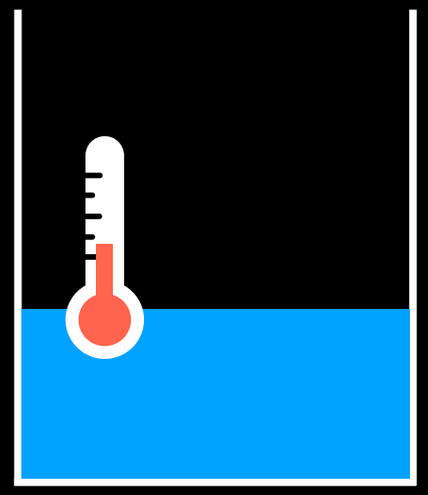
# Interpreting second-hand experiments

*“This opinion was first suggested to me by an experiment described by Dr. Boerhaave.*

*Boerhaave tells us that Fahrenheit agitated together quicksilver [mercury] and water of initially different temperatures.”*



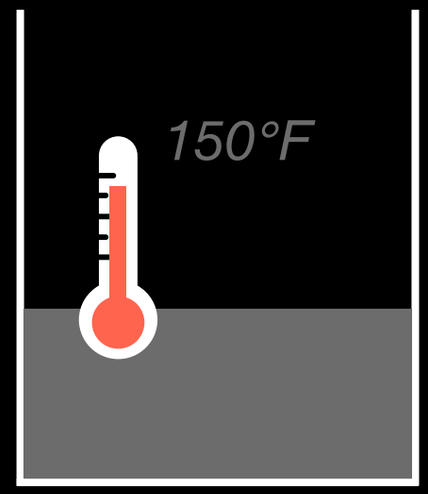
Mercury



Water

# Interpreting second-hand experiments

*“Let us suppose the water to be at 100°F and that an equal volume of warm quicksilver at 150°F is suddenly mixed and agitated with it.”*

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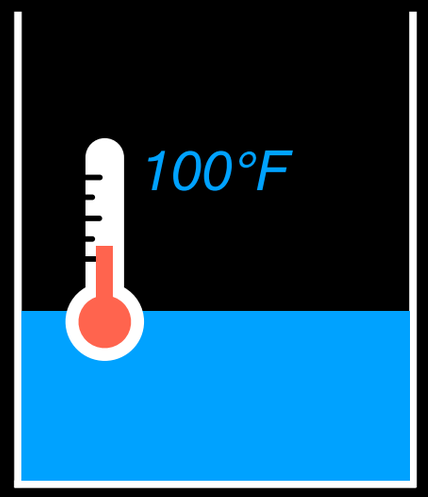


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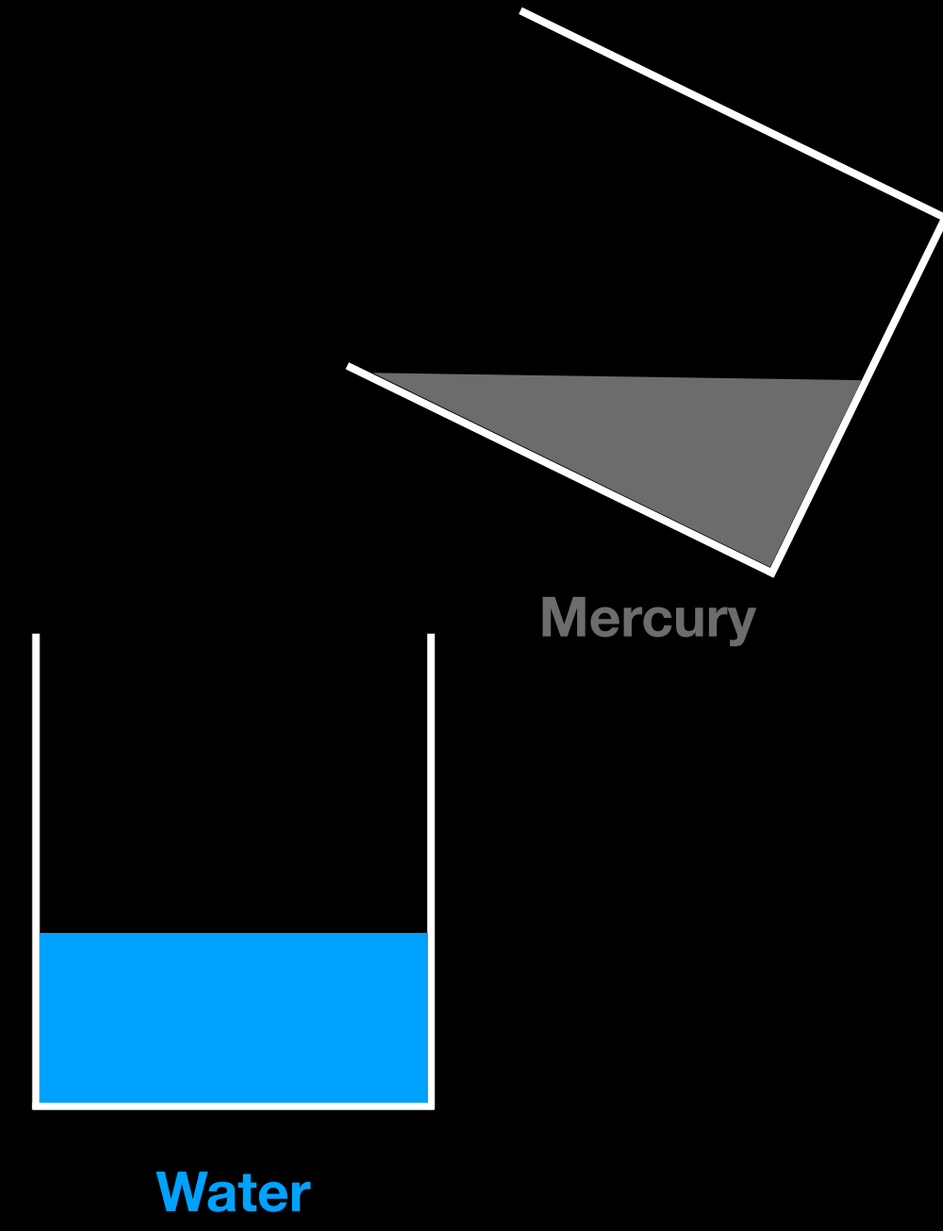

