



# HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

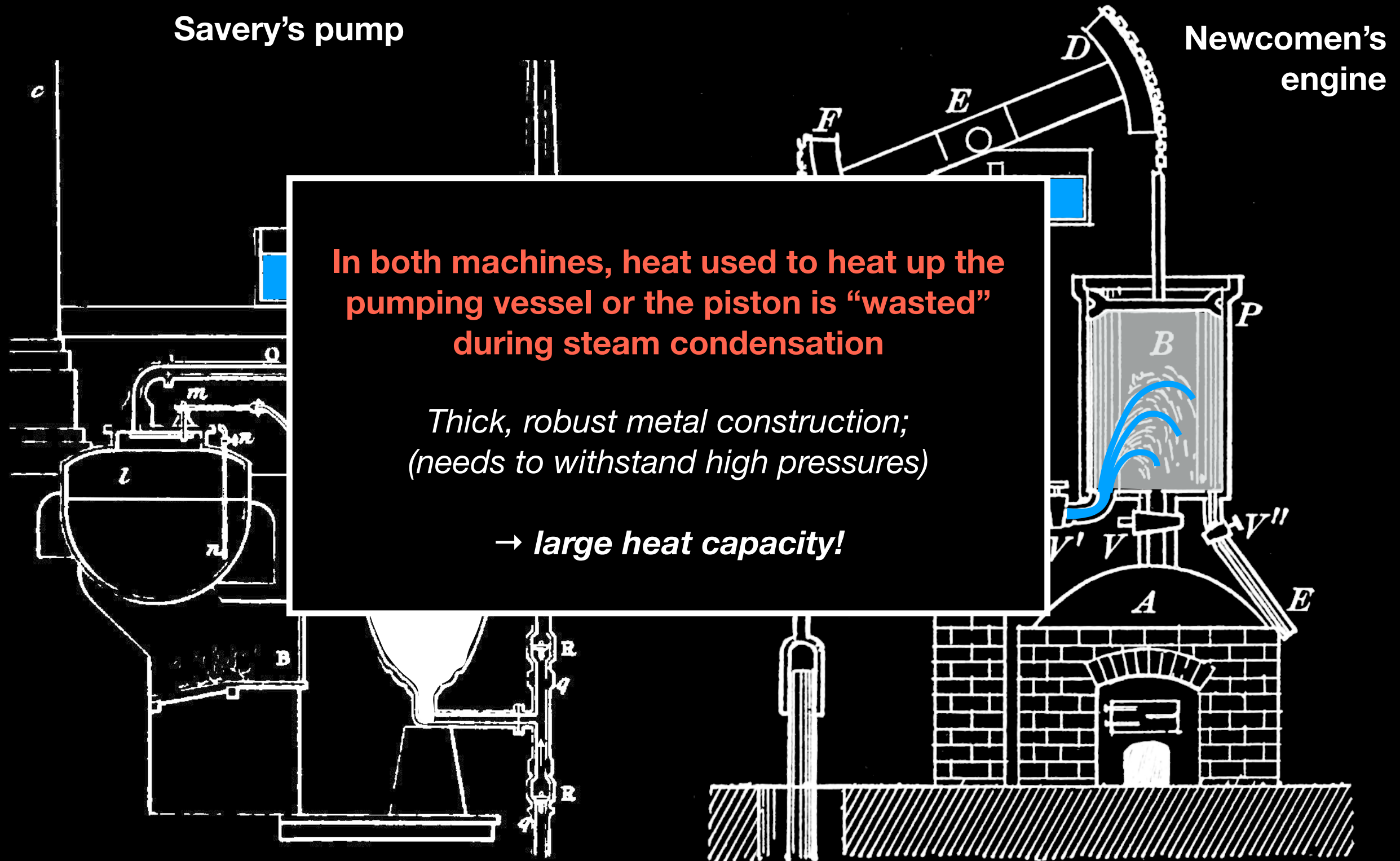
**A STORY OF INVENTION AND DISCOVERY**

**Additional Material**

Philipp Windischhofer  
*October 14, 2023*



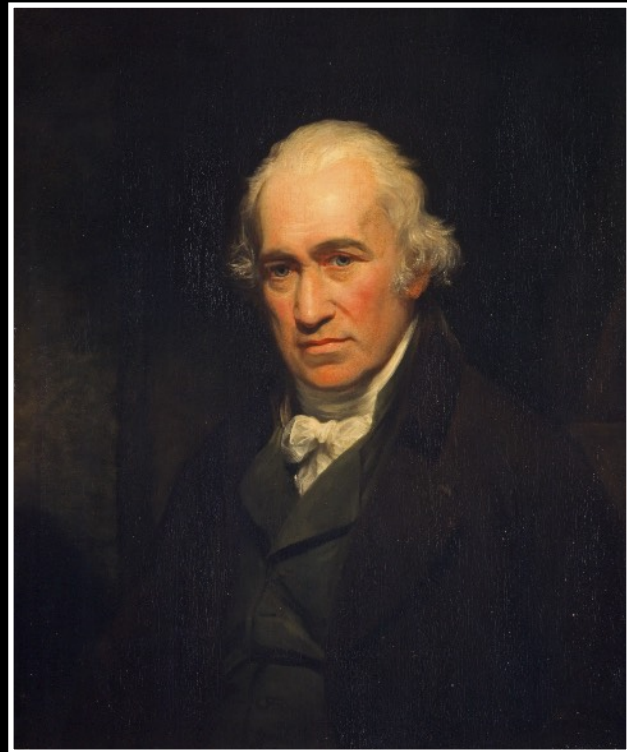
# The root of the inefficiency



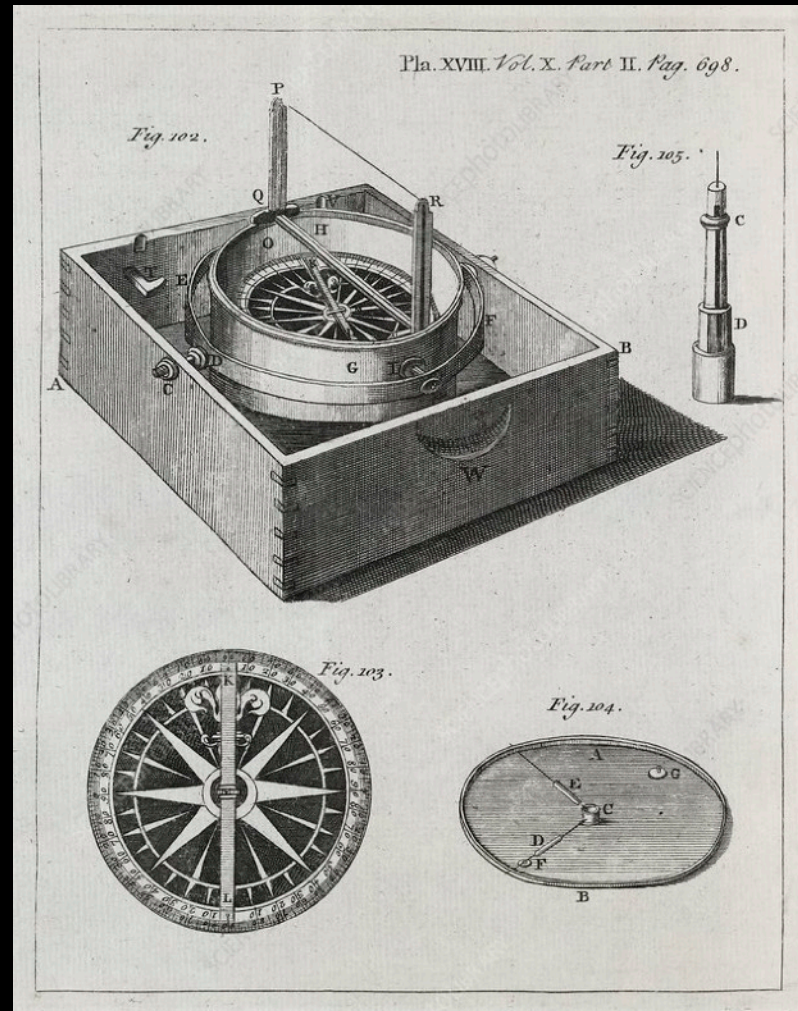


# James Watt

“Mathematical Instrument Maker  
to the University of Glasgow”



