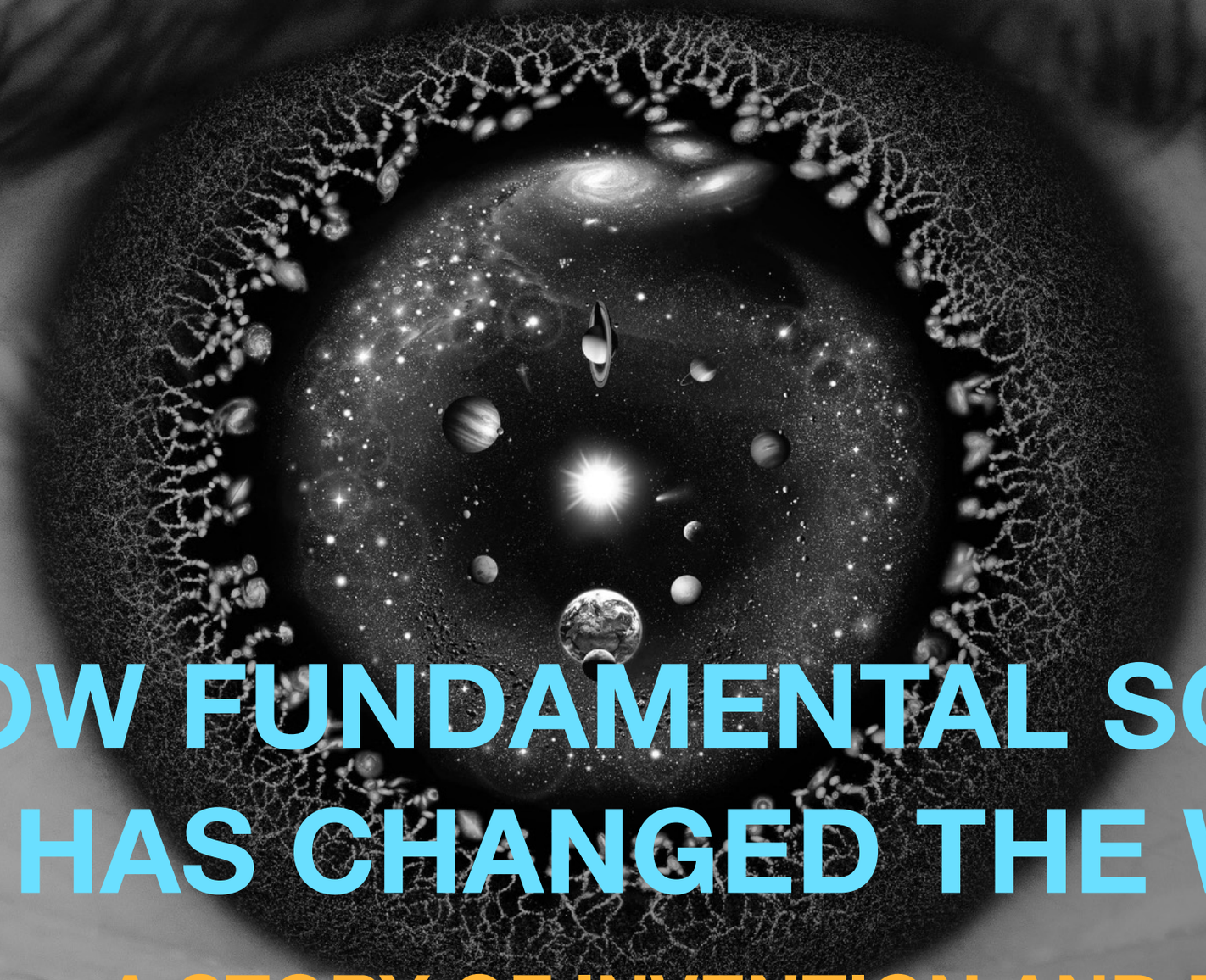
THE UNIVERSITY OF CHICAGO

ENRICO FERMI INSTITUTE



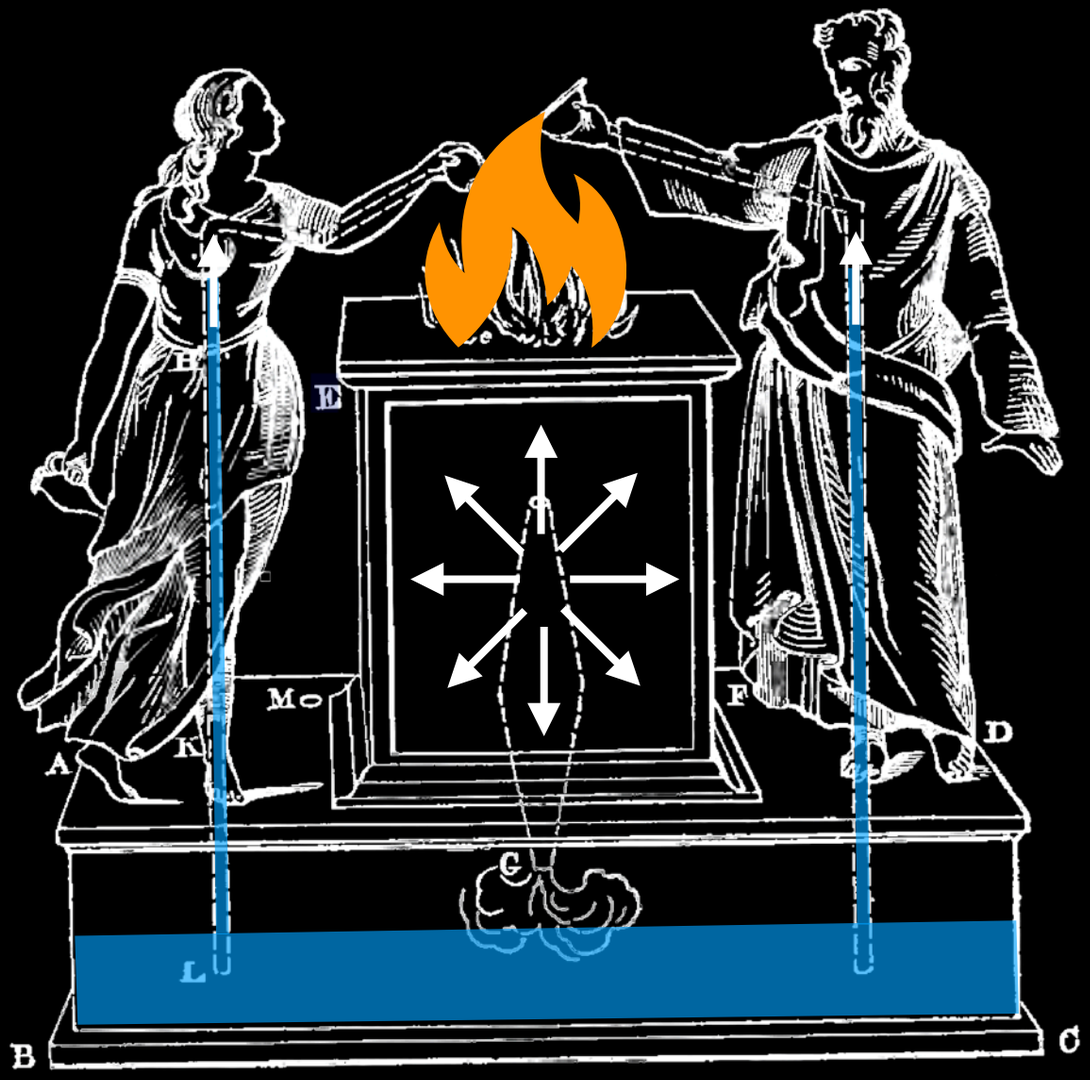
HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

A STORY OF INVENTION AND DISCOVERY

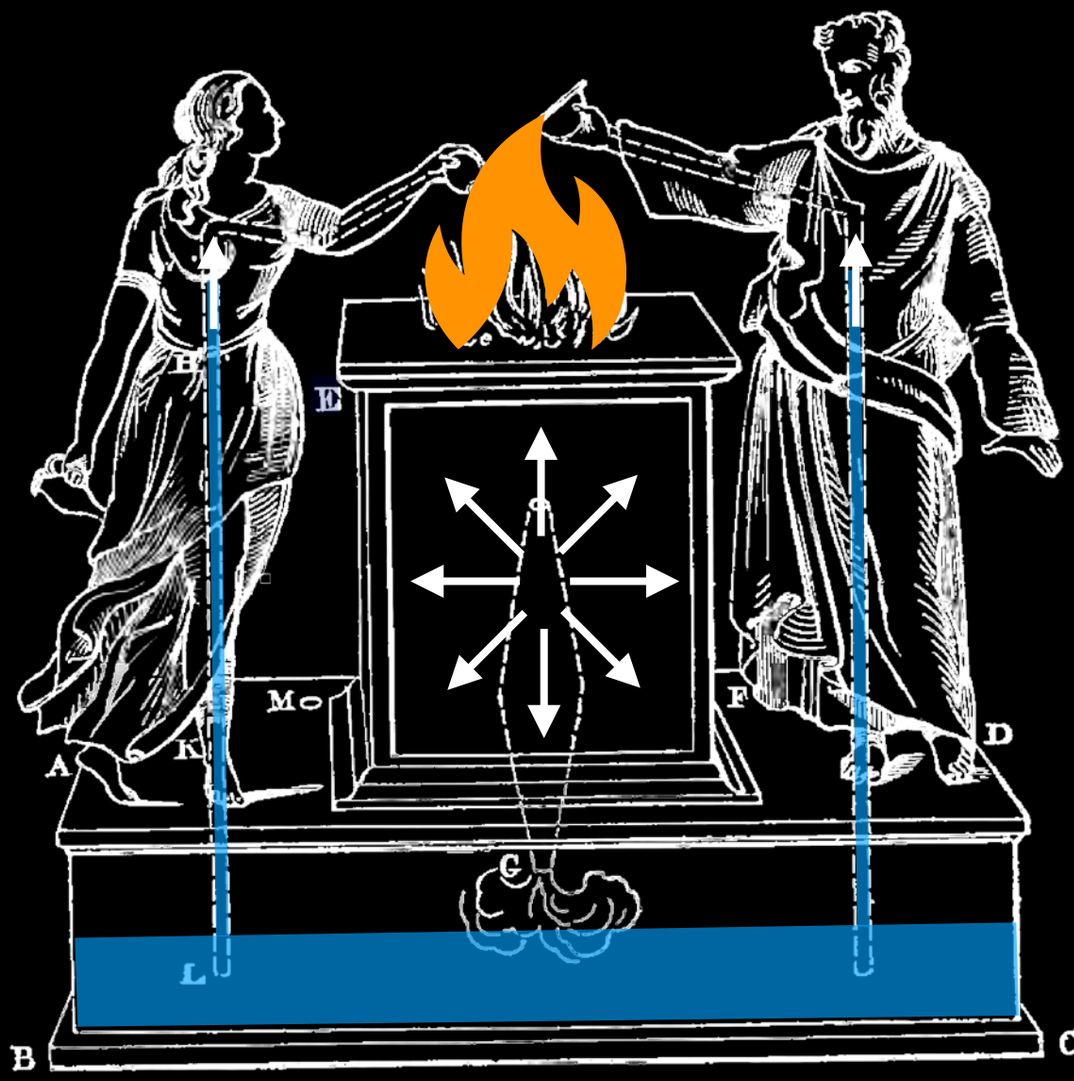
Philipp Windischhofer

October 14, 2023

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



Alexandria, 70 AD



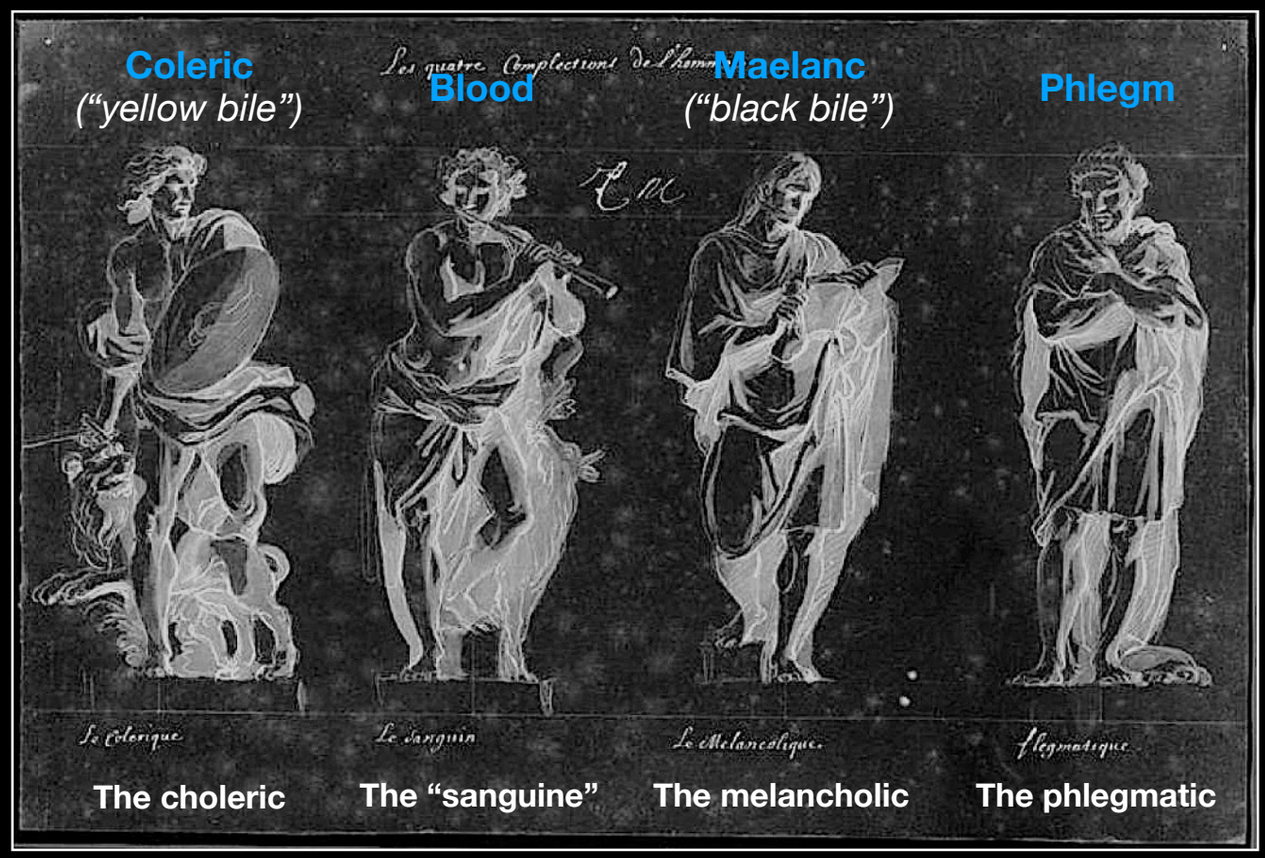
Alexandria, 70 AD

“Temperament”

↕

“Temperature”

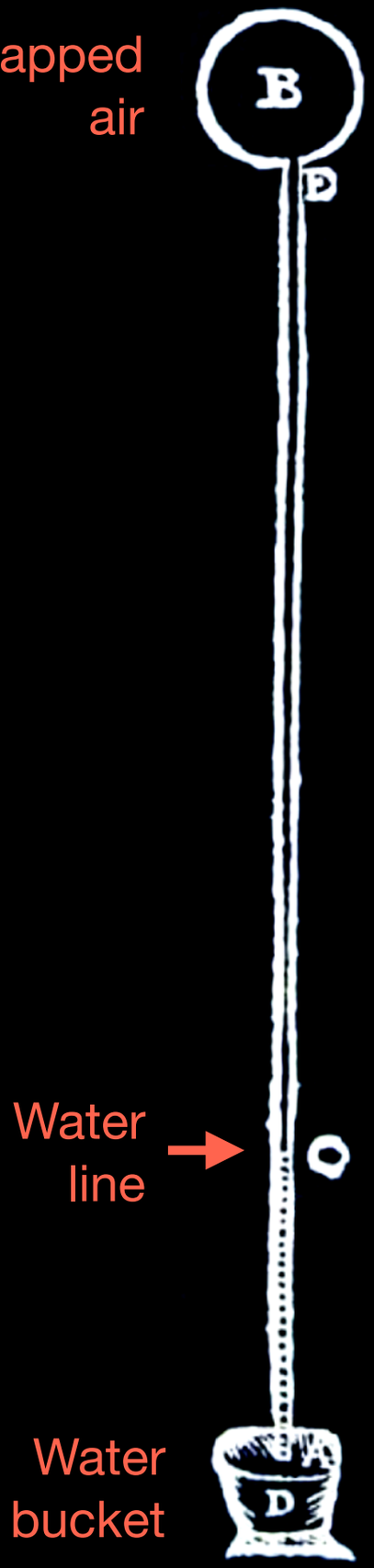
Pergamon, 140 AD

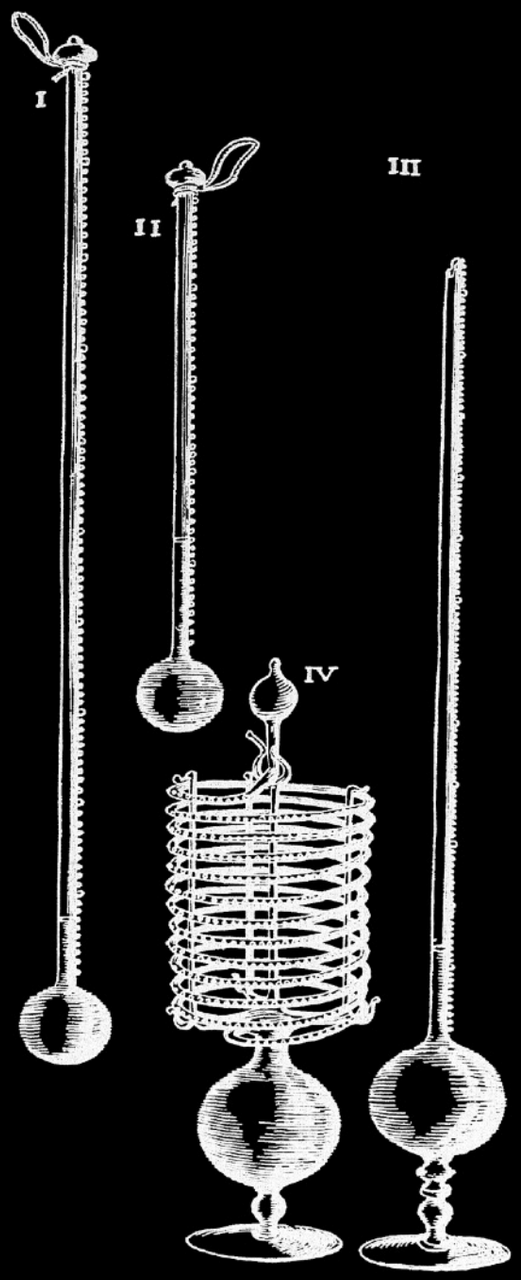


The choleric **The “sanguine”** **The melancholic** **The phlegmatic**

The first thermometers

“I have clearly seen […]
although our senses tell differently.”





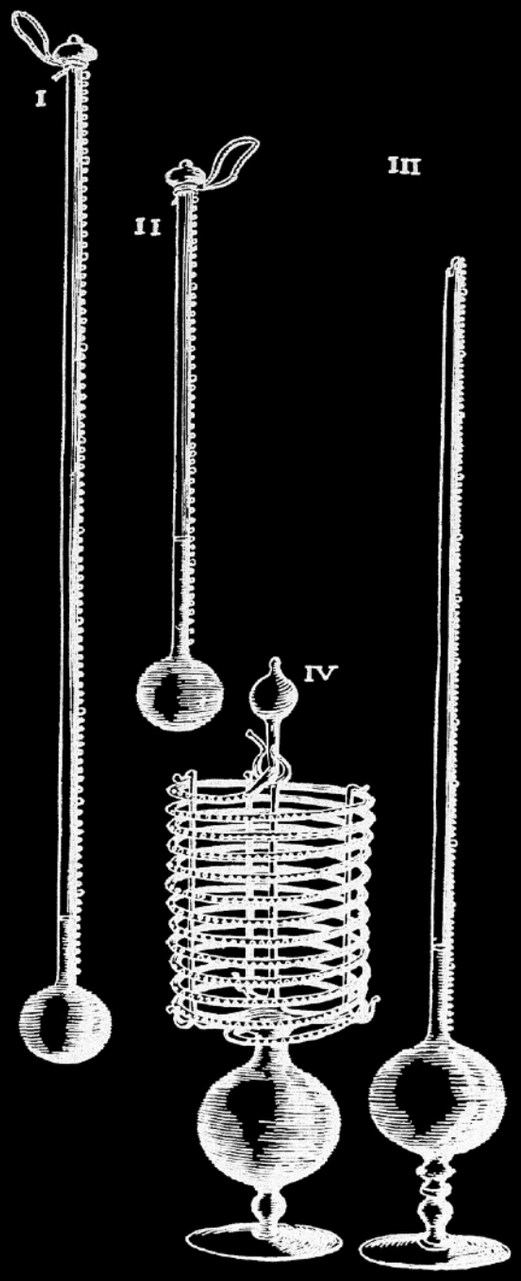
Trapped air

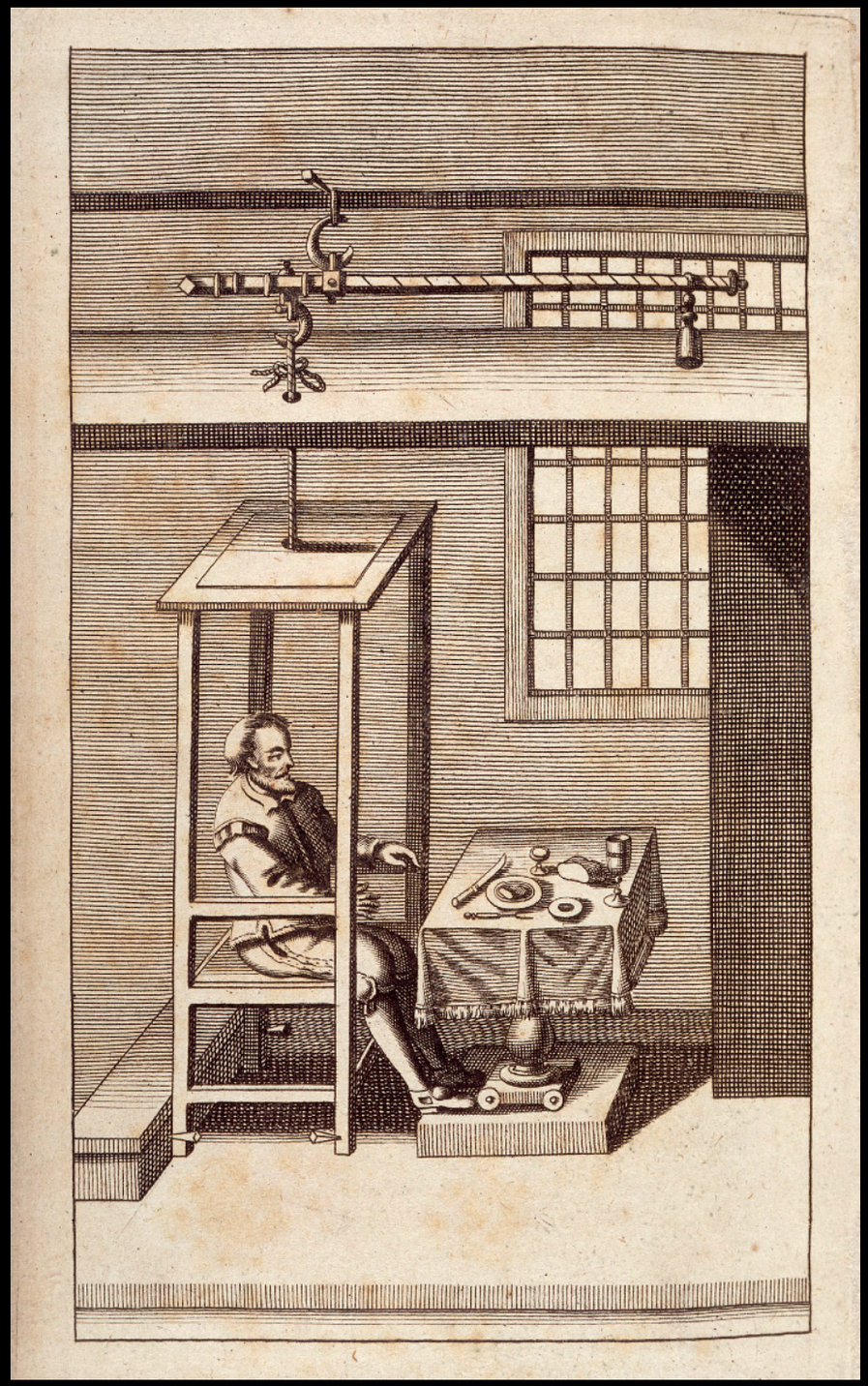
Water line

Water bucket

The first thermometers

“I have clearly seen […] although our senses tell differently.”





First uses in medicine

Thermometers measure temperature, but heat flows between objects

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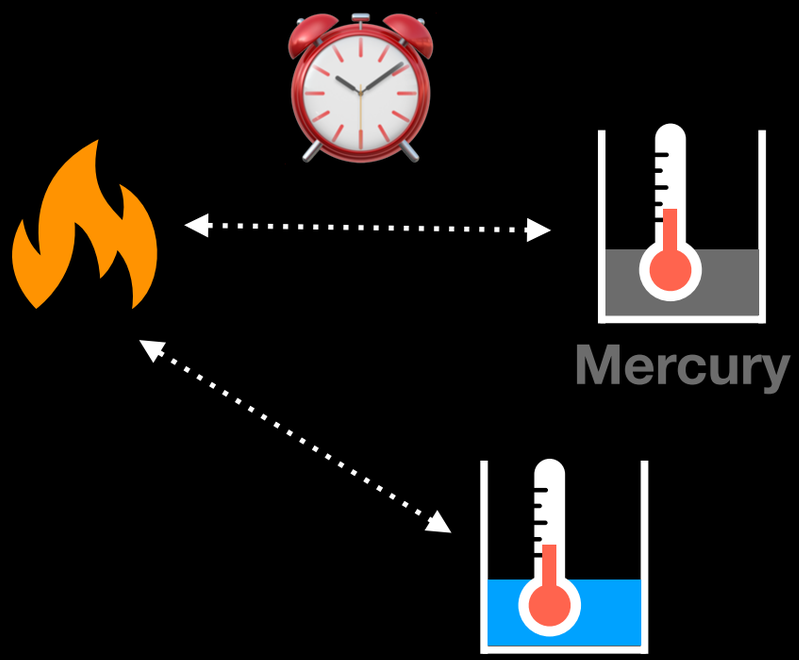
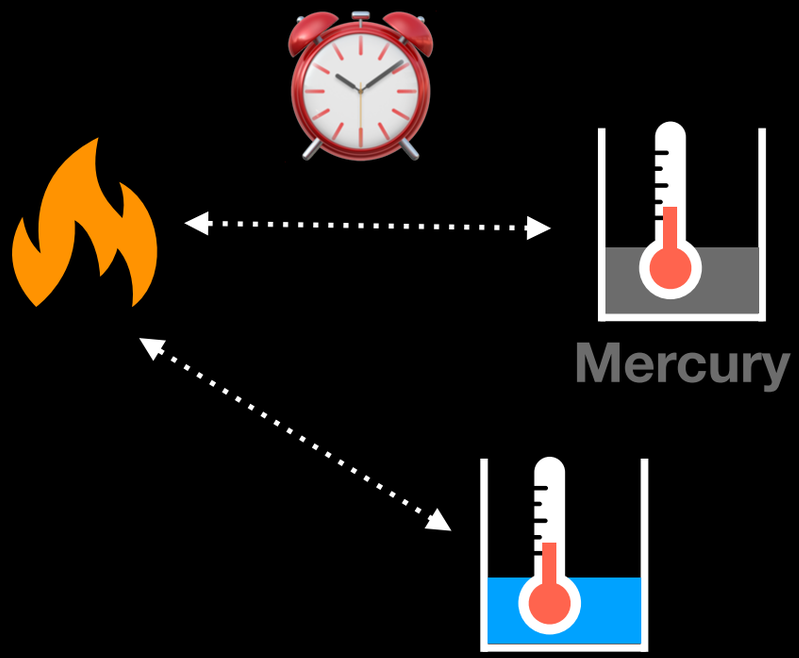


“Sensible heat”

Joseph Black:
Different bodies have different
“capacities for the matter of heat”

Thermometers measure temperature, but heat flows between objects

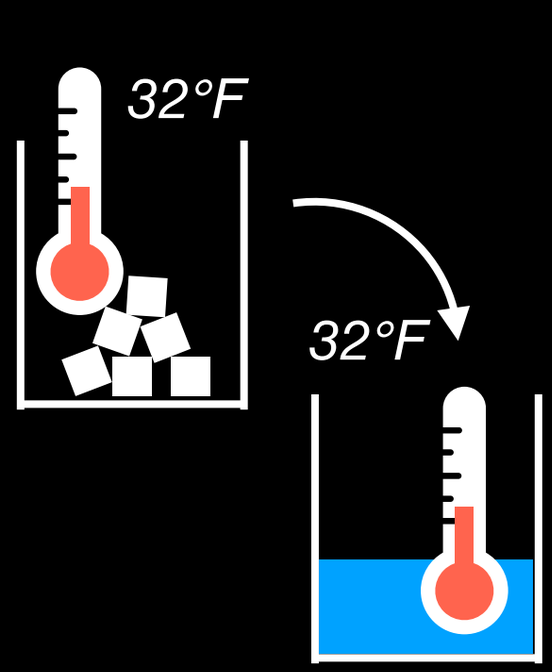


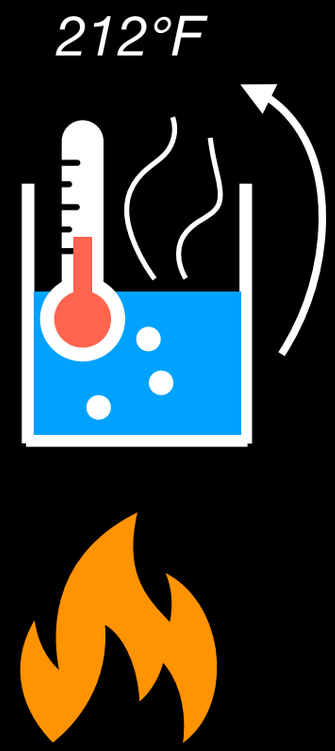
“Sensible heat”

Joseph Black:
Different bodies have different
“capacities for the matter of heat”

“Latent heat”

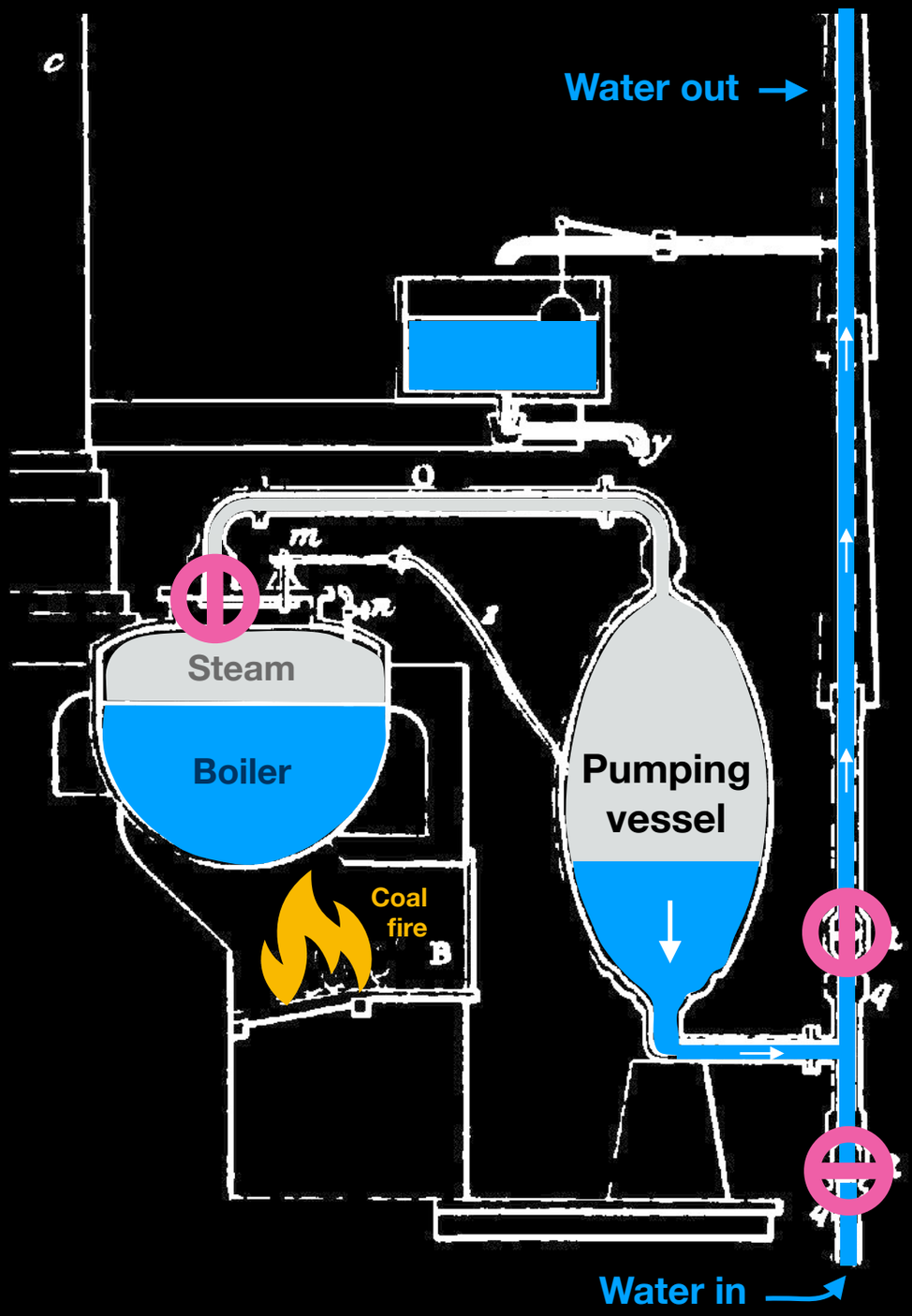
Melting or evaporating water requires heat that does *not* cause a temperature change





Captain Savery's steam pump

(1698)



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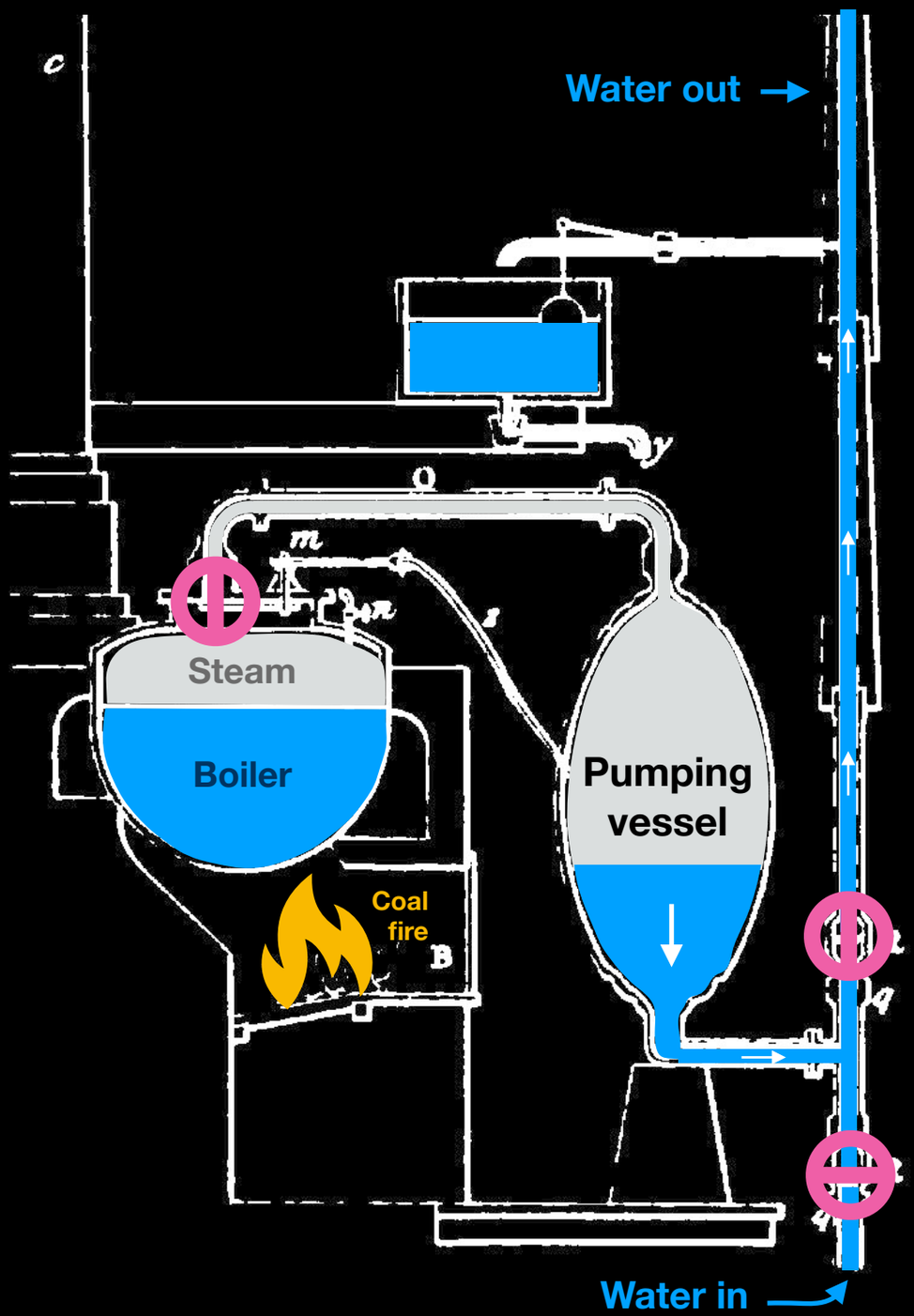
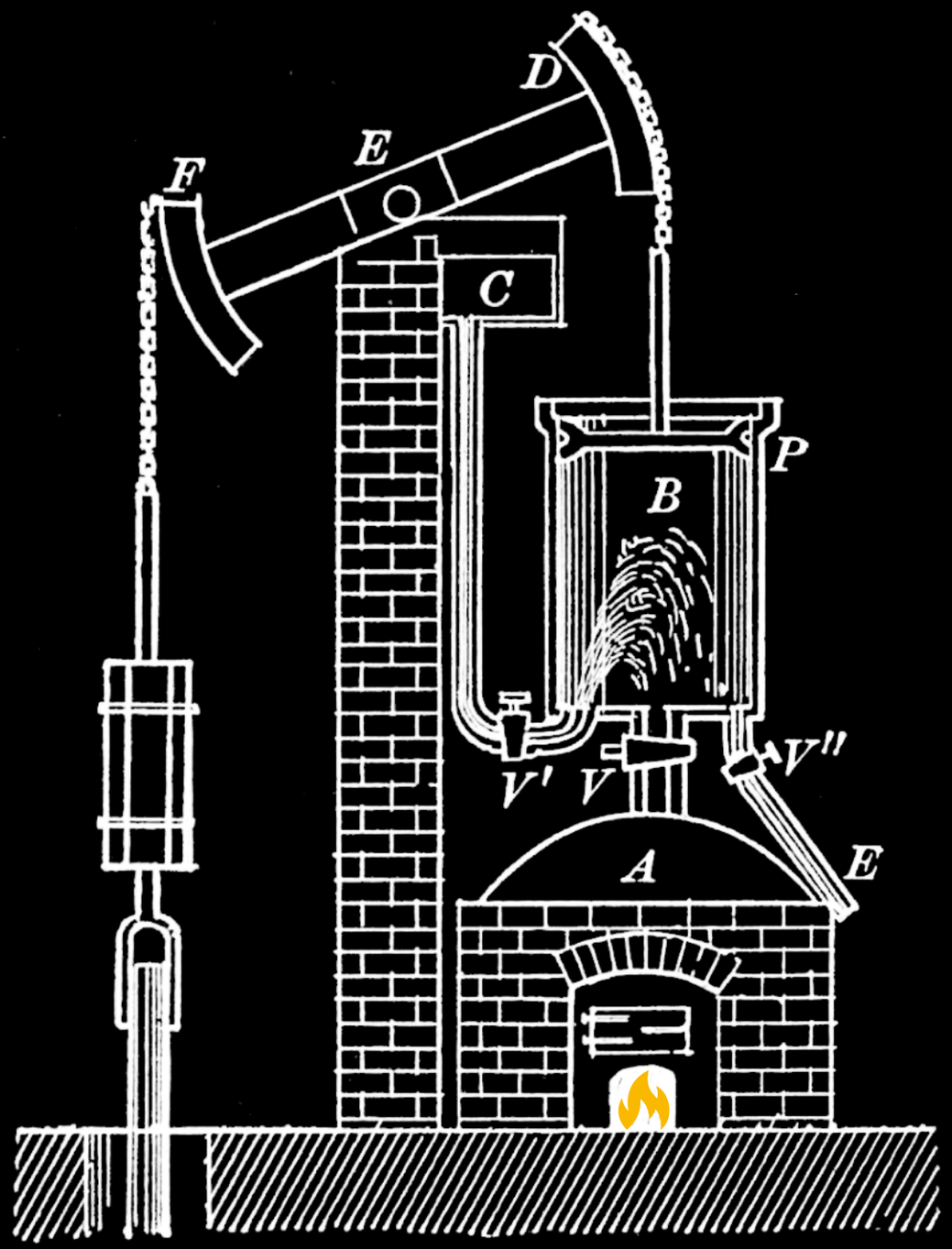
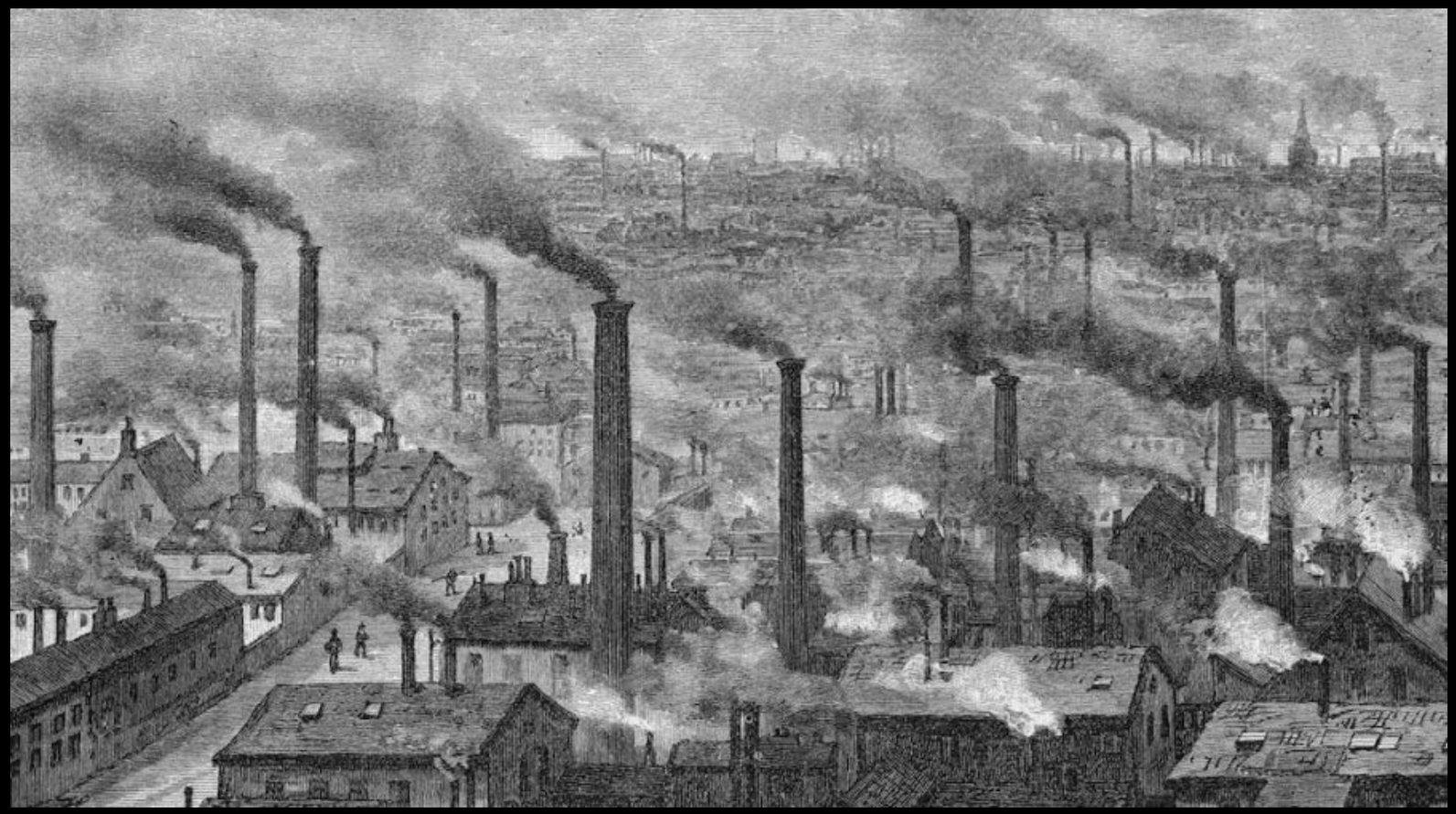




Thomas Newcomen's "atmospheric engine"
(1712)

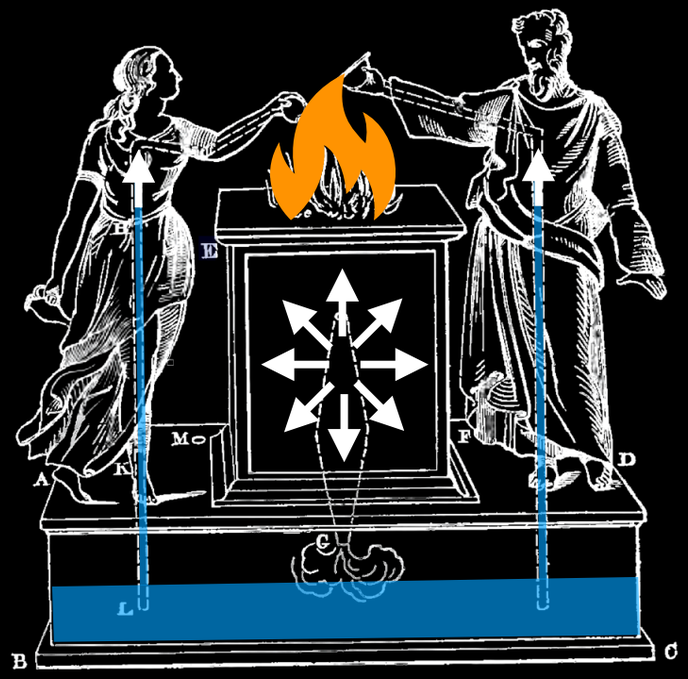
Extremely inefficient workhorse of the early industrial revolution:
deep coal mines, blast furnaces, …



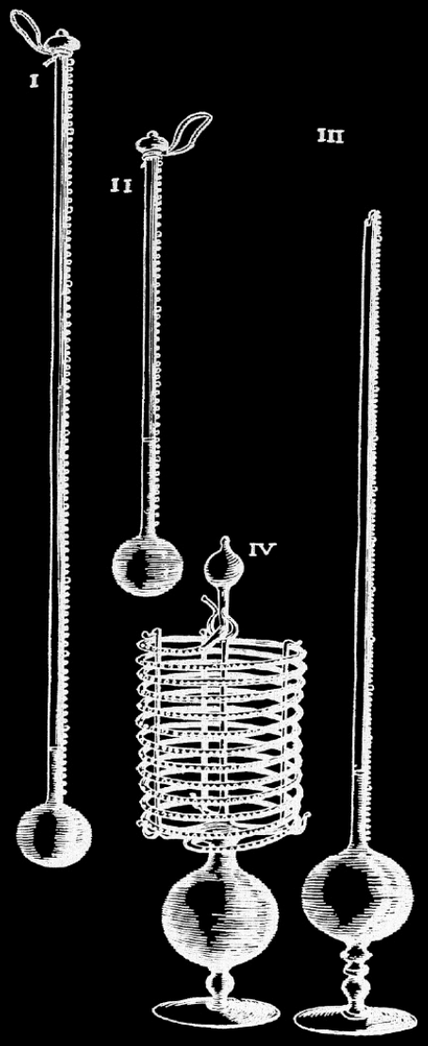
And was Jerusalem builded here,
Among these dark Satanic Mills?

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

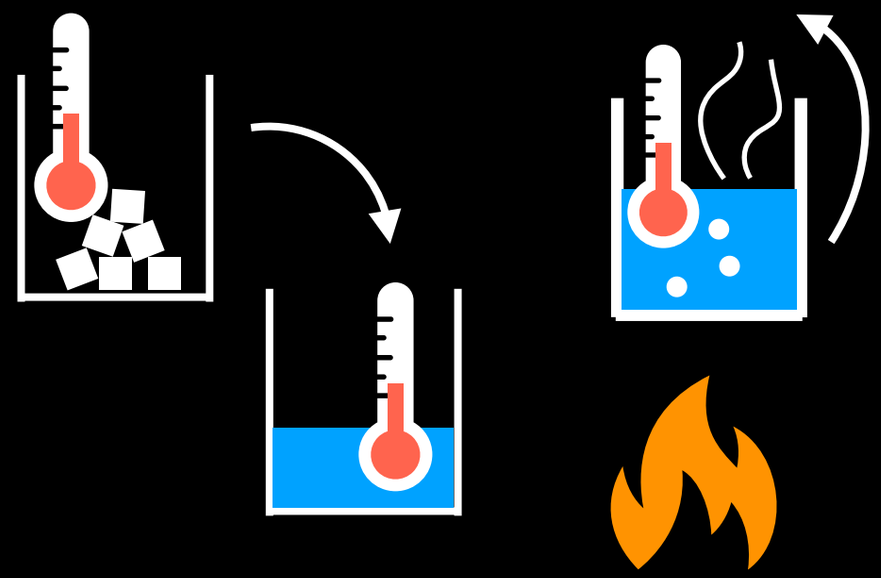
(1712)



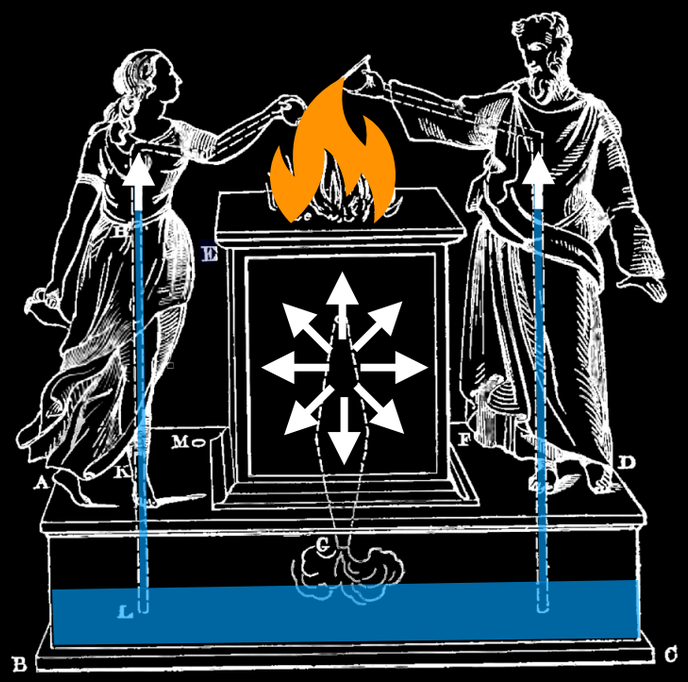
“Vague notions”

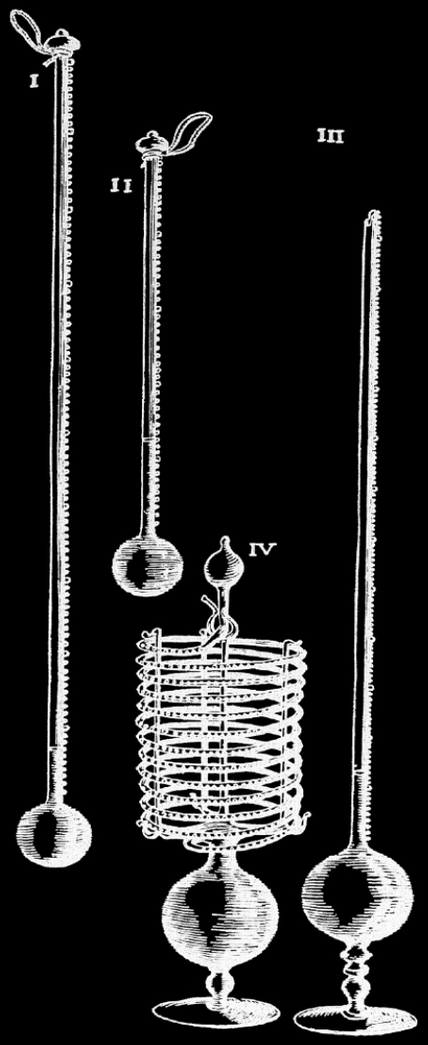


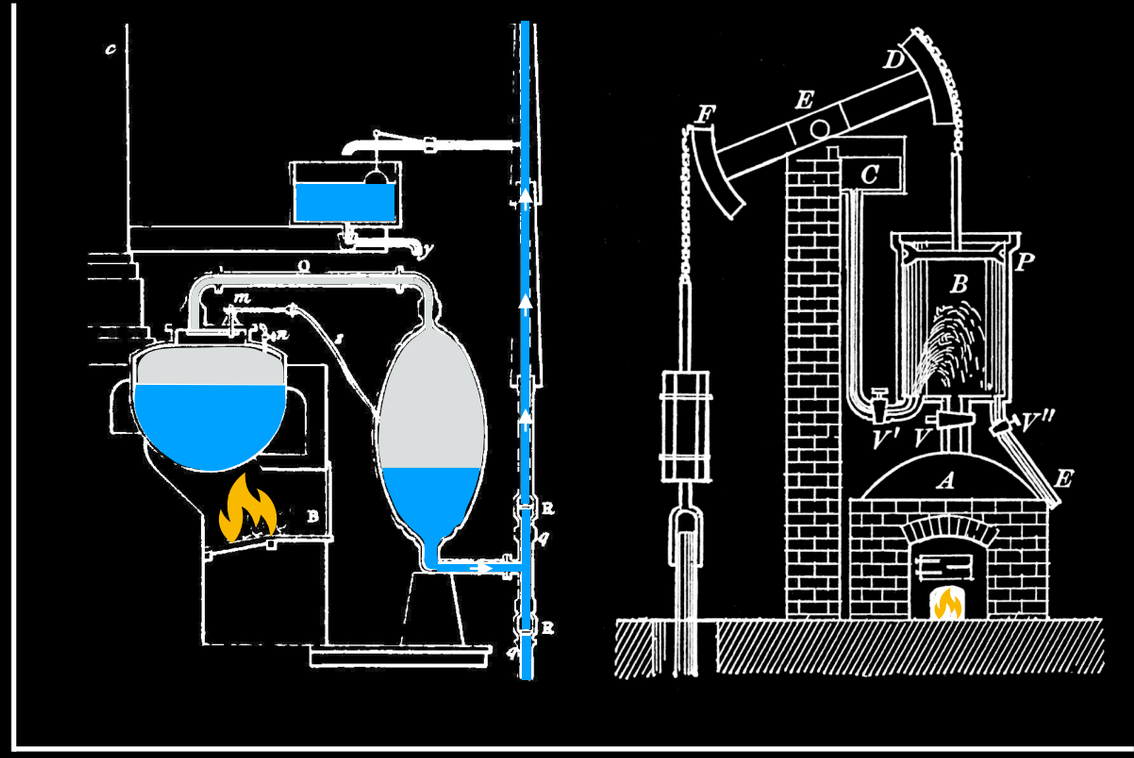
“Quantifying ignorance”



“Inventing narratives”

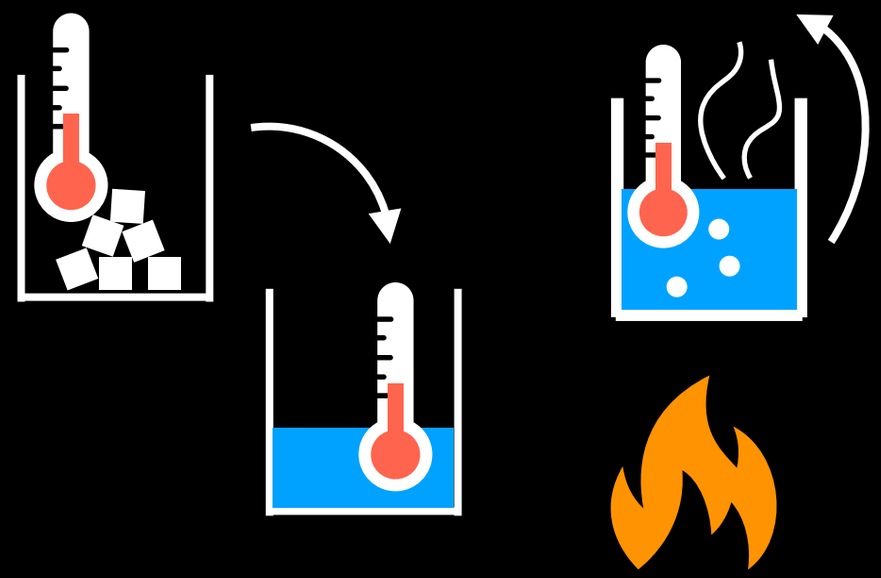






"Vague notions"

"Quantifying ignorance"



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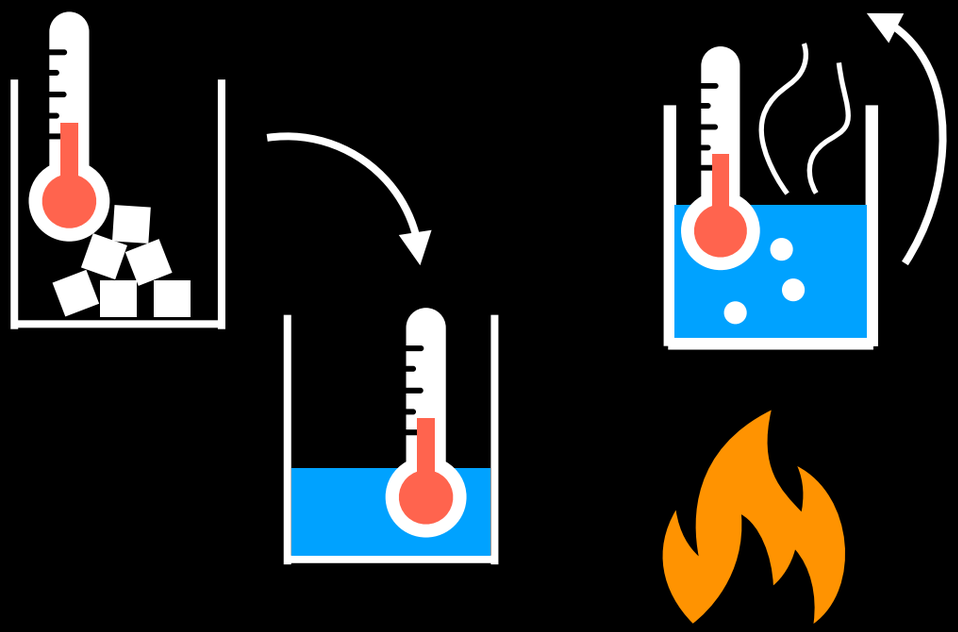
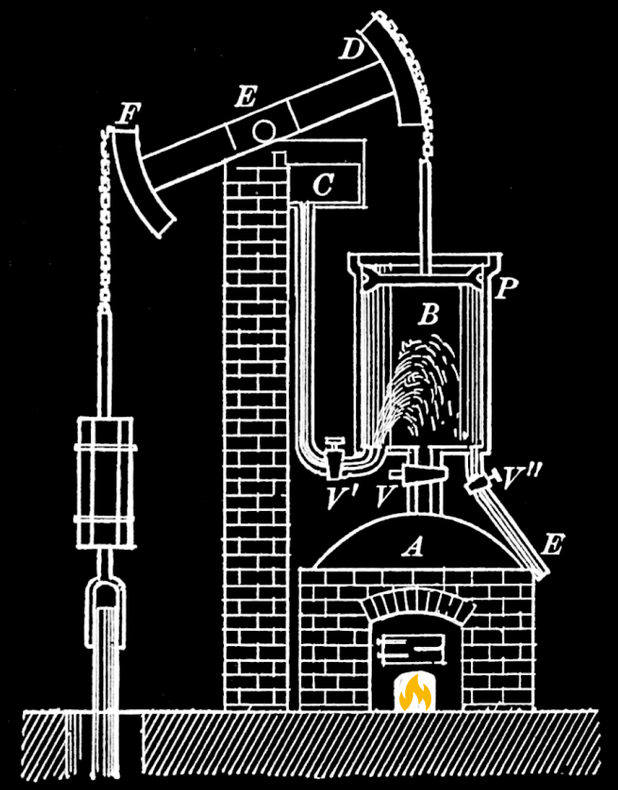


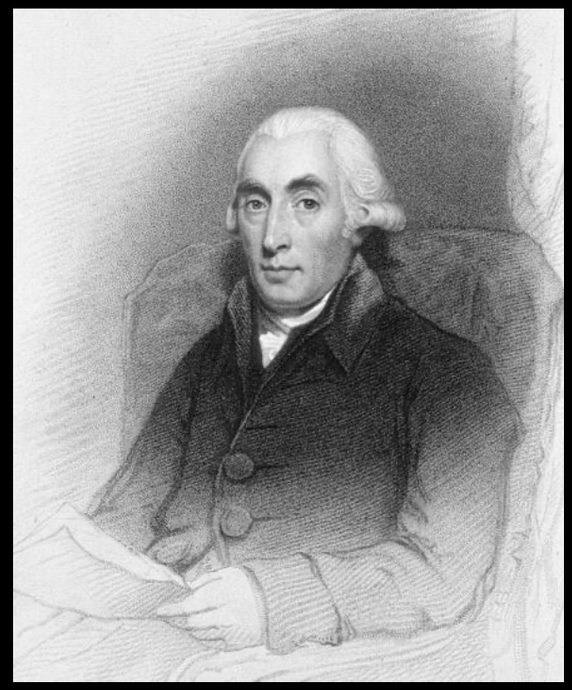


What is heat?

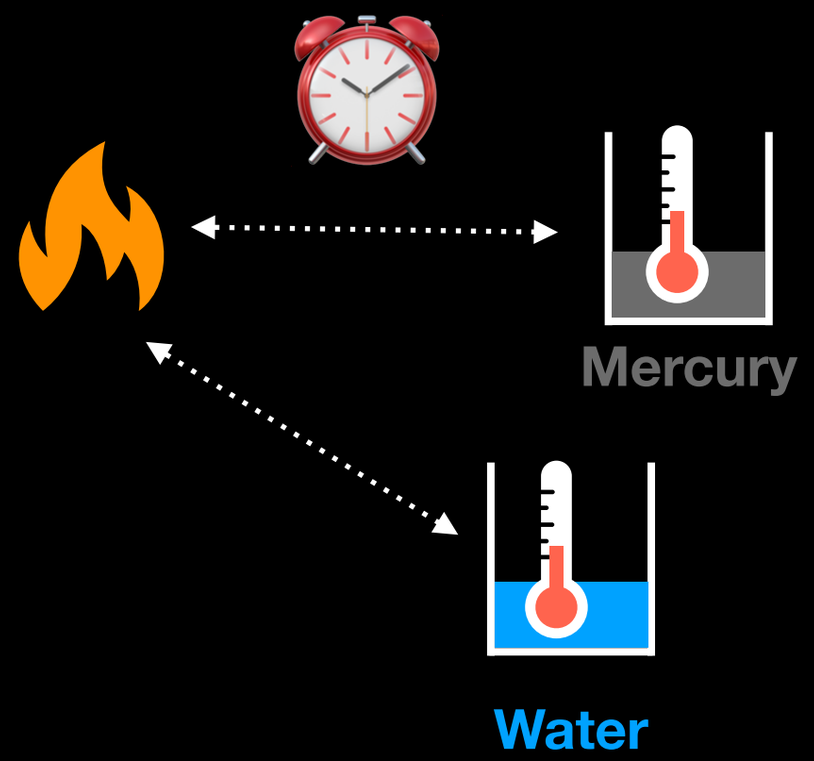
Back to Glasgow

University of Glasgow (1756–1766)

Newcomen's machine already well-established!

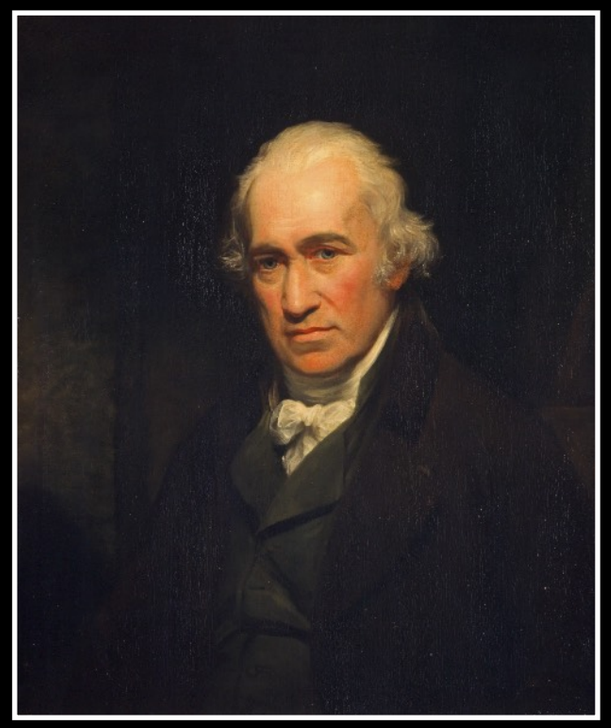


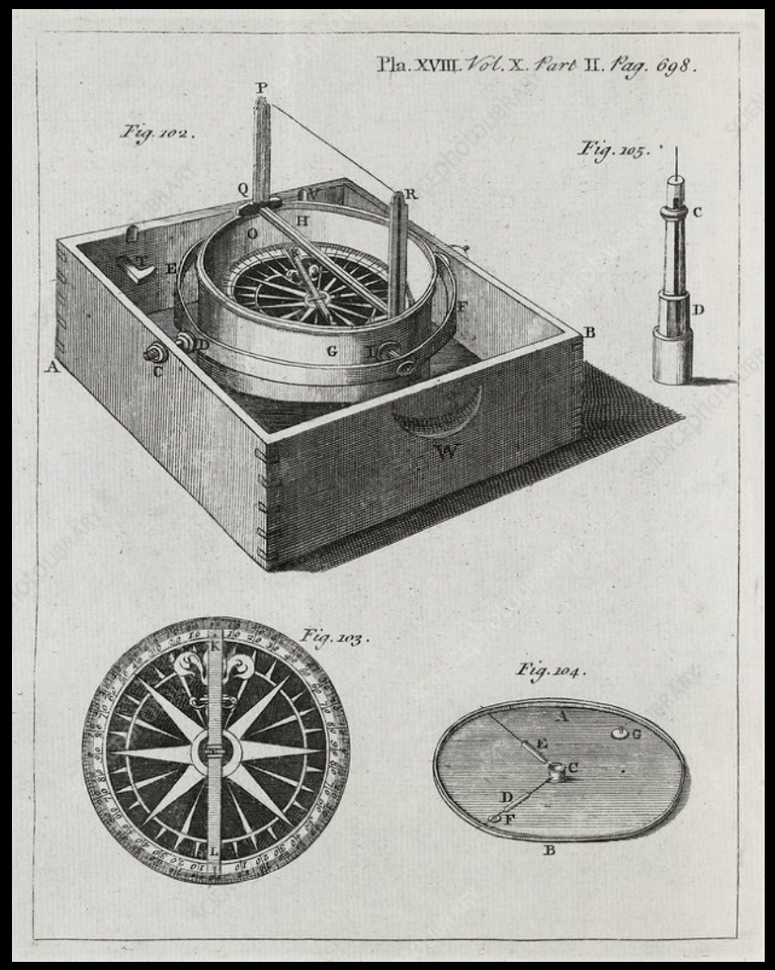
Joseph Black



James Watt

"Mathematical Instrument Maker
to the University of Glasgow"





Hadley's quadrant →

↑ Mariner's compass

James Watt

"Mathematical Instrument Maker
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"In the winter of 1763—1764, I had occasion to repair a model of a Newcomen's engine belonging to the Natural Philosophy class of the University of Glasgow."

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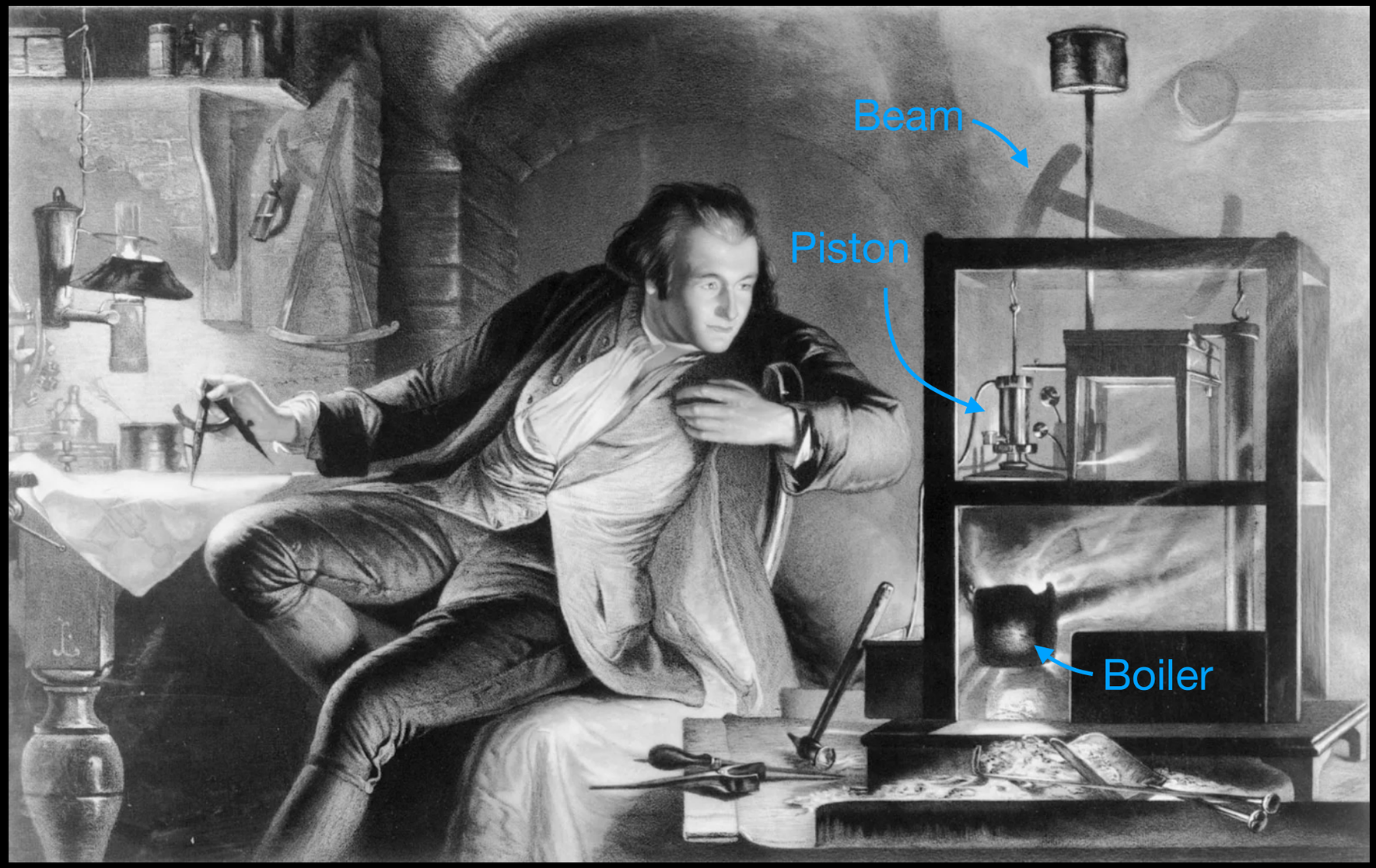

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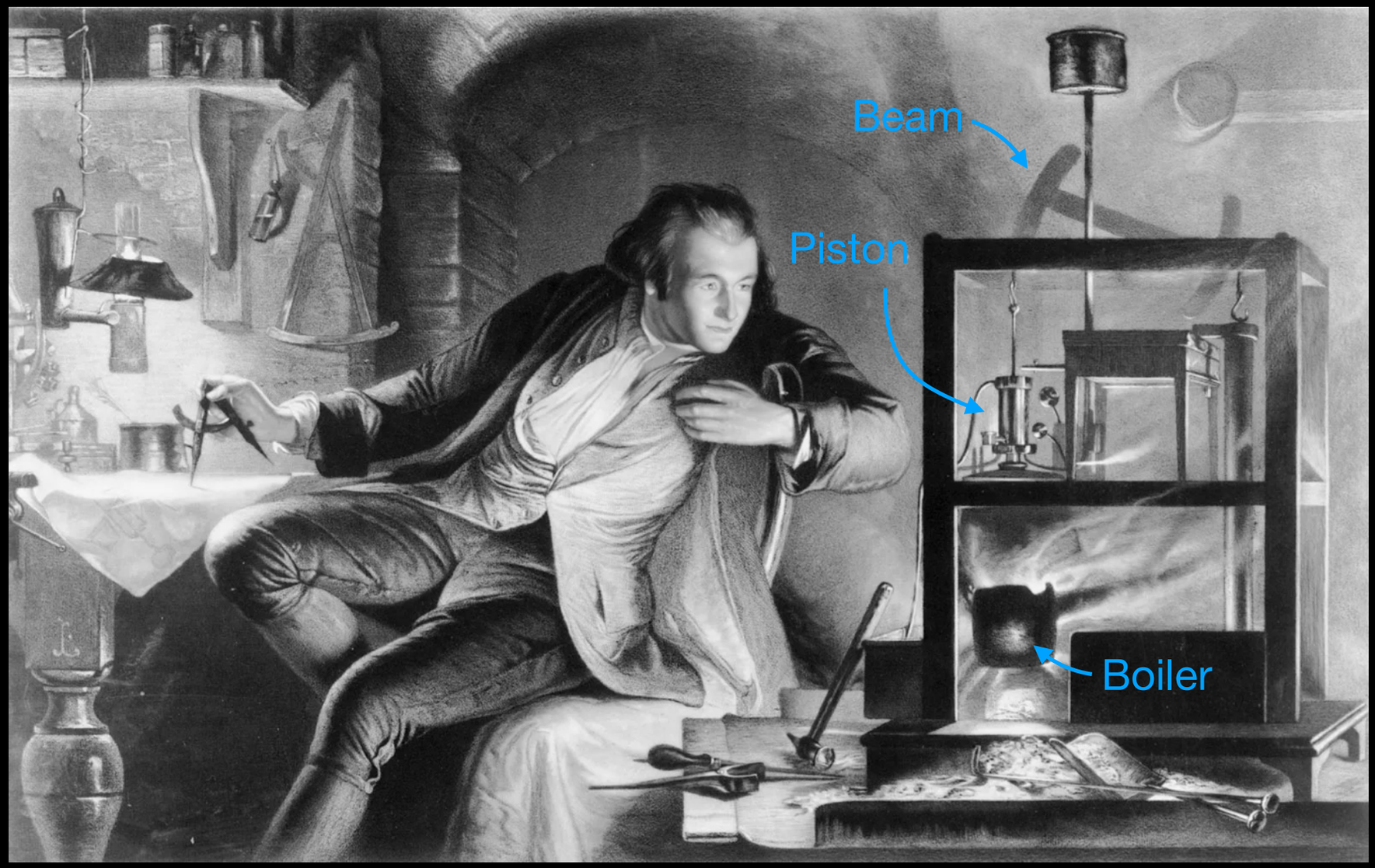
The model did not work well!

"I was surprised to find that its boiler could not supply it with steam, though apparently quite large enough."



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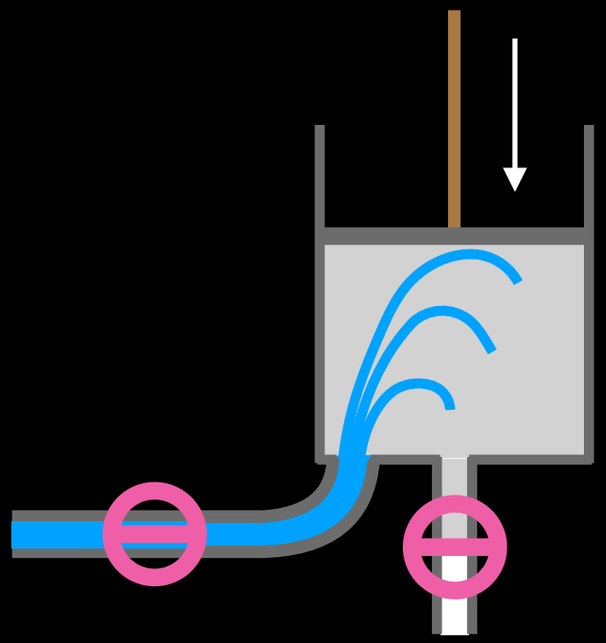
Tracing down the heat loss



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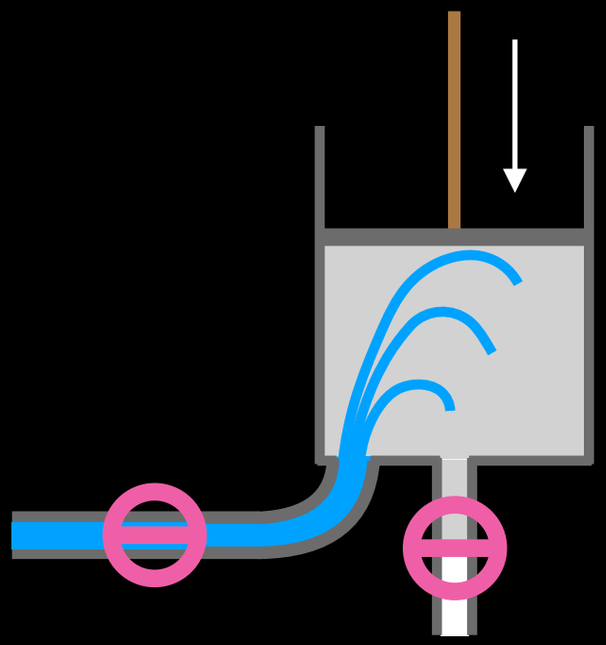
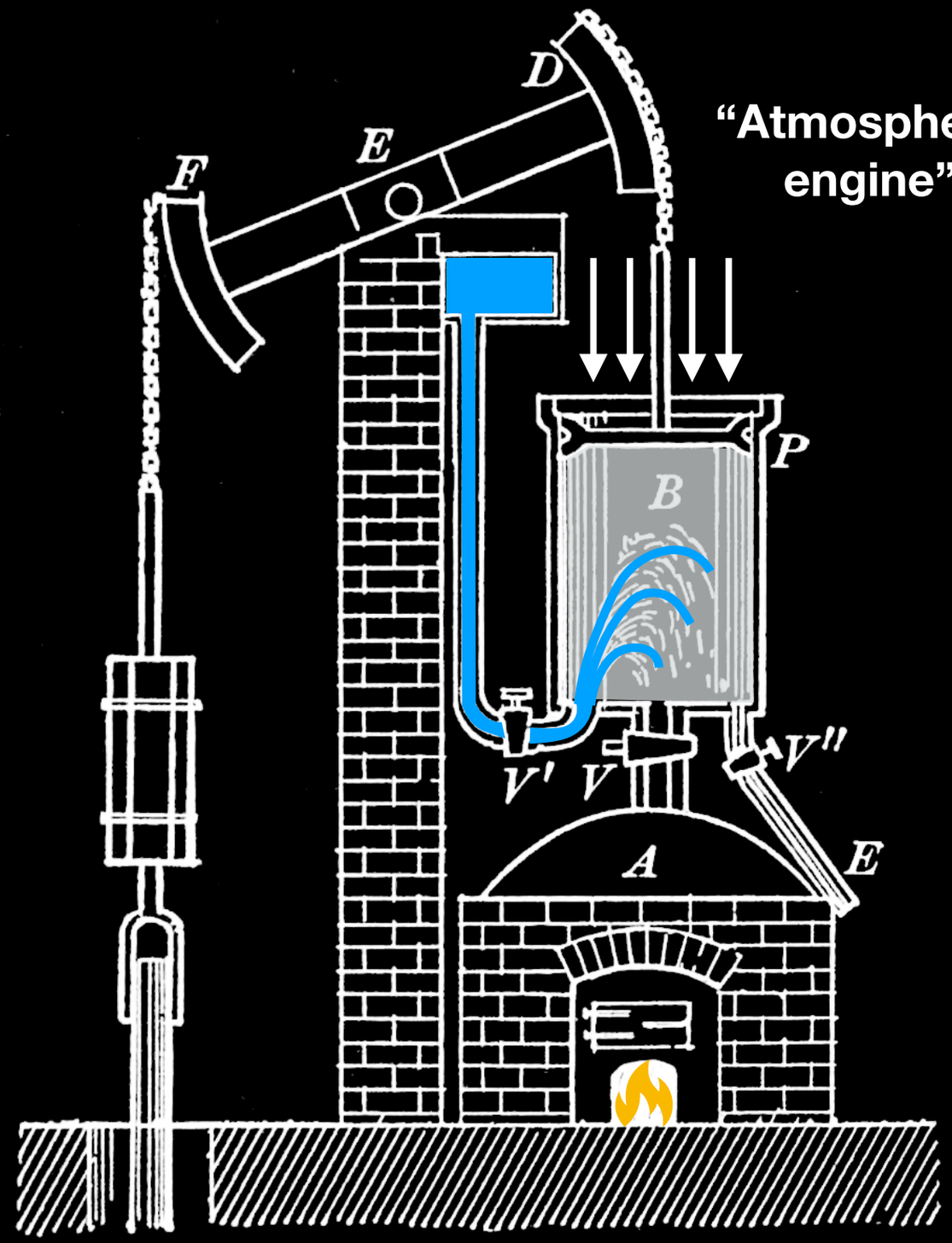
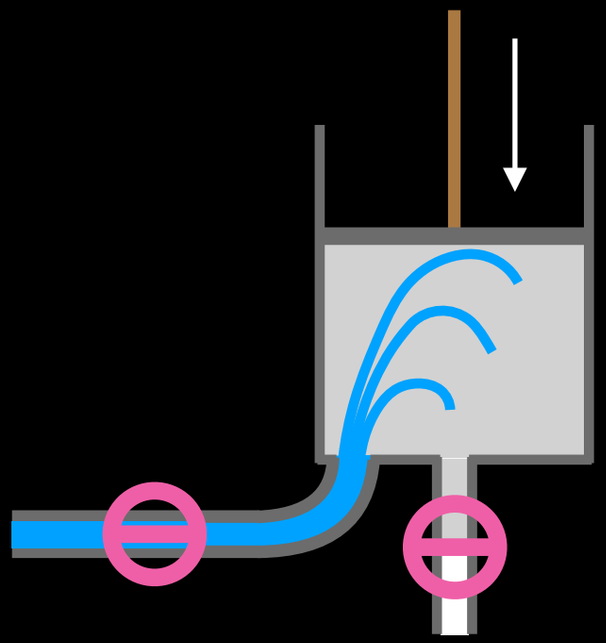




“Atmospheric engine”

Tracing down the heat loss



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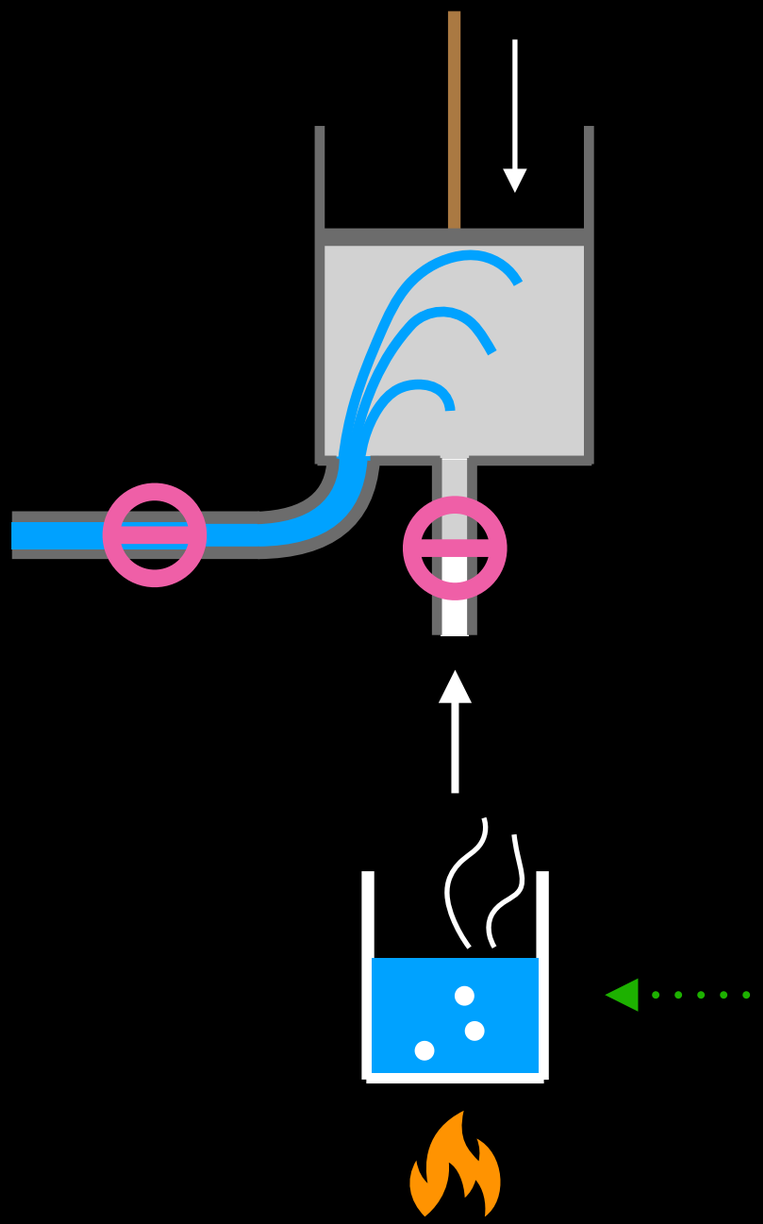
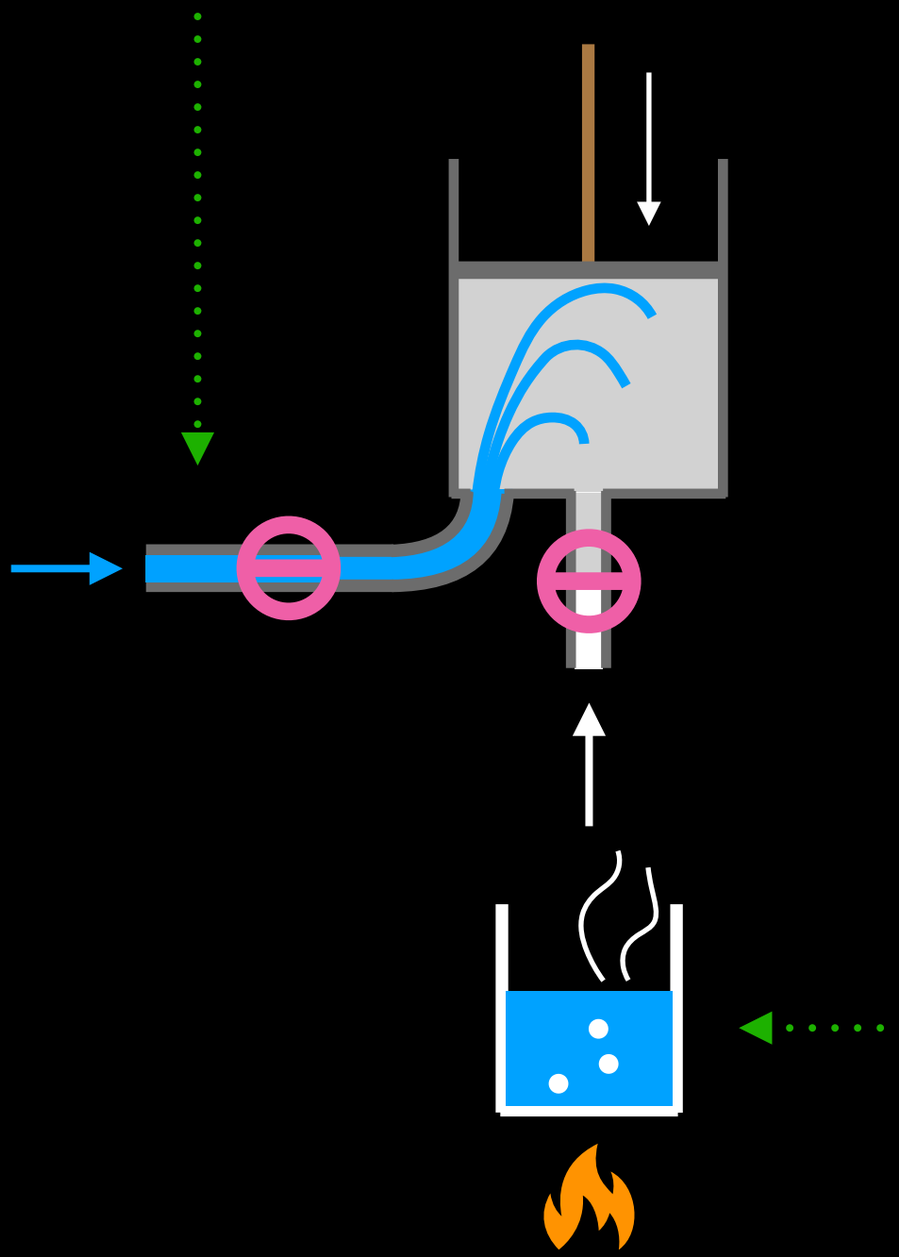


How much water needs to be evaporated to fill cylinder?

Tracing down the heat loss

How much water is needed to condense that steam?



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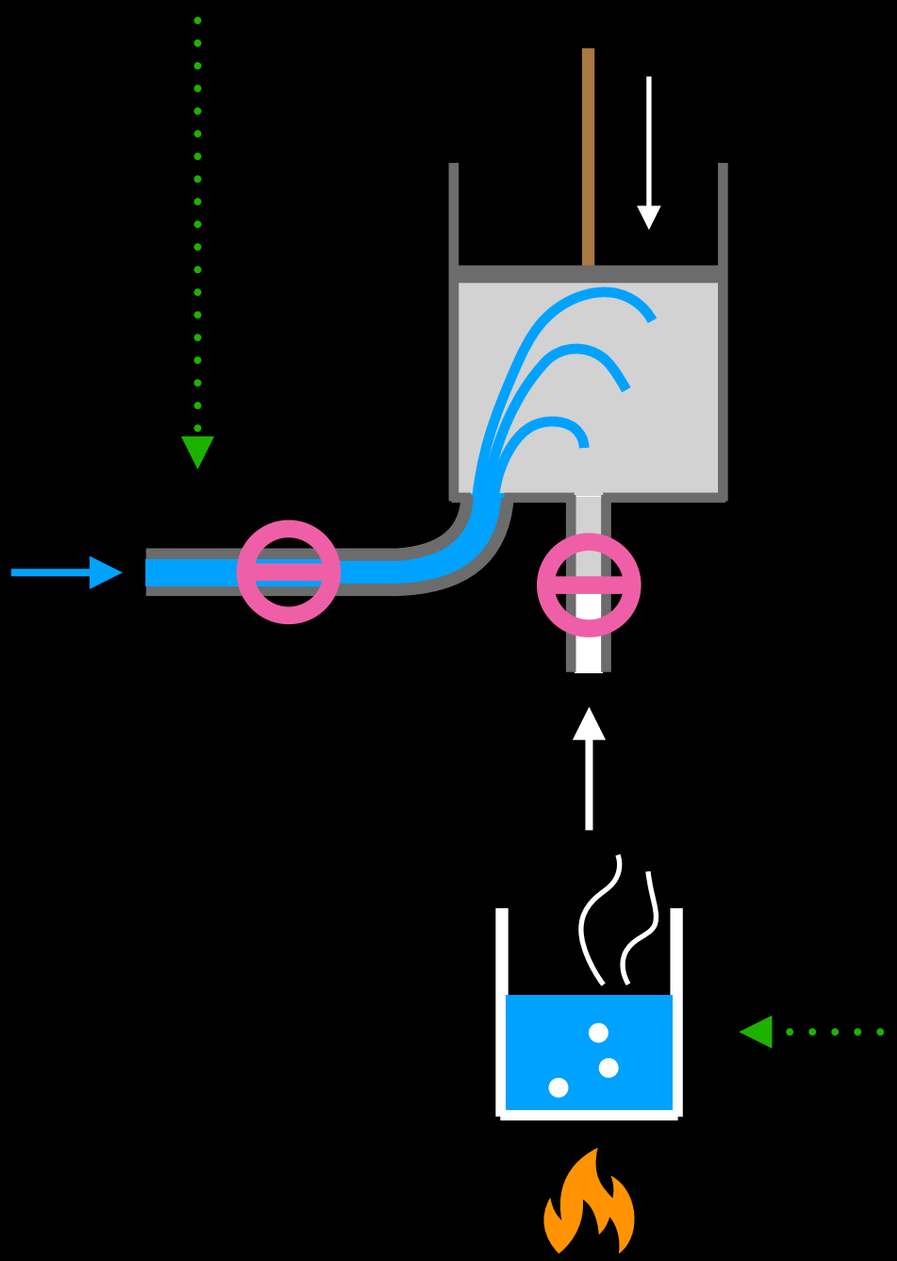

“I was astonished at the quantity of water required for the injection,

How much water needs to be evaporated to fill cylinder?

Tracing down the heat loss

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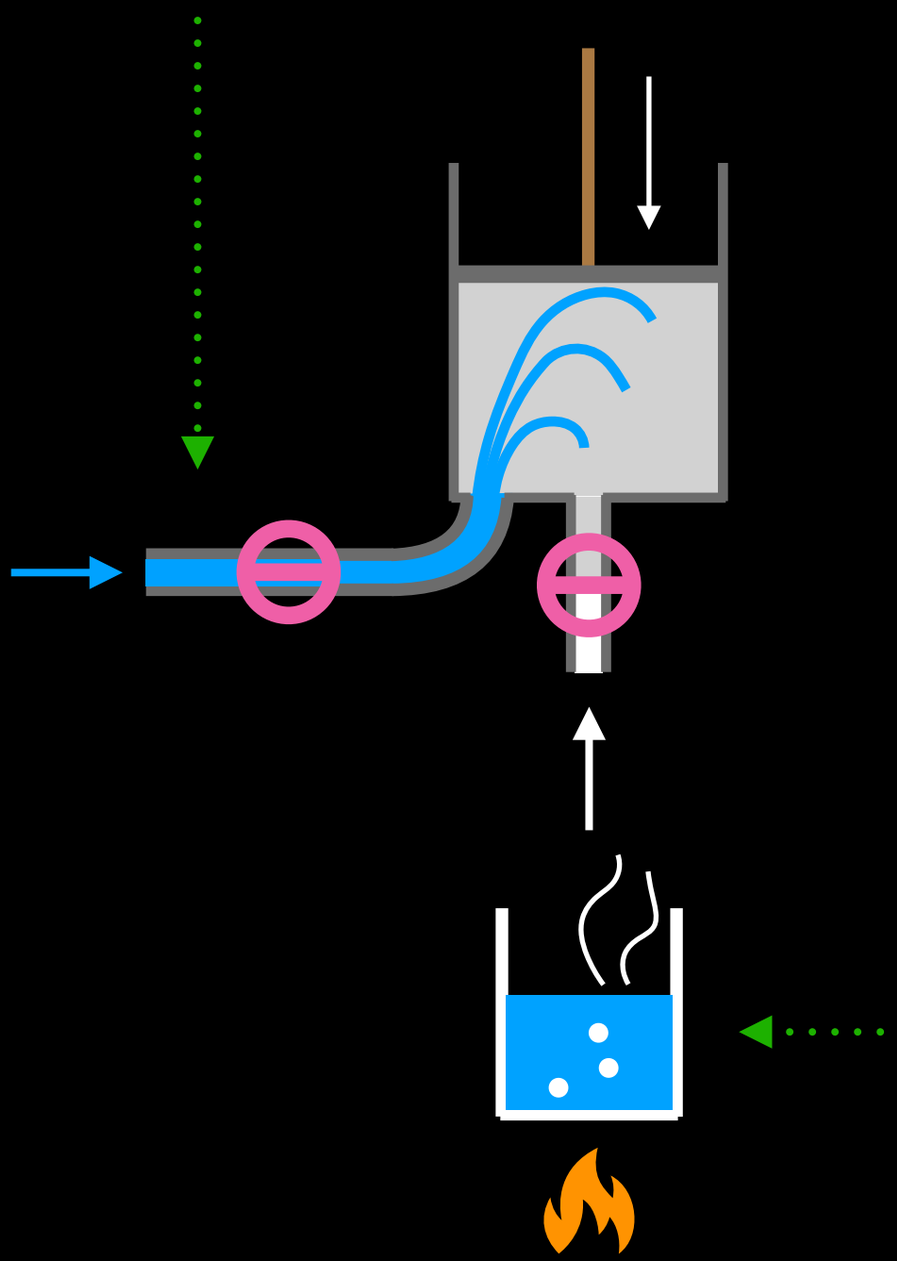

“I was astonished at the quantity of water required for the injection,
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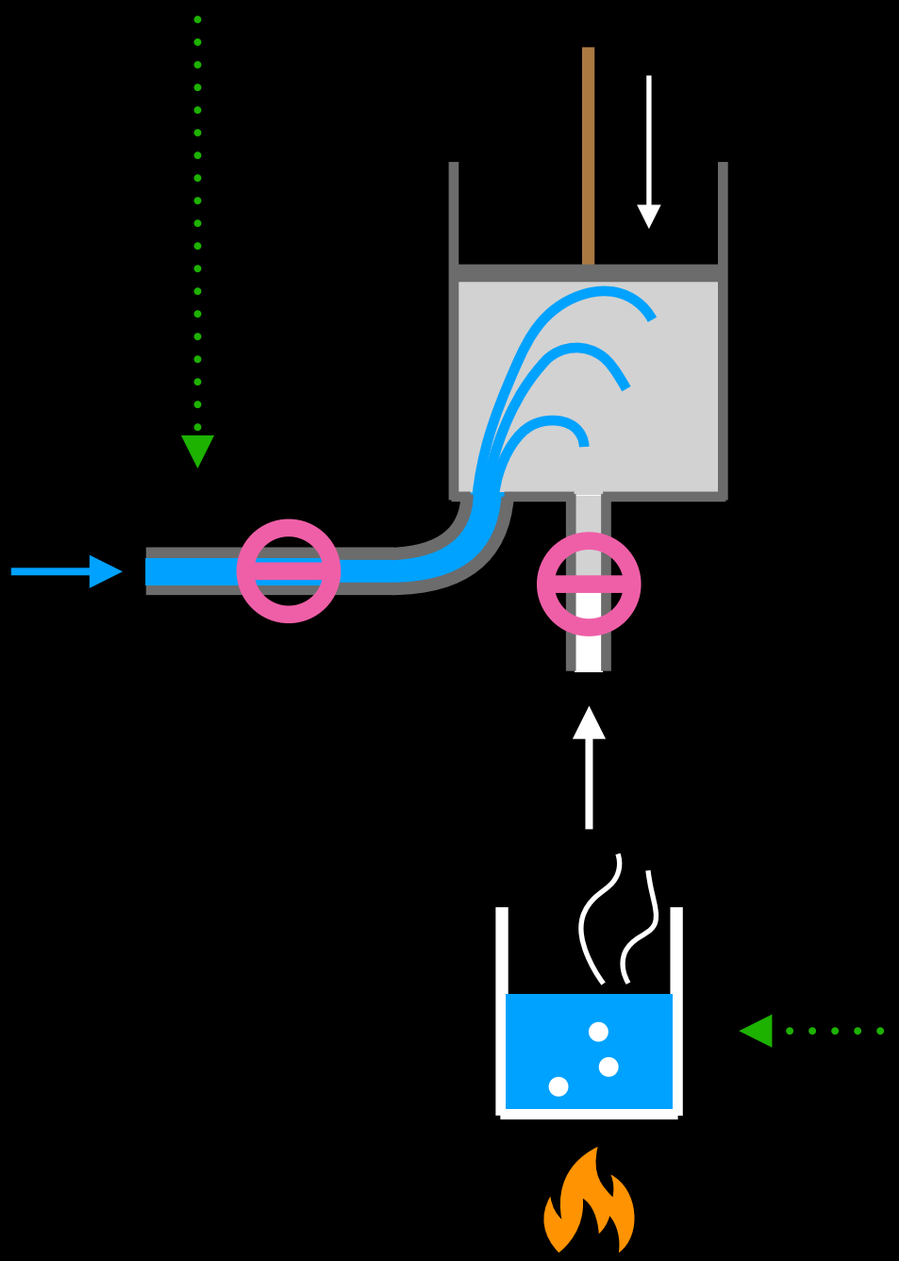

How much water needs to be evaporated to fill cylinder?