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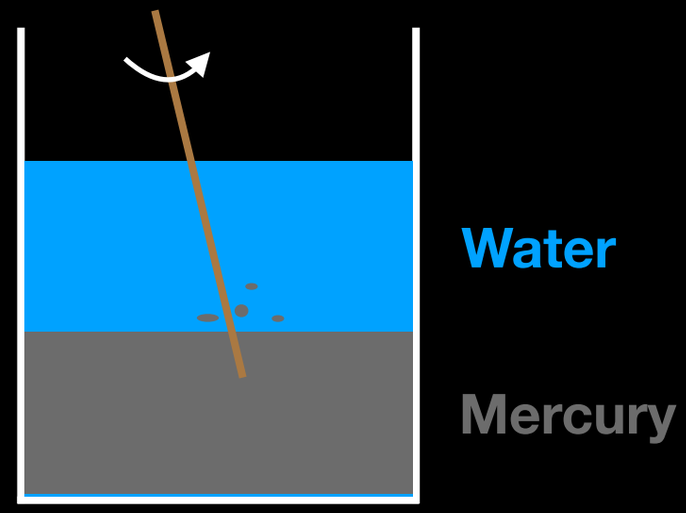

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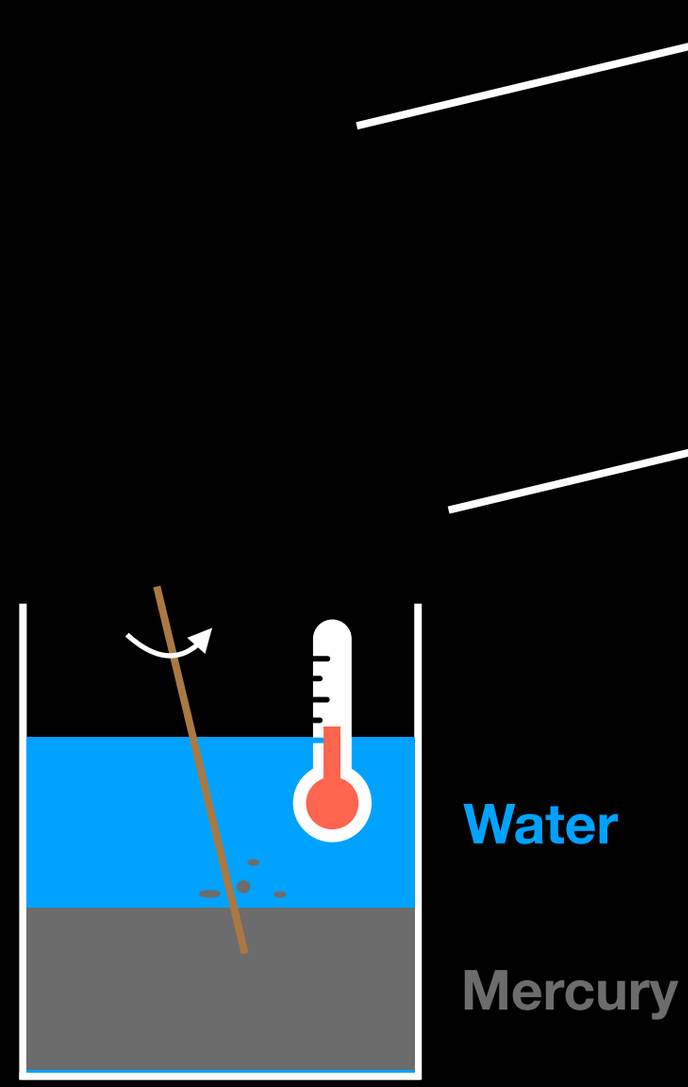
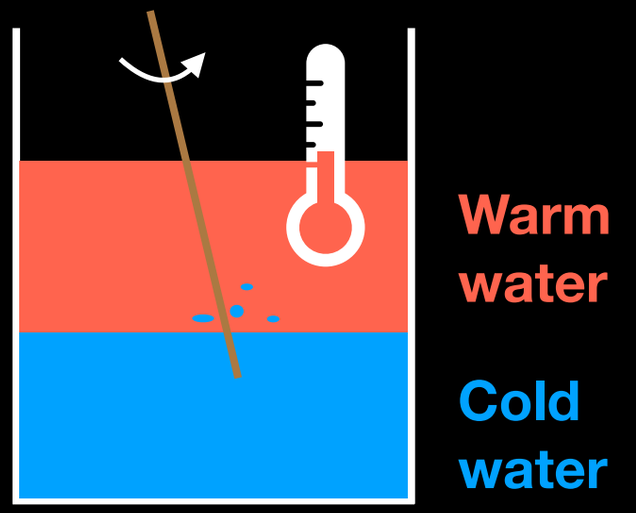