Hadley's  
quadrant



Mariner's compass





# James Watt

“Mathematical Instrument Maker  
to the University of Glasgow”



*“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.”*



# James Watt

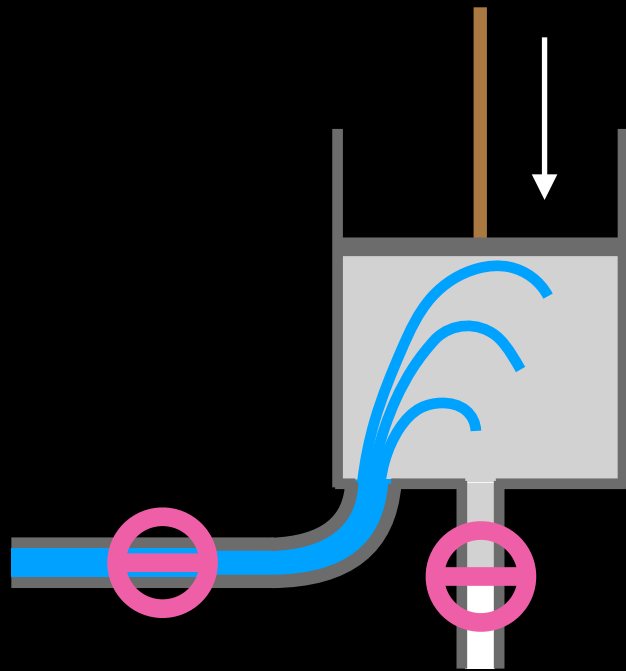
“Mathematical Instrument Maker  
to the University of Glasgow”



*“I set about repairing it as a mere mechanician; and when it was set to work,  
I was surprised to find that its boiler could not supply it with steam,  
though apparently quite large enough.”*



# Tracing down the heat loss

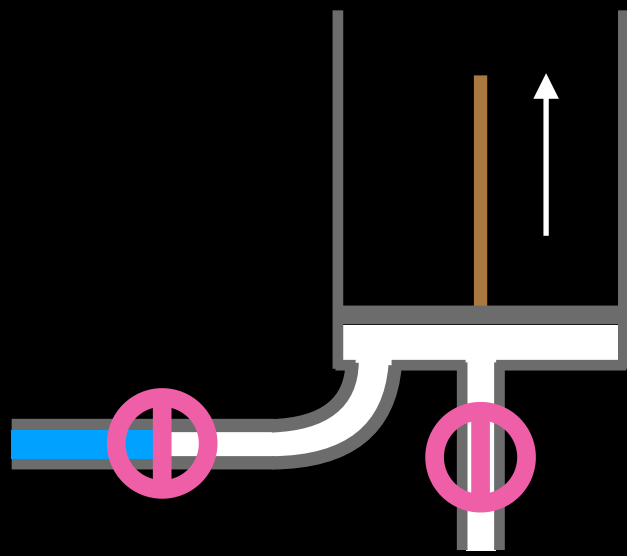


*“I was astonished at the quantity of water required for the injection, and the great heat it had acquired from the small quantity of water in the form of steam which had been used in filling the cylinder.”*

*“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.”*



# Tracing down the heat loss



*“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.”*

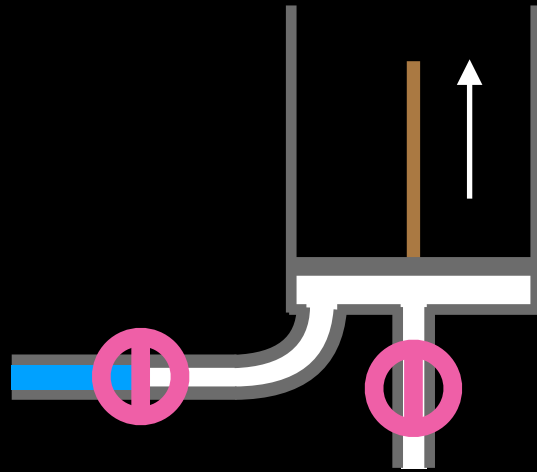
*“A boiler was constructed that showed the quantity of water evaporated in any given time, and thereby ascertained the quantity of steam used in every stroke by the engine, which I found to be several times the full of the cylinder.”*

**(He didn't seem to have heard of Black's "capacity for heat"!)**



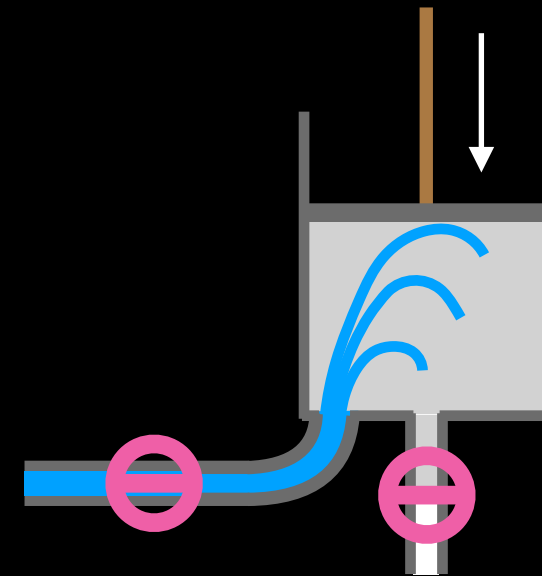
# Watt's improvements

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



*first, that the cylinder should be maintained always as hot as the steam which entered it;*

*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].*

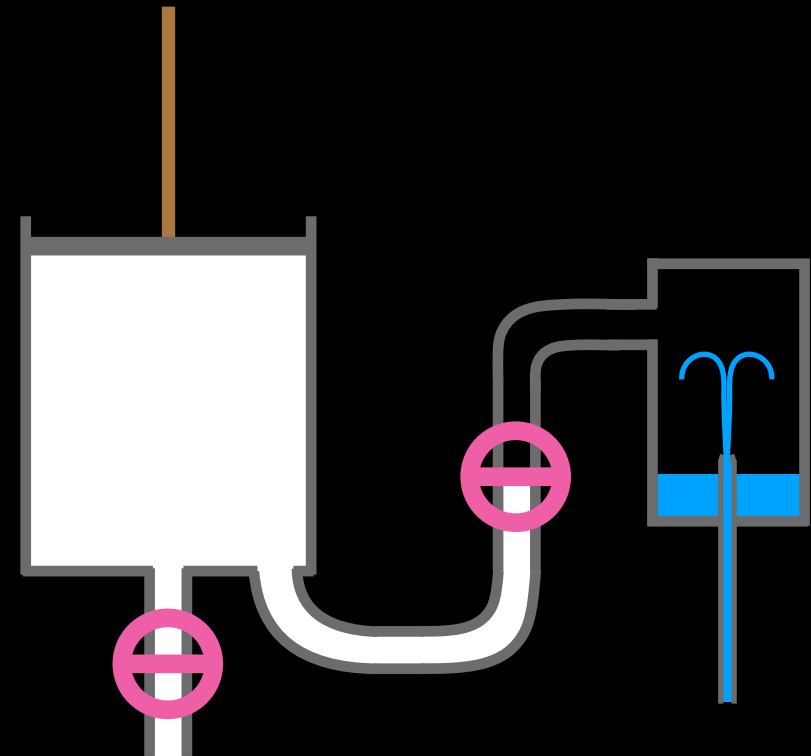


***The means of accomplishing the points did not immediately present themselves.”***



# 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 ...”*

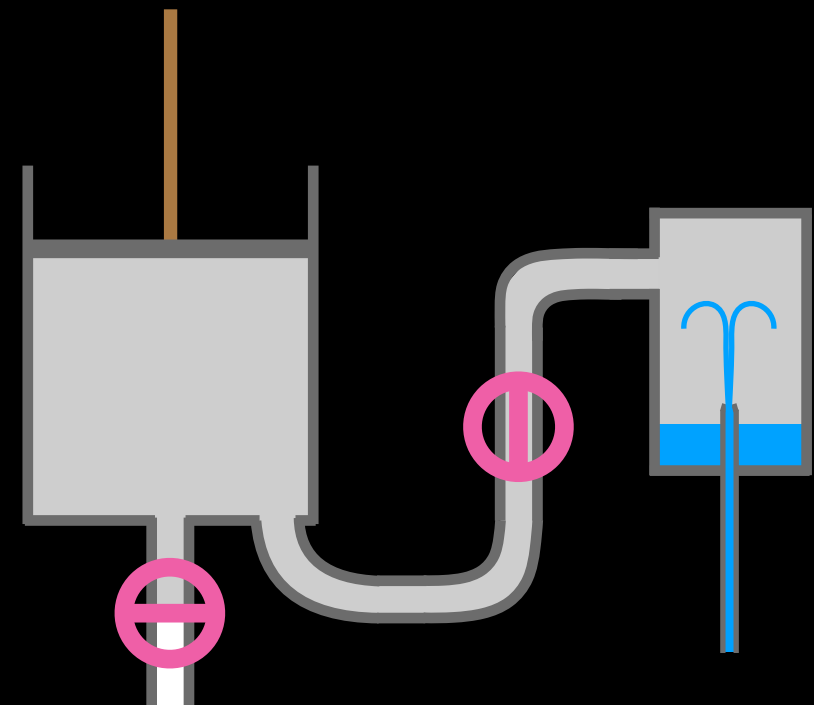




# Watt's improvements

*“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 ...”*

*“... the steam, as an elastic fluid, would immediately rush into the empty vessel ...”*