"I was astonished at the quantity of water required for the injection,
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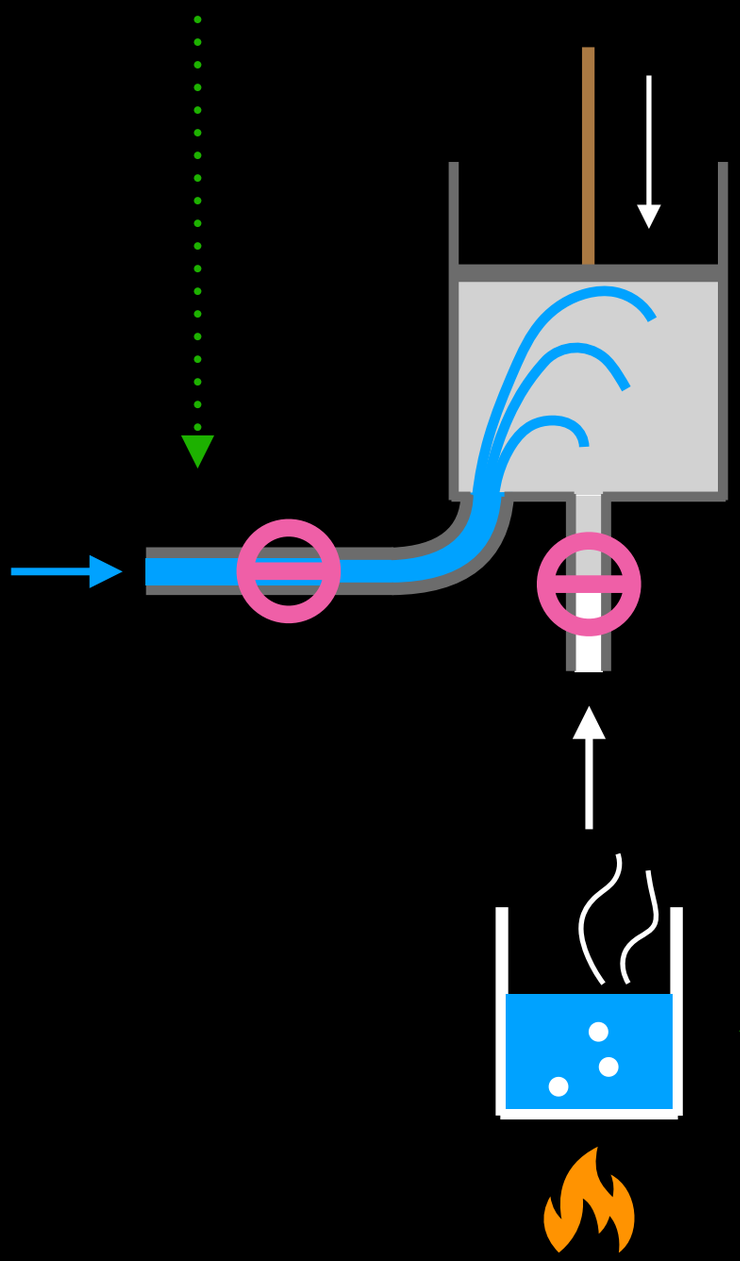
"Being struck with this remarkable fact, and not understanding the reason of it, I mentioned it to my friend Dr. Black,

Tracing down the heat loss

How much water is needed to condense that steam?



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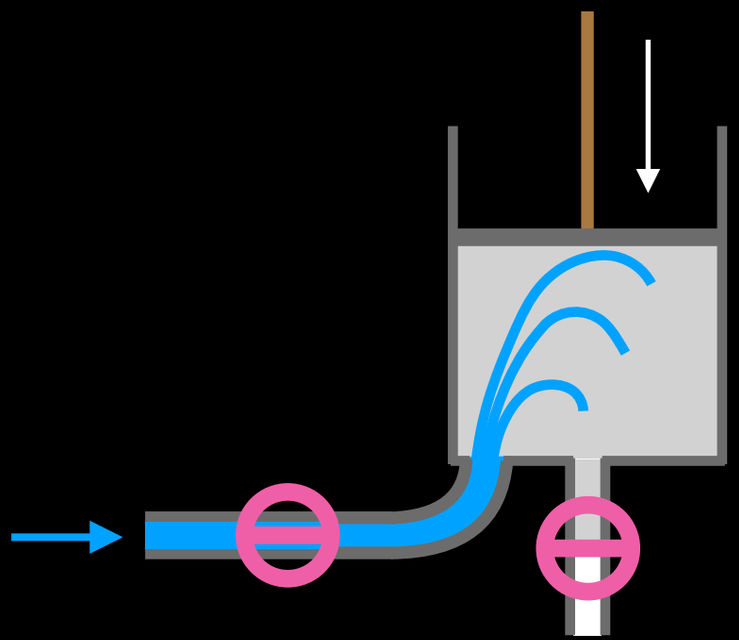
“I was astonished at the quantity of water required for the injection, and the great heat it had acquired from the small quantity of water in the form of steam which had been used in filling the cylinder.”

“Being struck with this remarkable fact, and not understanding the reason of it, I mentioned it to my friend Dr. Black, who then explained to me his doctrine of latent heat, which he had taught for some time.”

How much water to inject?



Powerful stroke: complete condensation of steam in piston

→ *“large quantities of injection”*

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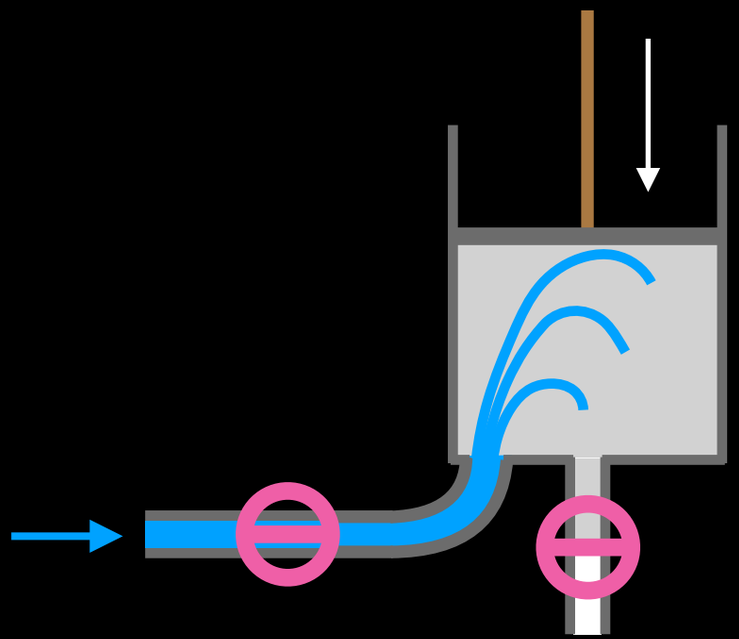

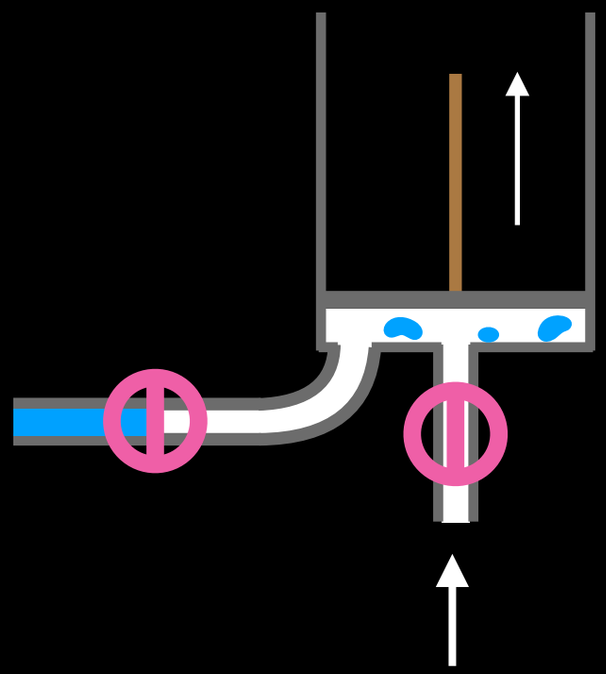

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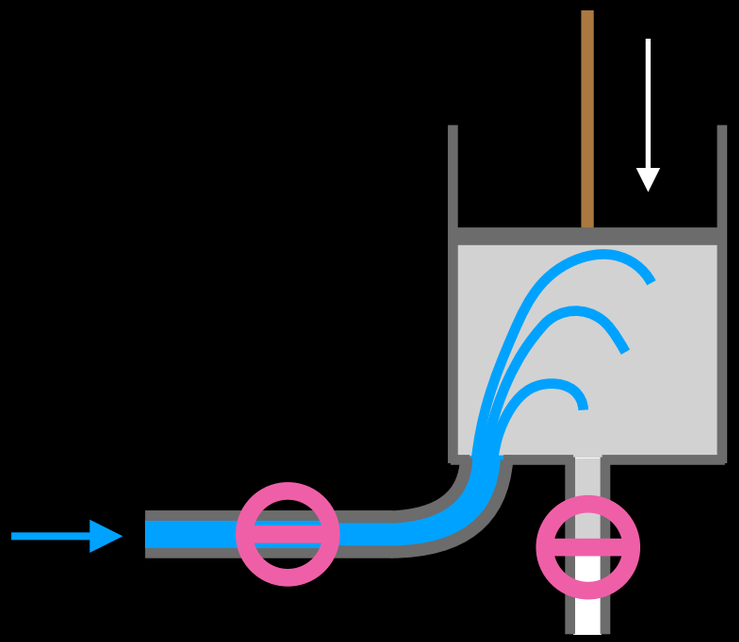
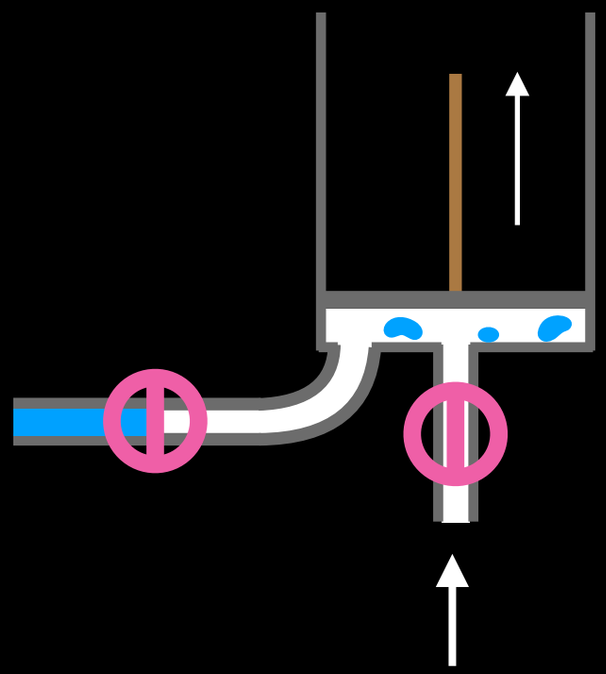


Powerful stroke: complete condensation of steam in piston
→ *“large quantities of injection”*

Efficient machine: keep piston hot
→ *“small injection”*



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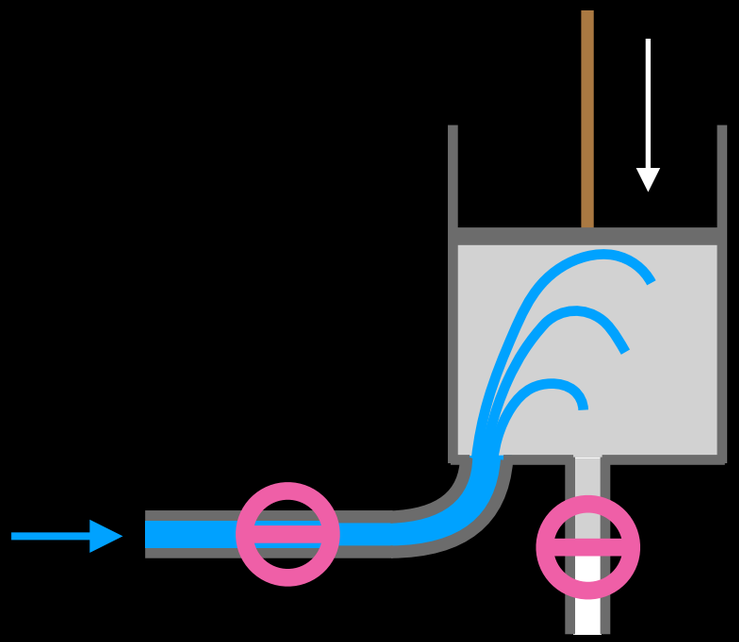

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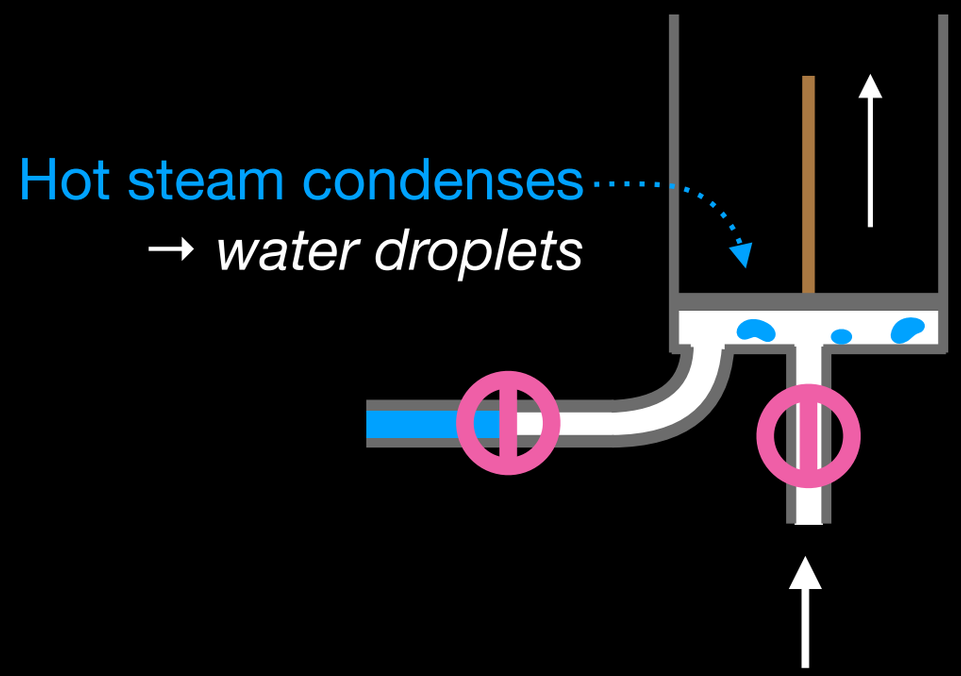

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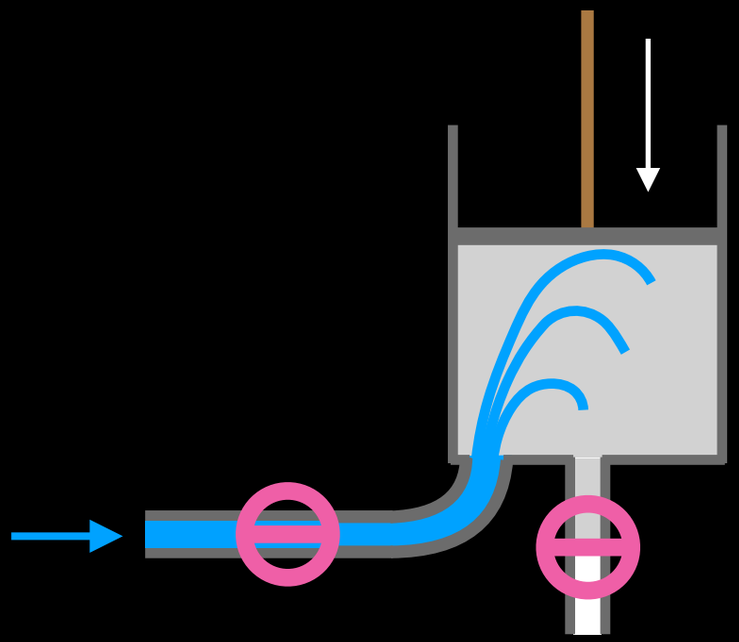

Powerful stroke: complete condensation of steam in piston
→ *“large quantities of injection”*

Efficient machine: keep piston hot
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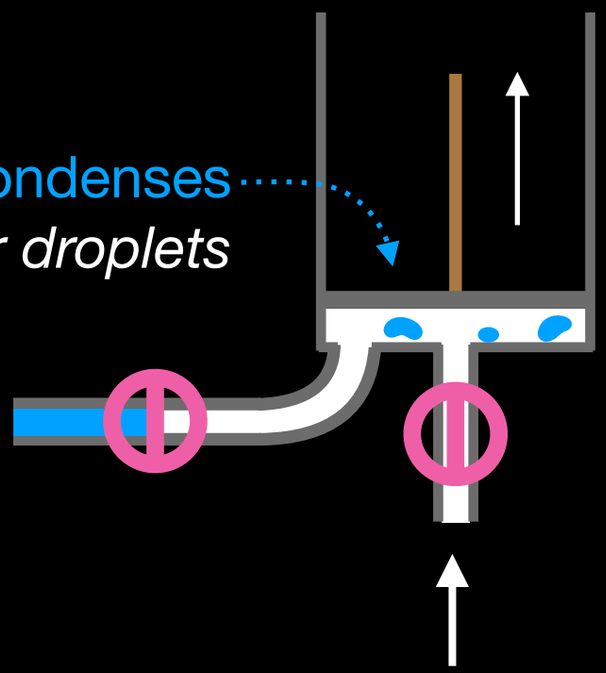
Hot steam condenses
→ *water droplets*



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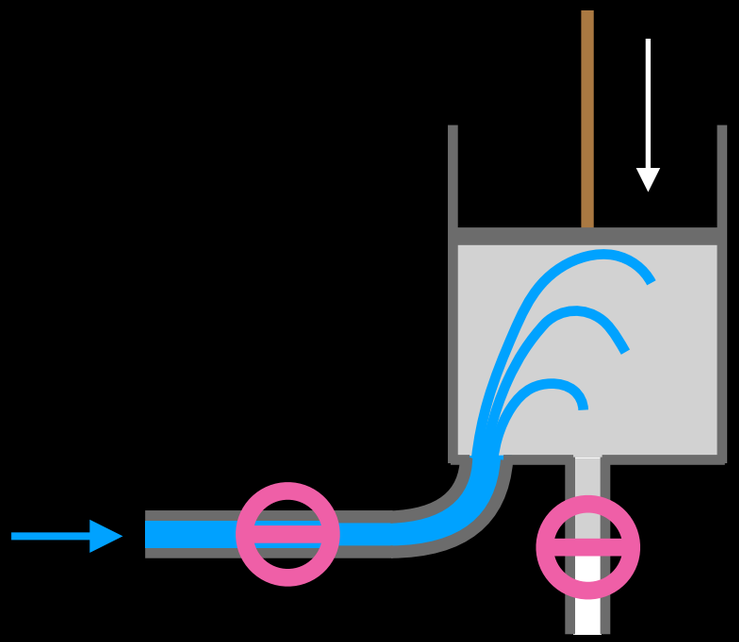

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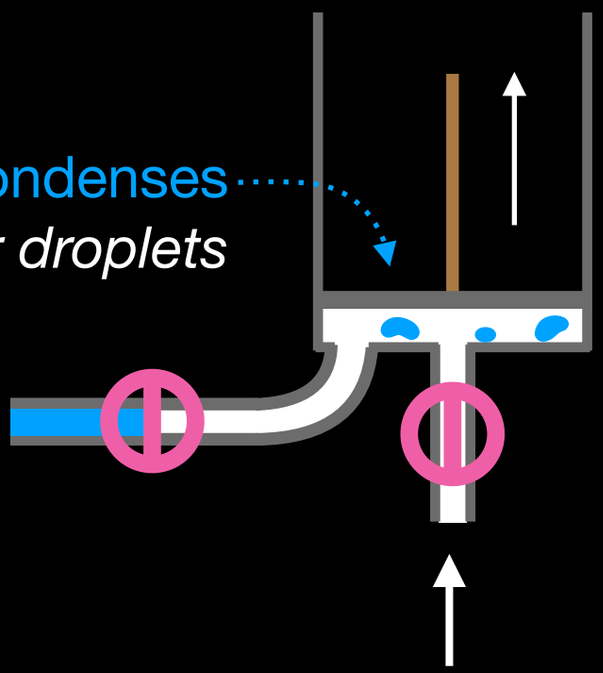
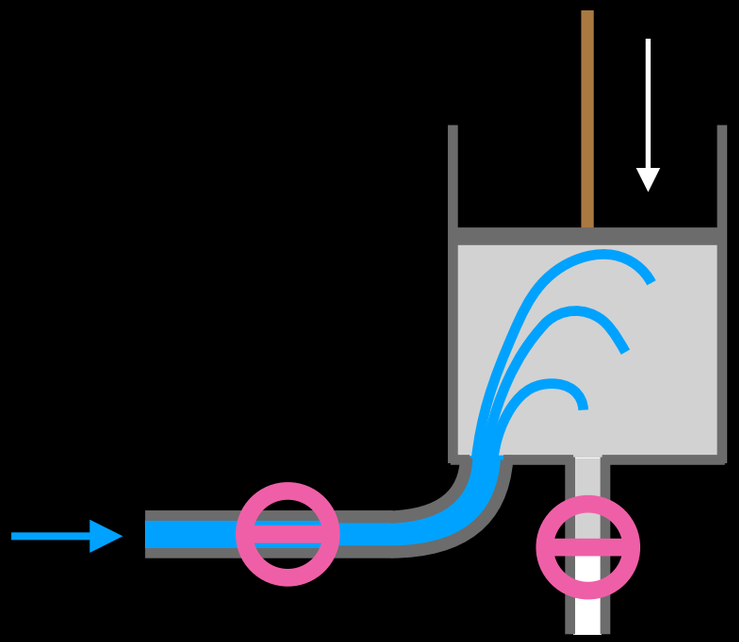


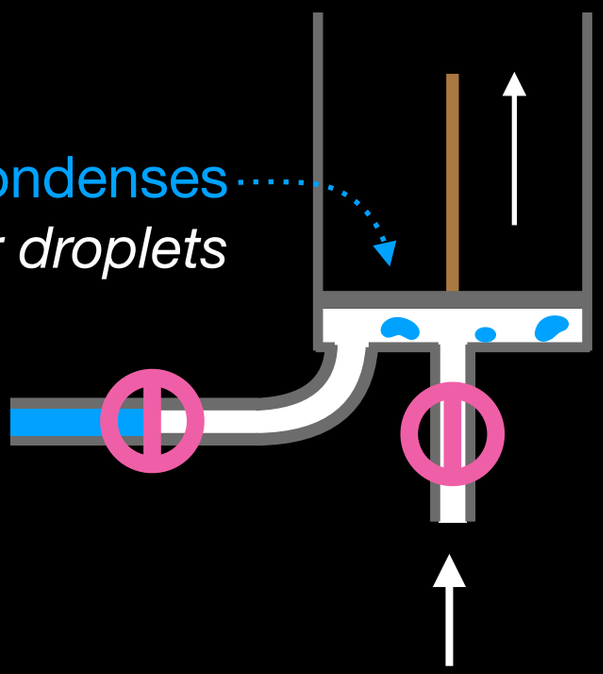
James Watt:
“It also appeared that throwing in large quantities of injection (so as to form a good vacuum) would cool the cylinder to much as to require quantities of steam to heat it again.”

How much water to inject?



Powerful stroke: complete condensation of steam in piston
→ *“large quantities of injection”*

Efficient machine: keep piston hot
→ *“small injection”*



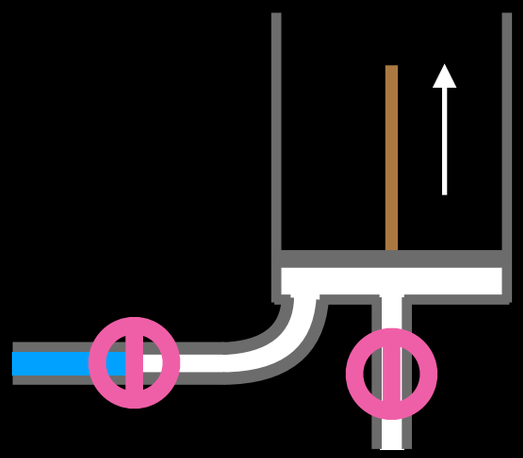
James Watt:
“It also appeared that throwing in large quantities of injection (so as to form a good vacuum) would cool the cylinder to much as to require quantities of steam to heat it again.”

Joseph Black:
The heat capacity of the piston complicates your life

Watt’s ideas

“In order to make the best use of steam,
it was necessary—

Watt’s ideas



“In order to make the best use of steam, it was necessary—

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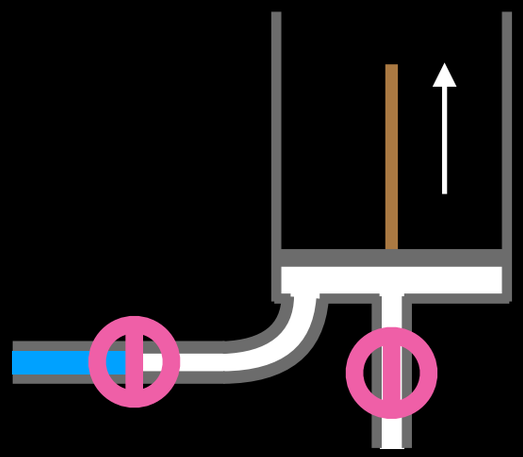

“In order to make the best use of steam, it was necessary—

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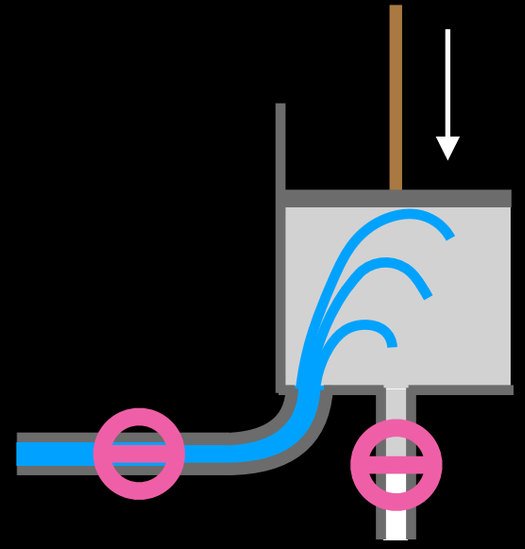
and, secondly that when the steam was condensed, the water of which it was composed, and the injection itself, should be cooled down as much as possible.



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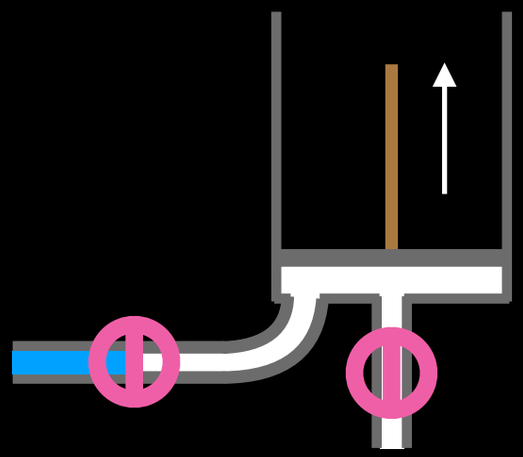

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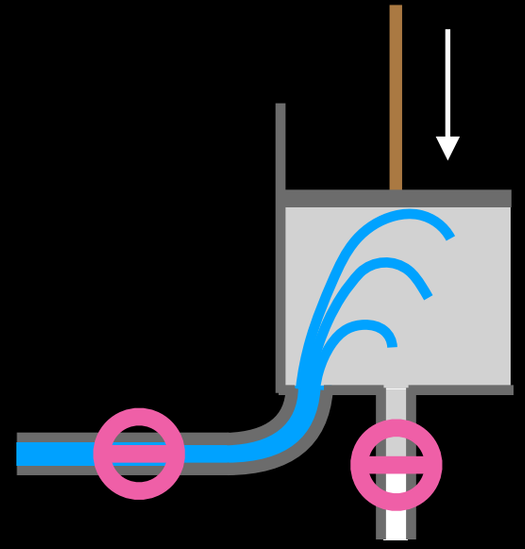
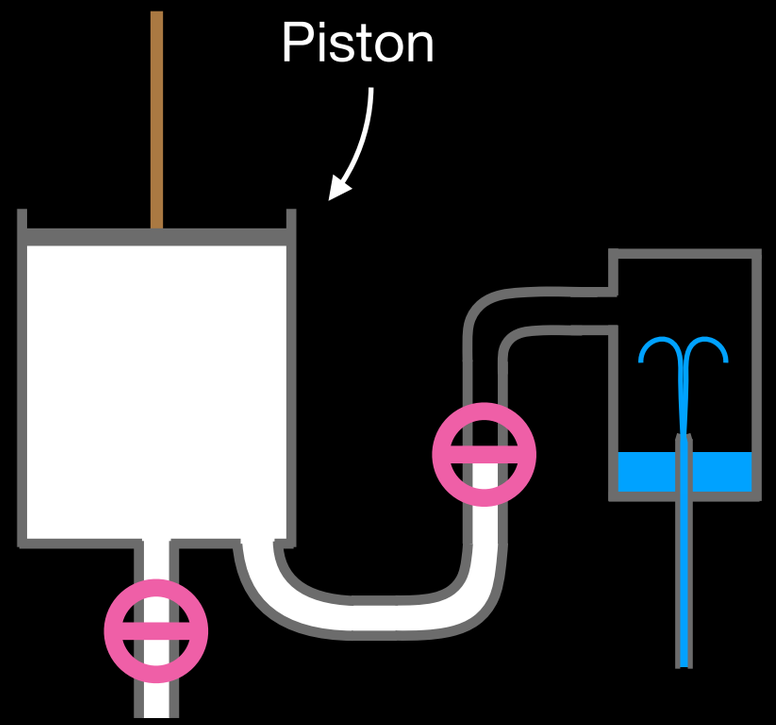


The means of accomplishing these points did not immediately present themselves.”

Watt’s improvements

“Early in 1765 it occurred to me, that if a communication were opened between a cylinder containing steam, and another vessel, kept very cool by an injection …”



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“Early in 1765 it occurred to me, that if a communication were opened between a cylinder containing steam, and another vessel, kept very cool by an injection …”

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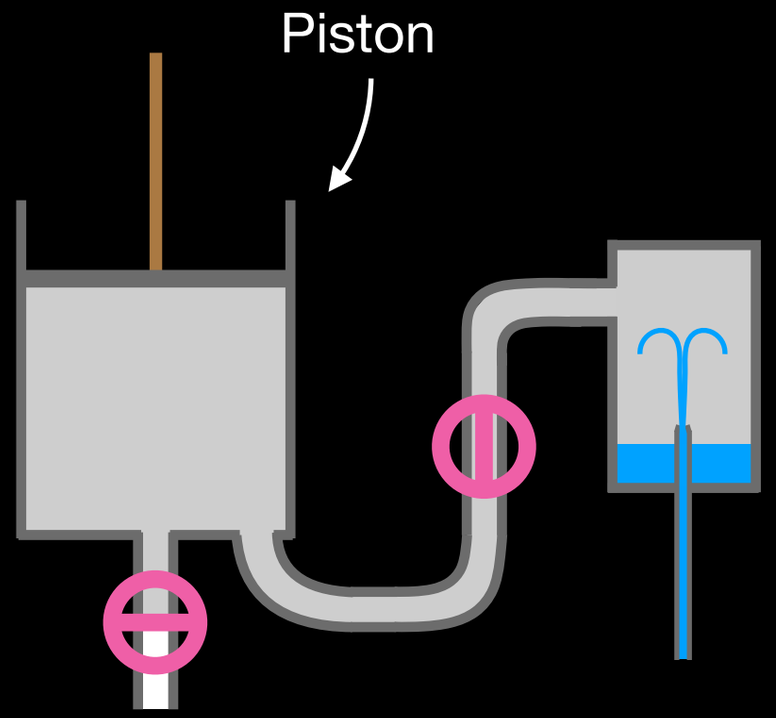

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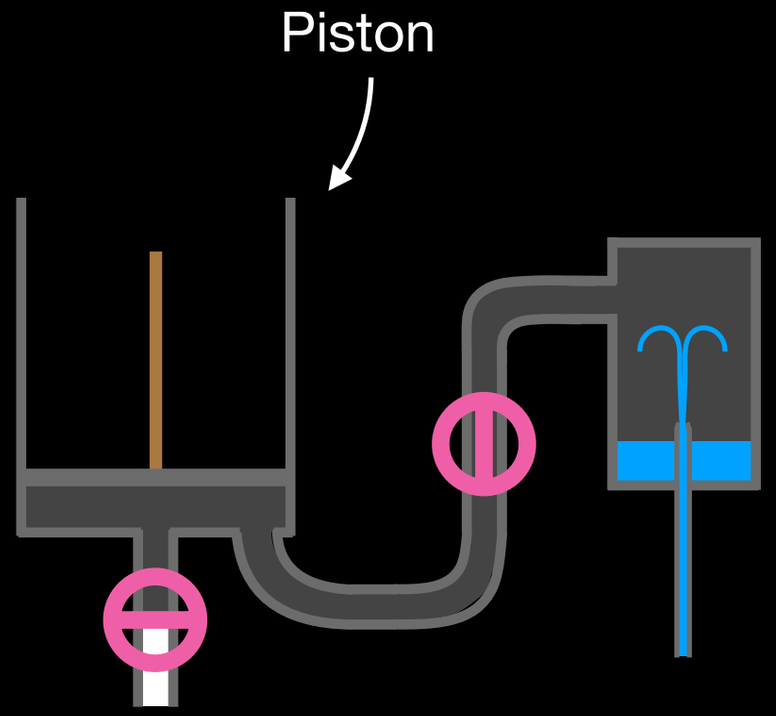

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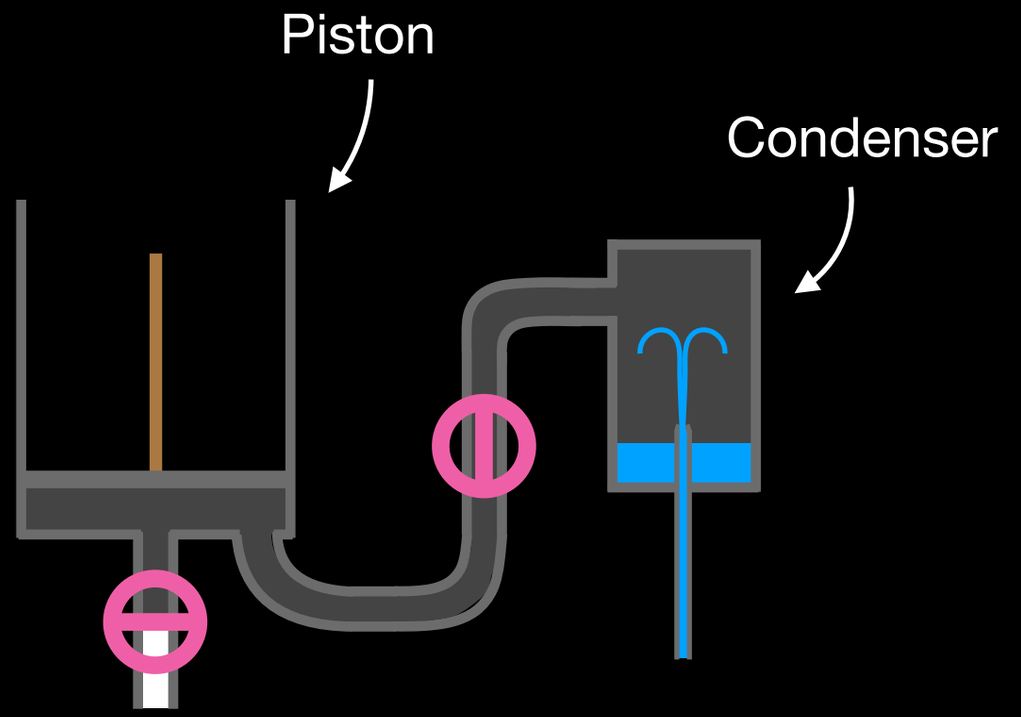

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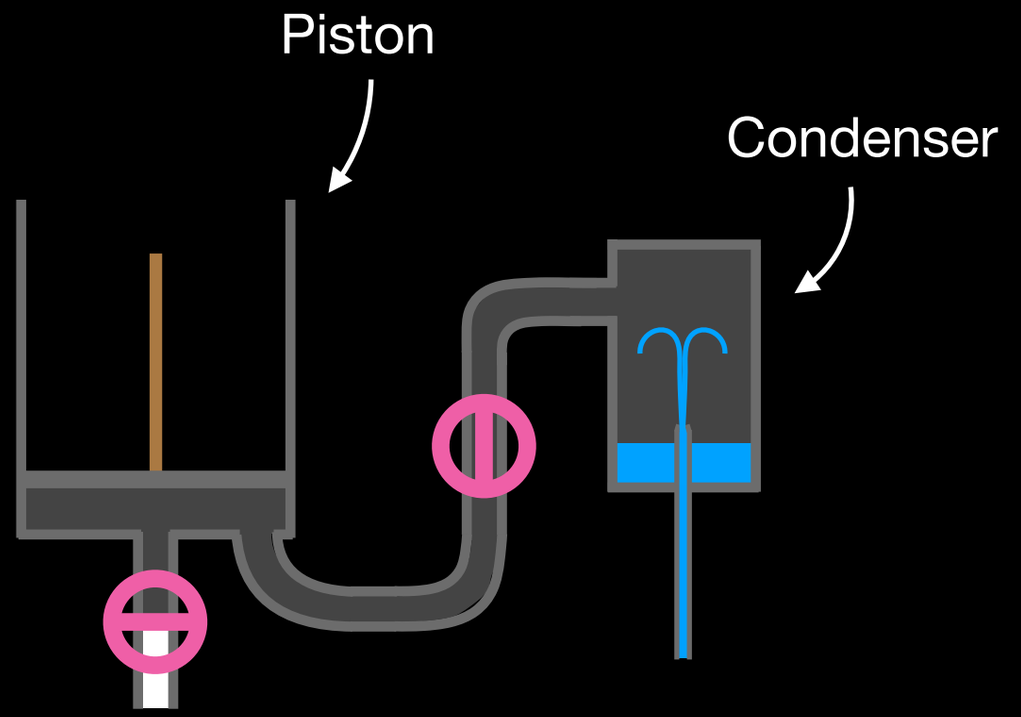
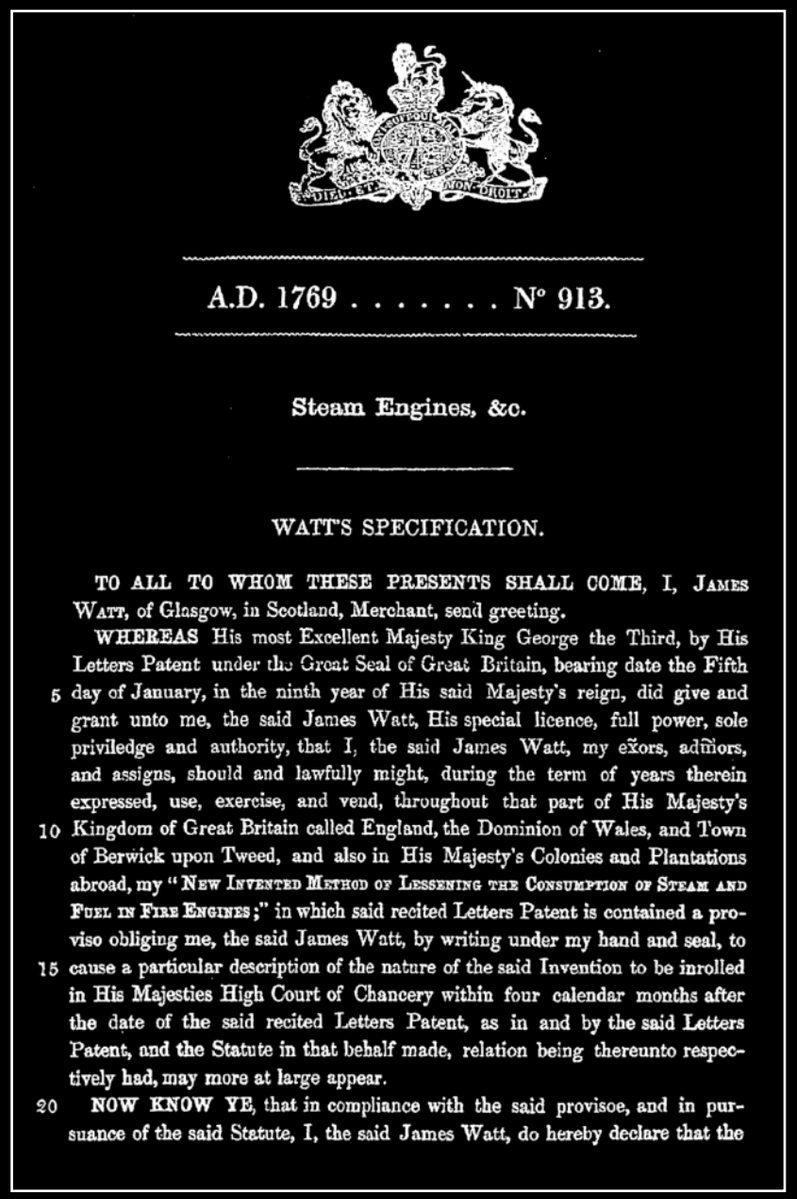


Piston stays hot, condenser stays cool!

Watt's patent

"When once the idea of the separate condensation was started,
in the course of one or two days the invention was complete in my mind …"

"… and I immediately set about an experiment to verify it practically."



A.D. 1769 . . . . . N° 913.

Steam Engines, &c.

WATT'S SPECIFICATION.

TO ALL TO WHOM THESE PRESENTS SHALL COME, I, JAMES WATT, of Glasgow, in Scotland, Merchant, send greeting.

WHEREAS His most Excellent Majesty King George the Third, by His Letters Patent under the Great Seal of Great Britain, bearing date the Fifth day of January, in the ninth year of His said Majesty's reign, did give and grant unto me, the said James Watt, His special licence, full power, sole priviledge and authority, that I, the said James Watt, my exors, admors, and assigns, should and lawfully might, during the term of years therein expressed, use, exercise, and vend, throughout that part of His Majesty's Kingdom of Great Britain called England, the Dominion of Wales, and Town of Berwick upon Tweed, and also in His Majesty's Colonies and Plantations abroad, my "NEW INVENTED METHOD OF LESSENING THE CONSUMPTION OF STEAM AND FUEL IN FIRE ENGINES;" in which said recited Letters Patent is contained a proviso obliging me, the said James Watt, by writing under my hand and seal, to cause a particular description of the nature of the said Invention to be inrolled in His Majesties High Court of Chancery within four calendar months after the date of the said recited Letters Patent, as in and by the said Letters Patent, and the Statute in that behalf made, relation being thereunto respectively had, may more at large appear.

NOW KNOW YE, that in compliance with the said provisoe, and in pursuance of the said Statute, I, the said James Watt, do hereby declare that the

Patent granted 1769:
"New invented method of lessening the consumption of steam and fuel in fire engines"

How to conquer the world?

Watt: “I would rather face a loaded cannon than settle an account or make a bargain.”

How to conquer the world?

Matthew Boulton

James Watt

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How to conquer the world?

Matthew Boulton **James Watt** **William Murdoch**

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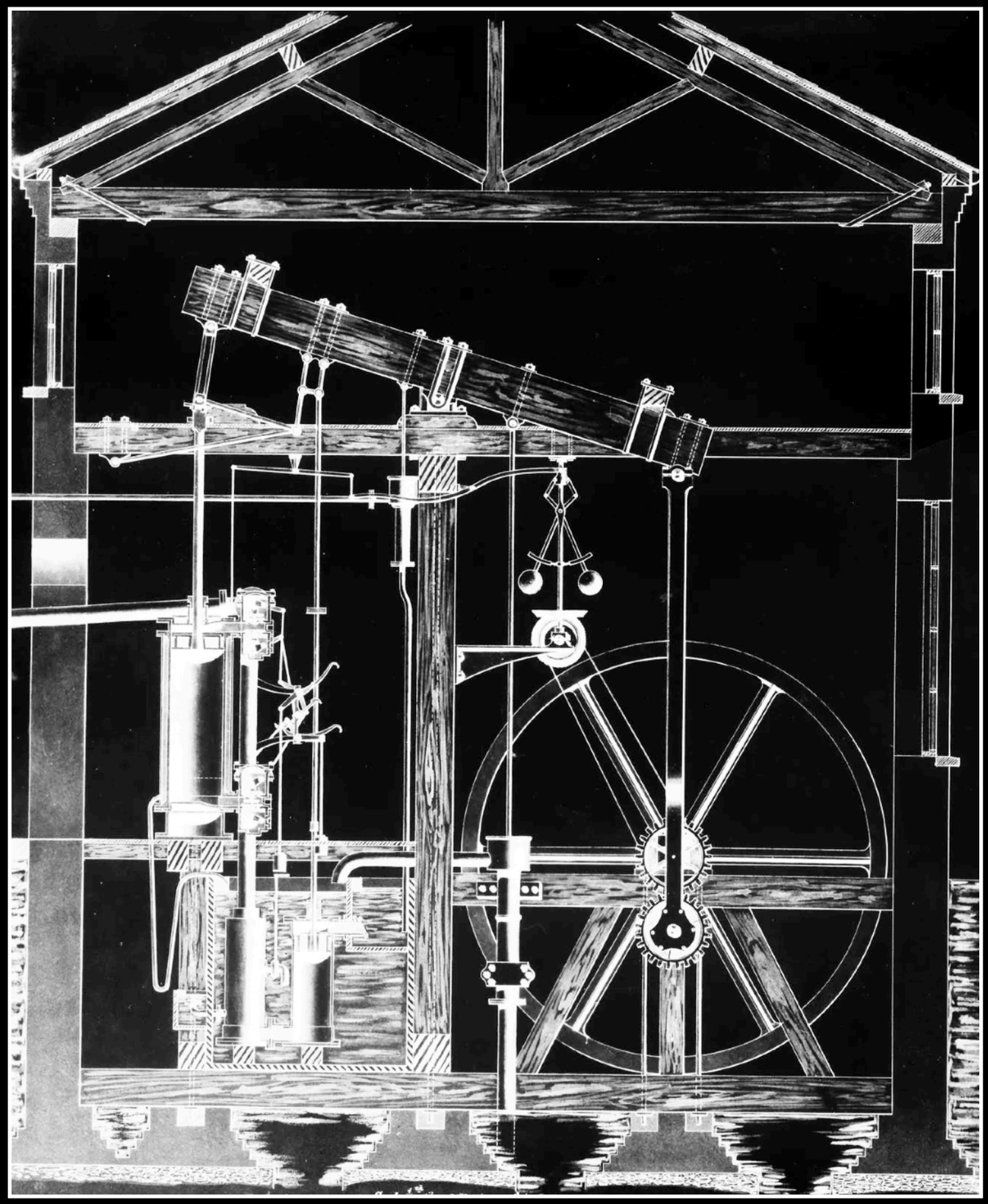
Watt, Boulton, and Murdoch conquer the world



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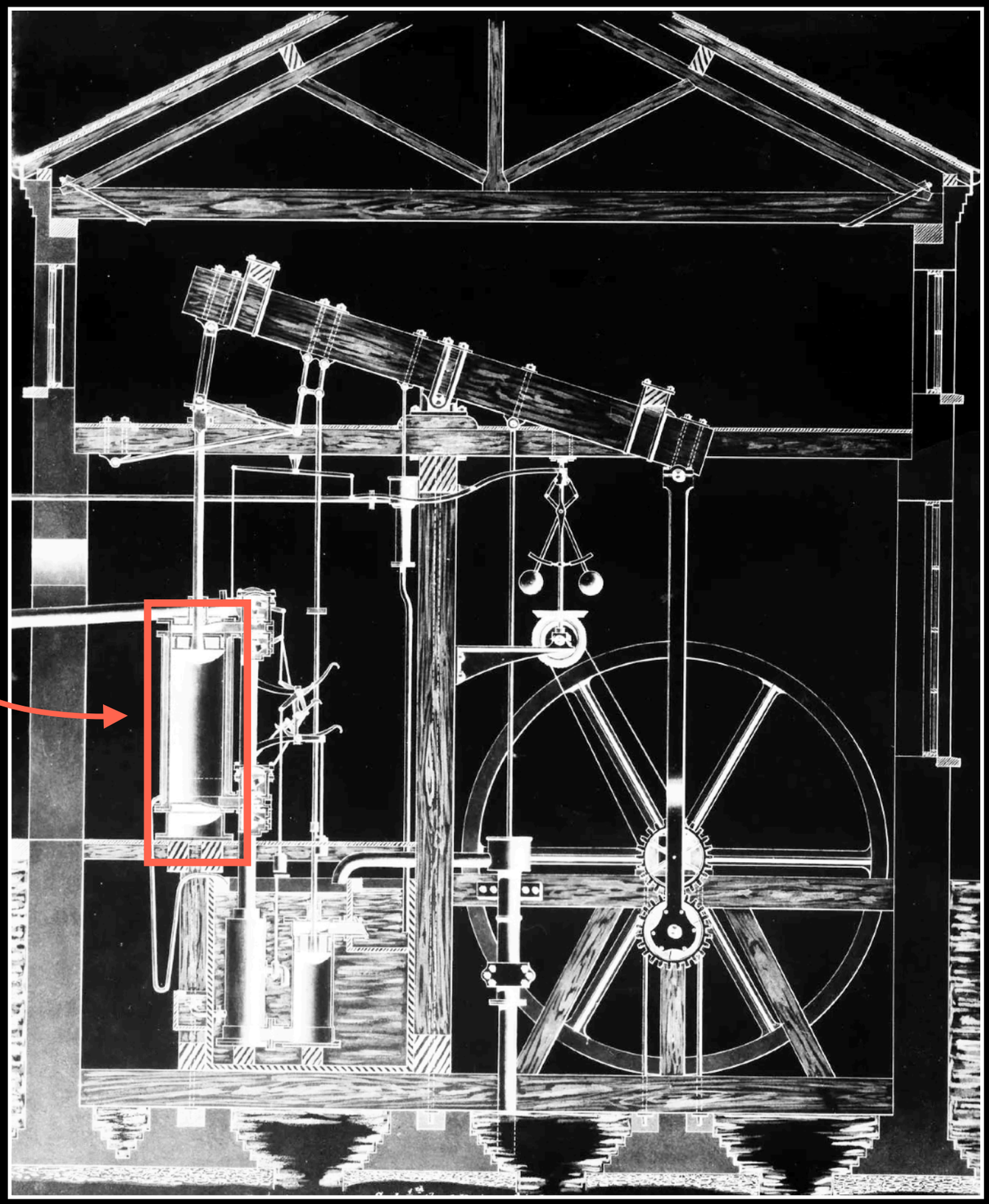

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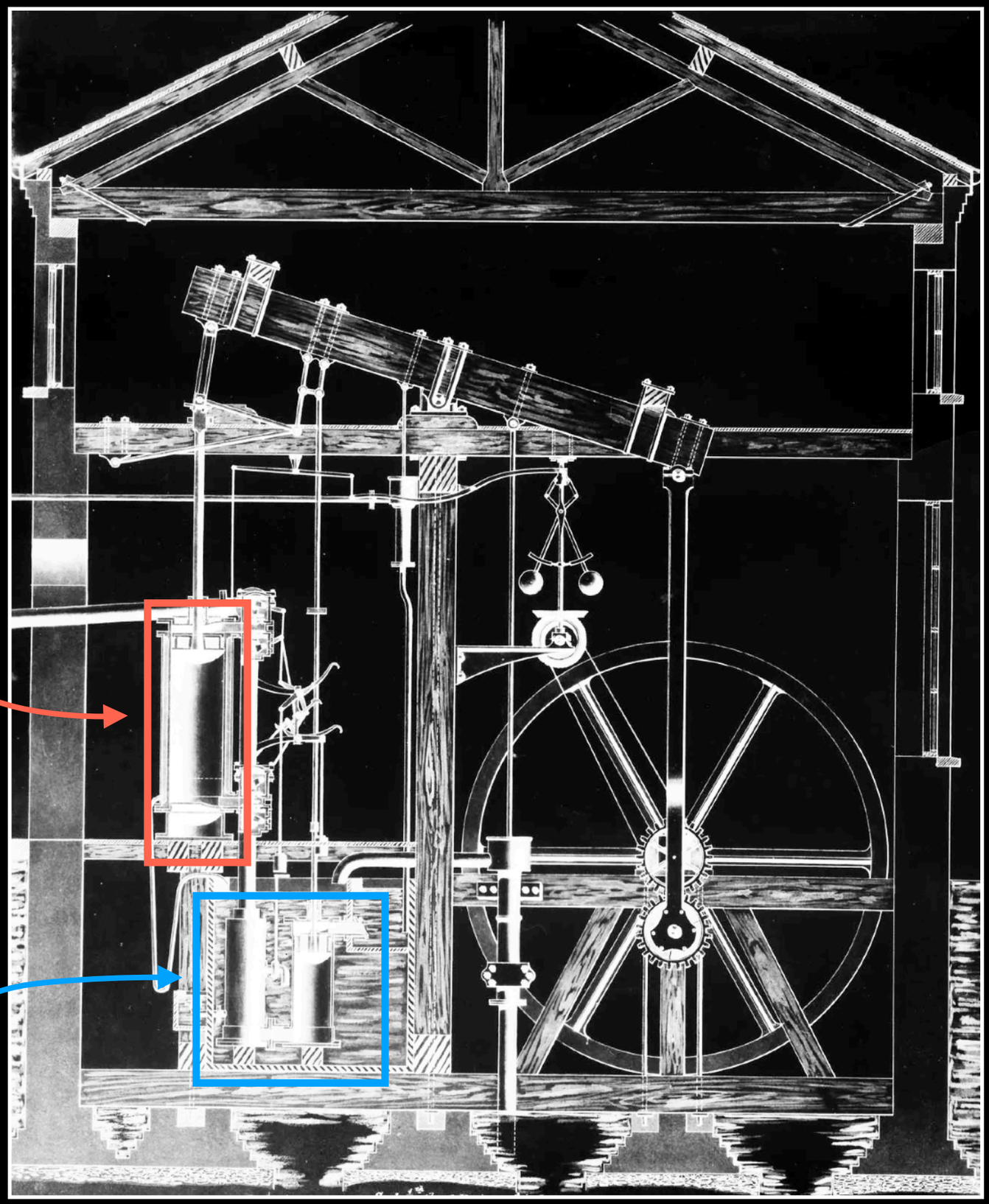

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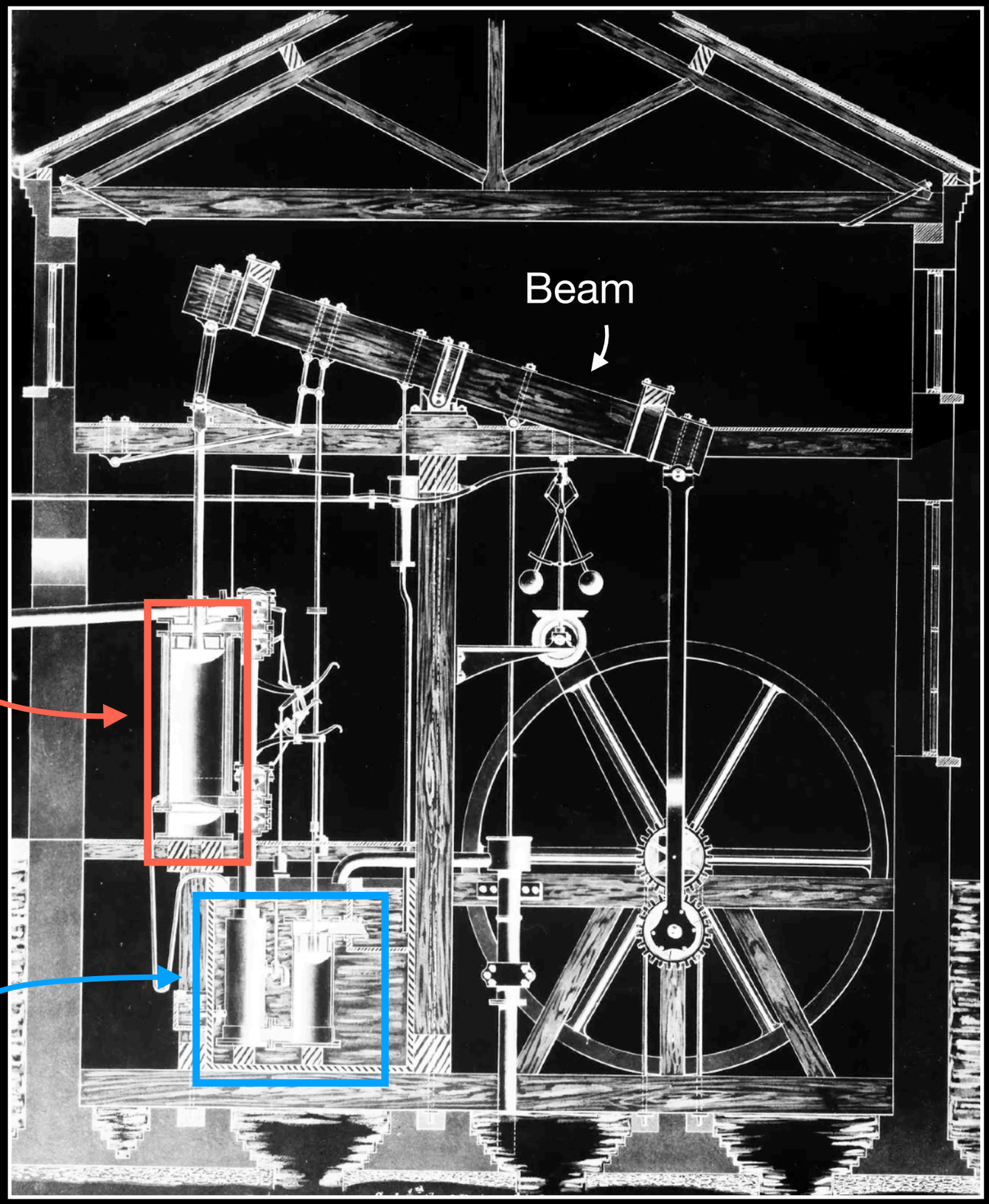

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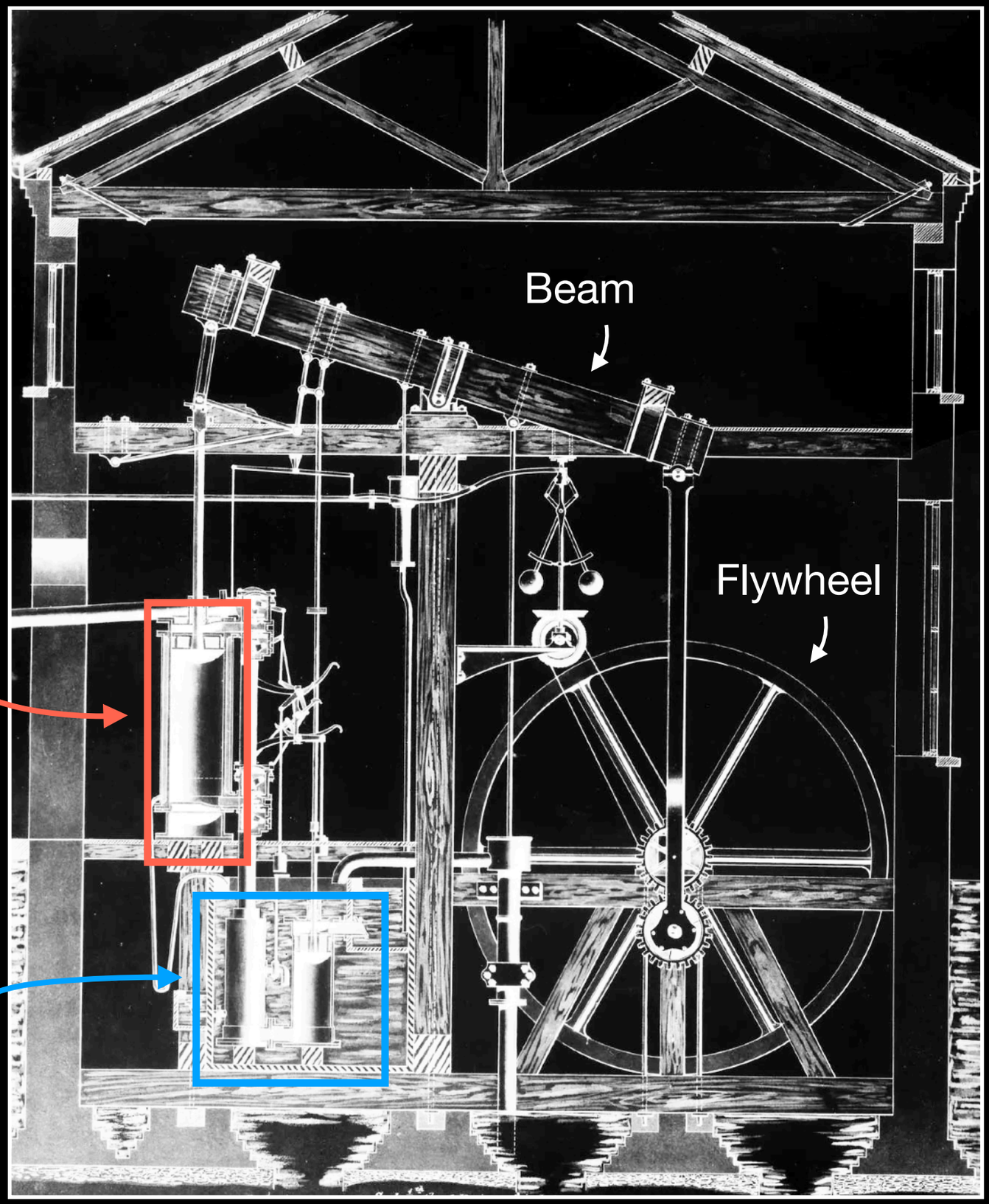

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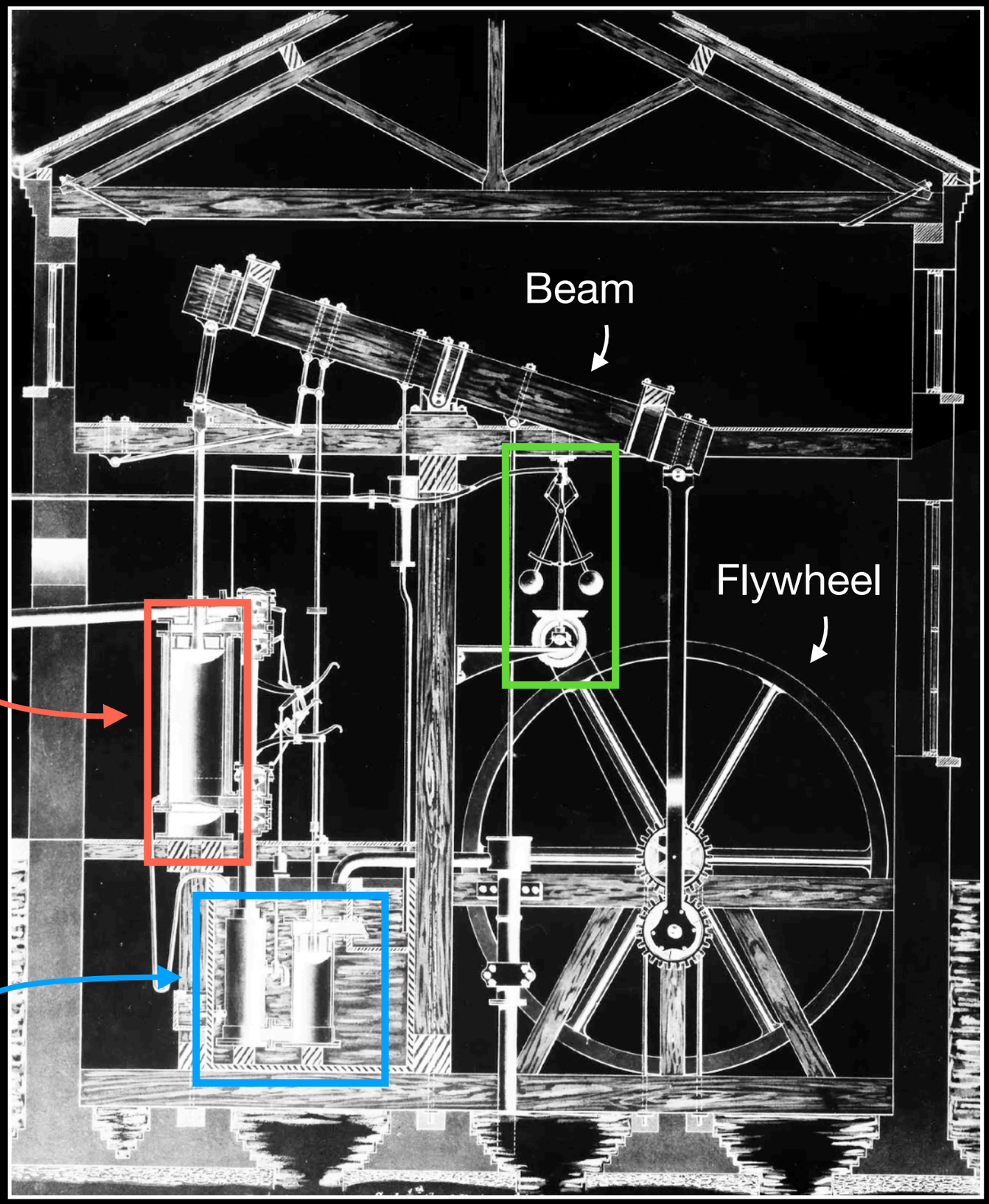

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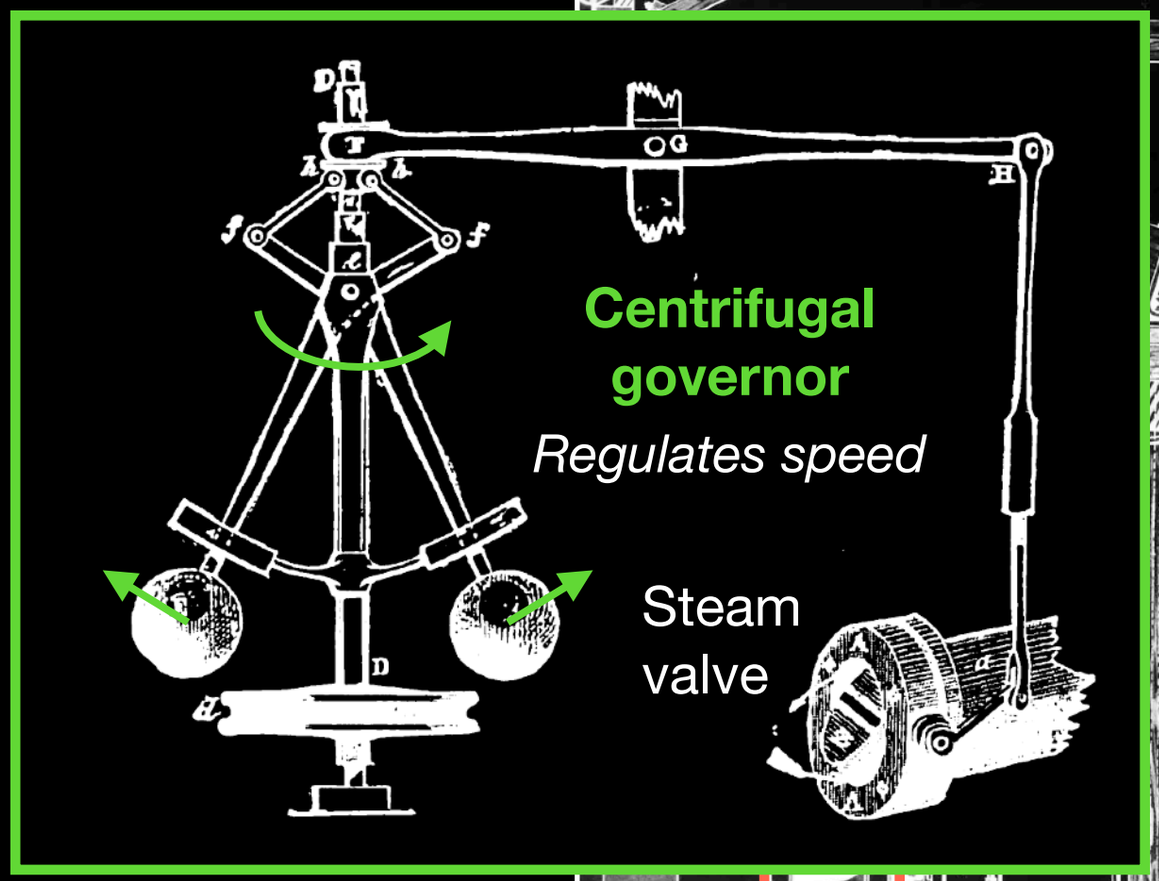

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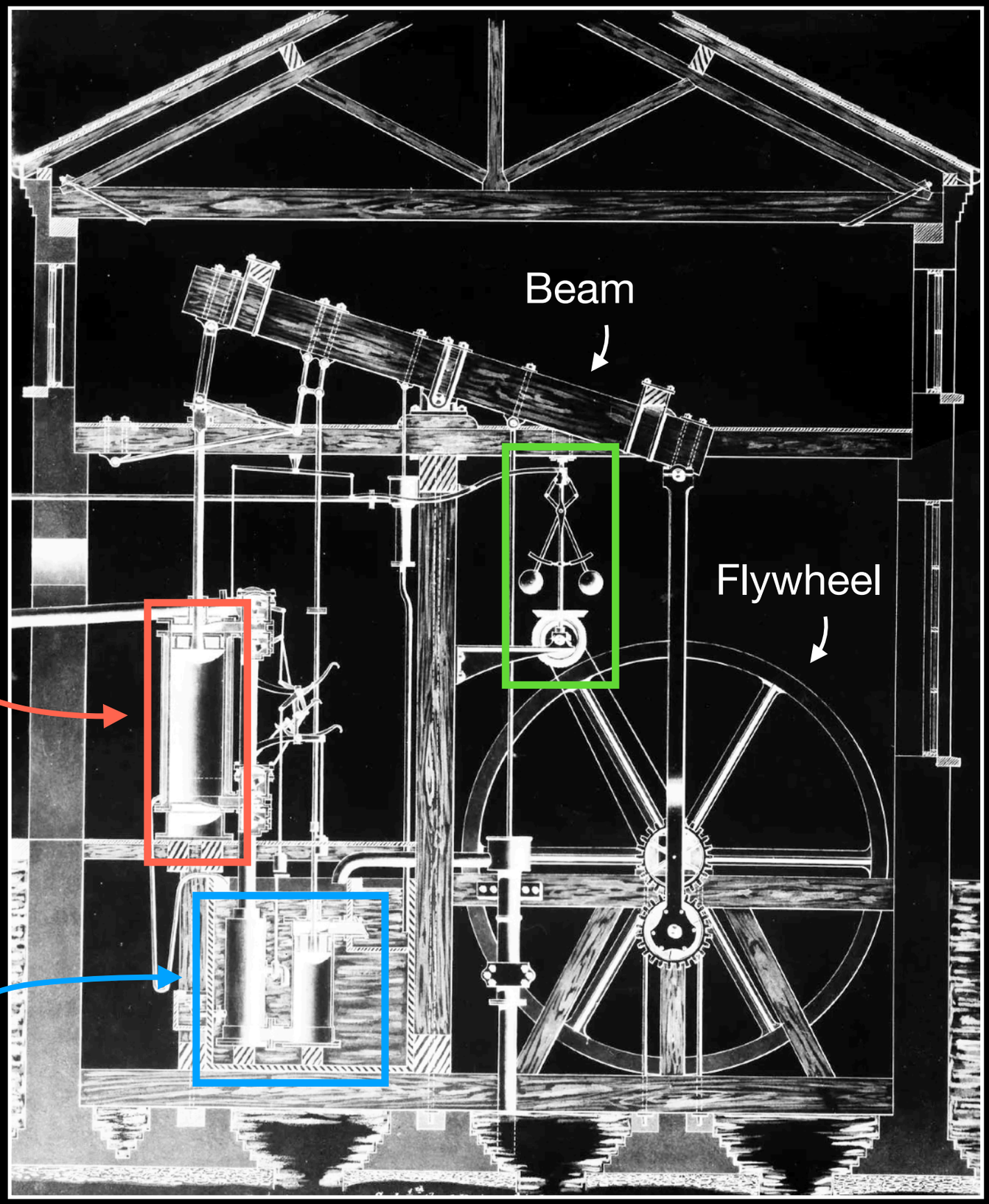

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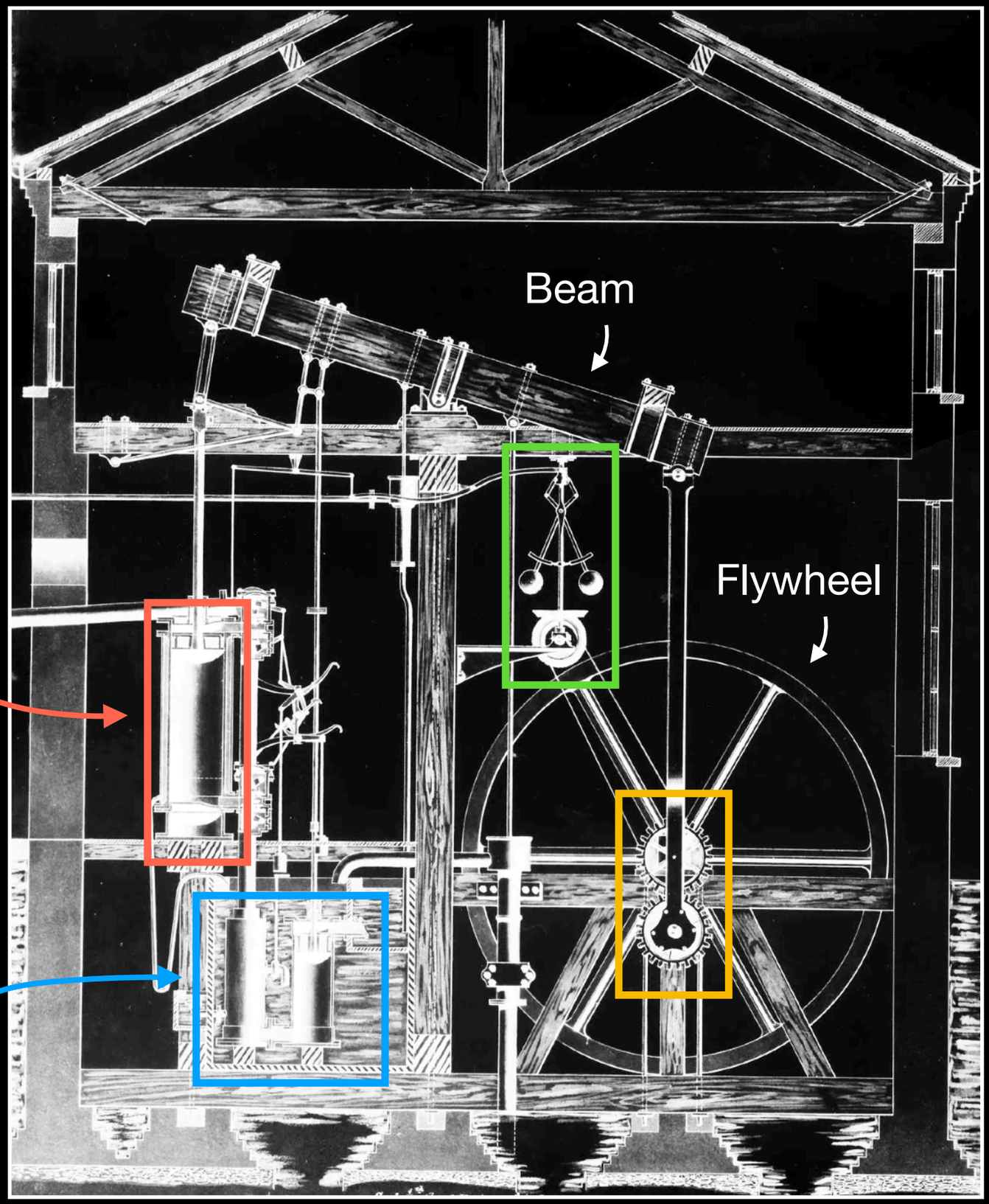

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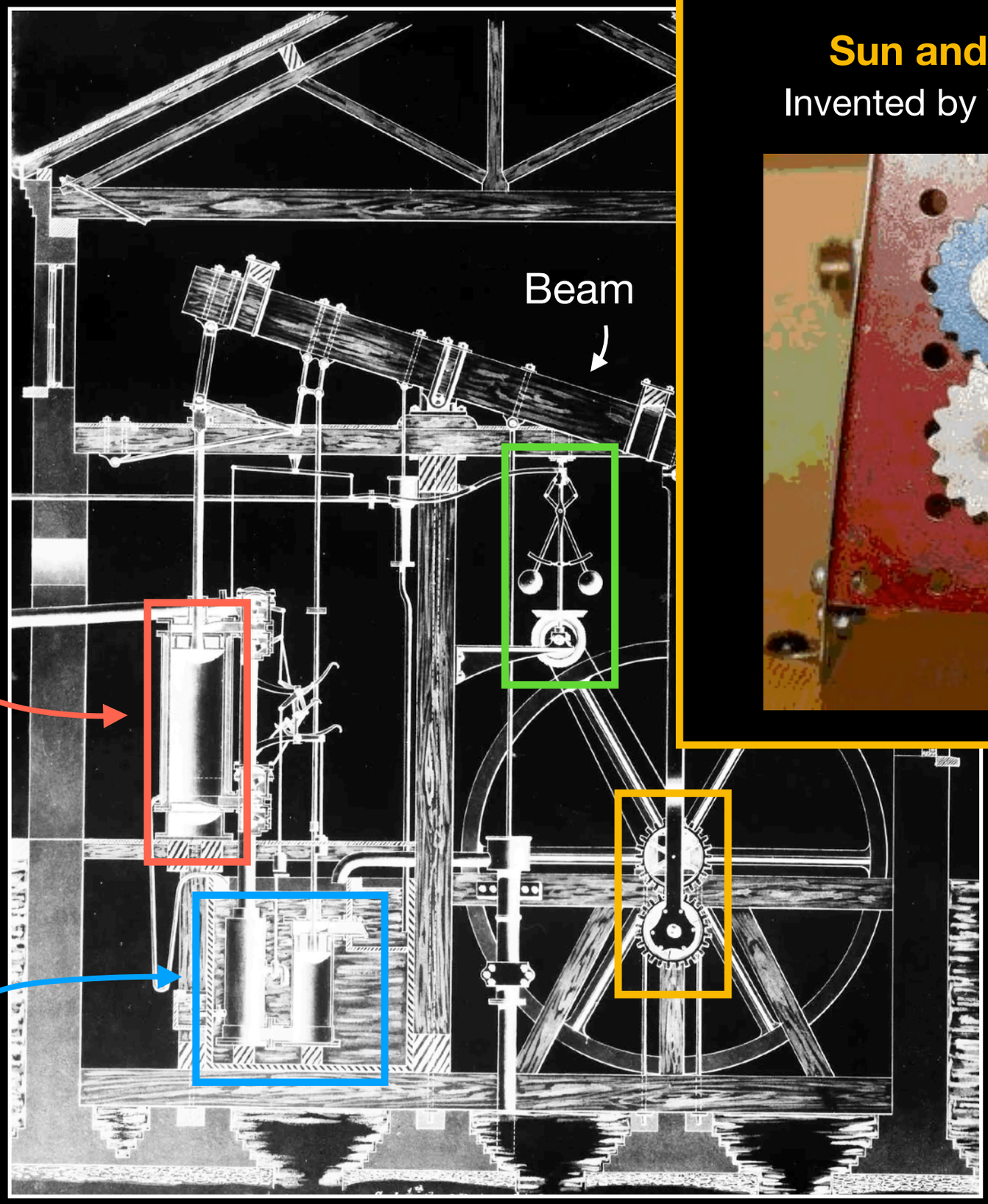
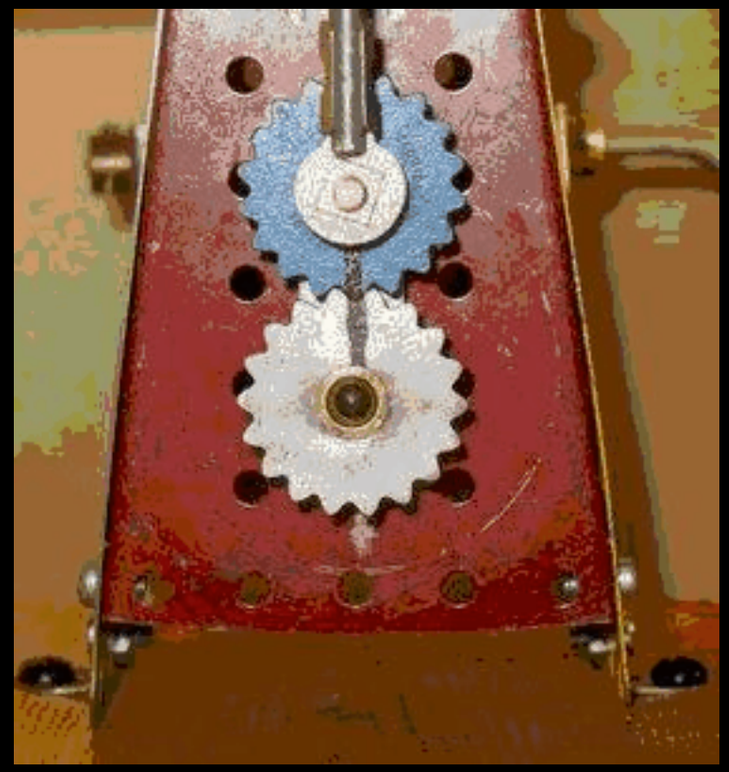


Sun and planet gear

Invented by William Murdoch



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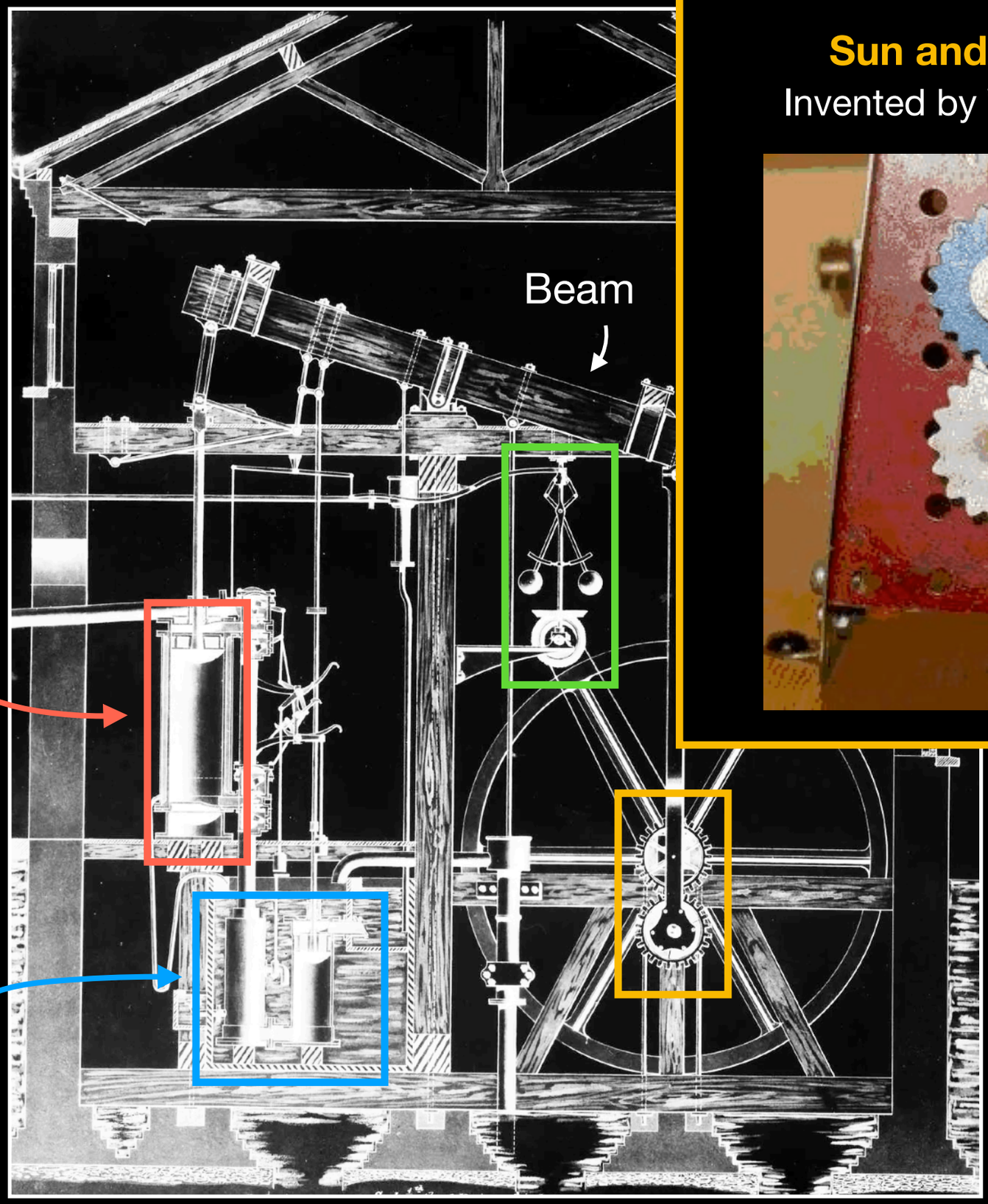

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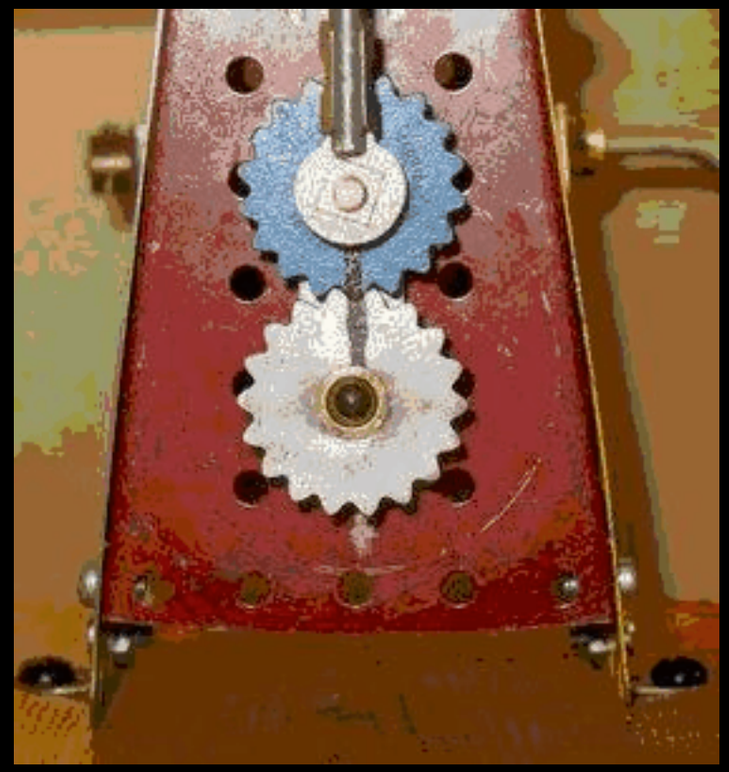
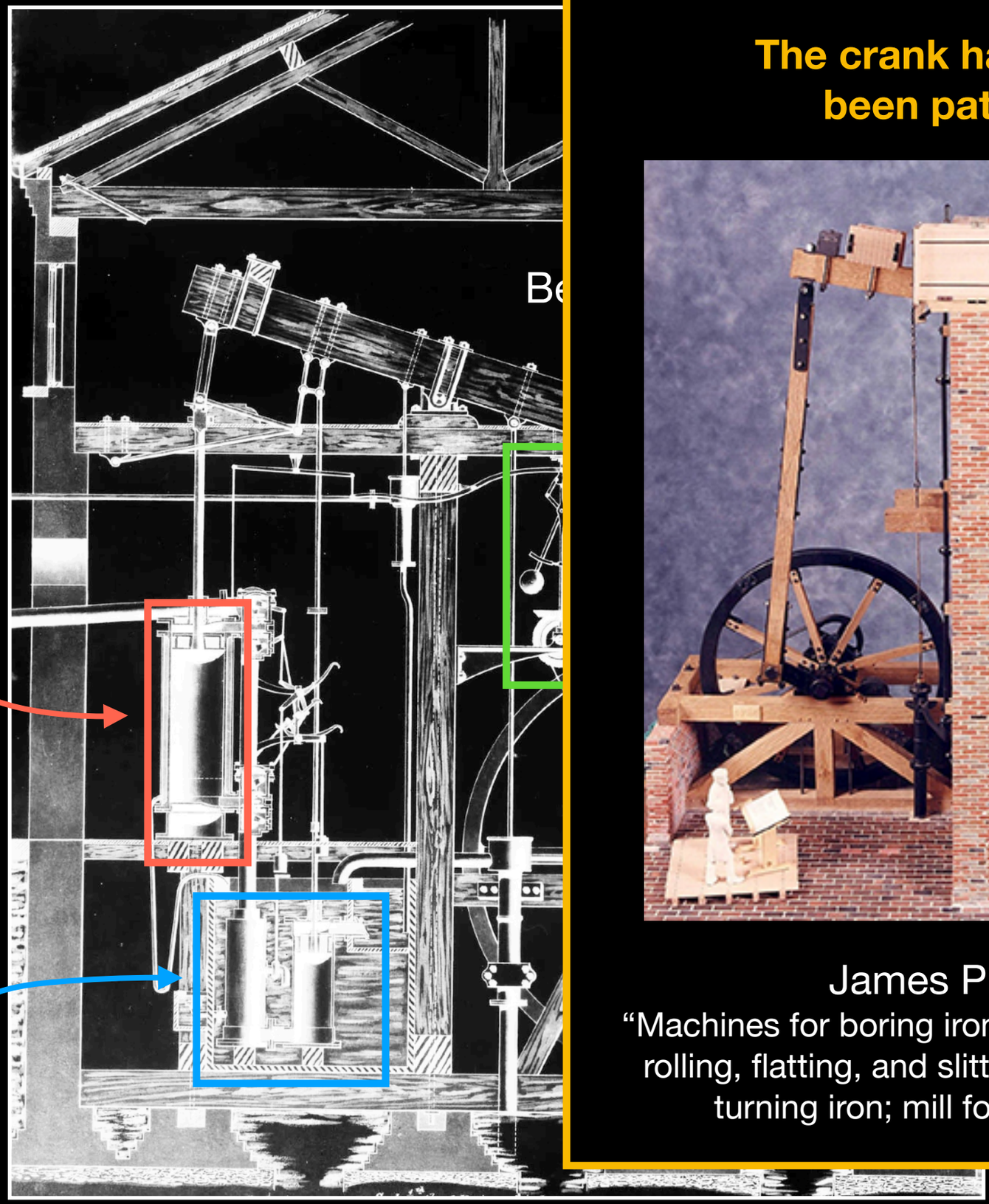


Watt, Boulton, and Murdoch conquer the world

Piston



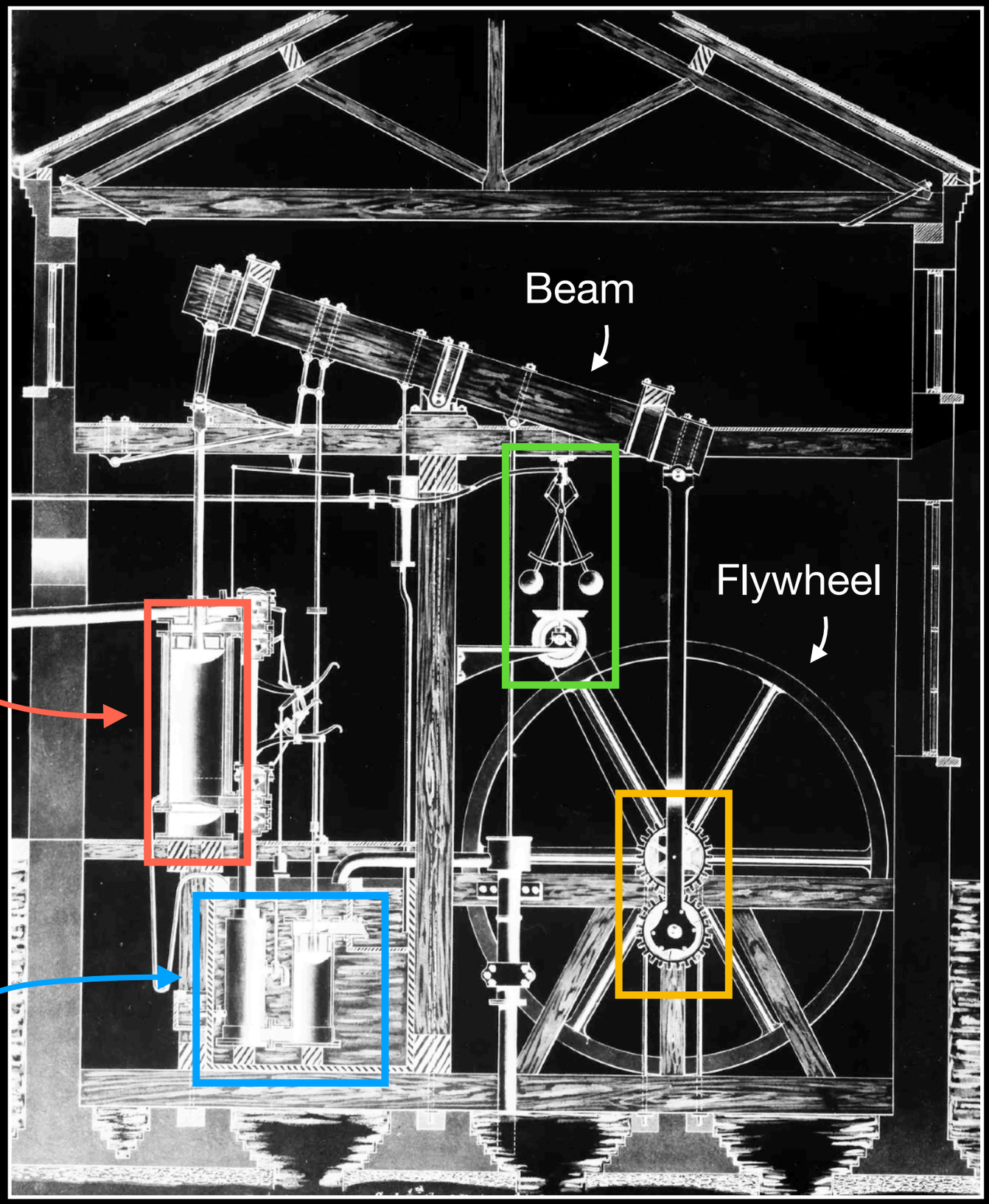
Condenser

The crank has already been patented!