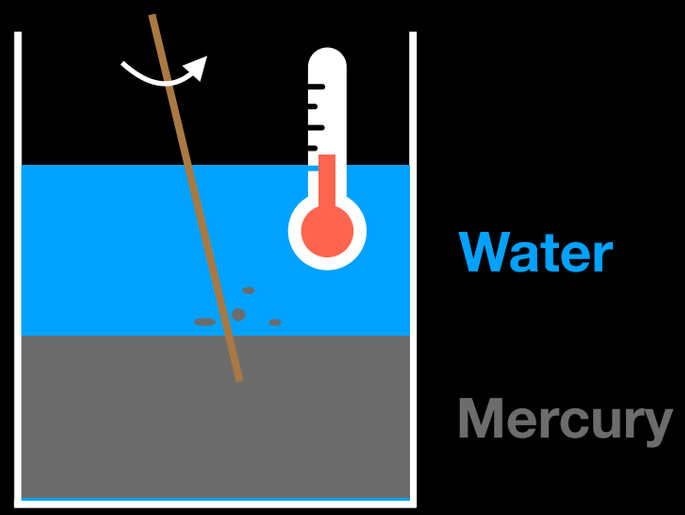
# Interpreting second-hand experiments

*“We know that the temperature midway between 100°F and 150°F is 125°F,*

*and we know that this middle temperature would be produced by mixing cold water at 100°F with an equal amount of warm water at 150°F,*

*the temperature of the warm water being lowered by 25 degrees while that of the cold is raised just as much.”*



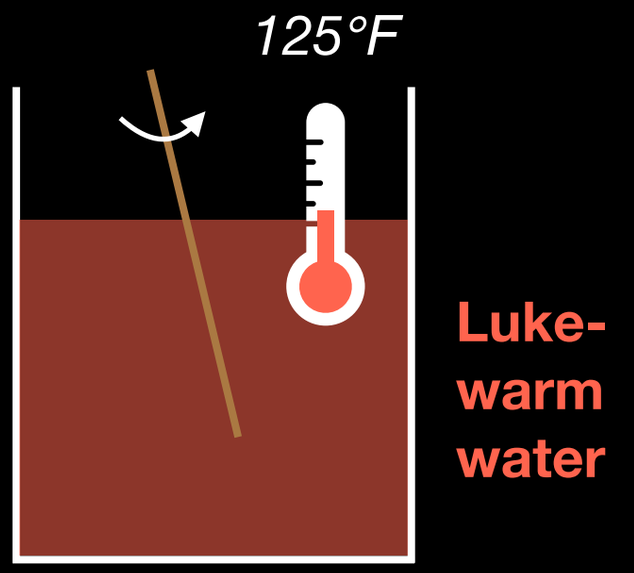



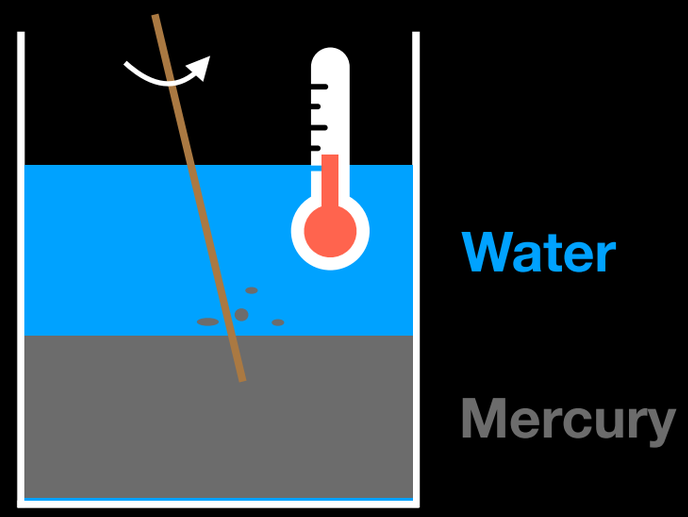
# Interpreting second-hand experiments

*"We know that the temperature midway between 100°F and 150°F is 125°F,*

*and we know that this middle temperature would be produced by mixing cold water at 100°F with an equal amount of warm water at 150°F,*

*the temperature of the warm water being lowered by 25 degrees while that of the cold is raised just as much."*




**Galen, 1640 years earlier:**
*"But we are also able to prepare [the moderate] in a certain way when we mix an equal mass of ice with boiling water."*

# Interpreting second-hand experiments

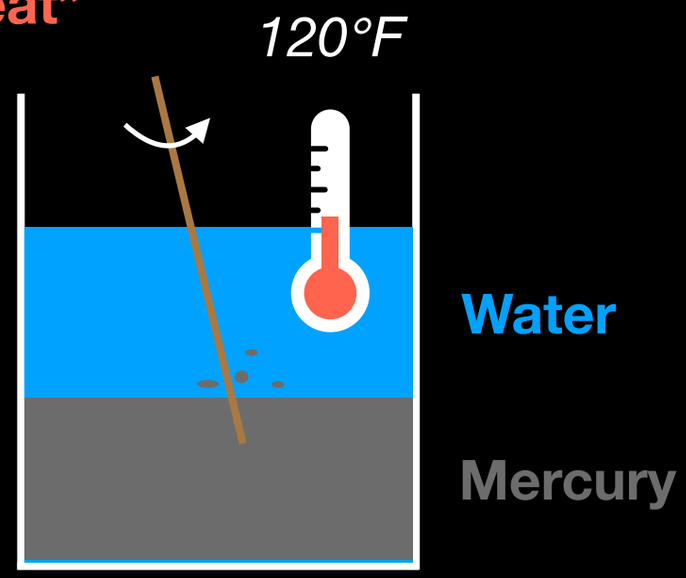
*“But when warm quicksilver is used in place of warm water, the temperature of the mixture turns out to be only 120°F, instead of 125°F.*