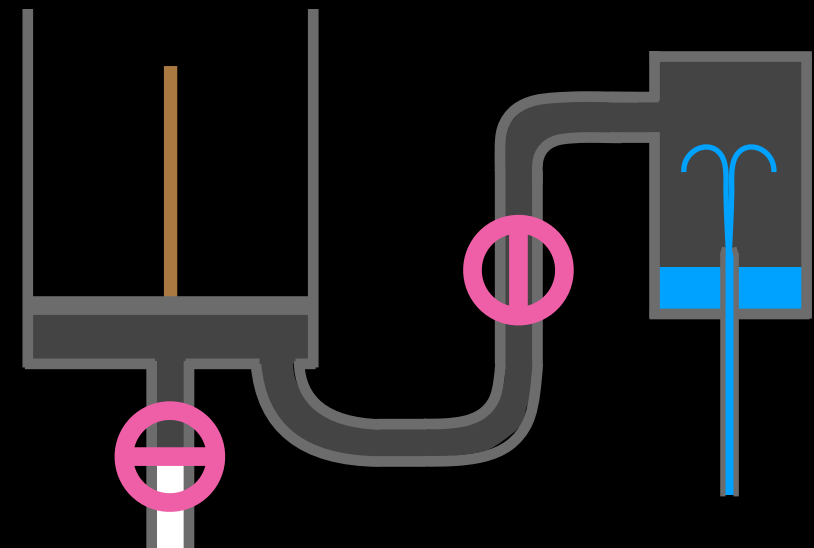


# Watt's improvements

*“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 ...”*

*“... the steam, as an elastic fluid, would immediately rush into the empty vessel ...”*

*“... until the whole was condensed.”*



**Piston stays hot, condenser stays cool!**



# James Watt conquers the world

*“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.

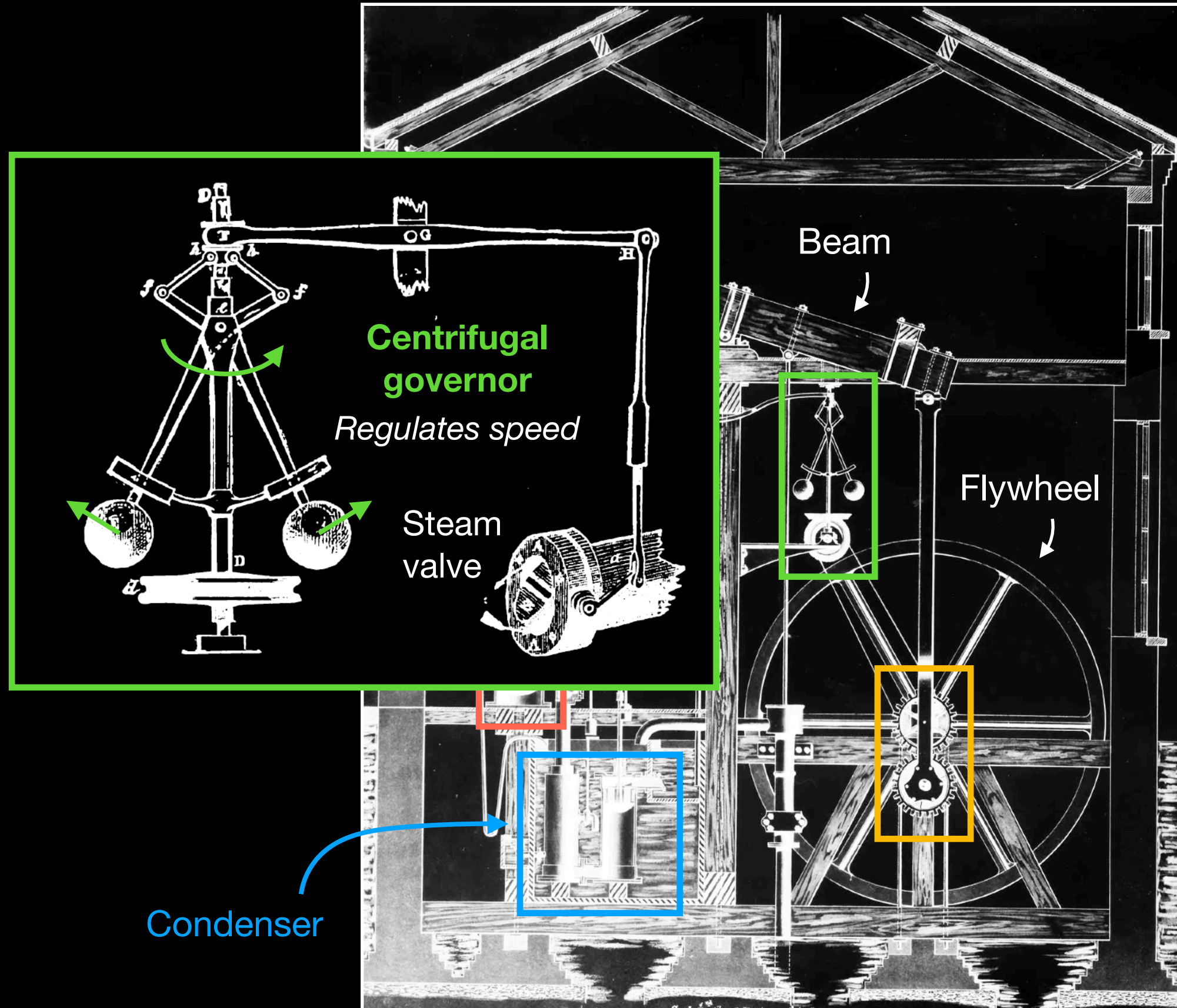
WHEREAS His most Excellent Majesty King George the Third, by His Letters Patent under the Great Seal of Great Britain, bearing date the Fifth day of January, in the ninth year of His said Majesty's reign, did give and grant unto me, the said James Watt, His special licence, full power, sole privilege 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 proviso, and in pursuance of the said Statute, I, the said James Watt, do hereby declare that the