James Pickard:

“Machines for boring iron; machine for forging, rolling, flatting, and slitting iron; machine for turning iron; mill for grinding corn”

Watt, Boulton, and Murdoch conquer the world



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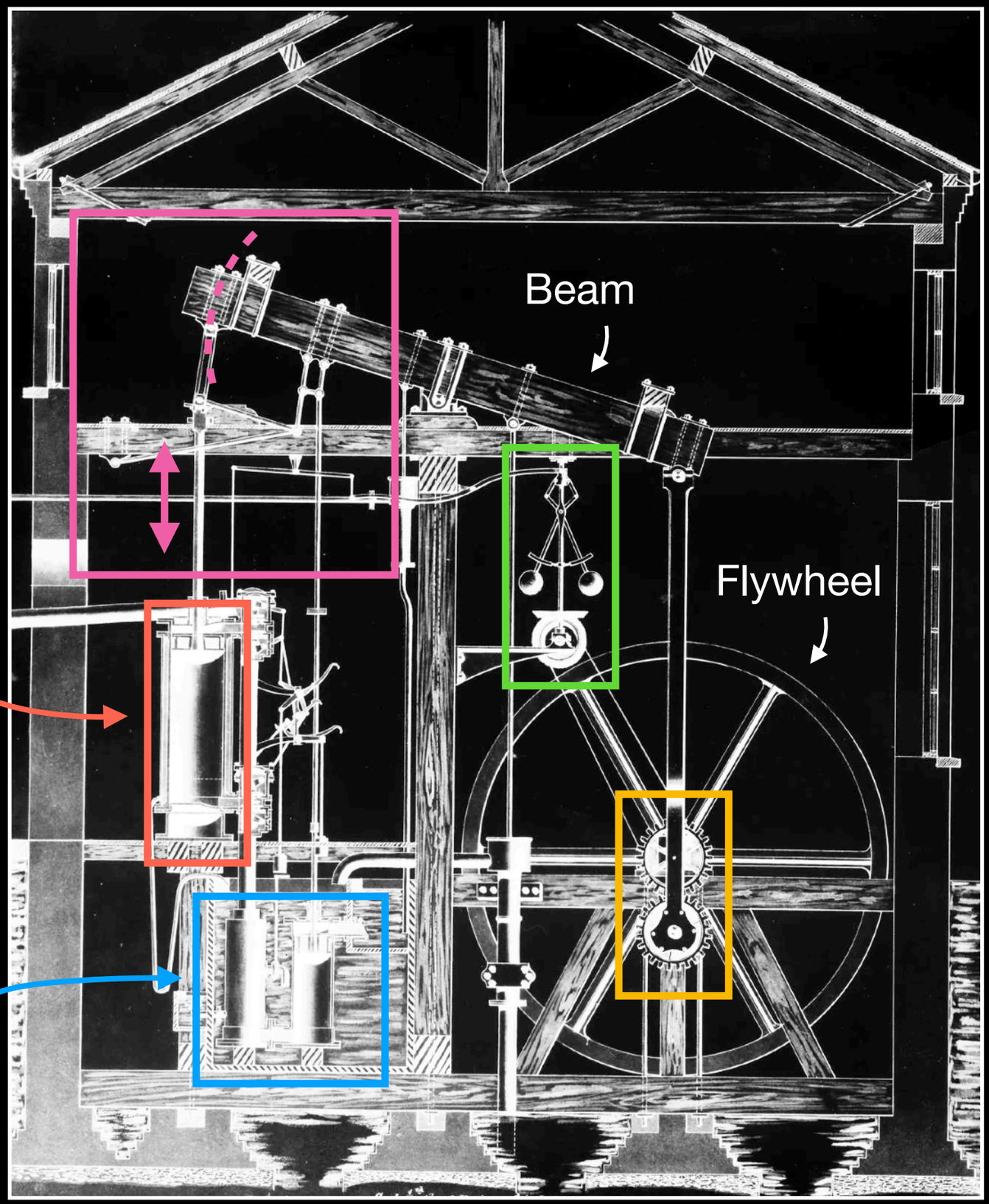

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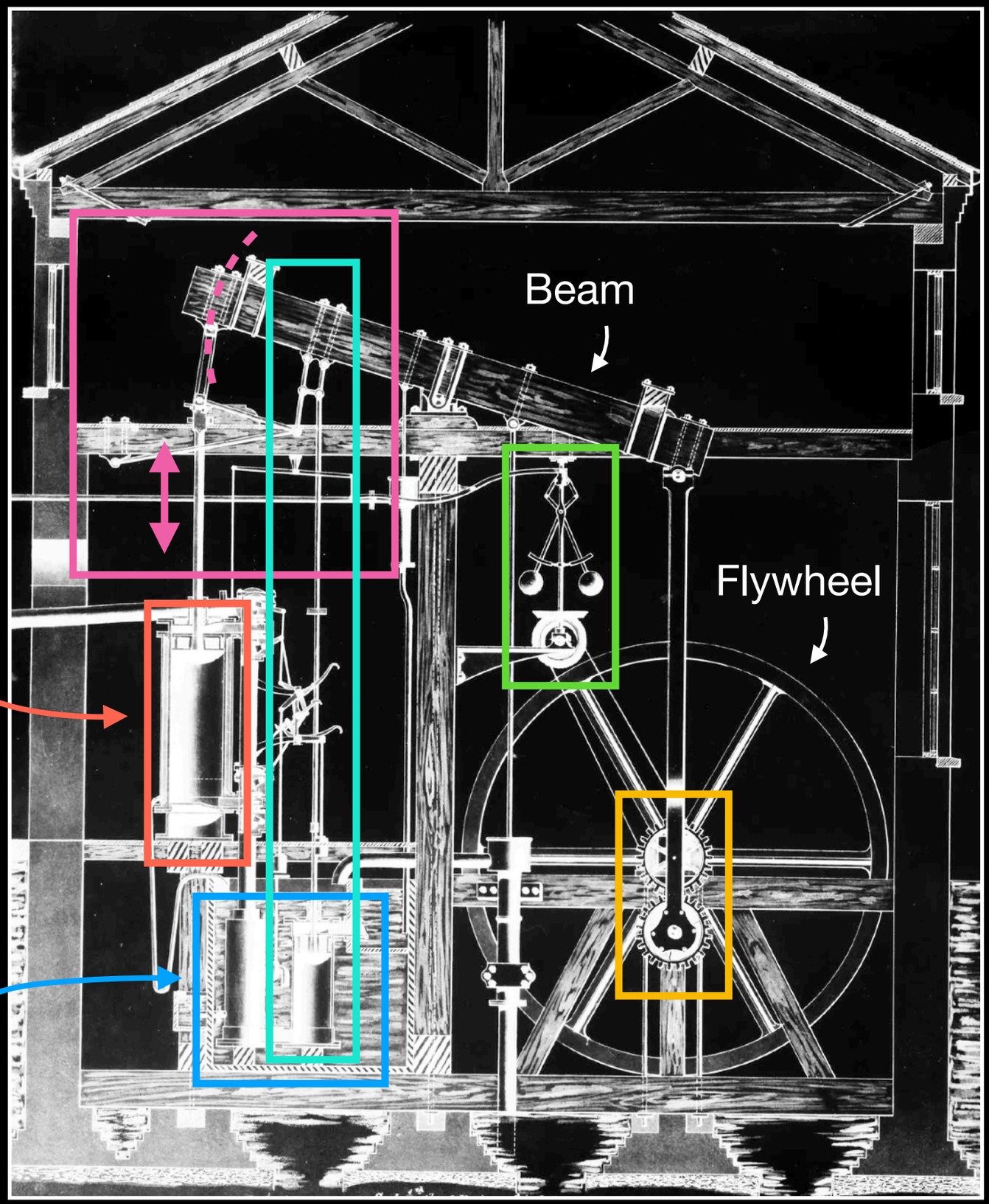

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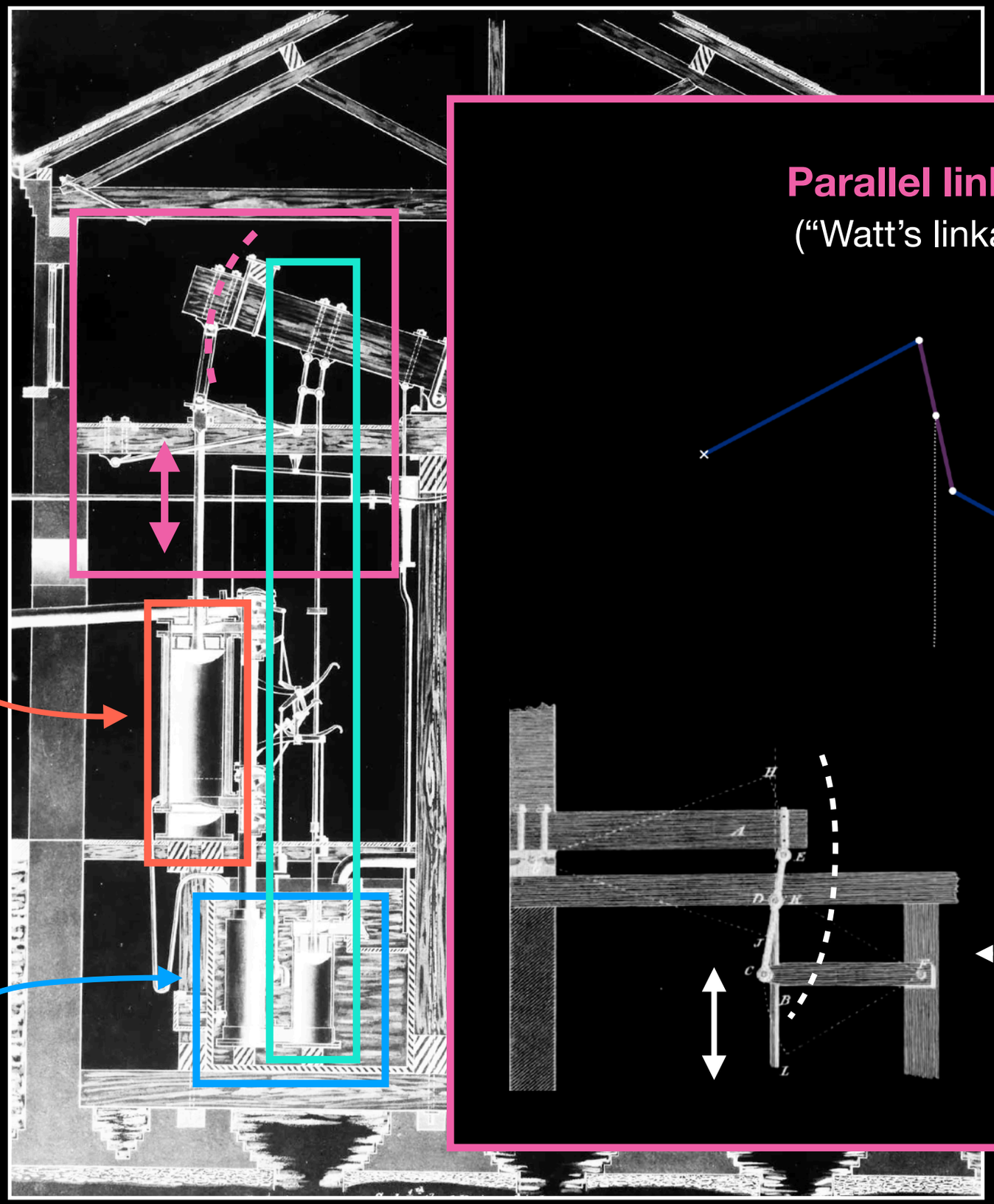


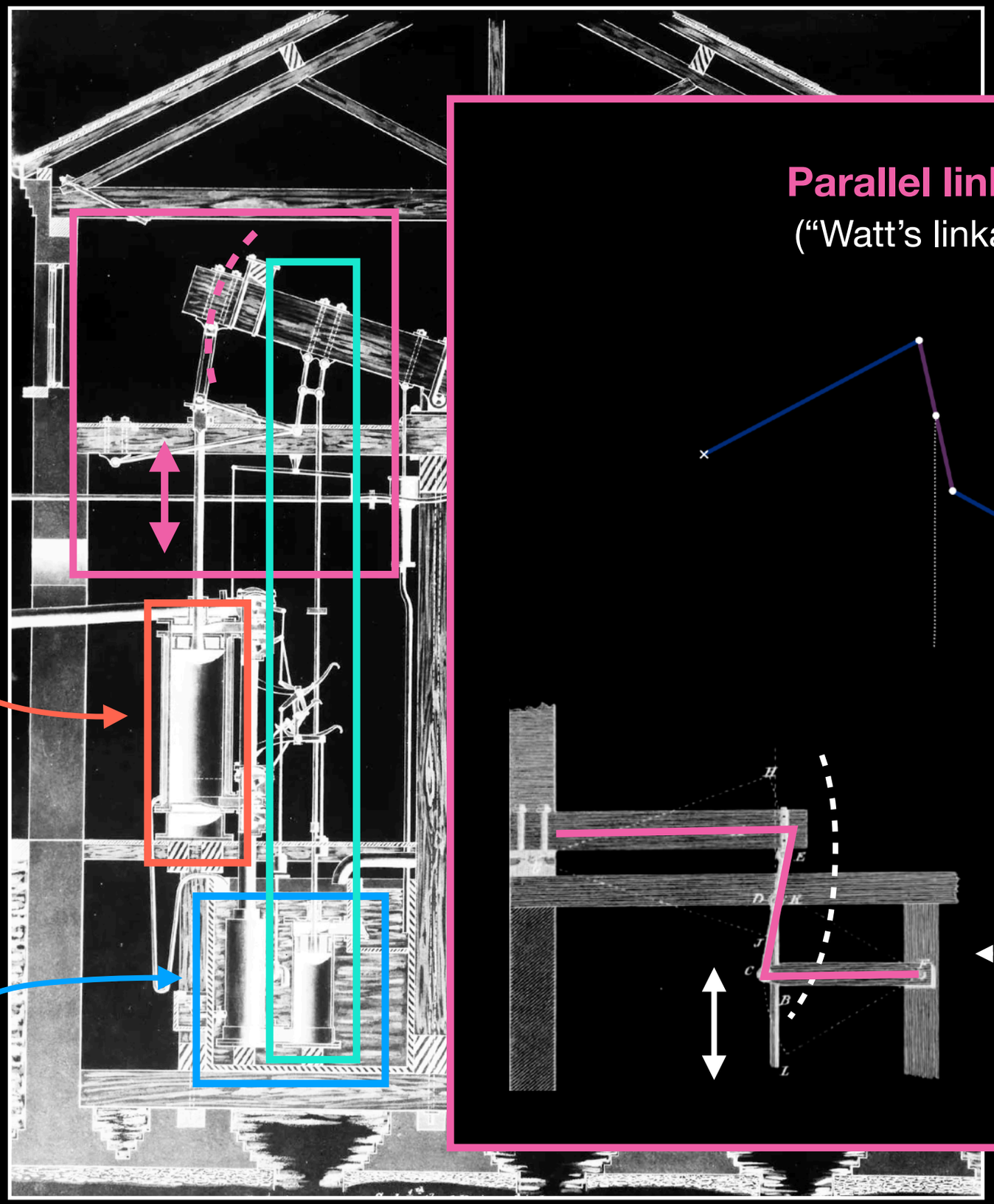
Piston

Condenser

Parallel linkage
("Watt's linkage")

From Watt's patent application

Watt, Boulton, and Murdoch conquer the world



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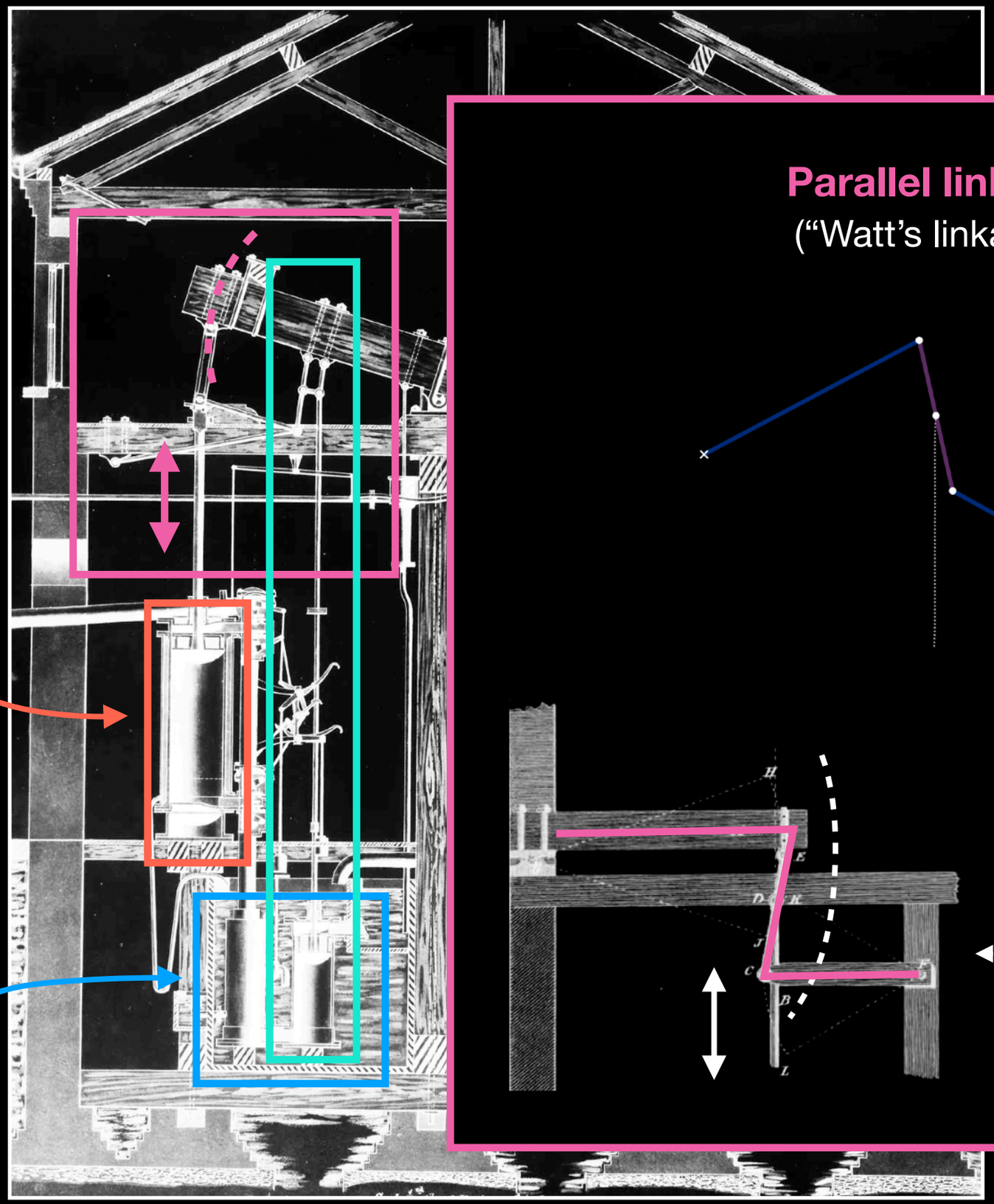

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Needs only a quarter of the fuel of a Newcomen engine!

Boulton & Watt don't charge for the engine,
they charge a certain percentage of the fuel savings

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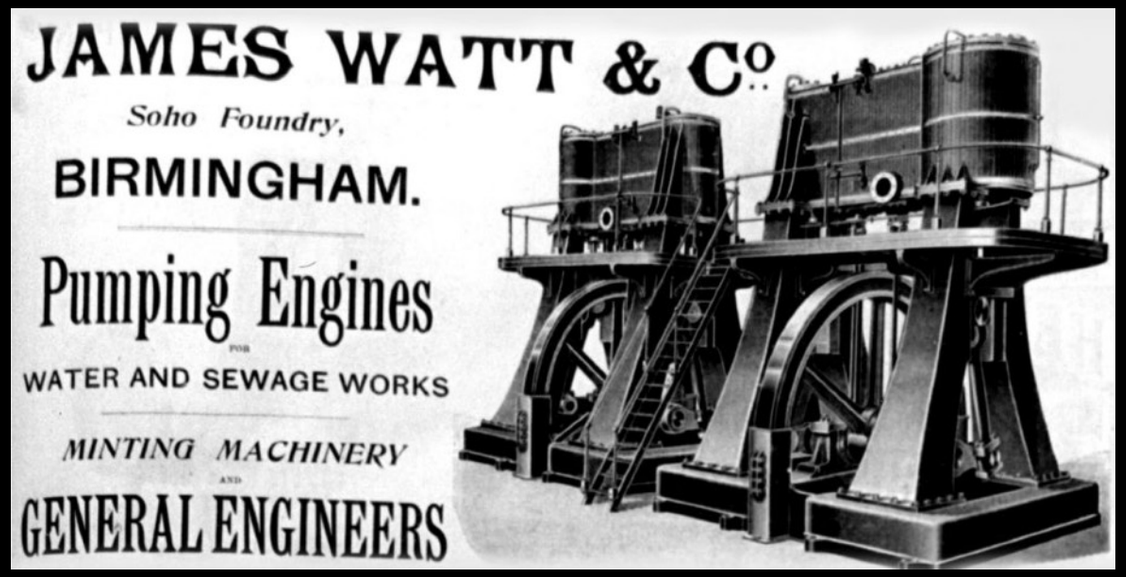

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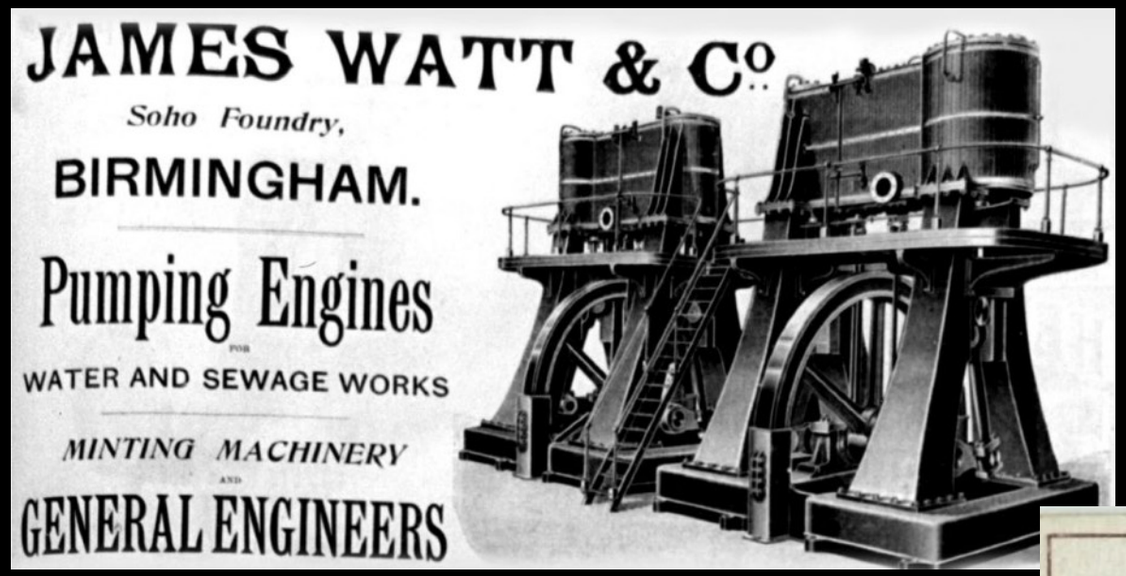

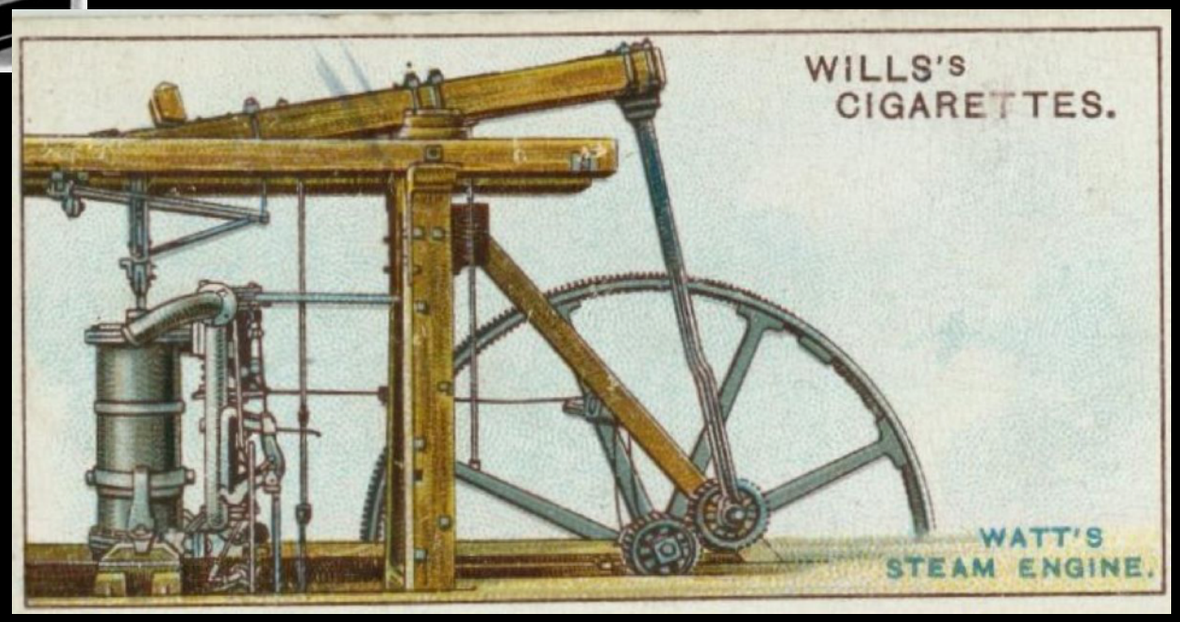

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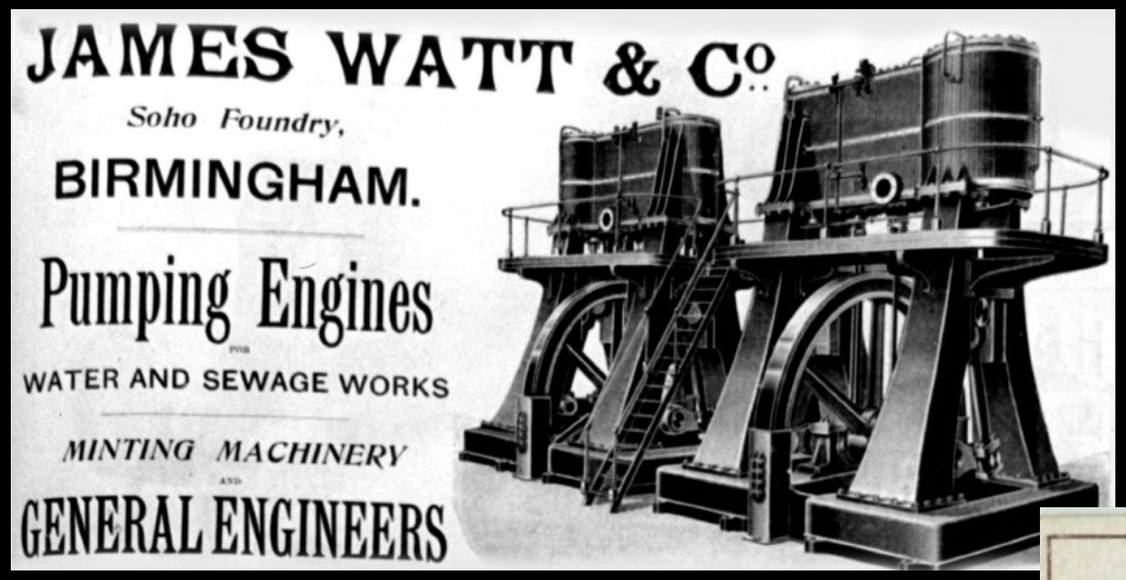

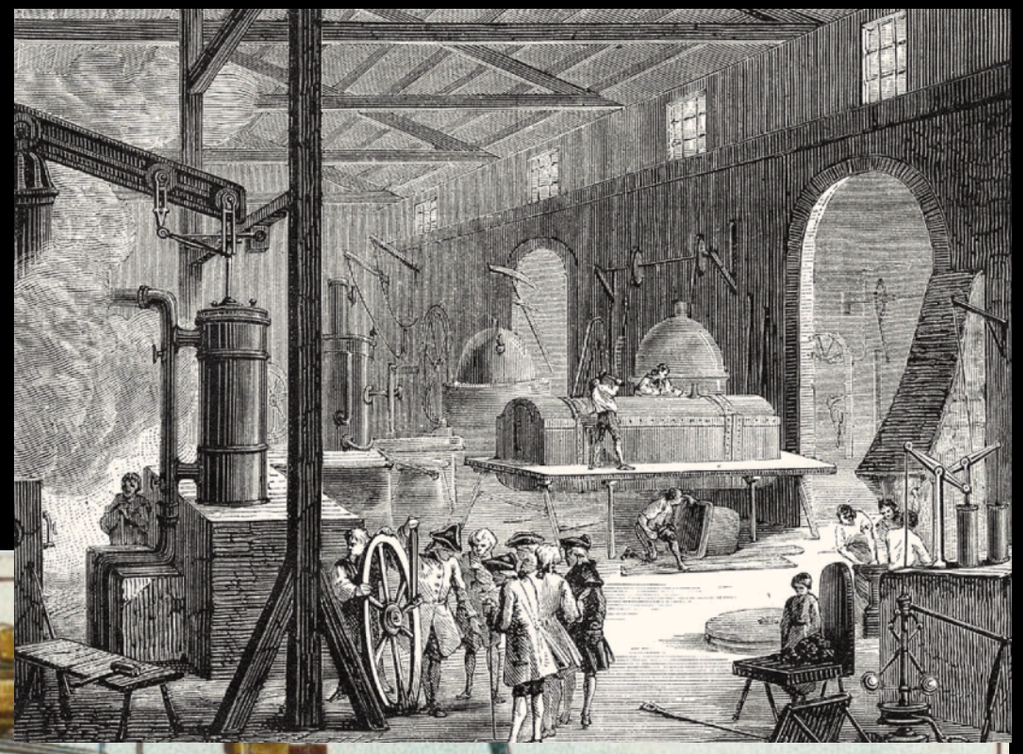

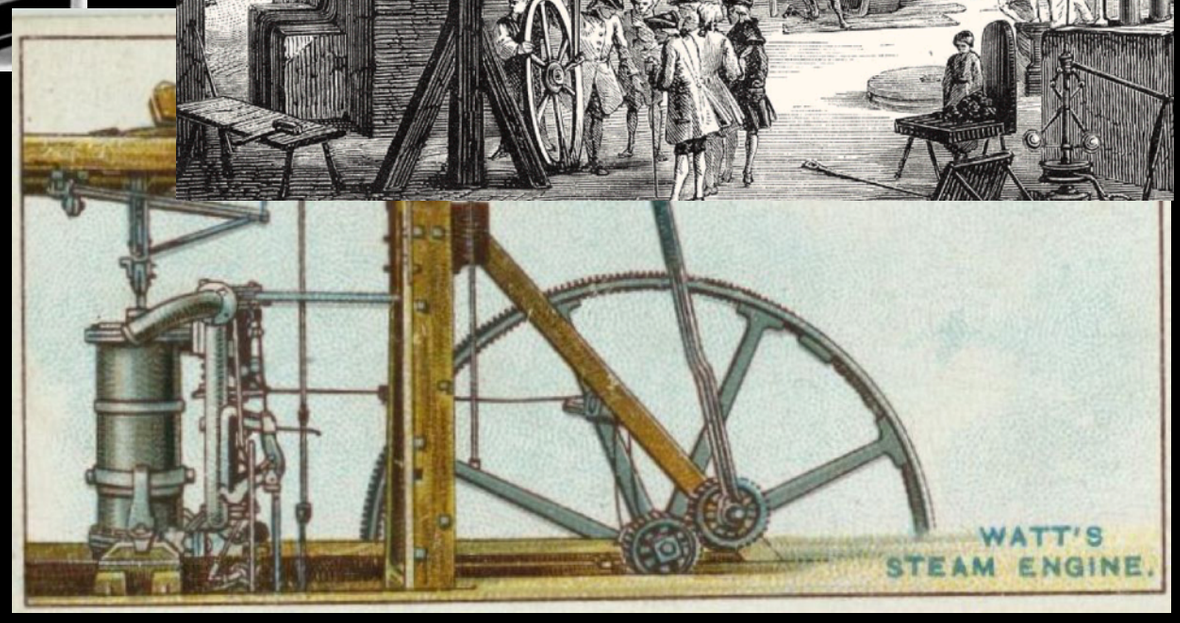

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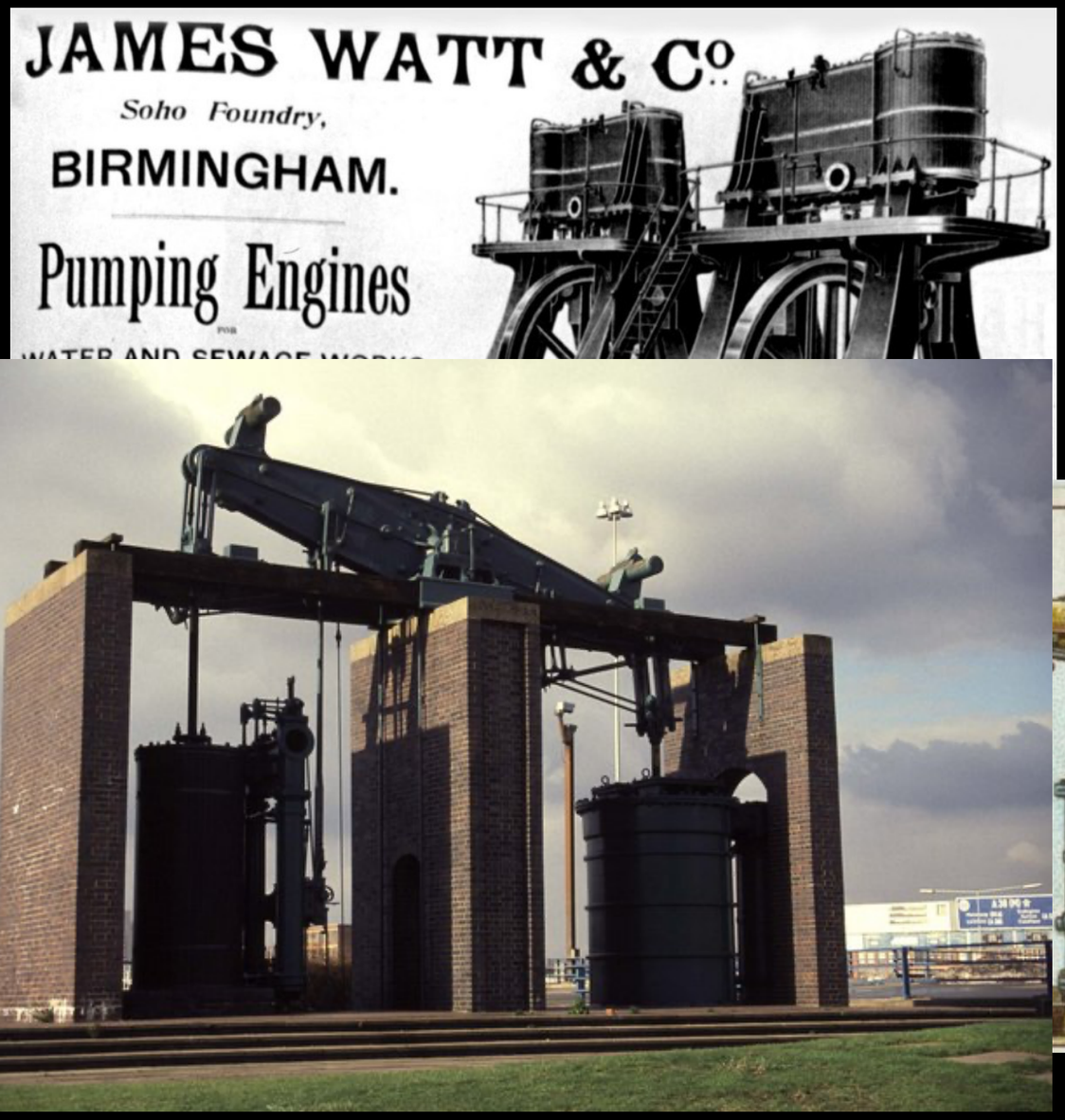

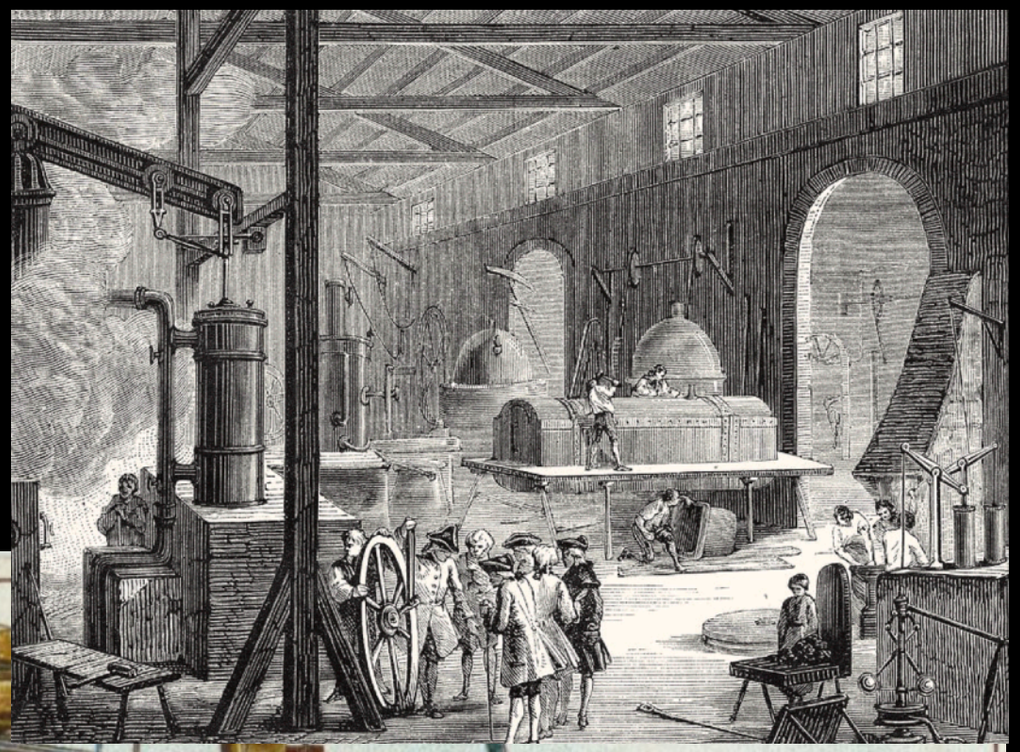

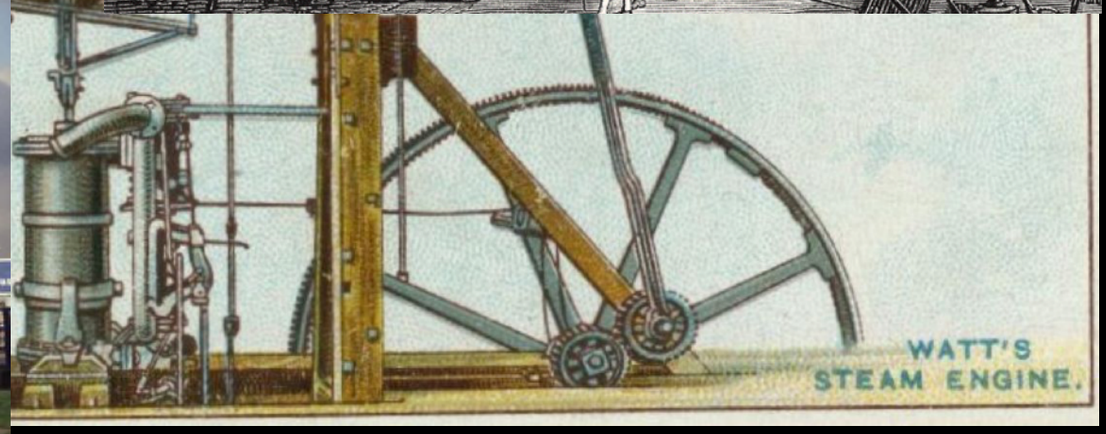

What is the true nature of heat?

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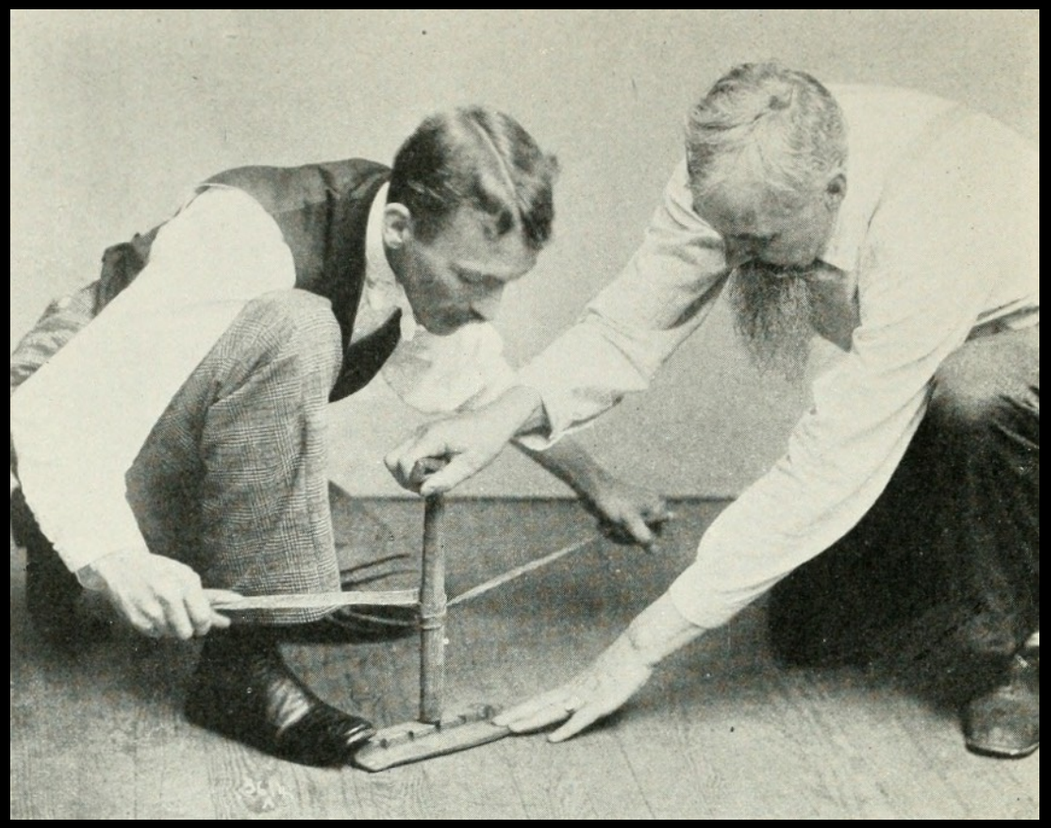
Kinetic theory

“Heat is a rapid internal tremor of the small particles of the heated bodies.”



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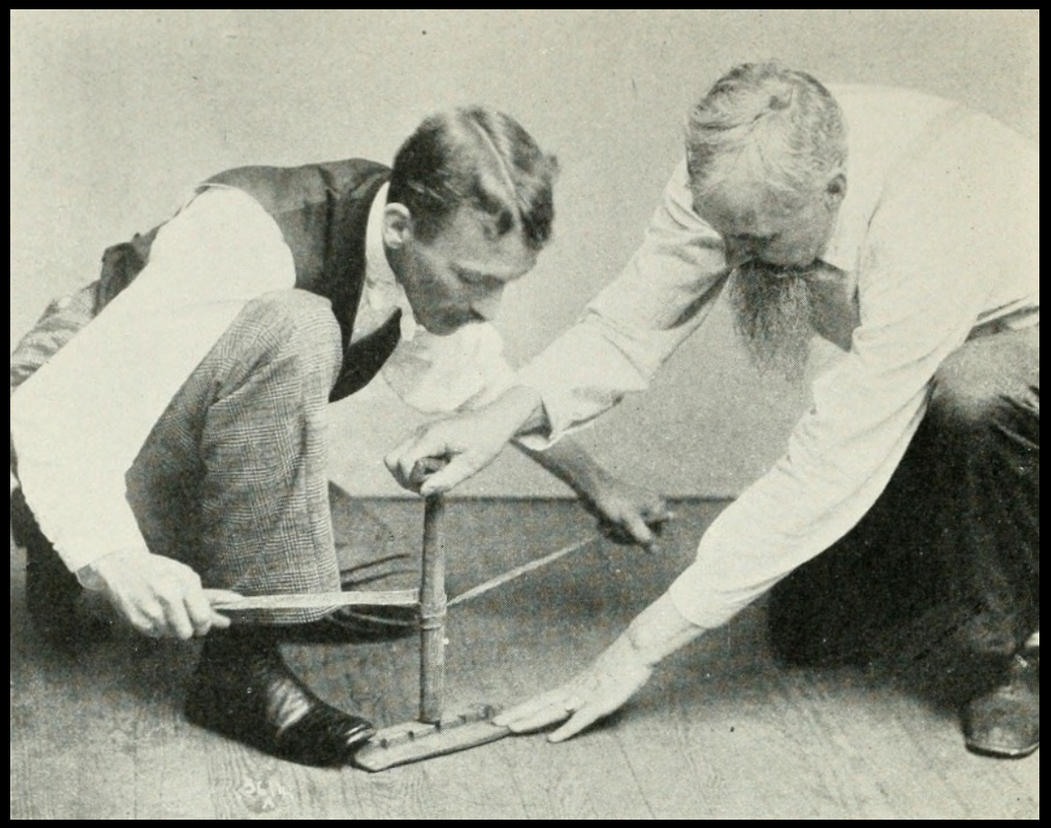

Ultimately ended up being correct!

But: not obvious at the time!

“Science should relate observable quantities. Interpreting laws in terms of unobservable entities are unverifiable fantasies.”

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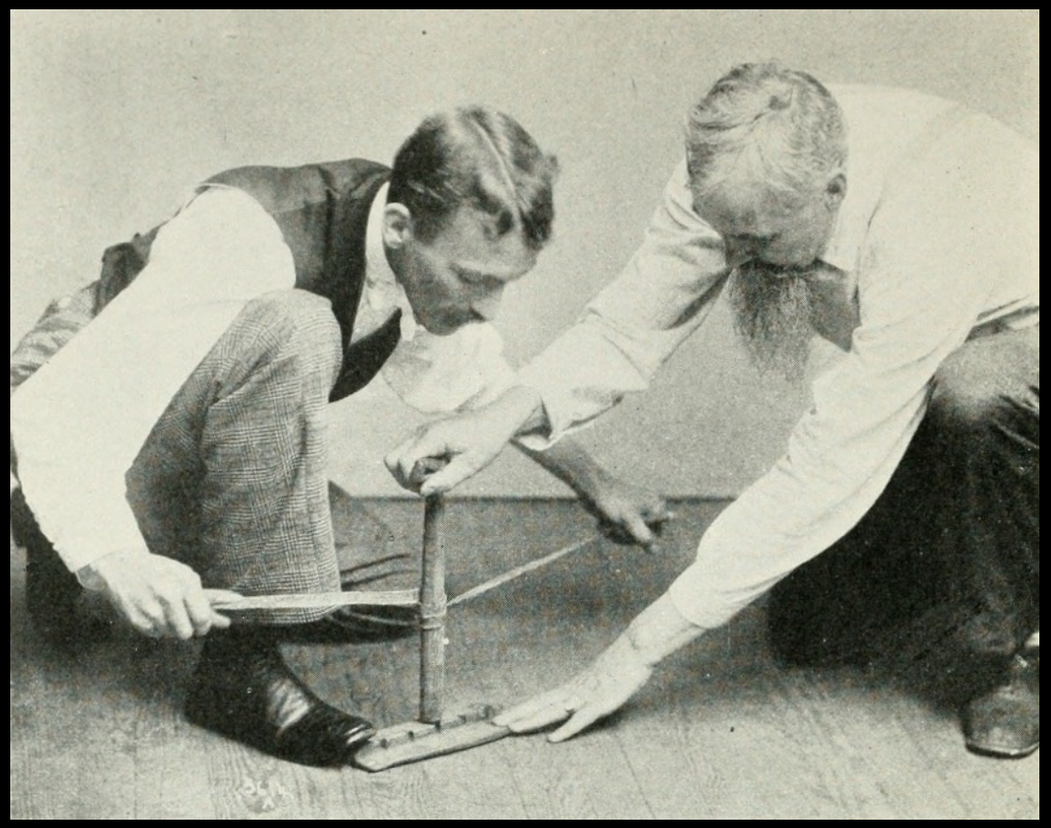

Ultimately ended up being correct!

But: not obvious at the time!

“Science should relate observable quantities. Interpreting laws in terms of unobservable entities are unverifiable fantasies.”

Black:
“The heat capacity of mercury is 26-28 times smaller than that of water.”

[But it’s density is 13-14 times higher!]

What is the true nature of heat?

Material theory

Matter of heat: “caloric”

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→ *Caloric leaks out of the pores of the body*

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Objects expand when heated
→ *Caloric flows into the body*

Hot objects cool down
→ *Caloric leaks out of the pores of the body*

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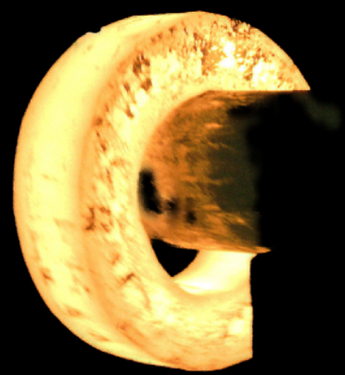
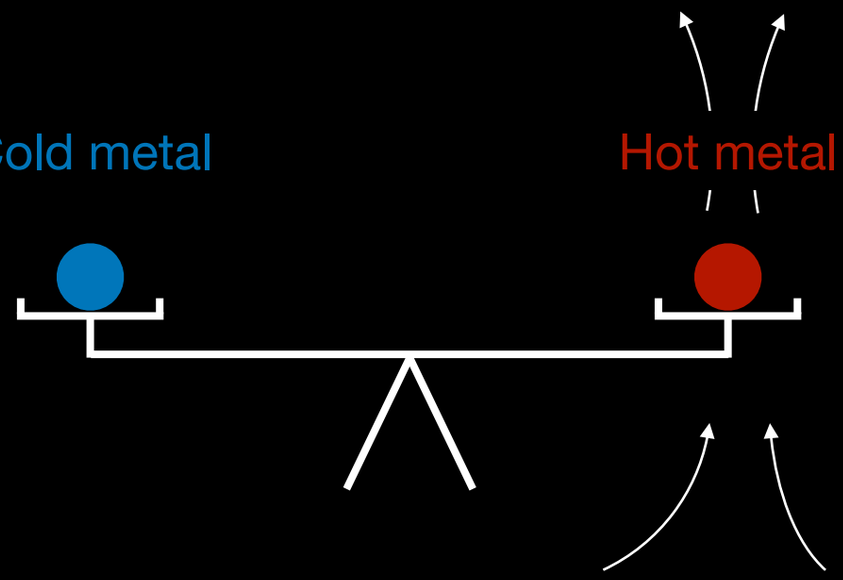
Does heat have weight?

Weigh metals at different temperatures





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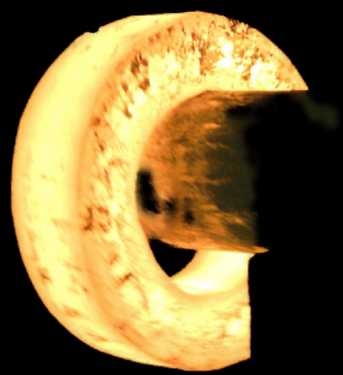

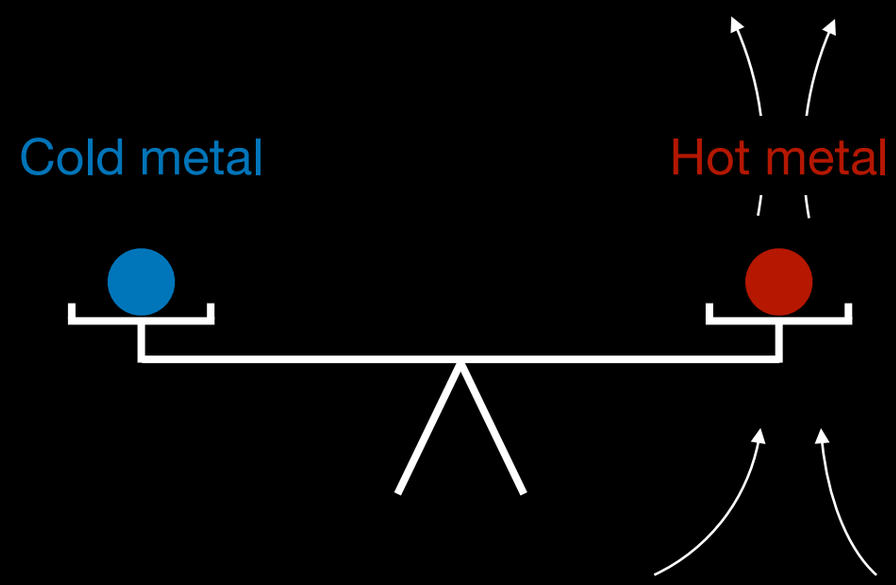

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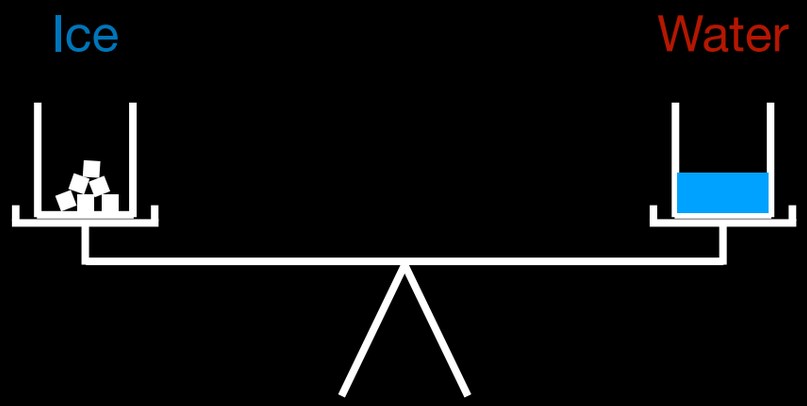

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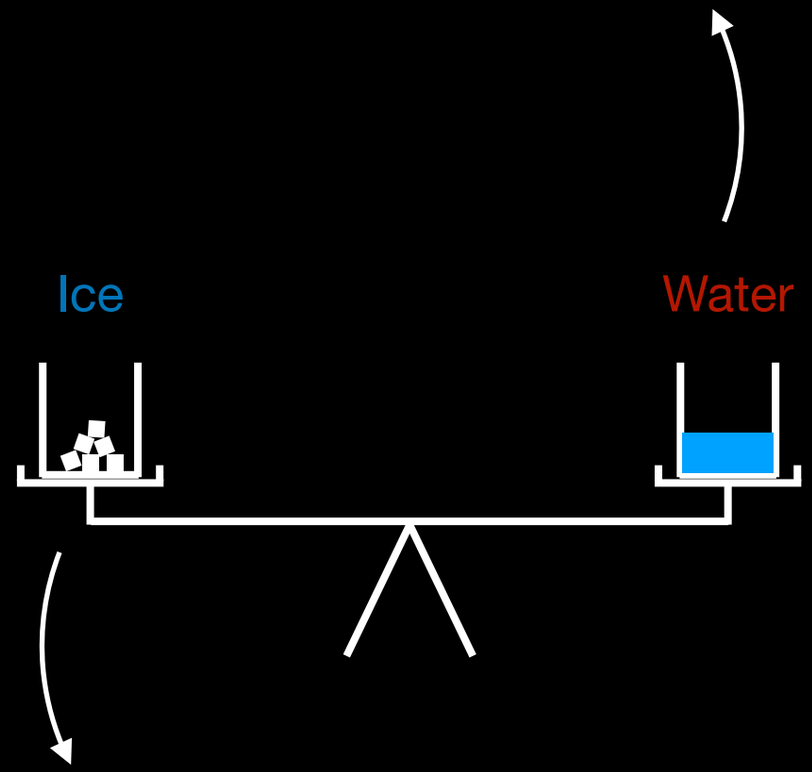

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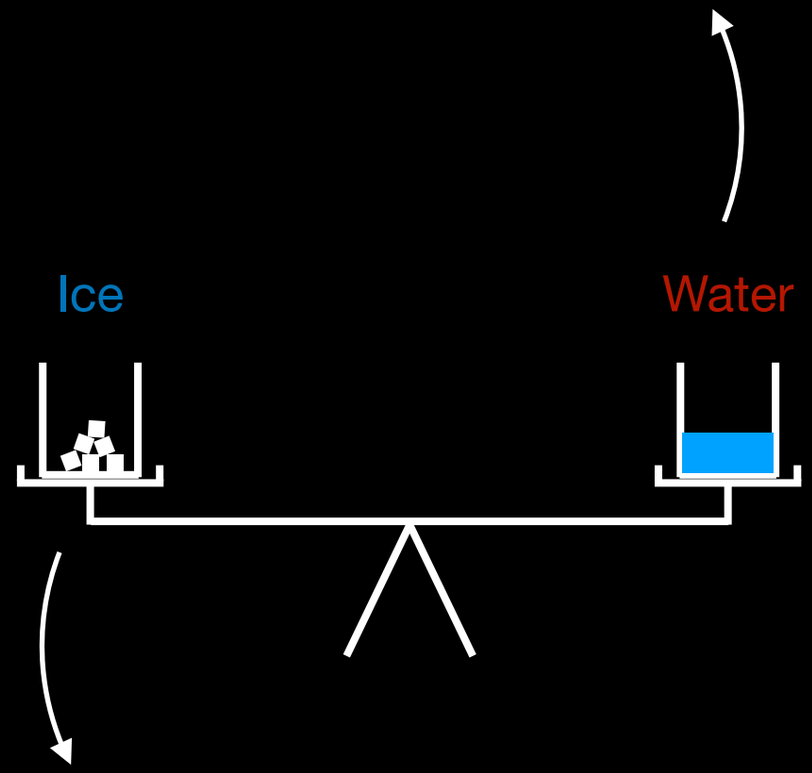

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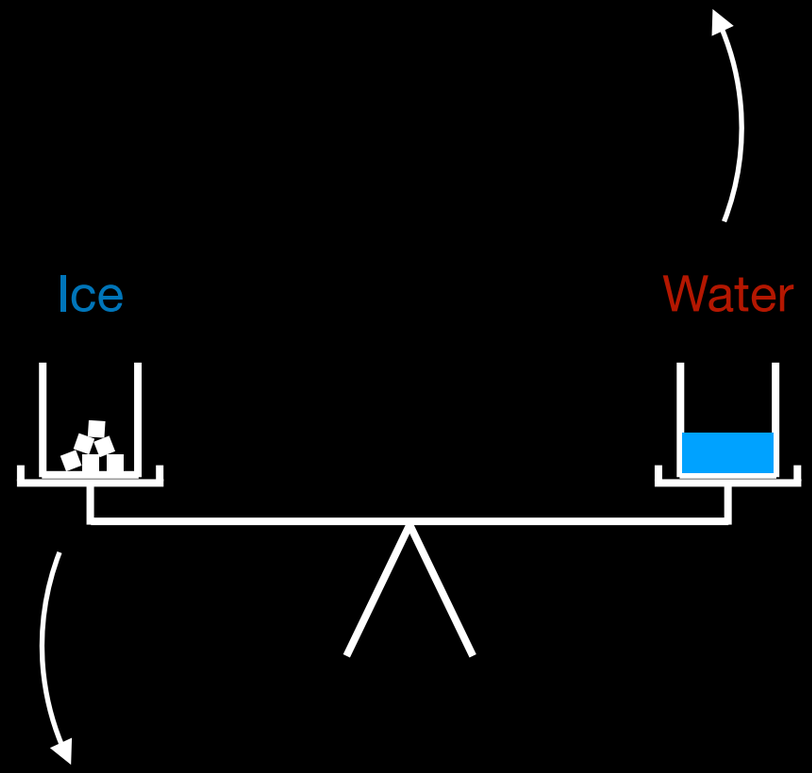

Made many convincing predictions!

Sadi Carnot

Military engineer

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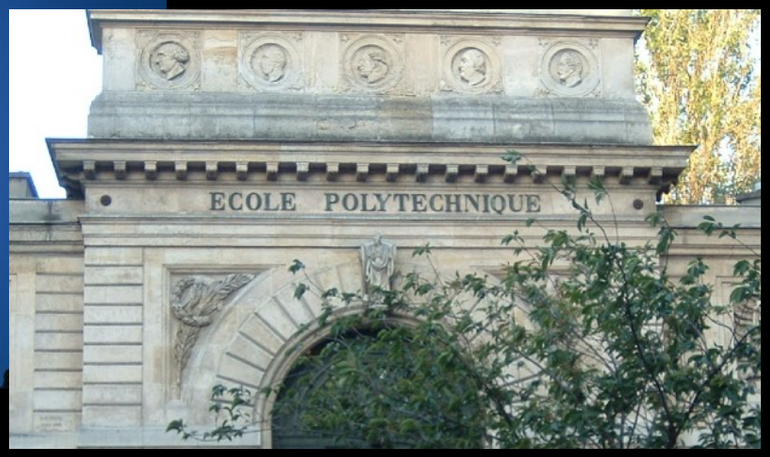
1811-1814: education at Ecole Polytechnique



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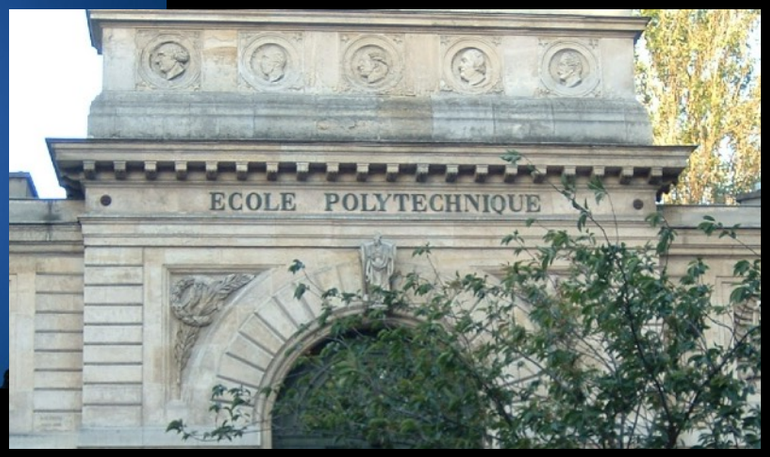

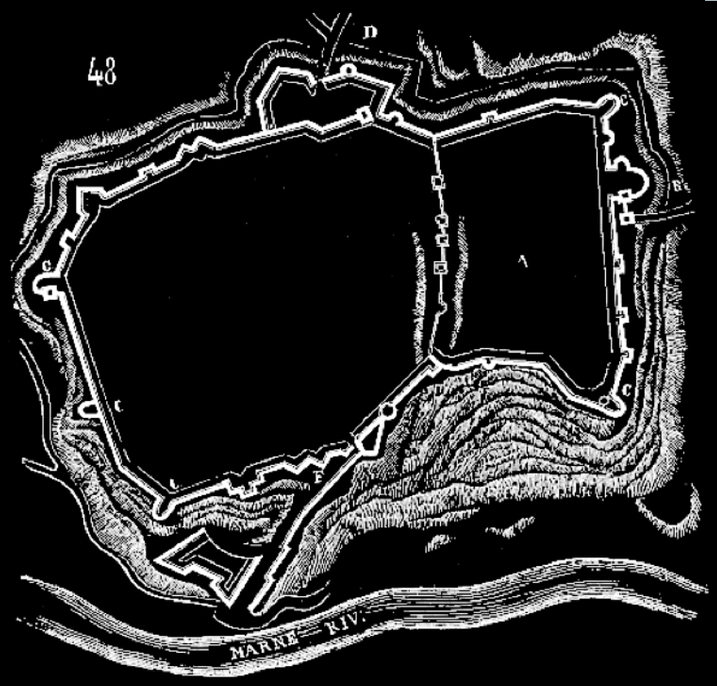

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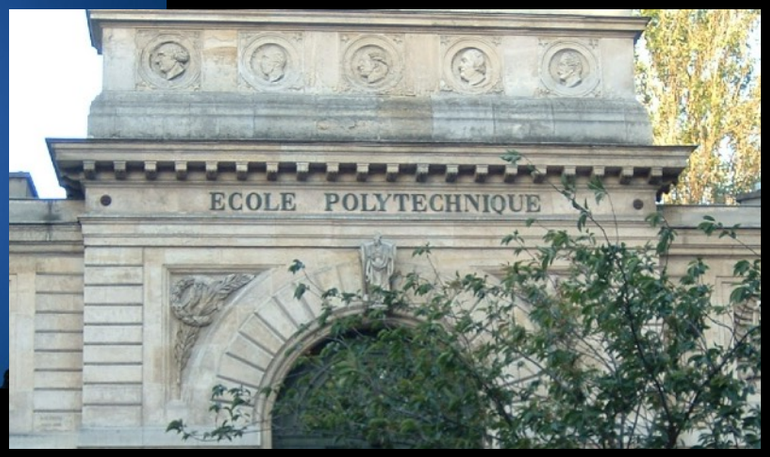

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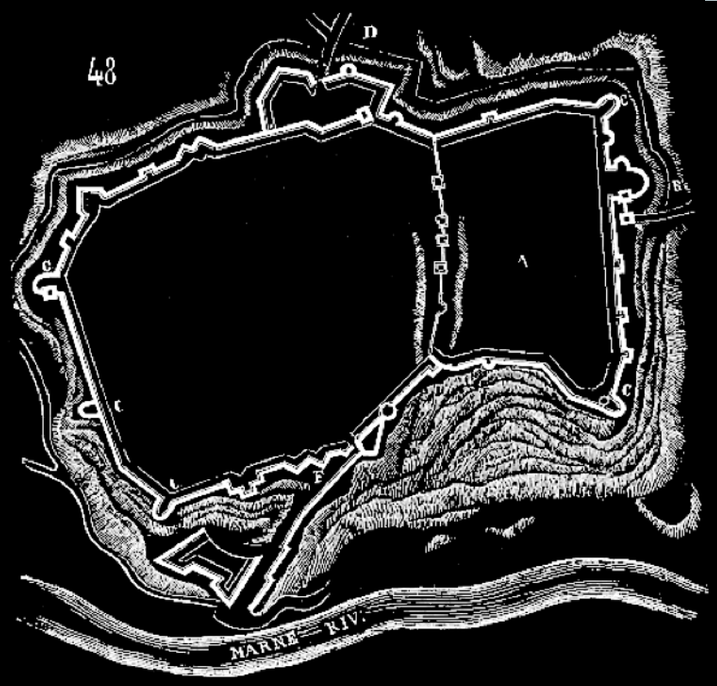

1819-1827: leave on half-pay, remained on-call for duty

Attended lectures, visited factories …

1815-1818: inspecting fortifications, writing reports, …

How efficient can a steam engine be?

RÉFLEXIONS

SUR

LA PUISSANCE MOTRICE DU FEU

ET SUR

LES MACHINES PROPRES A DÉVELOPPER CETTE PUISSANCE (1).

PAR S. CARNOT,

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(Paris, Bachelier, 1824.)

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"Notwithstanding the work of all kinds done by steam-engines, their theory is very little understood, and the attempts to improve them are still directed almost by chance."

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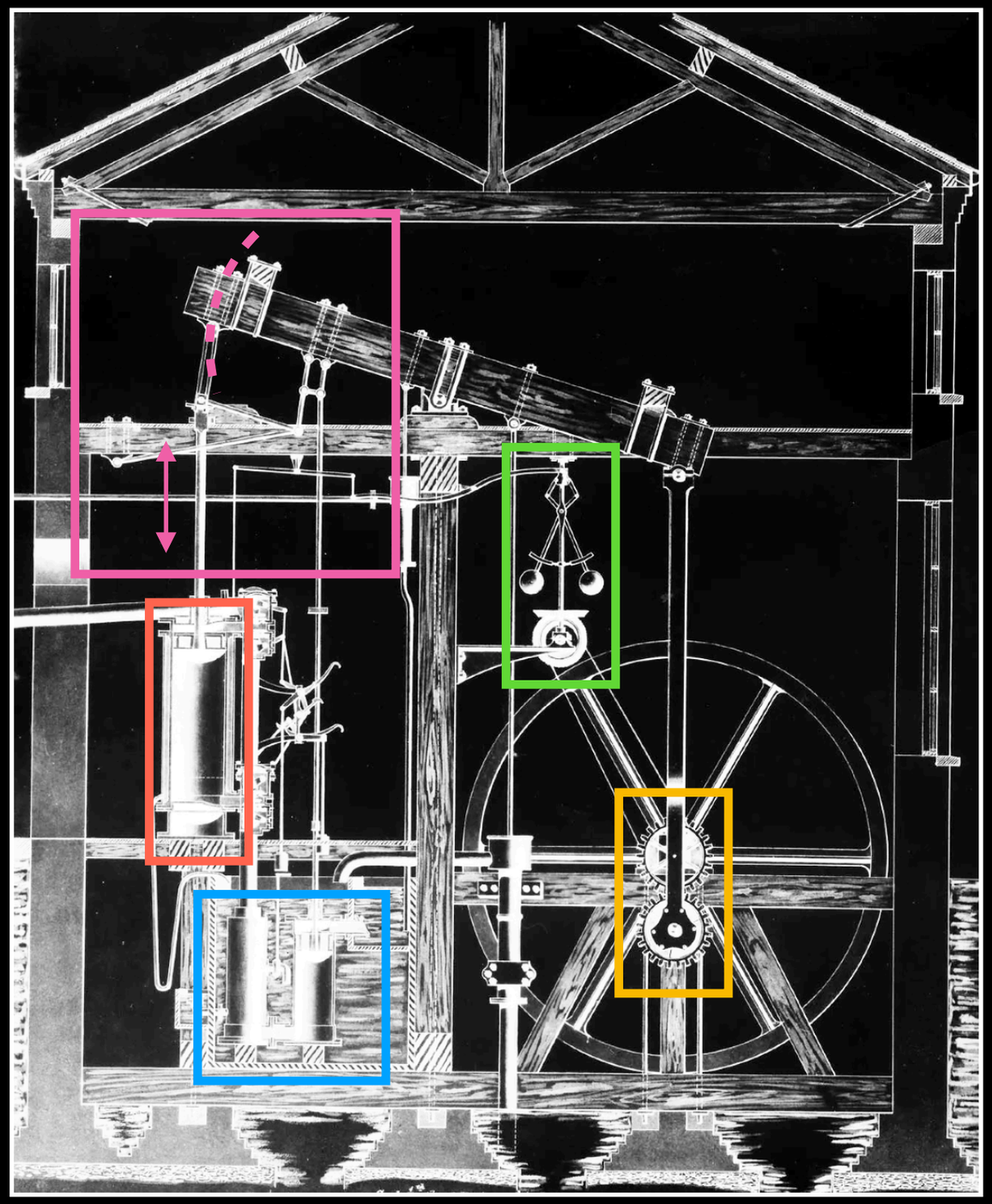
Is there an ideal steam engine?

“Do the possible improvements in steam engines have an assignable limit,
a limit which the nature of things will not allow to be surpassed by any means whatever?”



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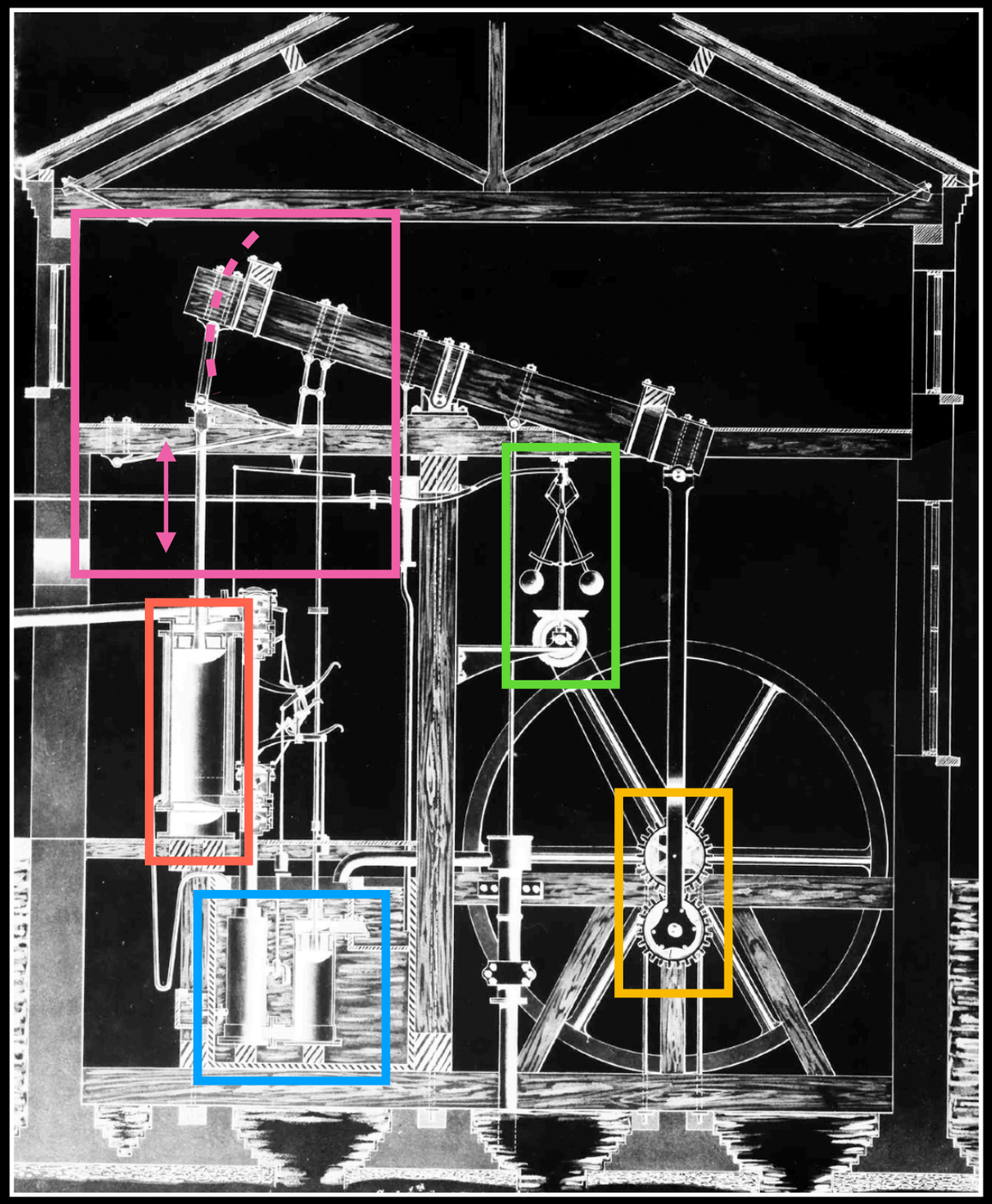

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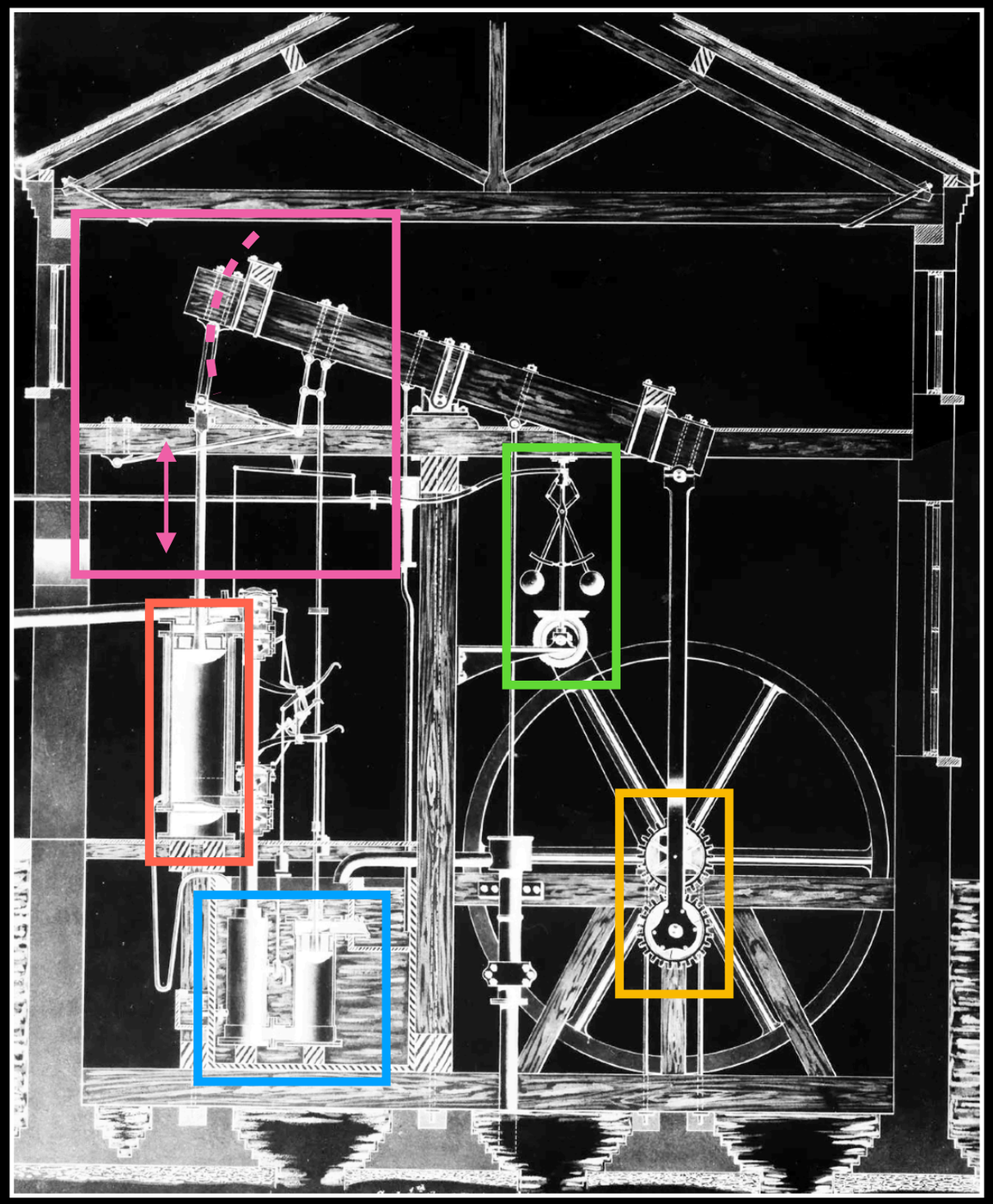

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“For example, are there agents preferable to the vapor of water for developing the motive power of heat?”

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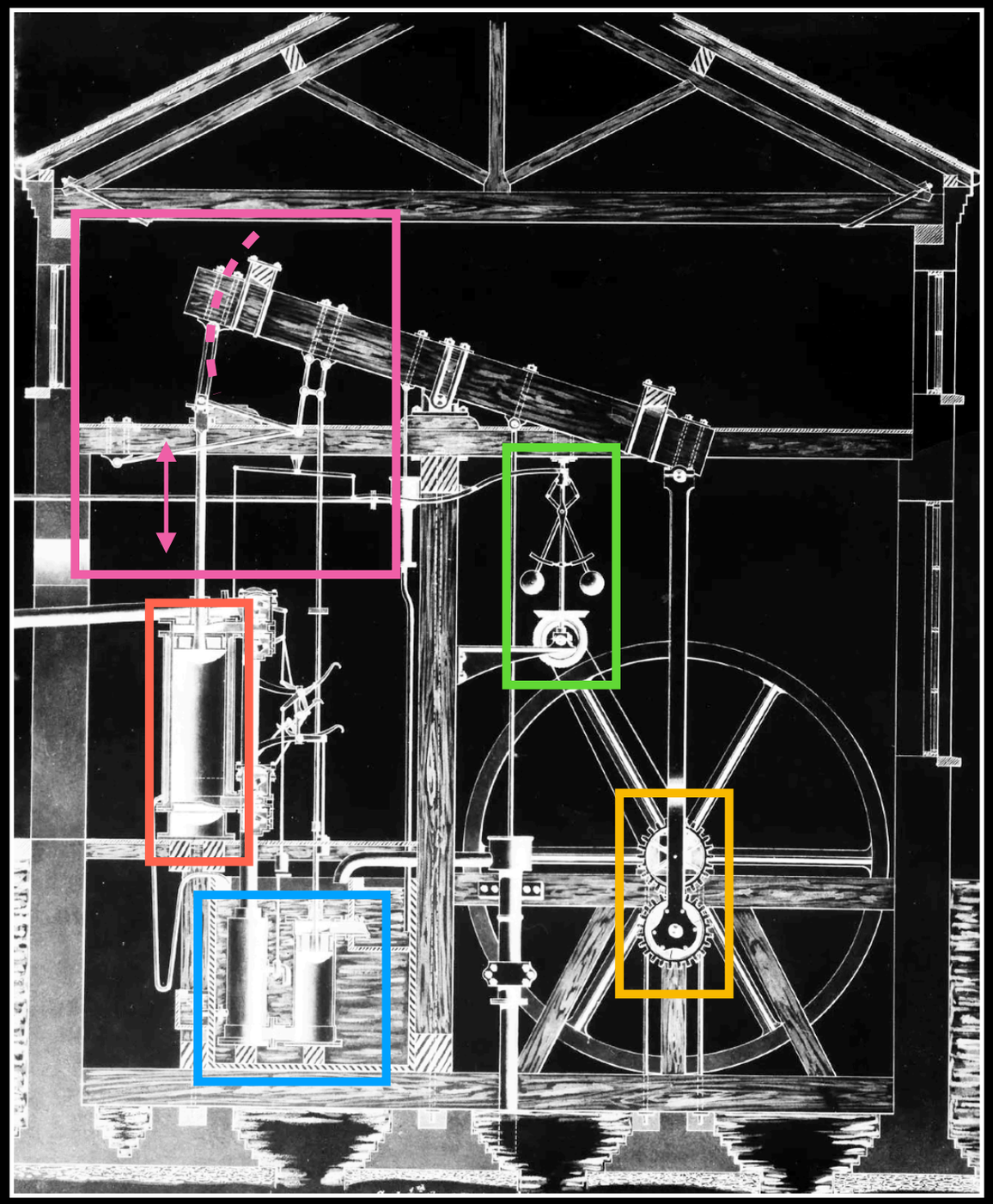

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Carnot’s criticism:

“The phenomenon of the production of motion by heat has not been considered from a sufficiently general point of view.”

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Let’s strip away all the practical details!

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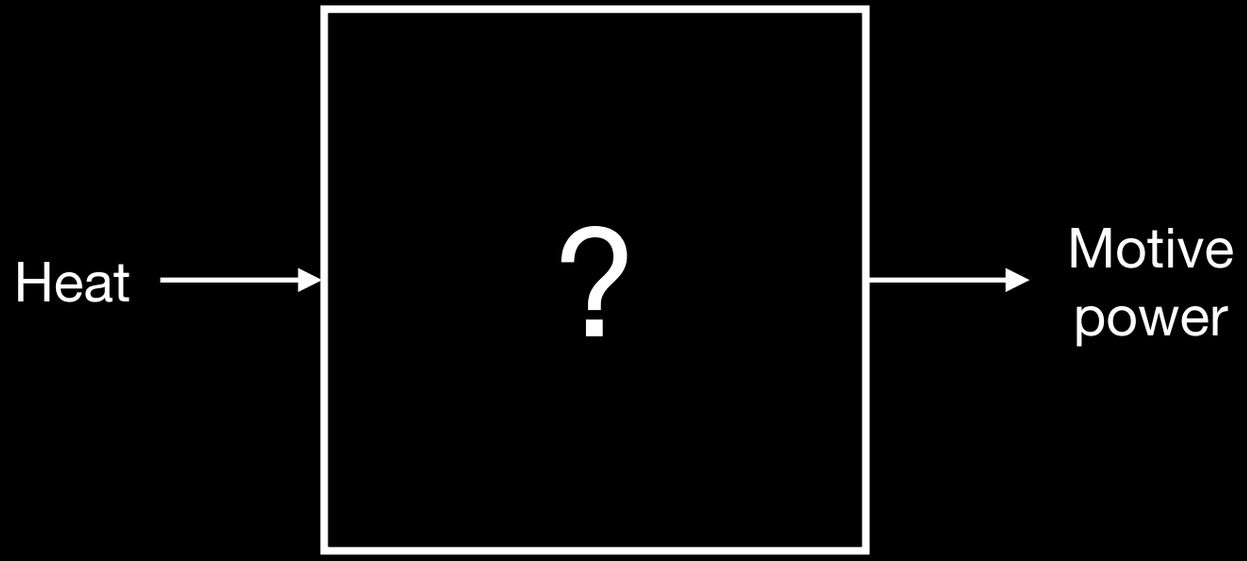
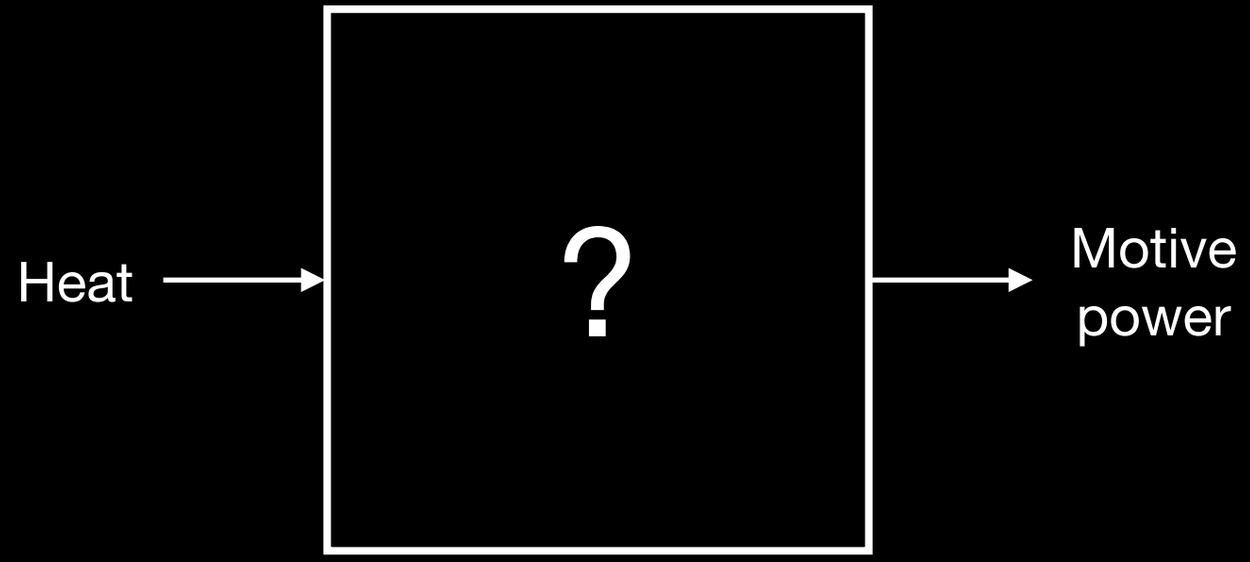


Carnot's approach

Let's strip away all the practical details!

"It is necessary to establish principles applicable not only to steam engines but to all imaginable heat engines, whatever the working substance and whatever the method by which it is operated."



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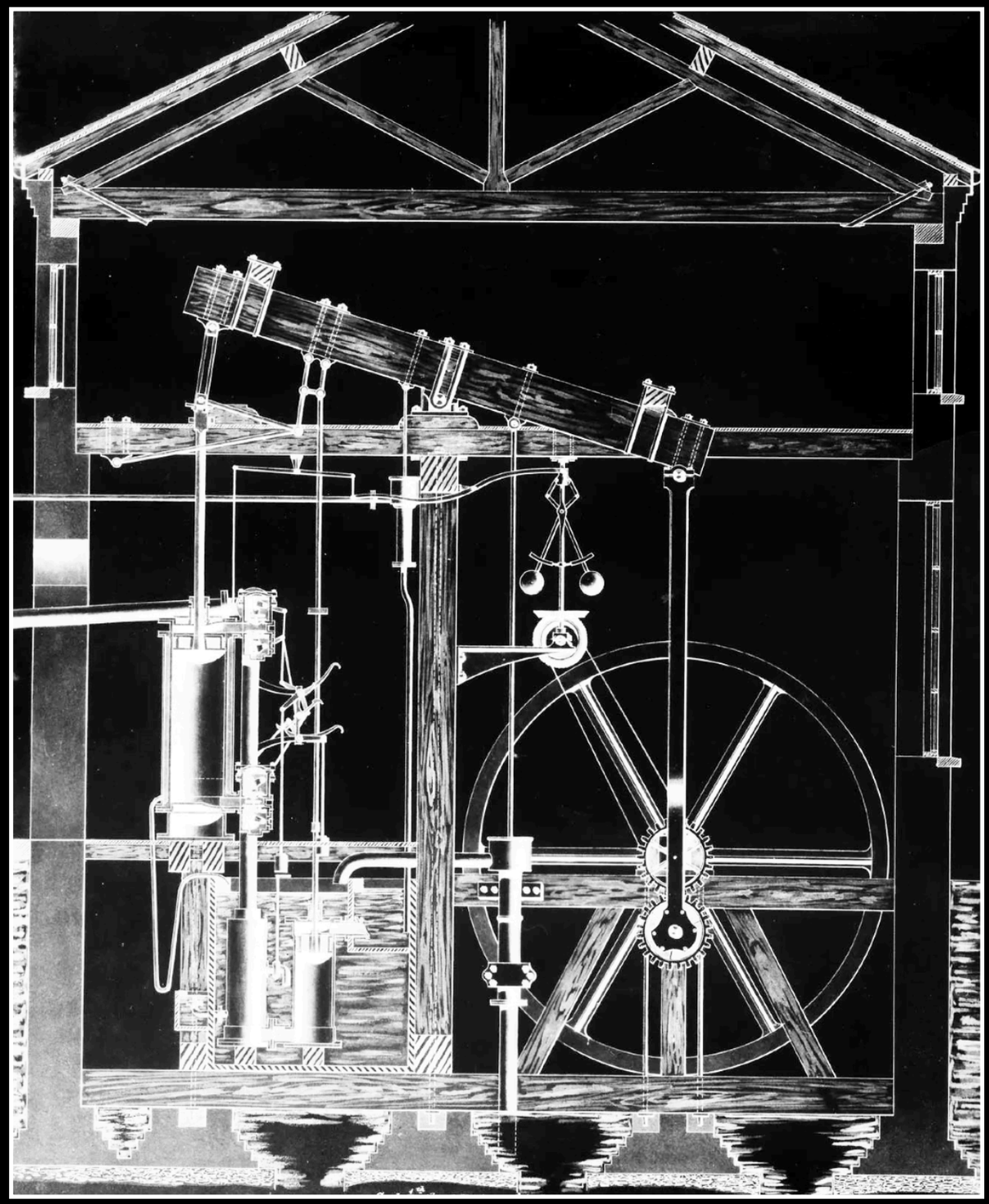

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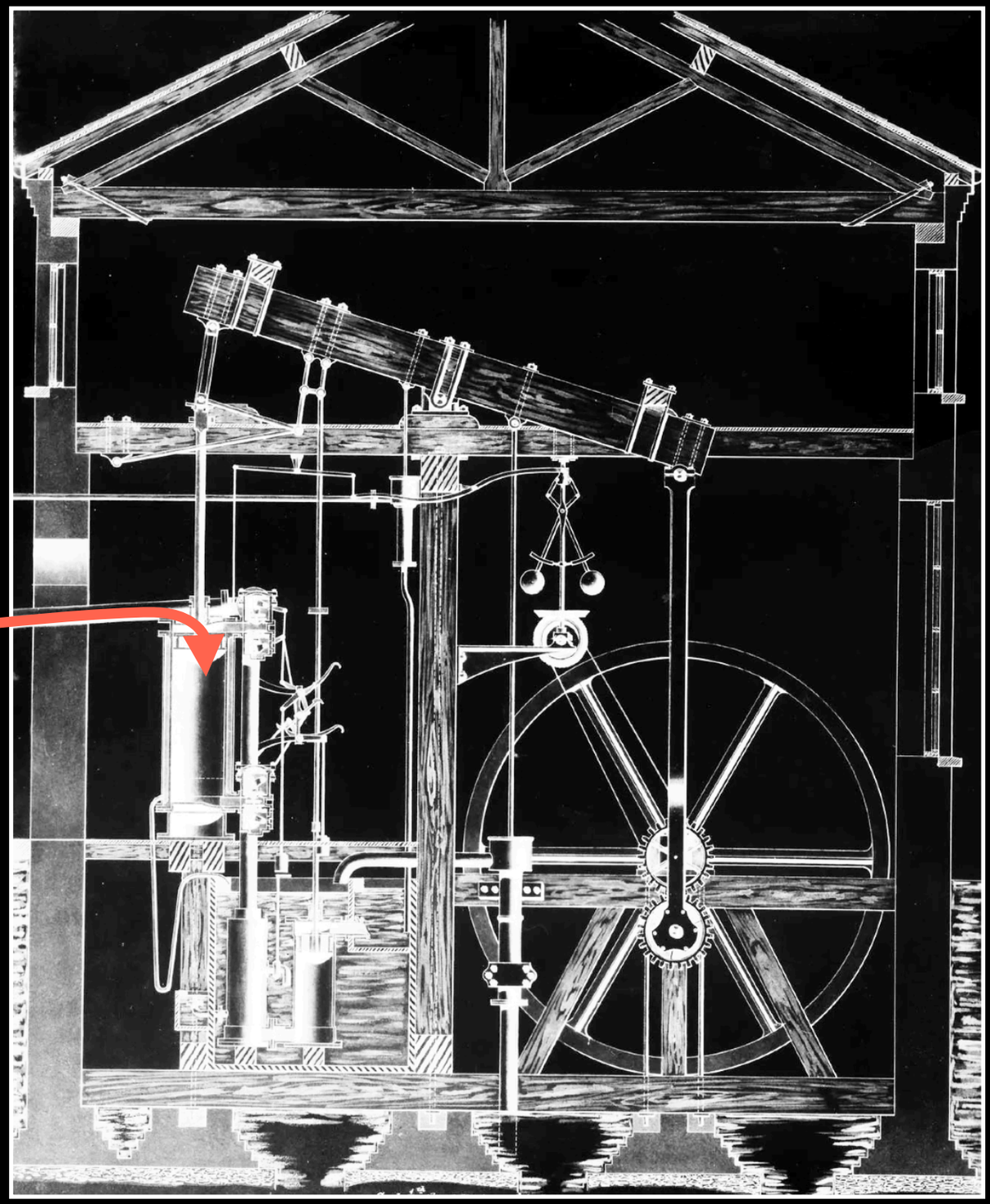

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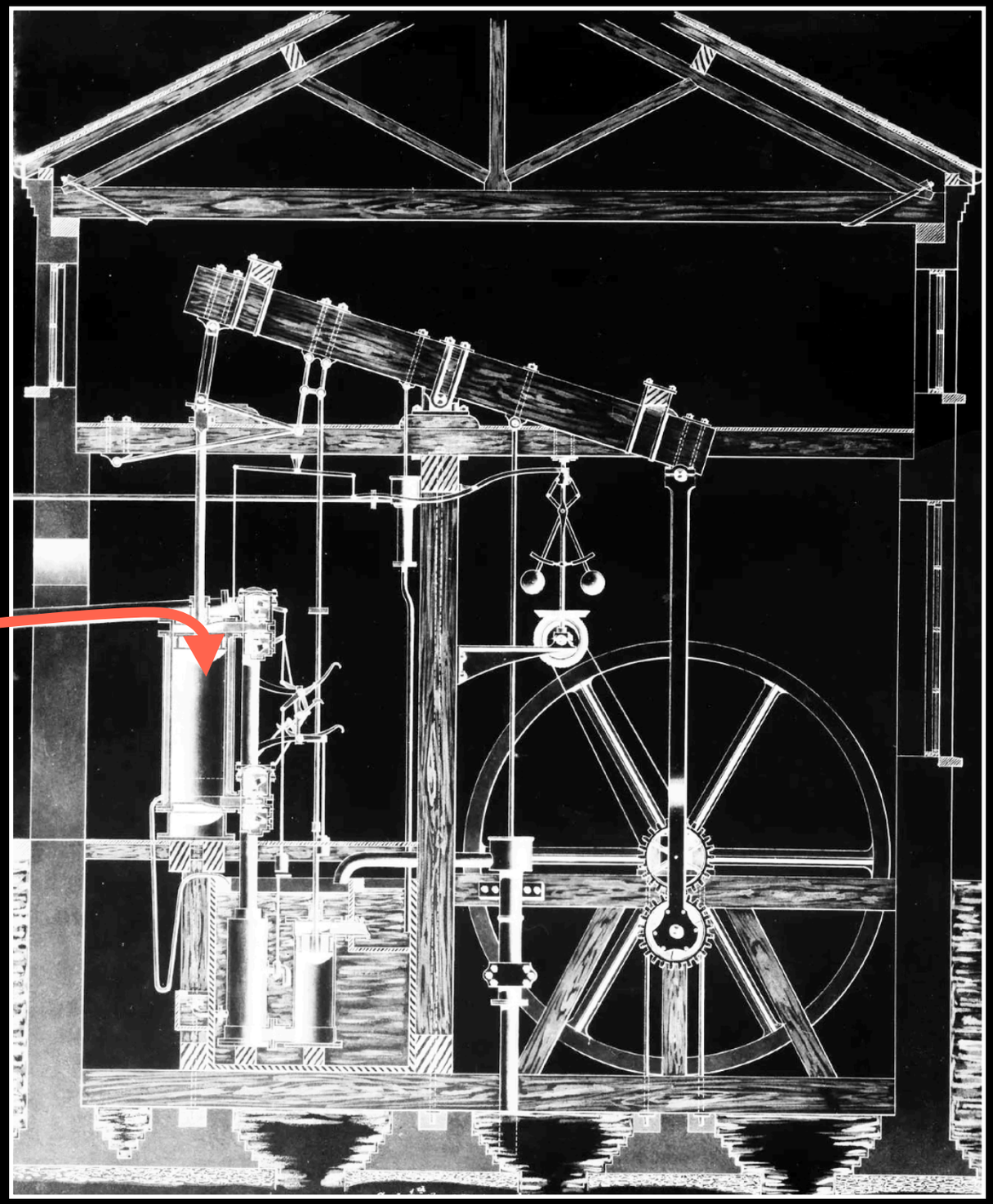
T_{hot}



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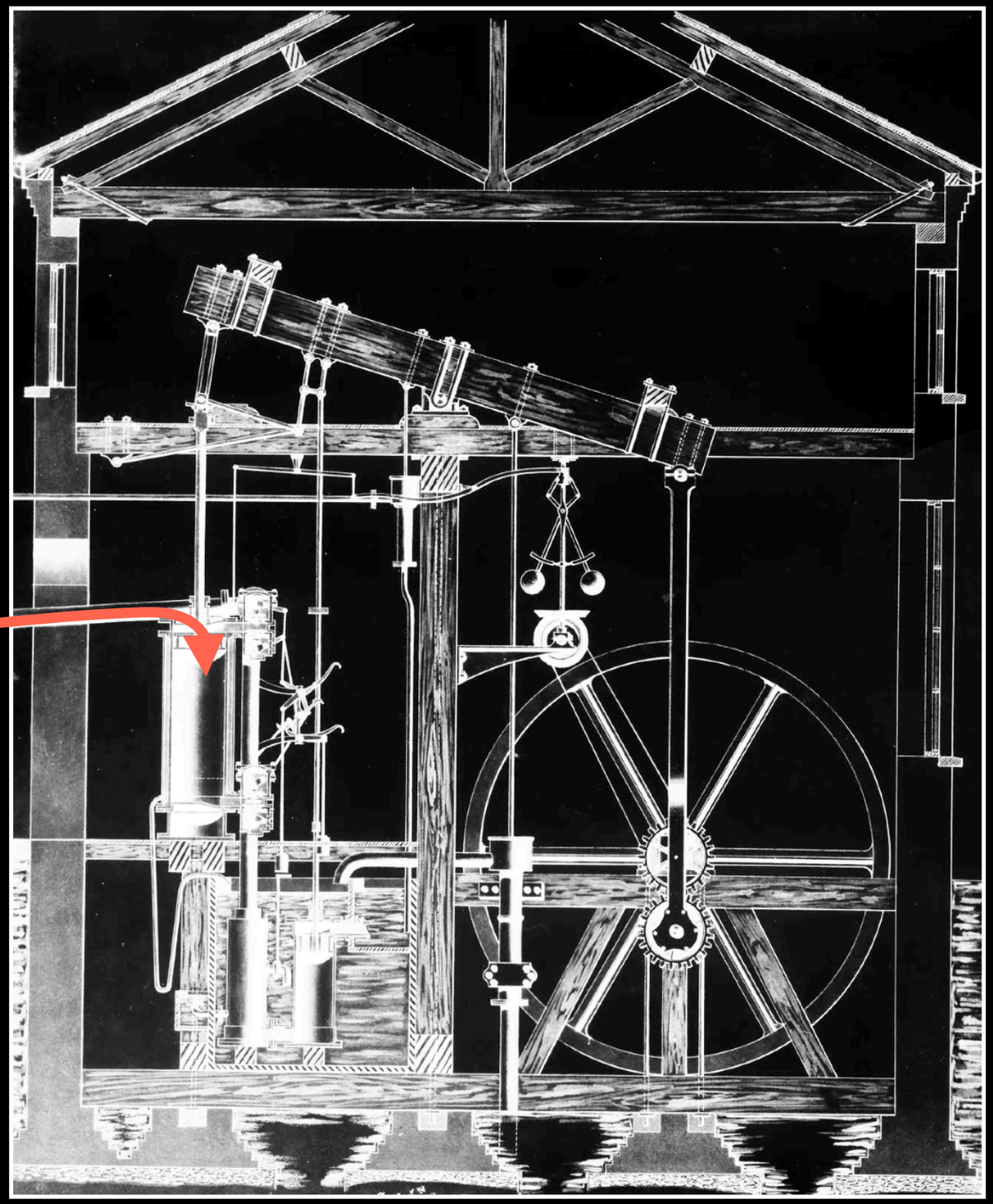

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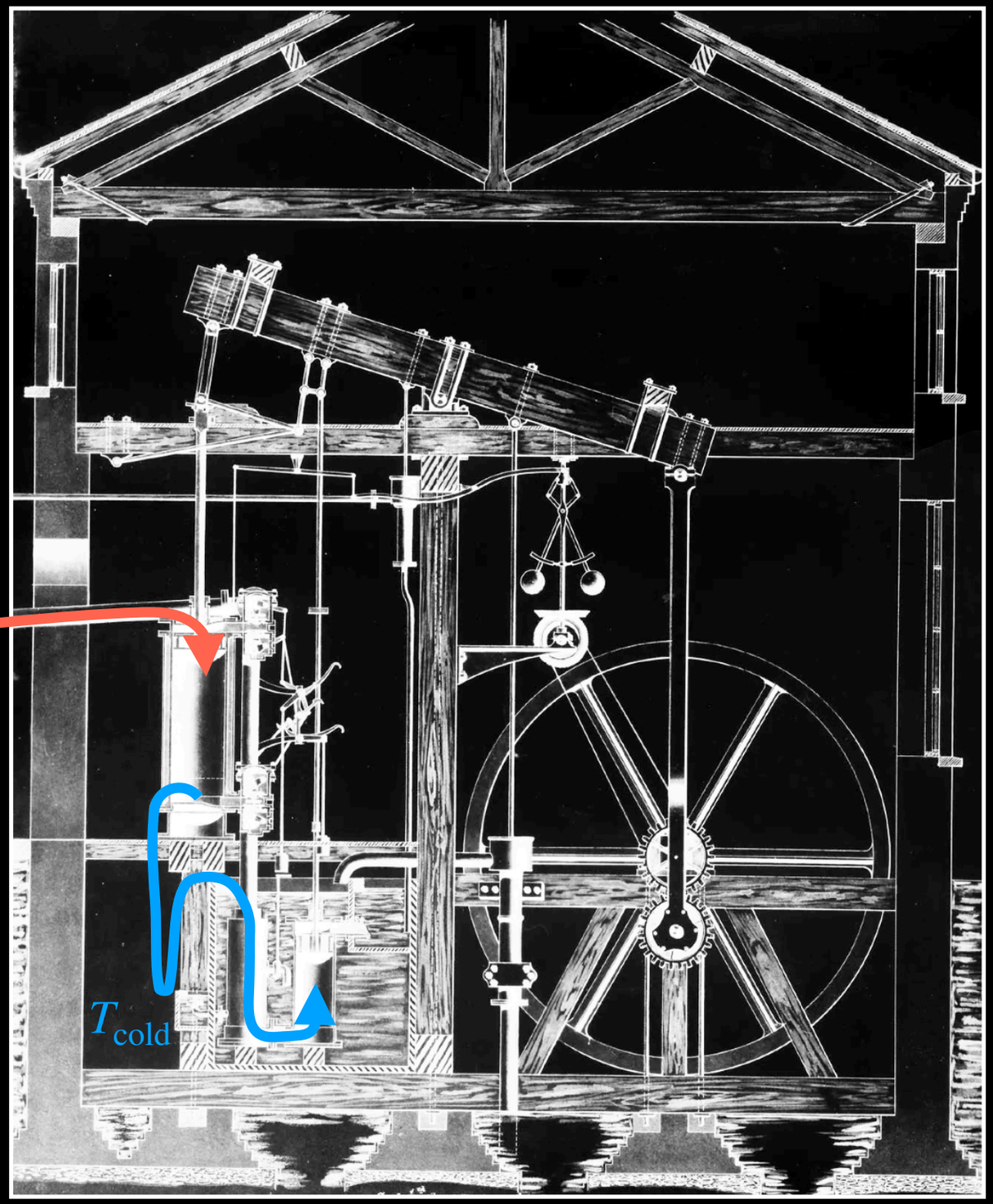

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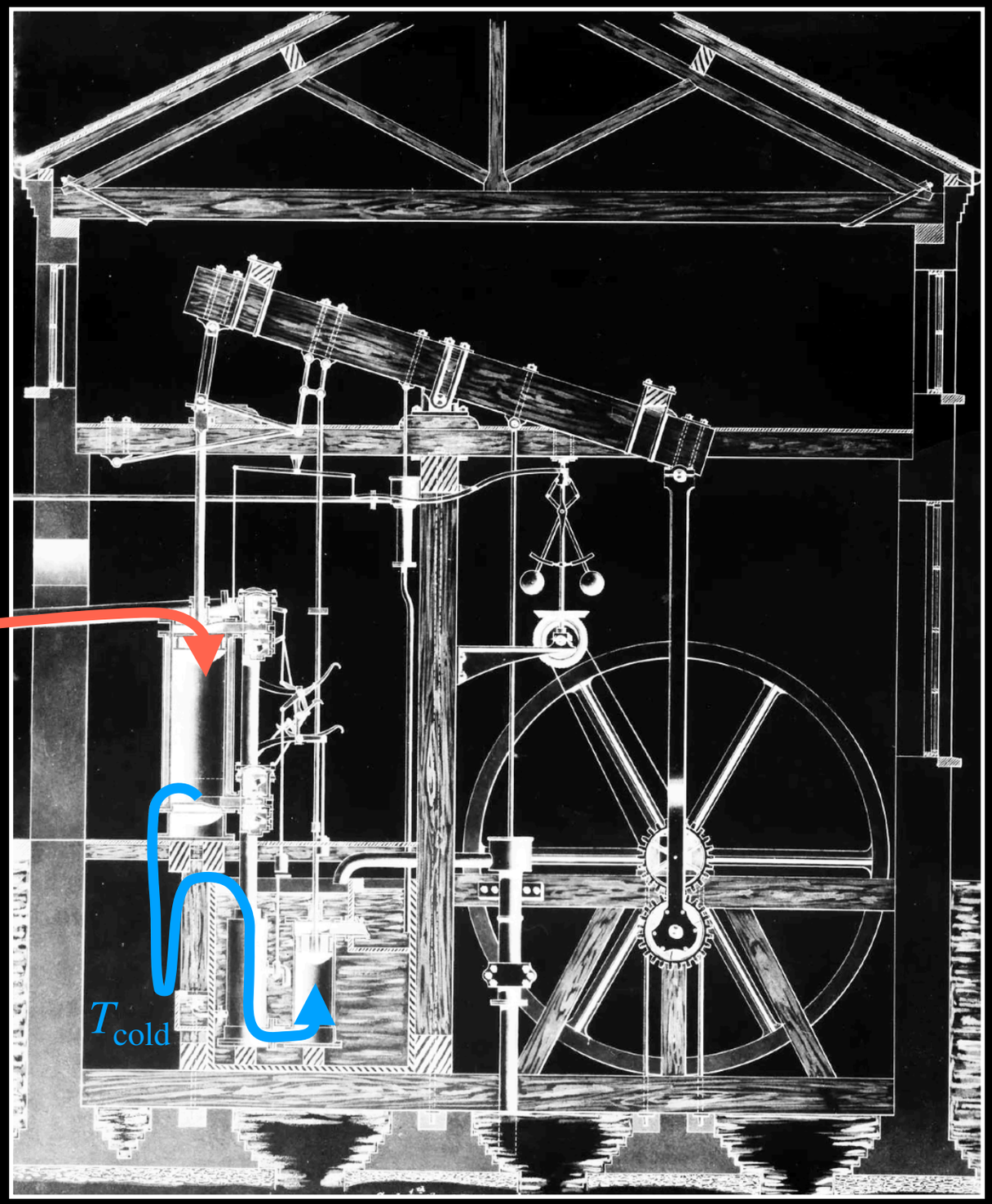
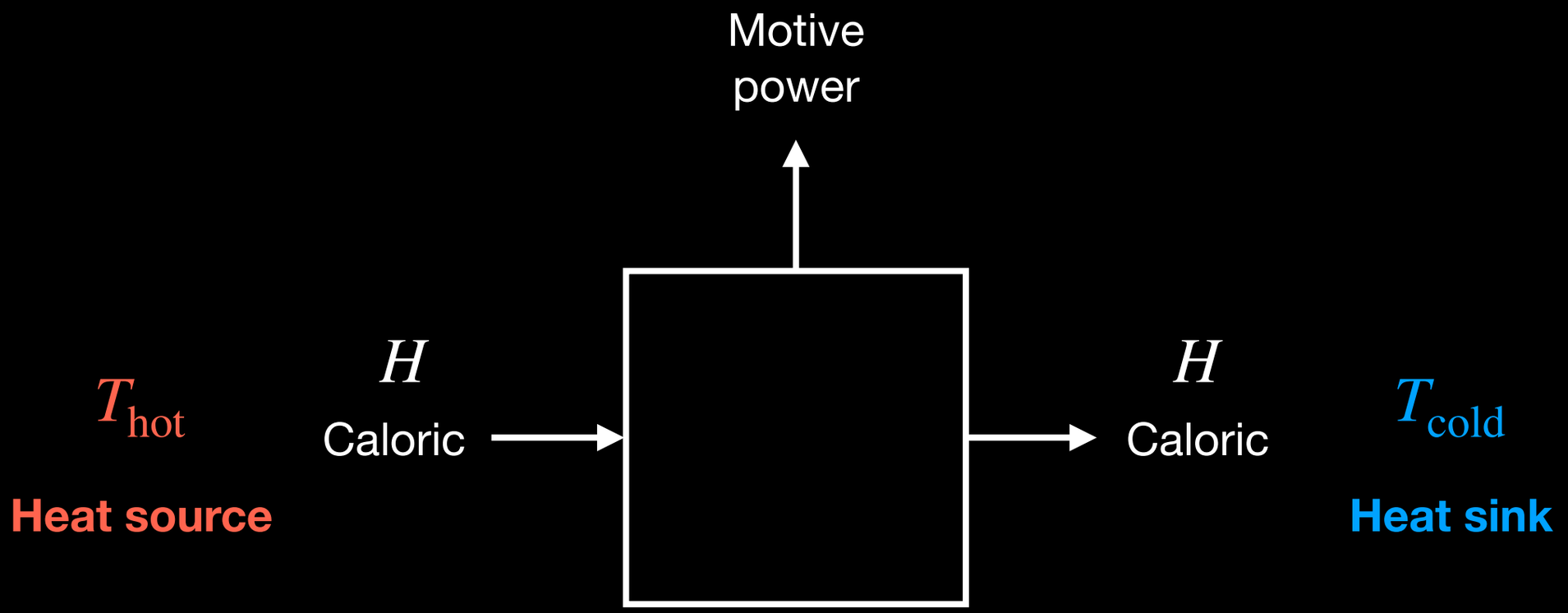


The temperature difference is crucial!