*The quicksilver, therefore, has cooled through 30 degrees, while the water has become warmer by 20 degrees only;*

*and yet the quantity of heat which the water has gained is the very same as that which the quicksilver has lost.*

*This shows that the same quantity of heat has more effect in warming quicksilver than in warming an equal volume of water, and therefore that a smaller quantity of it is sufficient for increasing the temperature of quicksilver by the same number of degrees.”*

**“Conservation of heat”**



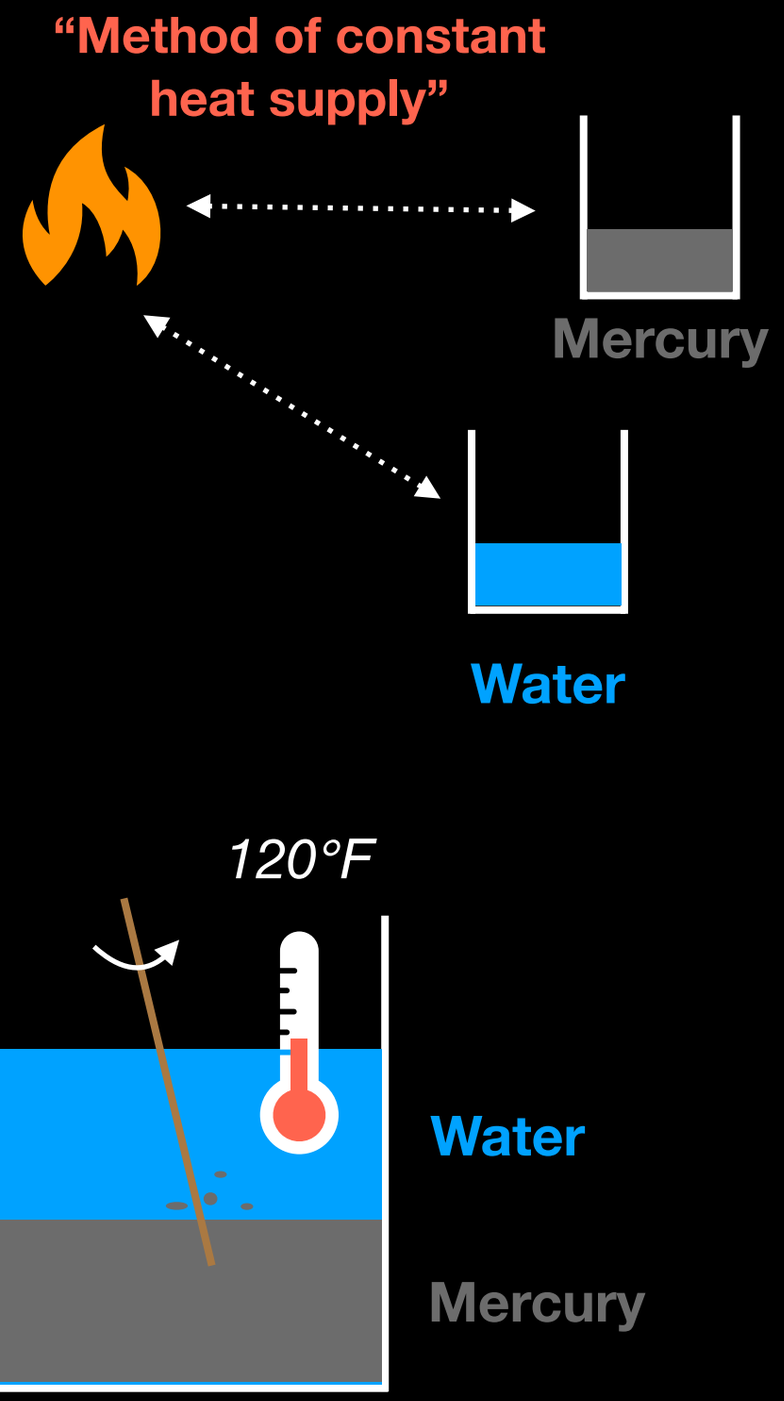
# Interpreting second-hand experiments

*"As soon as I understood Fahrenheit's experiment in the matter I have now explained it, I found a remarkable agreement between it and some experiments described by Dr. Martine.*

*Dr. Martine placed, before a good fire, and at equal distances from it, some water and an equal volume of quicksilver.*

*He found that the quicksilver was warmed by the fire almost twice as fast as the water; and after the trial, having heated these two liquids to the same temperature, he placed them in a stream of cold air and found that the quicksilver always cooled much faster than the water.*

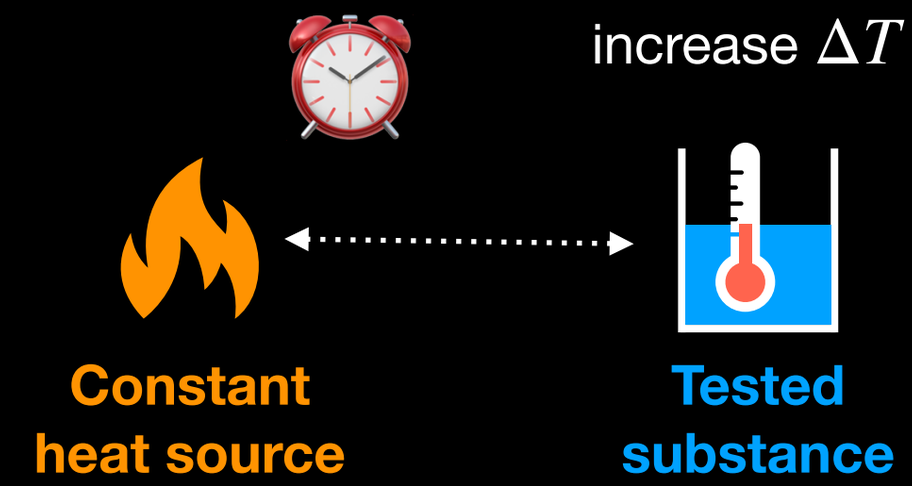
*Before these experiments we're made, it was supposed [by their weight difference] that the time needed for the quicksilver to heat or cool would be longer than for an equal volume of water, in the proportion of 13 or 14 to one."*