**Patent granted 1769:**

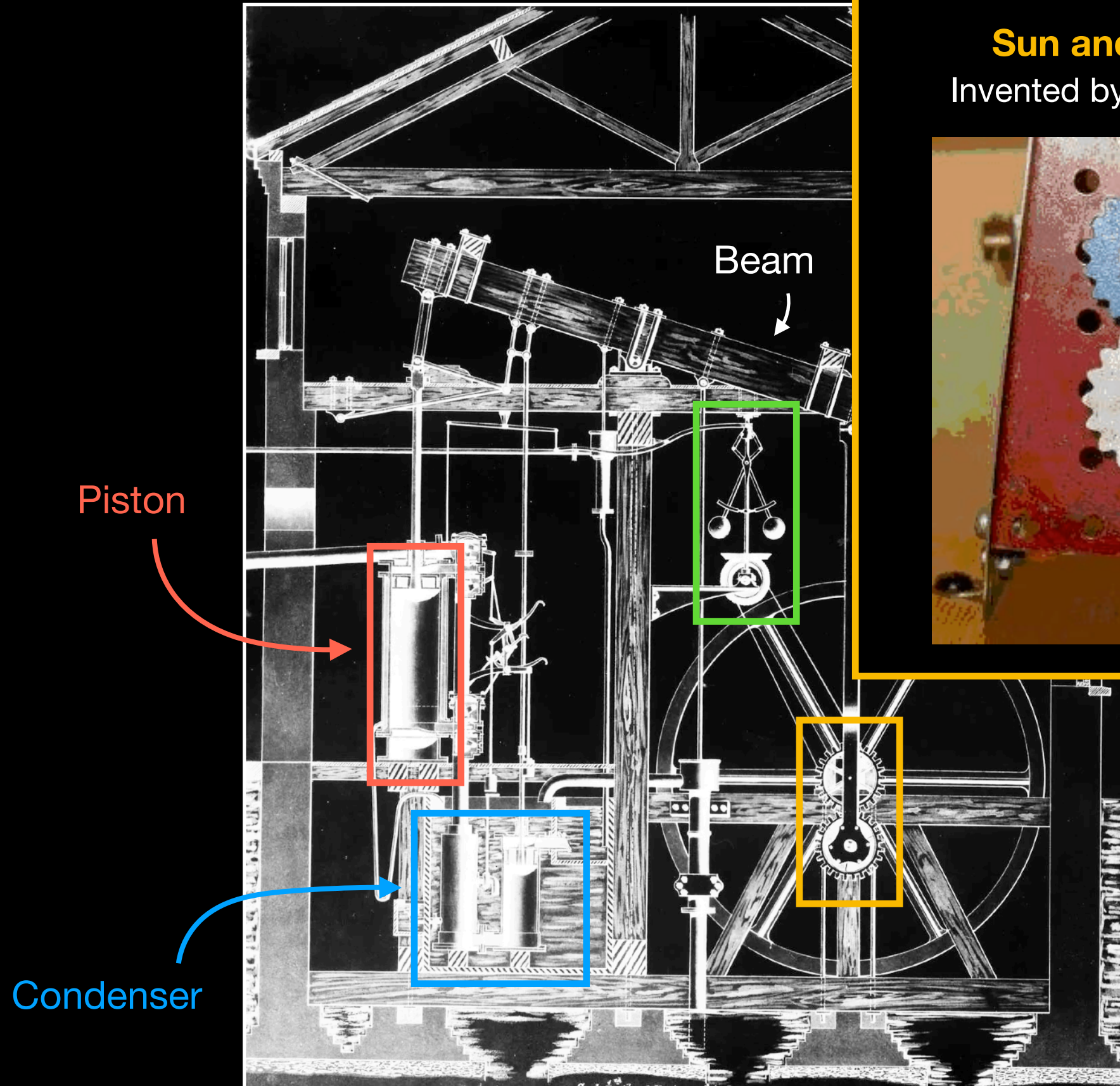
**“New invented method of lessening the consumption of steam and fuel in fire engines”**