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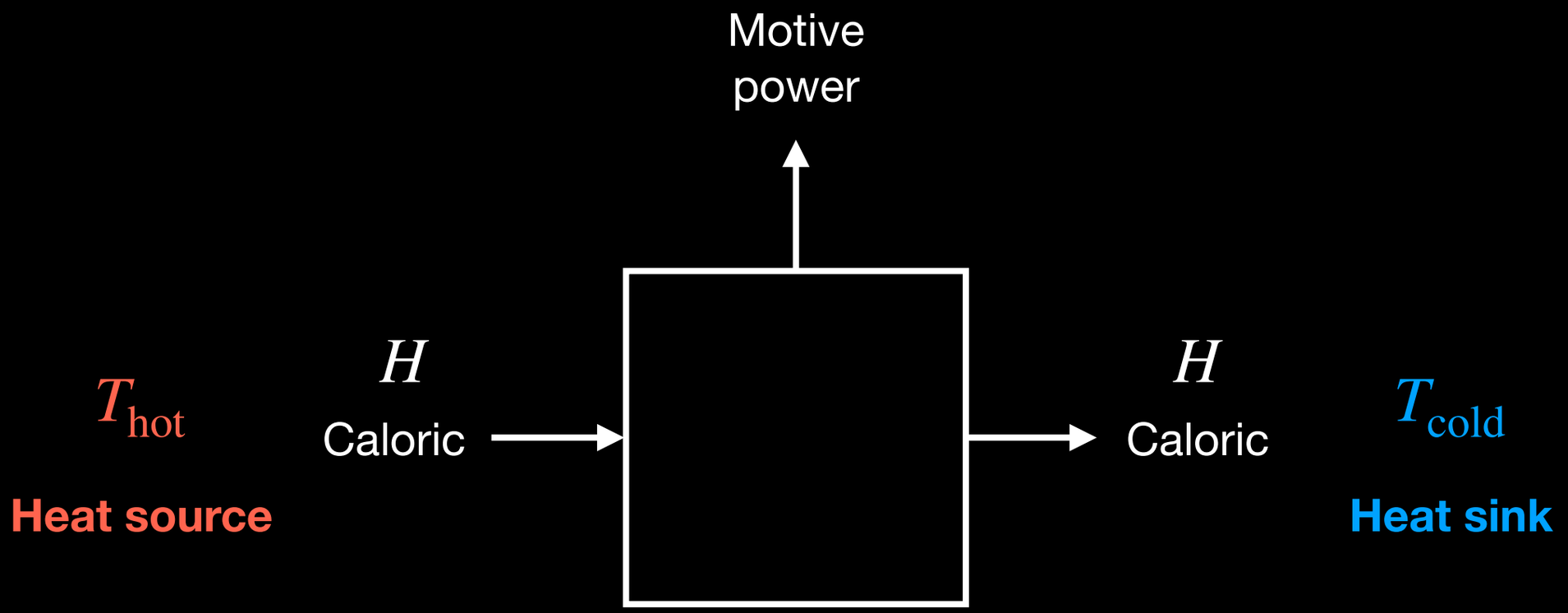

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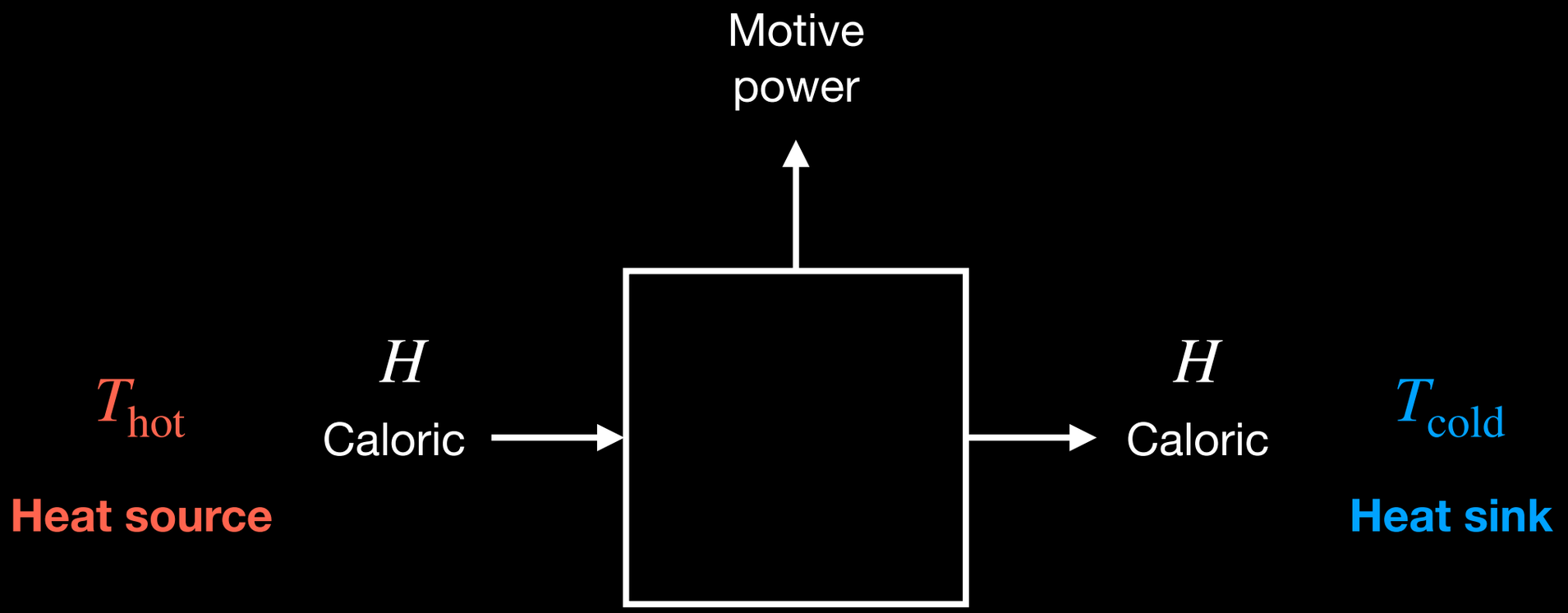

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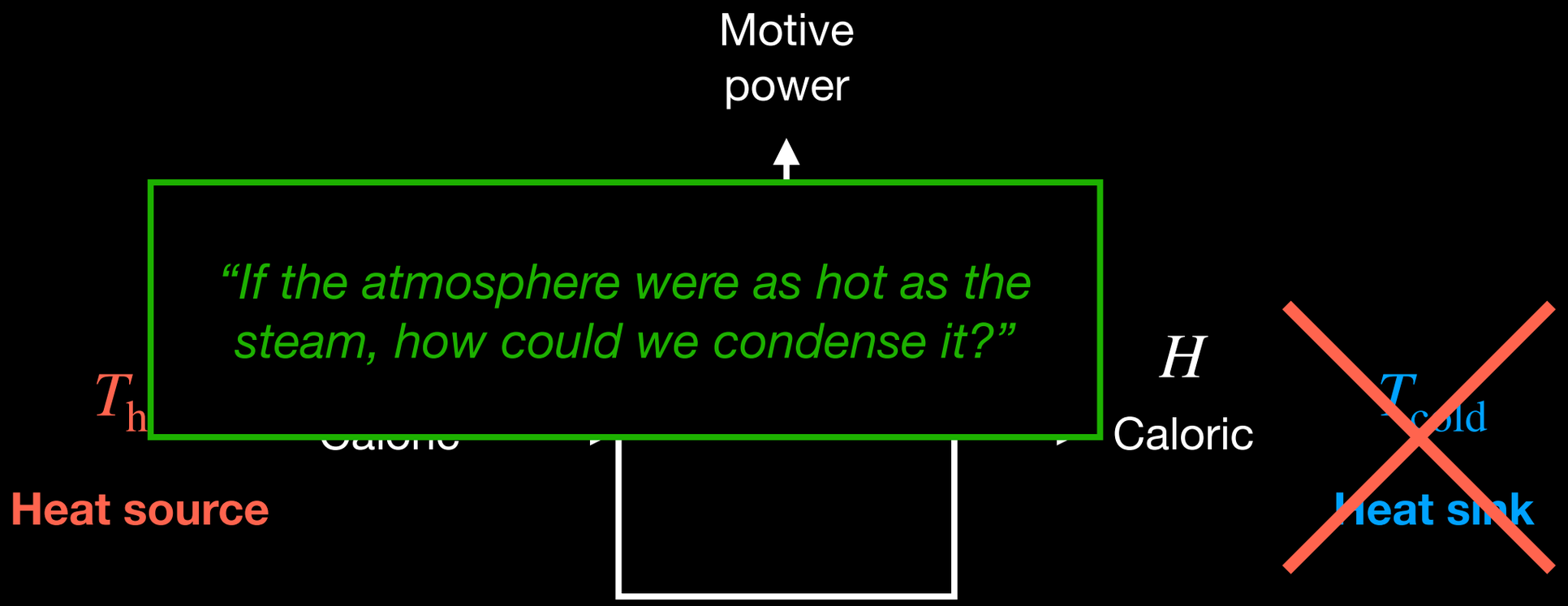

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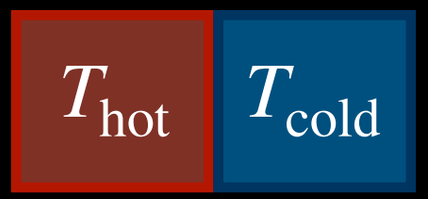
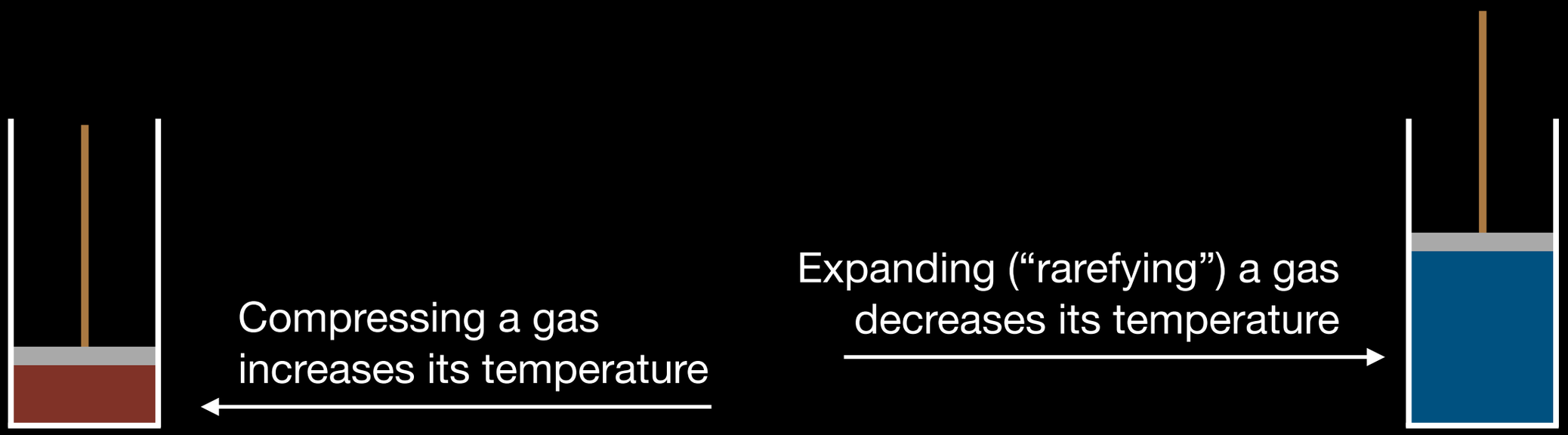
How to avoid losses?

“The contact of bodies of different temperatures should be avoided as much as possible.”

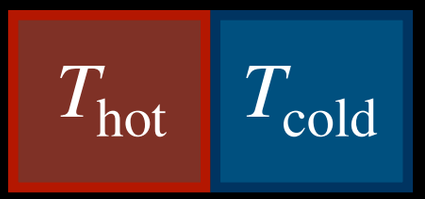


How to avoid losses?

“There should not occur any change of temperature that is not due to a change of volume.”

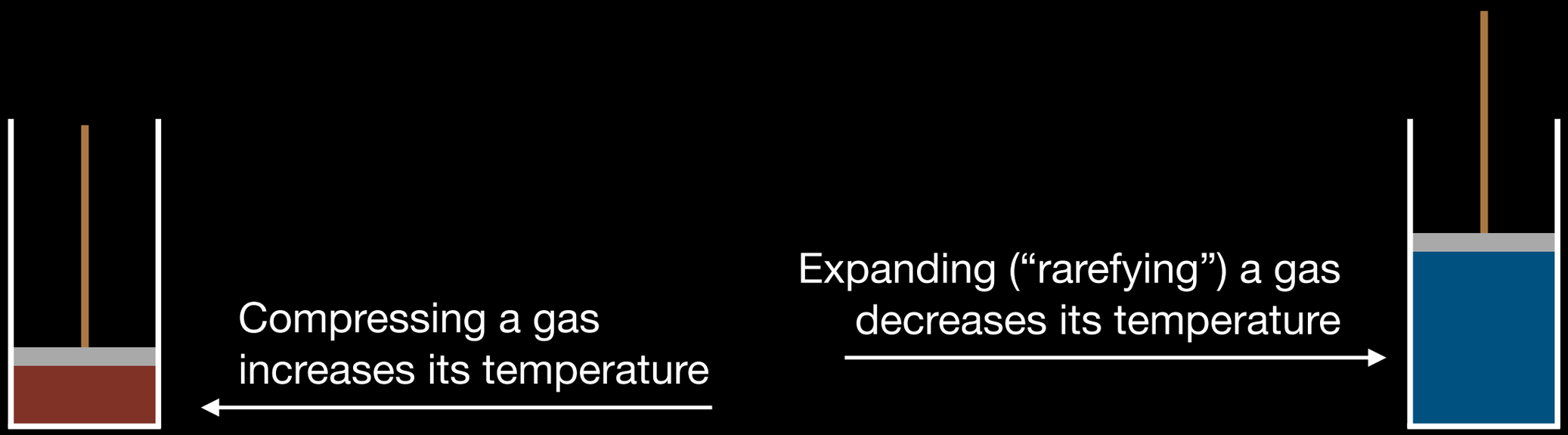


“The contact of bodies of different temperatures should be avoided as much as possible.”



How to avoid losses?

“There should not occur any change of temperature that is not due to a change of volume.”



How to avoid losses?

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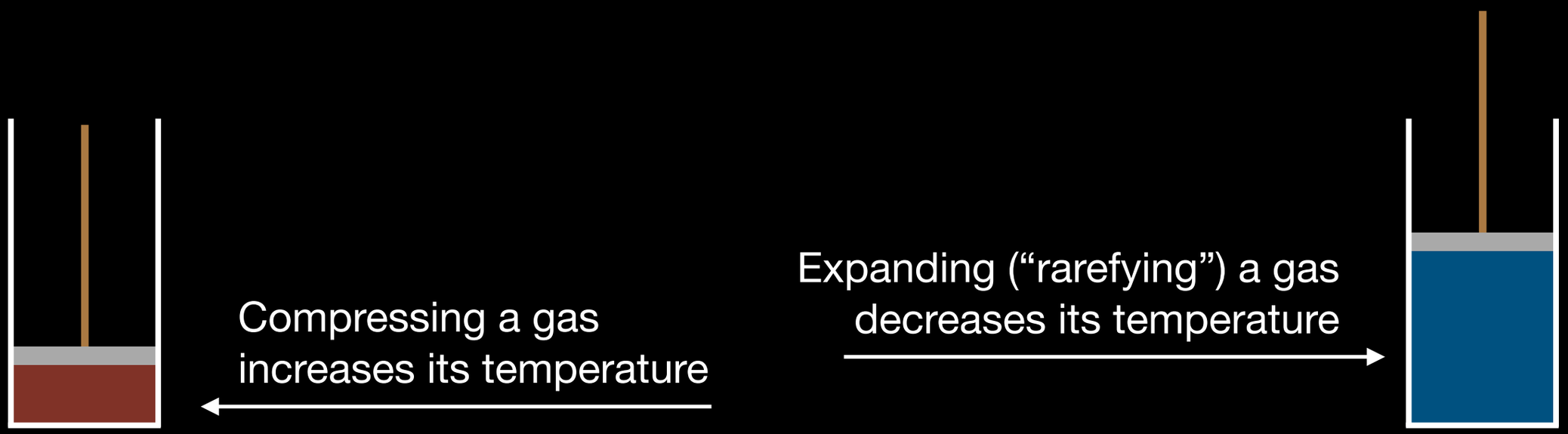
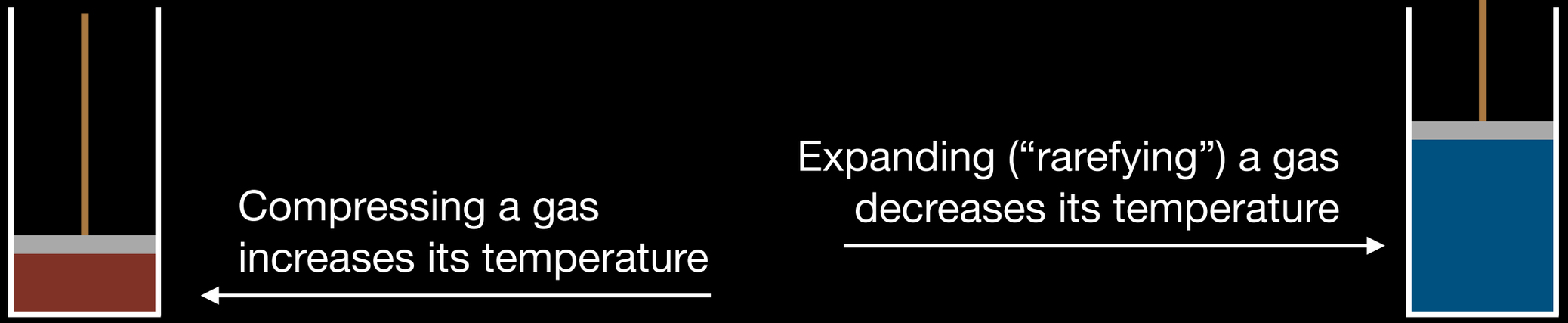
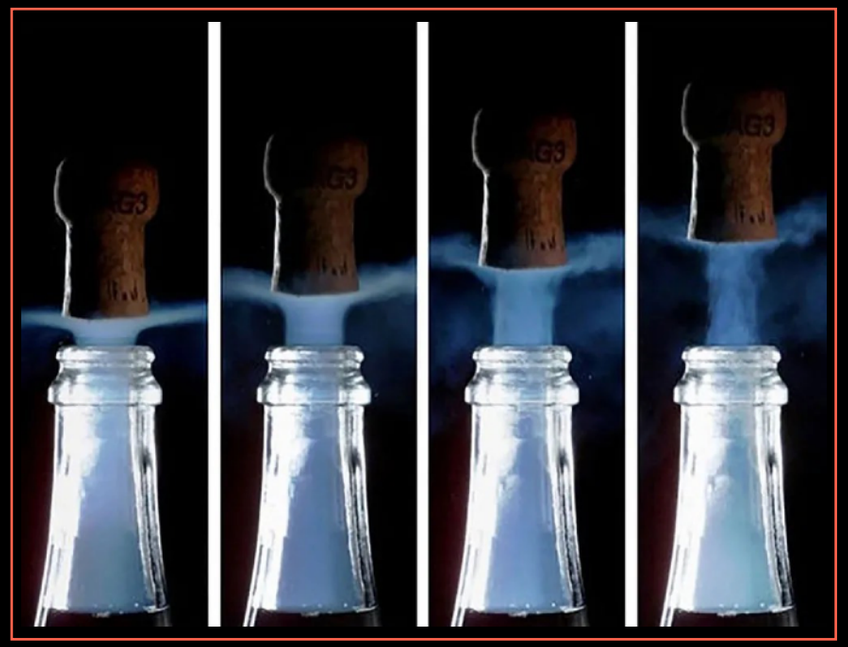


How to avoid losses?

“There should not occur any change of temperature that is not due to a change of volume.”





[Smithsonian magazine]

Carnot's idealized engine

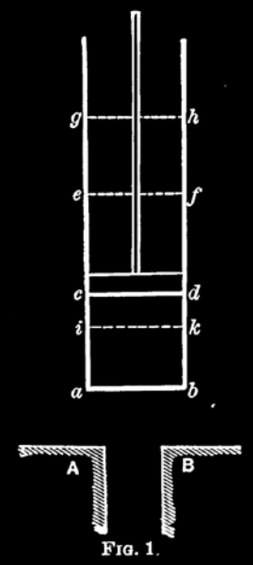
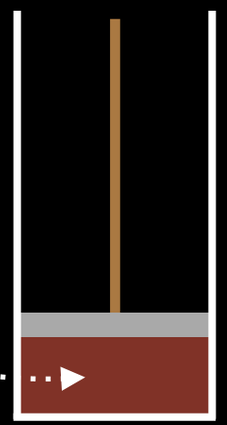


FIG. 1.

Working medium:
Temperature T_{hot}
Volume V_{min}



Hot reservoir

Cold reservoir

Carnot's idealized engine

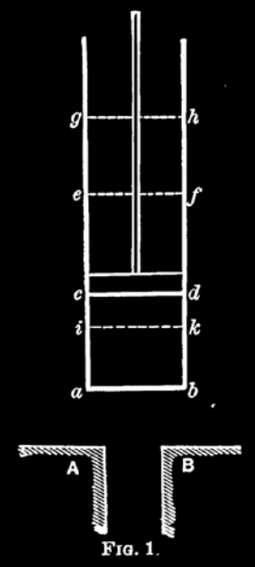
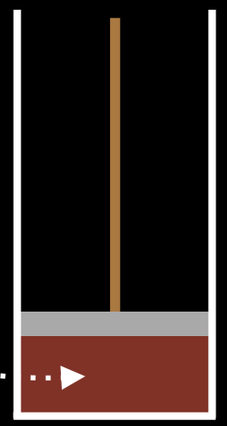


Fig. 1.

Working medium:
Temperature T_{hot}
Volume V_{min}



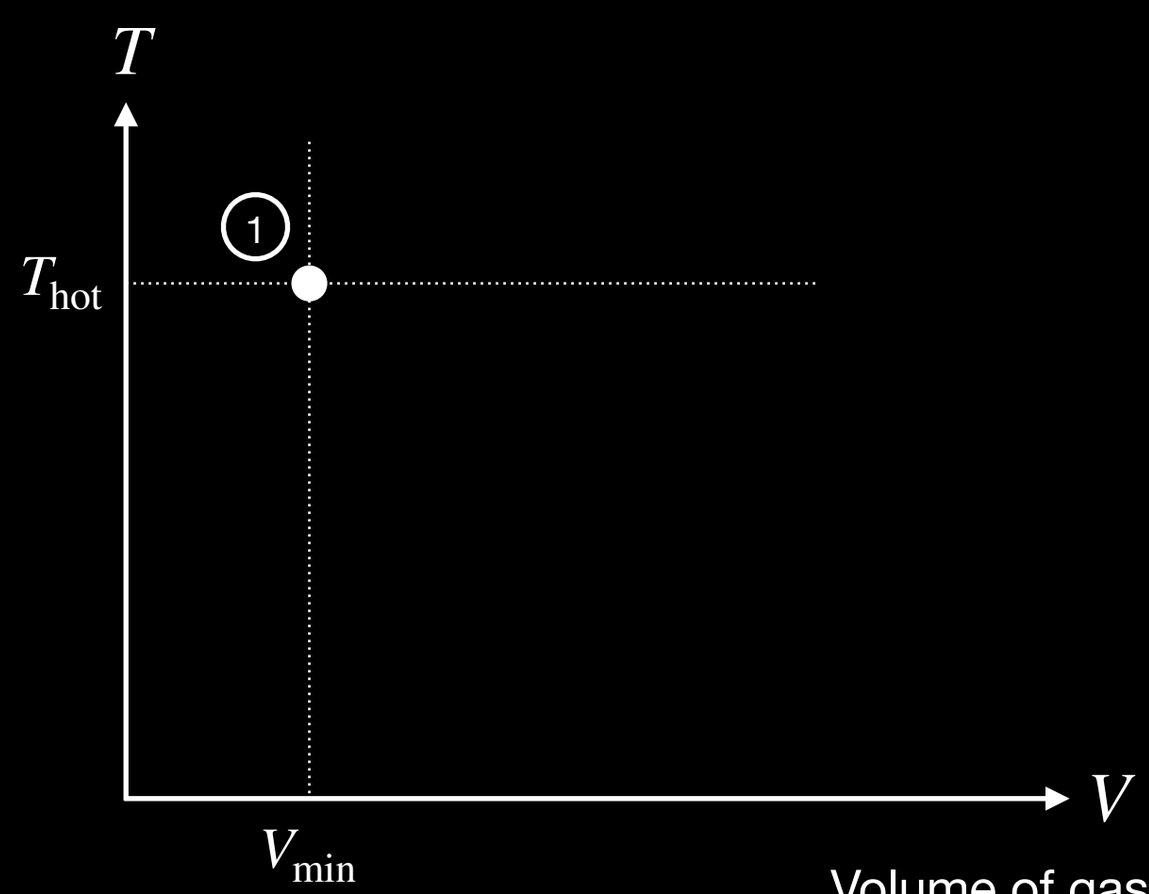
T_{hot}

Hot reservoir

T_{cold}

Cold reservoir

Temperature of gas in cylinder



Volume of gas in cylinder

Carnot’s idealized engine

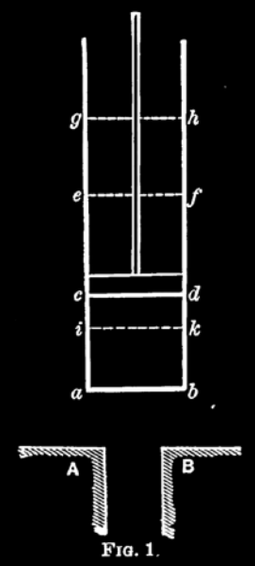
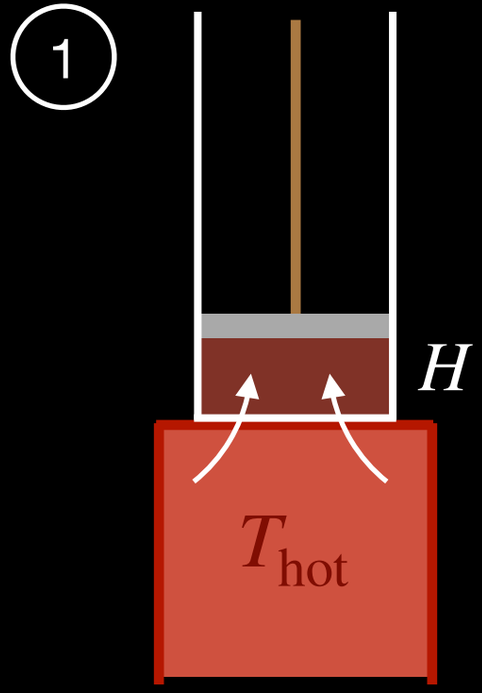
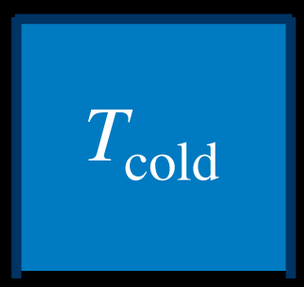


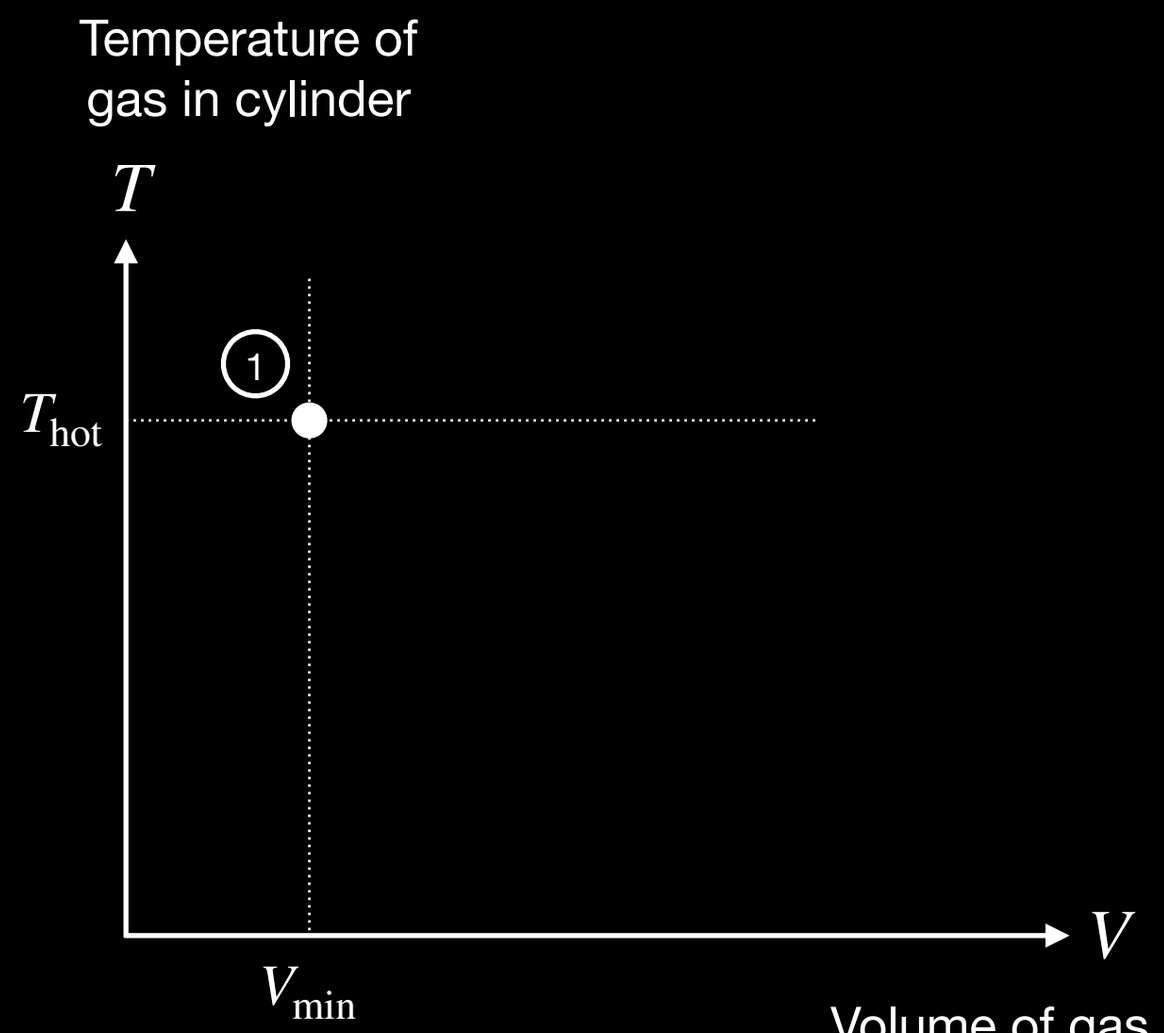
Fig. 1.



Hot reservoir



Cold reservoir



Carnot's idealized engine

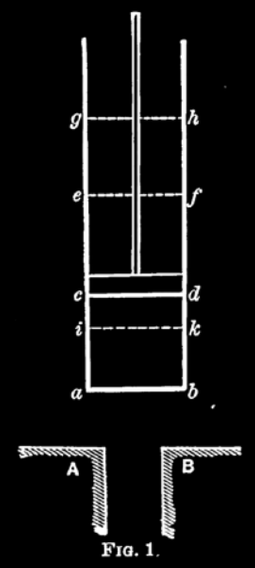
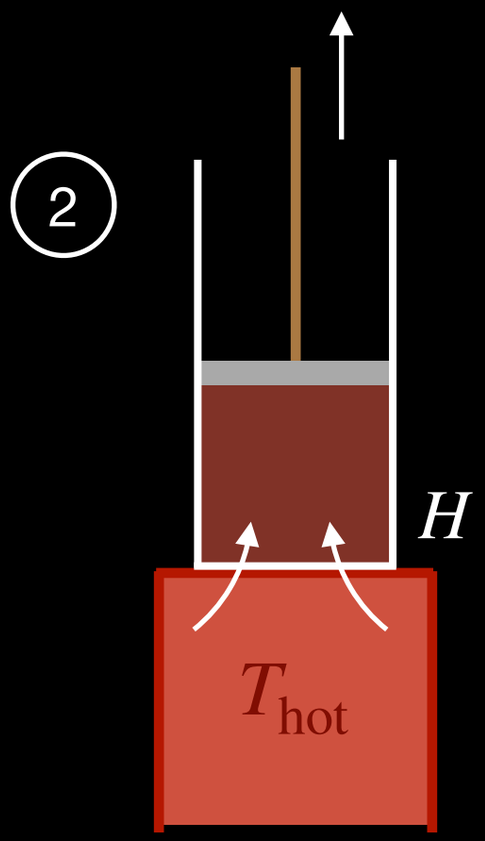
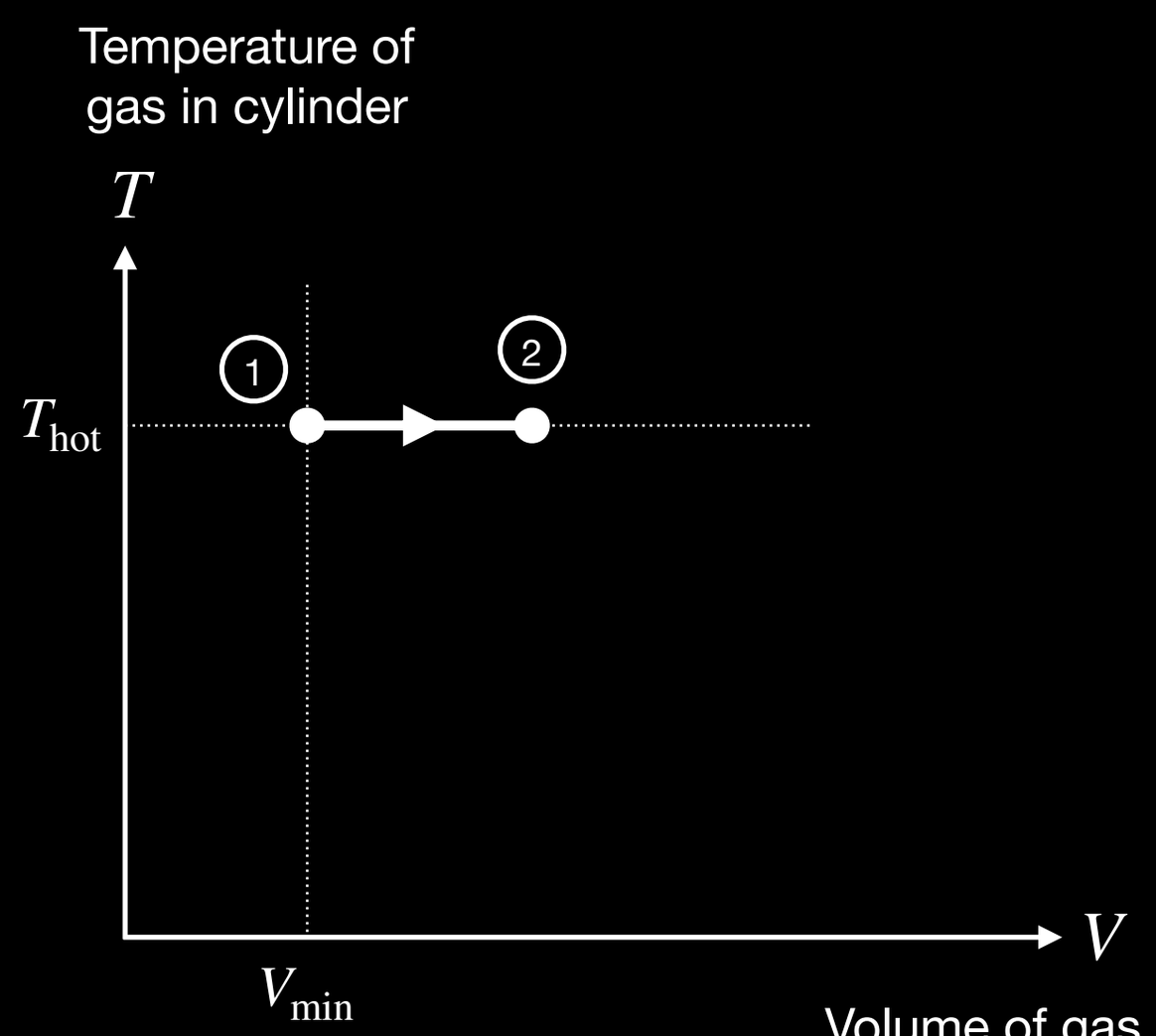


Fig. 1.



Hot reservoir

Cold reservoir



Carnot's idealized engine

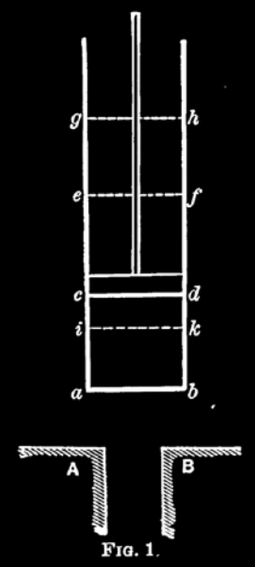
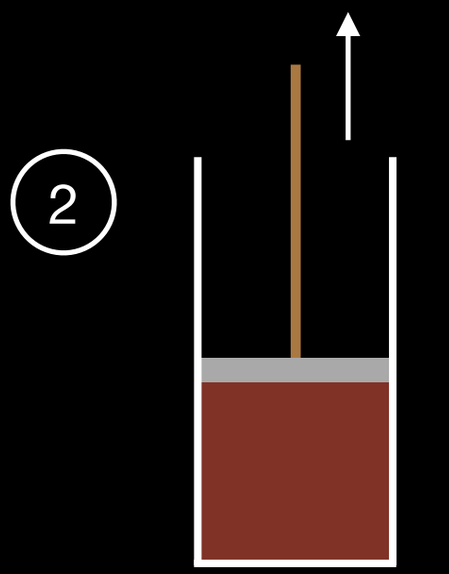


FIG. 1.

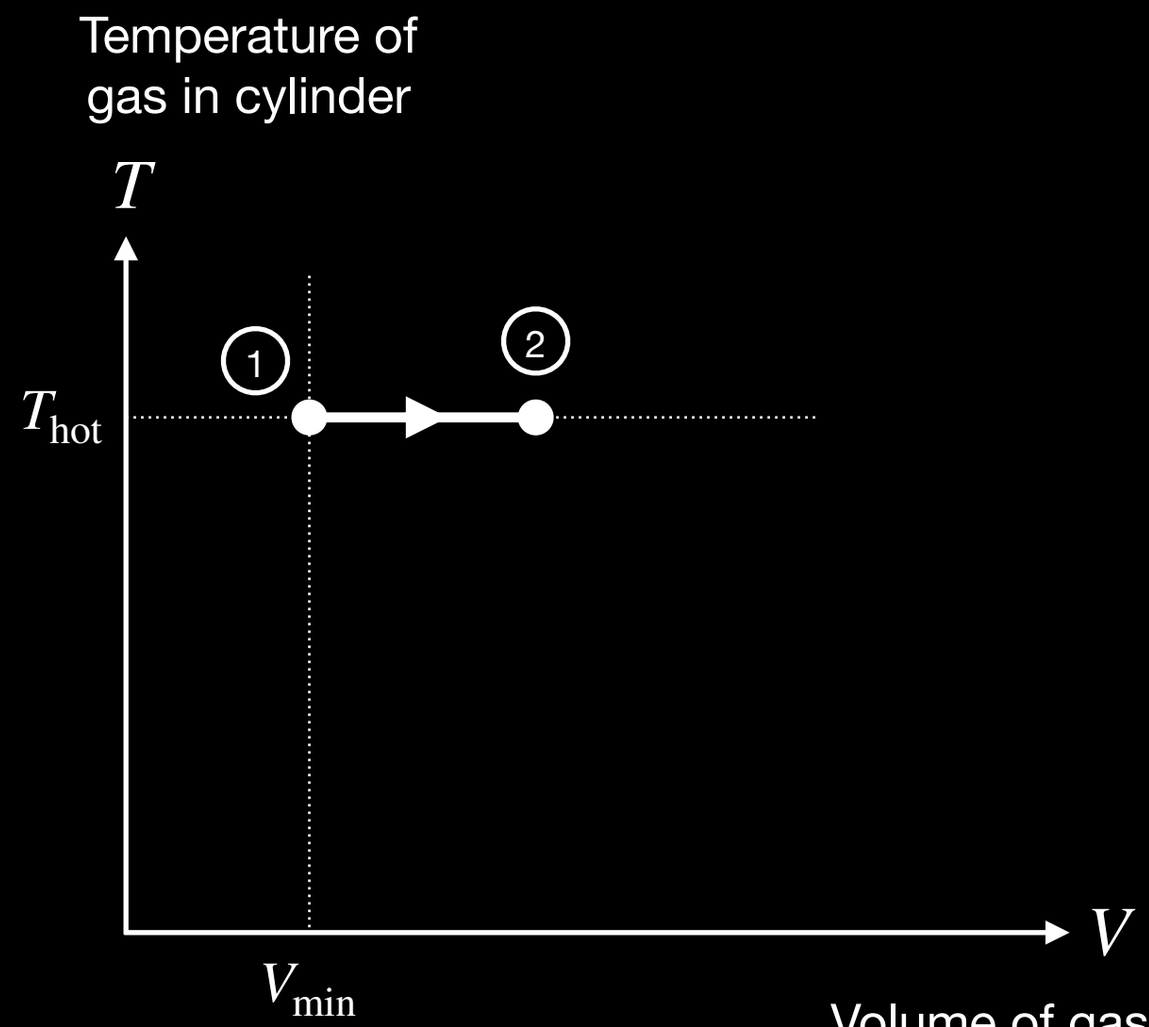


T_{hot}

Hot reservoir

T_{cold}

Cold reservoir



Carnot’s idealized engine

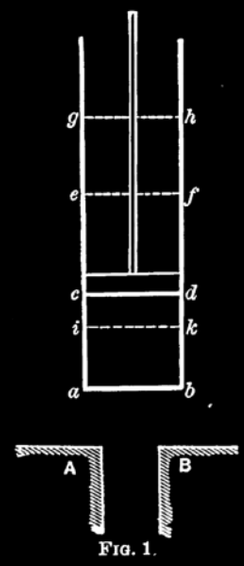
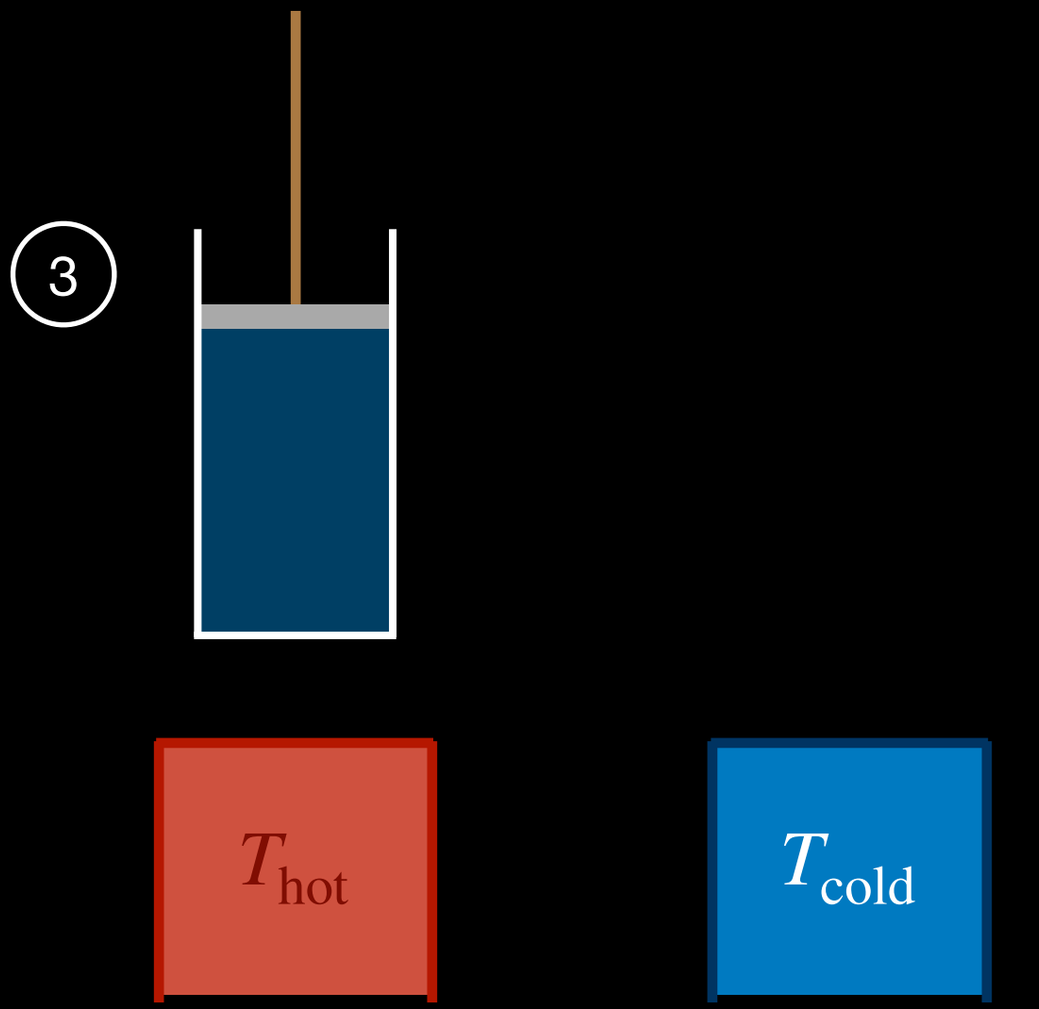
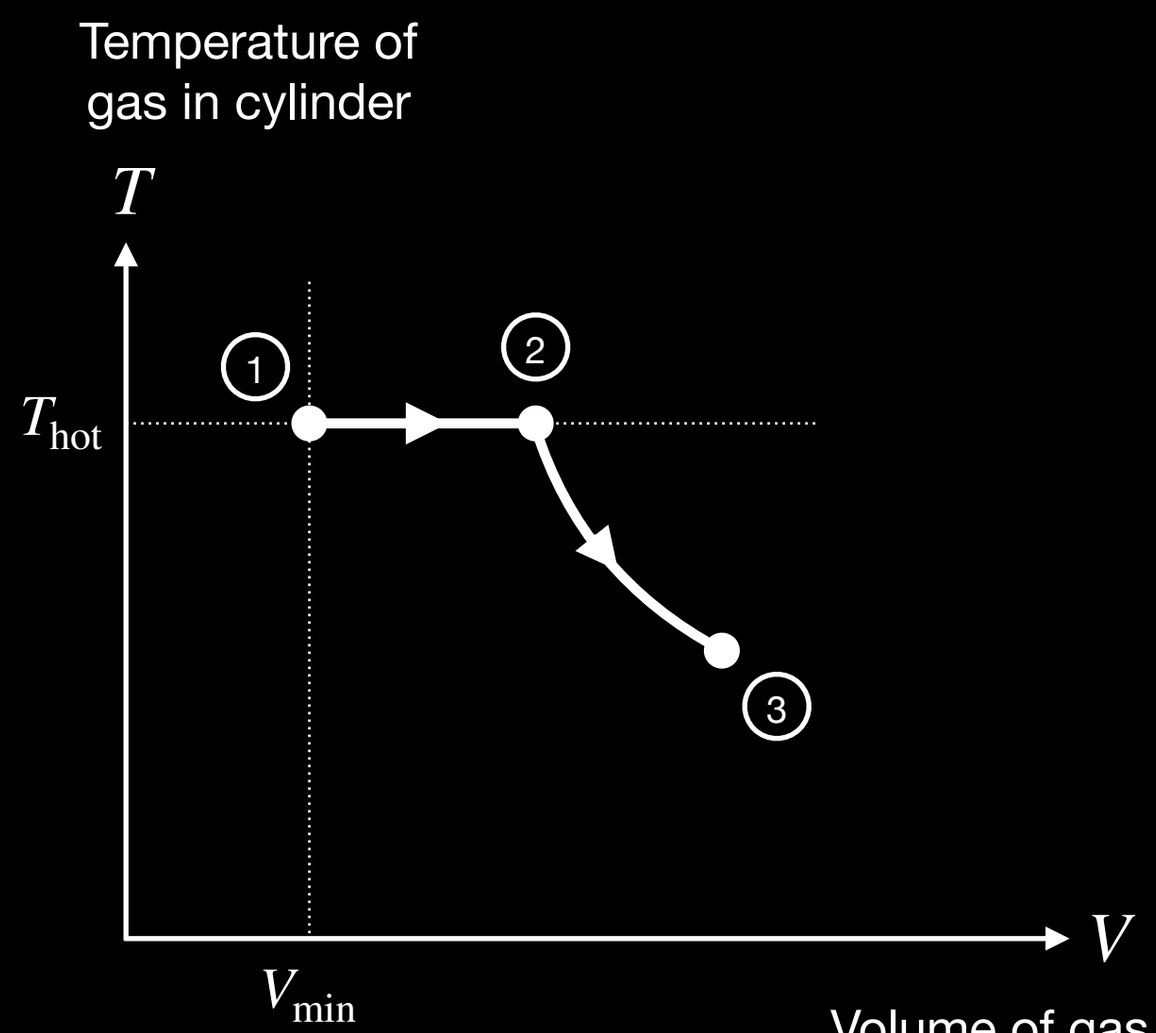


FIG. 1.





Carnot's idealized engine

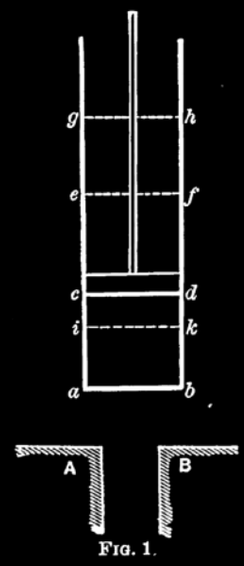
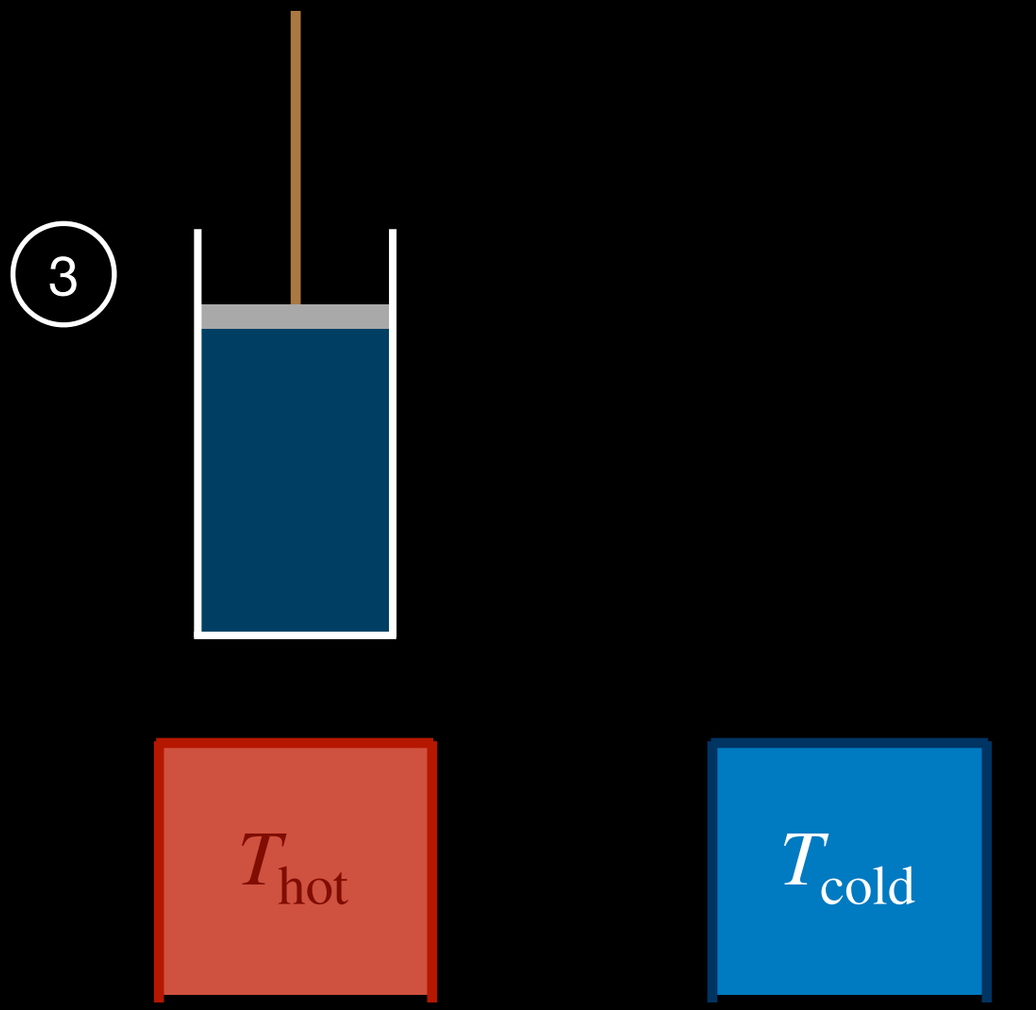
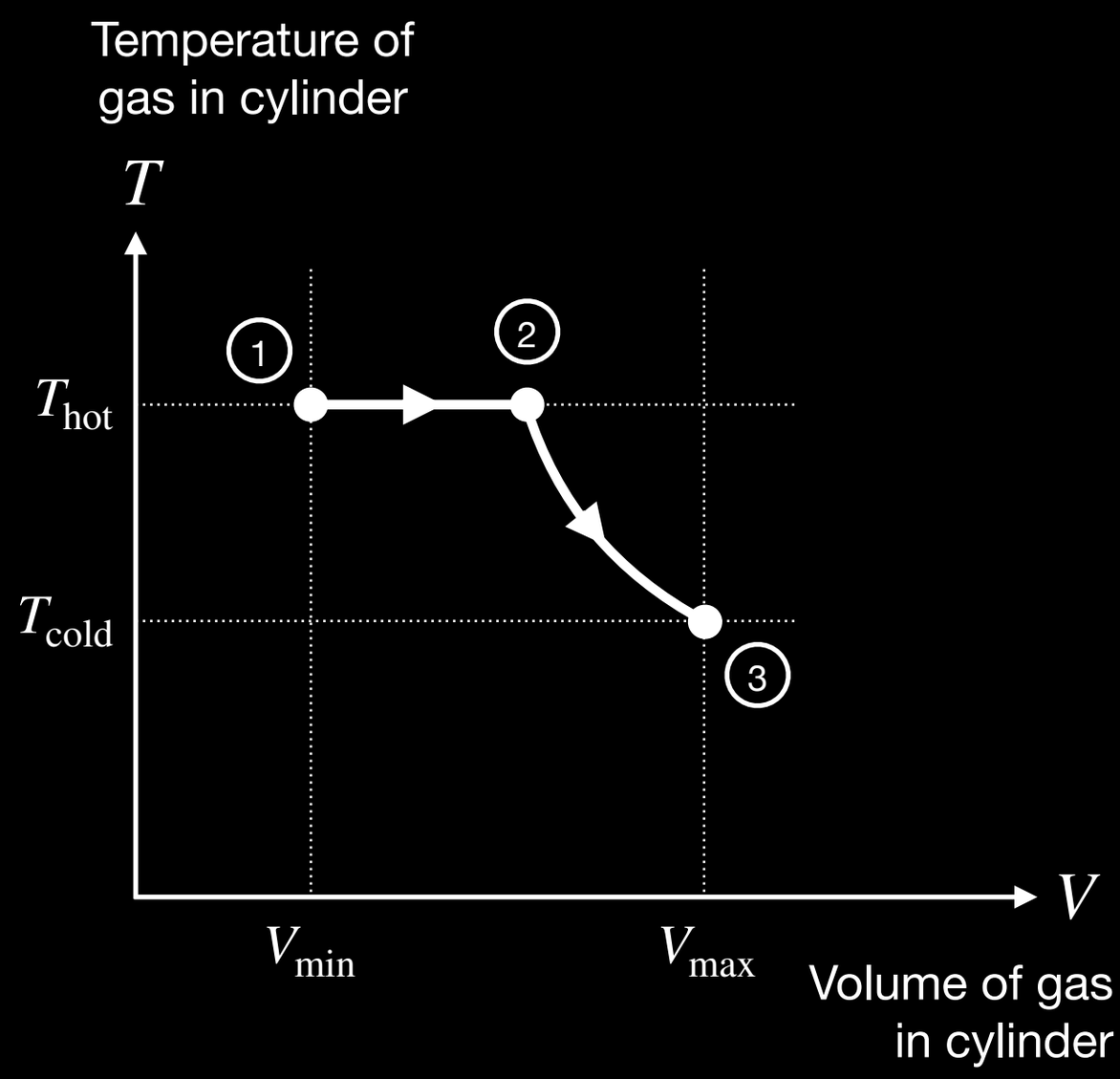


FIG. 1.





Carnot's idealized engine

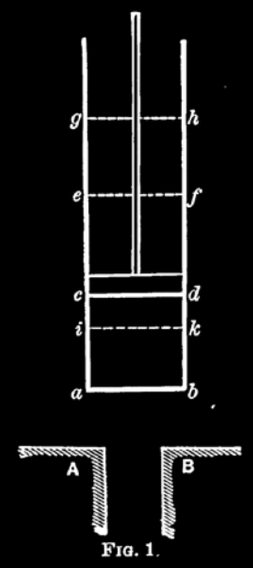
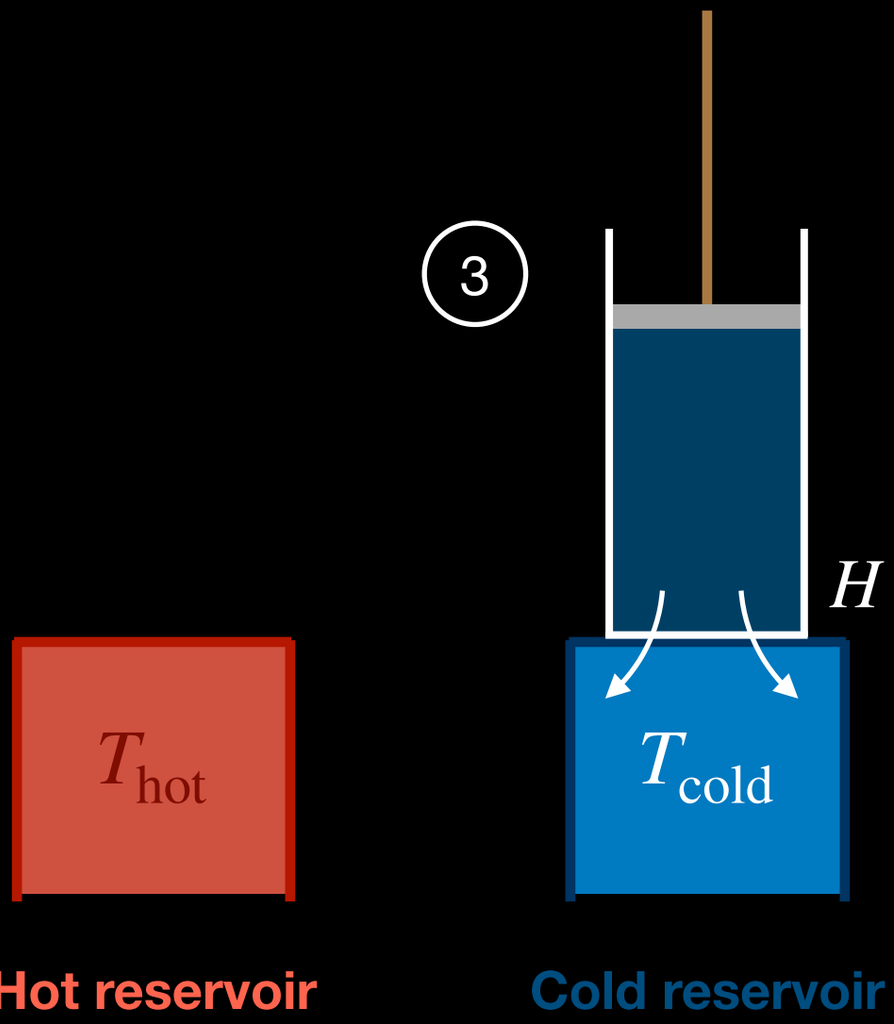
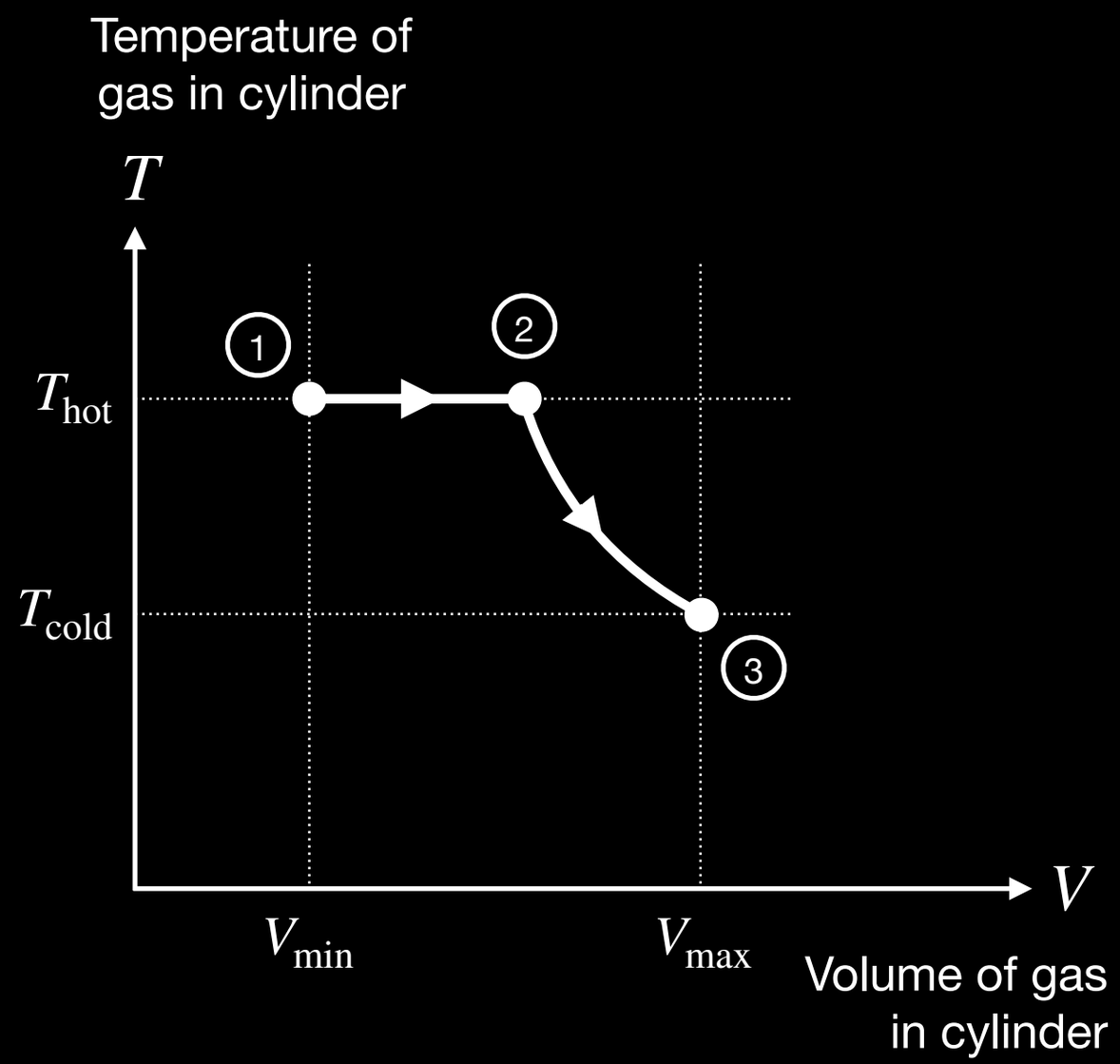


Fig. 1.





Carnot's idealized engine

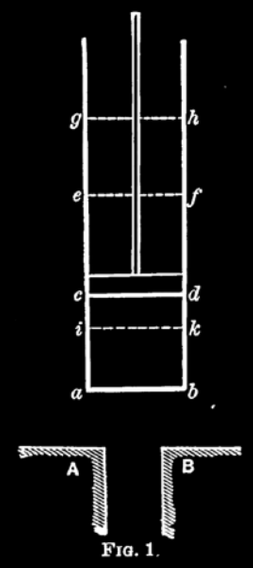
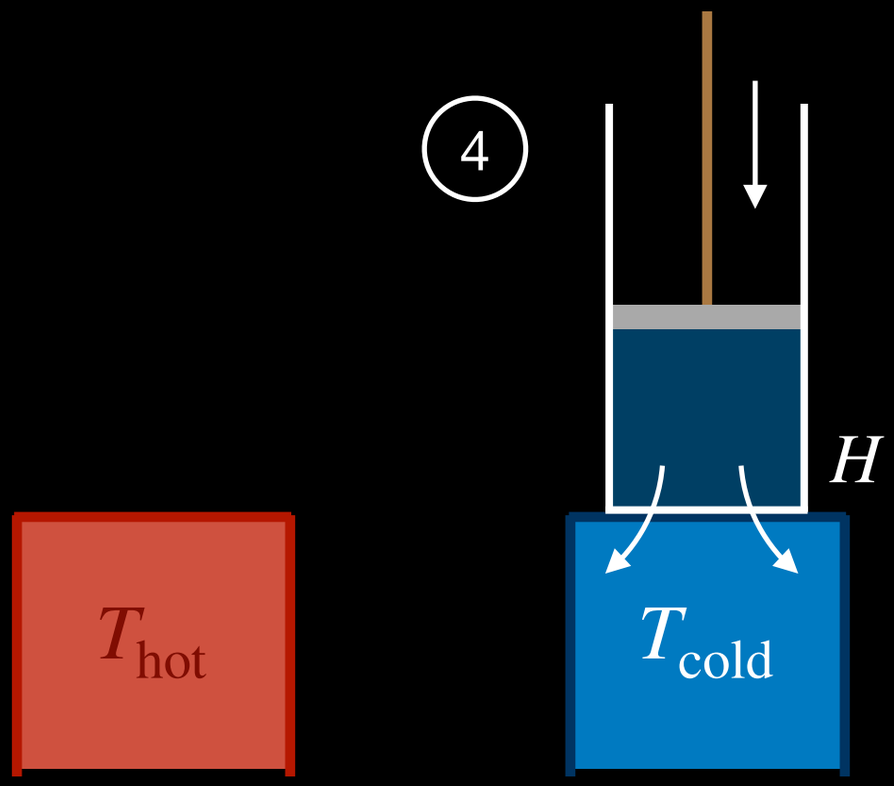
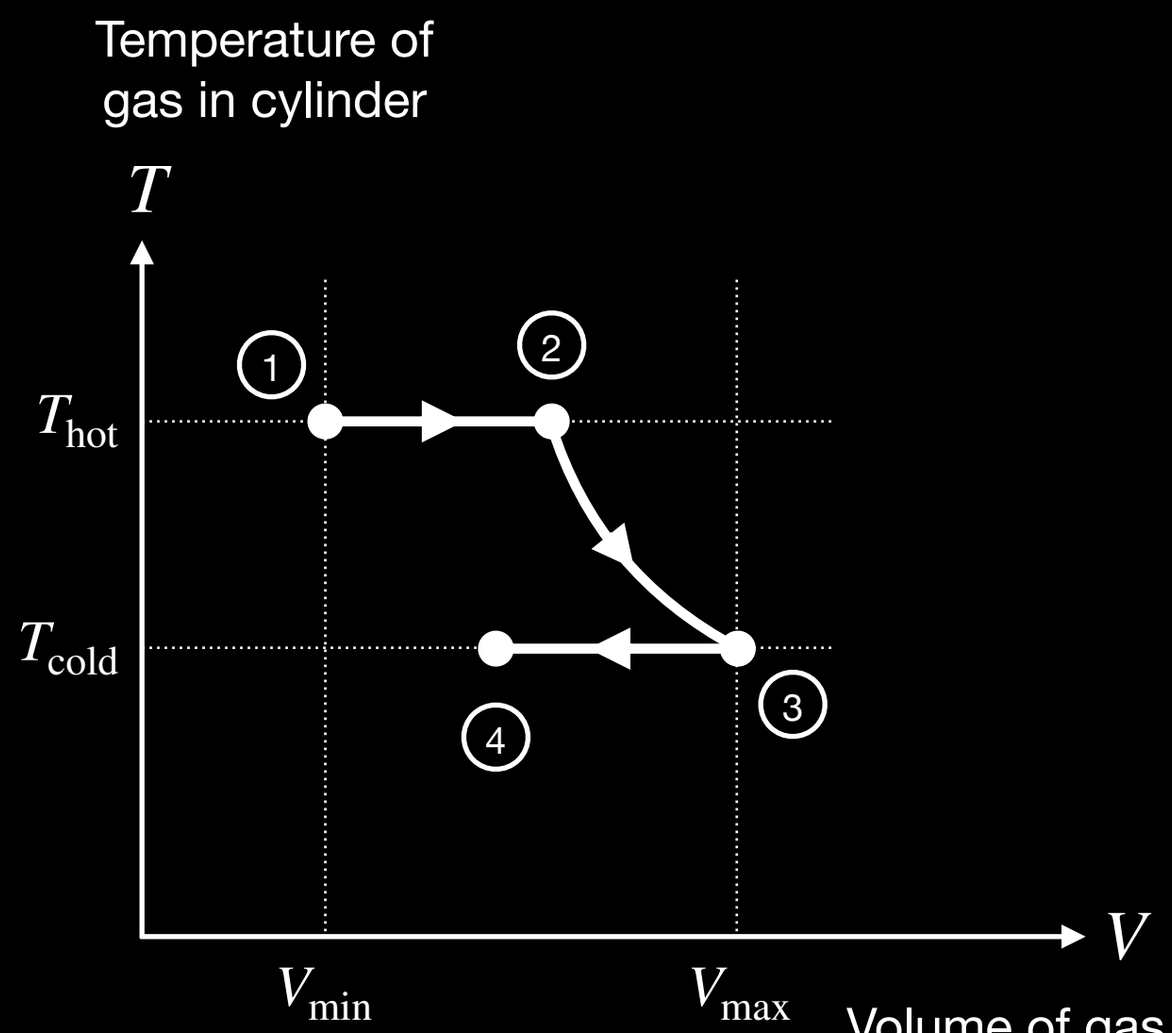


Fig. 1.





Carnot's idealized engine

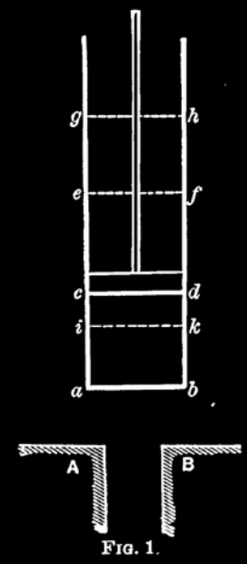
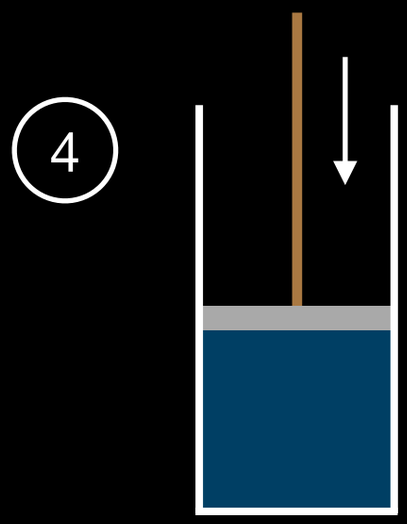


FIG. 1.

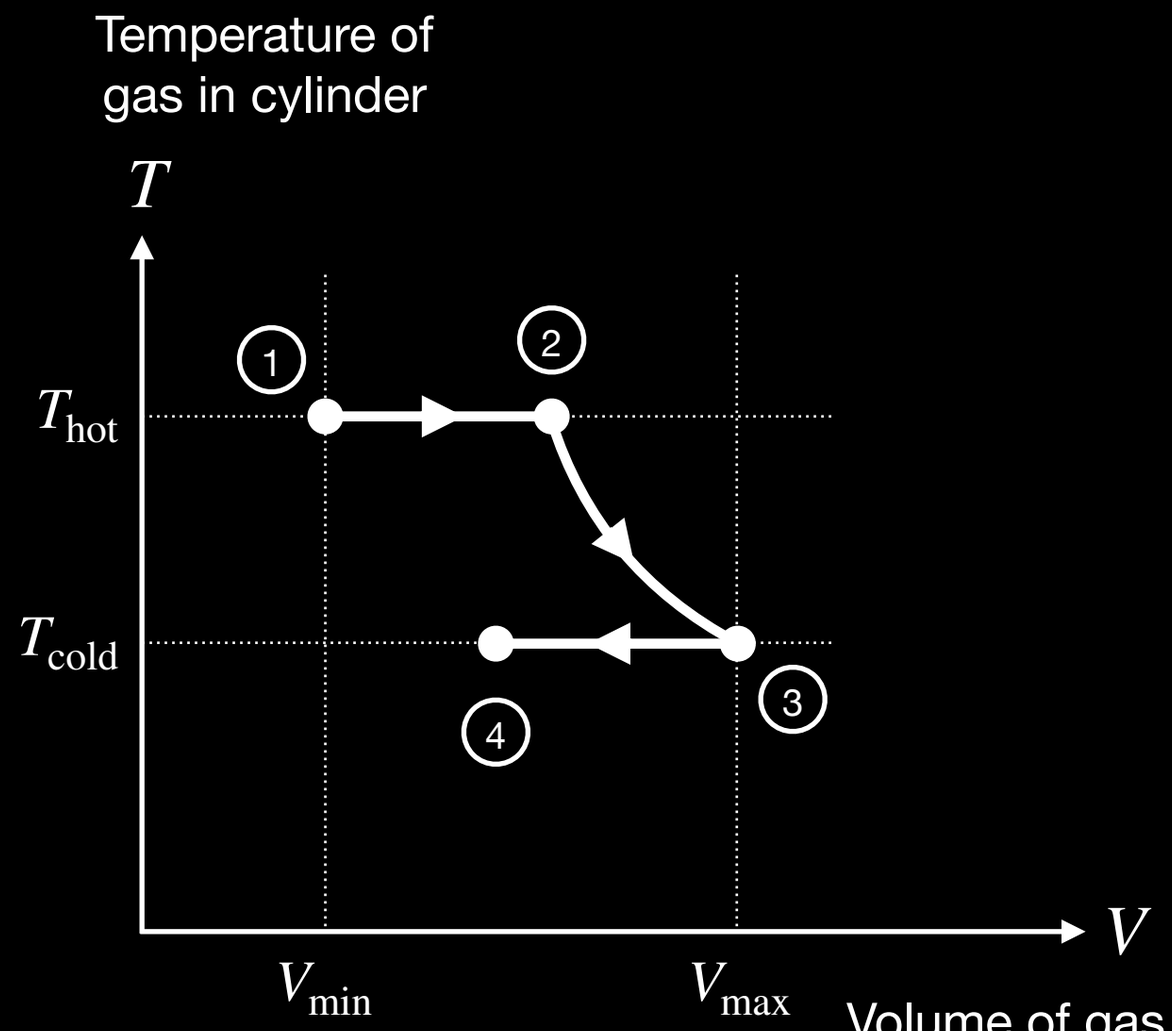


T_{hot}

Hot reservoir

T_{cold}

Cold reservoir



Carnot's idealized engine

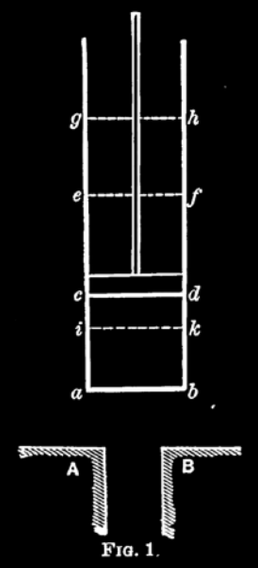
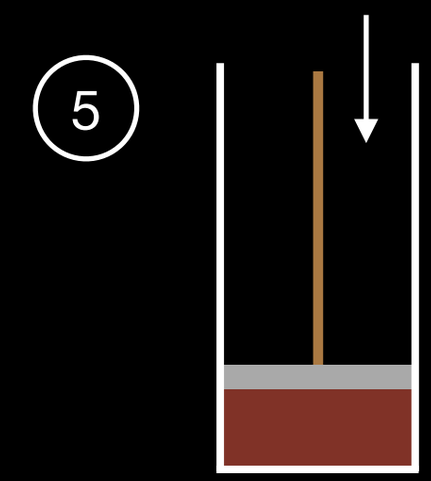


FIG. 1.

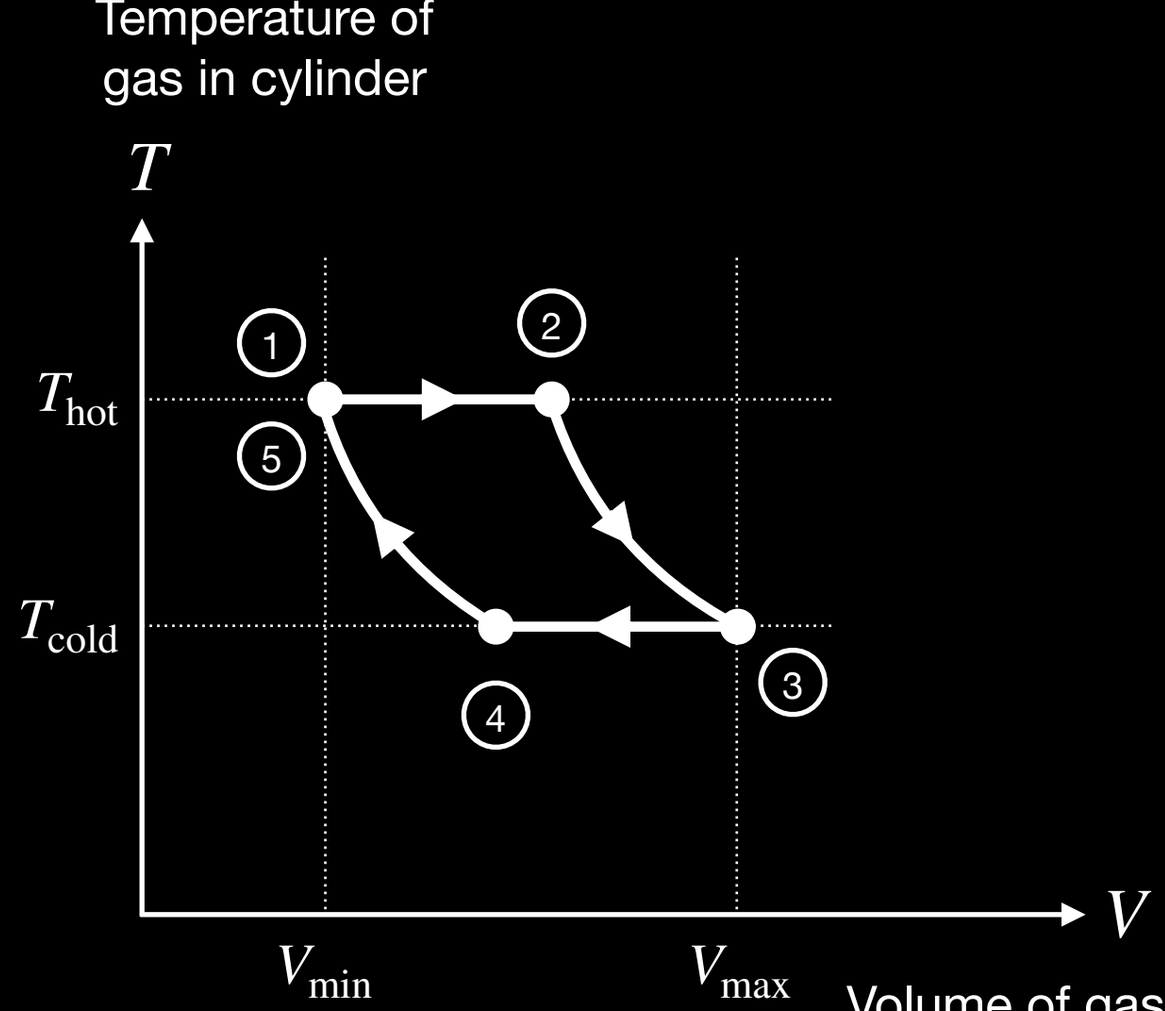


T_{hot}

Hot reservoir

T_{cold}

Cold reservoir



Carnot's idealized engine

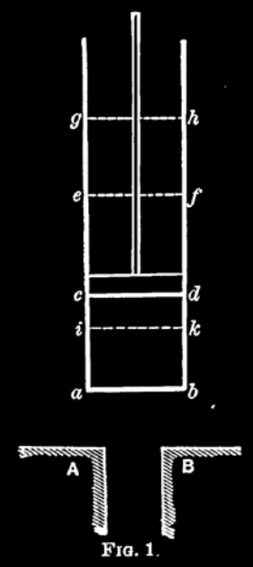
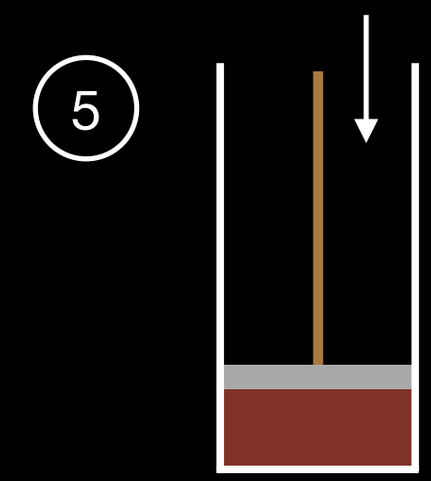


FIG. 1.