# Black's "capacity for heat"

**Black's own experiments:**

1) Expose tested substance (of weight $w$) to heat source for fixed amount of time
2) Measure time needed to produce a certain temperature increase




**Important:** heat source must provide equal amounts of heat in equal intervals of time

**Then:** total amount of heat imparted on tested substance is proportional to measured time

$$H \propto w \cdot \Delta T$$

"Sensible heat" provided

Weight of tested substance

Rise in temperature

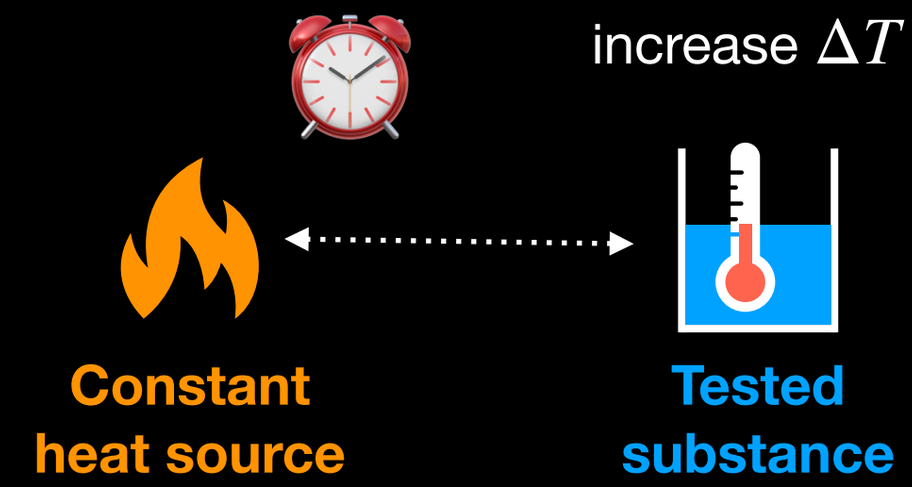
"Heating twice as much material takes twice the heat"

"Doubling the temperature increase takes twice the heat"

# Black's "capacity for heat"

**Black's own experiments:**

1) Expose tested substance (of weight $w$) to heat source for fixed amount of time
2) Measure time needed to produce a certain temperature increase




**Important:** heat source must provide equal amounts of heat in equal intervals of time

**Then:** total amount of heat imparted on tested substance is proportional to measured time

$$H = s \cdot w \cdot \Delta T$$

"Sensible heat" provided

"Capacity for the matter of heat"

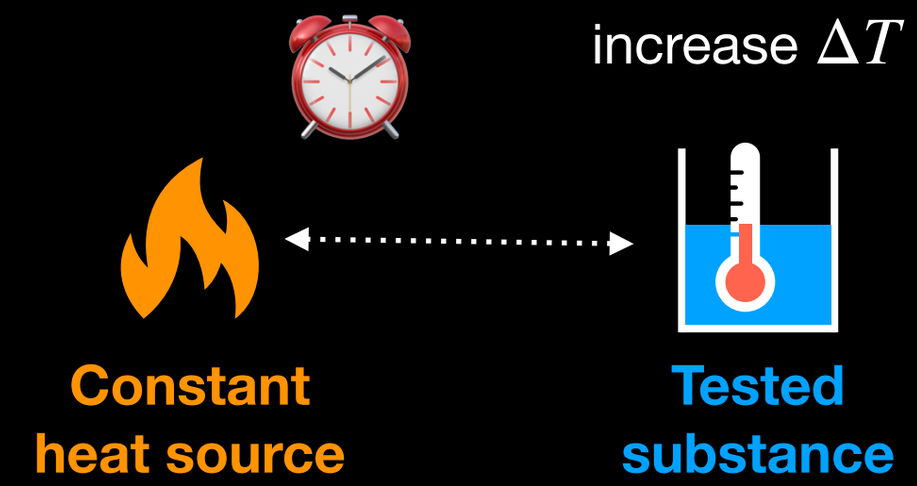
Weight of tested substance

Rise in temperature

# Black's "capacity for heat"

*"He found that the quicksilver was warmed by the fire almost twice as fast as the water […]"*

*"Before these experiments we're made, it was supposed [by their weight difference] that the time needed for the quicksilver to heat or cool would be longer than for an equal volume of water, in the proportion of 13 or 14 to one."*




→ "The heat capacity of mercury is 26-28 times smaller than that of water."
*(The modern value is ~30 times smaller than water.)*

$$H = s \cdot w \cdot \Delta T$$

"Sensible heat" provided

"Capacity for the matter of heat"

Weight of tested substance

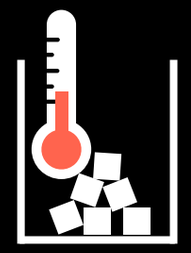
Rise in temperature

# A thought experiment

*"Each different kind of matter must be heated to a particular temperature to render it liquid, and below this temperature it is solid. This temperature is therefore called the freezing or the melting point of the substance.*