# Watt, Boulton, and Murdoch conquer the world

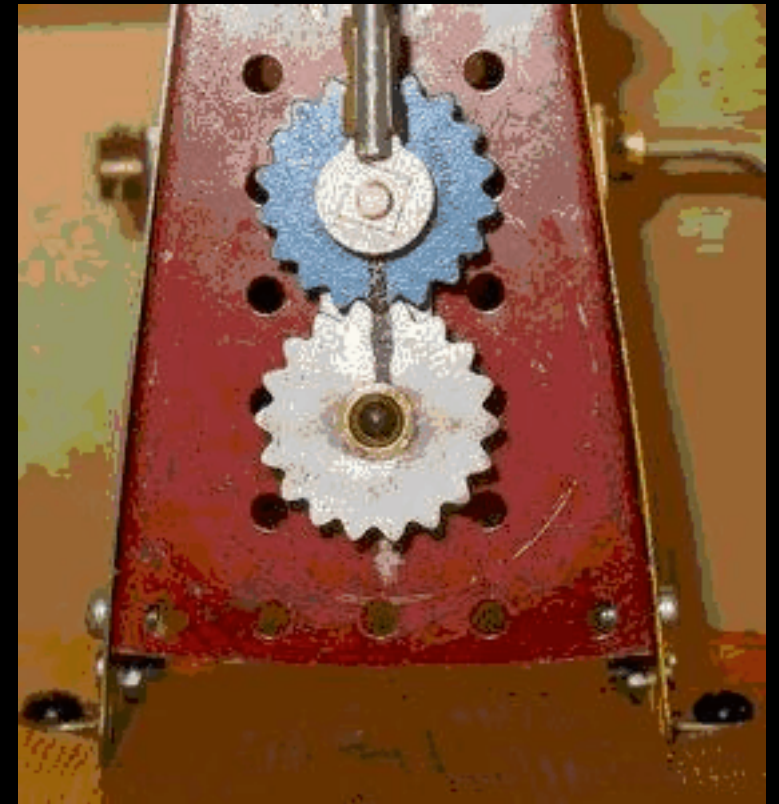




# Watt, Boulton, and Murdoch conquer the world

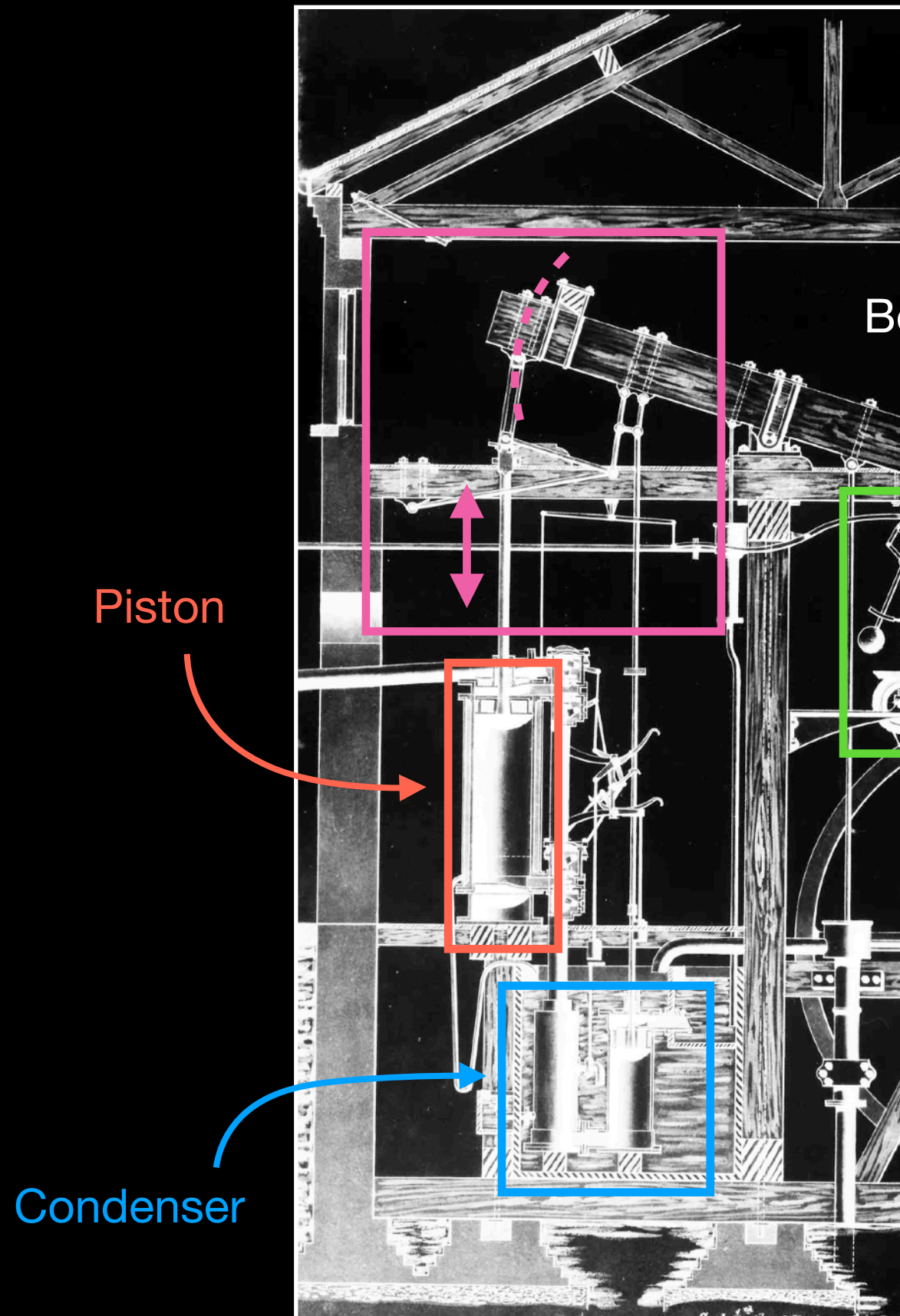


**Sun and planet gear**  
Invented by William Murdoch

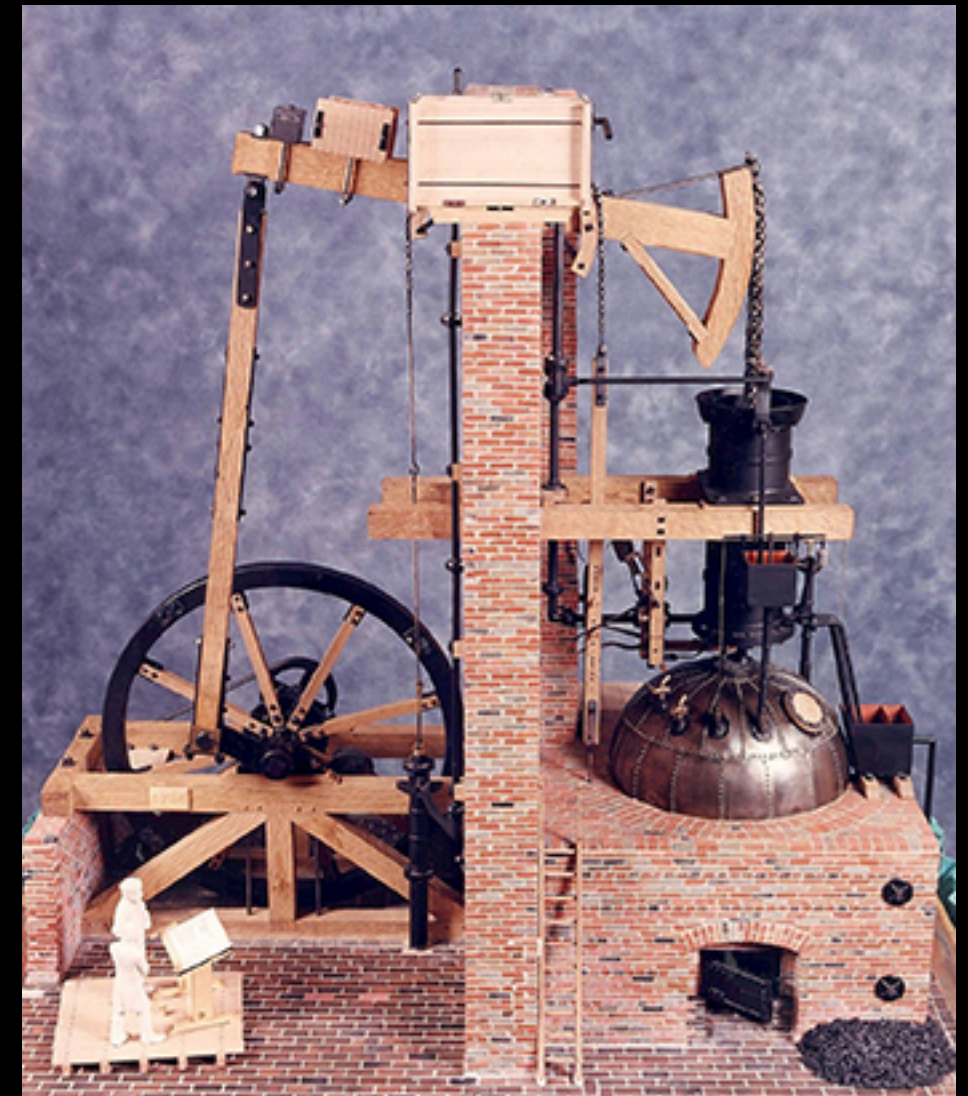




# Watt, Boulton, and Murdoch conquer the world



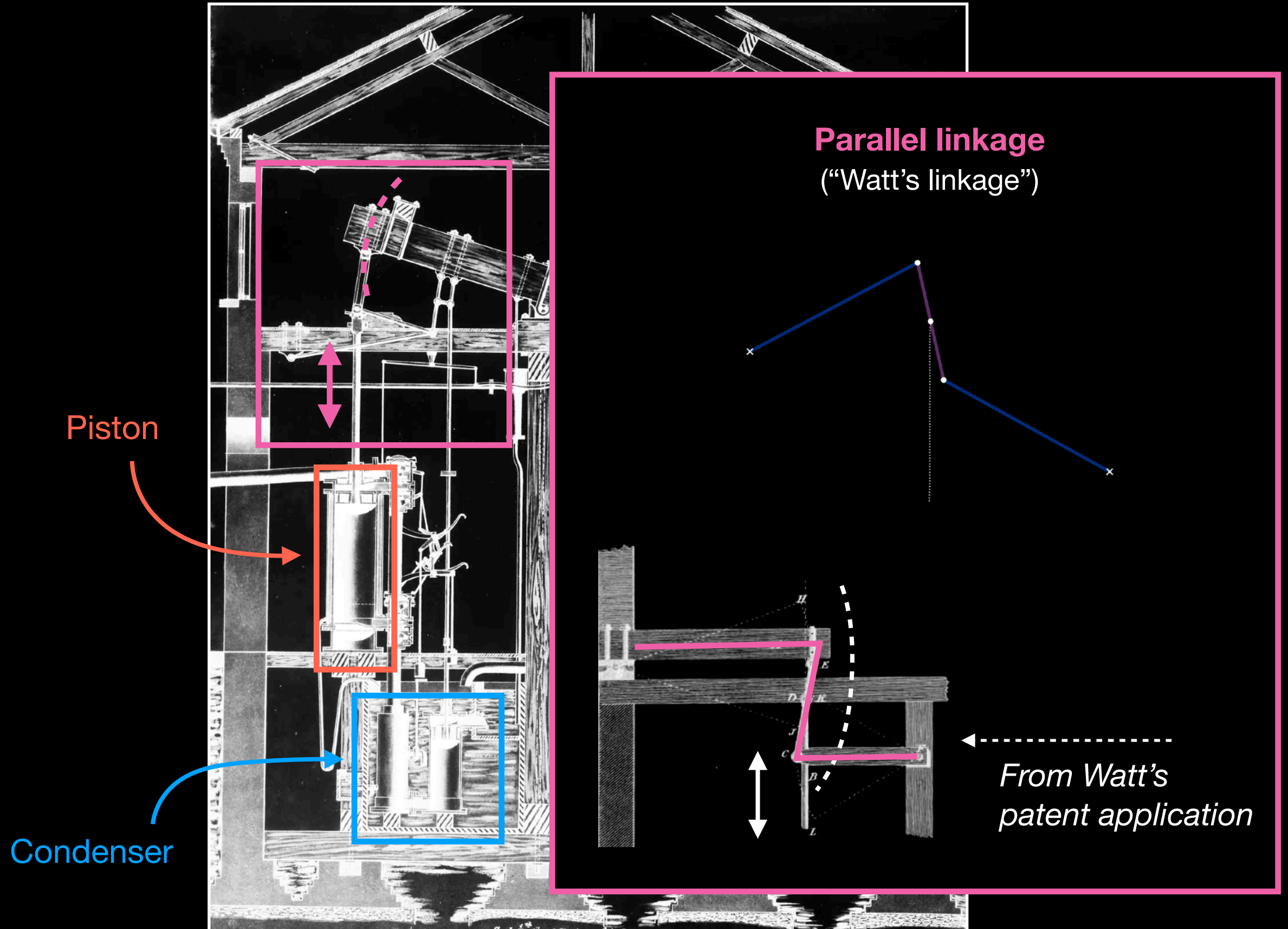
**The crank has already  
been patented!**