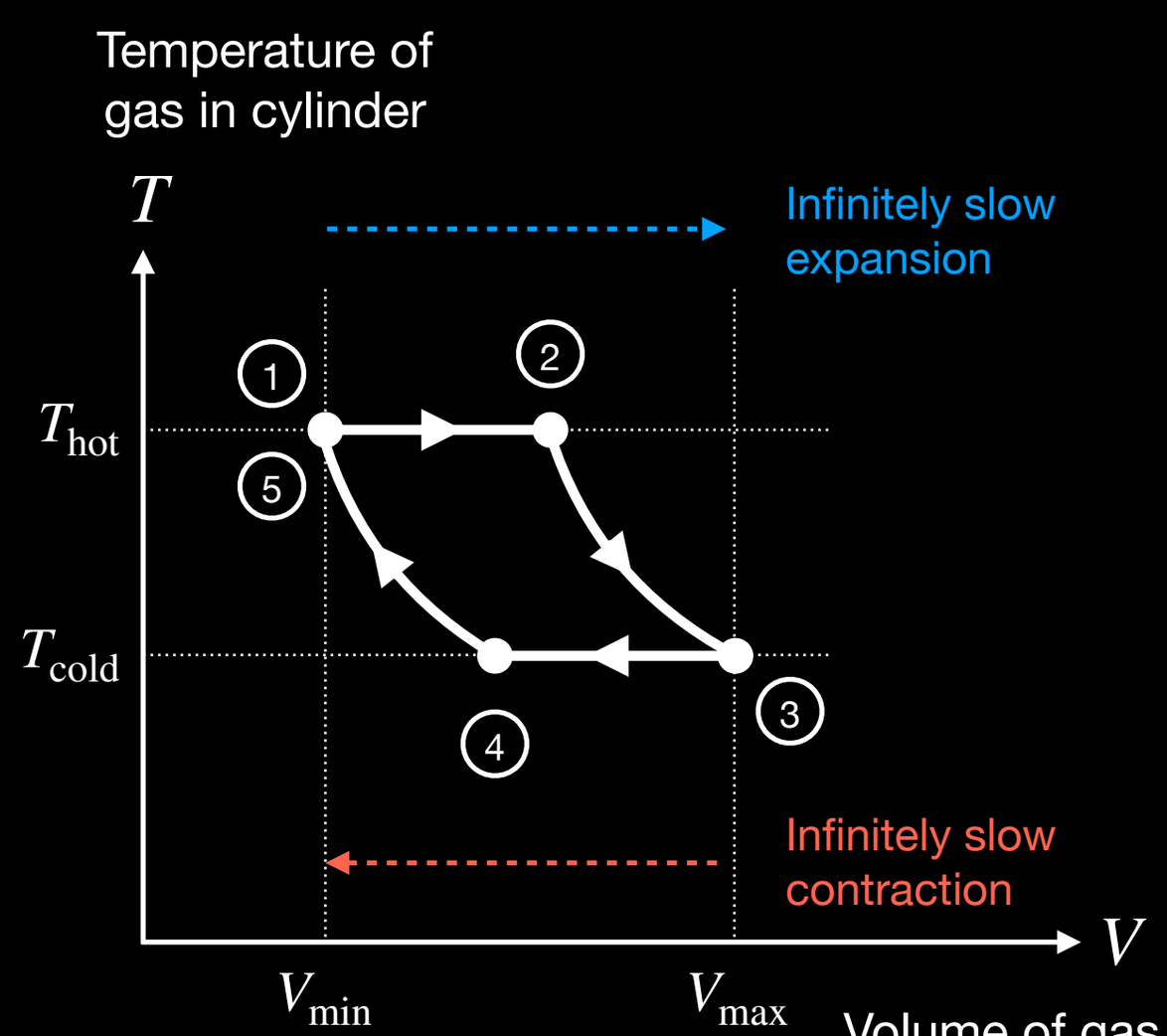


T_{hot}

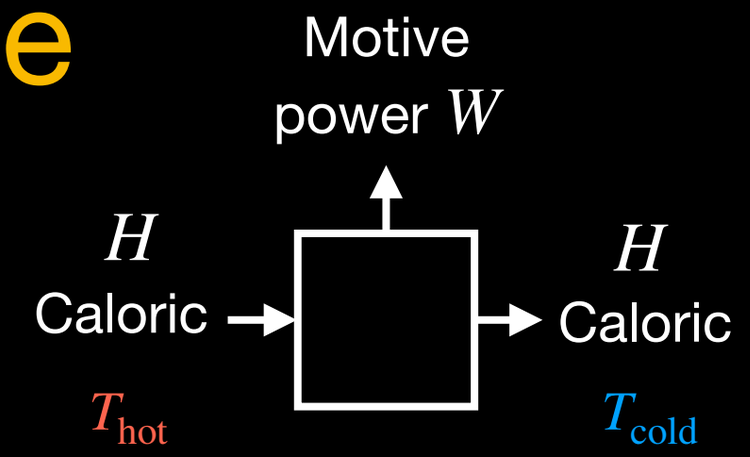
Hot reservoir

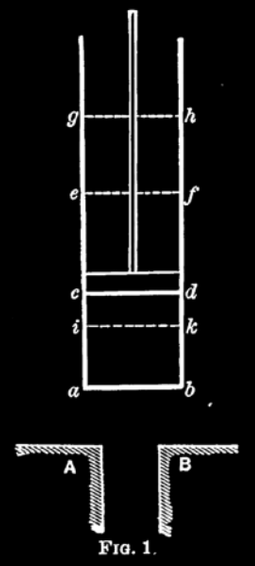
T_{cold}

Cold reservoir



Carnot's idealized engine





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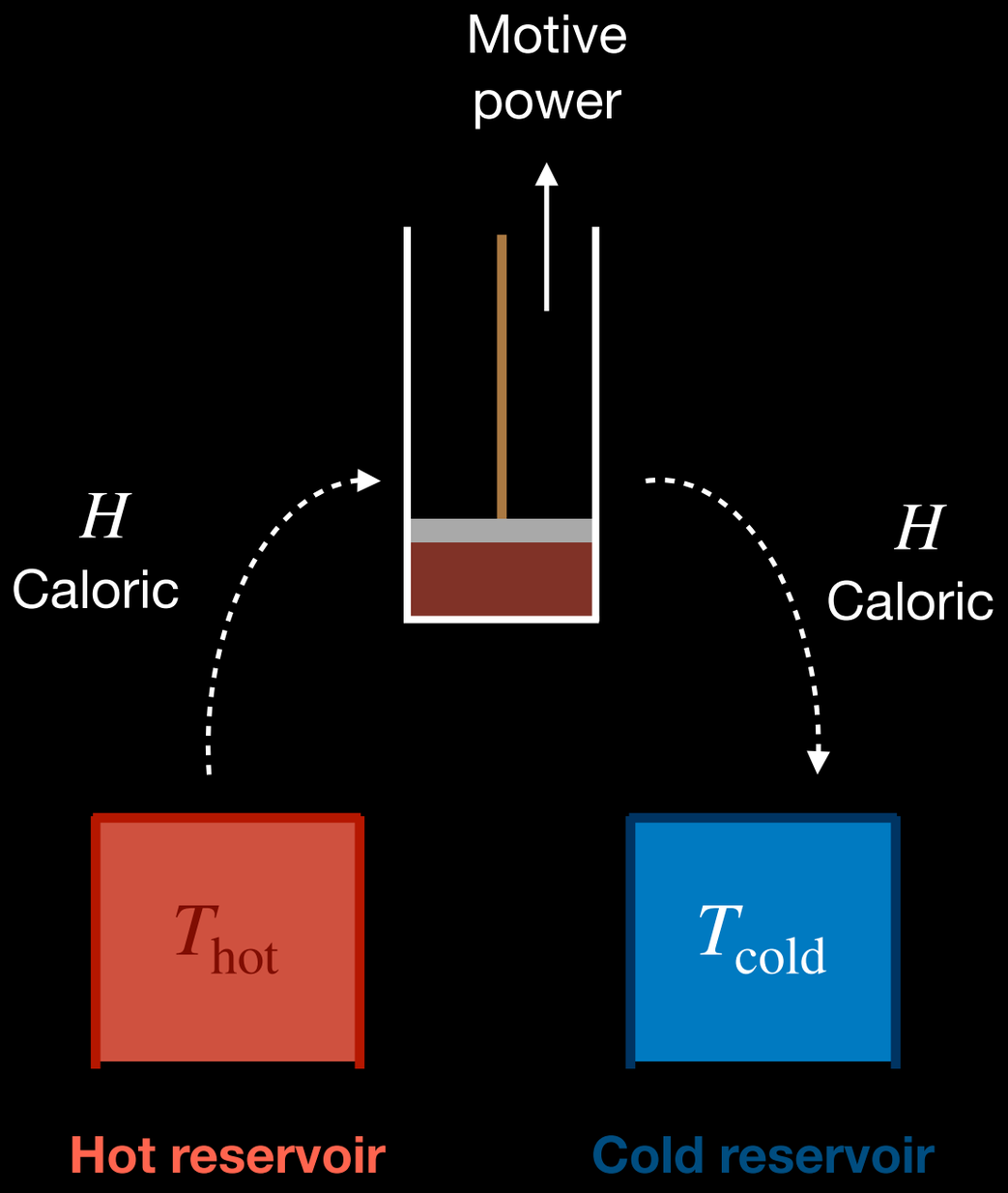
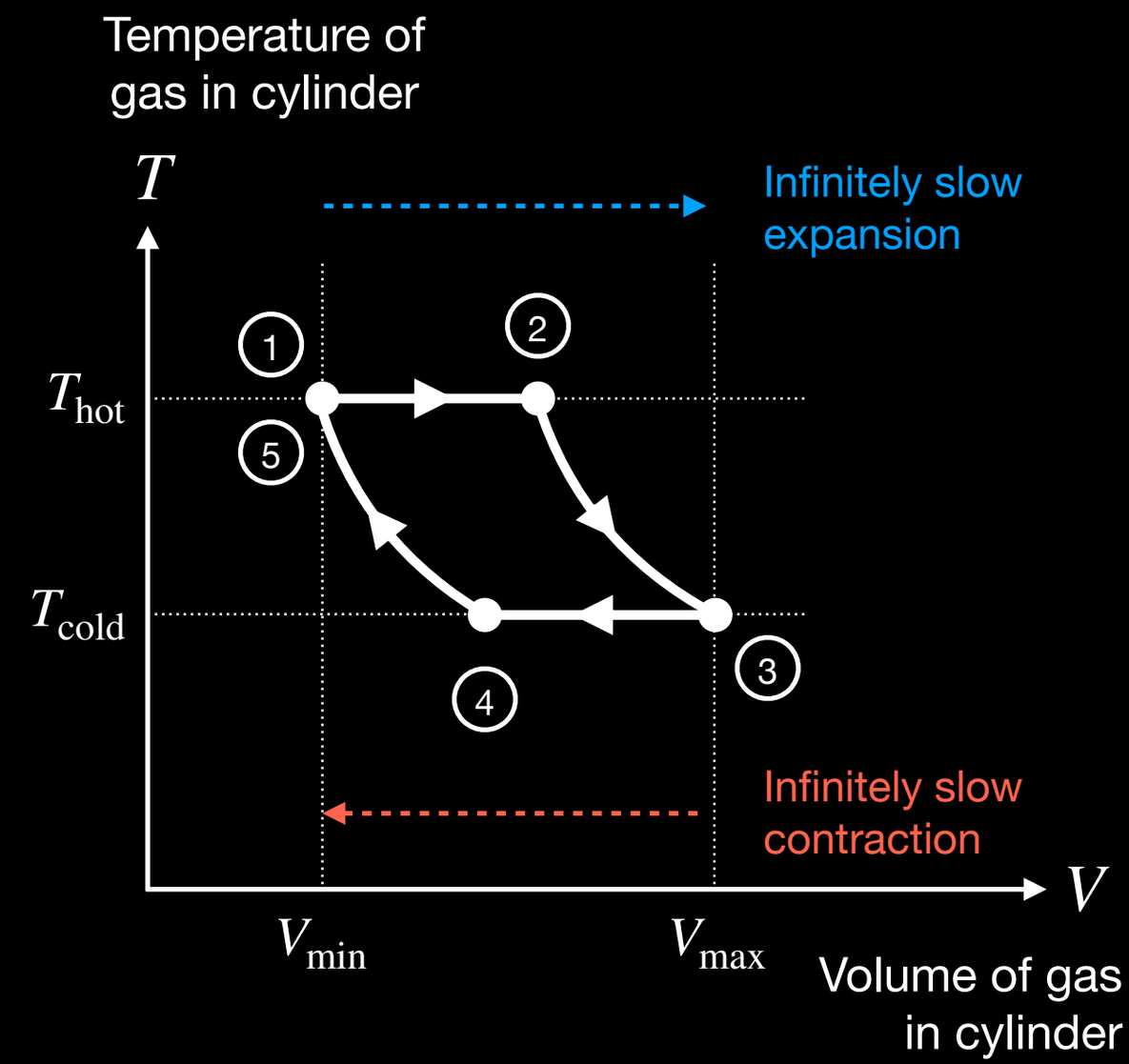
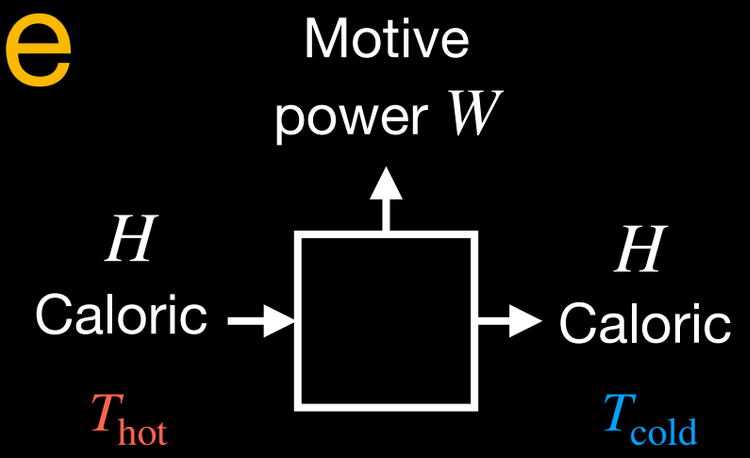
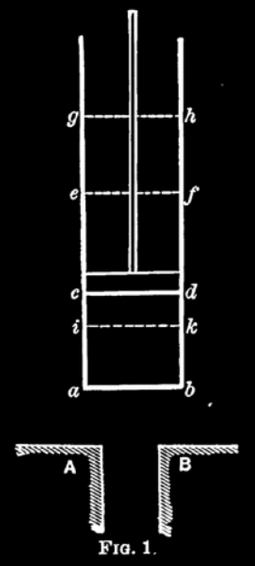




Carnot's idealized engine





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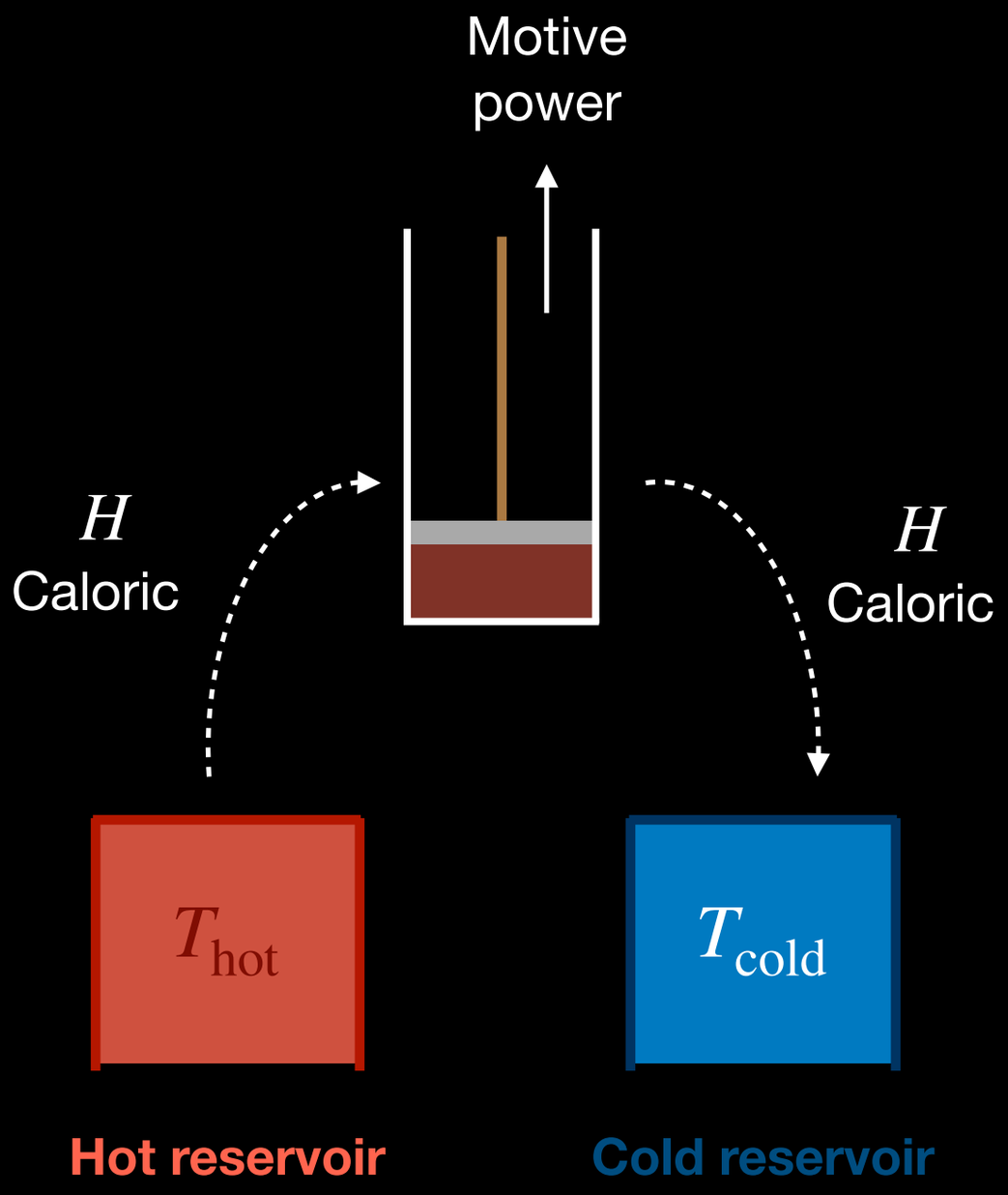
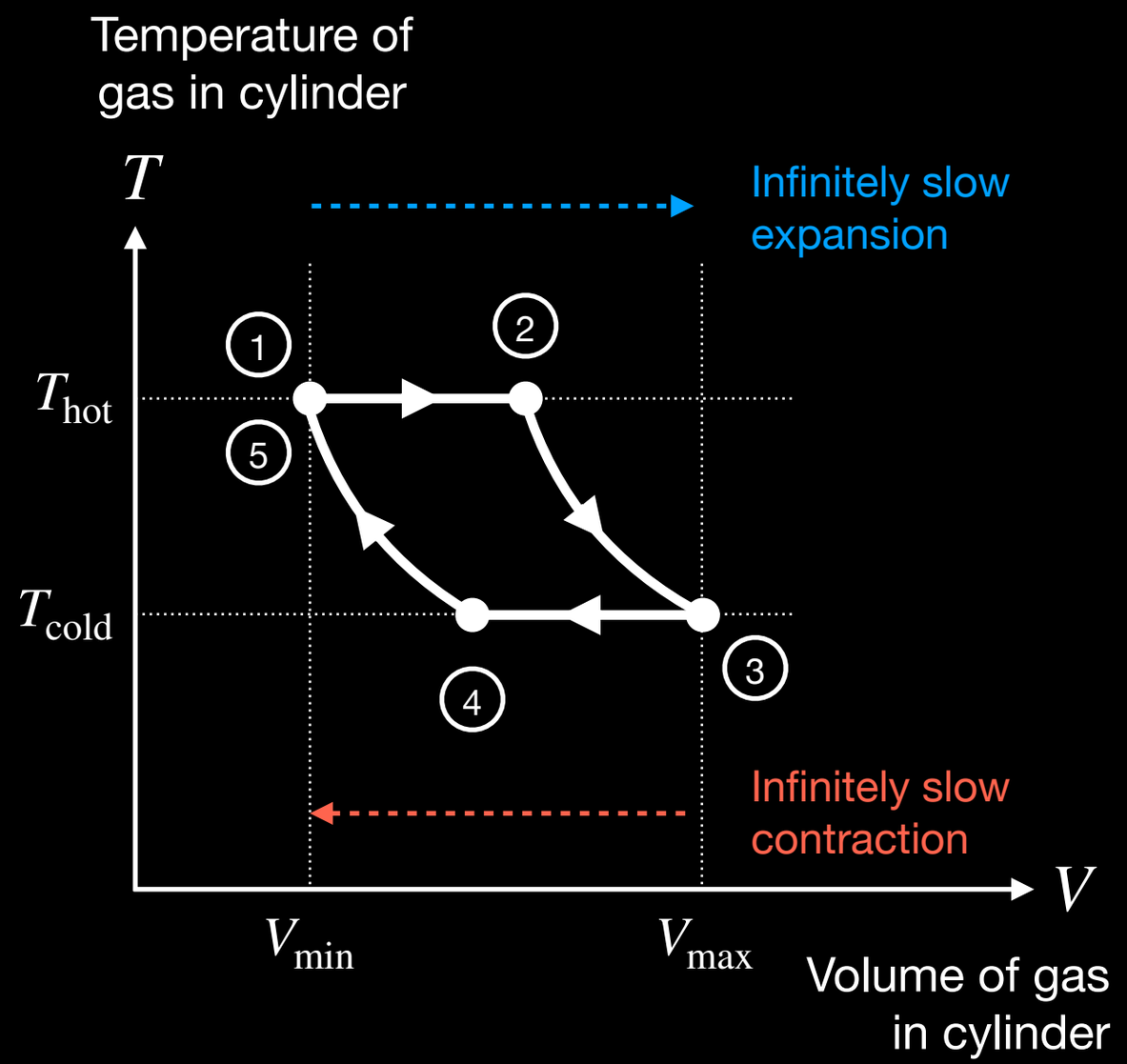




This is the most efficient heat engine of any kind!

Carnot’s idealized heat pump

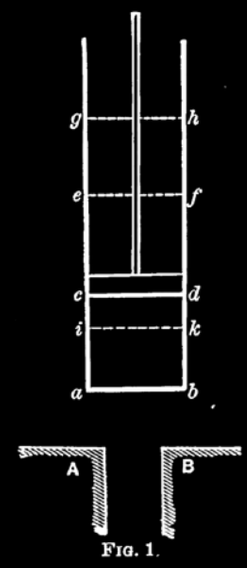
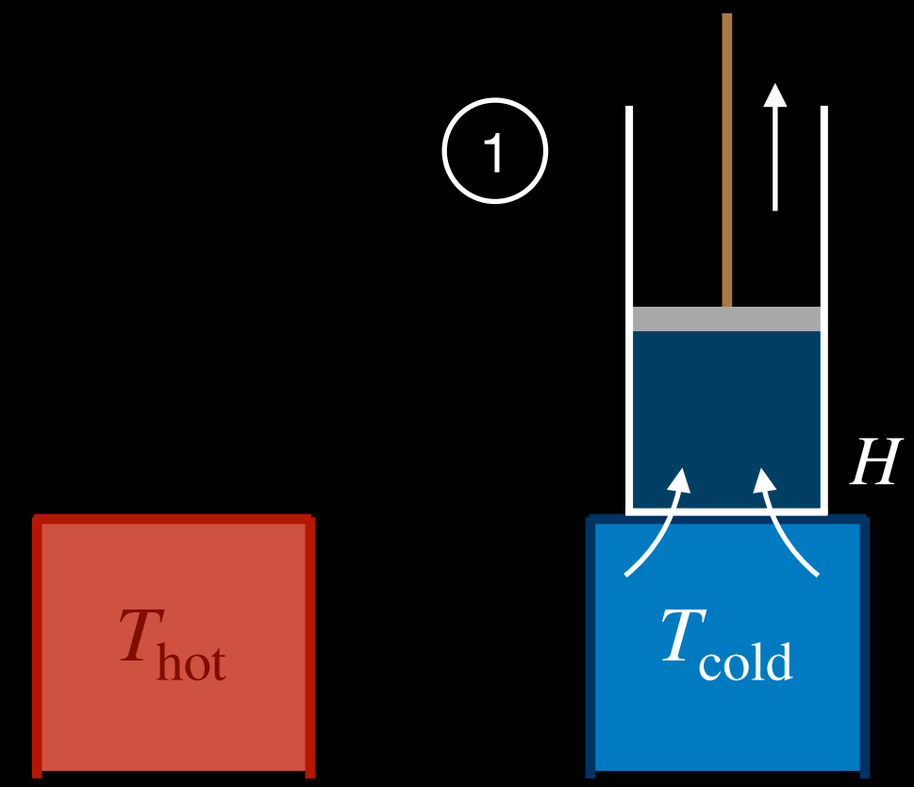


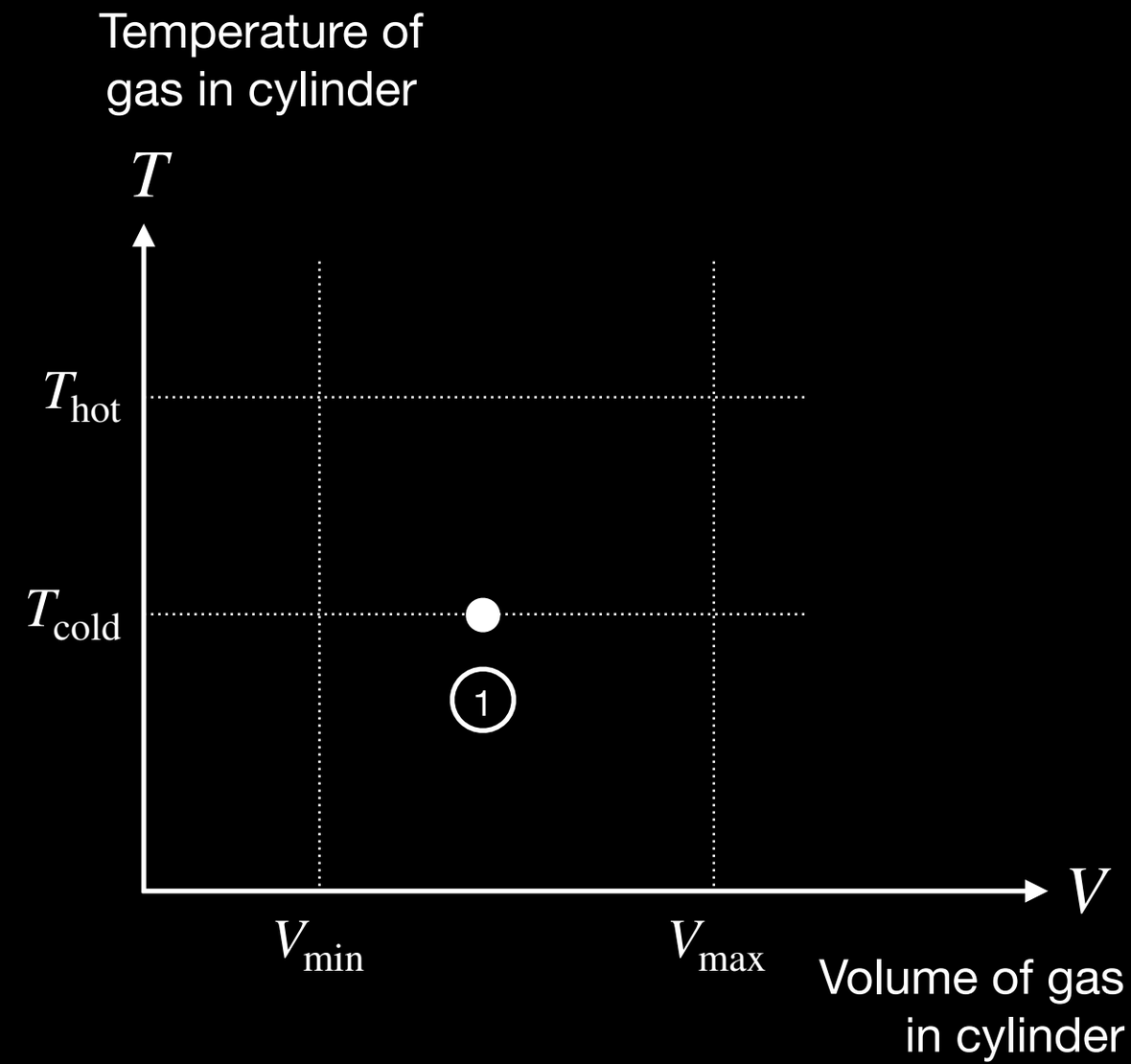
Fig. 1.

Running the engine backwards gives a heat pump!

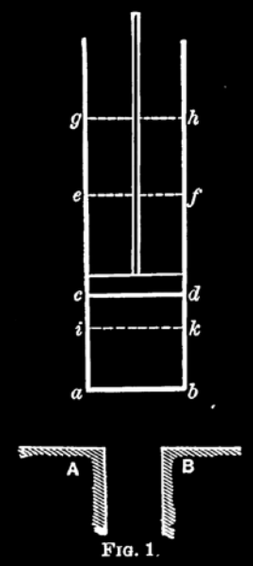


Hot reservoir

Cold reservoir



Carnot's idealized heat pump



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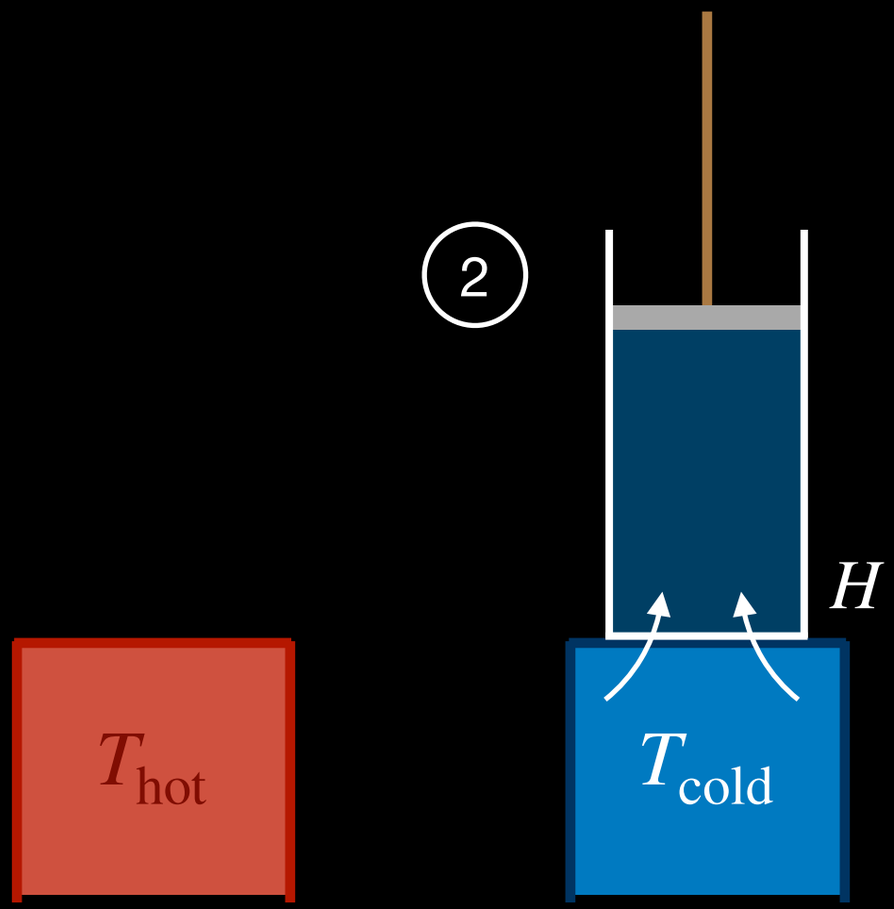
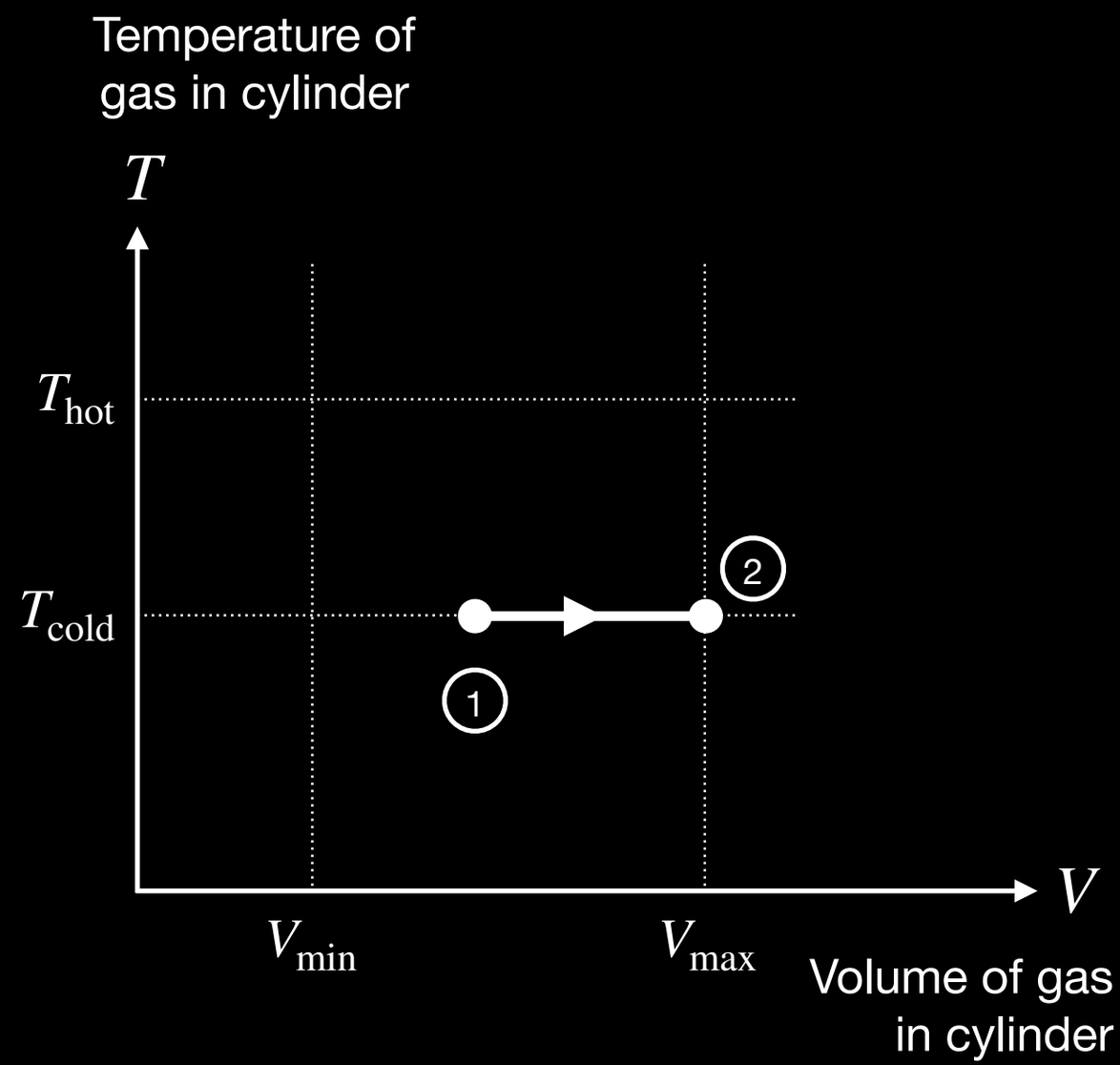
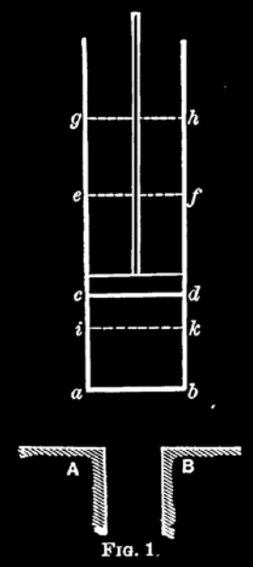
Running the engine backwards gives a heat pump!



Hot reservoir **Cold reservoir**



Carnot’s idealized heat pump



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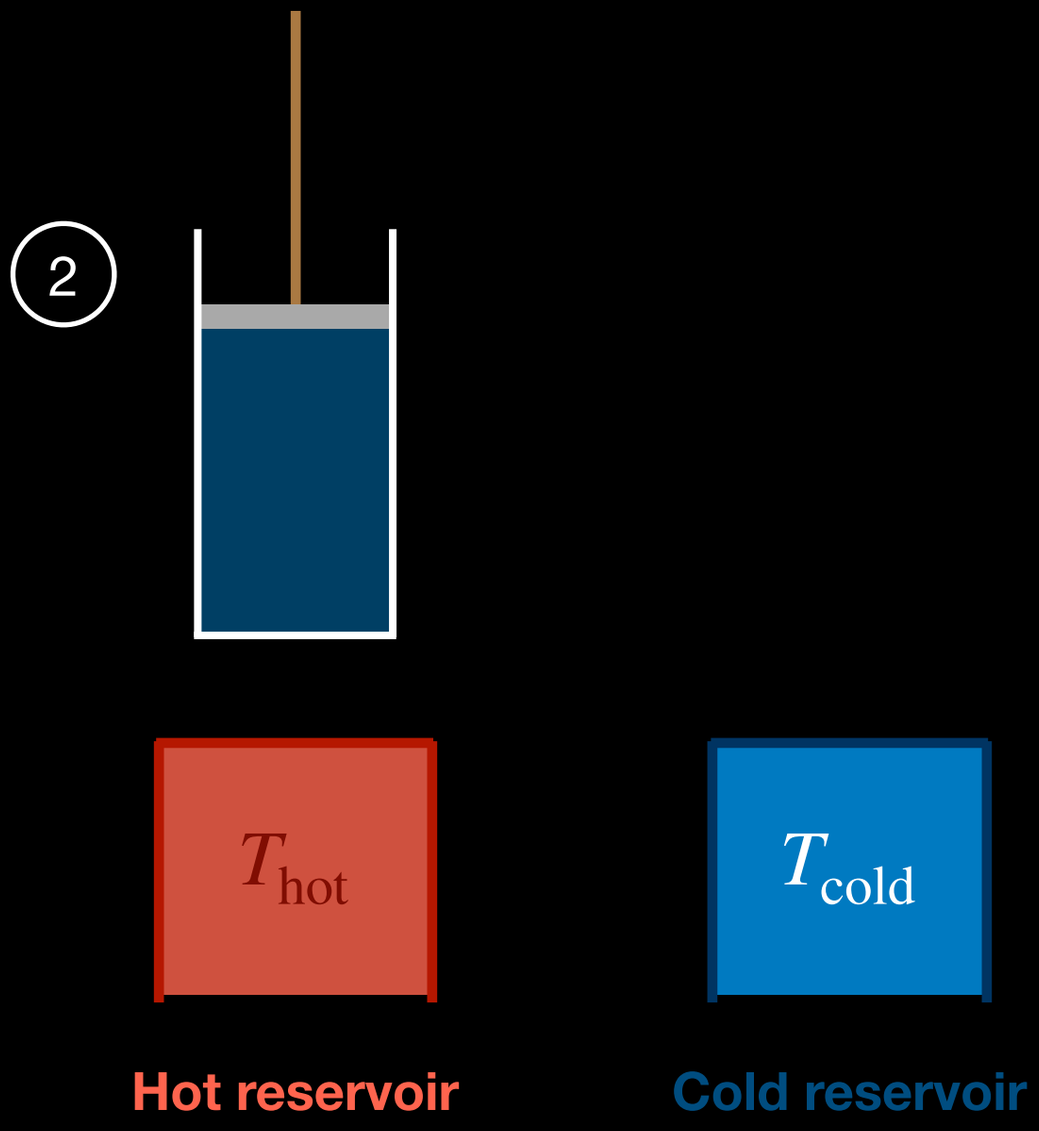
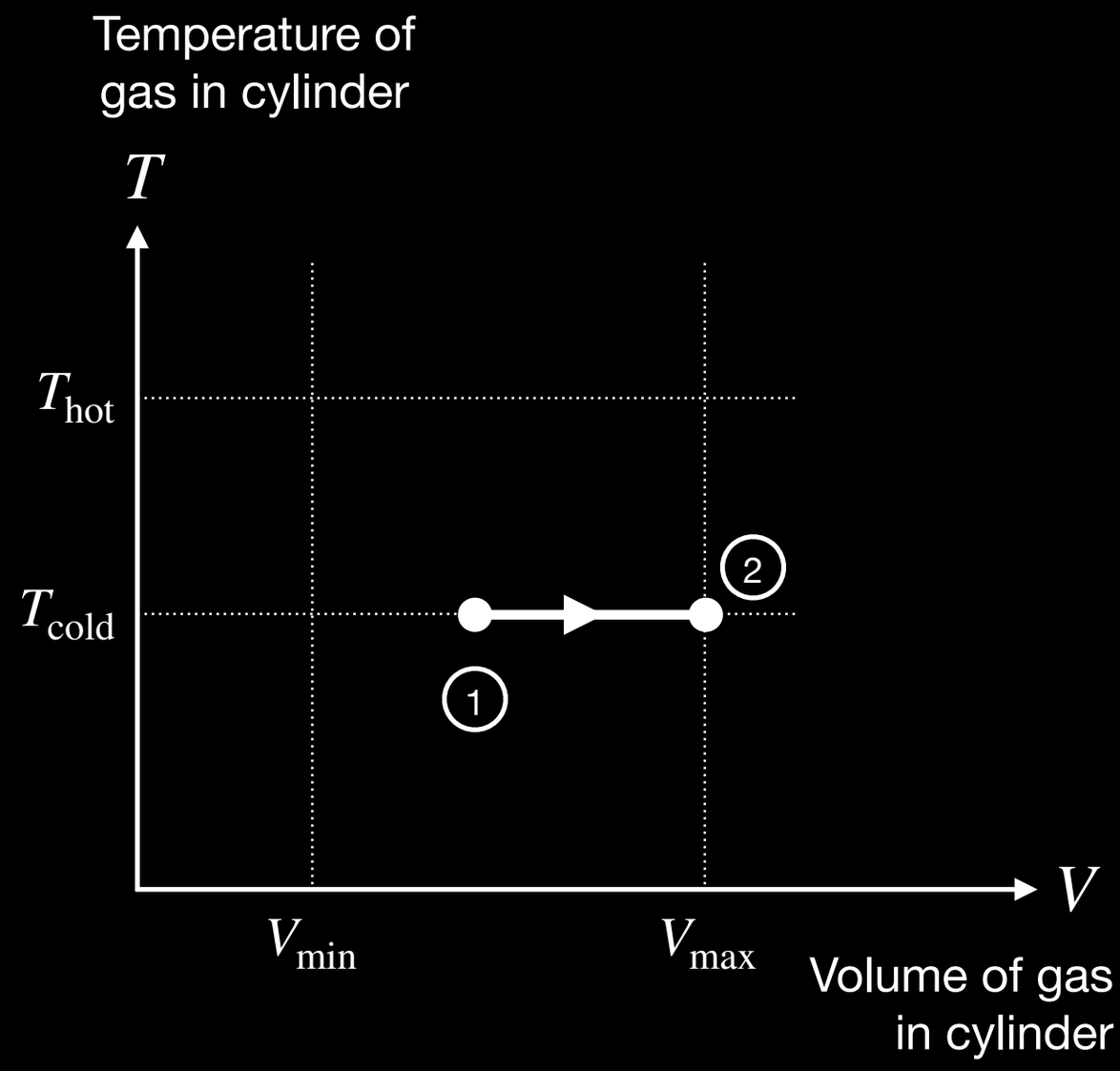
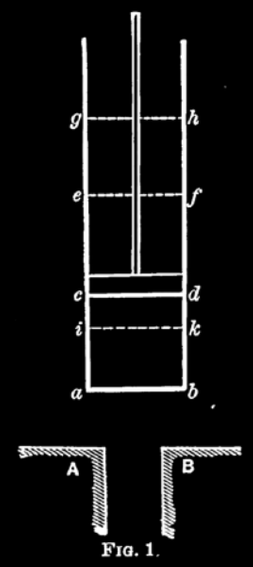


Hot reservoir **Cold reservoir**



Carnot's idealized heat pump



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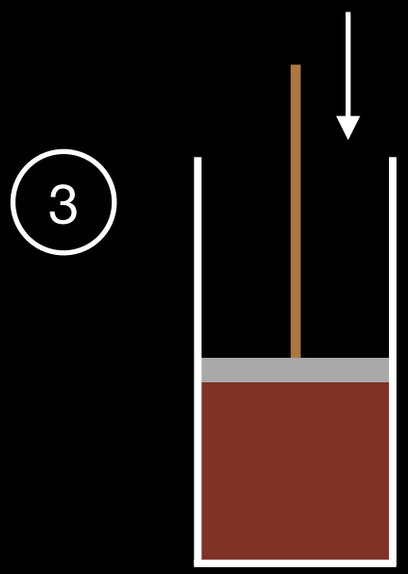
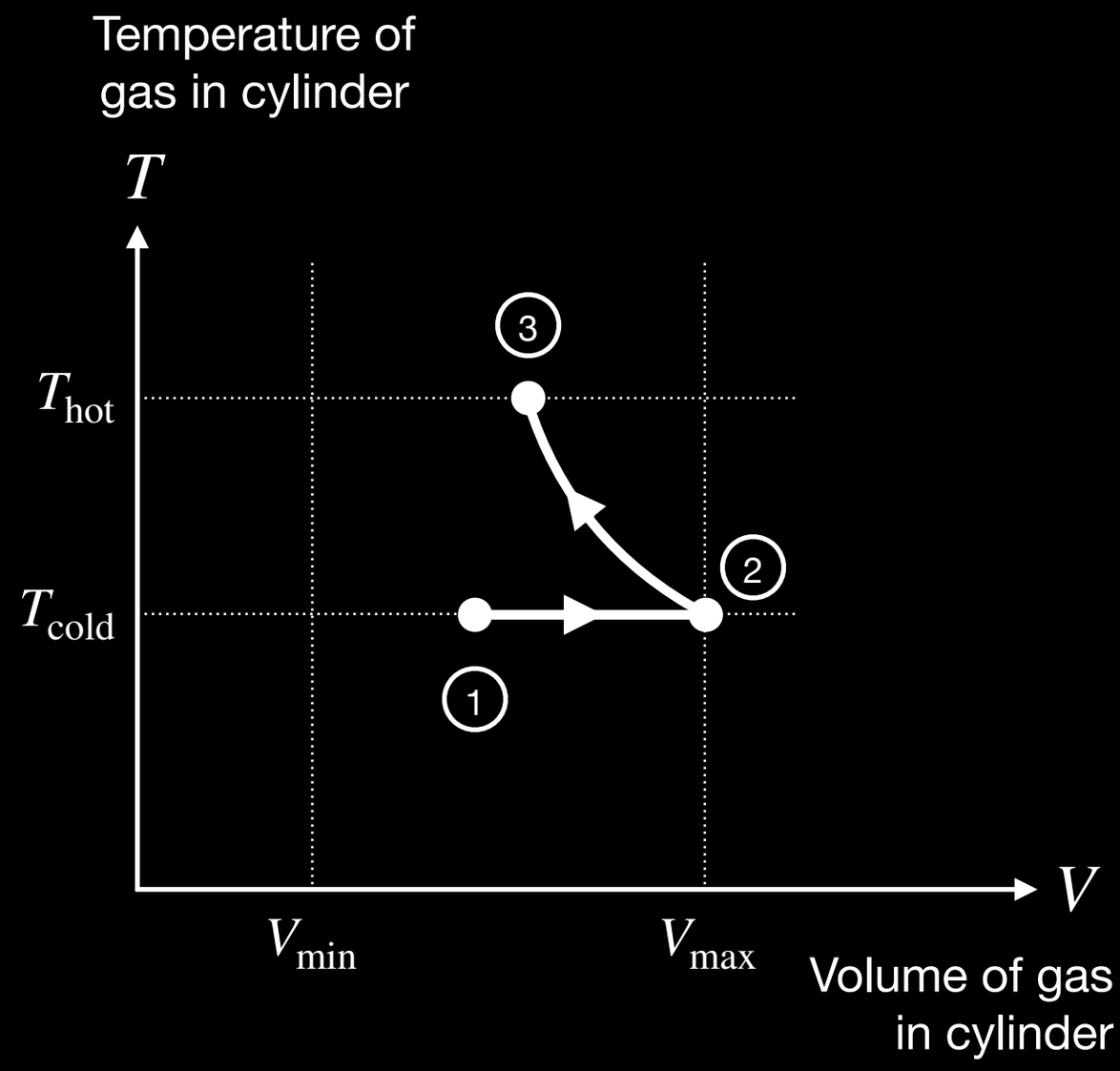


Hot reservoir

Cold reservoir



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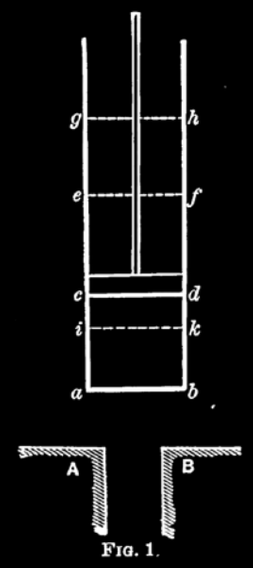

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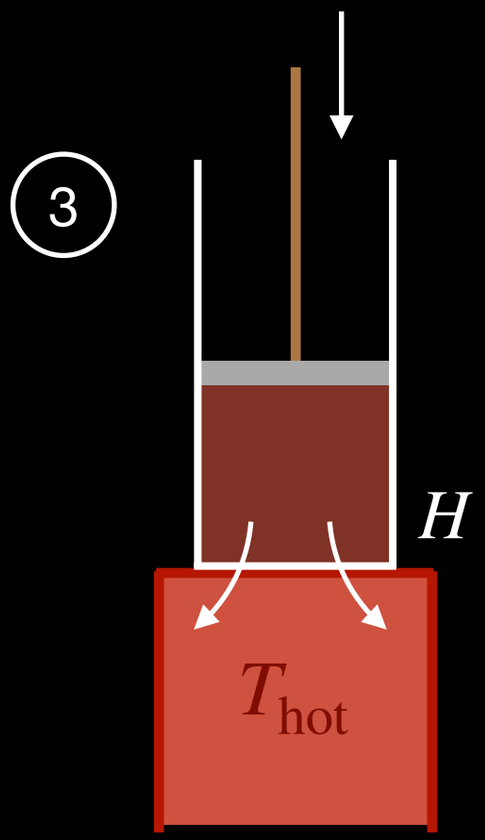
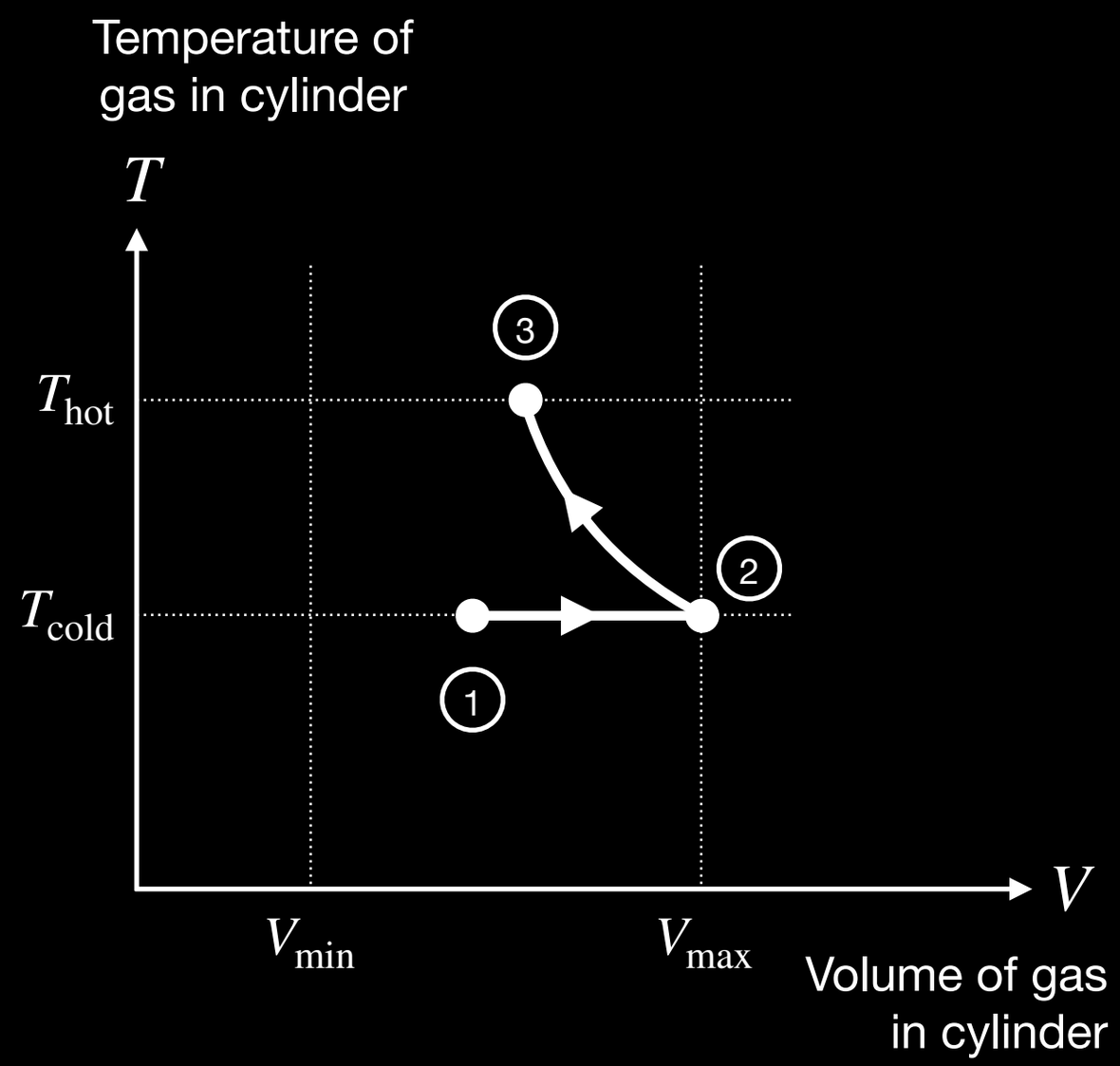


Hot reservoir

Cold reservoir



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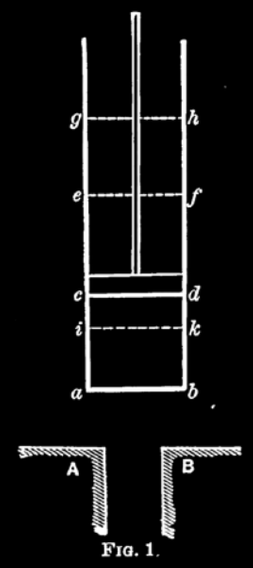

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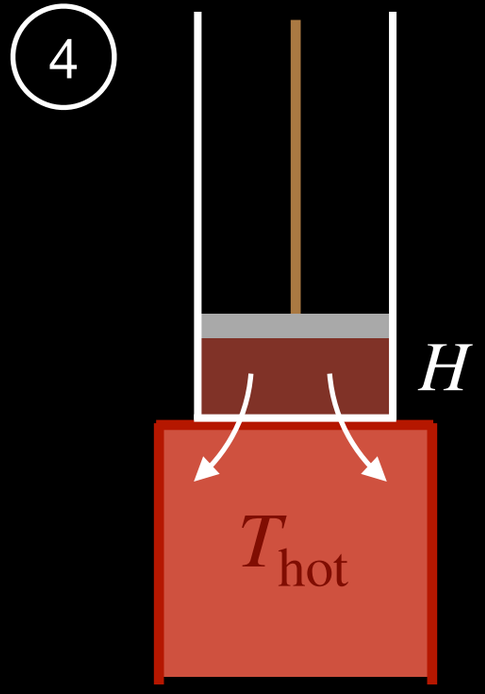

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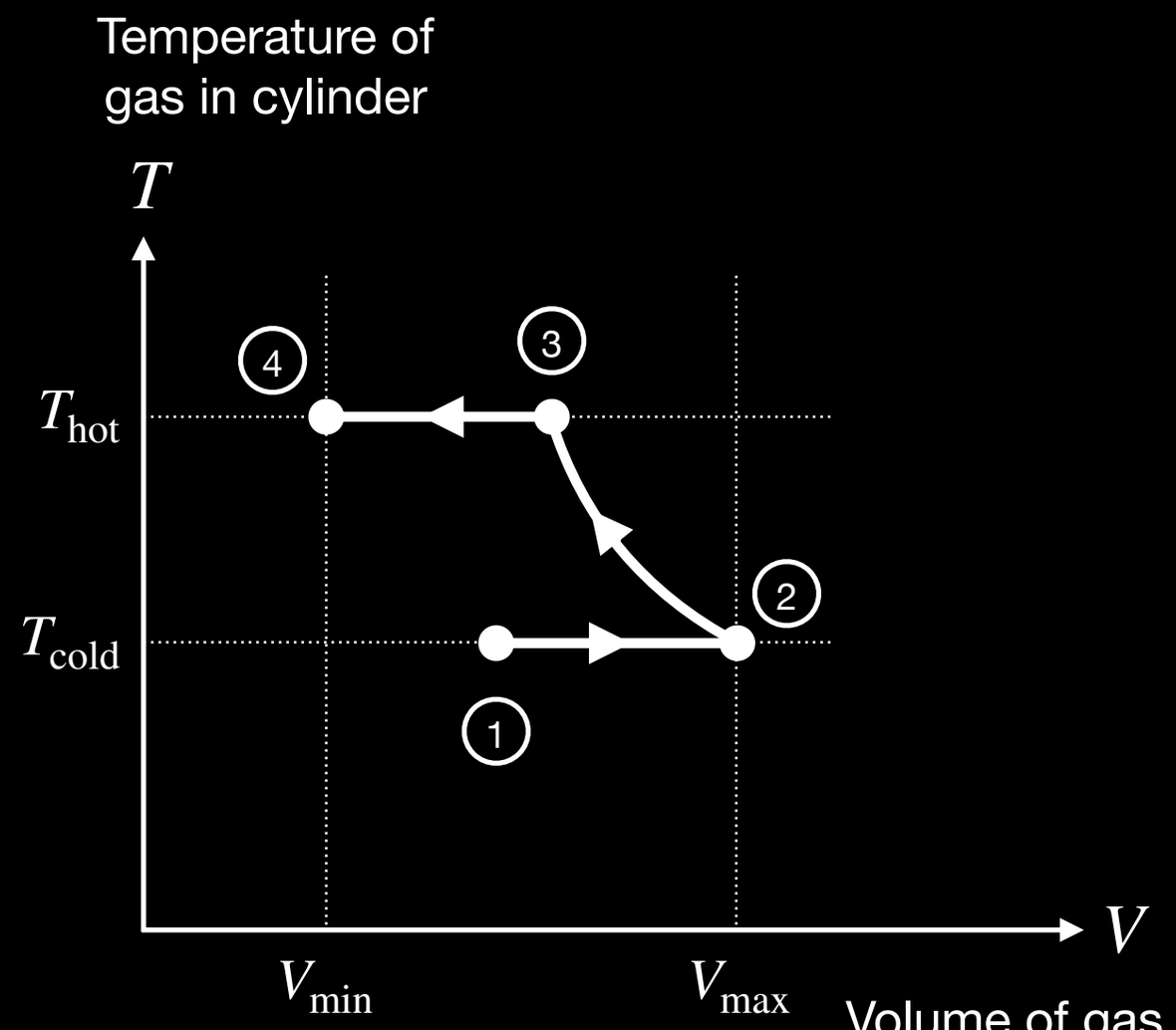

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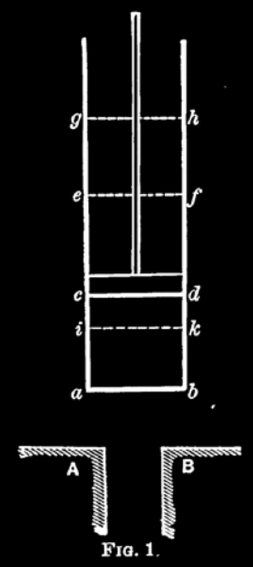

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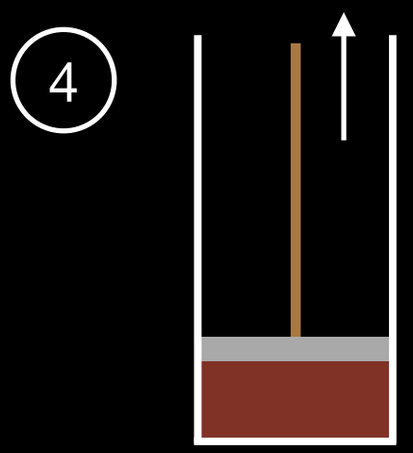

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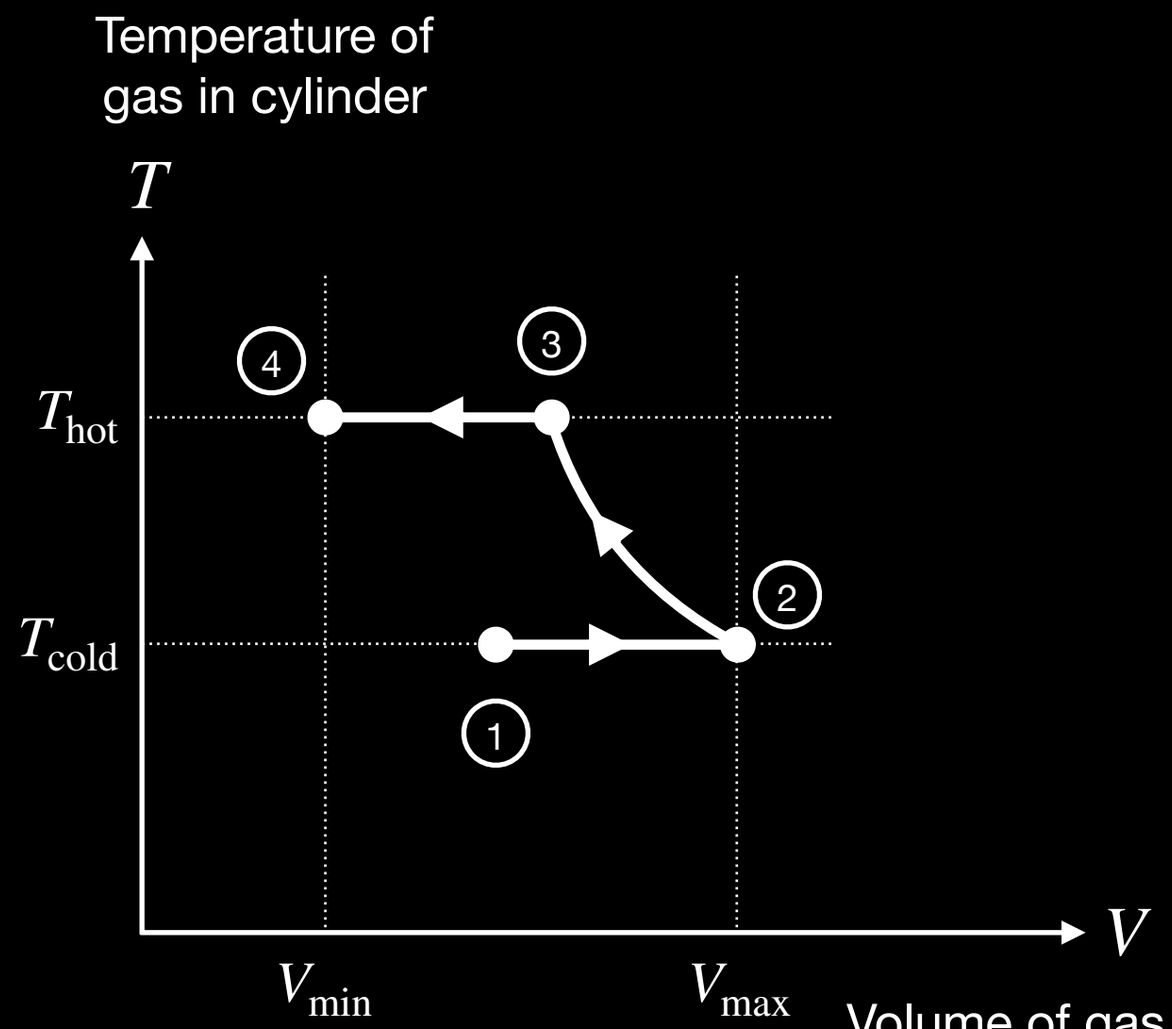

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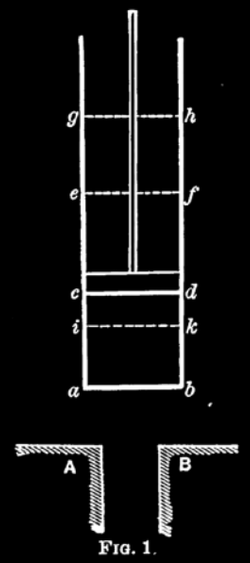

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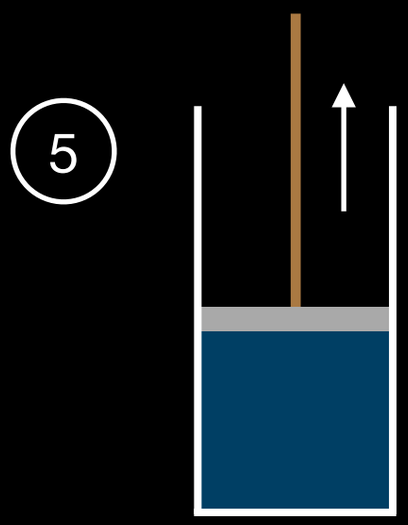

T_{hot}

Hot reservoir

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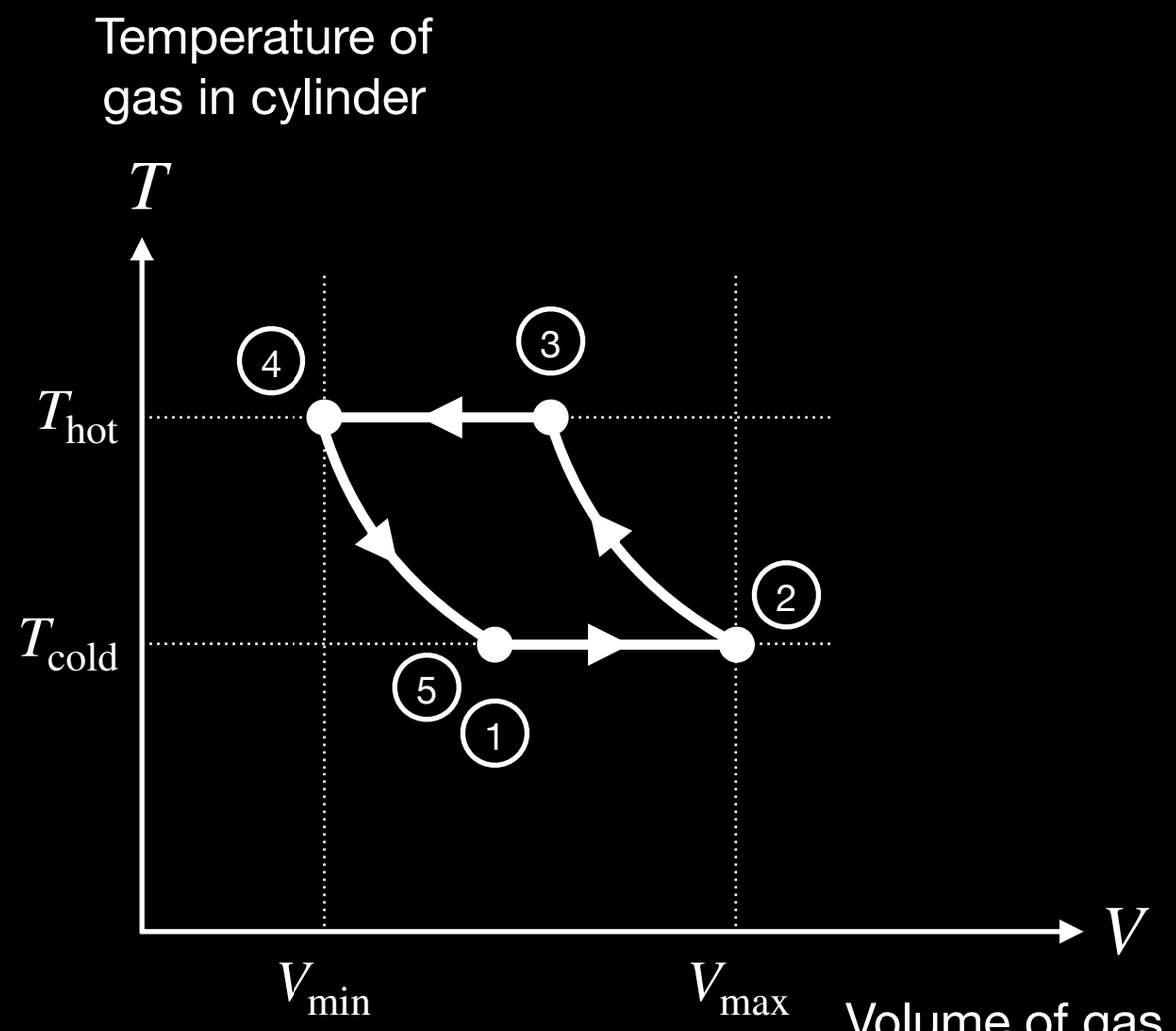

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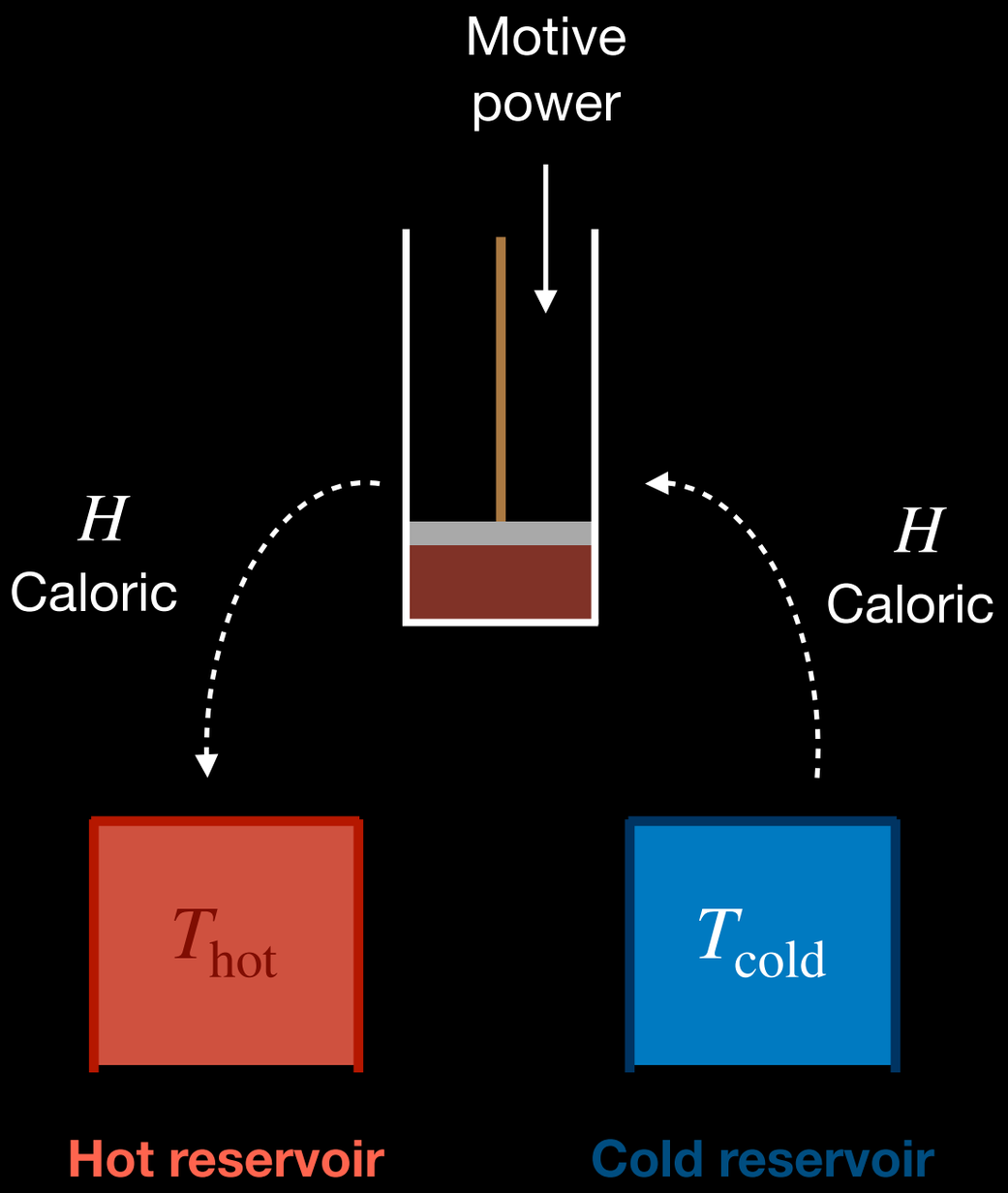
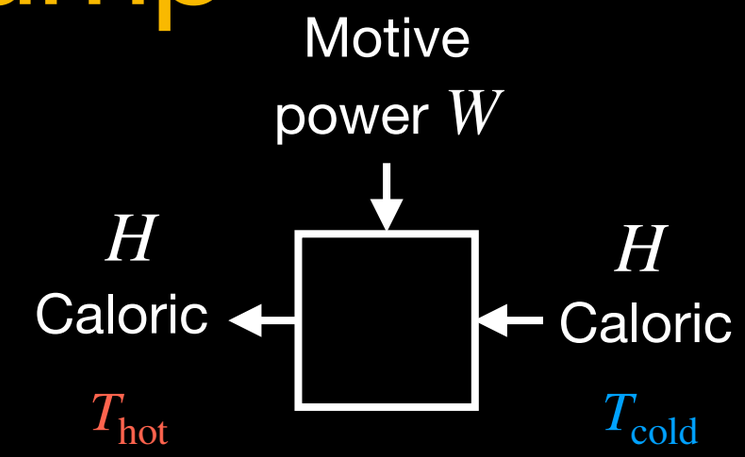
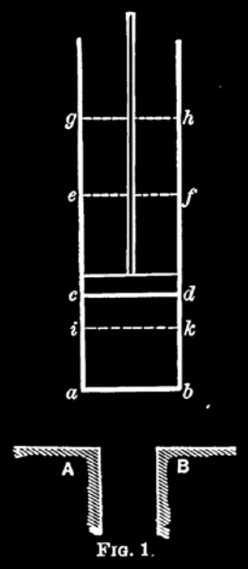
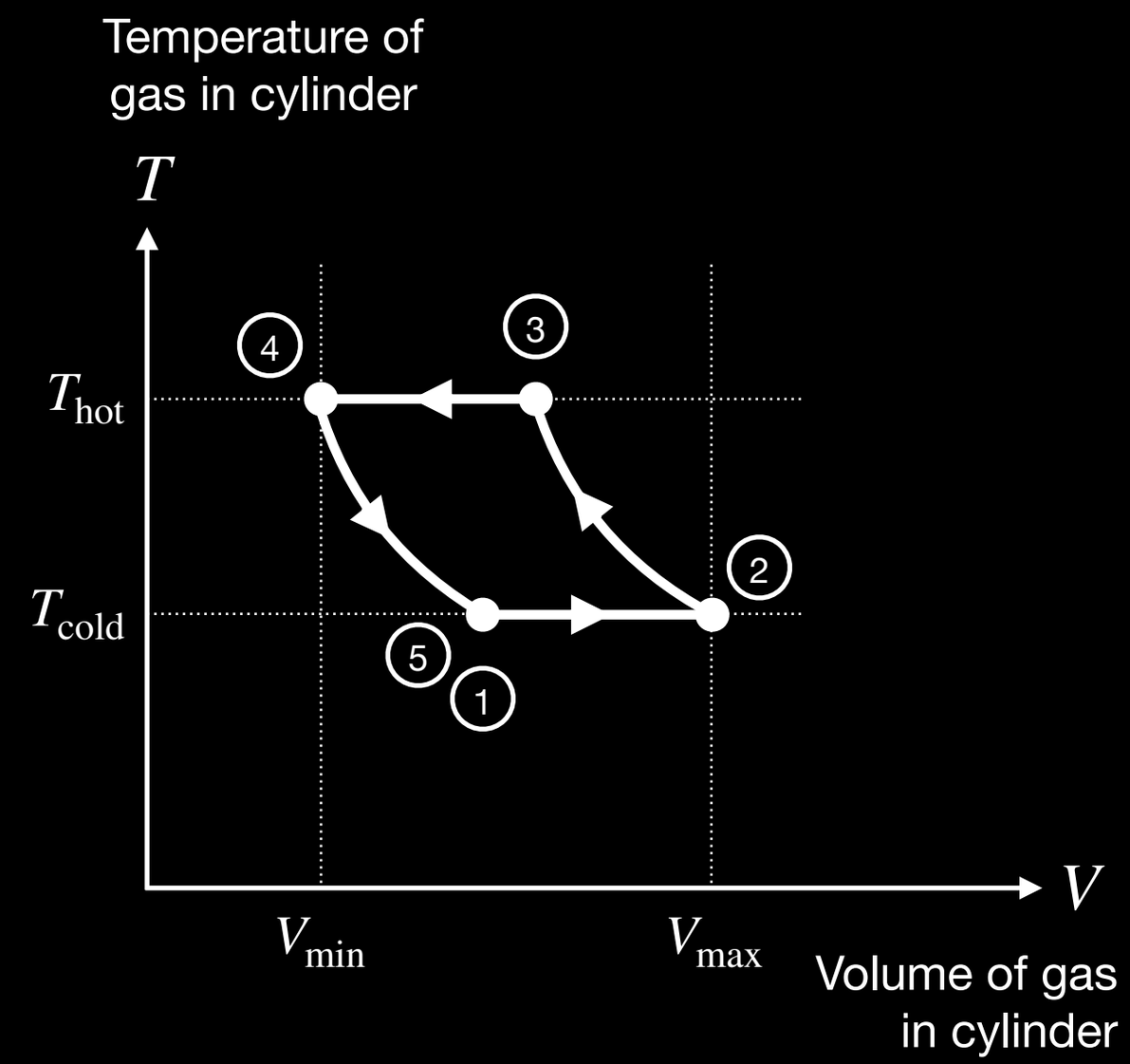
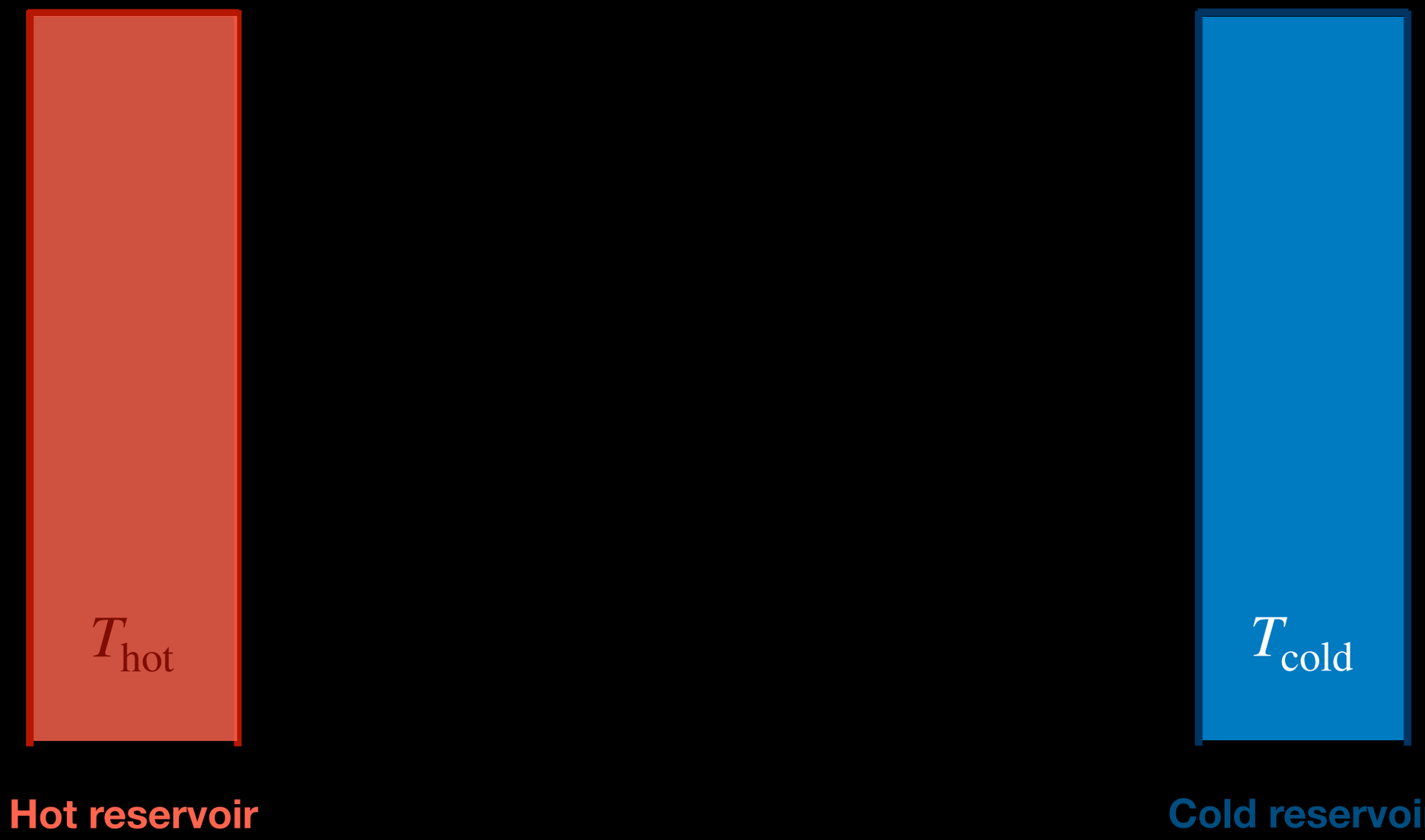








A thought experiment



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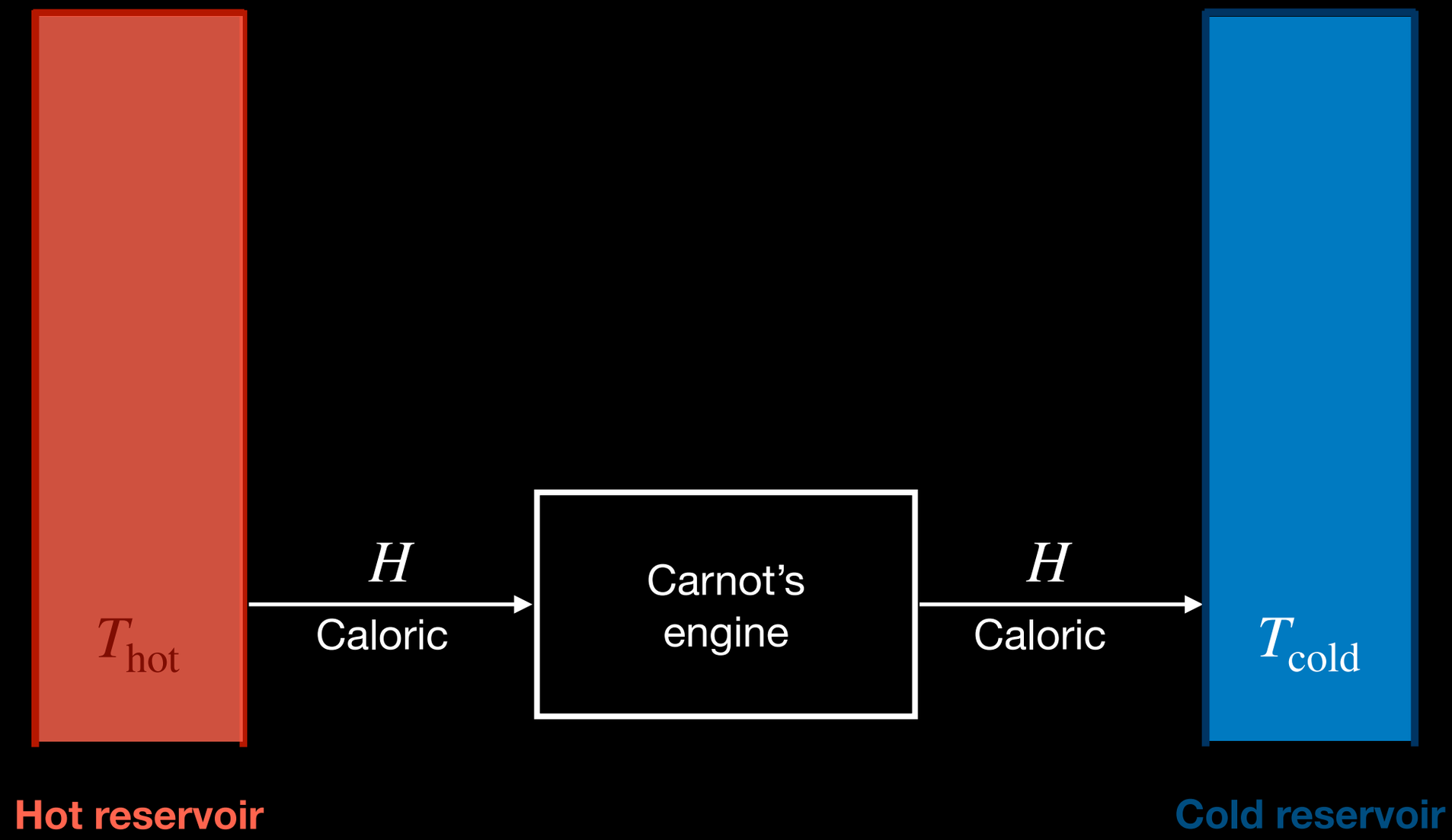

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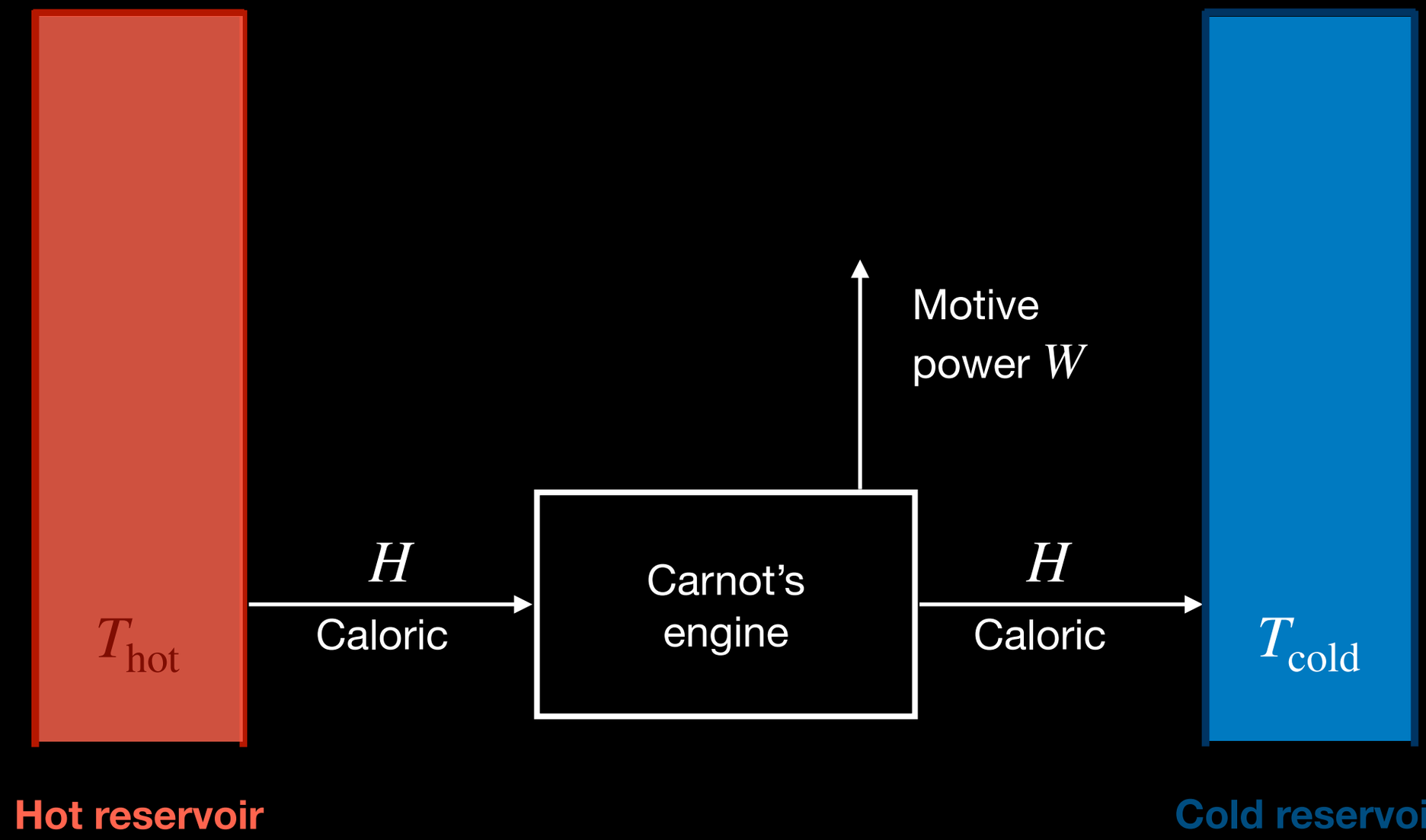

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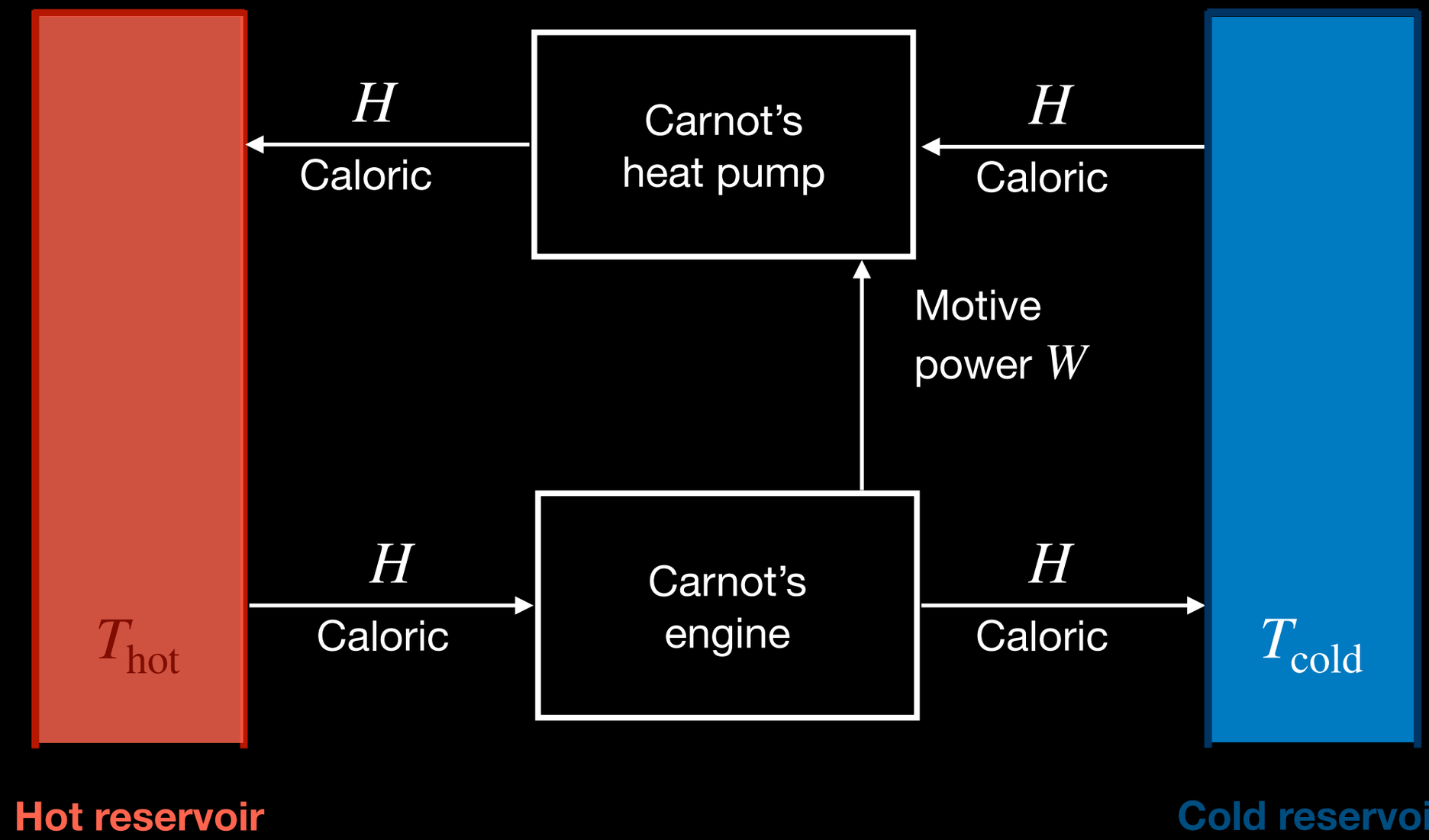

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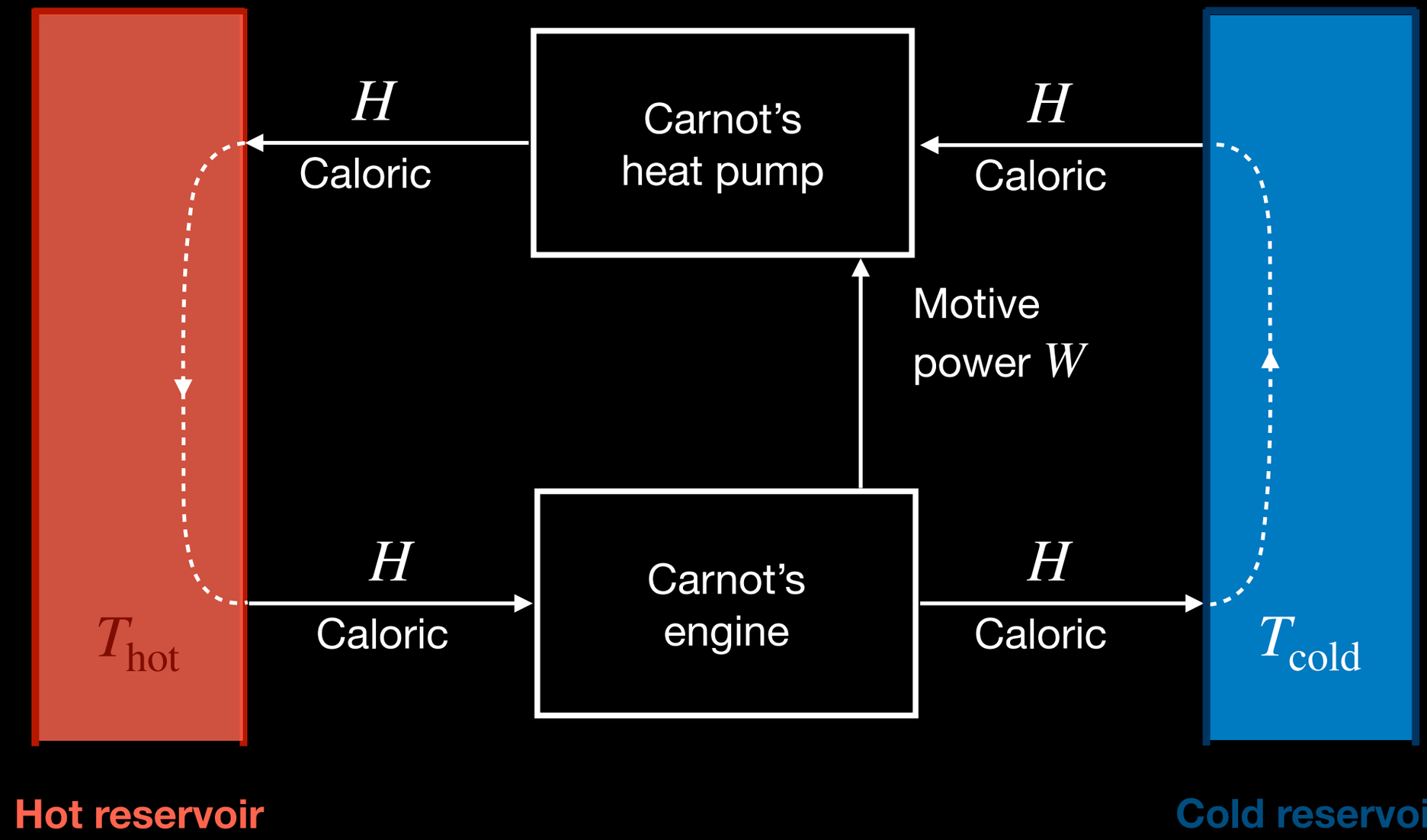

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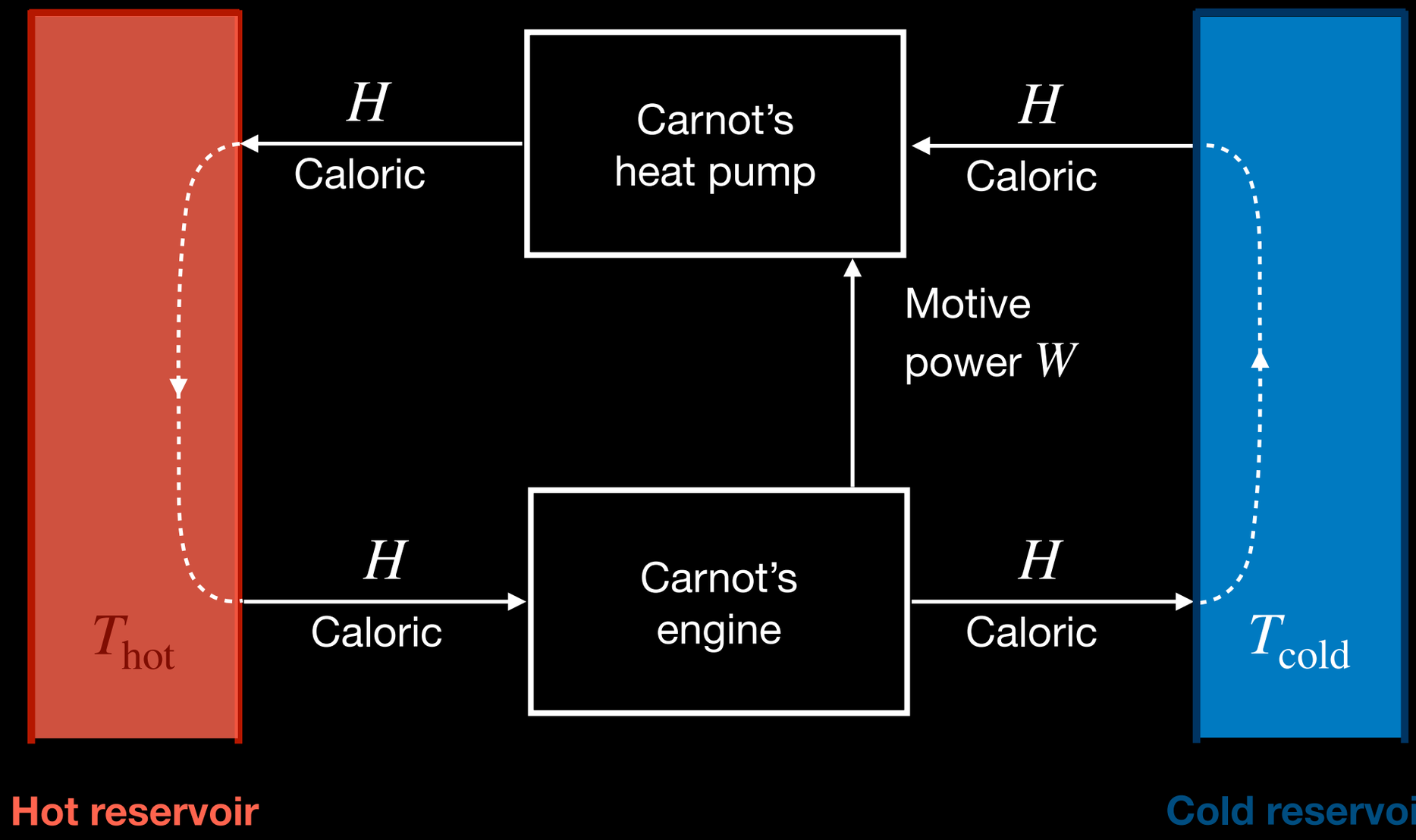
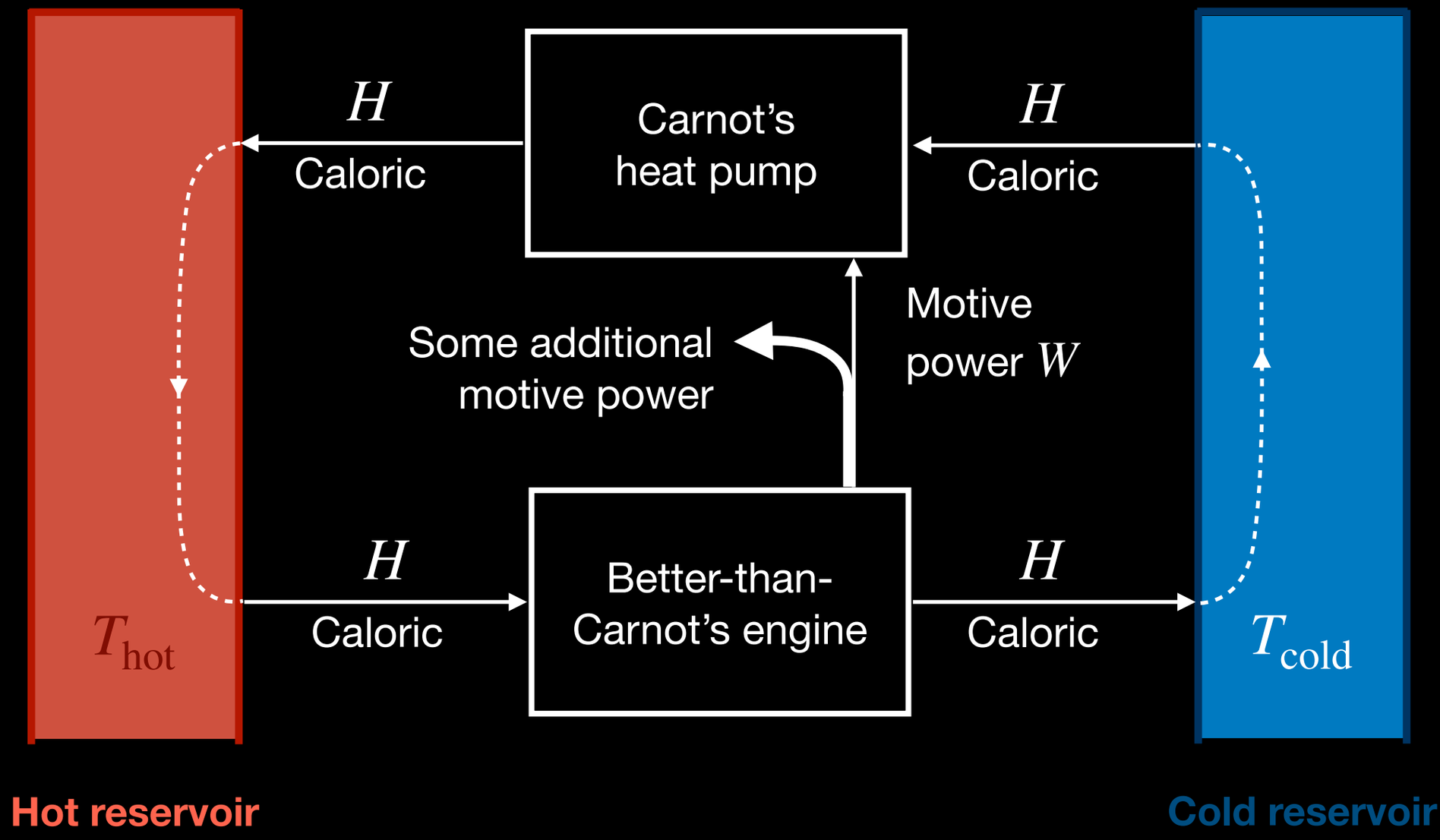


No useful mechanical work done, but also no net exchange of caloric!