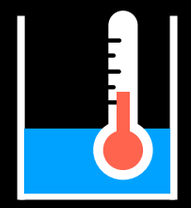
*Melting had been universally considered as produced by the addition of a very small quantity of heat to a solid body, once it had been warmed up to its melting point.*

*It was believed that this small addition of heat during melting was needed to produce a small rise in temperature, as indicated by a thermometer."*



***Just* below freezing point**

*Ice cubes*



***Just* above freezing point**

*Water*

"Sensible heat" provided

Rise in temperature

$$H = s \cdot w \cdot \Delta T$$

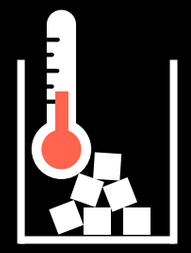
"Capacity for the matter of heat"

Weight of tested substance

# A thought experiment

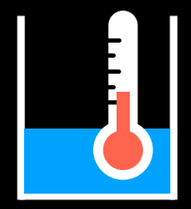
*“This was the universal opinion on the subject, so far as I know, when I began to read my lectures in the University of Glasgow in the year 1757.*

*But I soon found reason to object to it, as inconsistent with many remarkable facts, when attentively considered; and I endeavored to show that these facts are convincing proofs that liquefaction is produced by heat in a very different manner.”*



***Just* below freezing point**

*Ice cubes*



***Just* above freezing point**

*Water*

“Sensible heat” provided

Rise in temperature

$$H = s \cdot w \cdot \Delta T$$

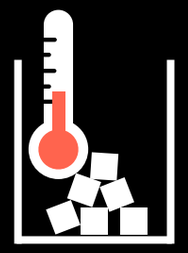
“Capacity for the matter of heat”

Weight of tested substance

# A thought experiment

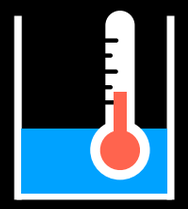
*“If we attend to the manner in which ice and snow melt when exposed to the air of a warm room, we can easily perceive that, however cold they might be at first, they soon warm up to their melting point and begin to melt at their surfaces.*

*And if the common opinion had been well founded—if the complete change of them into water required only the further addition of a very small quantity of heat—the mass ought all to be melted within a very few minutes or seconds by the heat incessantly communicated from the surrounding air.”*



**_Just_ below freezing point**

*Ice cubes*



**_Just_ above freezing point**

*Water*

“Sensible heat” provided

Rise in temperature

$$H = s \cdot w \cdot \Delta T$$

“Capacity for the matter of heat”

Weight of tested substance

# A thought experiment

*“Were this really the case, the consequences of it would be dreadful in many cases; for, even as things are at present, the melting of large amounts of snow and ice occasions violent torrents and great inundations in the cold countries or in the rivers that come from them.*

*But, were the ice and snow to melt suddenly, as they would if the former opinion of the action of heat in melting them were well founded, the torrents and inundations would be incomparably more irresistible and dreadful.*

*They would tear up and sweep away everything, and this so suddenly that mankind would have great difficulty in escaping from their ravages.”*

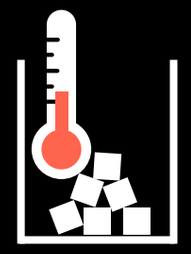
[Source]

# A different “type” of heat

*“The opinion I formed from attentive observation of the facts and phenomena is as follows.*

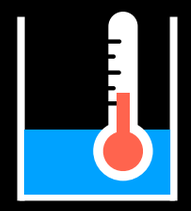
*When ice or any other solid substance is melted, I am of the opinion that it receives a much larger quantity of heat than what is perceptible in it immediately afterwards by a thermometer.*

*This heat must be added to give it the form of a liquid; and I affirm that this large addition of heat is the principal and most immediate cause of the liquefaction induced.”*



***Just* below freezing point**

*Ice cubes*



***Just* above freezing point**

*Water*

**This “new” type of heat is <u>not</u> “sensible heat”**

**Today we call it *“latent heat”***

$$H = s \cdot w \cdot \Delta T$$

“Sensible heat” provided

Rise in temperature

“Capacity for the matter of heat”

Weight of tested substance

# On boiling water

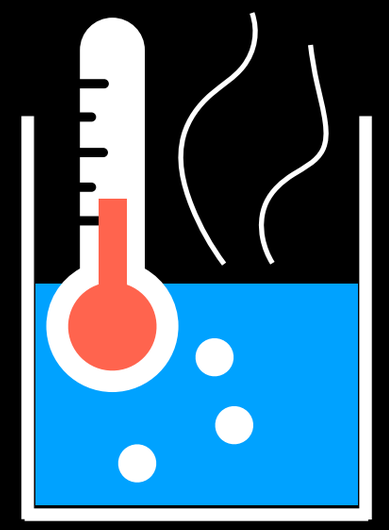
*“Another peculiarity attends the boiling of liquids.*

*However long and violently we boil a liquid, we cannot make it in the least hotter than when it began to boil. The thermometer always points at the same degree, namely the boiling point of the liquid.*

*When these facts and appearances were first observed, they seemed surprising.*

*Some thought that [the boiling of the water] was occasioned by that part of the heat which the water was incapable of receiving, and which forced its way through.*

*Others imagined that the agitation proceeded from the air which water is known to contain and which is expelled during boiling.”*