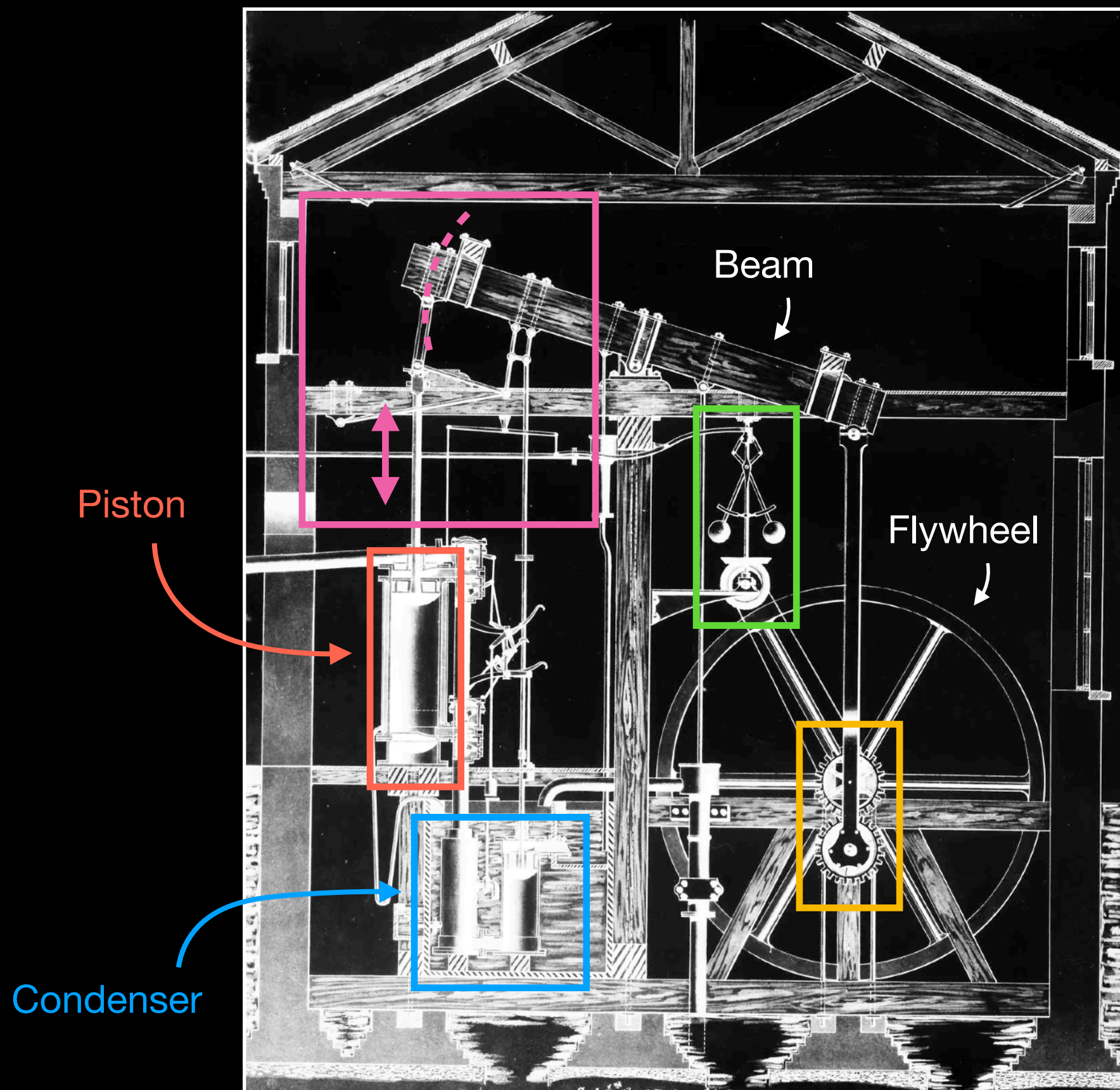
James Pickard:  
“Machines for boring iron; machine for forging,  
rolling, flattening, and slitting iron; machine for  
turning iron; mill for grinding corn”



# Watt, Boulton, and Murdoch conquer the world



# Watt, Boulton, and Murdoch conquer the world

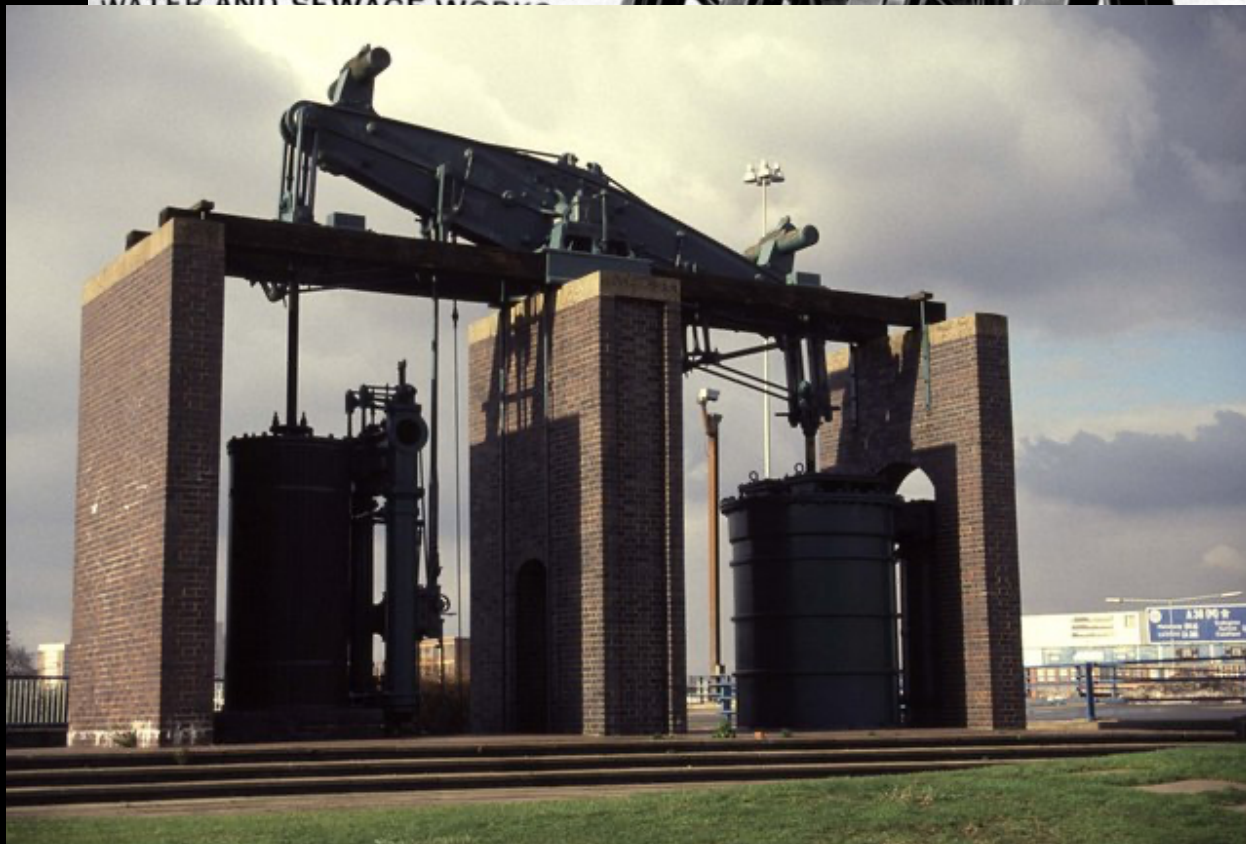
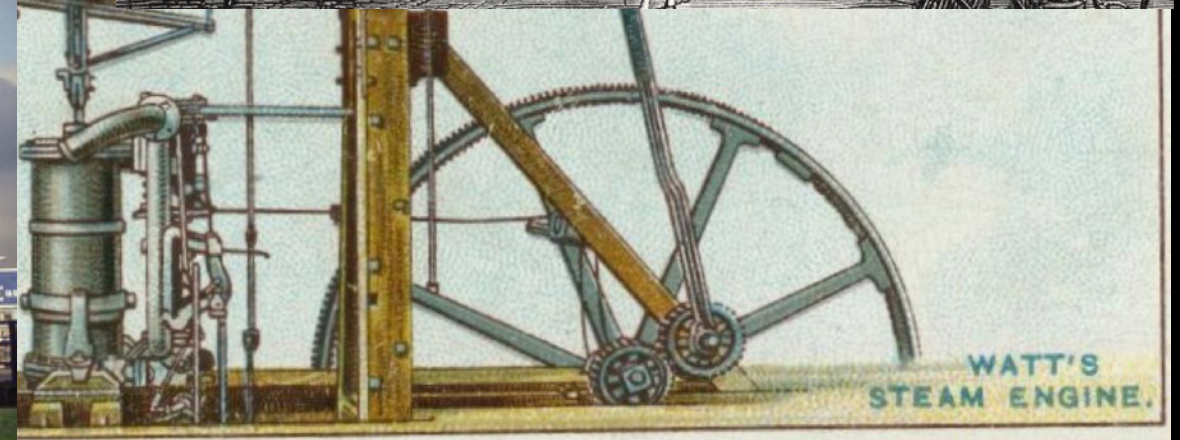
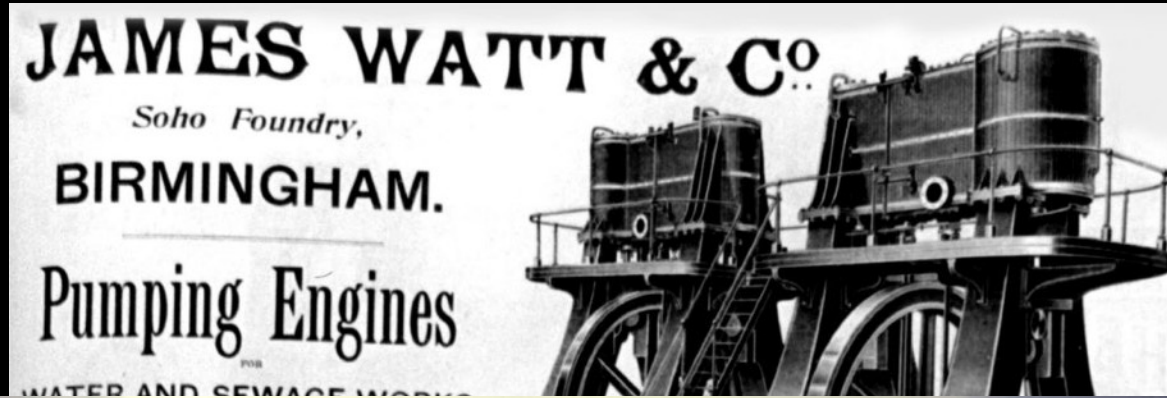