A thought experiment



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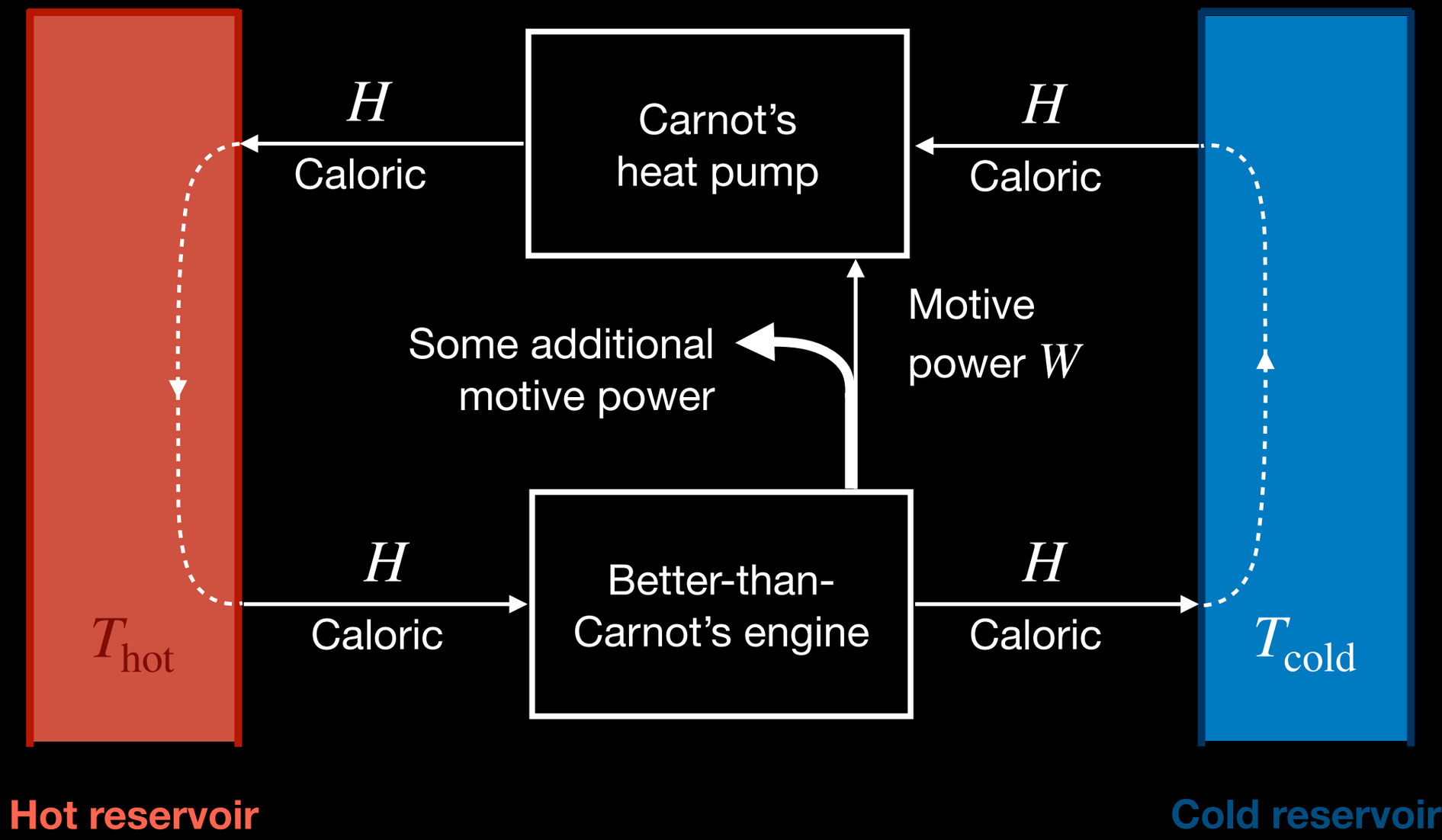
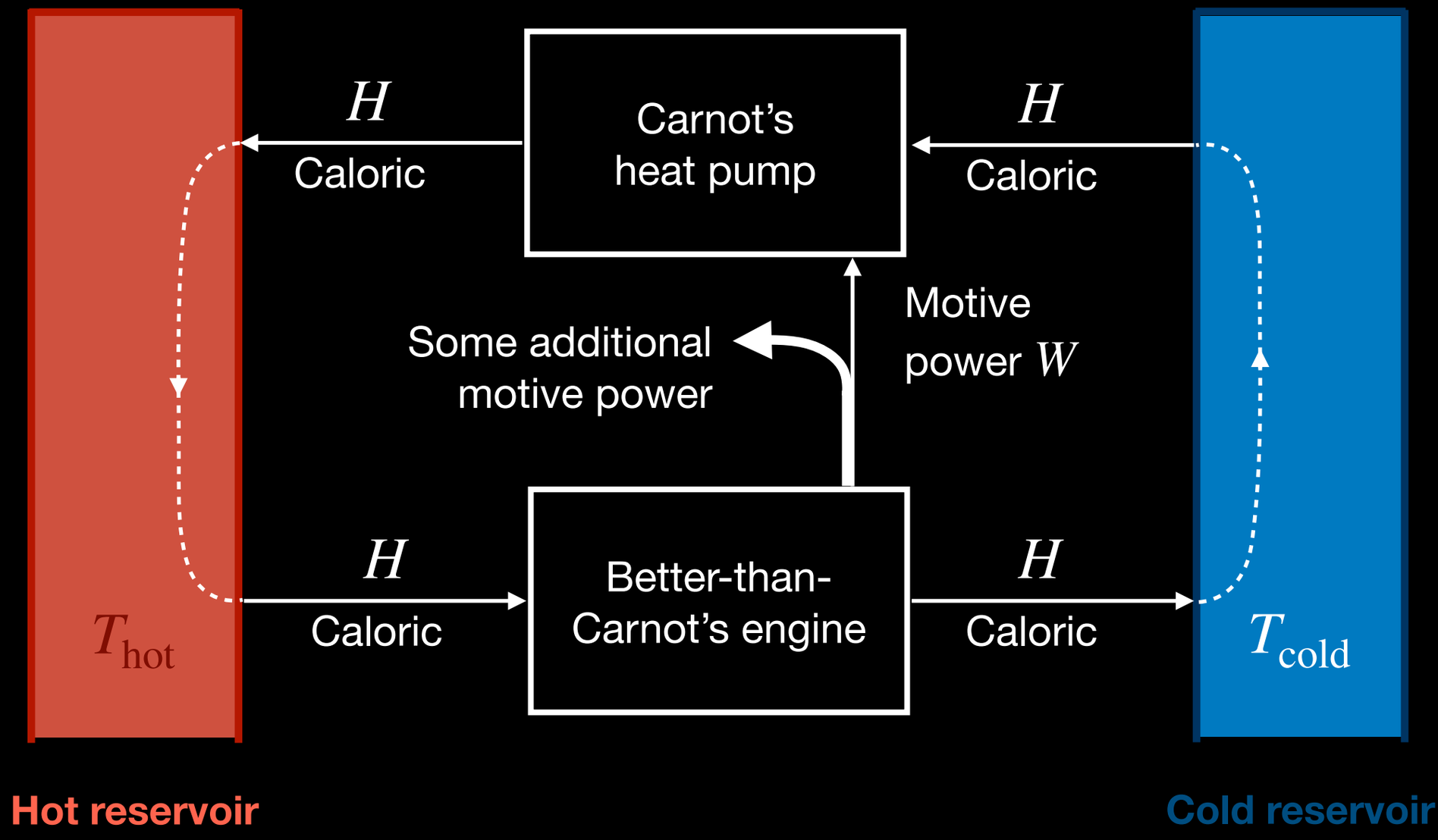


This arrangement would produce motive power out of nothing!

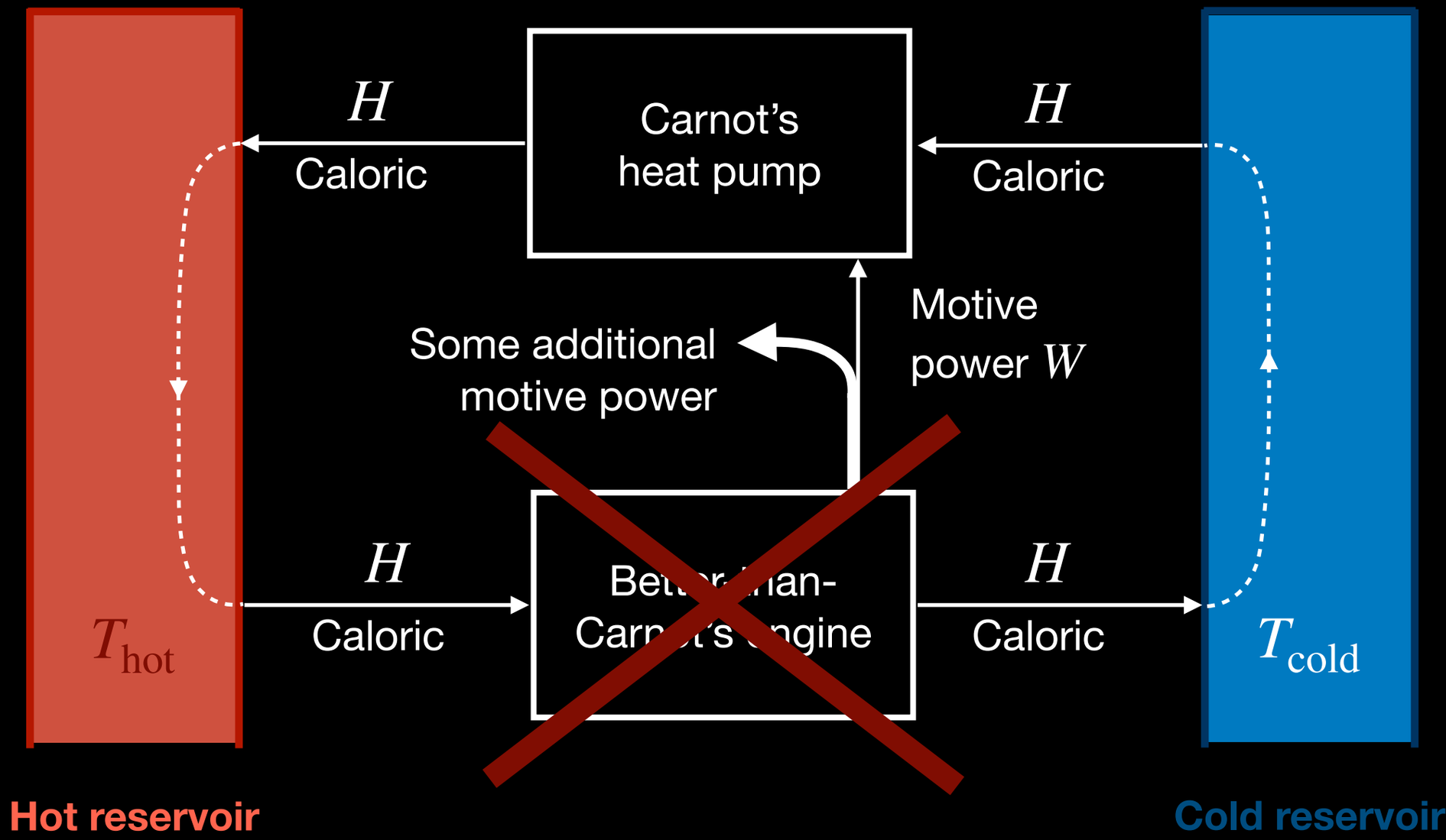
A thought experiment



This arrangement would produce motive power out of nothing!

There cannot be a heat engine of any kind more efficient that Carnot's!

A thought experiment



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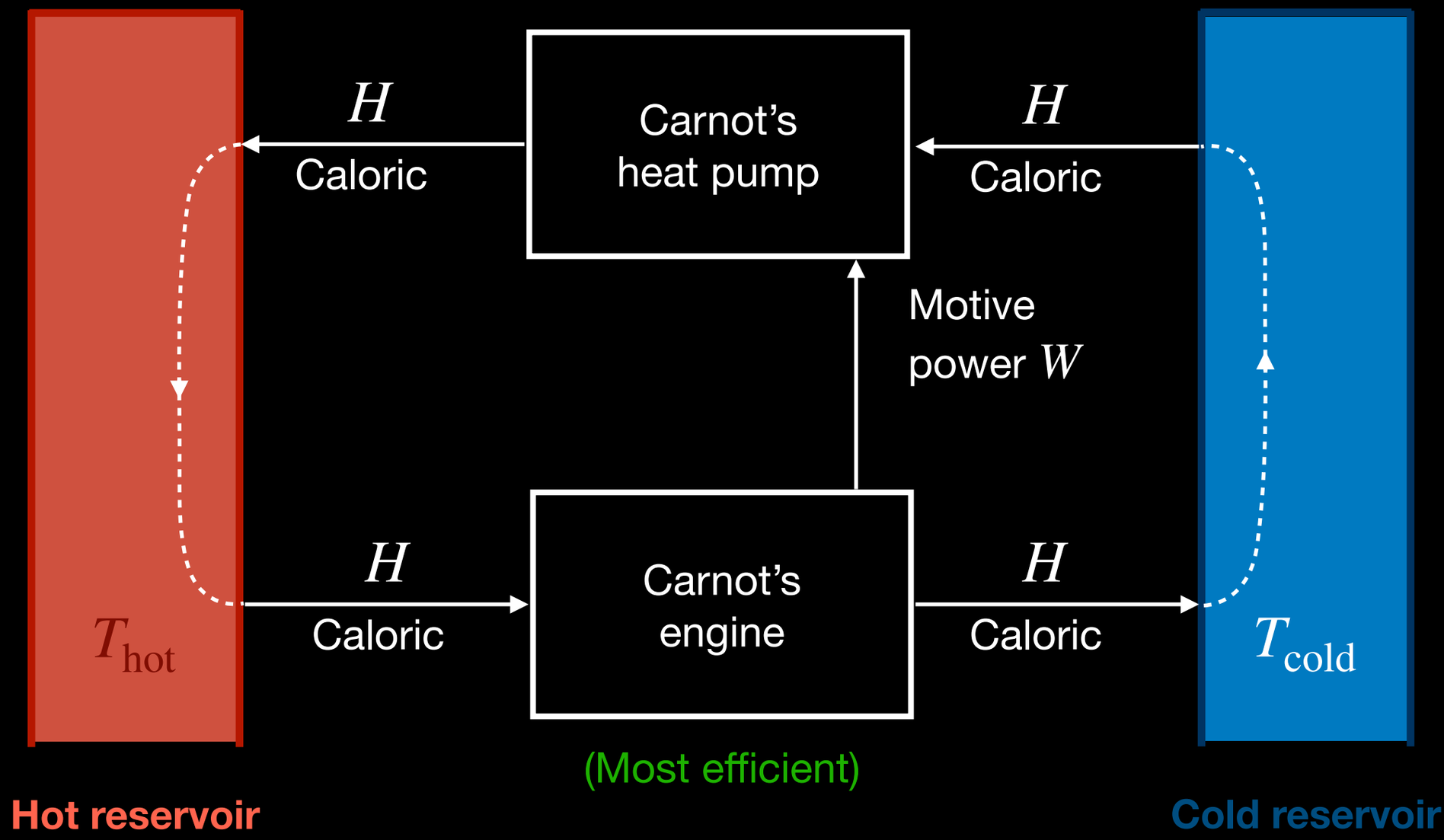

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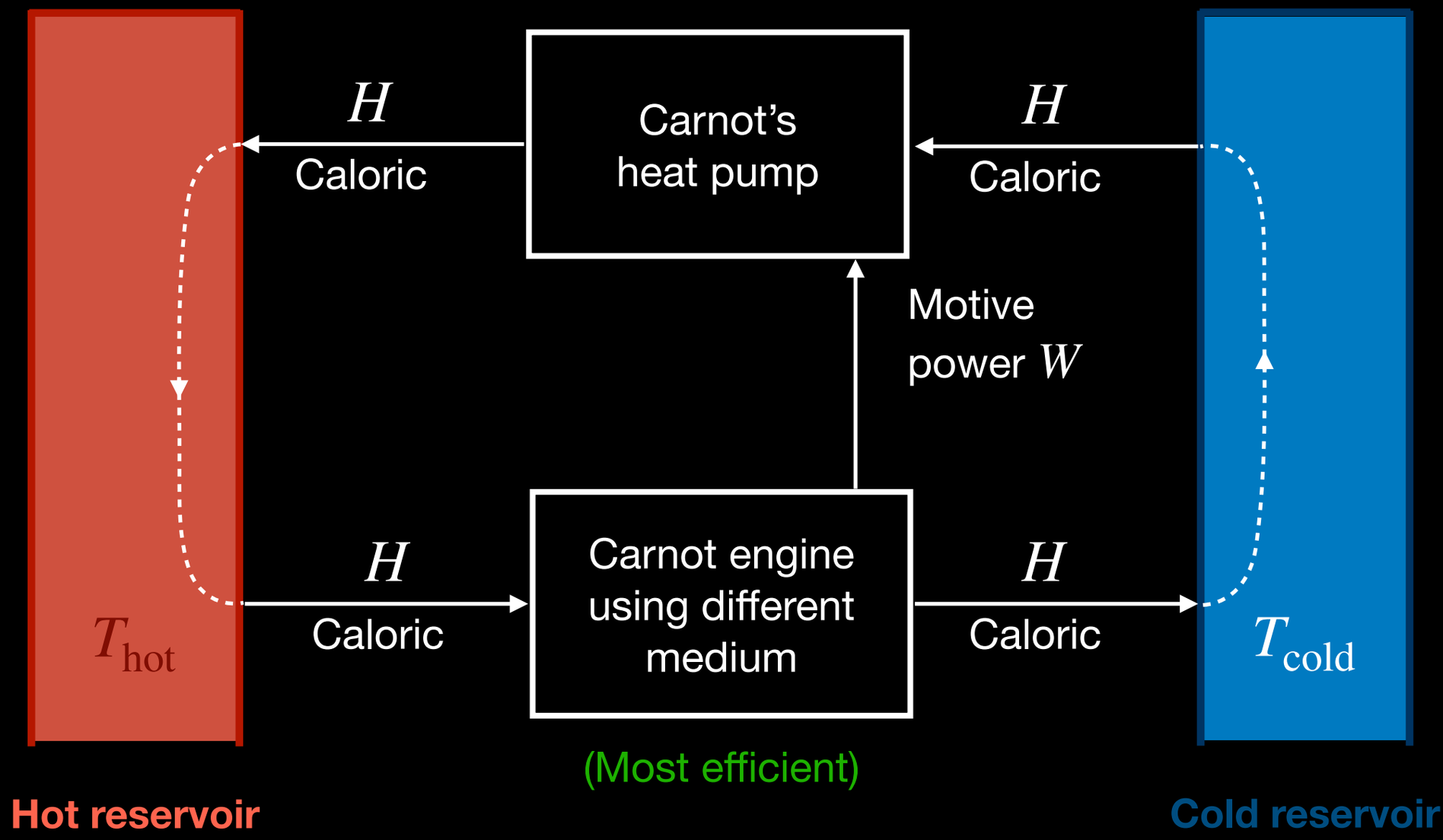

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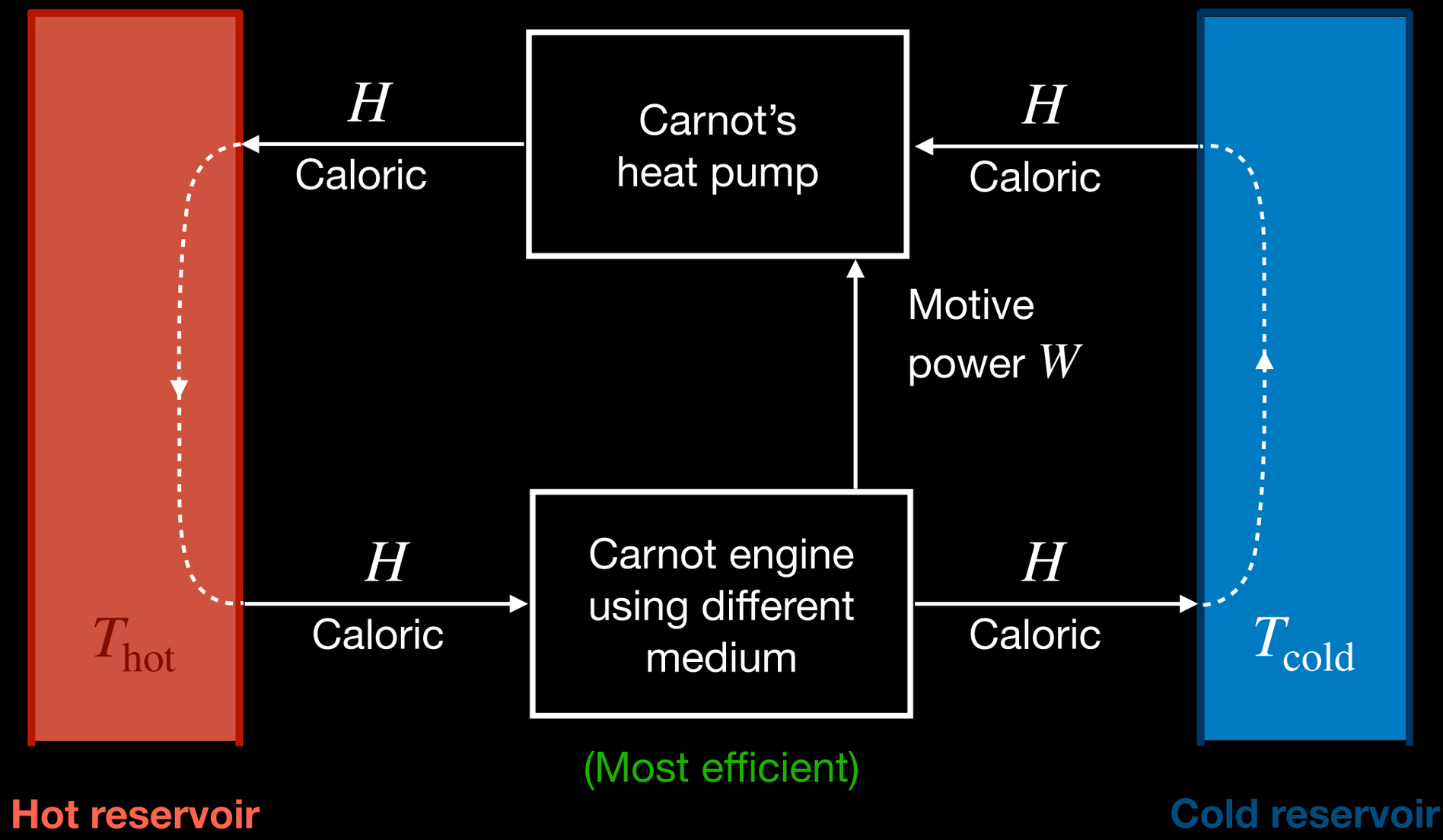
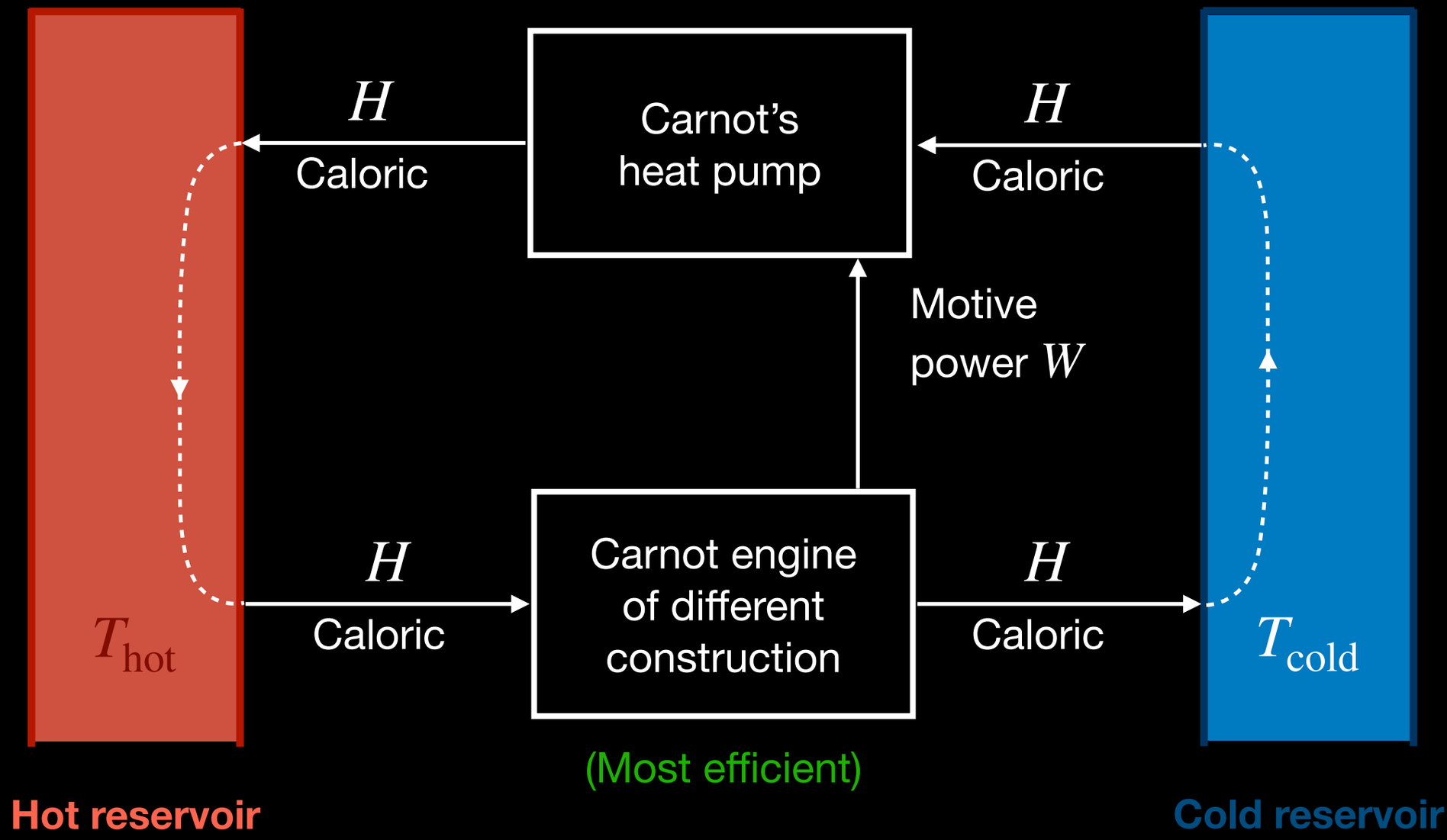


Using a different operating medium cannot improve the efficiency of the engine!

A thought experiment



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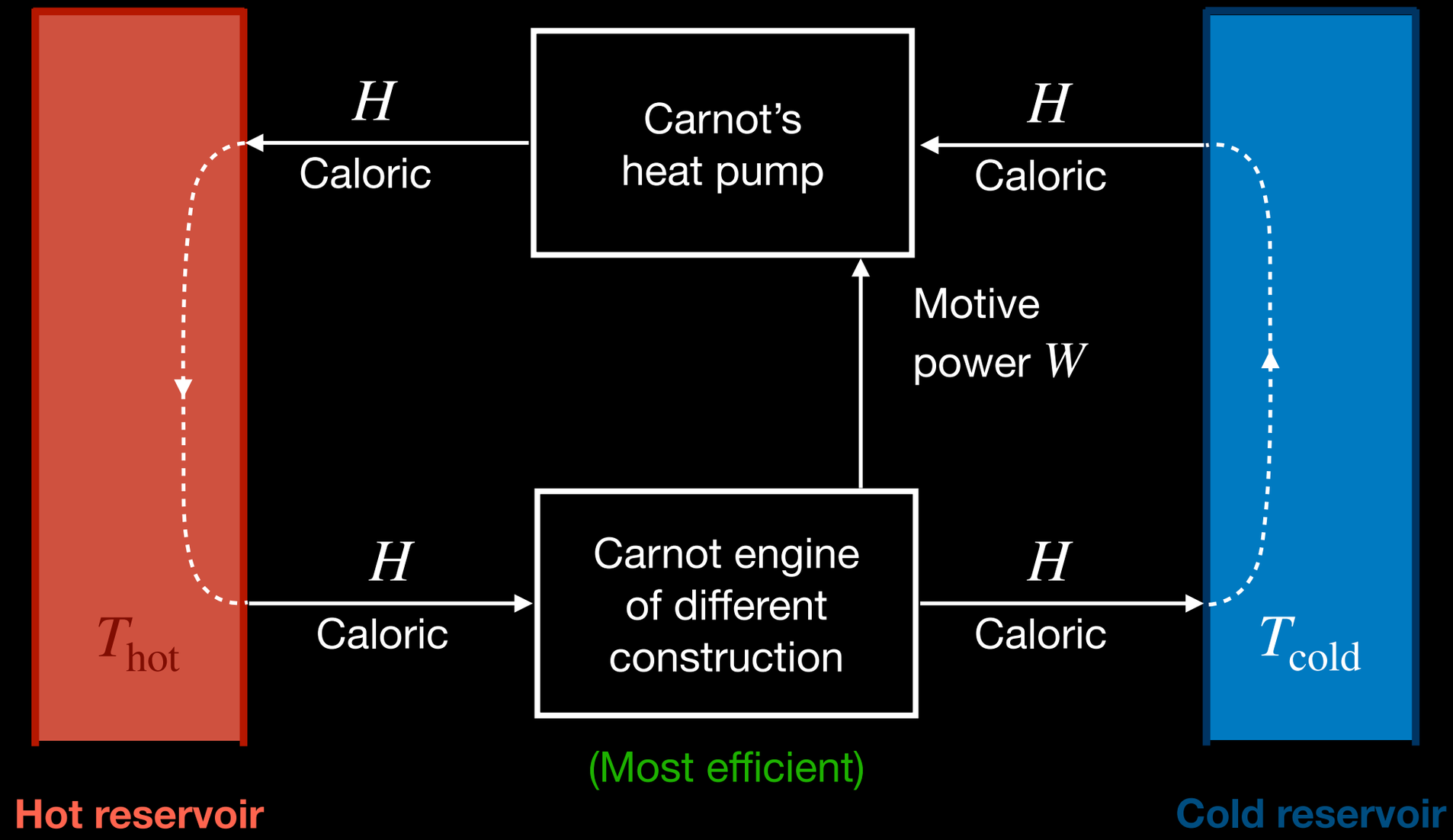
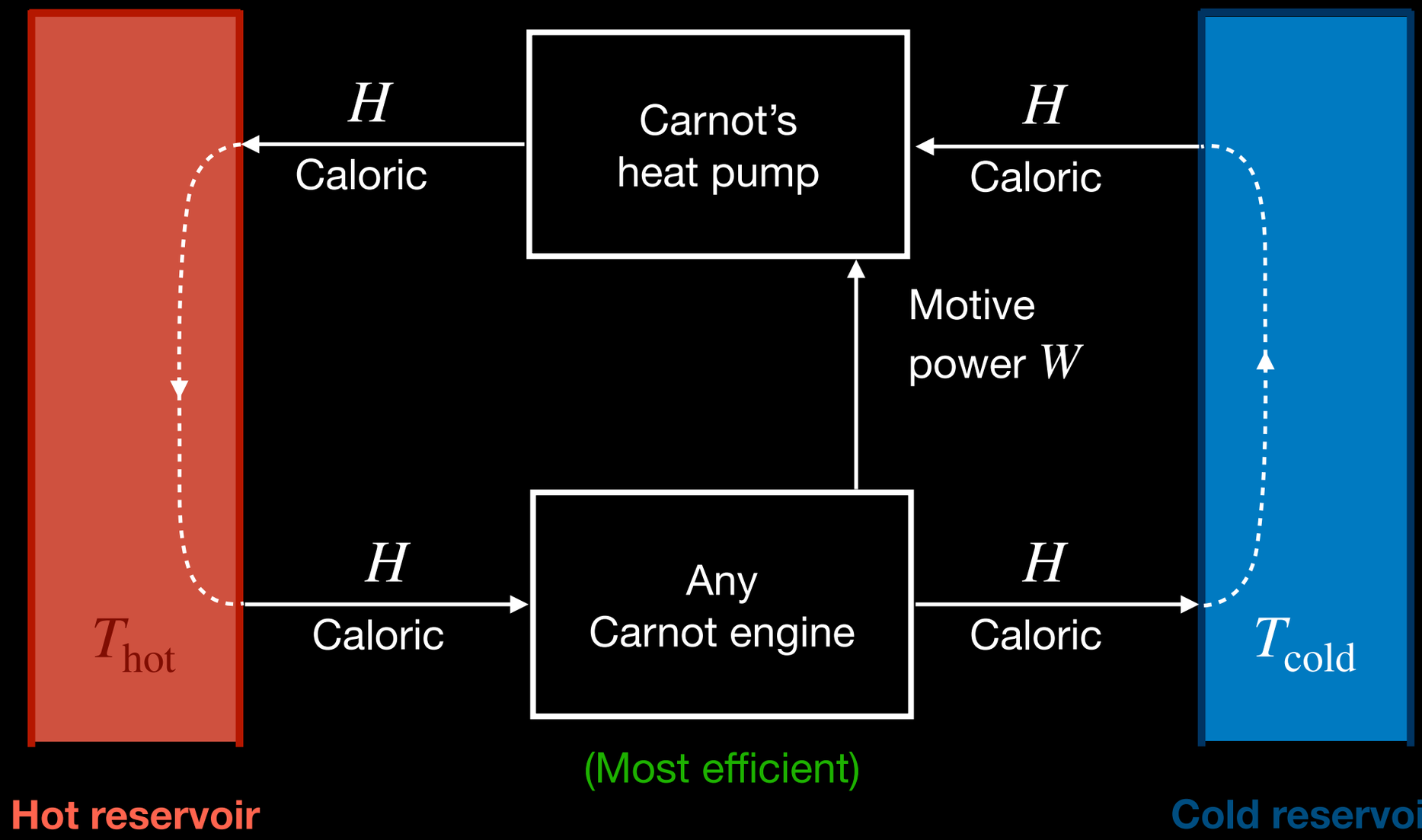


Using a different internal mechanism cannot improve the efficiency of the engine!

A thought experiment



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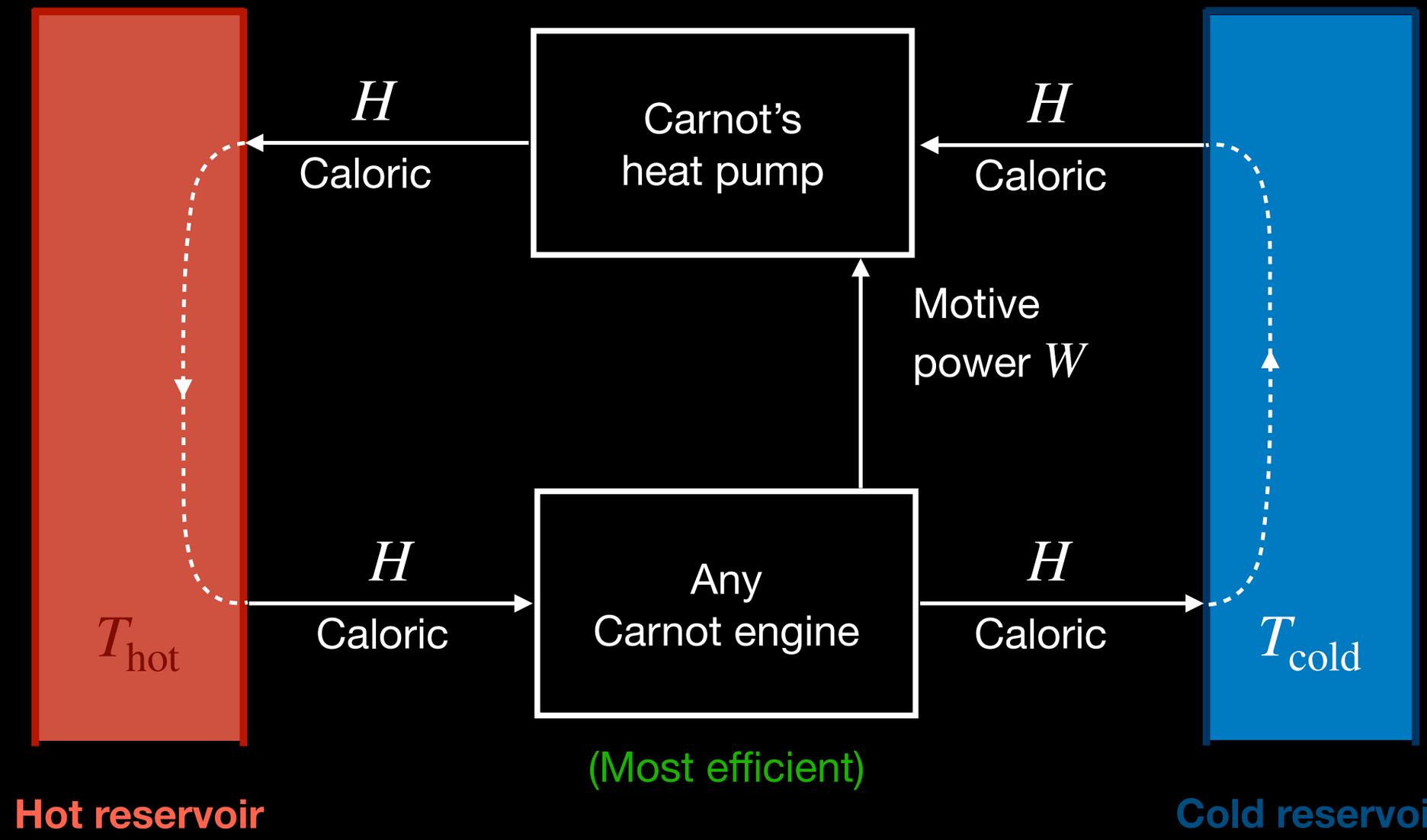
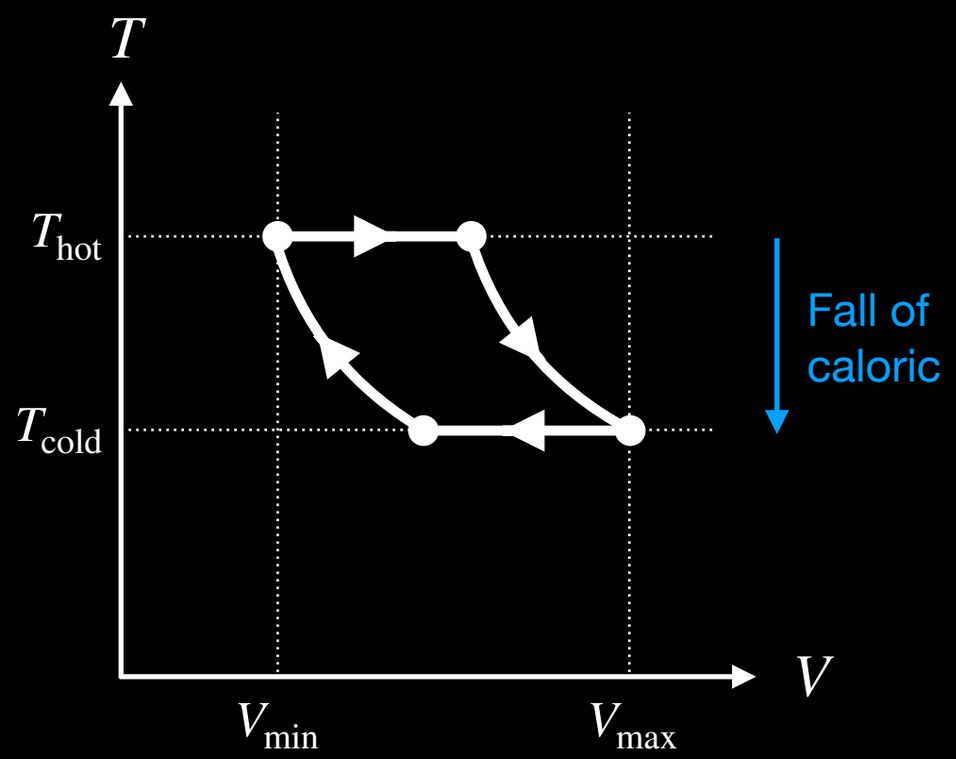


The maximum possible efficiency only depends on the temperatures of the reservoirs, not on the internal construction of the engine!

Carnot's conclusions

How to build an good heat engine:



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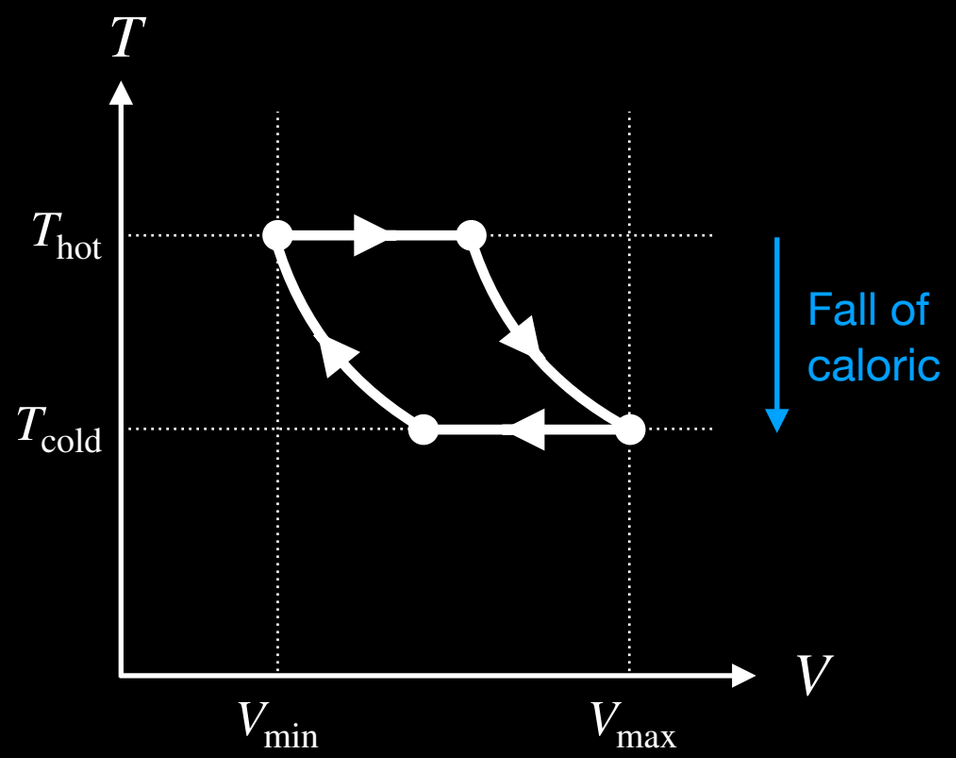
How to build an good heat engine:

1) Make the hot reservoir as hot as possible.



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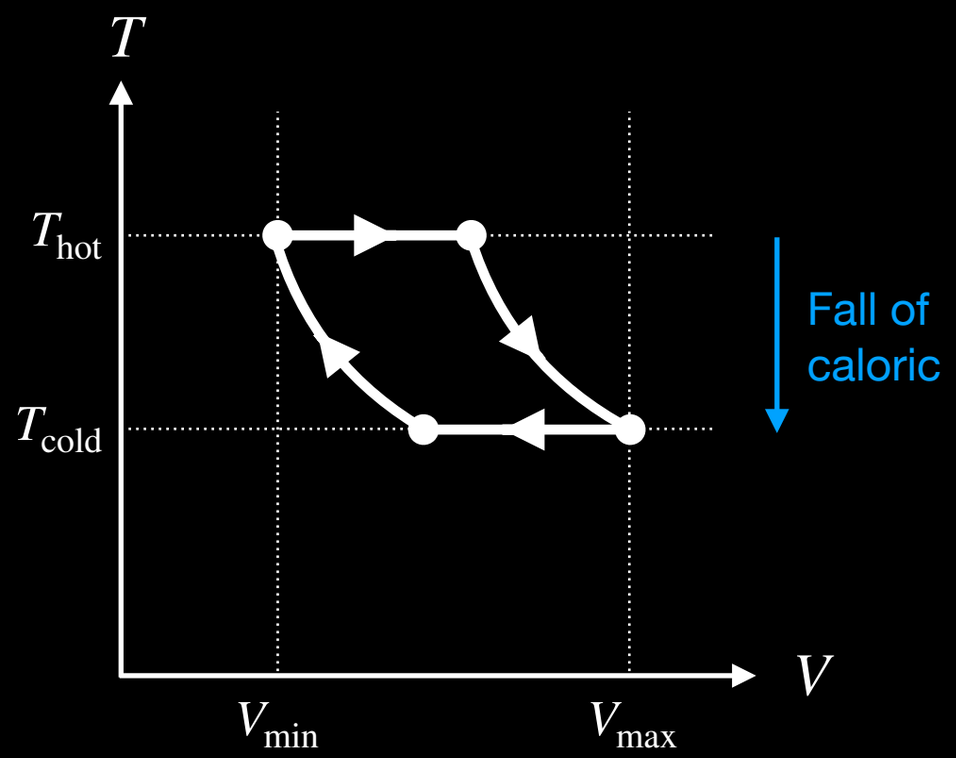
2) Make the cold reservoir as cold as possible.



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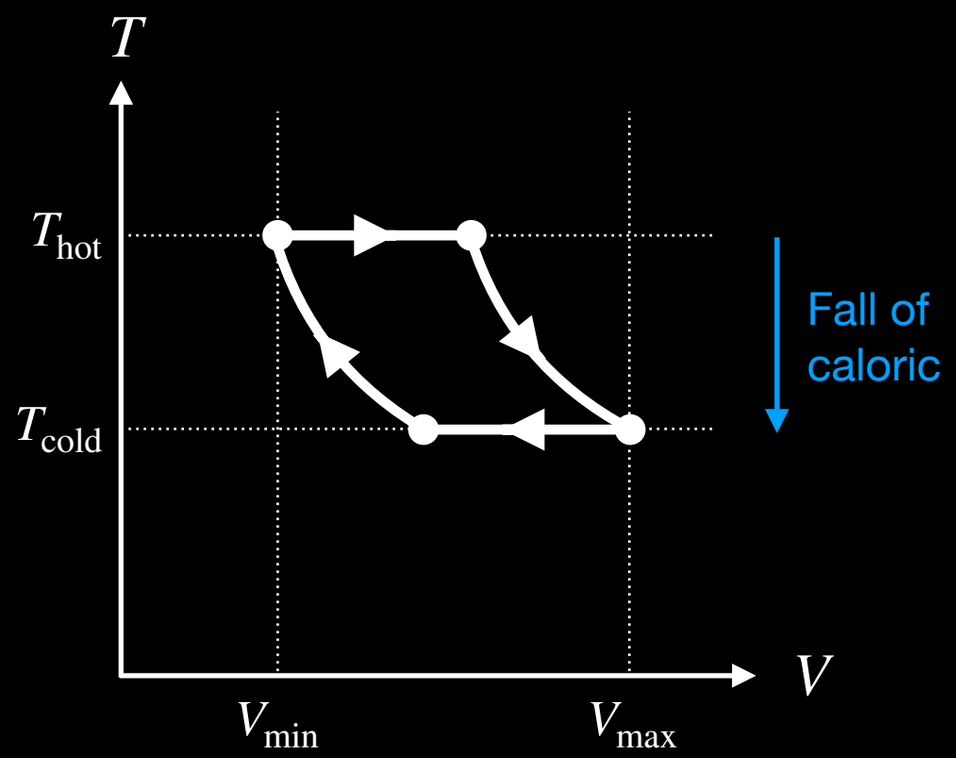
How to build an good heat engine:

1) Make the hot reservoir as hot as possible.

2) Make the cold reservoir as cold as possible.

3) Don't bring hot bodies in direct physical contact with cold bodies.



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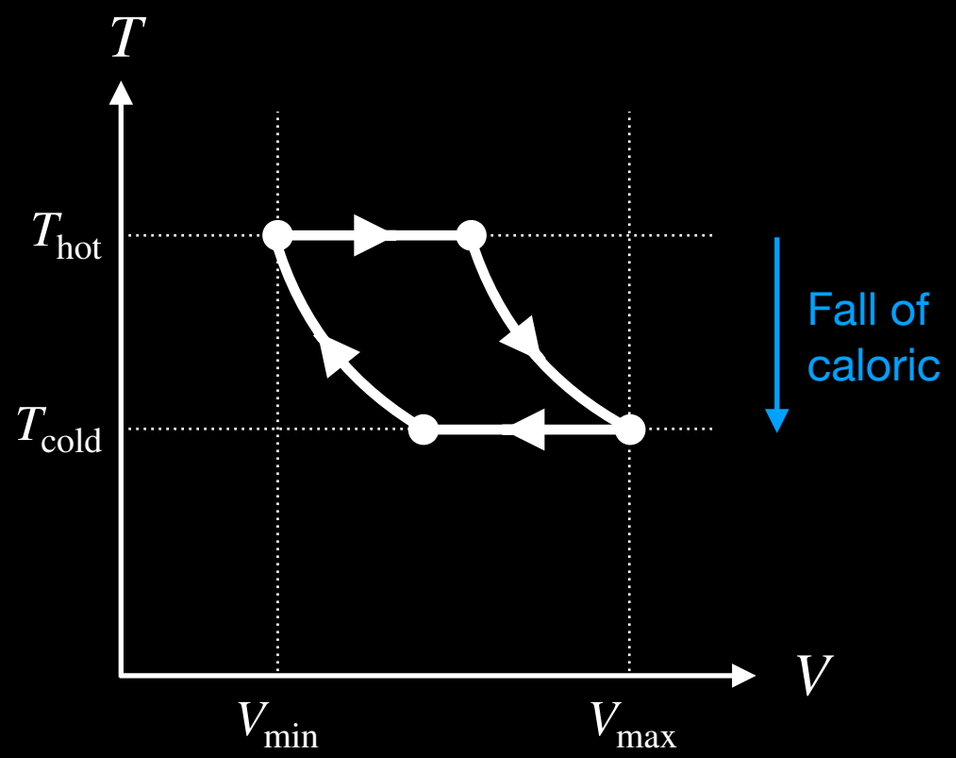
(Such a machine would run infinitely slowly!)



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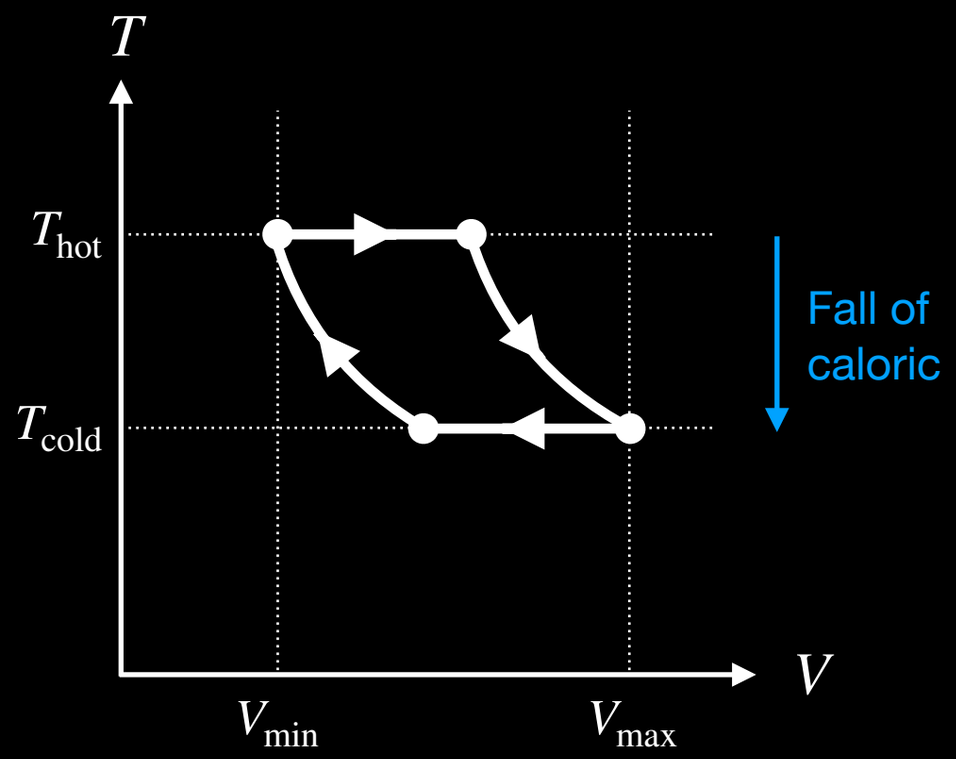

Aspects that do not matter:

Operating medium, detailed technical construction

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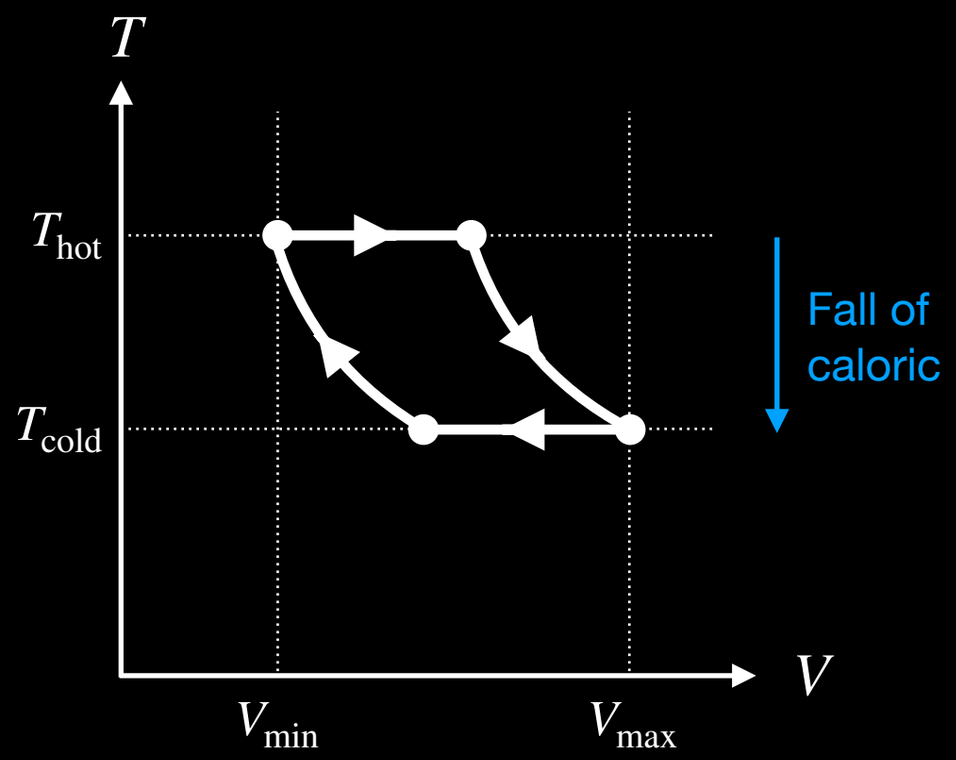

Aspects that do not matter:

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Understanding the fundamentals

⇕

Understanding what is possible or impossible

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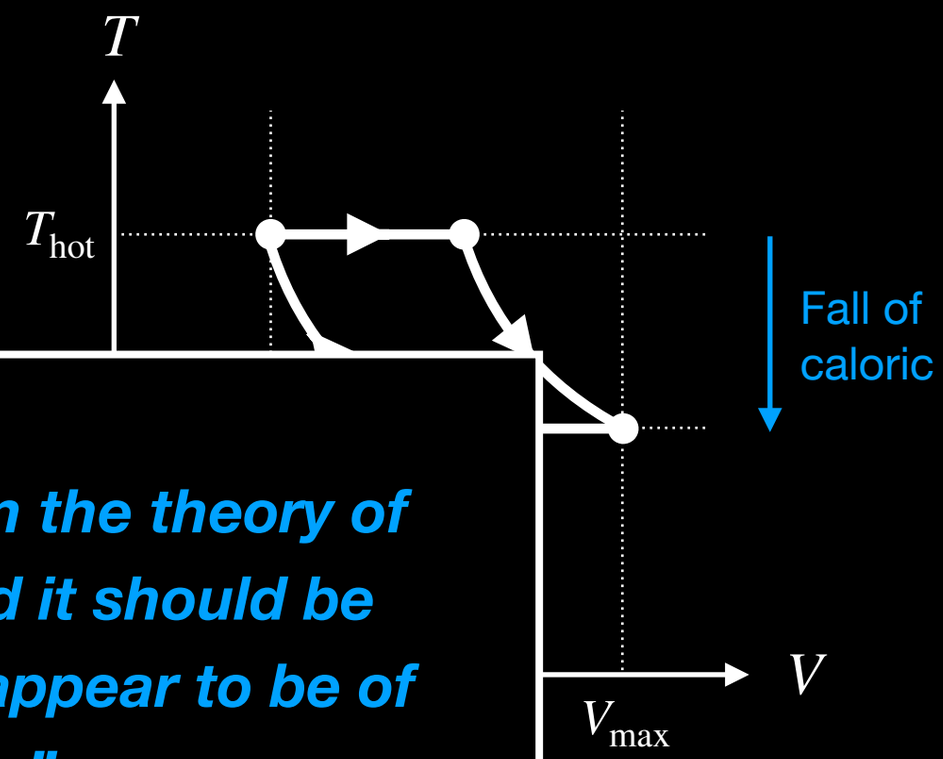

"These conclusions are based upon the theory of heat as it is understood today, and it should be said that this foundation does not appear to be of unquestionable solidity."

(1824)

Understanding the fundamentals

↕

Understanding what is possible or impossible

Benjamin Thompson —Count Rumford

Personal assistant, jack of all trades

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Personal assistant, jack of all trades

Designer of military uniforms

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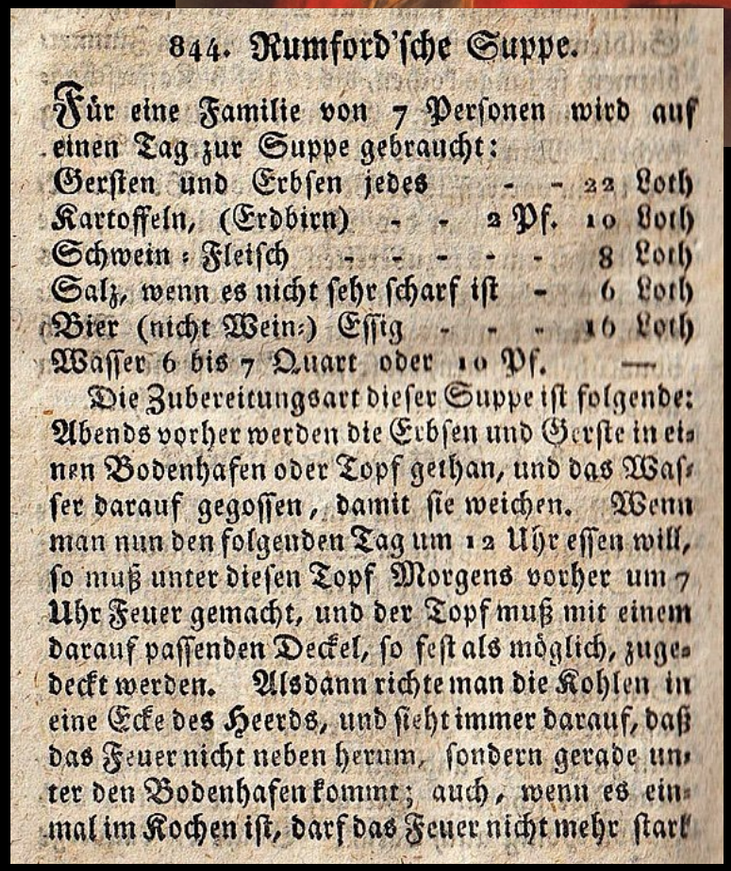
Designer of military uniforms

Inventor of soup recipes



844. Rumford'sche Suppe.

Für eine Familie von 7 Personen wird auf einen Tag zur Suppe gebraucht:

Gersten und Erbsen jedes	- -	22 Loth
Kartoffeln, (Erdbirn)	- -	2 Pf. 10 Loth
Schwein-Fleisch	- - - - -	8 Loth
Salz, wenn es nicht sehr scharf ist	-	6 Loth
Bier (nicht Wein-) Essig	- - -	16 Loth
Wasser 6 bis 7 Quart oder 10 Pf.		—

Die Zubereitungsart dieser Suppe ist folgende: Abends vorher werden die Erbsen und Gerste in einen Bodenhafen oder Topf gethan, und das Wasser darauf gegossen, damit sie weichen. Wenn man nun den folgenden Tag um 12 Uhr essen will, so muß unter diesen Topf Morgens vorher um 7 Uhr Feuer gemacht, und der Topf muß mit einem darauf passenden Deckel, so fest als möglich, zugedeckt werden. Alsdann richte man die Kohlen in eine Ecke des Heerds, und sieht immer darauf, daß das Feuer nicht neben herum, sondern gerade unter den Bodenhafen kommt; auch, wenn es einmal im Kochen ist, darf das Feuer nicht mehr stark

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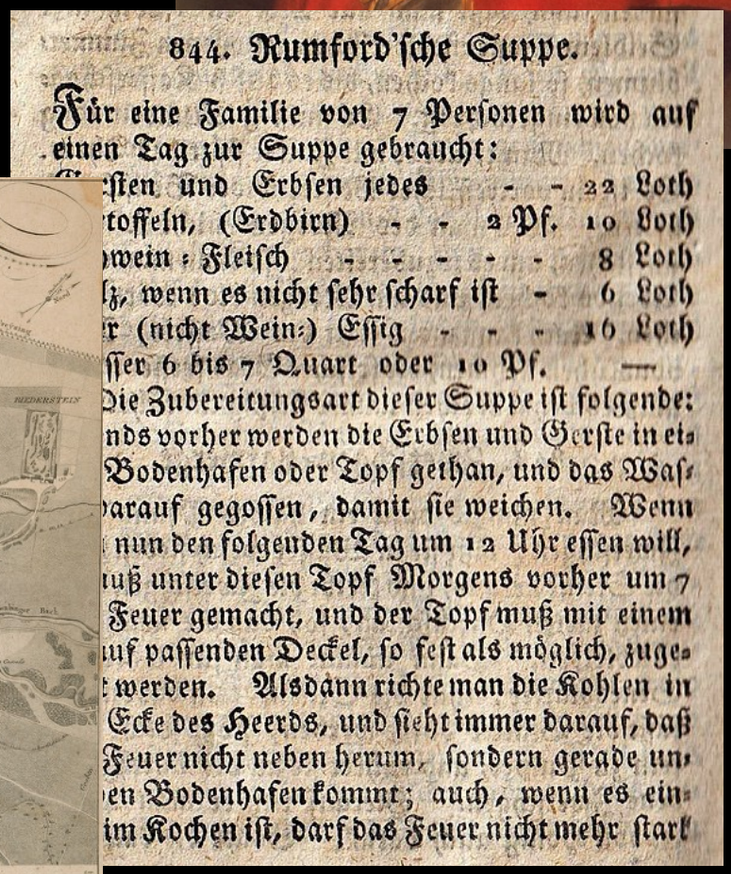
Personal assistant, jack of all trades

Designer of military unifo

Planter of trees in the English Garten

[source]



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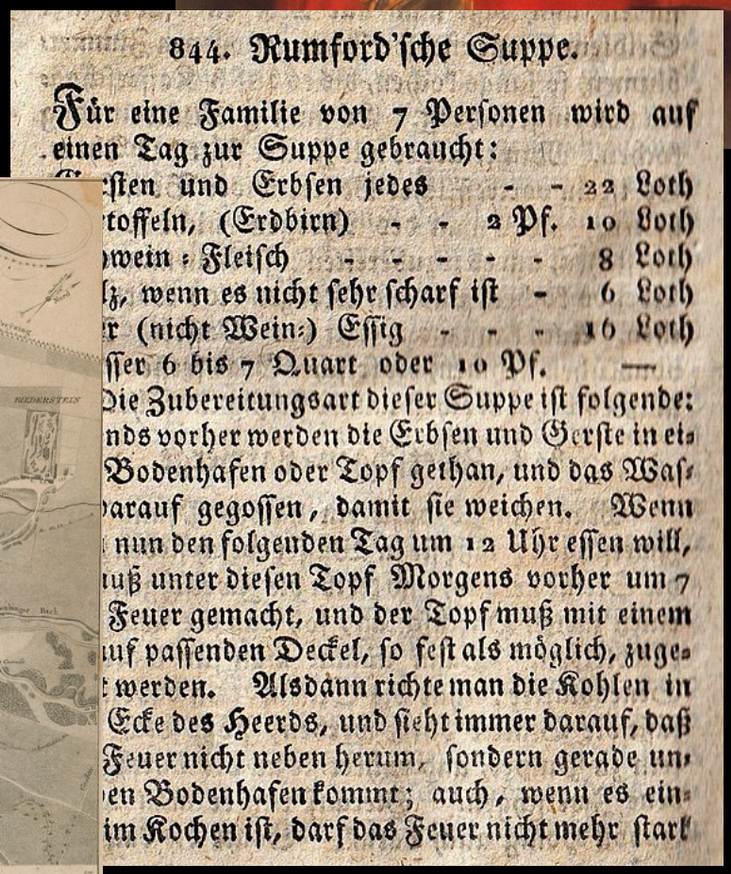

844. Rumford'sche Suppe.

Für eine Familie von 7 Personen wird auf einen Tag zur Suppe gebraucht:

sten und Erbsen jedes - - 22 Loth
toffeln, (Erdbirn) - - 2 Pf. 10 Loth
wein-Fleisch - - - - - 8 Loth
lz, wenn es nicht sehr scharf ist - 6 Loth
r (nicht Wein-) Essig - - - 16 Loth
sser 6 bis 7 Quart oder 10 Pf. —

Die Zubereitungsart dieser Suppe ist folgende:
nds vorher werden die Erbsen und Gerste in ei-
Bodenhafen oder Topf gethan, und das Was-
arauf gegossen, damit sie weichen. Wenn
nun den folgenden Tag um 12 Uhr essen will,
uß unter diesen Topf Morgens vorher um 7
Feuer gemacht, und der Topf muß mit einem
uf passenden Deckel, so fest als möglich, zuge-
werden. Alsdann richte man die Kohlen in
Ecke des Heerds, und sieht immer darauf, daß
Feuer nicht neben herum, sondern gerade un-
en Bodenhafen kommt; auch, wenn es ein-
im Kochen ist, darf das Feuer nicht mehr stark

"I am persuaded that a habit of keeping the eyes open to everything that is going on in the ordinary course of the business of life has oftener led to useful doubts and sensible schemes for investigation and improvement than all the more intense meditations of philosophers in the hours expressly set apart for study."

The cannon boring experiments

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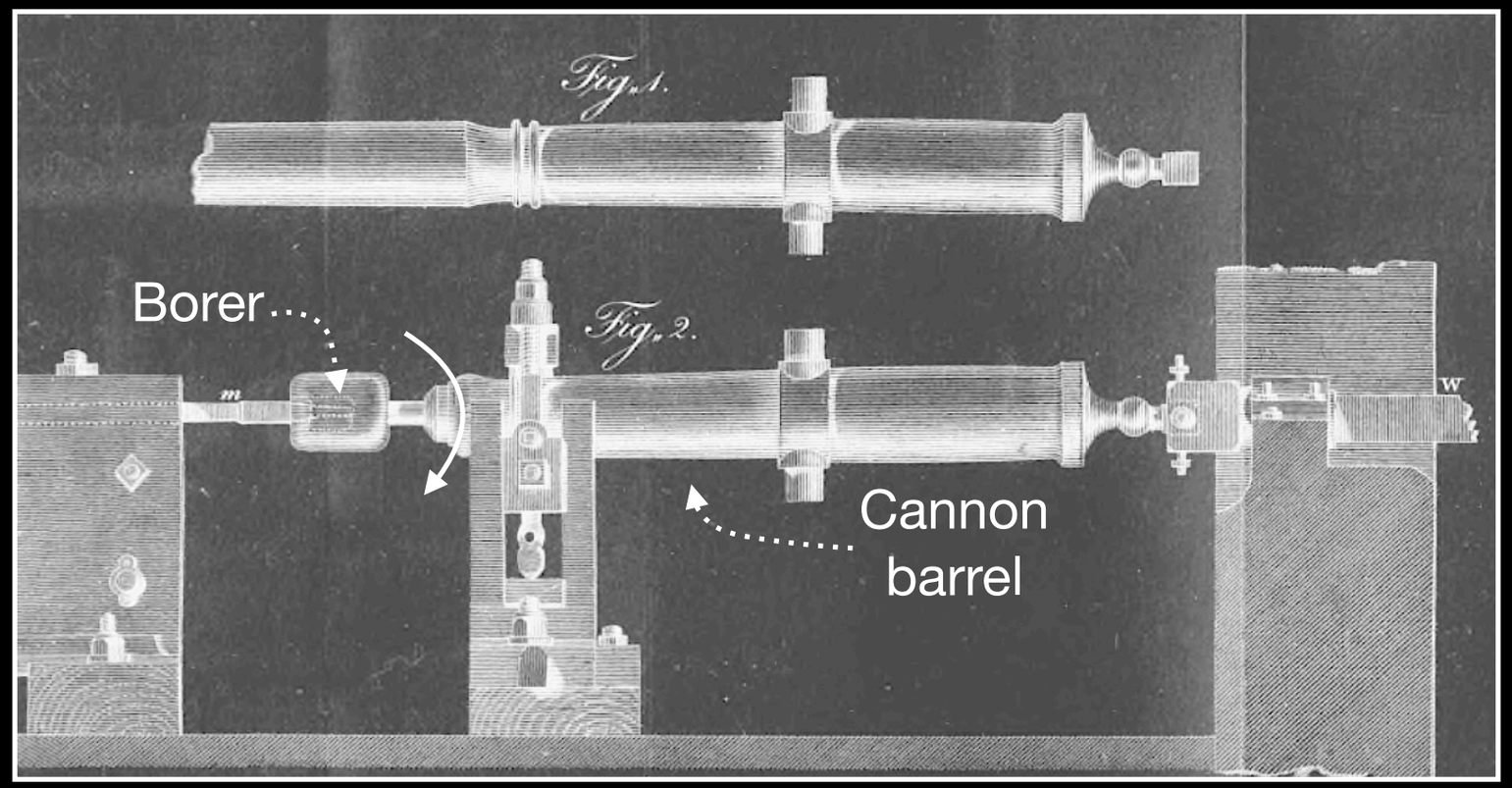

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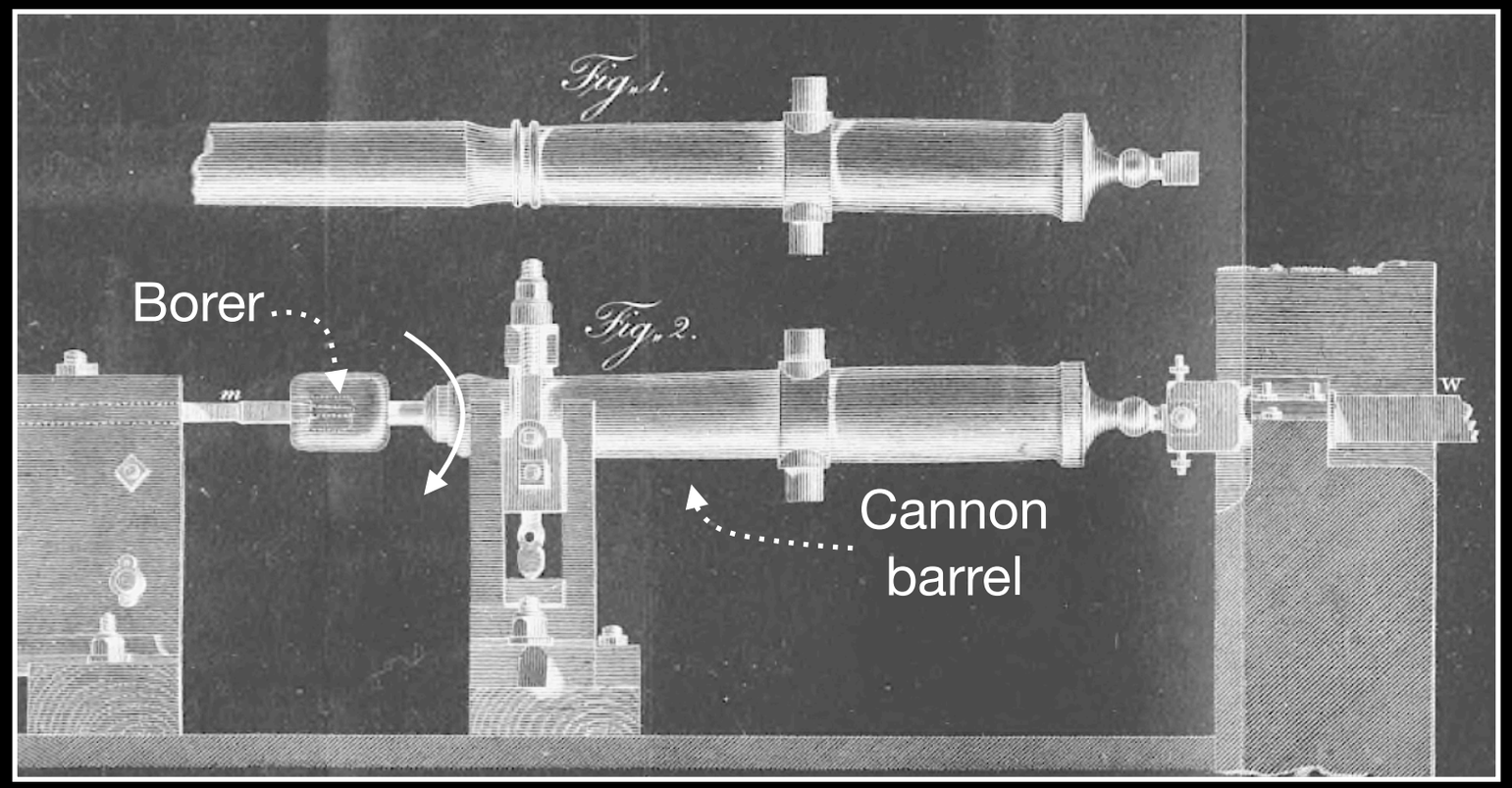

“A thorough investigation seemed to give a farther insight into the hidden nature of heat […]”

The cannon boring experiments

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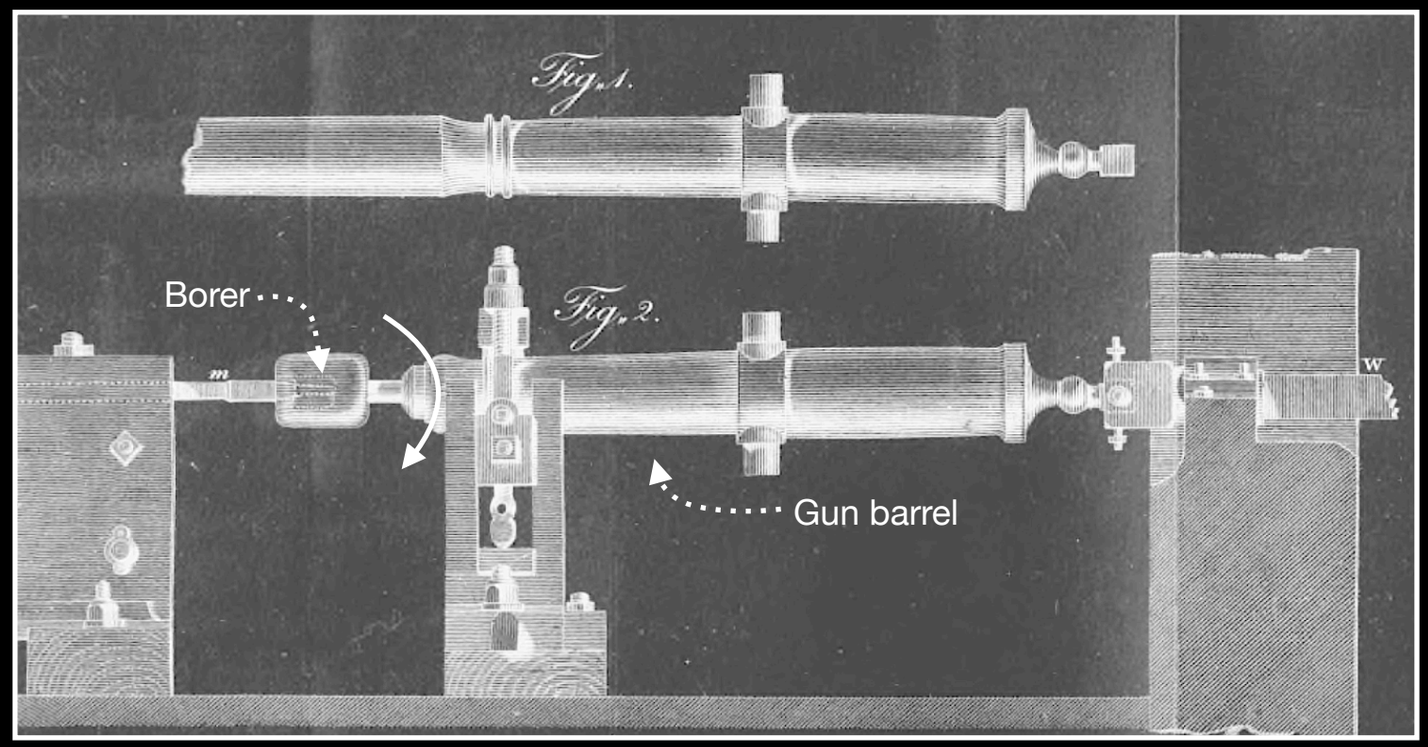

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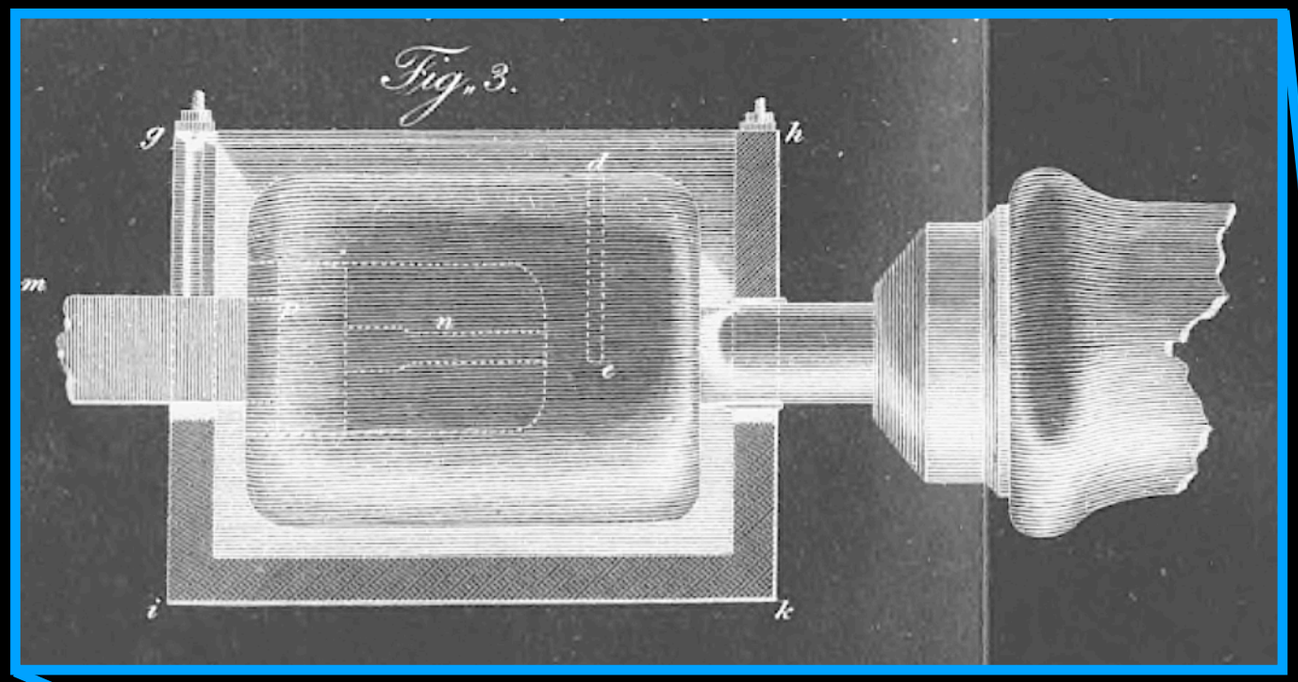

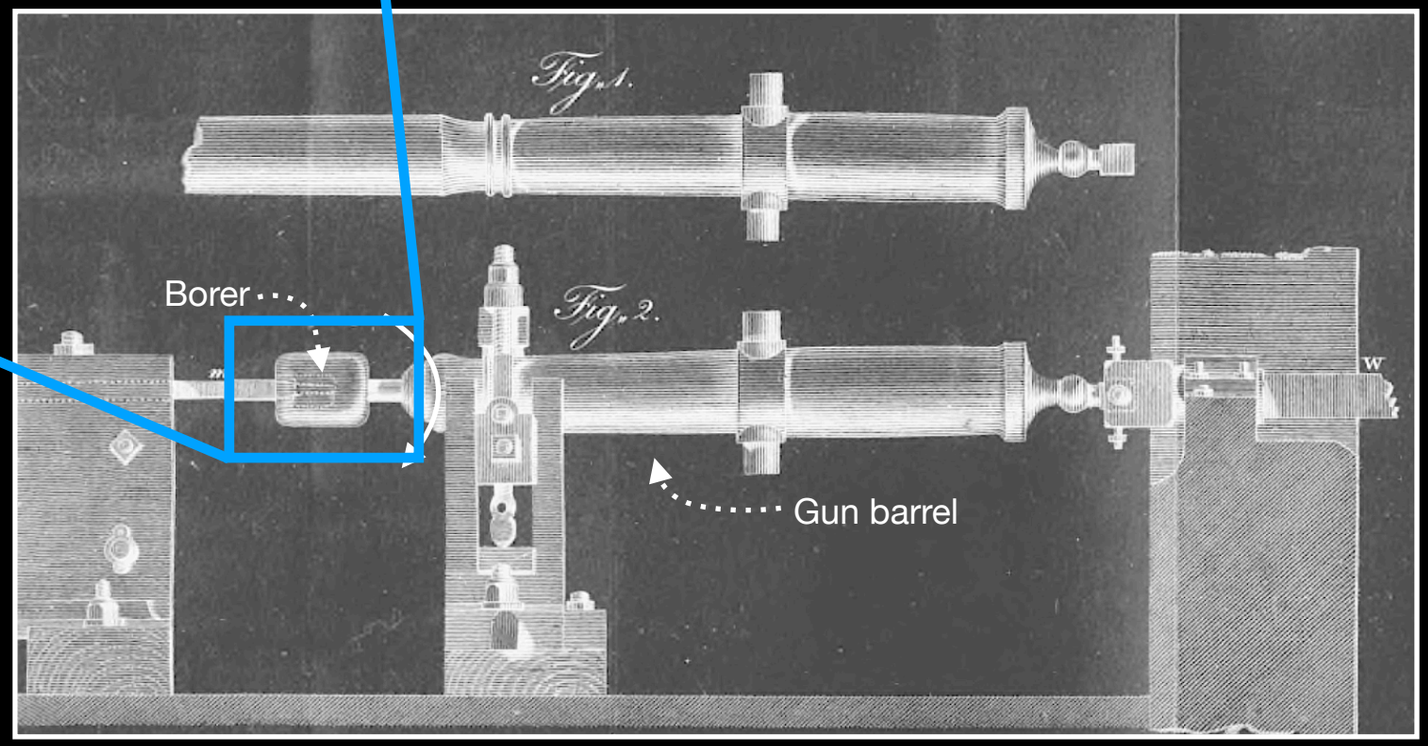

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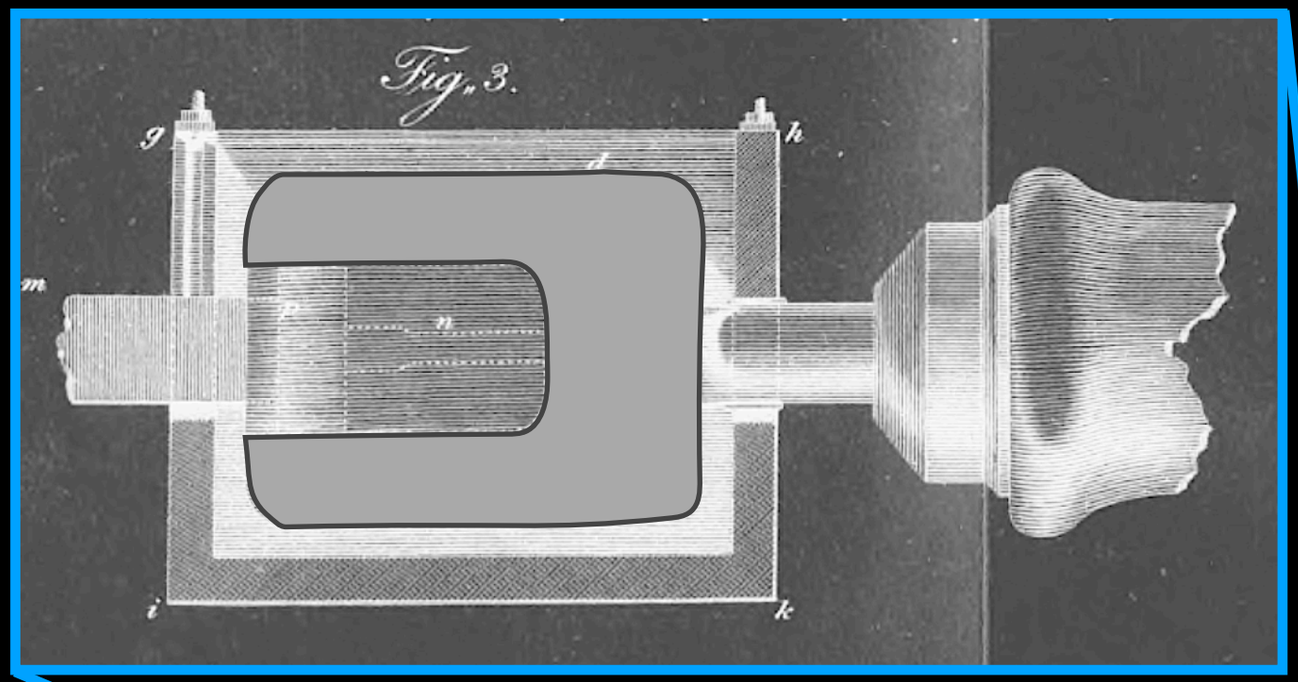
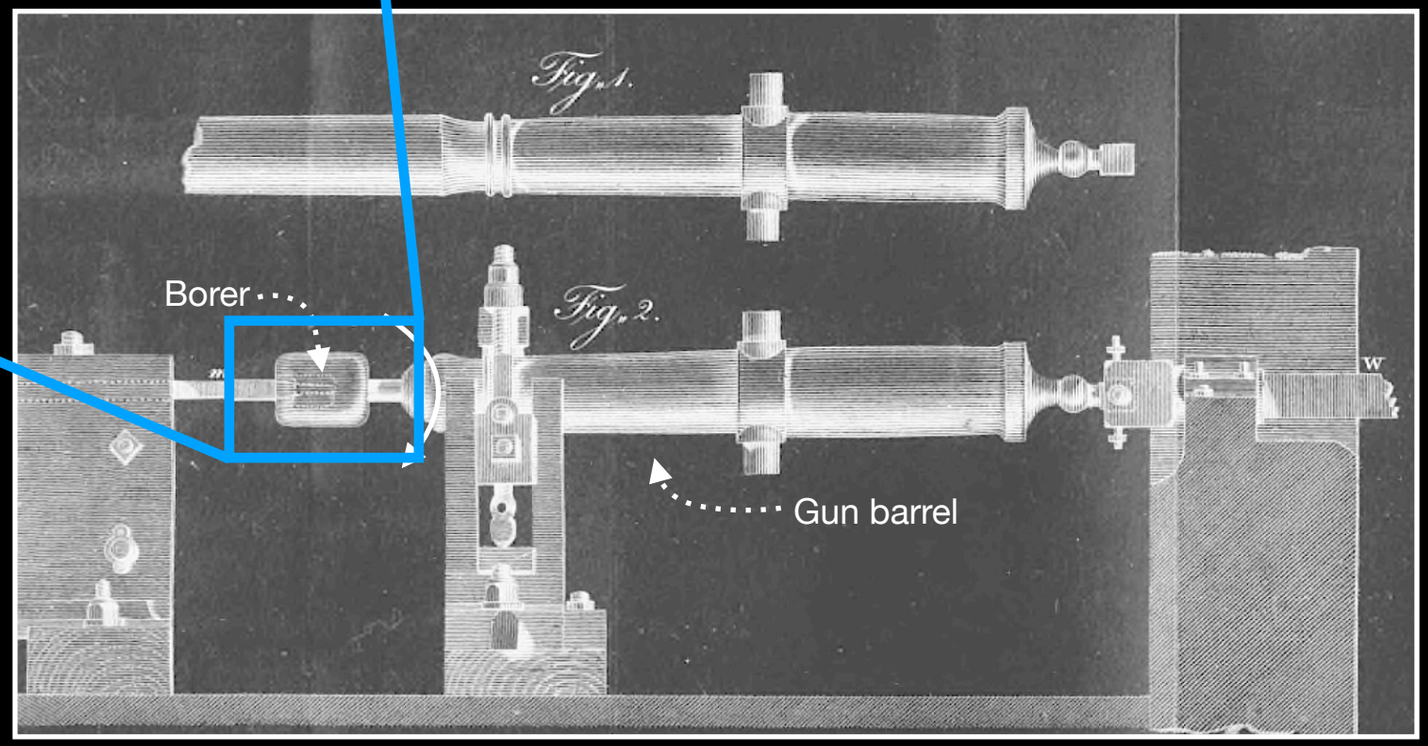
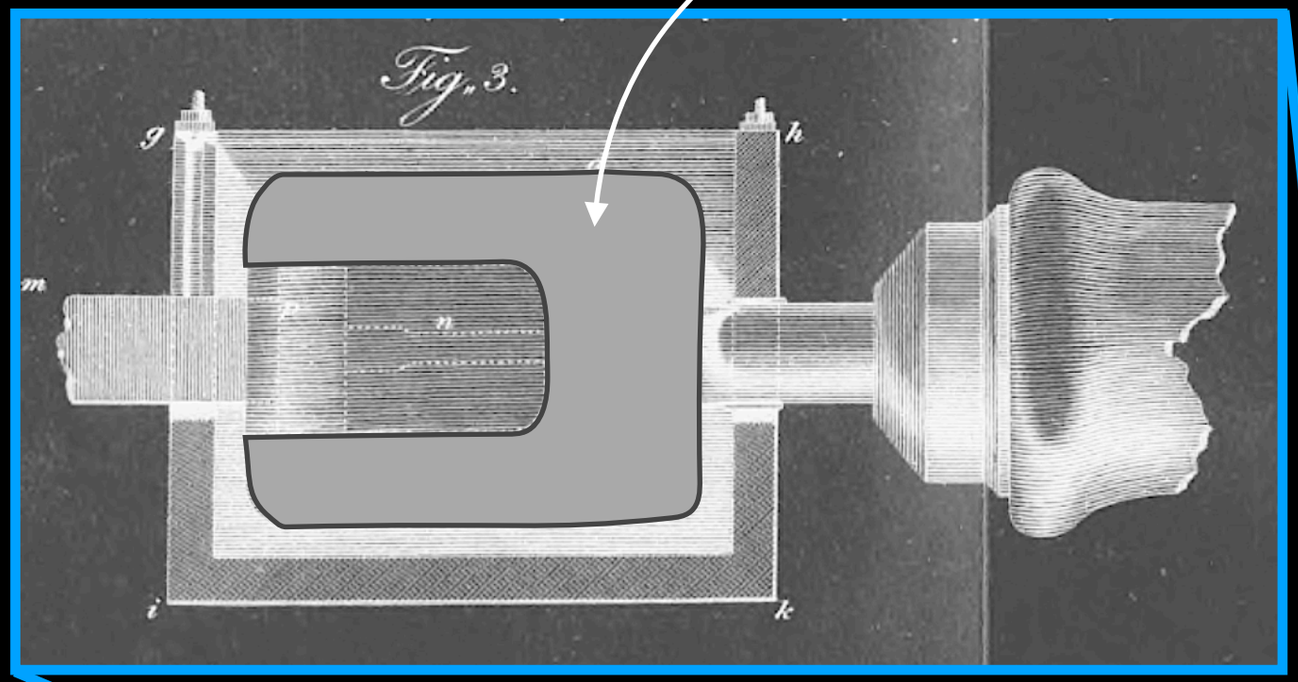
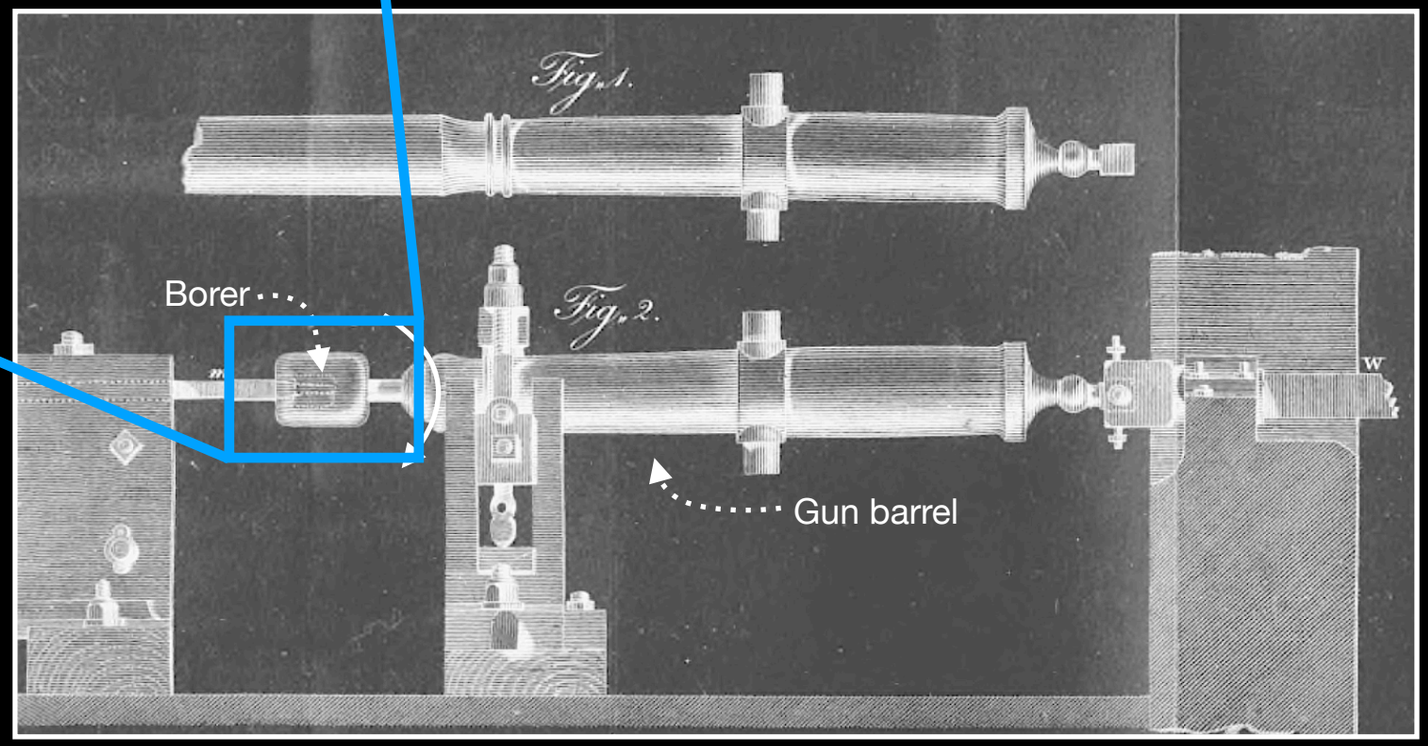




The cannon boring experiments

Hollow metal cylinder





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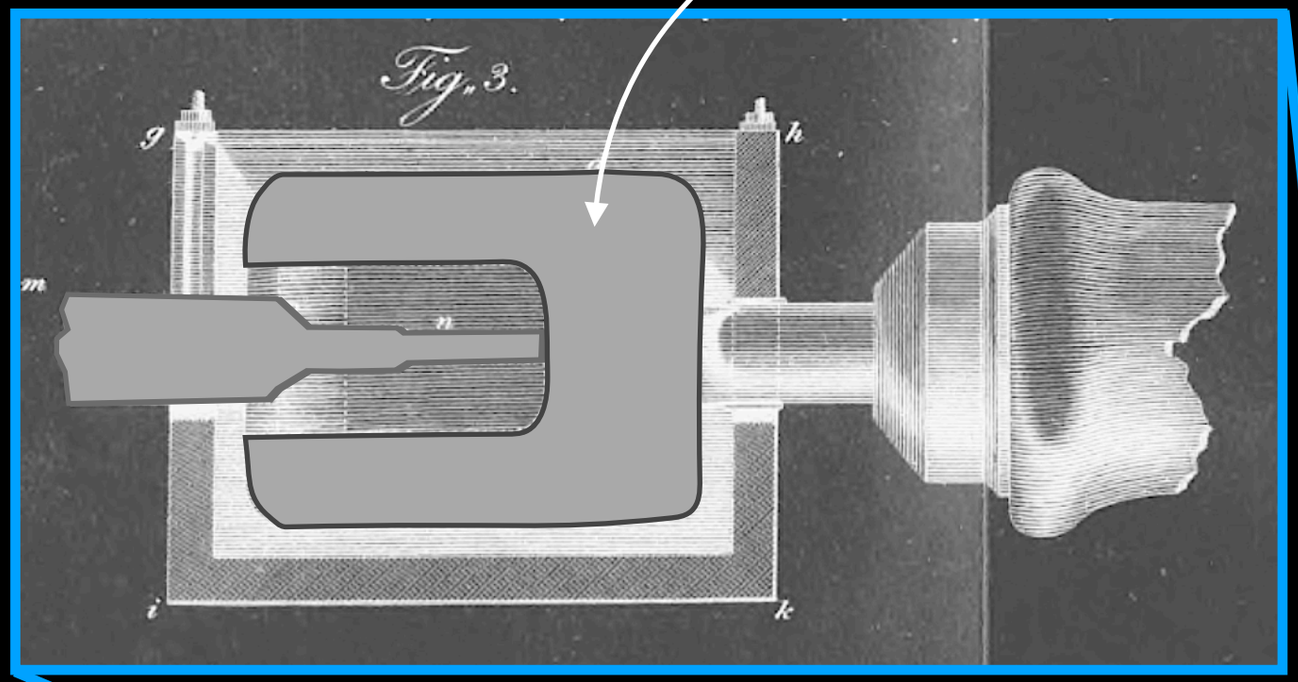