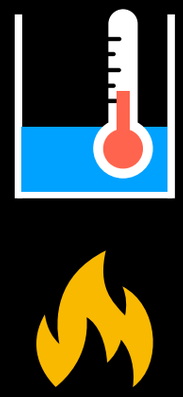


# On boiling water

*“This is the only account that was given of this subject before I began to deliver these lectures.*

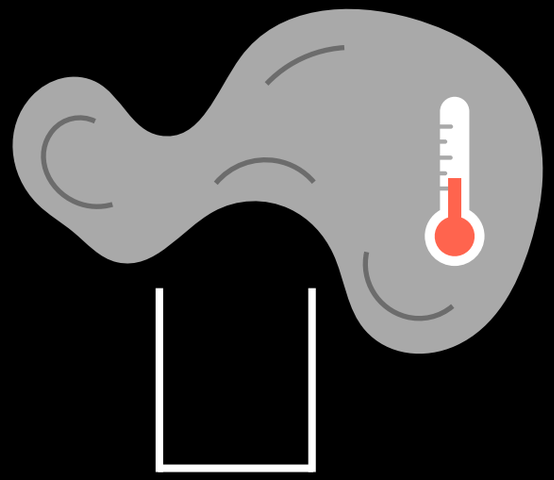
*It used to be taken for granted that, after a liquid was heated up to its boiling point, nothing further was necessary but the addition of a little more heat to change it into vapor.*

*It was also supposed that when this vapor was so far cooled as to be ready for recondensation, this condensation, or return to the liquid state, would happen at once, in consequence of the vapor’s losing only a very small quantity of heat.”*



**_Just_ below boiling point**

*Water*



**_Just_ above boiling point**

*Steam*

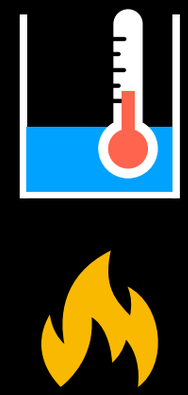
# On boiling water

*“The undeniable consequence of this, if the old view were correct, should be an explosion of the whole water with a violence equal to that of gun-powder.*

*But I can easily show, in the same manner as in the case of liquefaction, that a very large quantity of heat is necessary for the production of vapor.*

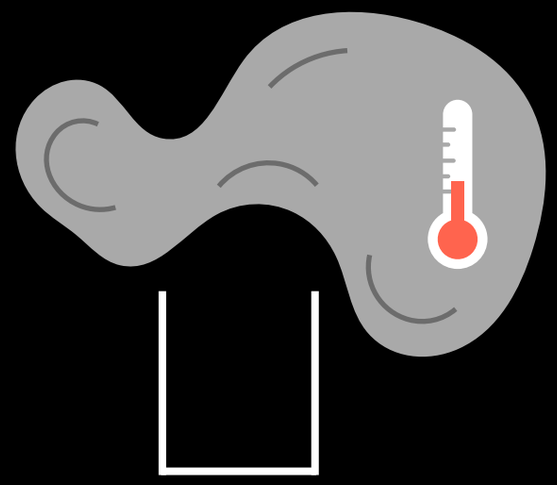
*This large quantity of heat is necessary for the production of vapor, it enters into the vapor gradually, while it is forming.*

*On the other hand, I can show that when the steam is condensed back into water, the very same large quantity of heat comes out of it, and the water into which it is changed does not become sensibly colder by the loss of this large quantity of heat.”*