# Watt, Boulton, and Murdoch conquer the world

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*

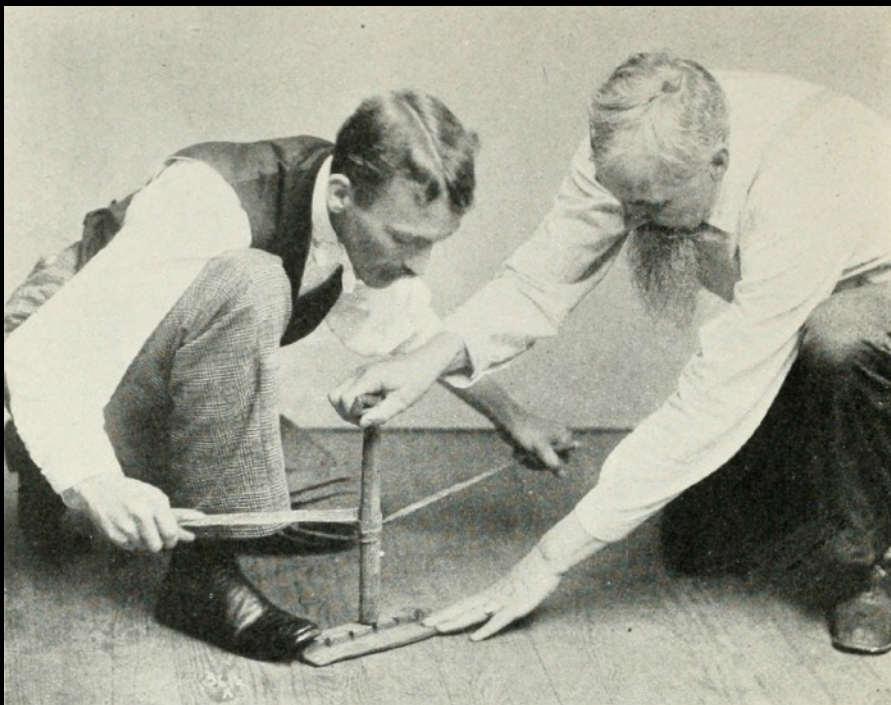




# What is the true nature of heat?

## Kinetic theory

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



*“Savages in different parts of the world have recourse to the friction of pieces of wood for kindling their fires.”*

**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"

*"Caloric is an elastic fluid, the particles of which repel one another strongly."*

*"The particles of caloric are attracted by the particles of ordinary matter."*

*"Caloric is indestructible and uncreatable."*



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



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

# What is the true nature of heat?

## Material theory

Matter of heat: "caloric"

*"Caloric is an elastic fluid, the particles of which repel one another strongly."*

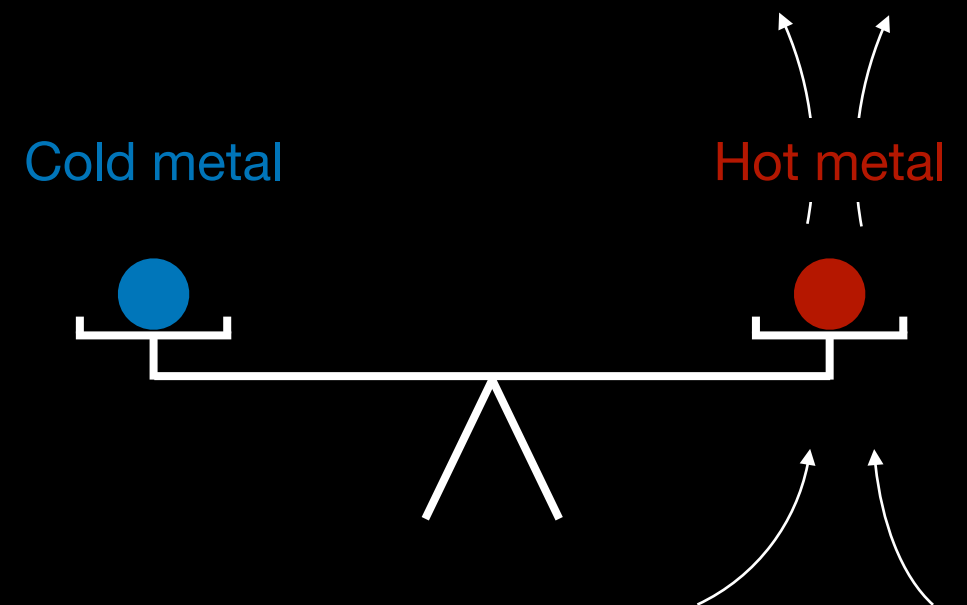
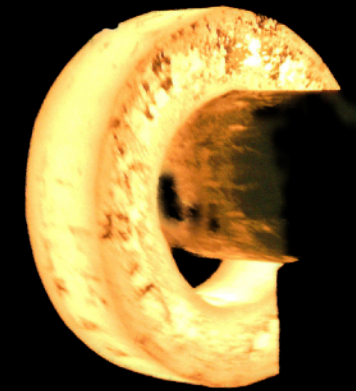
*"The particles of caloric are attracted by the particles of ordinary matter."*

*"Caloric is indestructible and uncreatable."*

*"There is sensible caloric and latent caloric."*

## Does heat have weight?

*Weigh metals at different temperatures*



**But:** surface oxidation, updraft



# What is the true nature of heat?

## Material theory

*Matter of heat: “caloric”*

*“Caloric is an elastic fluid, the particles of which repel one another strongly.”*