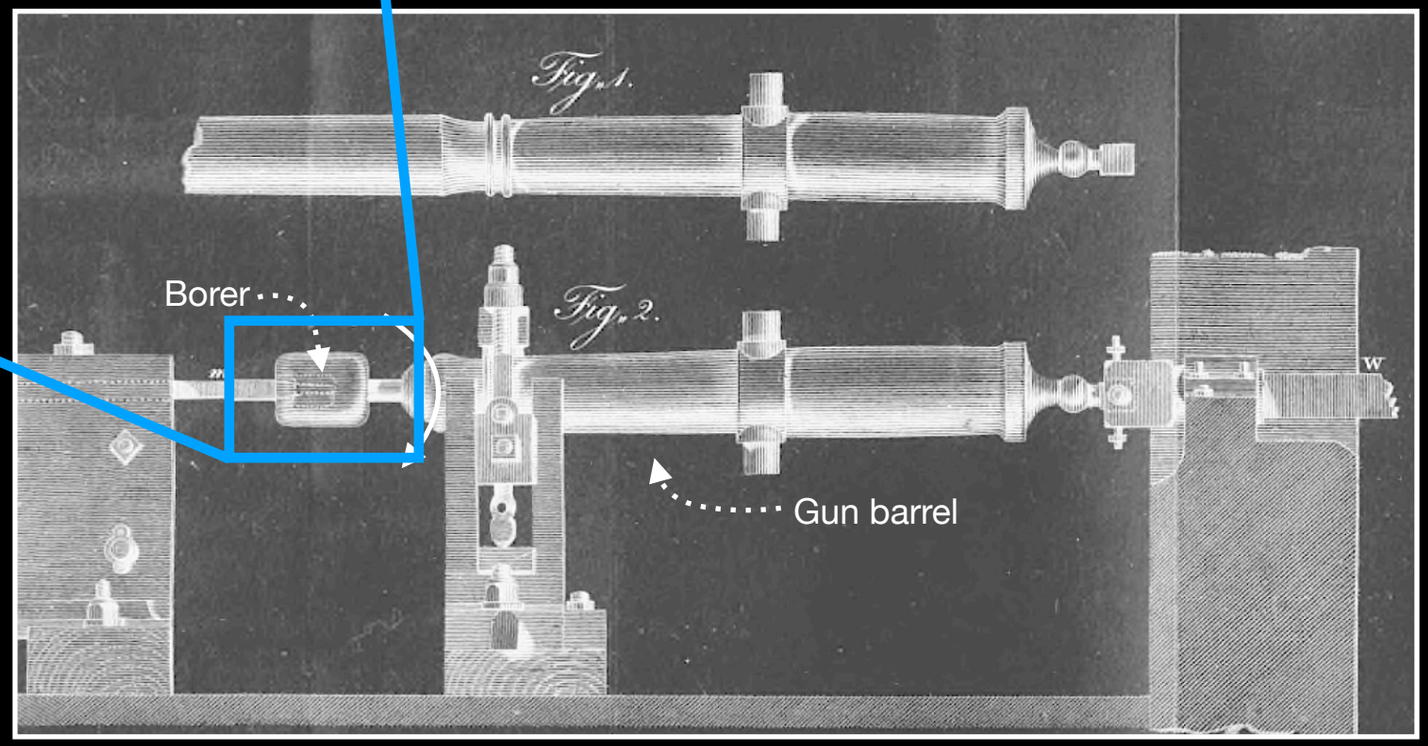

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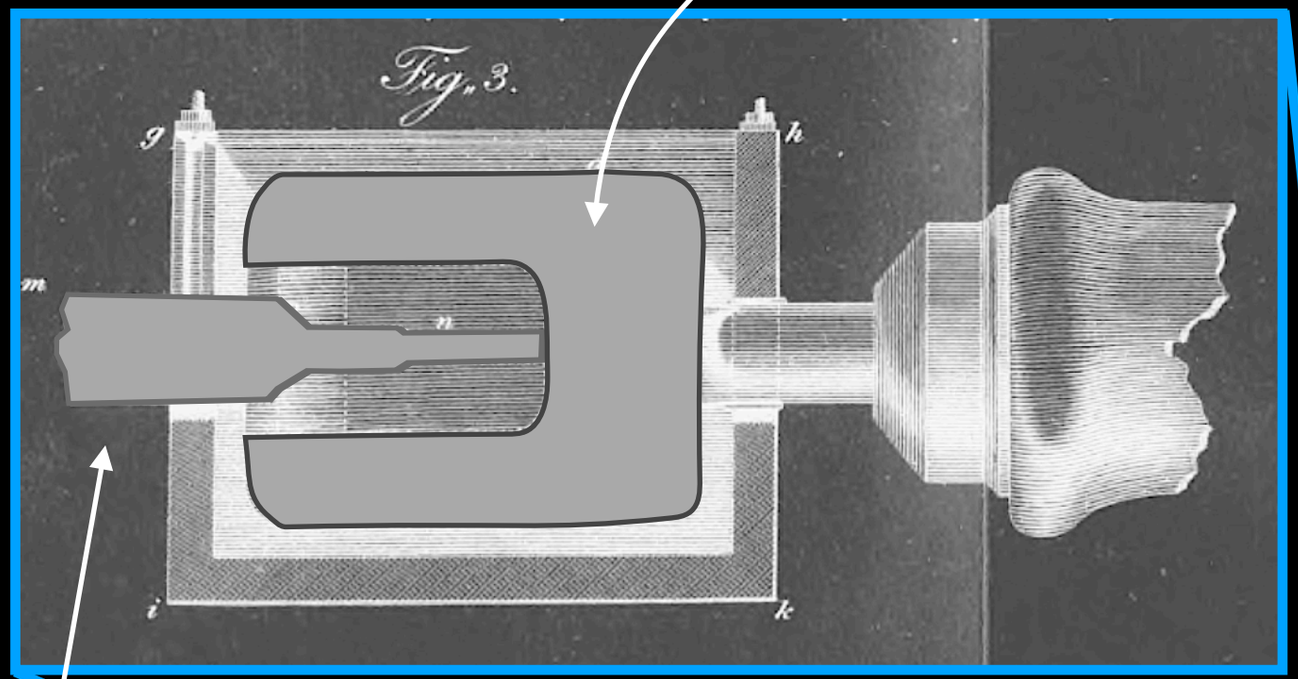
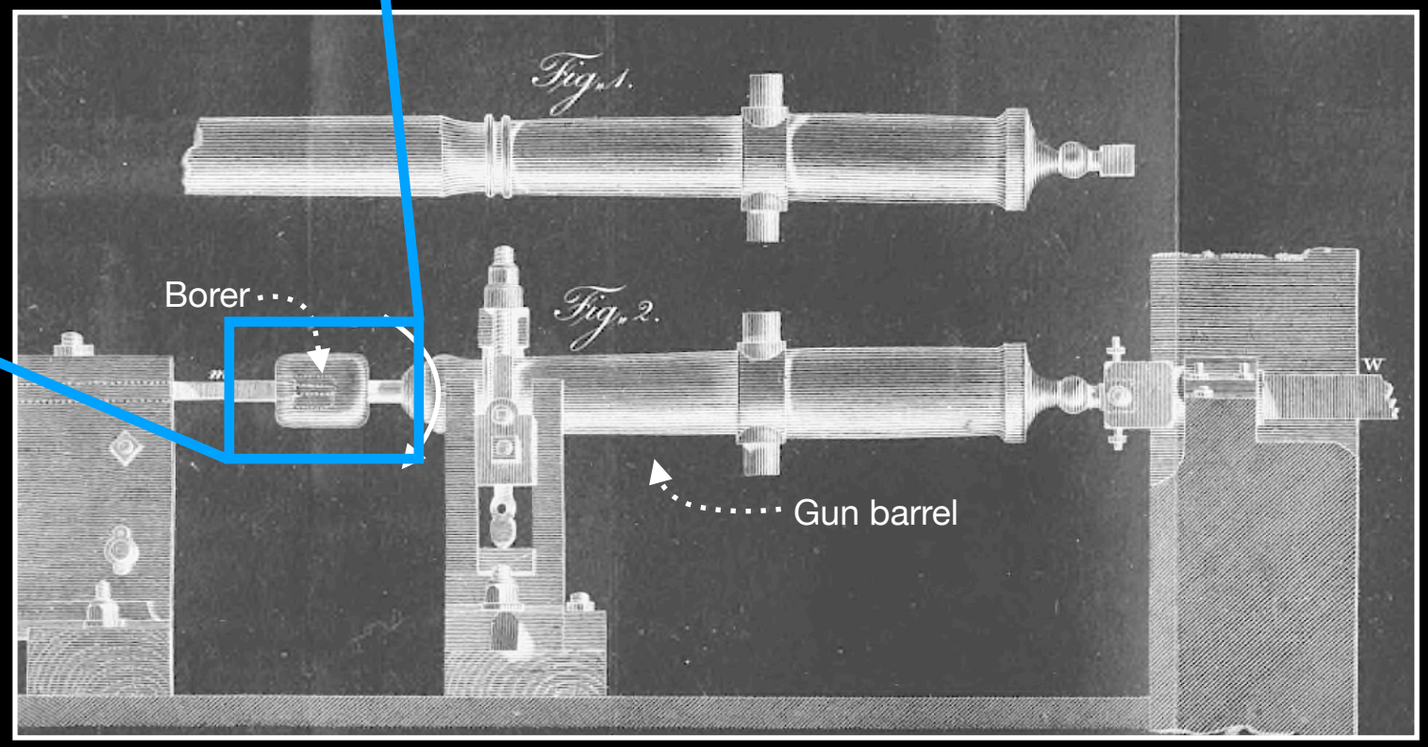


Blunt borer



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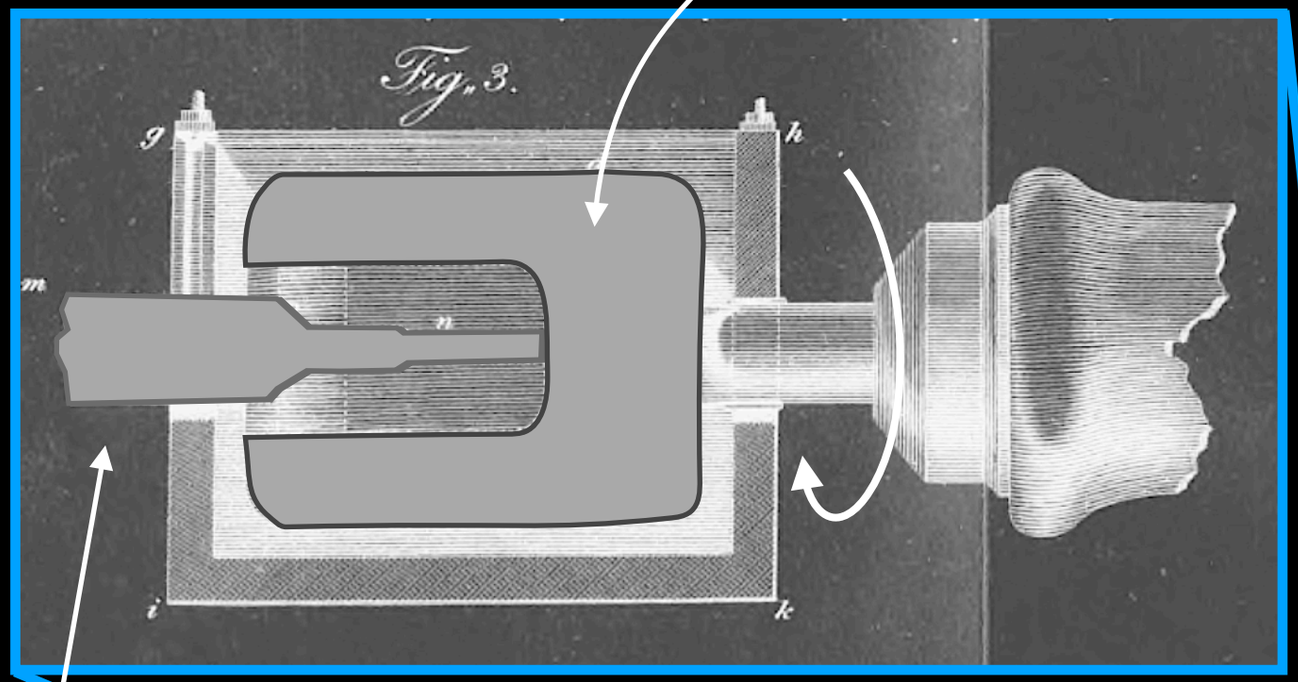

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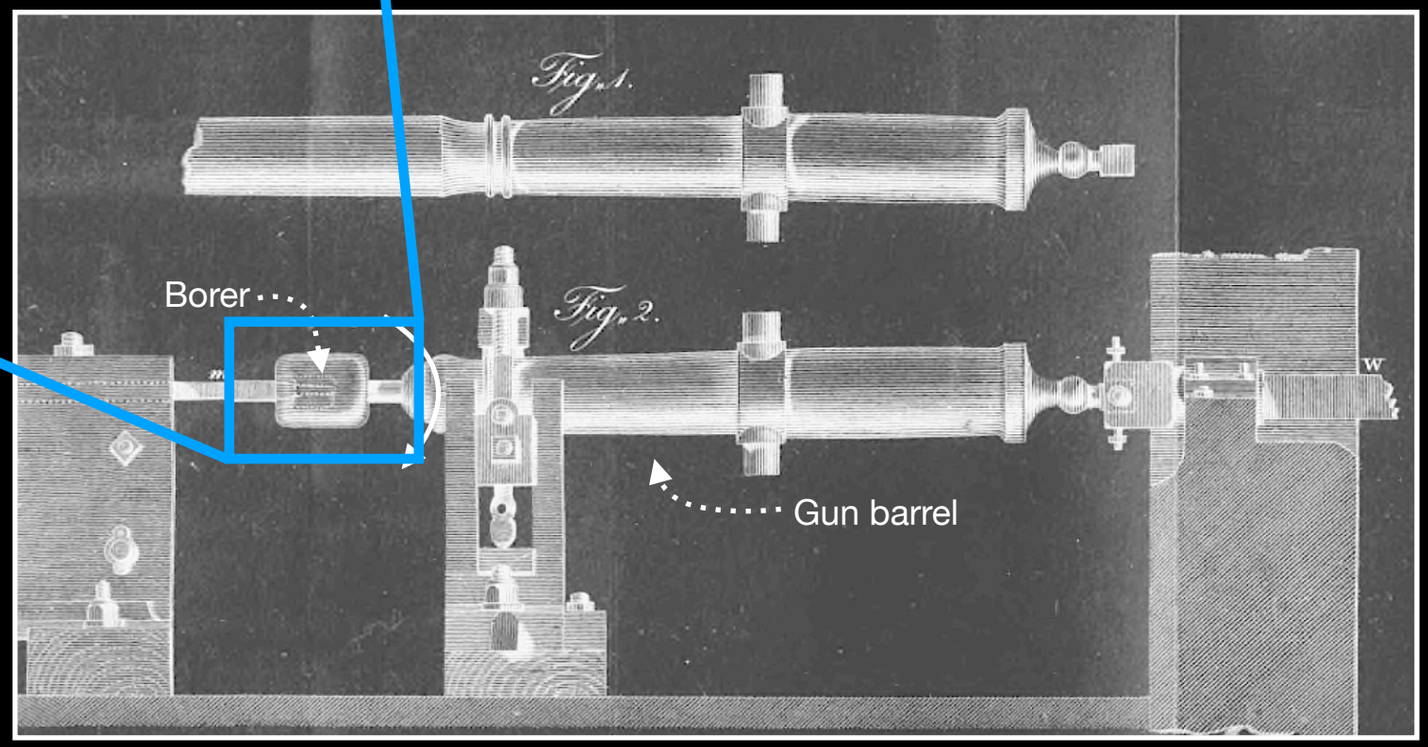

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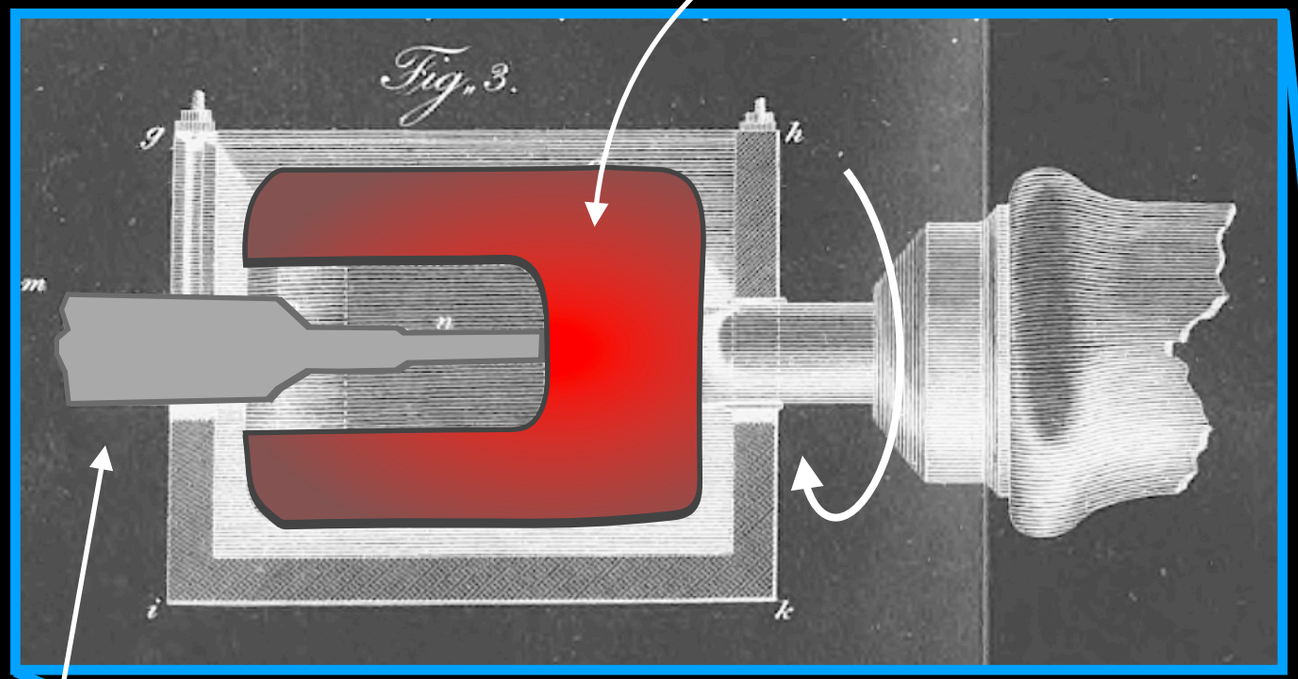

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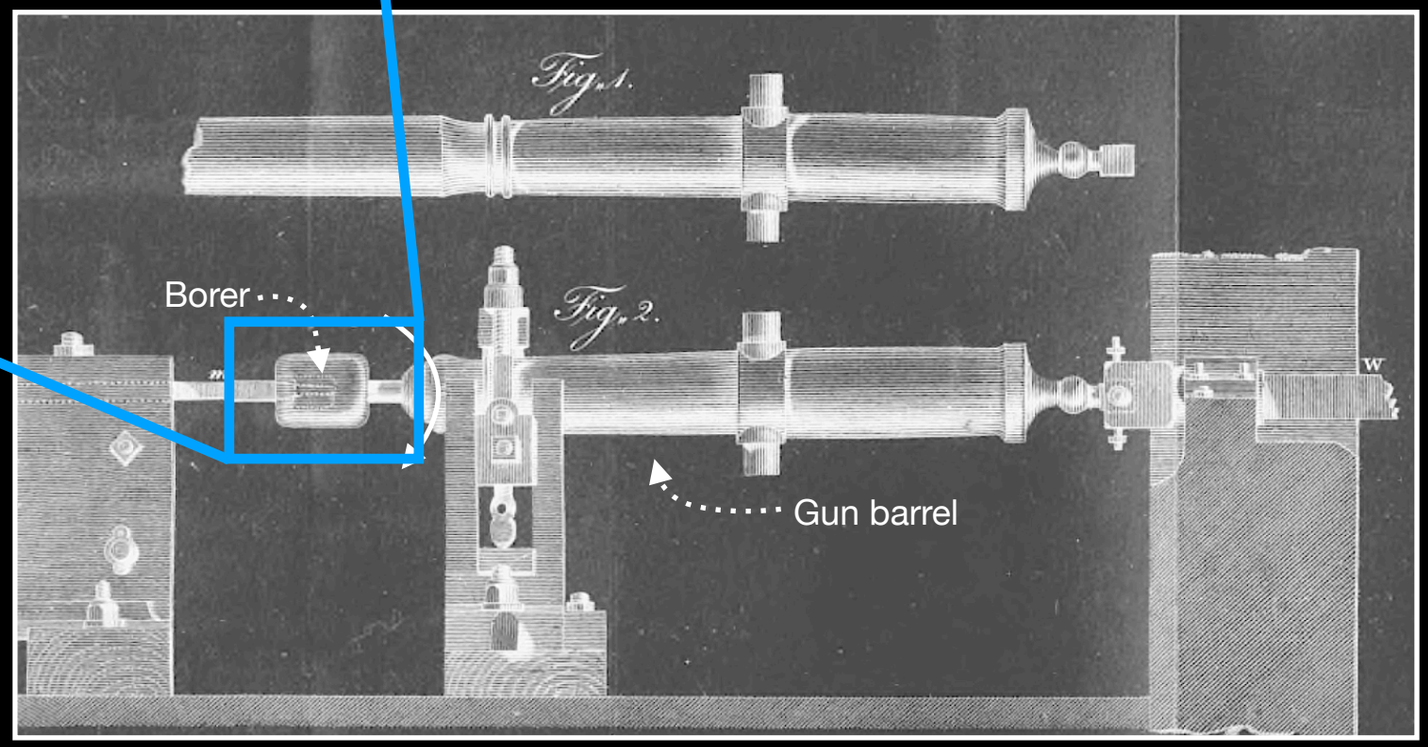

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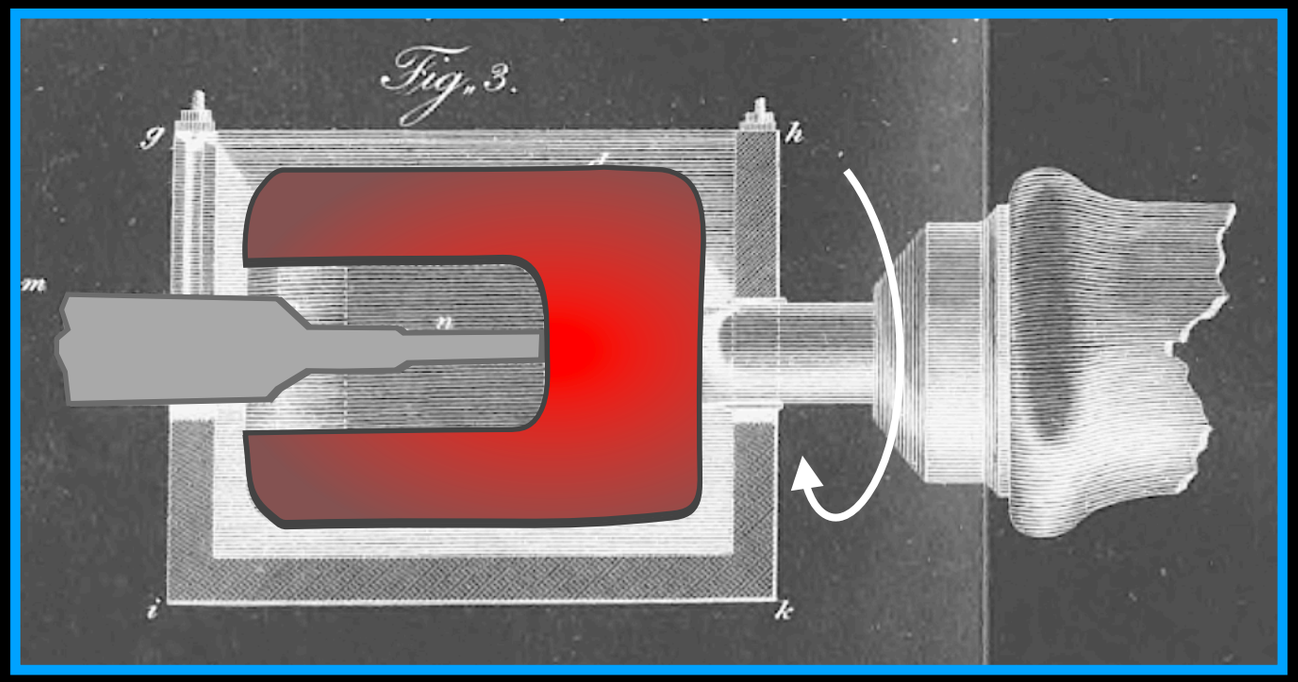

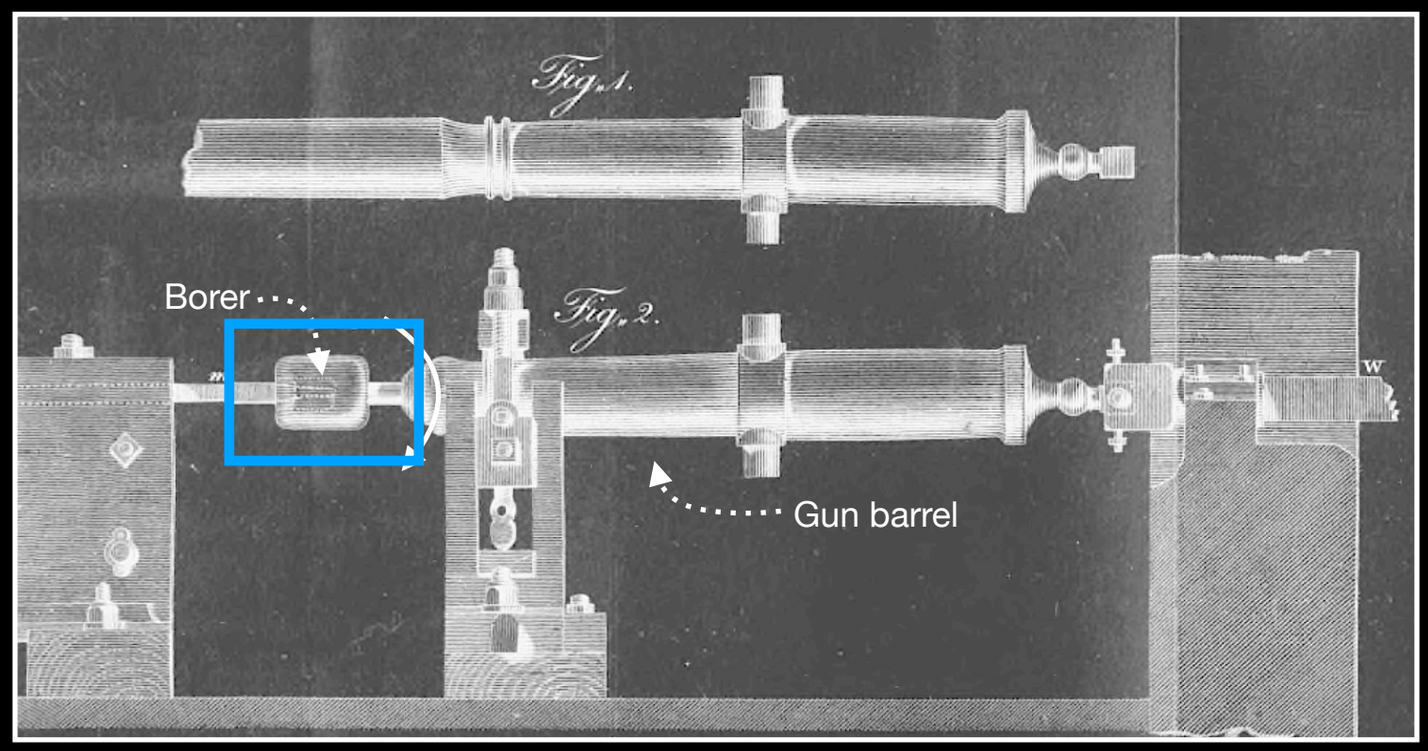

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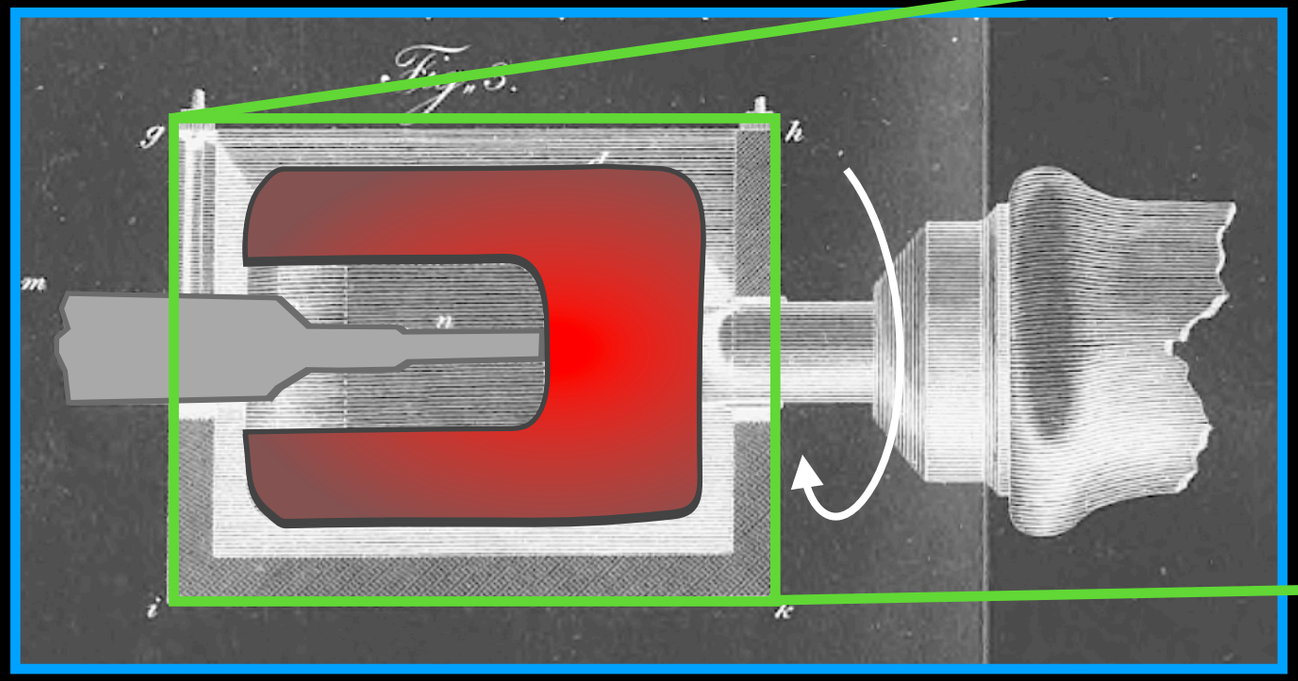

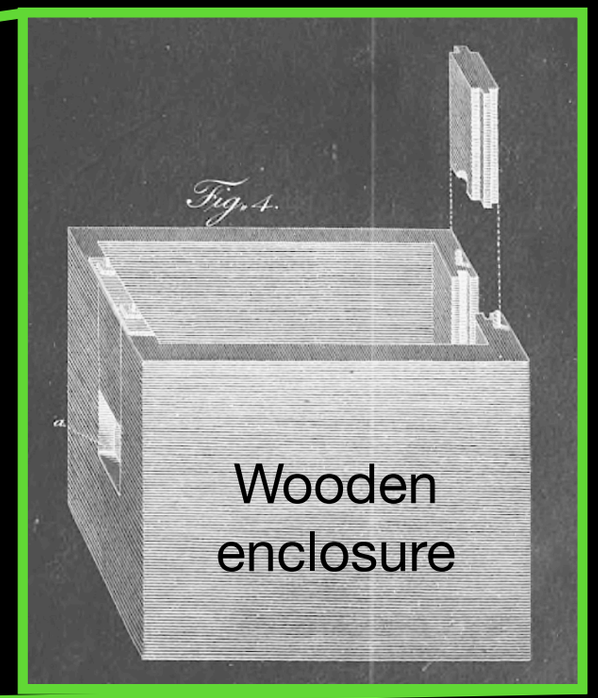

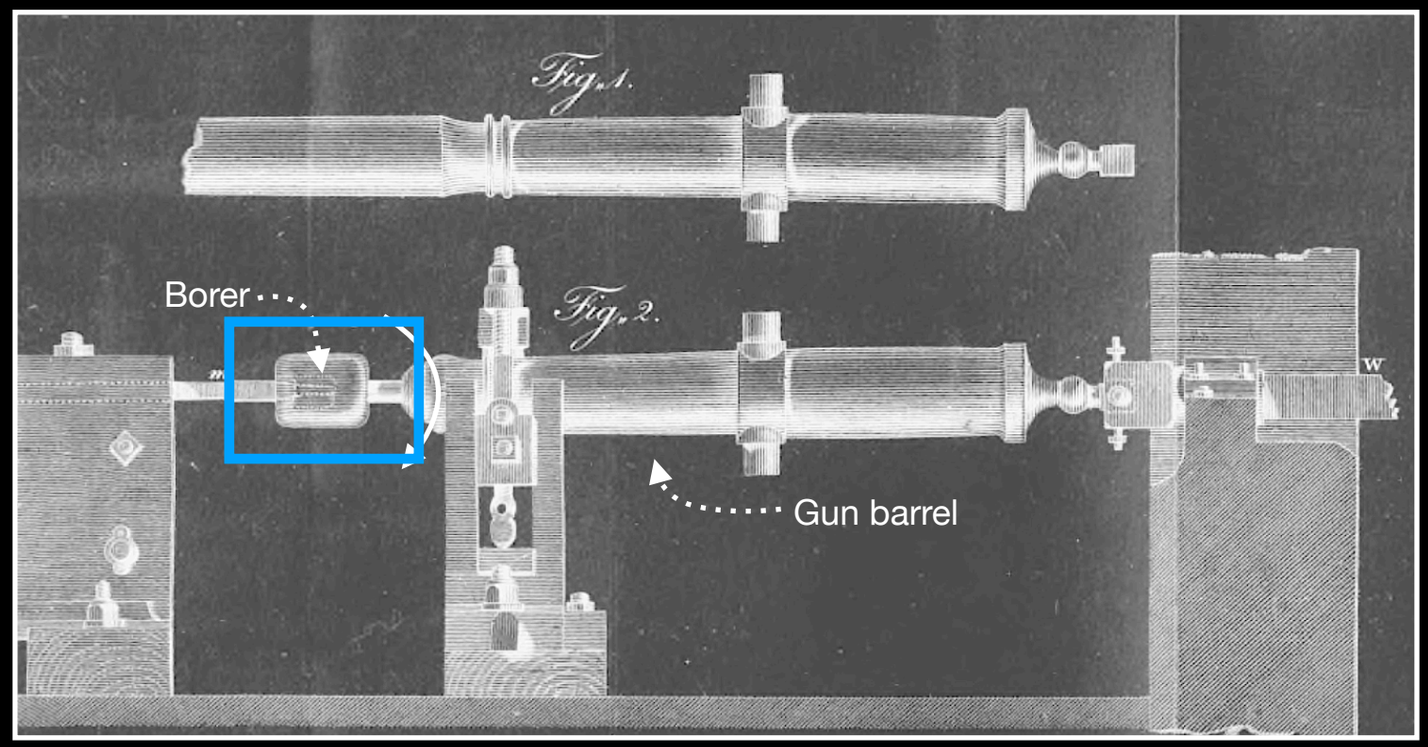

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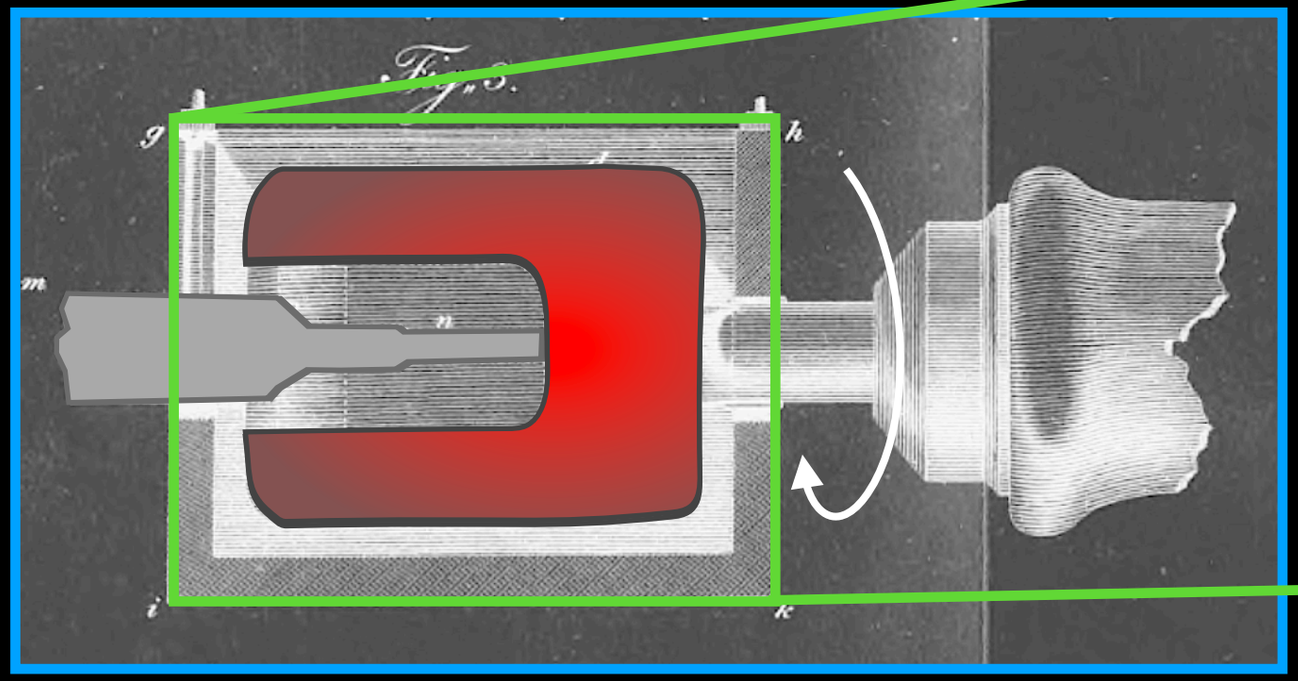
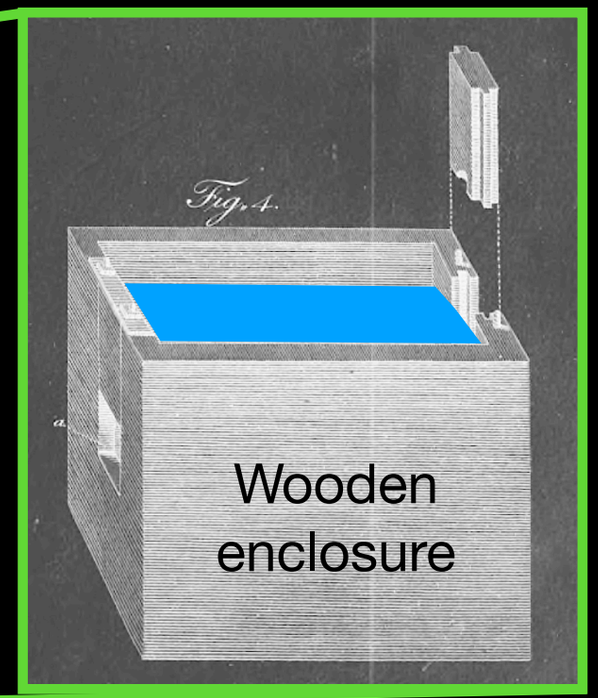
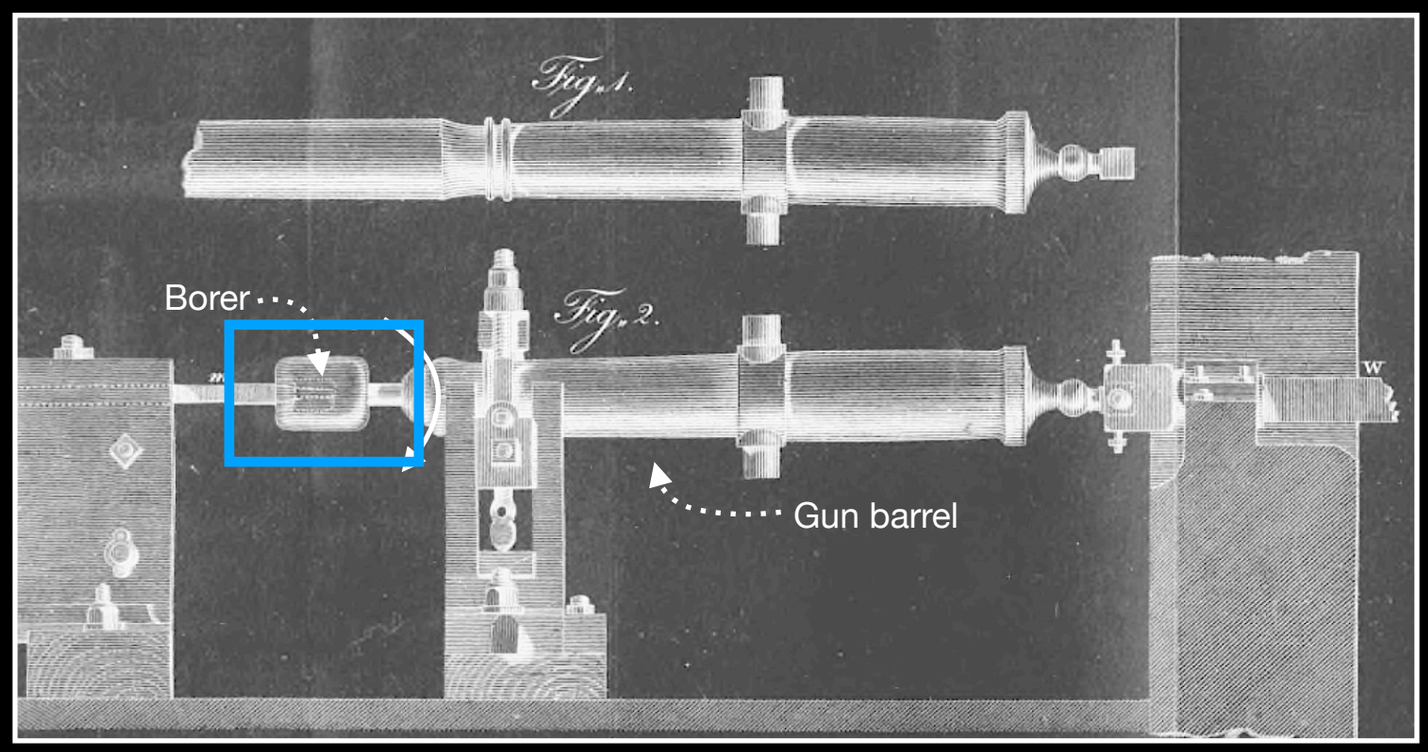




“The box was filled with cold water of temperature 60°F and the machinery was put into motion […], with the cylinder rotating at the rate of about 32 times in a minute.”



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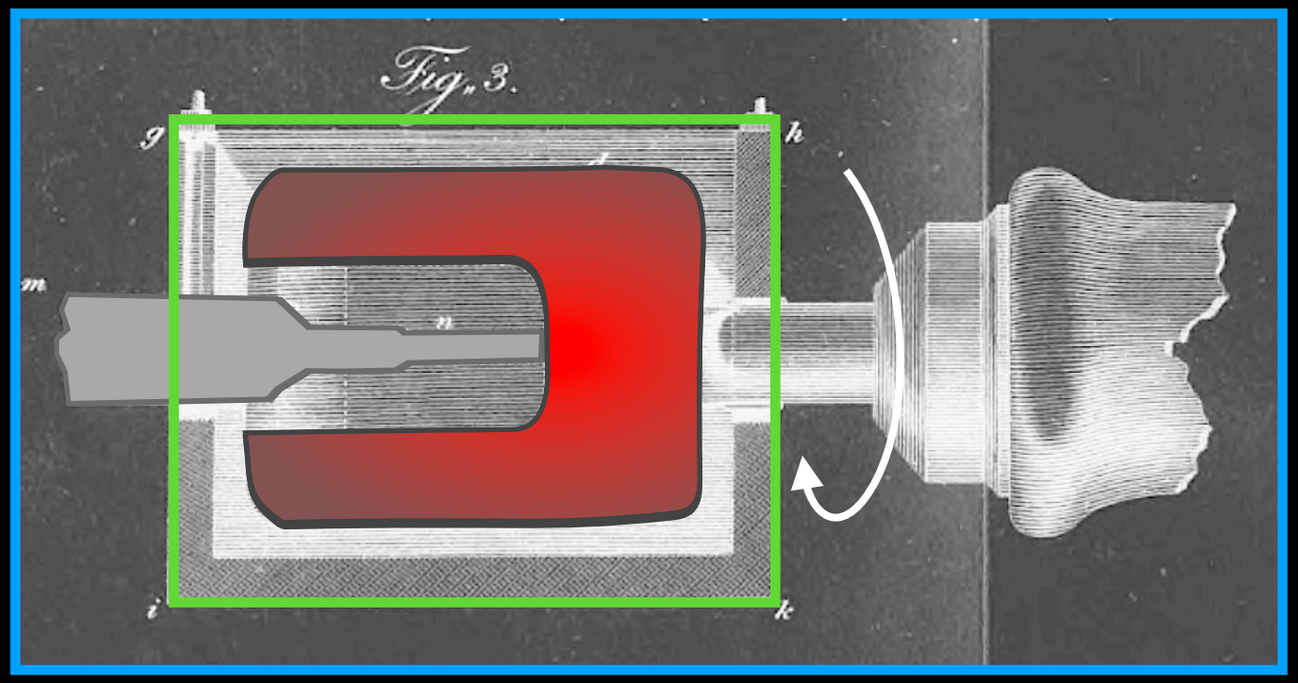
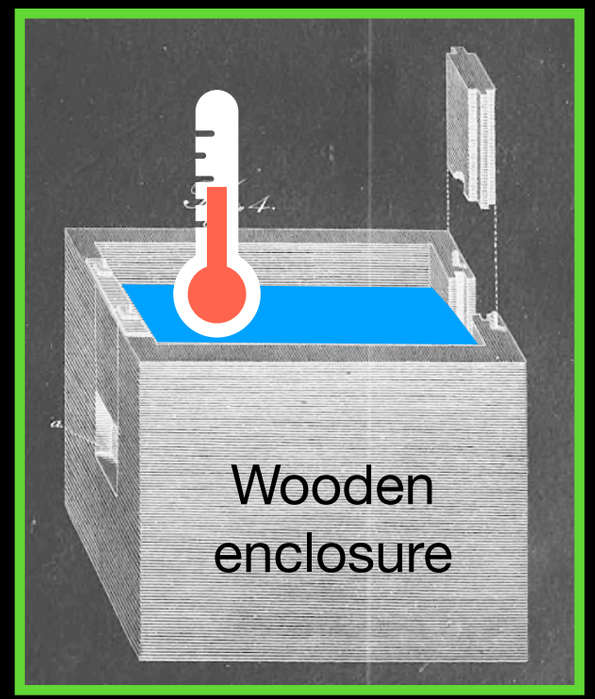
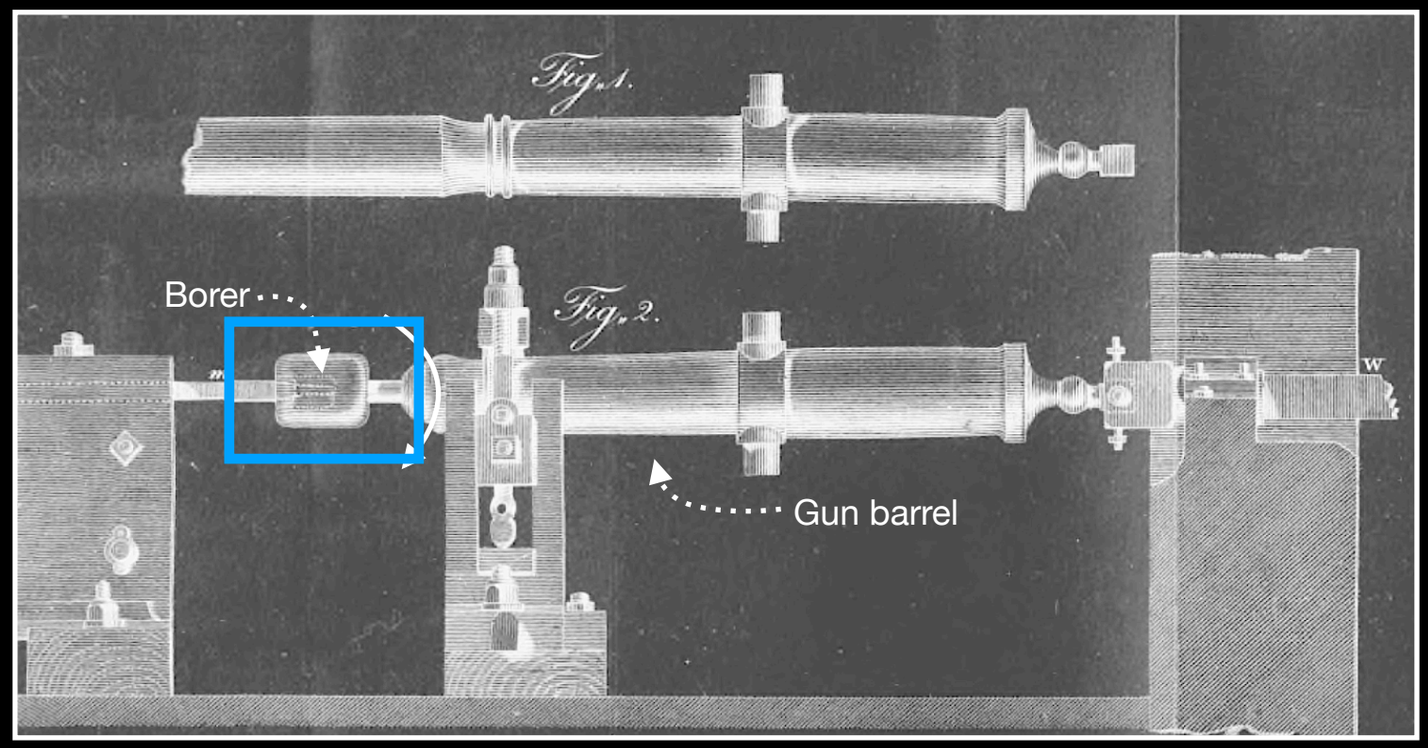




“At the end of 1 hour I found, by plunging a thermometer into the water in the box, that its temperature had been raised to no less than 107°F.”



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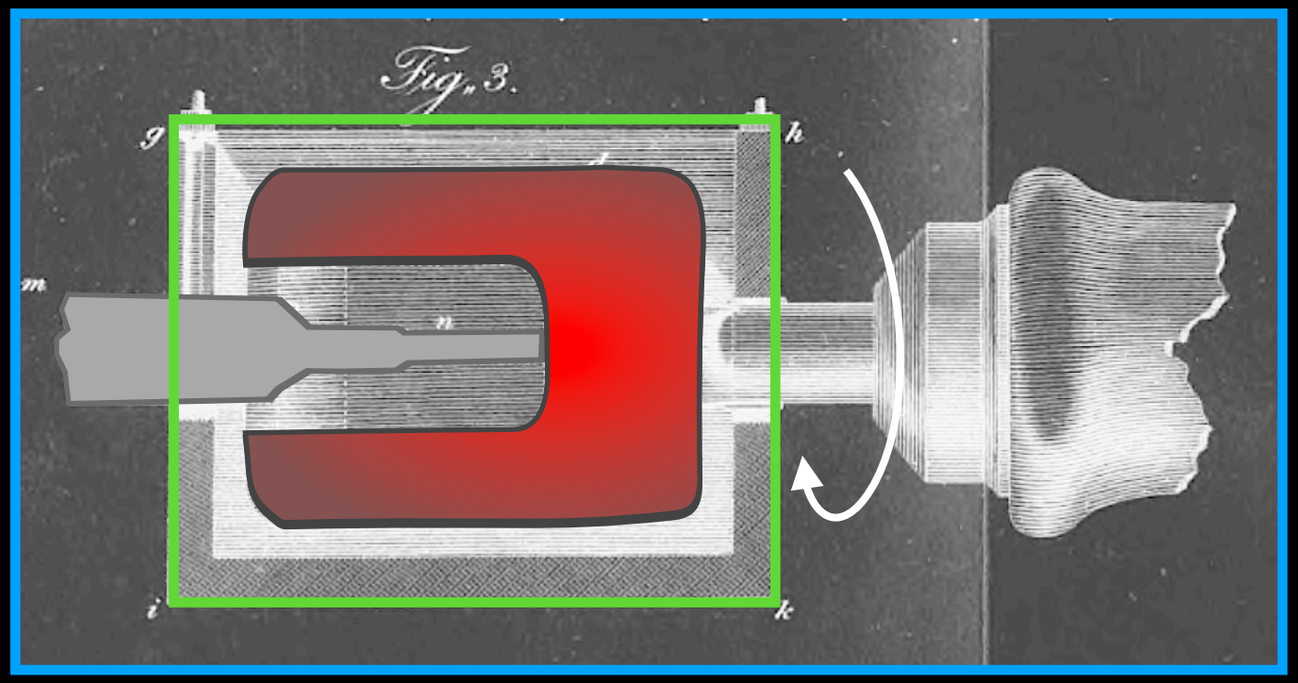
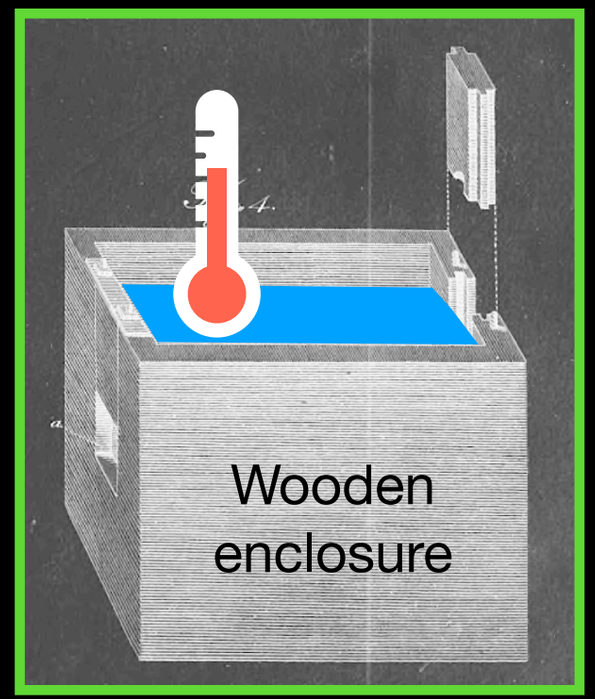
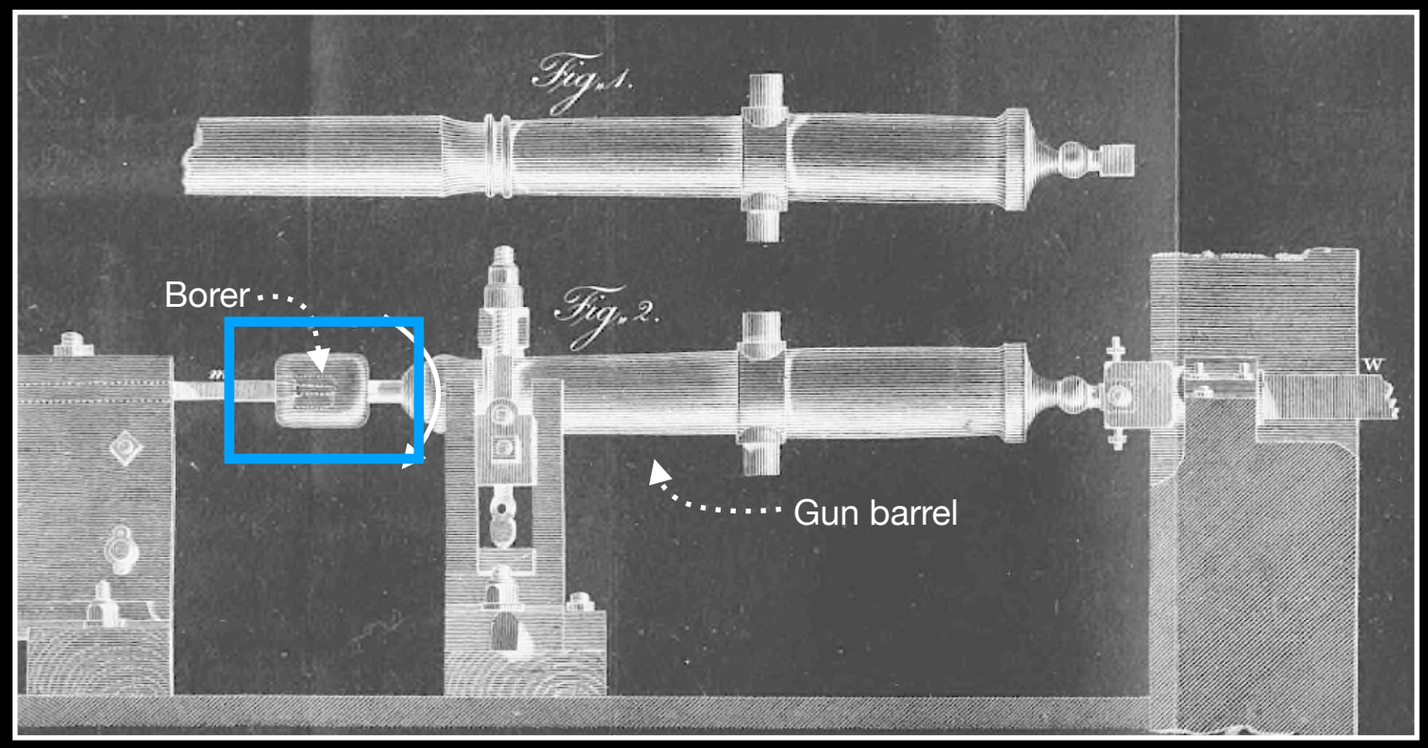




“At the end of 2 hours, the temperature of the water was found to be 178°F.”



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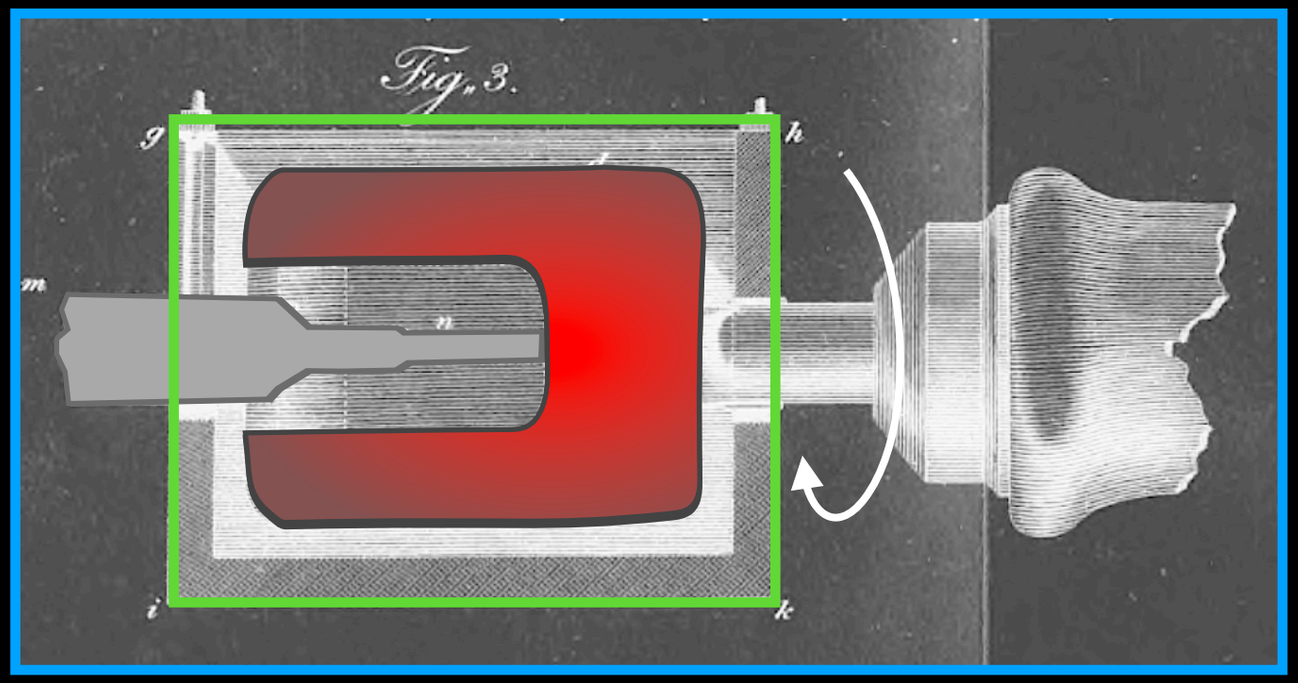
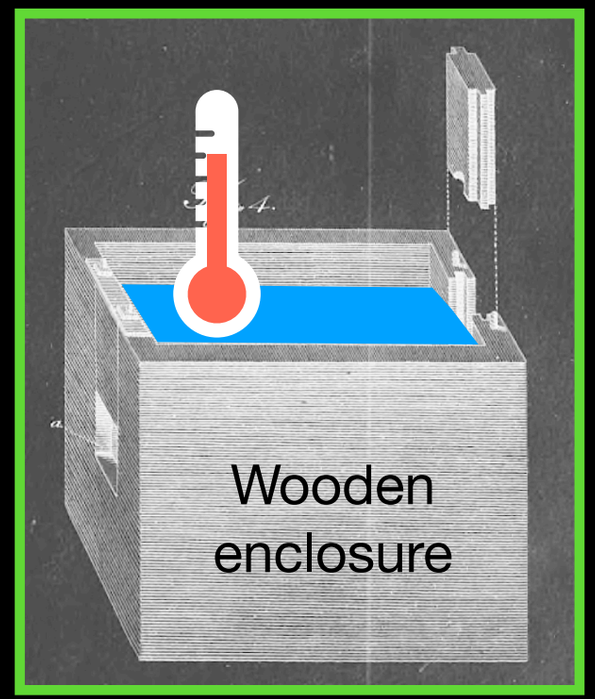
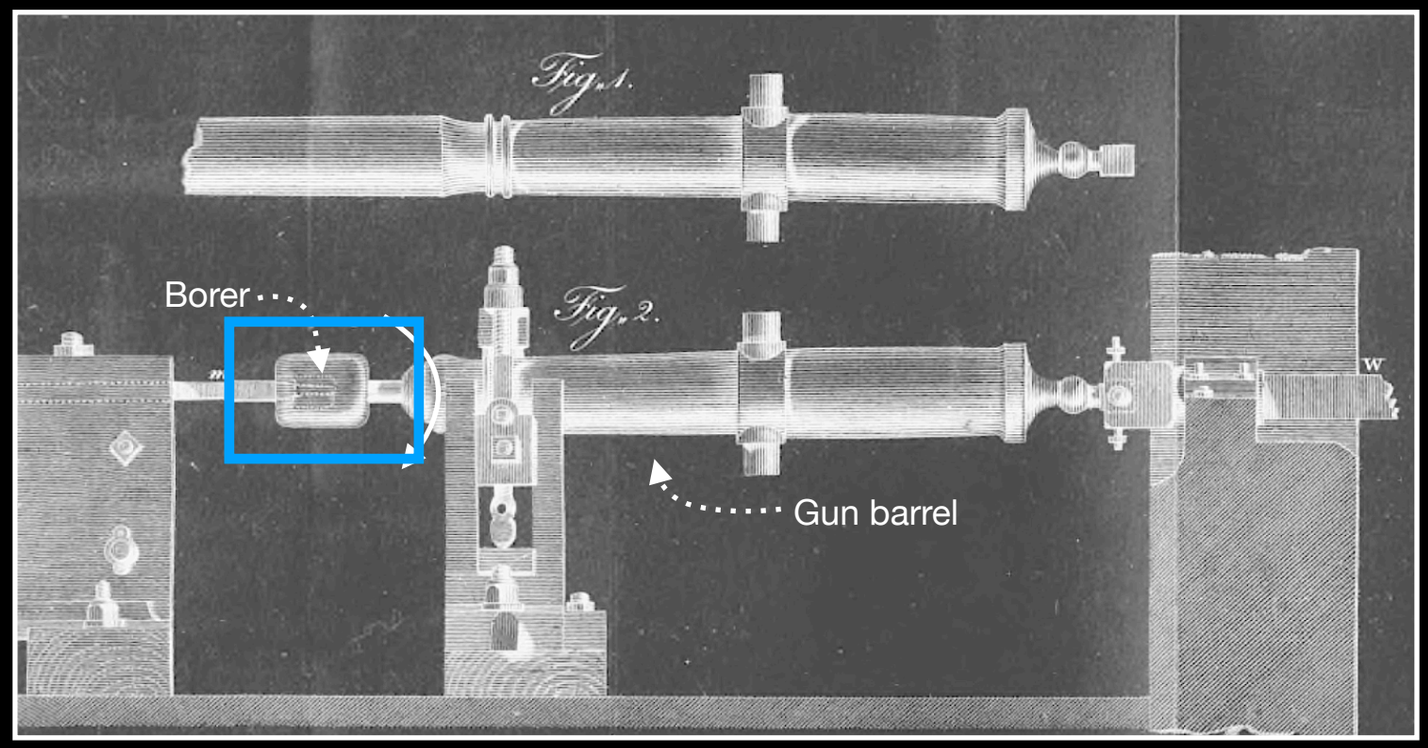




“At 2 hours and 20 minutes it was 200°F.”



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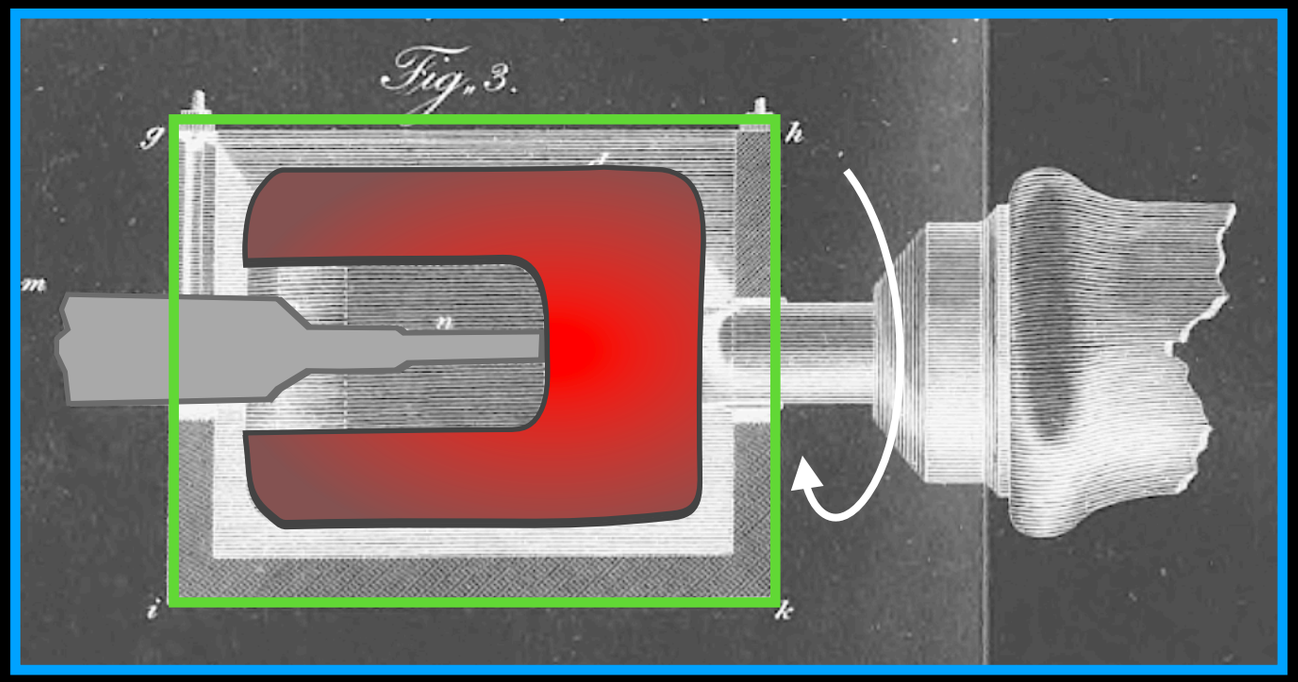
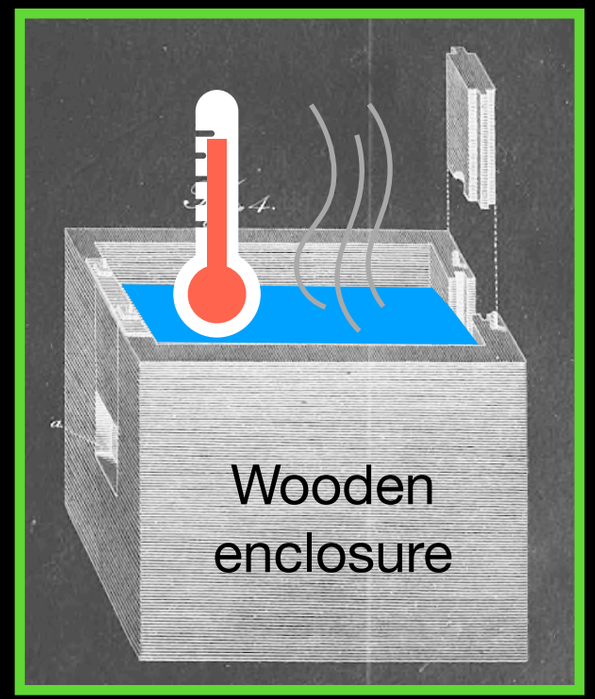
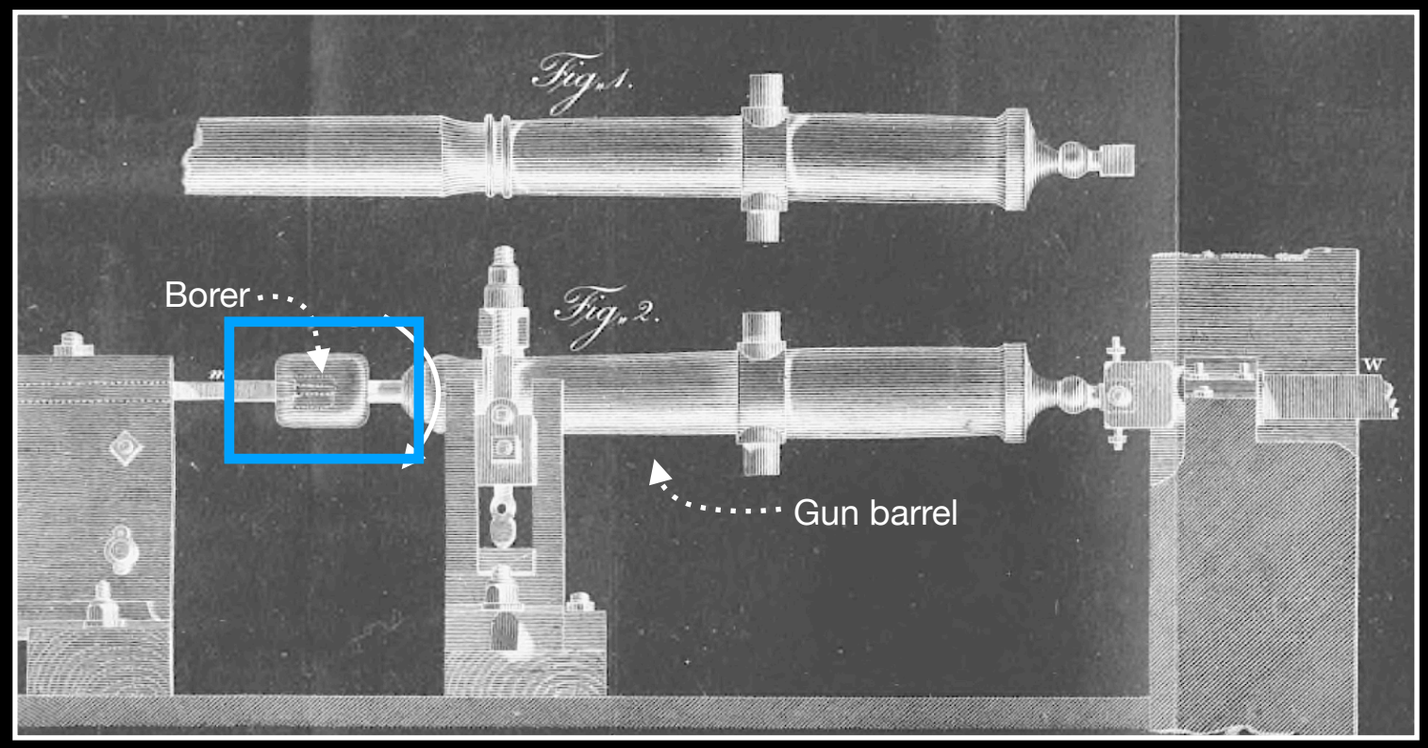


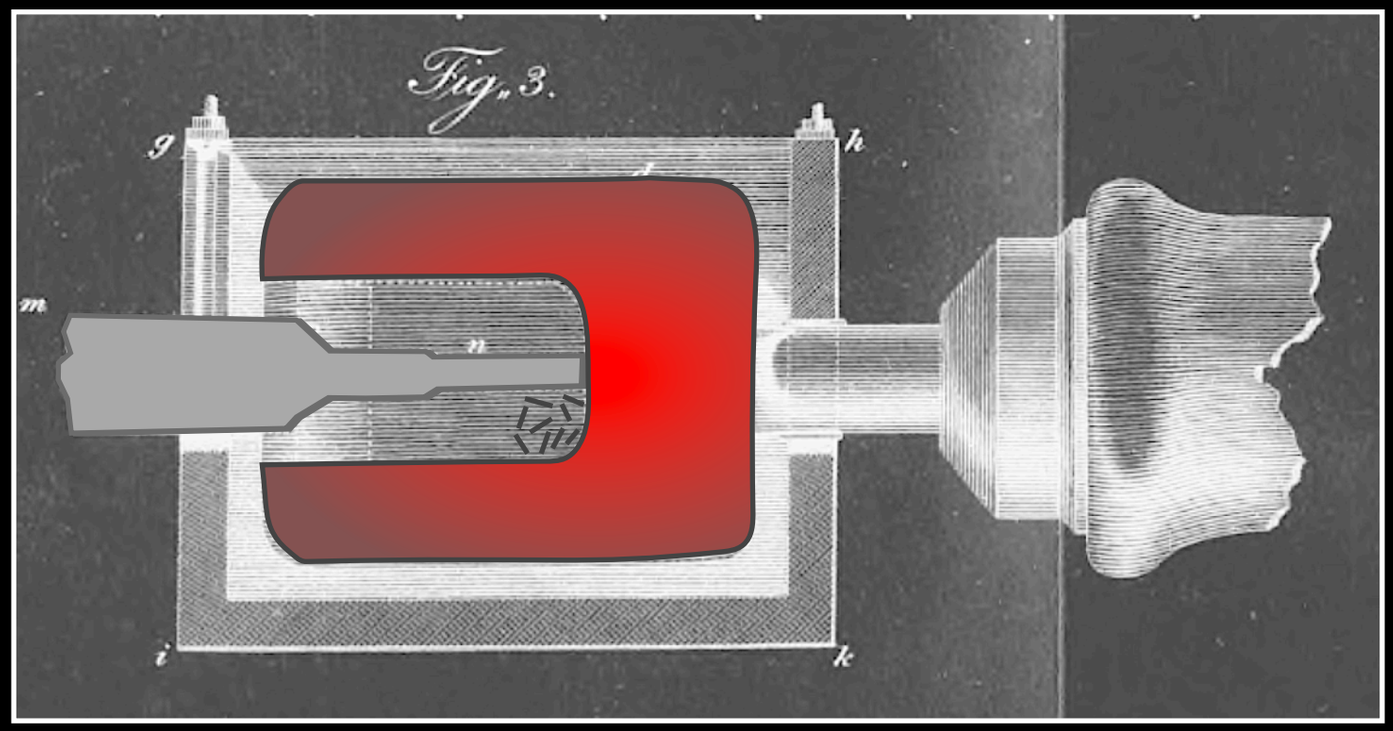


“At 2½ hours it ACTUALLY BOILED!”



“From whence came this heat?”

“Was it furnished by the small particles of metal, detached from the larger solid mass on their being rubbed together?”



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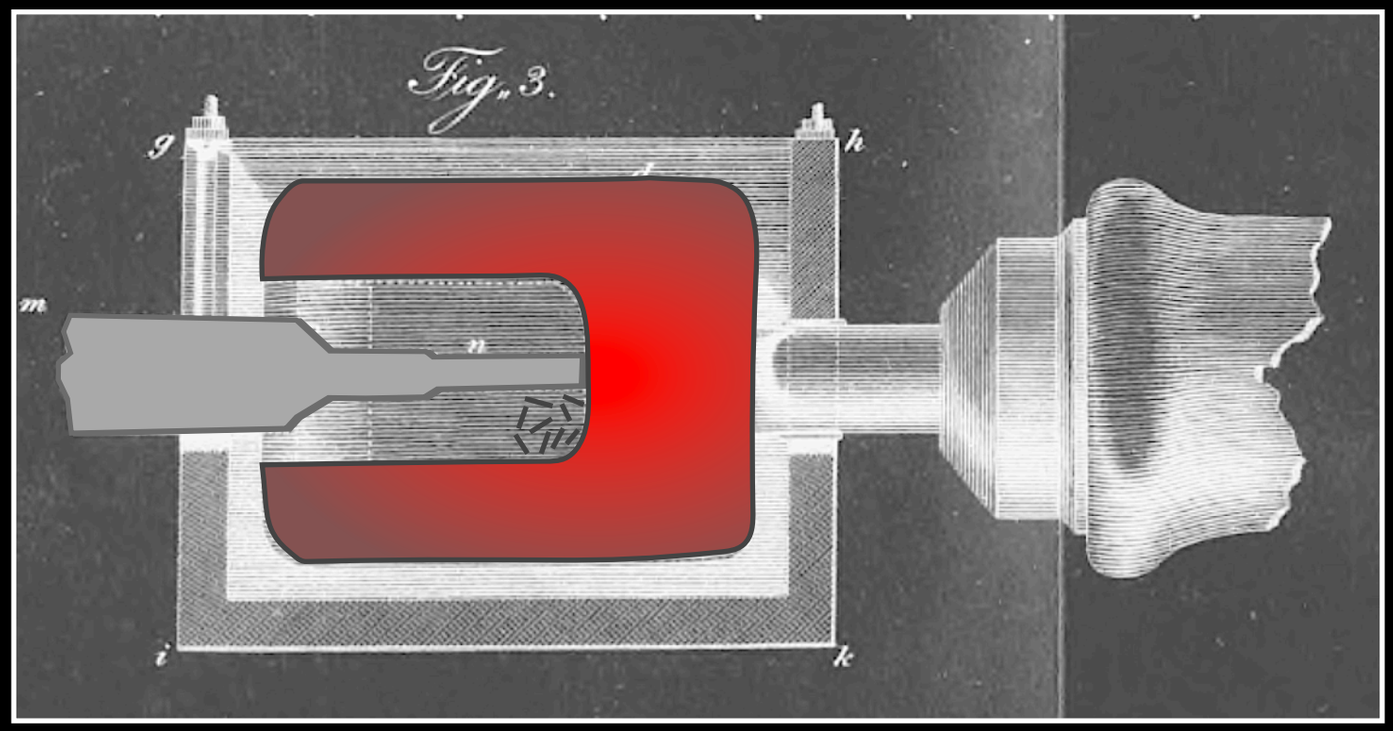
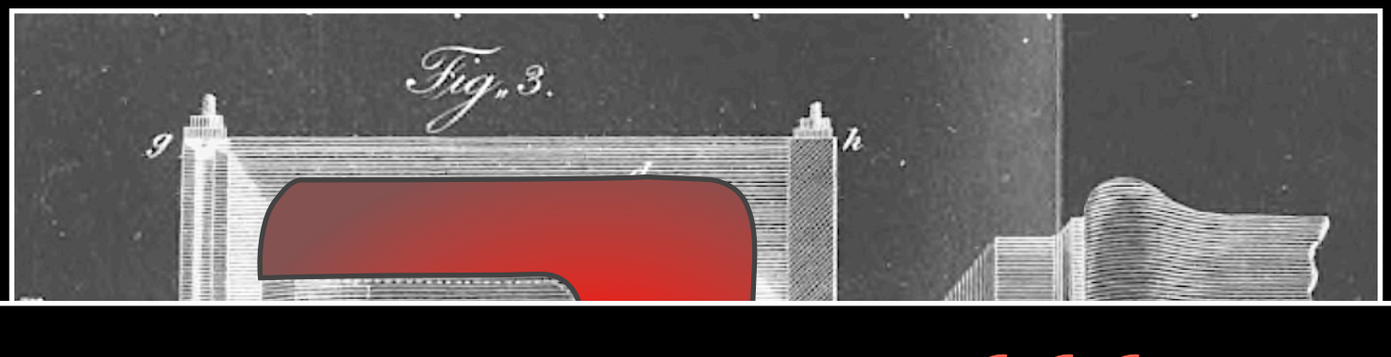


“If this were the case, according to the modern doctrine of caloric, the specific heat of the metal chips, ought not only to be changed, but the change undergone by them should be sufficiently large to account for all the heat produced.”

“From whence came this heat?”

“Was it furnished by the small particles of metal, detached from the larger solid mass on their being rubbed together?”



Caloric “squeezed” out of metal during boring

→ *attractive force between caloric and metal chips reduced*

→ *chips absorb less caloric when heated*

→ *chips have lower heat capacity*

“If th … at of
th… em

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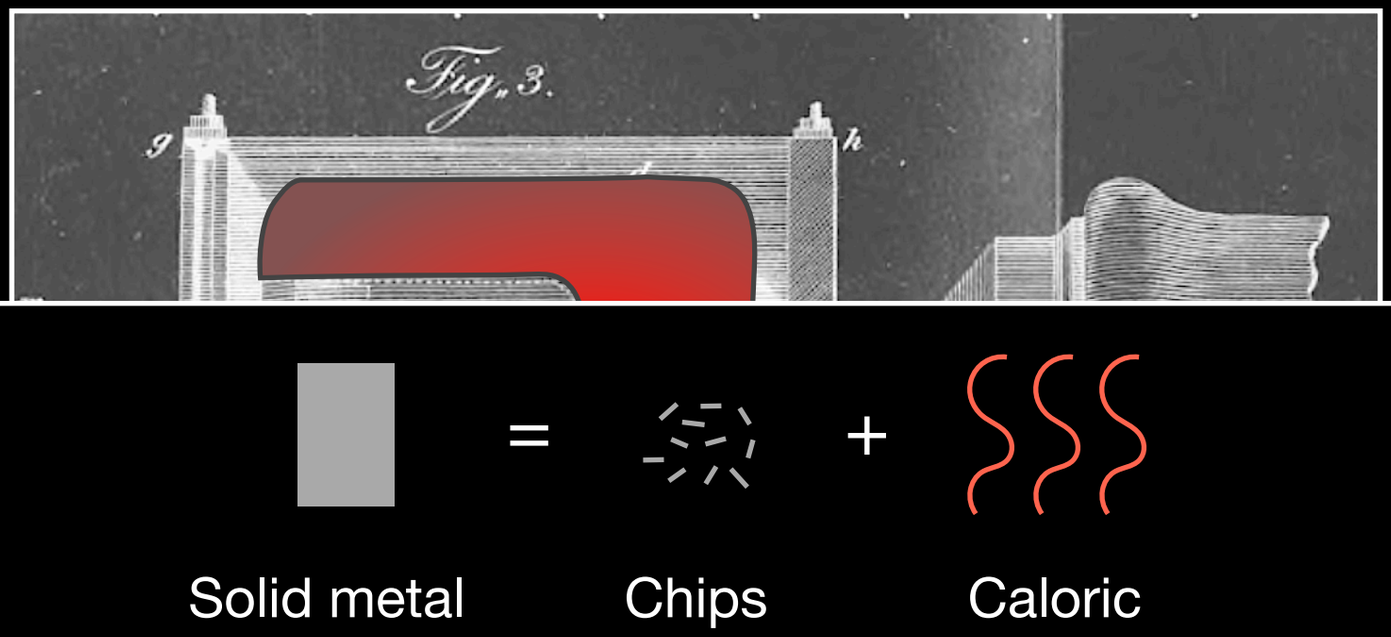

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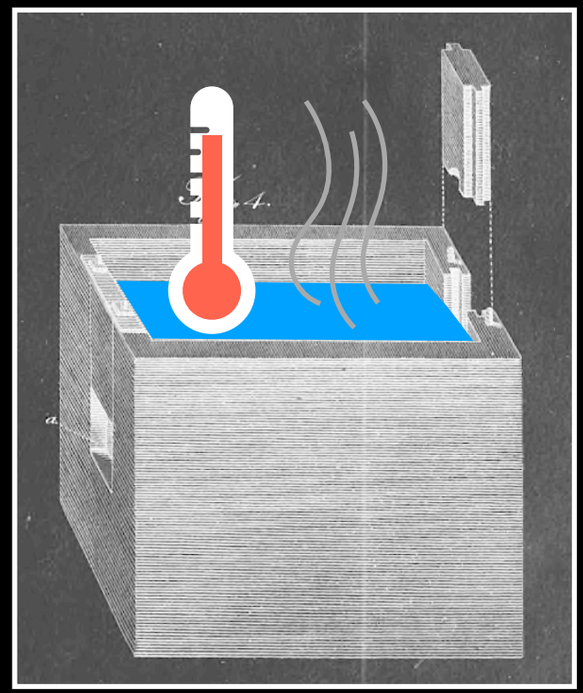
“If th … at of the … em

“But no such change had taken place […]”

“From whence came this heat?”

“From whence came this heat?”

“Was it furnished by the water that surrounded the machinery?”



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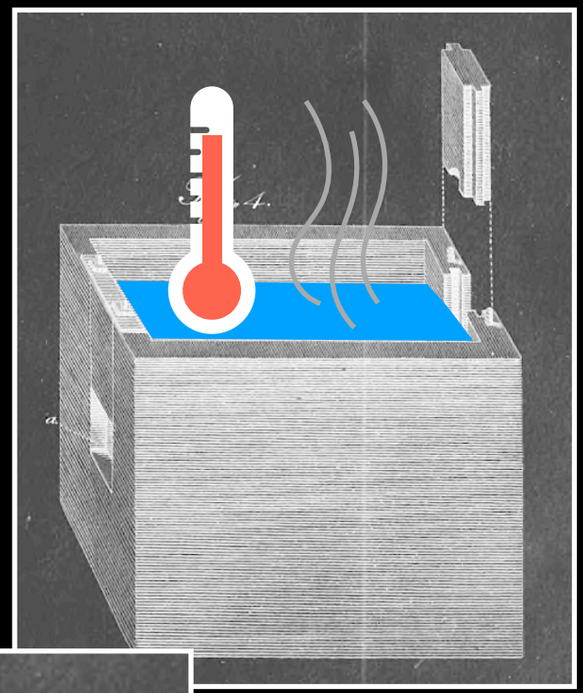
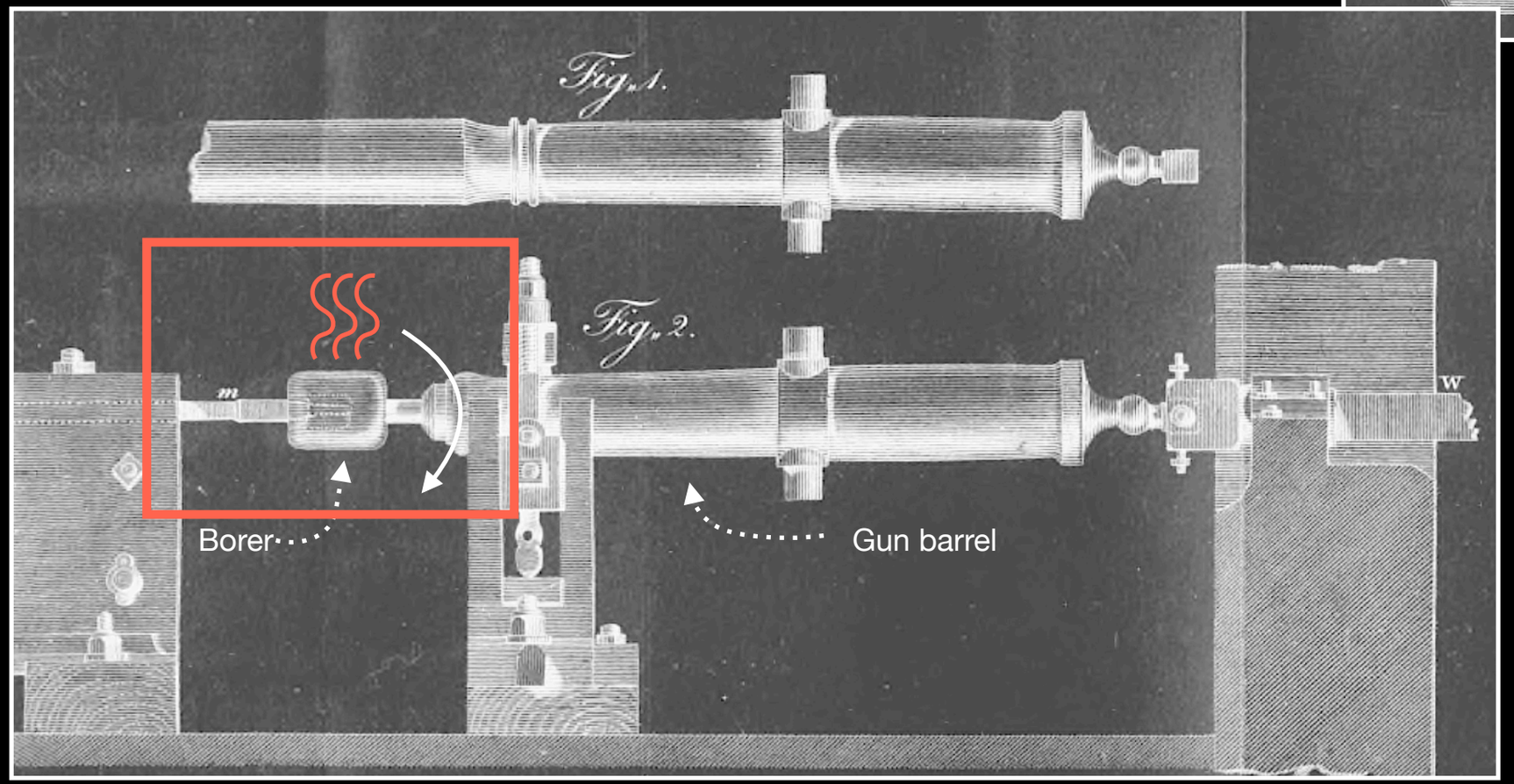
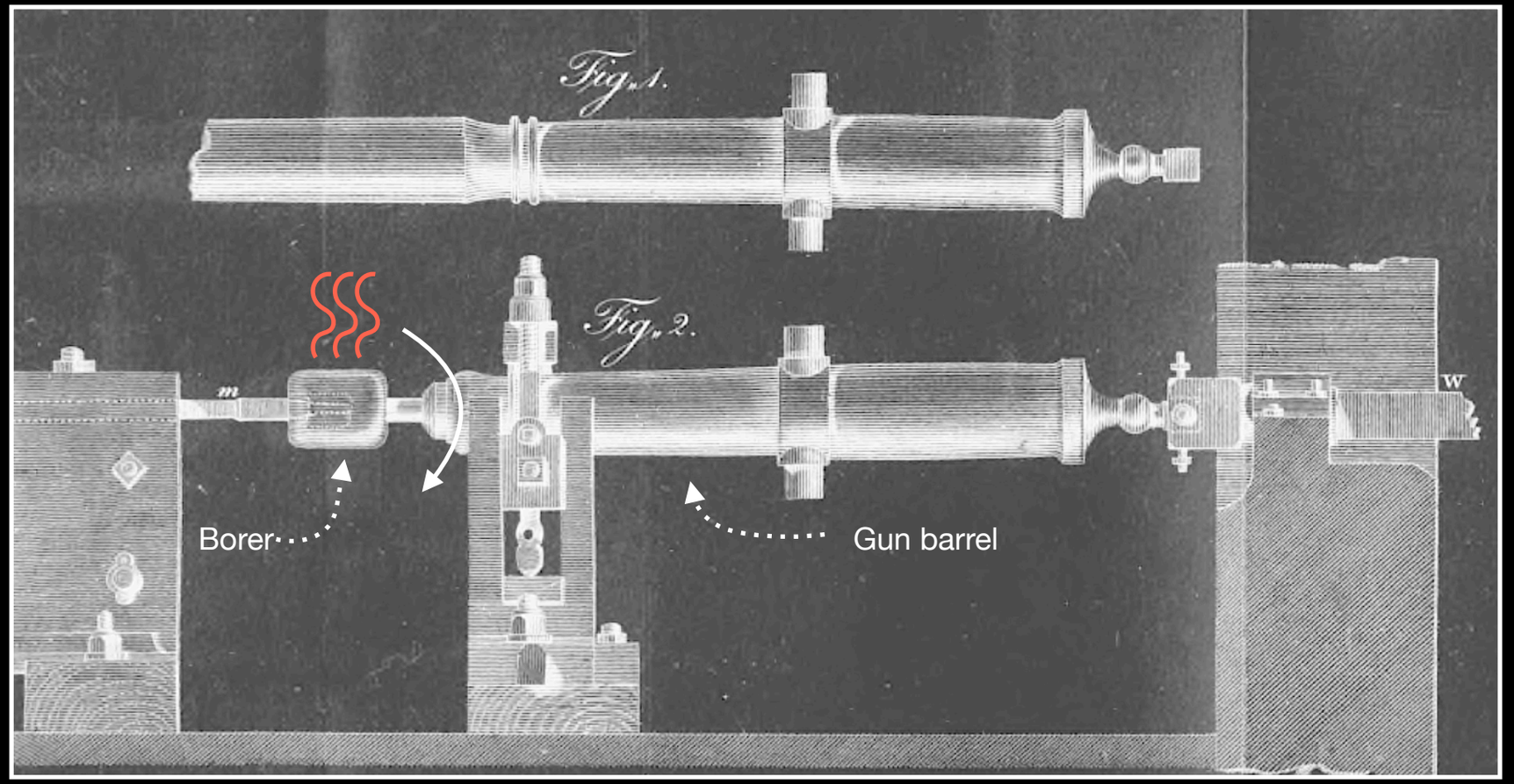


“Was it furnished by means of the iron bar to the end of which the blunt steel borer was fixed?”



“From whence came this heat?”

He concludes: heat could not have been injected from the outside!

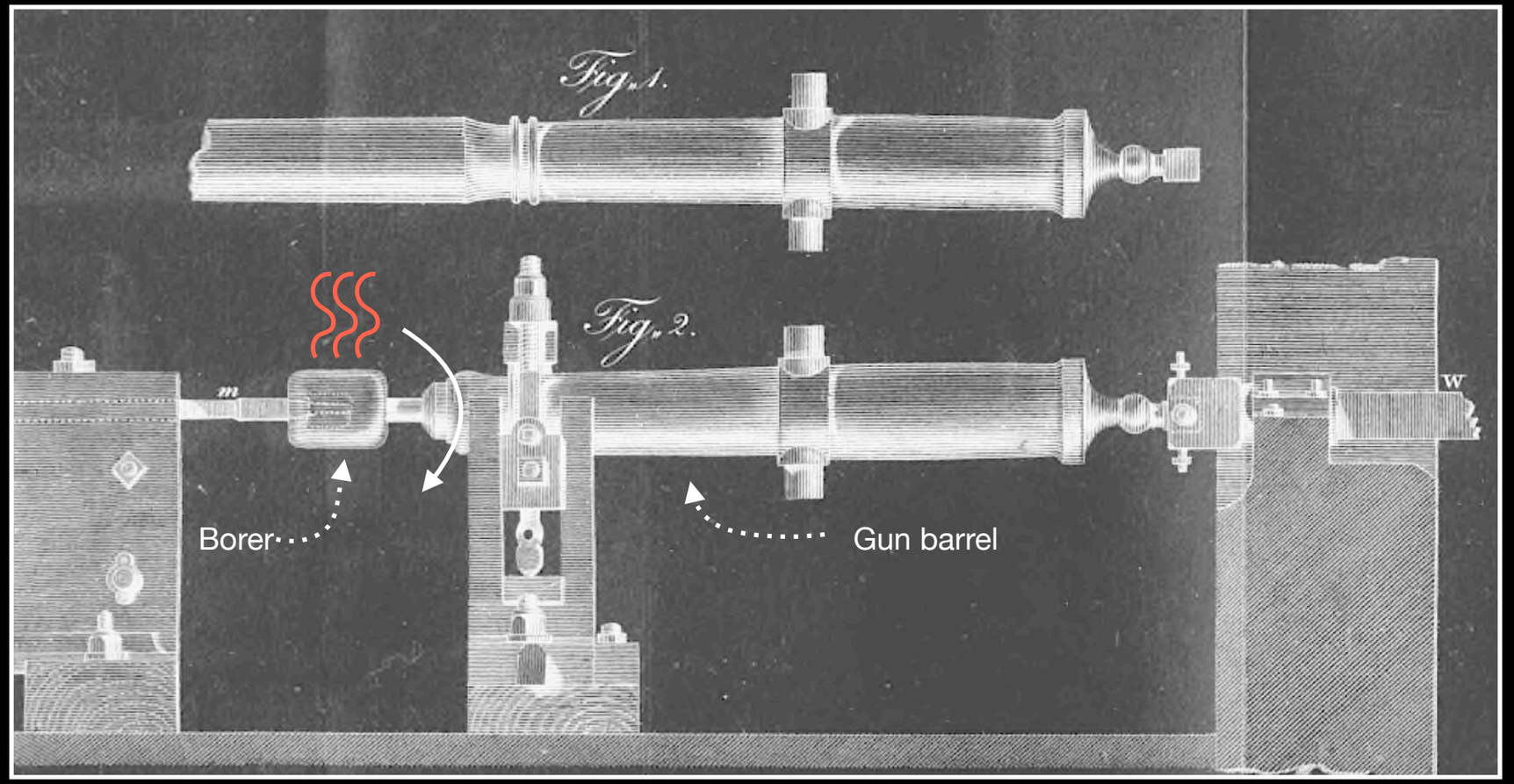


“From whence came this heat?”

He concludes: heat could not have been injected from the outside!

“It is very difficult for me to form any distinct idea of anything capable of being excited and communicated in the matter in which heat was excited and communicated in this experiment, except it be MOTION.”