**_Just_ below boiling point**

*Water*



**_Just_ above boiling point**

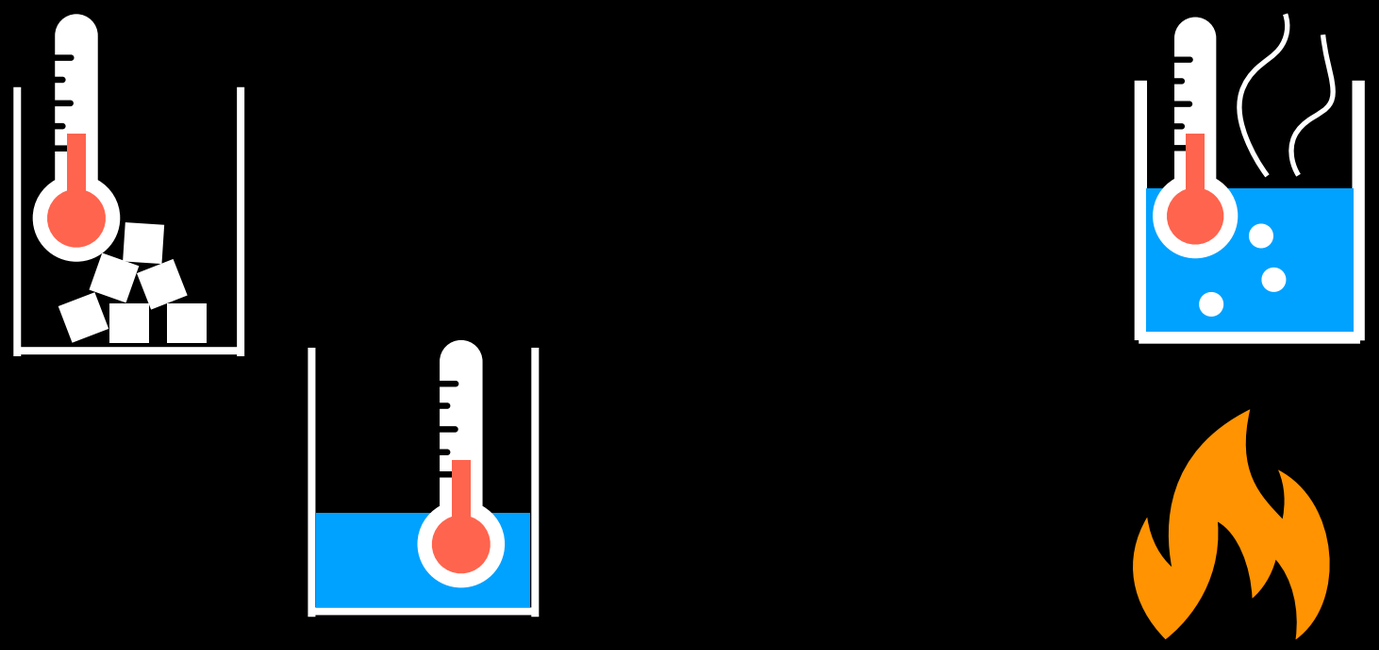
*Steam*

# Blacks' great synthesis: latent heat

"During the boiling, heat is absorbed by the water and enters into the composition of the steam produced from it, in the same manner as it is absorbed by ice in melting and enters into the composition of the resulting water.

And, as the ostensible effect of the heat in this latter case consists, not in warming the surrounding bodies, but in converting the ice into water.

Considered as the cause of warmth, we do not perceive its presence: it is concealed, or latent, and I gave it the name of latent heat."

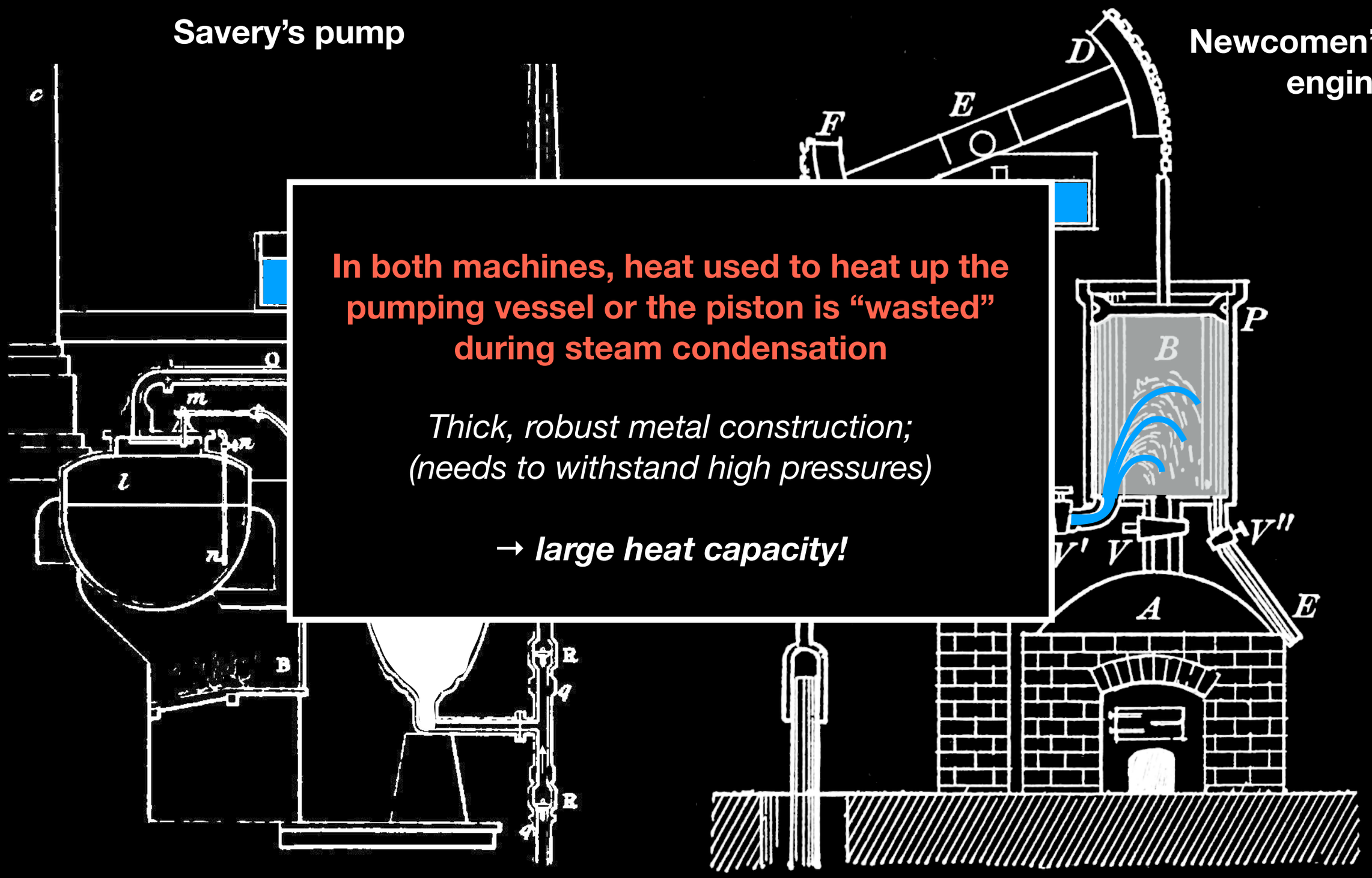


**Black discovered the existence of latent heat, but could not (yet) explain its origins.**

# The root of the inefficiency

**Savery's pump**

**Newcomen's engine**




**In both machines, heat used to heat up the pumping vessel or the piston is "wasted" during steam condensation**

*Thick, robust metal construction;*
*(needs to withstand high pressures)*

→ ***large heat capacity!***

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