(1798)



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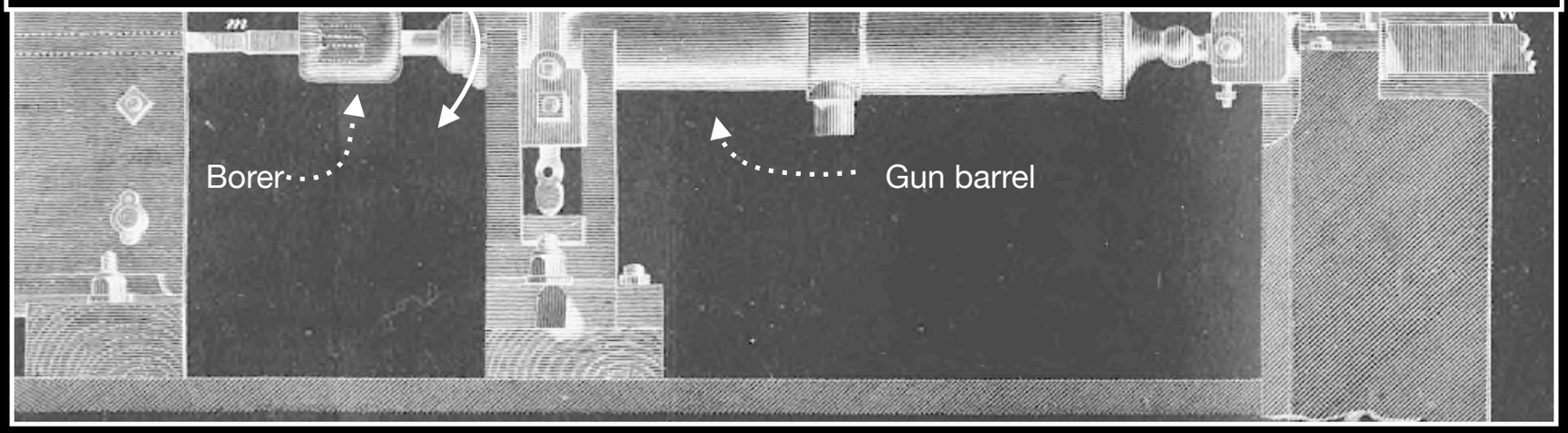
The caloricists did not accept Rumford’s conclusions!

Too many loopholes in his experiment:

Exact amount of mechanical energy used?

Exact amount of heat generated?



James Prescott Joule

Physicist and brewer

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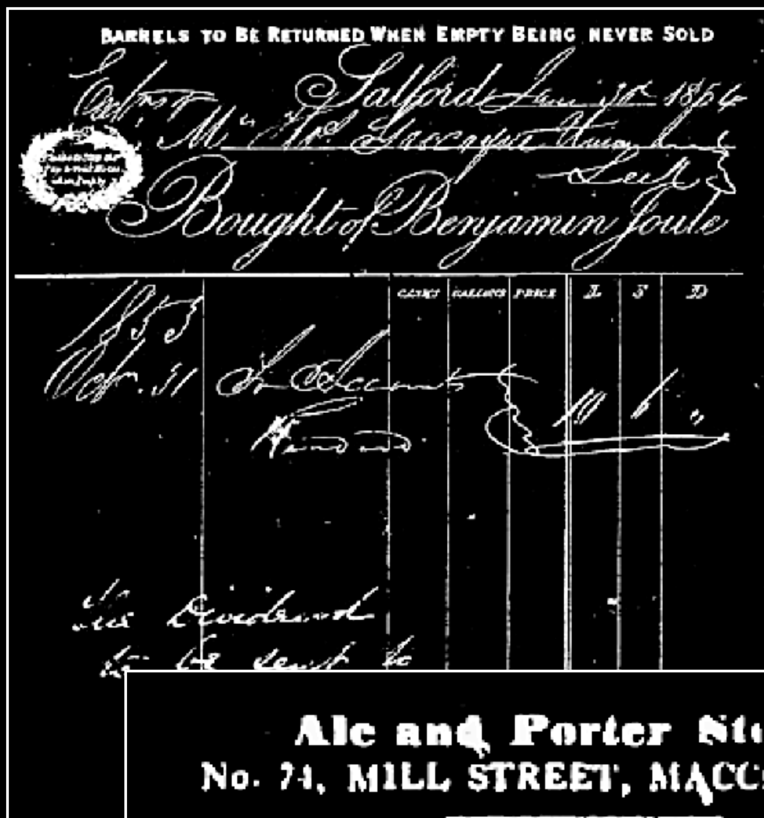
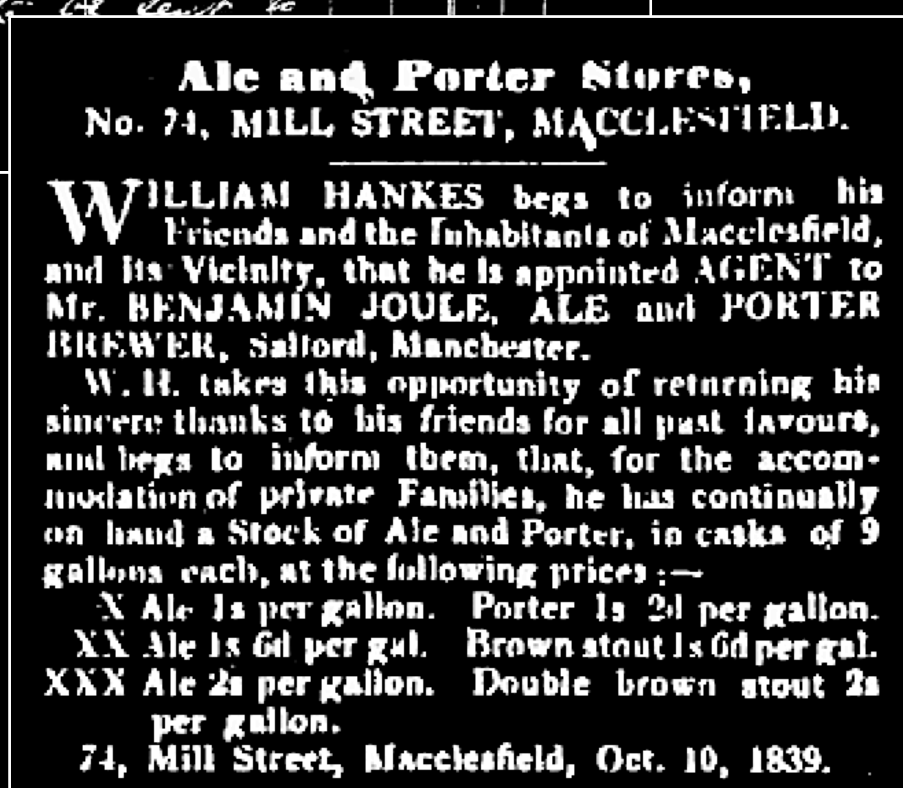




Ale and Porter Stores,
No. 74, MILL STREET, MACCLESFIELD.

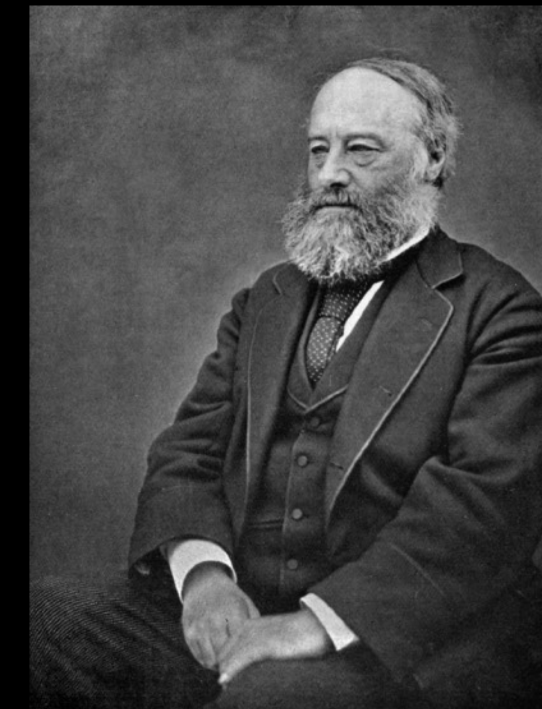
WILLIAM HANKES begs to inform his Friends and the Inhabitants of Macclesfield, and its Vicinity, that he is appointed AGENT to Mr. BENJAMIN JOULE, ALE and PORTER BREWER, Salford, Manchester.

W. H. takes this opportunity of returning his sincere thanks to his friends for all past favours, and begs to inform them, that, for the accommodation of private Families, he has continually on hand a Stock of Ale and Porter, in casks of 9 gallons each, at the following prices:—

X Ale 1s per gallon. Porter 1s 2d per gallon.
XX Ale 1s 6d per gal. Brown stout 1s 6d per gal.
XXX Ale 2s per gallon. Double brown stout 2s per gallon.

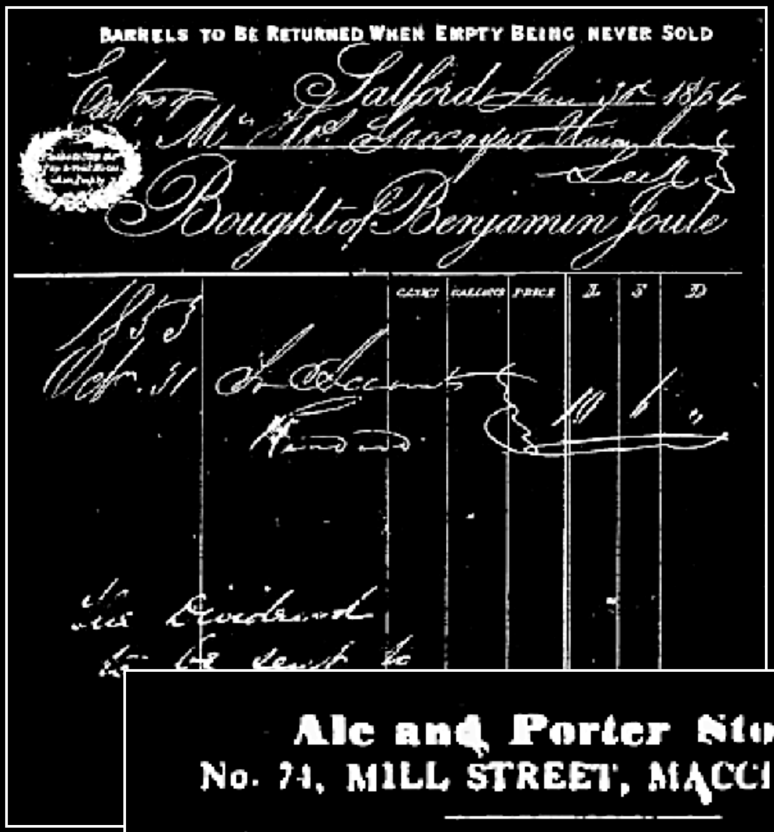
74, Mill Street, Macclesfield, Oct. 10, 1839.

Worked (and later managed) his father's brewery …



James Prescott Joule

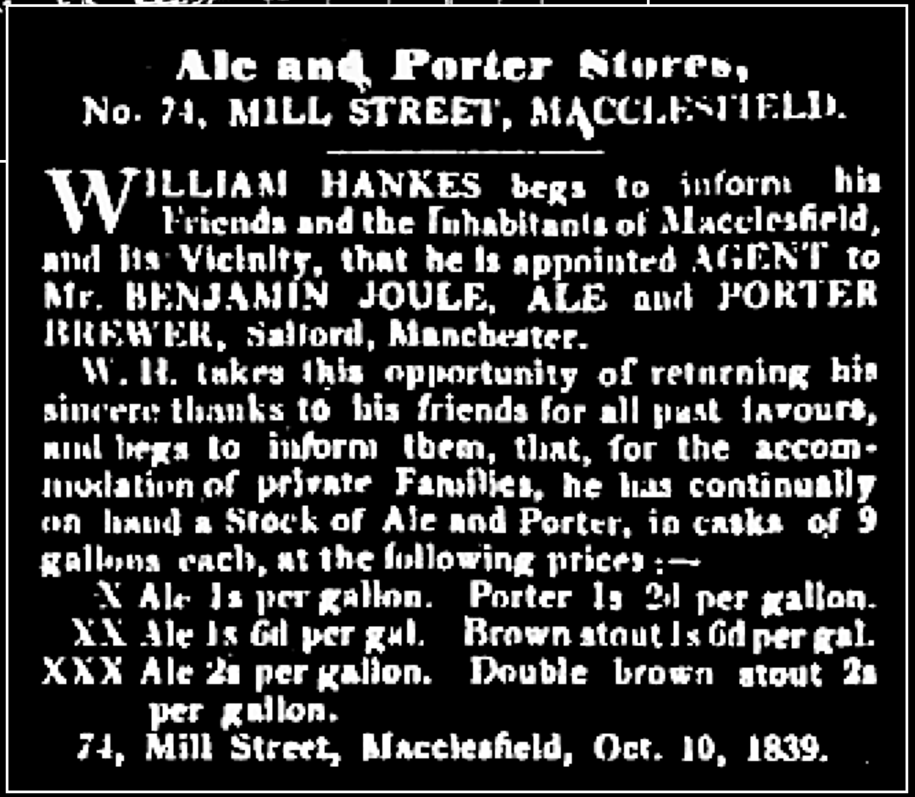
Physicist and brewer



BARRELS TO BE RETURNED WHEN EMPTY BEING NEVER SOLD

Salford Jan 1st 1854

Bought of Benjamin Joule



Ale and Porter Stores,
No. 74, MILL STREET, MACCLESFIELD.

WILLIAM HANKES begs to inform his Friends and the Inhabitants of Macclesfield, and its Vicinity, that he is appointed AGENT to Mr. BENJAMIN JOULE, ALE and PORTER BREWER, Salford, Manchester.

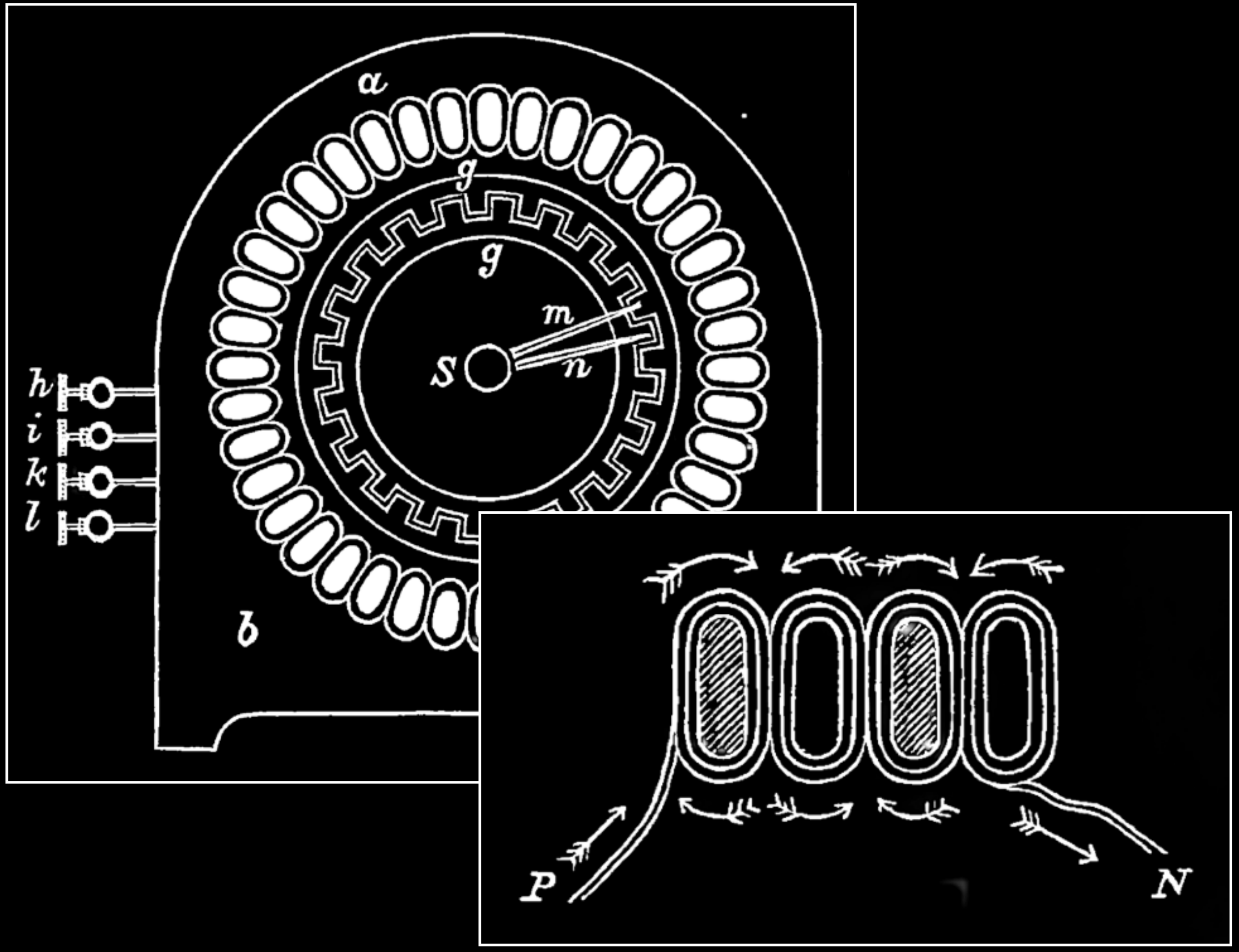
W. H. takes this opportunity of returning his sincere thanks to his friends for all past favours, and begs to inform them, that, for the accommodation of private Families, he has continually on hand a Stock of Ale and Porter, in casks of 9 gallons each, at the following prices:—

X Ale 1s per gallon. Porter 1s 2d per gallon.
XX Ale 1s 6d per gal. Brown stout 1s 6d per gal.
XXX Ale 2s per gallon. Double brown stout 2s per gallon.

74, Mill Street, Macclesfield, Oct. 10, 1839.

Worked (and later managed) his father's brewery …

… while conducting experiments with electricity

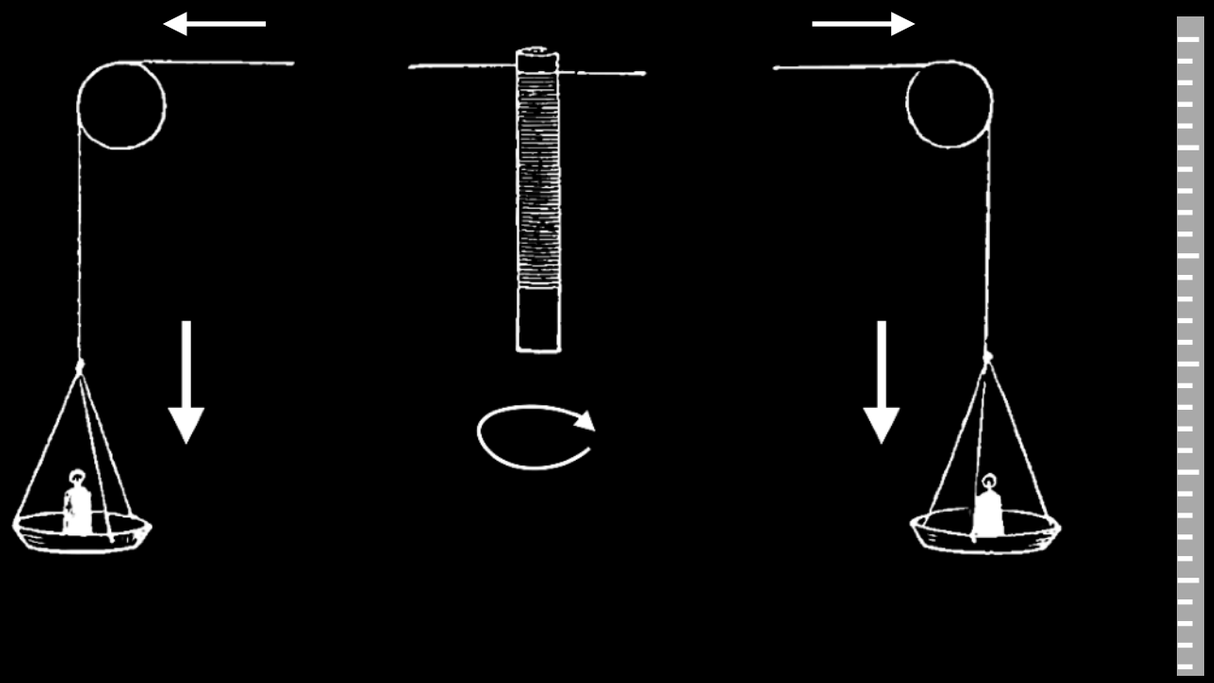


Joule’s experiments

High-precision analog of Rumford’s cannon boring

Joule’s experiments

High-precision analog of Rumford’s cannon boring



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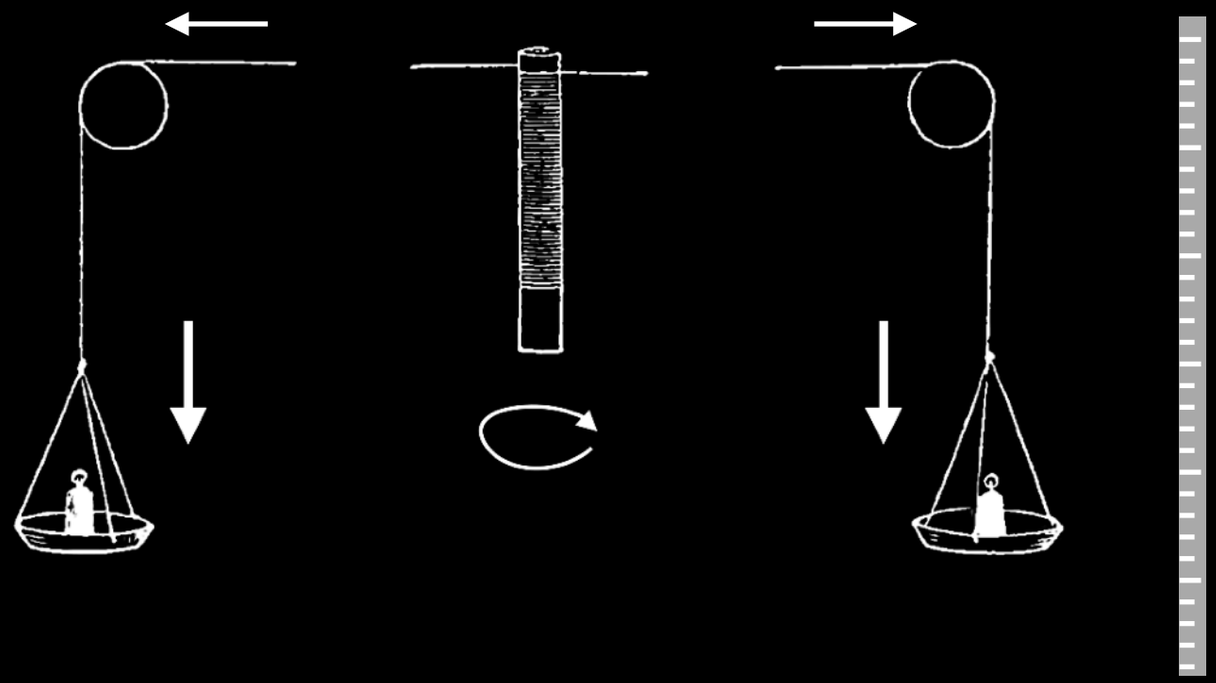

Horses driving the borer

↓

Drop well-measured weights by well-measured distance

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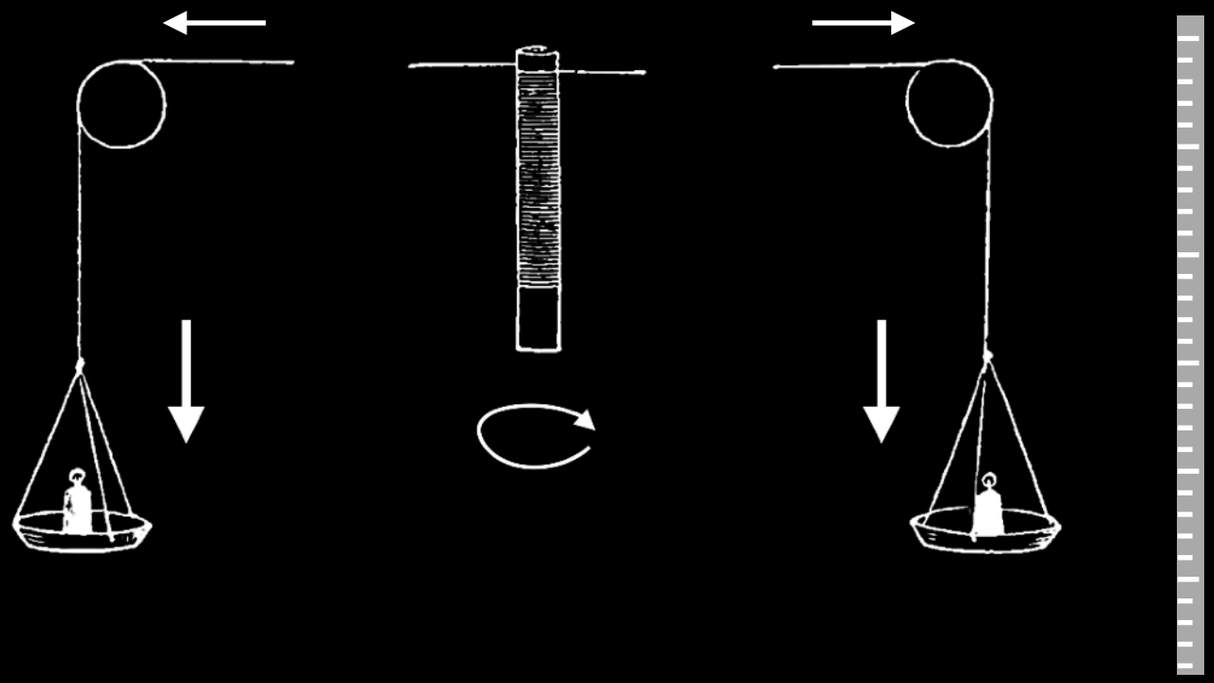
High-precision analog of Rumford’s cannon boring



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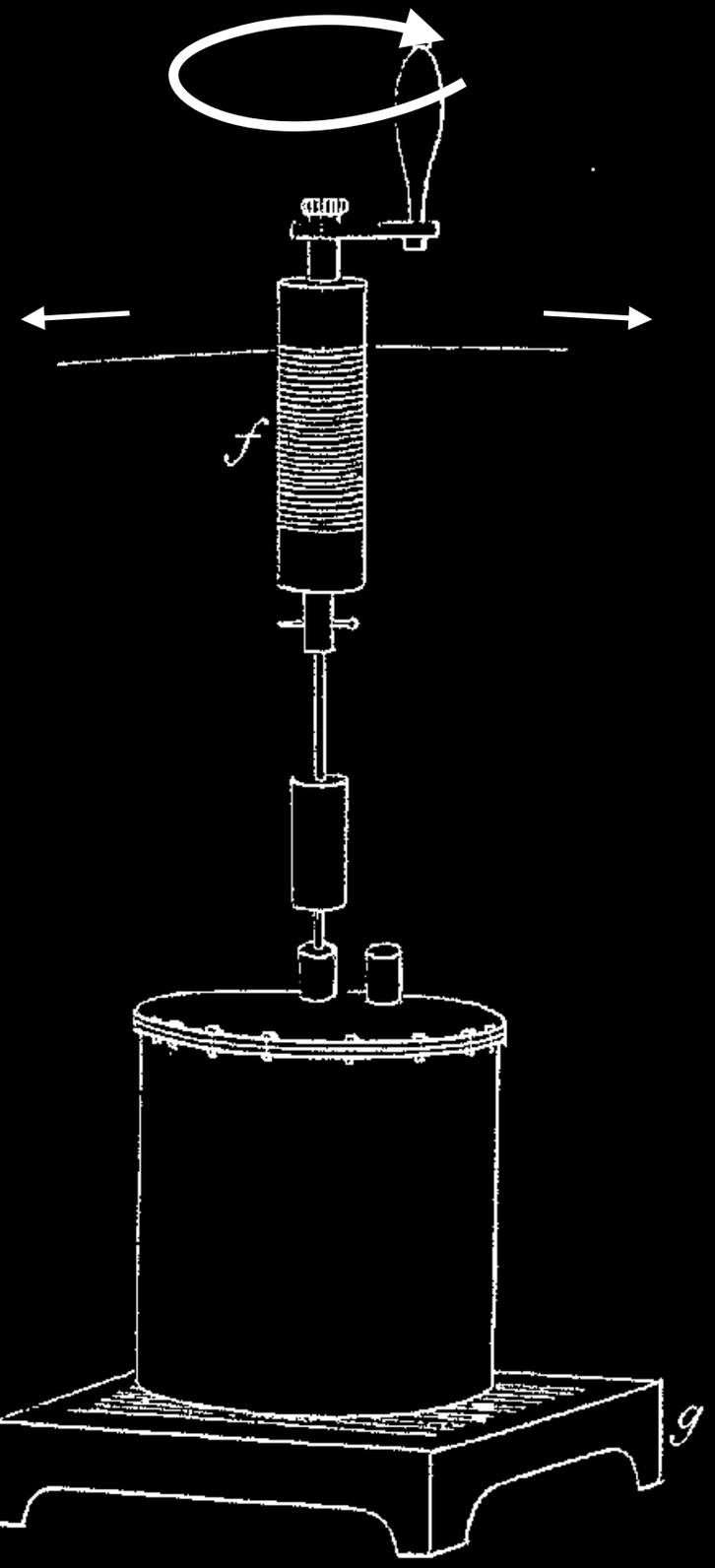

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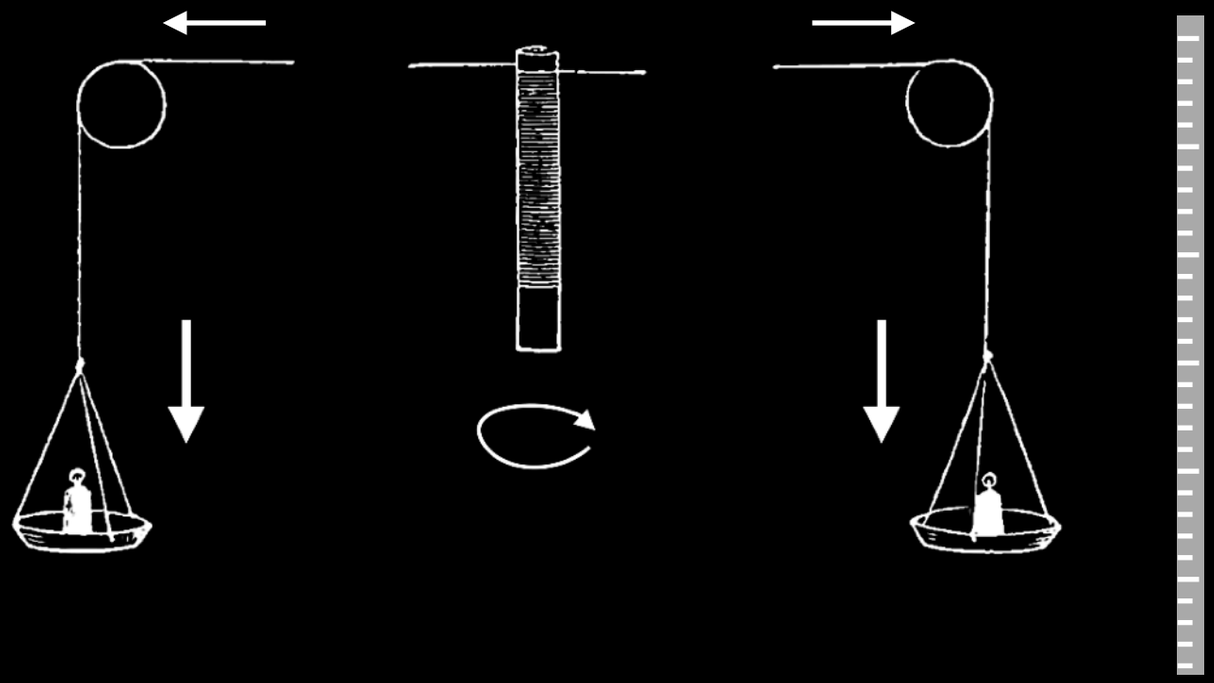

Horses driving the borer

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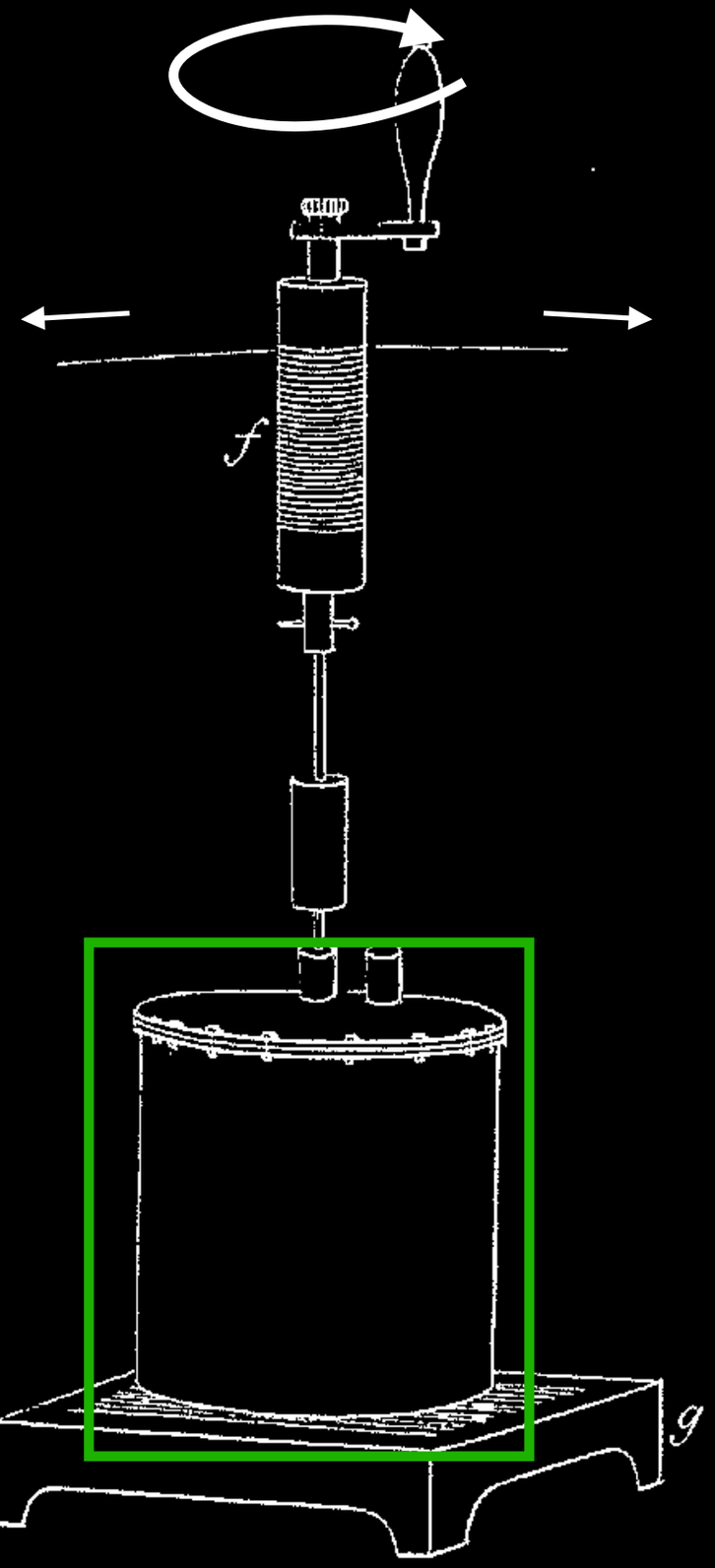
Drop well-measured weights by well-measured distance

Well-insulated “friction chamber” →



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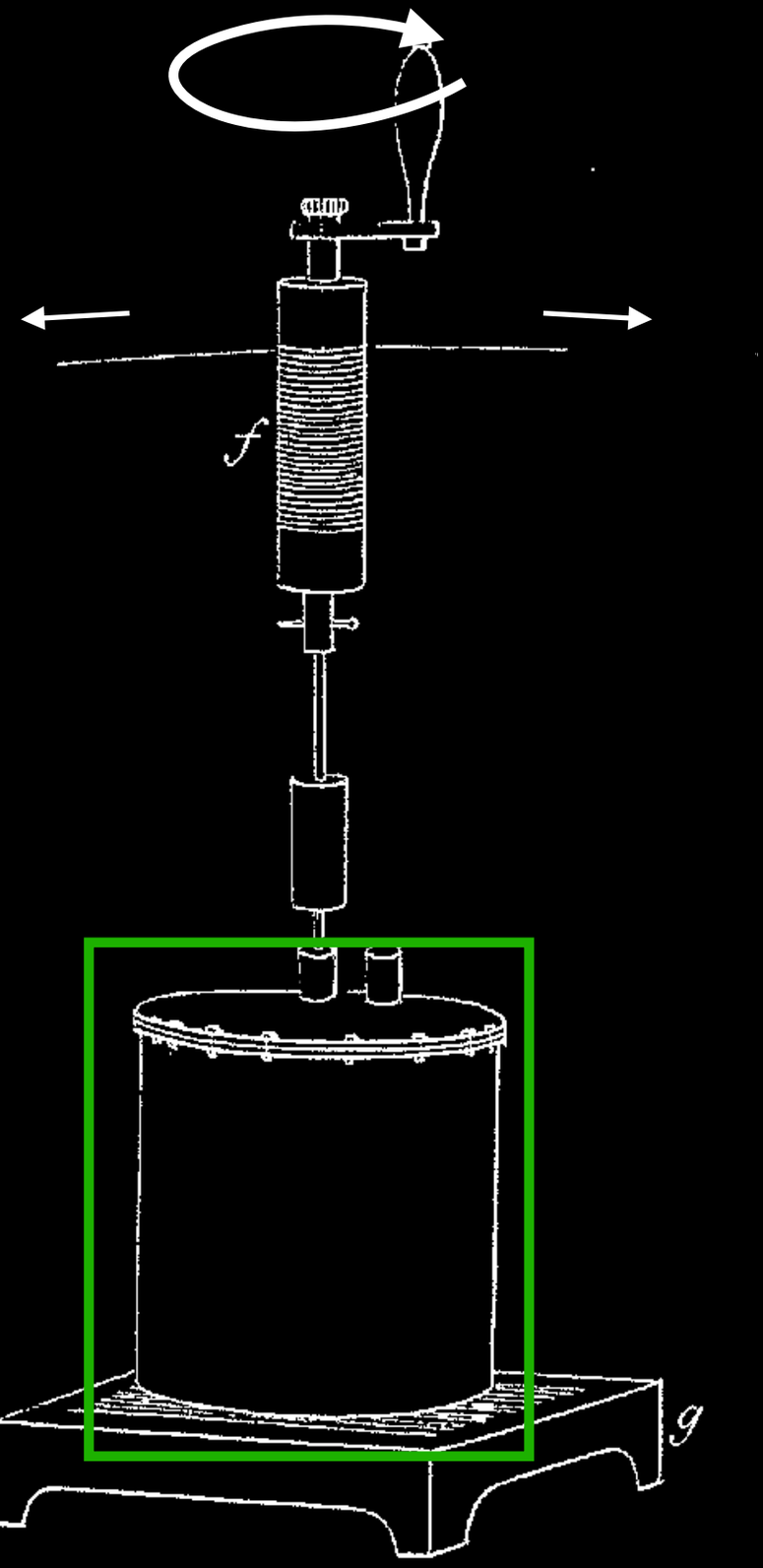

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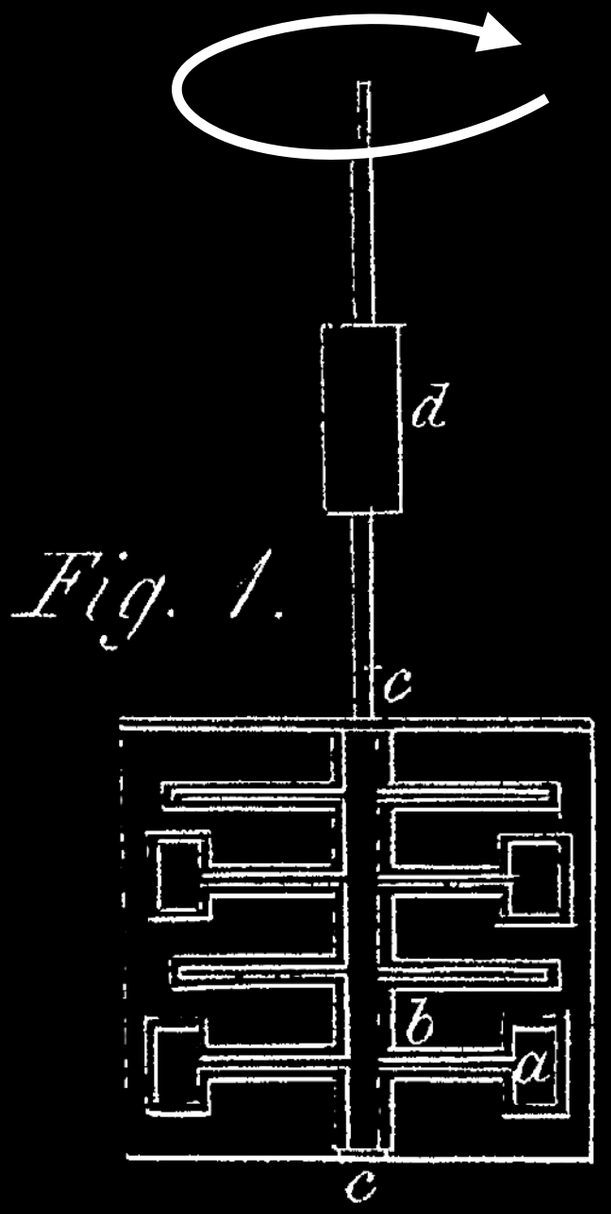
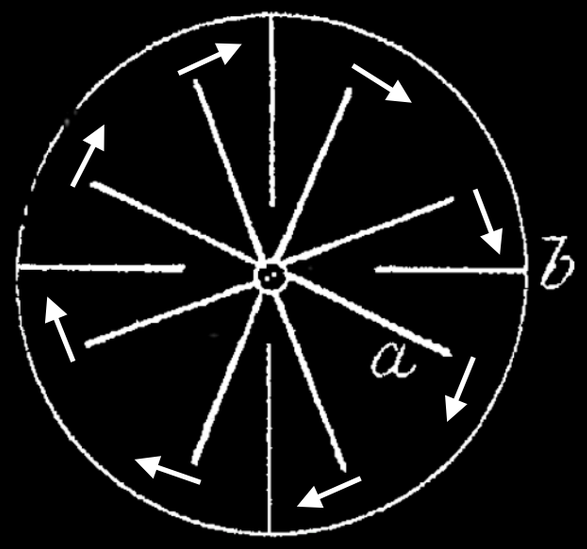
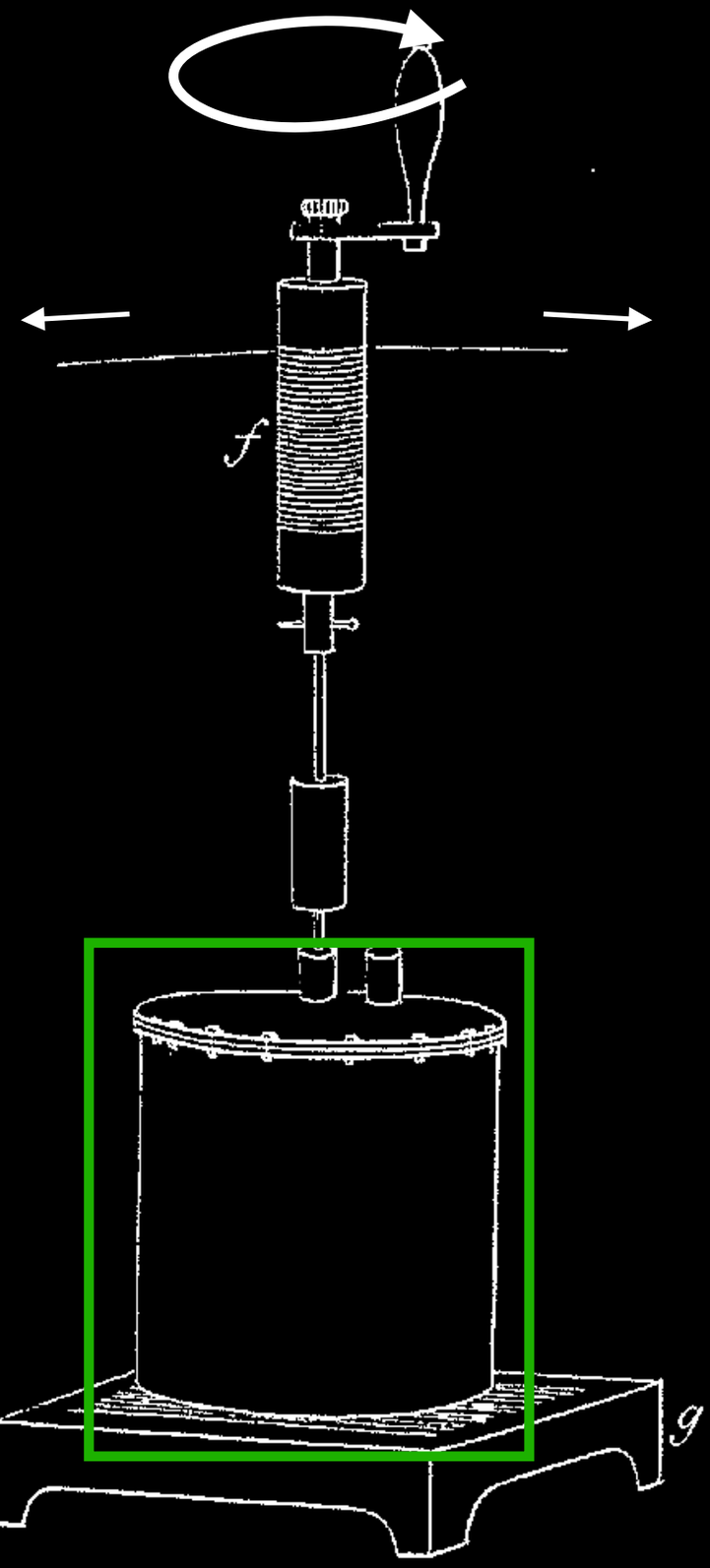


Fig. 1.





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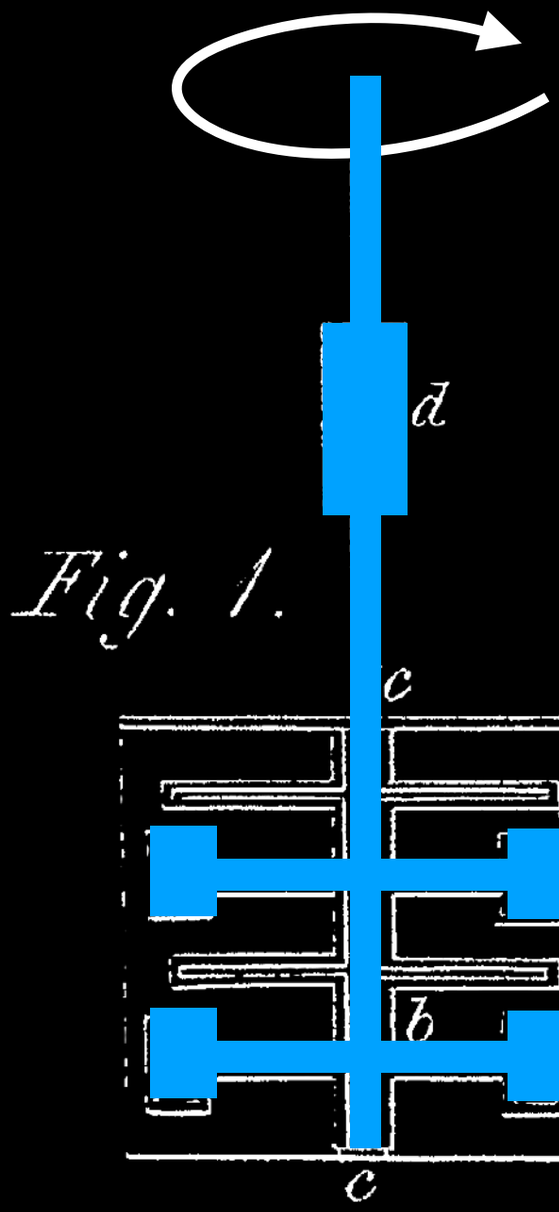
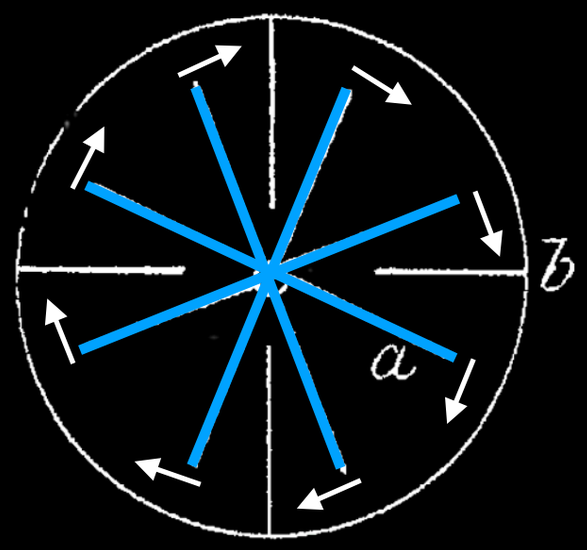
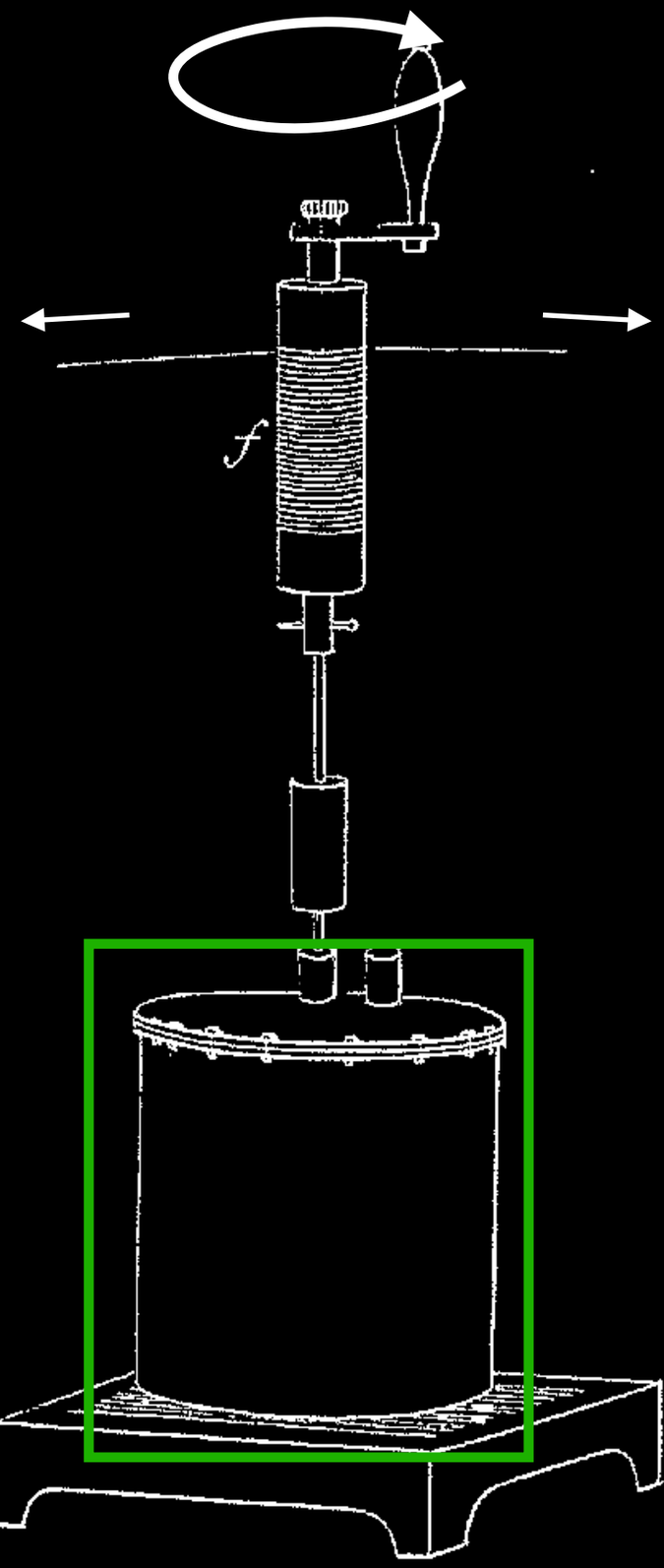




Rotating paddle-wheel



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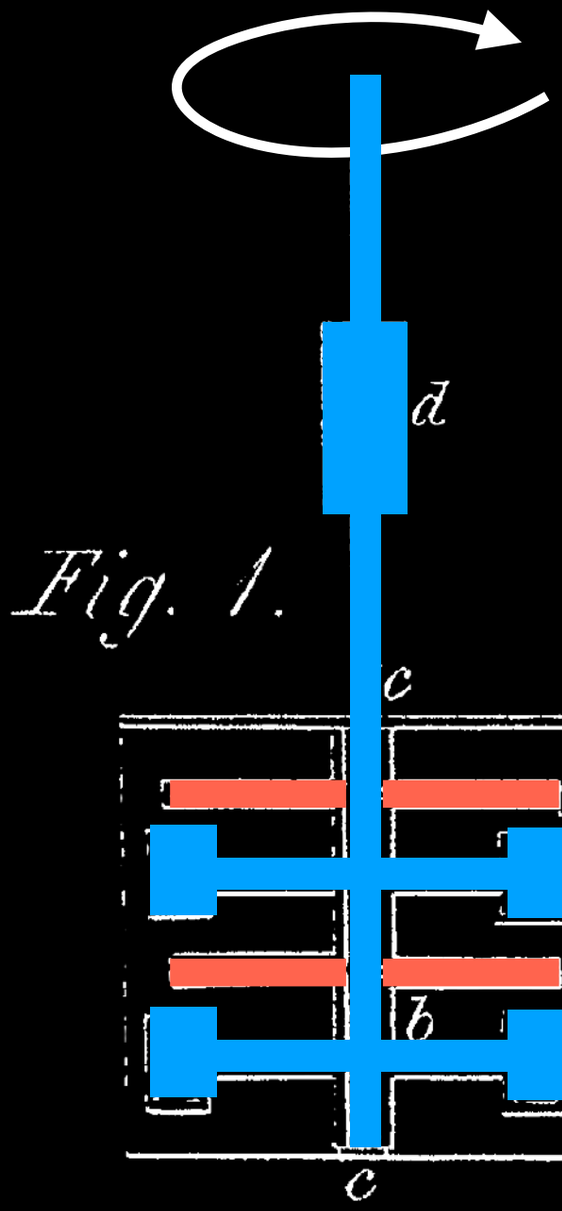
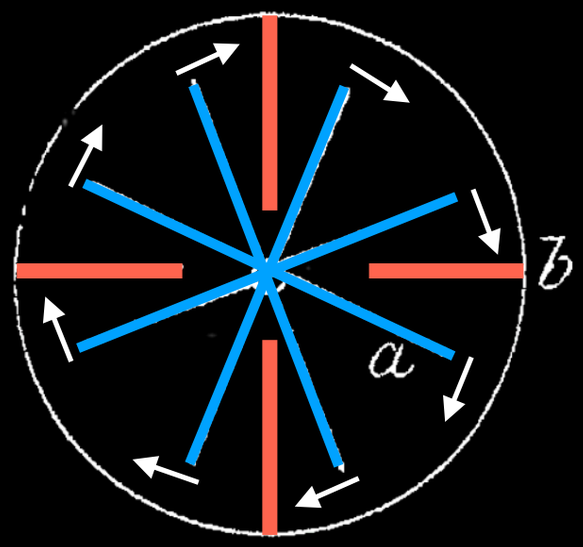
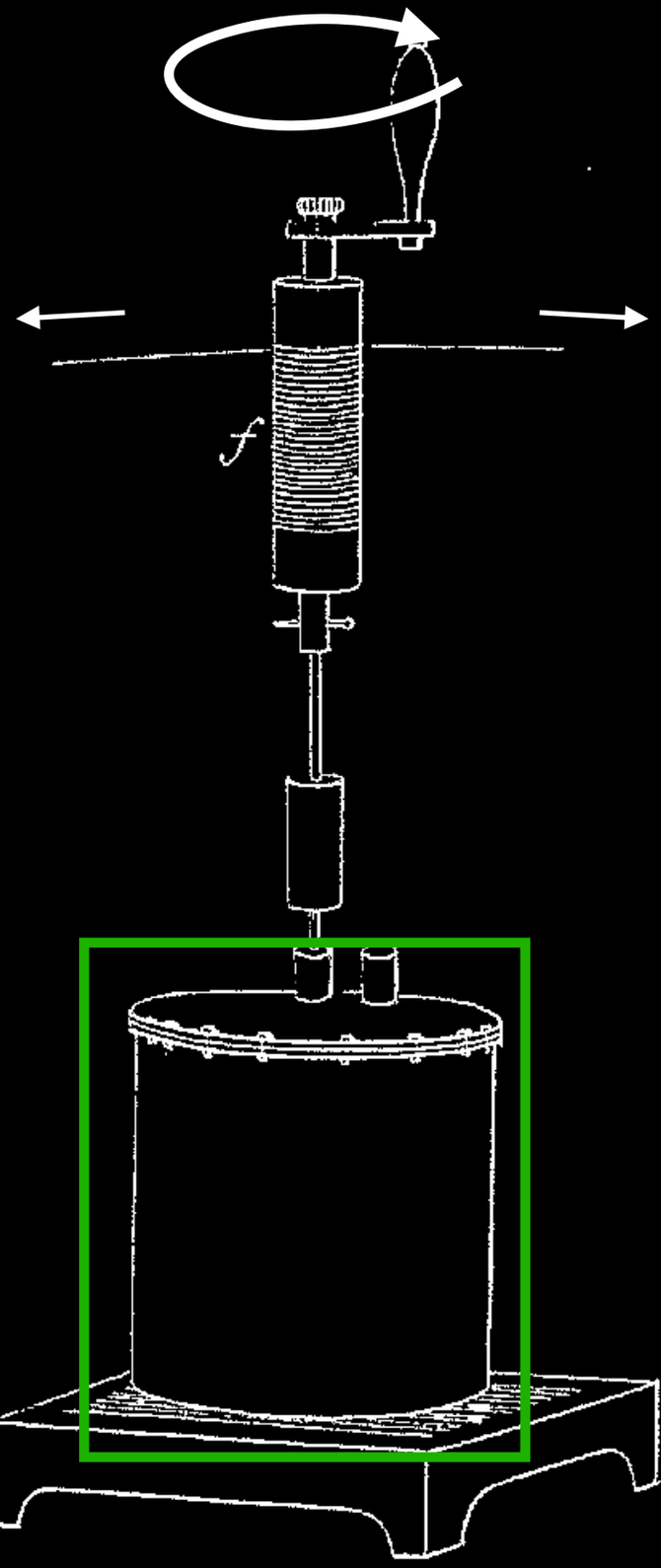




Rotating paddle-wheel

Fixed fins
(To stop water from flowing)



Joule's experiments

TABLE I.

No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and column 3.	Temperature of apparatus.		Gain or loss of heat during experiment.
				Commencement of experiment.	Termination of experiment.	
1 Friction	1256·96	57°·698	2°·252—	55°·118	55°·774	0°·656 gain
1 Radiation ...	0	57·868	2·040—	55·774	55·882	0·108 gain
2 Friction	1255·16	58·085	1·875—	55·882	56·539	0·657 gain
2 Radiation ...	0	58·370	1·789—	56·539	56·624	0·085 gain
3 Friction	1253·66	60·788	1·596—	58·870	59·515	0·645 gain
3 Radiation ...	0	60·926	1·373—	59·515	59·592	0·077 gain
4 Friction	1252·74	61·001	1·110—	59·592	60·191	0·599 gain
4 Radiation ...	0	60·890	0·684—	60·191	60·222	0·031 gain
1	2	3	4	5	6	7

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Distance measured to 1/100th of an inch!

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Temperature measured to 1/1000th of a °F!

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Distance measured to 1/100th of an inch!

Temperature measured to 1/1000th of a °F!

"Increasing the temperature of a pound of water by 1°F requires the expenditure of a mechanical force represented by the fall of 772 lbs. through the space of one foot."

The mechanical equivalent of heat

It does not matter how the “mechanical force is expended” to heat the water!

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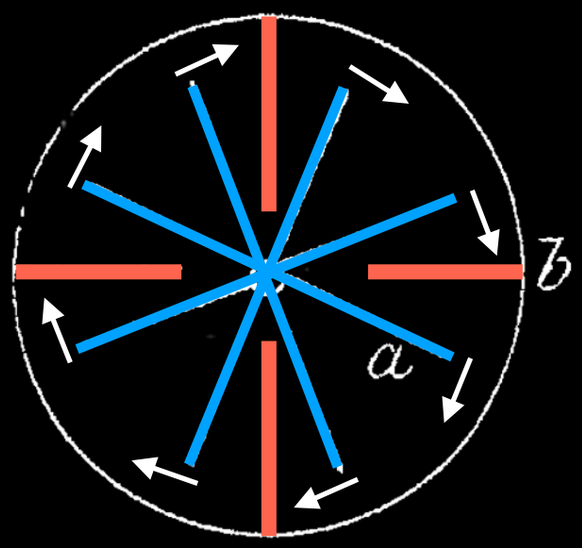

Paddle-wheel

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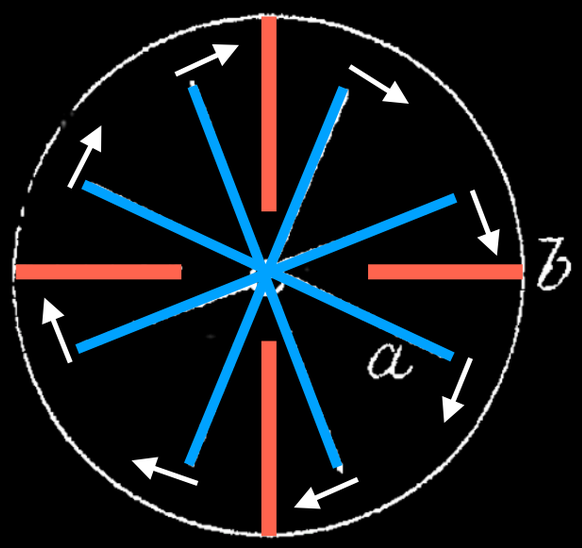

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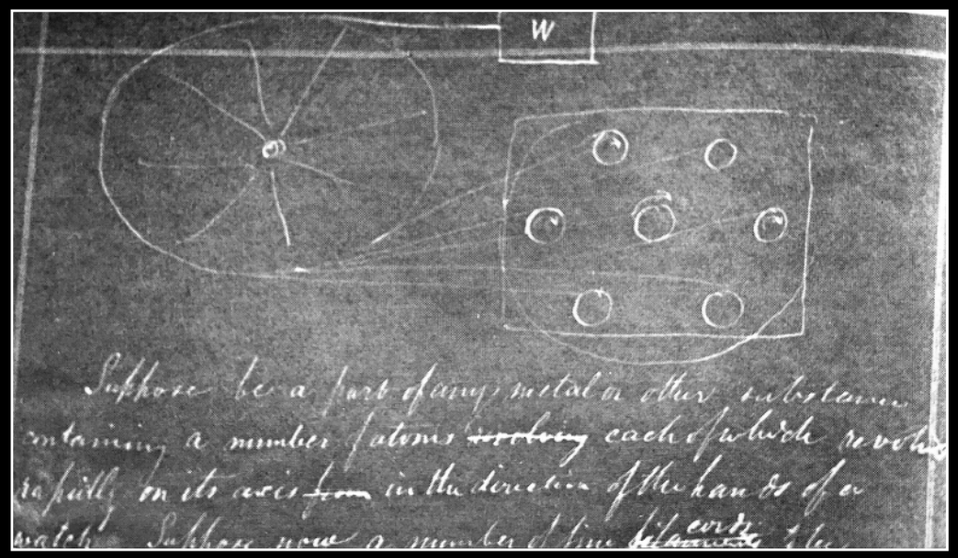

Forcing water through tiny holes
(from Joule’s notebooks)

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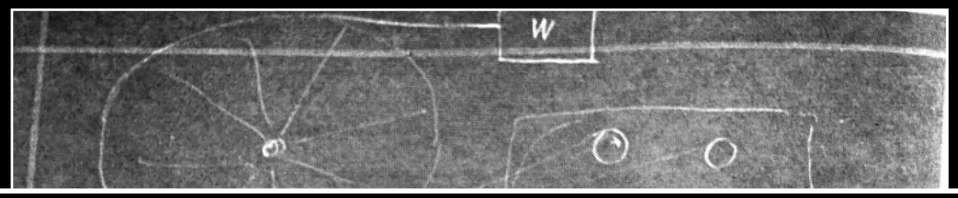
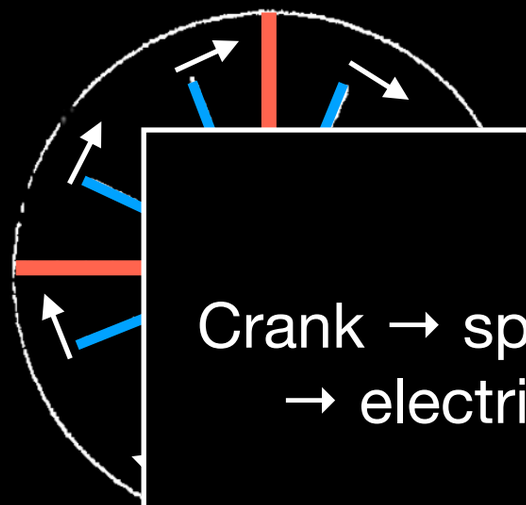
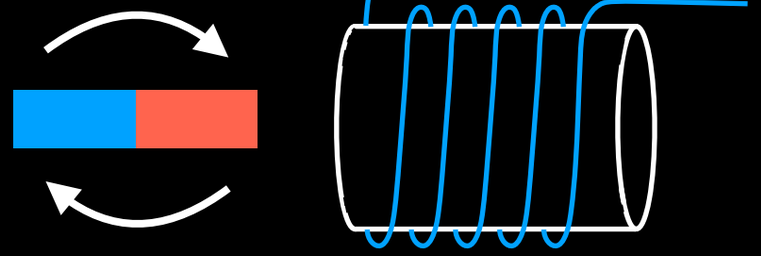
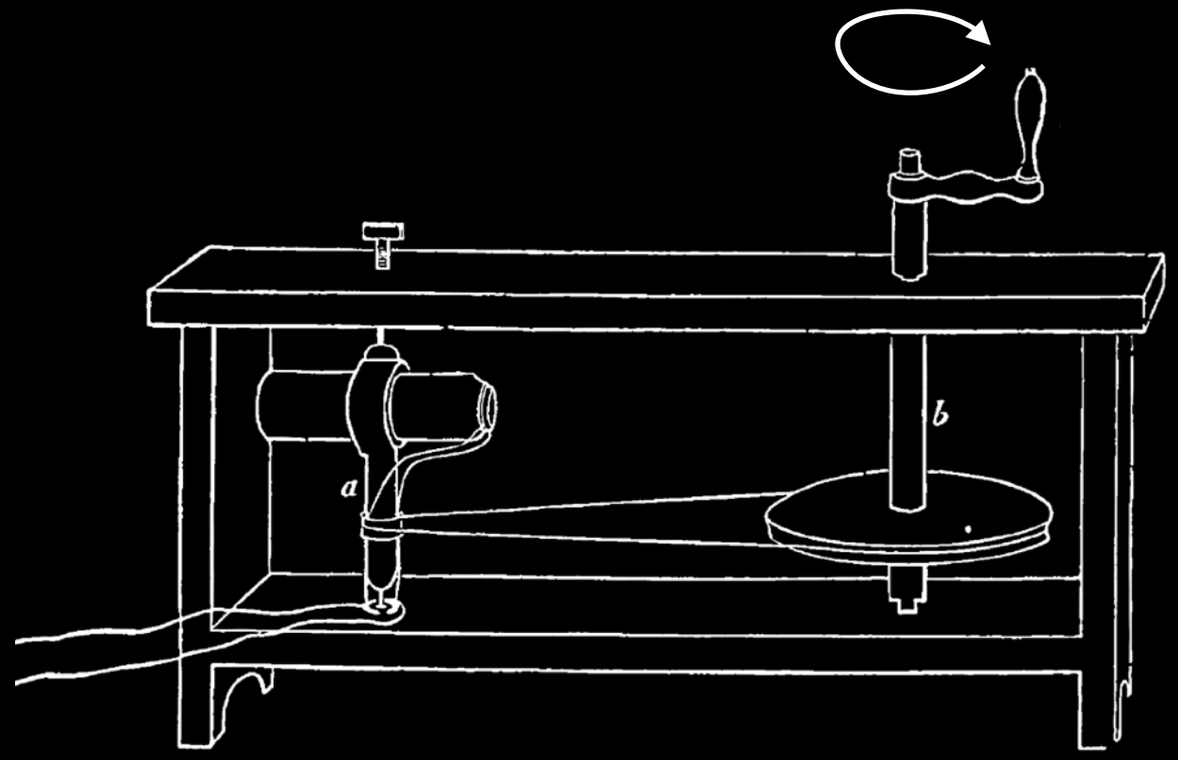




Crank → spinning magnet
→ electricity → heat





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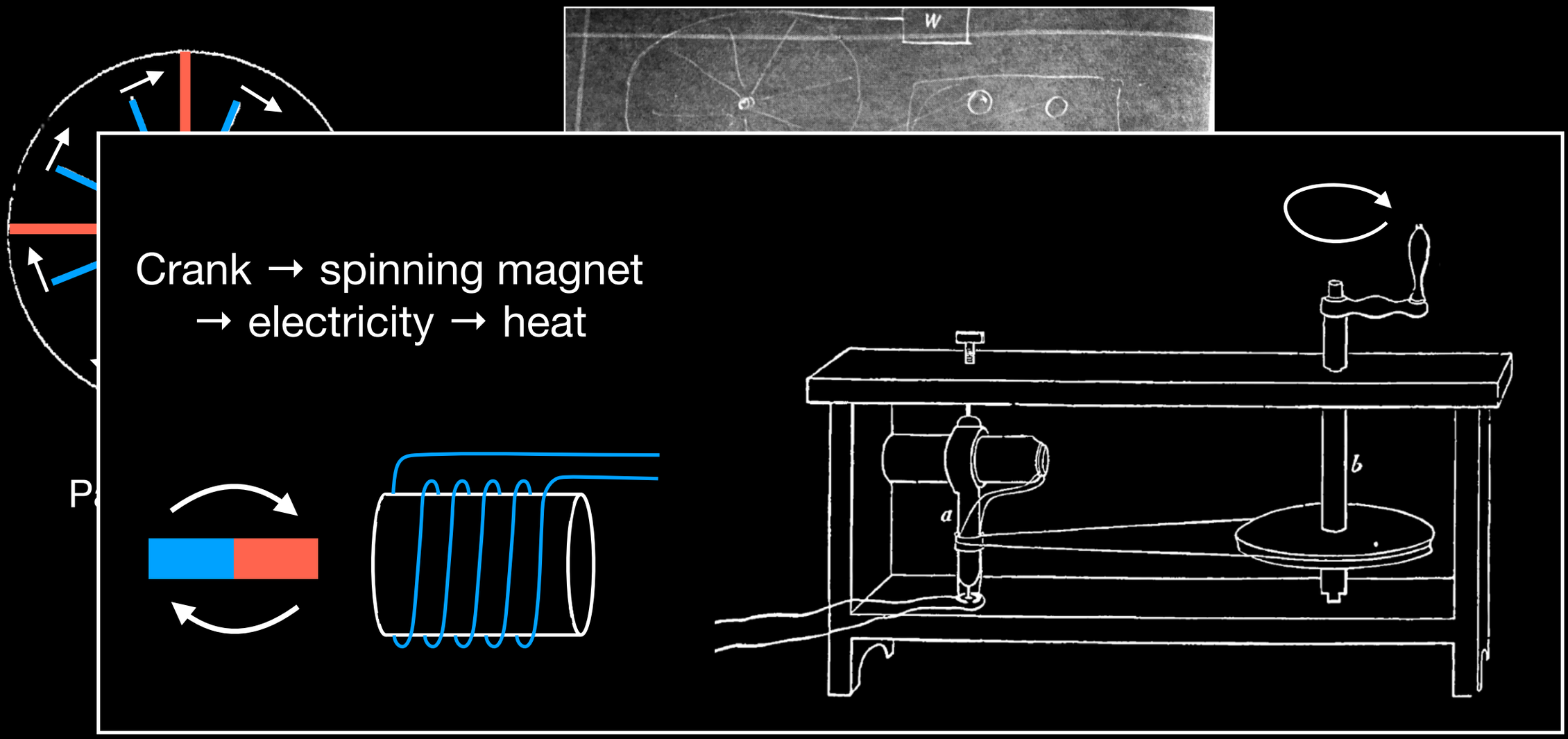
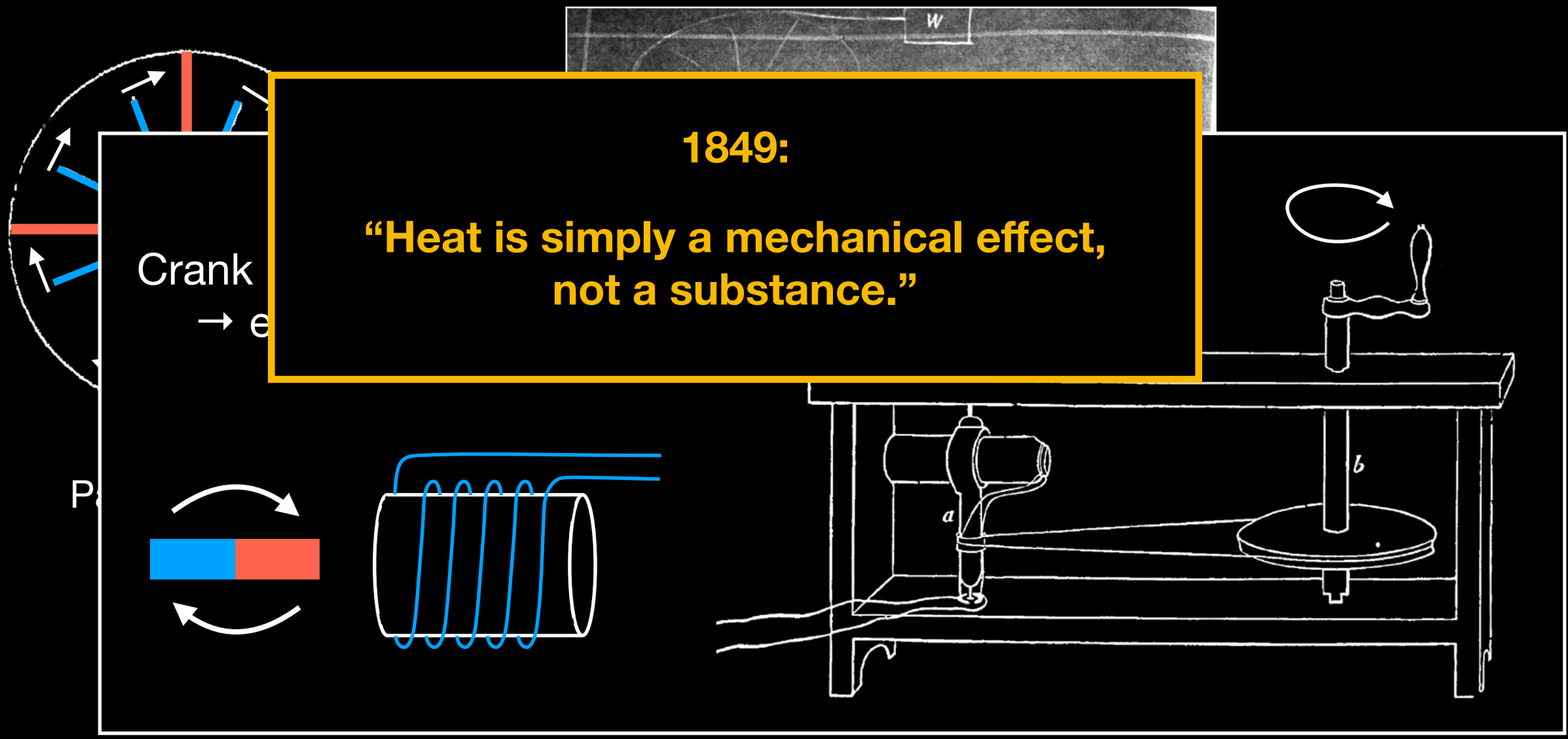


“1°F of heat per lb. of water is therefore <u>equivalent</u> to a mechanical force capable of raising a weight of 896 lb. to the perpendicular height of one foot.”

The mechanical equivalent of heat

It does not matter how the "mechanical force is expended" to heat the water!



1849:

"Heat is simply a mechanical effect, not a substance."

"1°F of heat per lb. of water is therefore <u>equivalent</u> to a mechanical force capable of raising a weight of 896 lb. to the perpendicular height of one foot."

… and the rest is history

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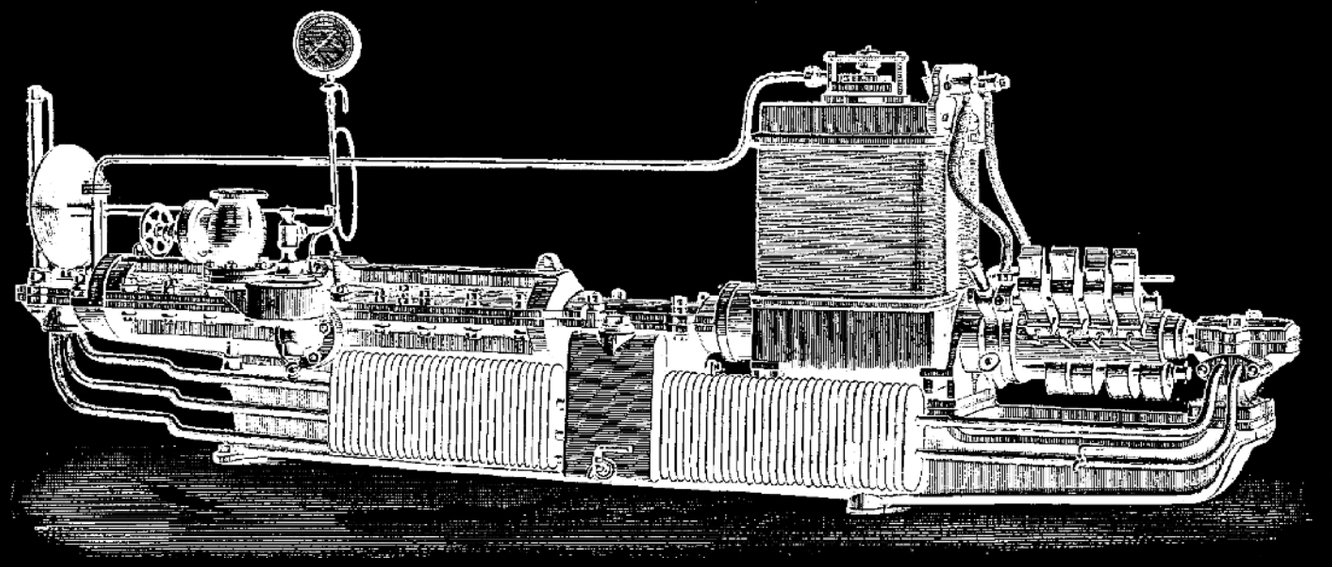

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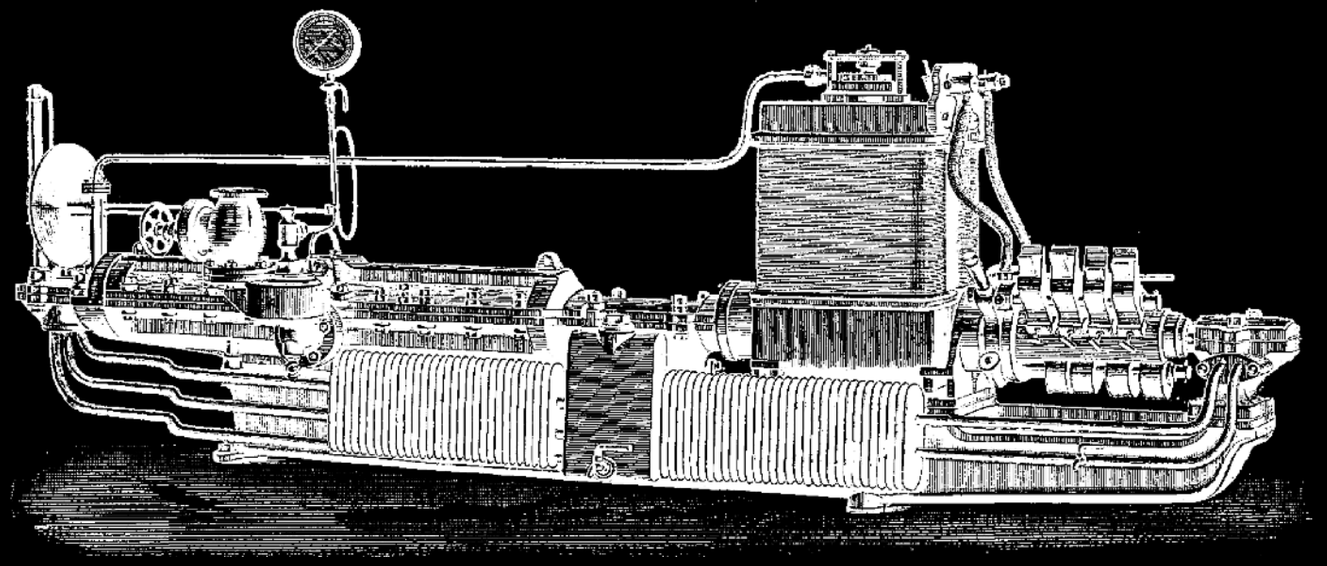
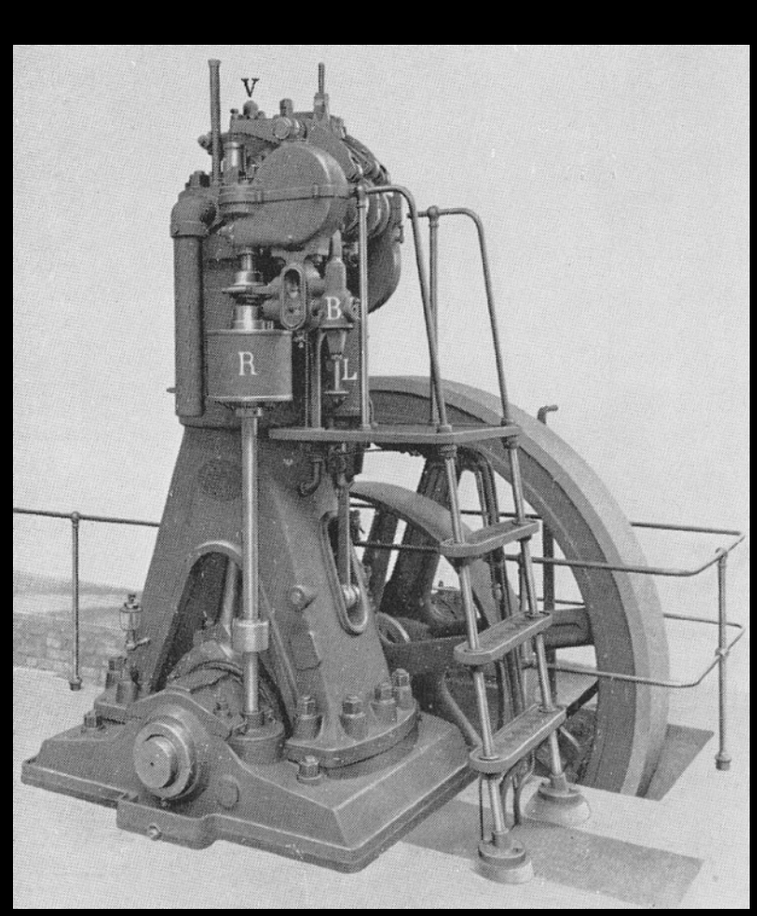


1892: Rudolf Diesel: “Theory and construction of a rational heat motor with the purpose of replacing the steam engine”
→ inspired by Carnot’s theory



Today

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Steam turbines provide the vast majority of today's electricity

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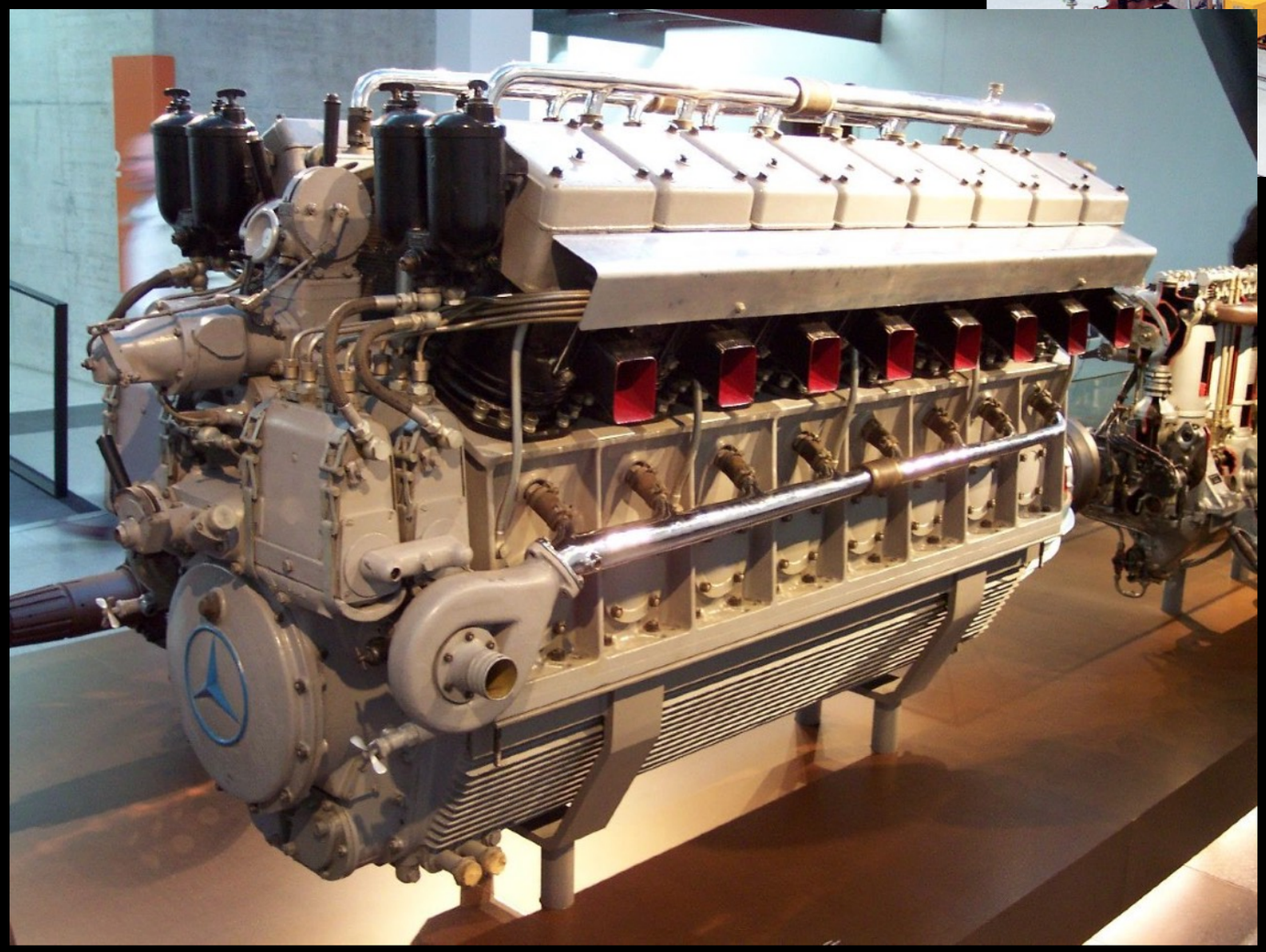
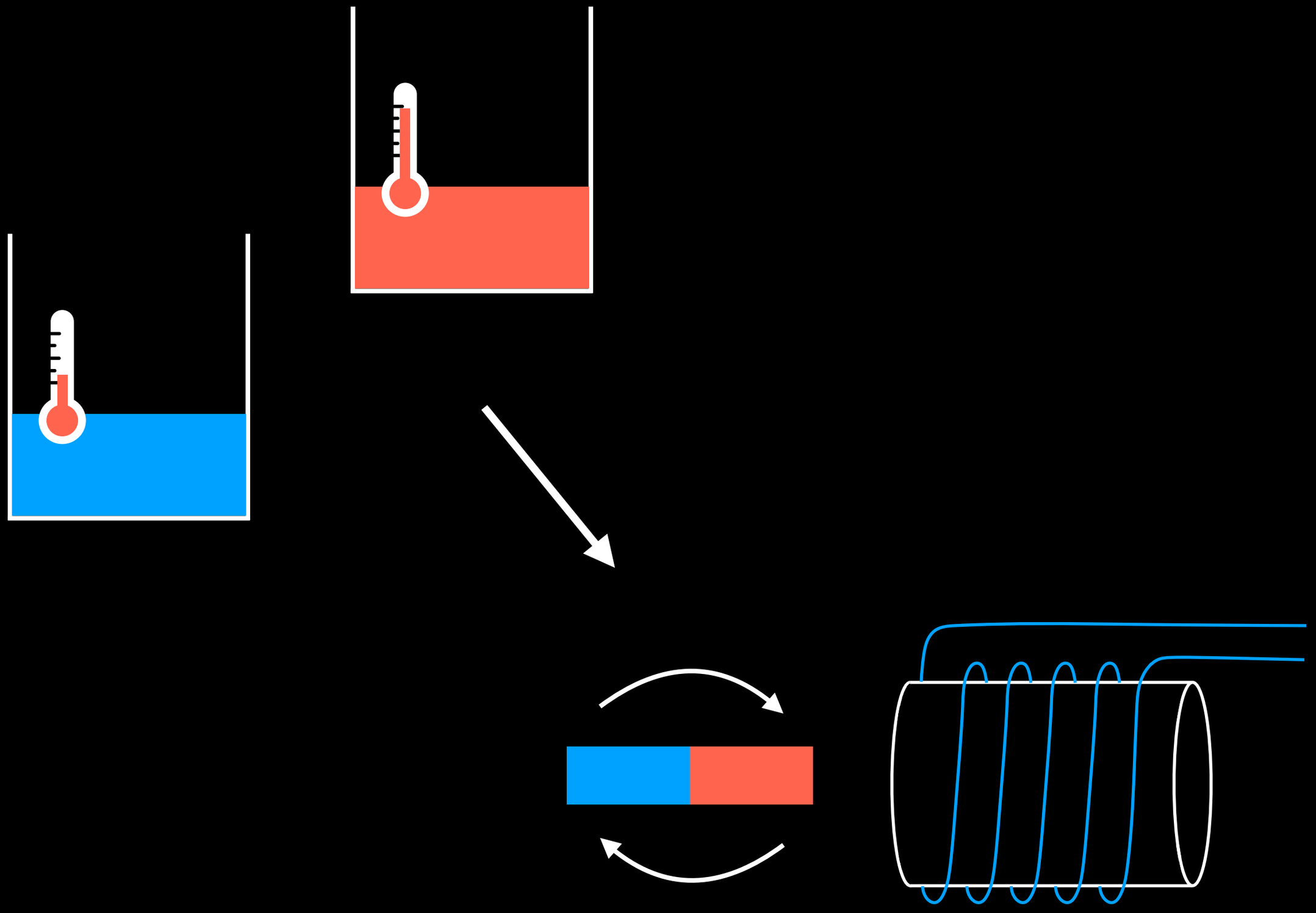
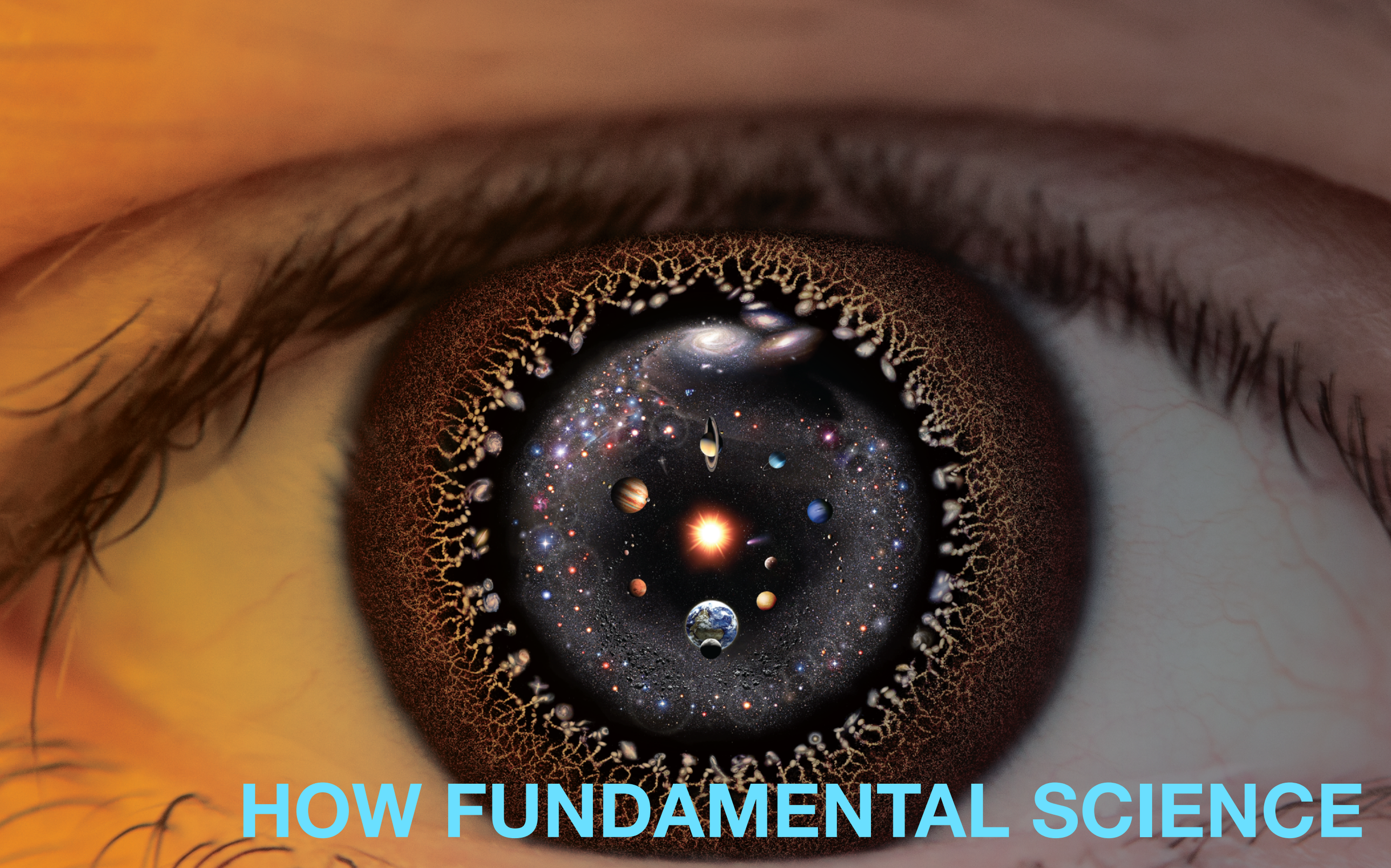


Internal combustion engines power the vast majority of today's vehicles





HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

A STORY OF INVENTION AND DISCOVERY

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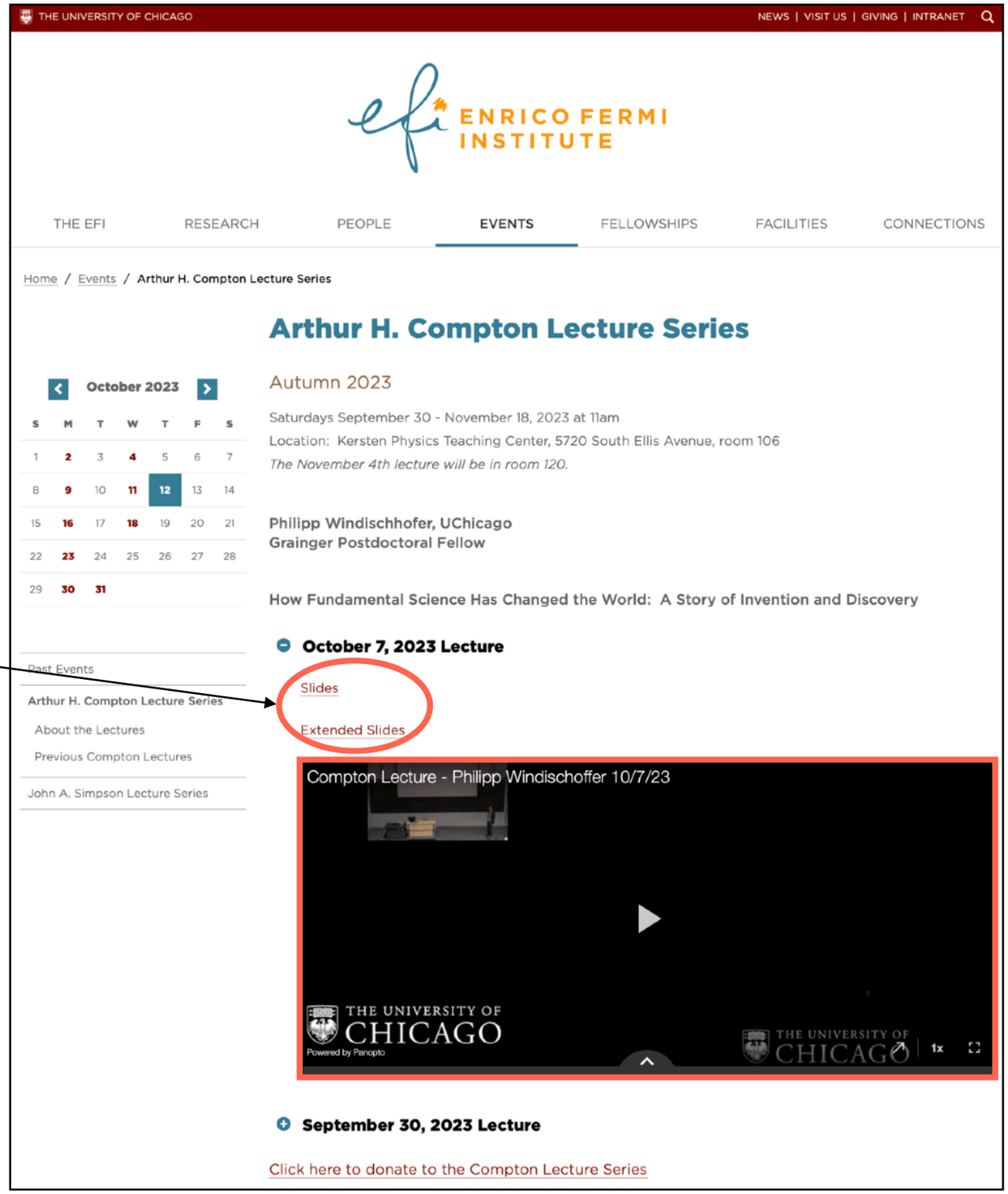

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