*“The particles of caloric are attracted by the particles of ordinary matter.”*

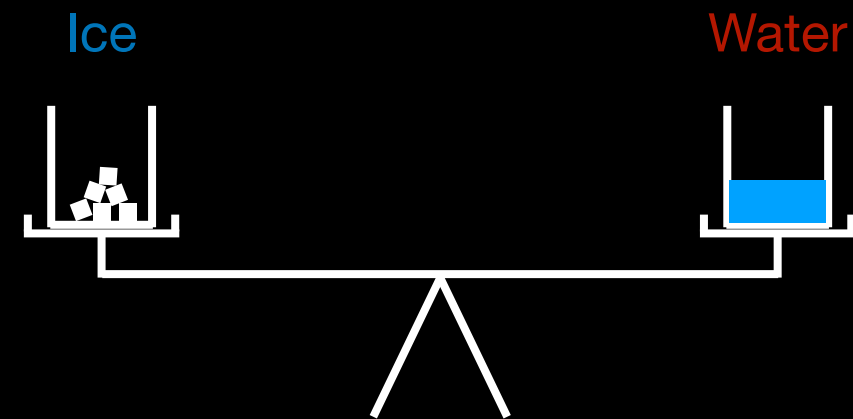
*“Caloric is indestructible and uncreatable.”*

*“There is sensible caloric and latent caloric.”*

*“Caloric does not have appreciable weight.”*

**Does heat have weight?**

*Weigh water and melting ice*



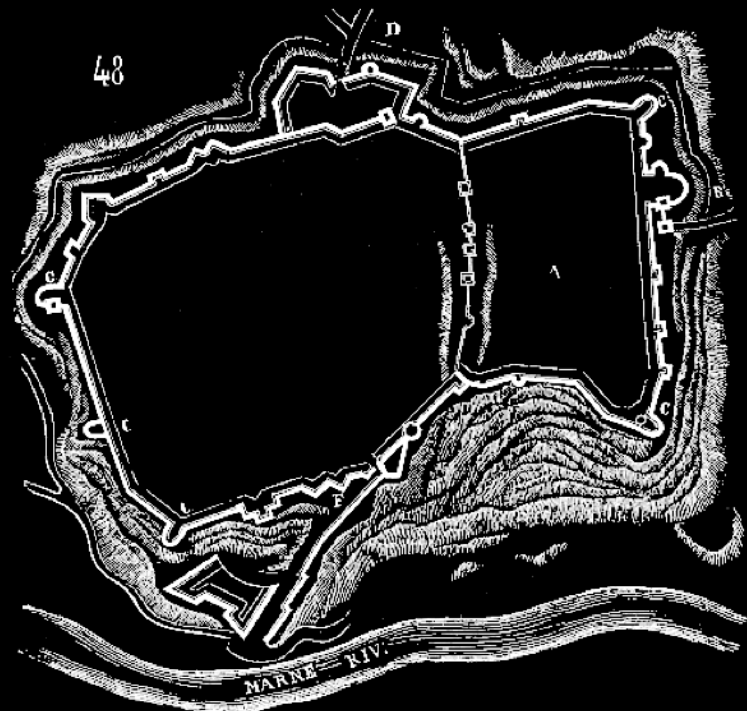
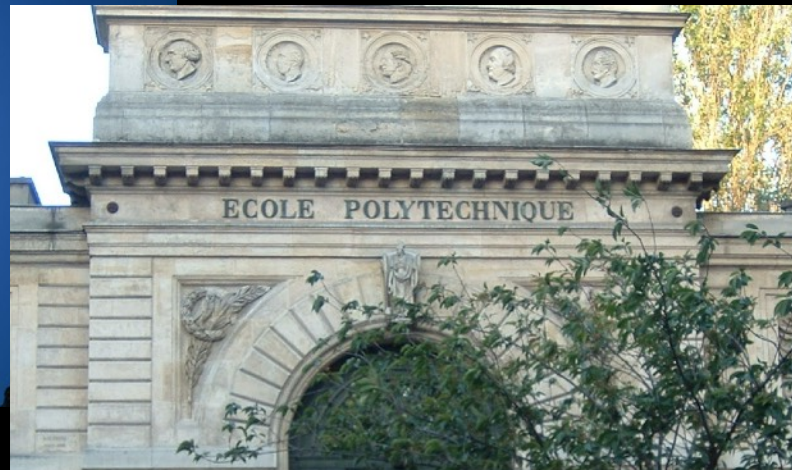
**Made many convincing predictions!**

# Sadi Carnot

Military engineer



**1811-1814:** education at  
Ecole Polytechnique



**1819-1827:** leave on half-pay, remained on-call for duty  
*Attended lectures, visited factories ...*

**1815-1818:** inspecting fortifications, writing reports, ...

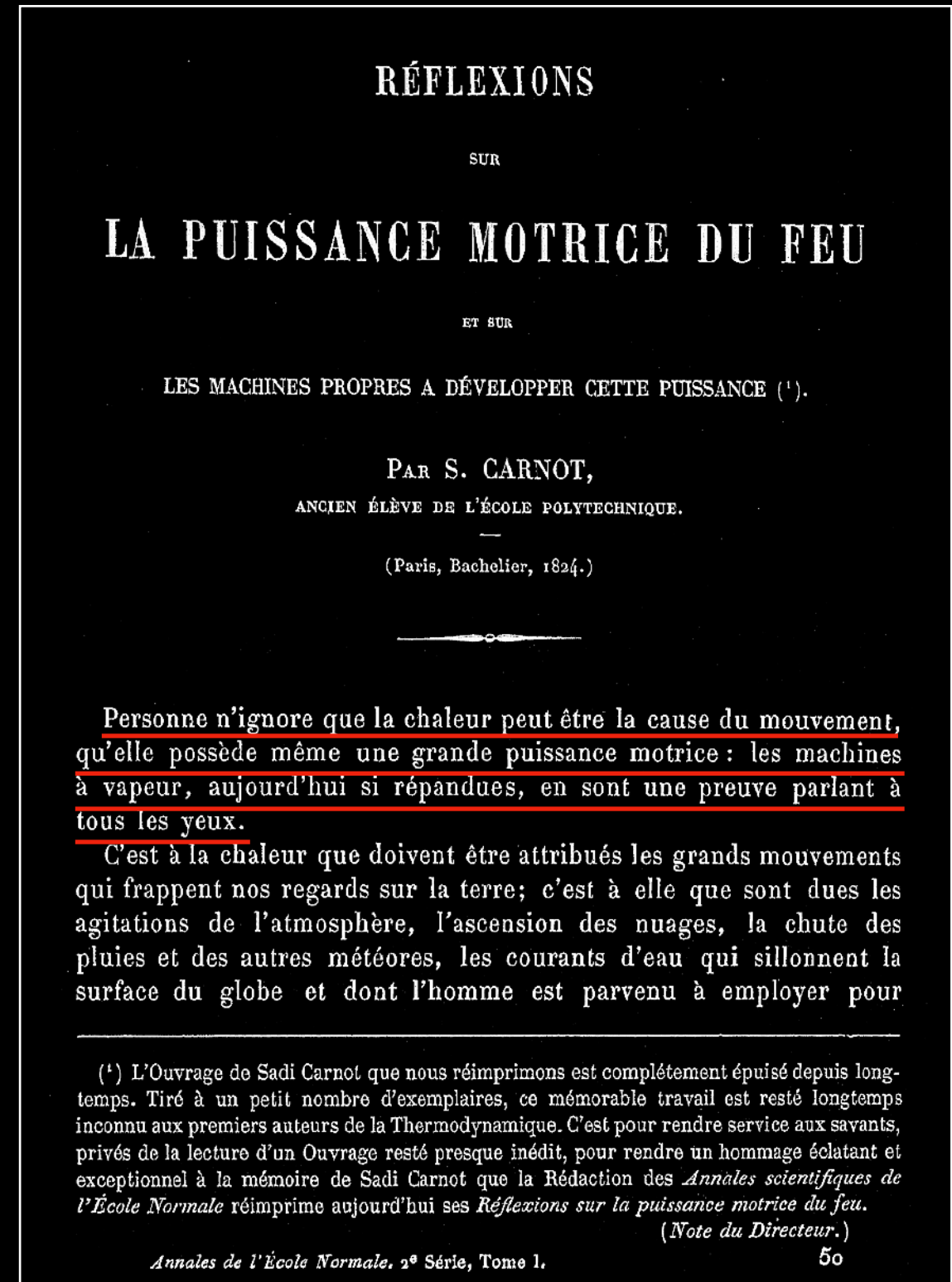


# How efficient can a steam engine be?

*“Heat possesses vast motive power no one can doubt, in these days when the steam engine is everywhere so well known.”*

*“The study of these engines is of the greatest interest; their importance is enormous [...].”*

*“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.”*



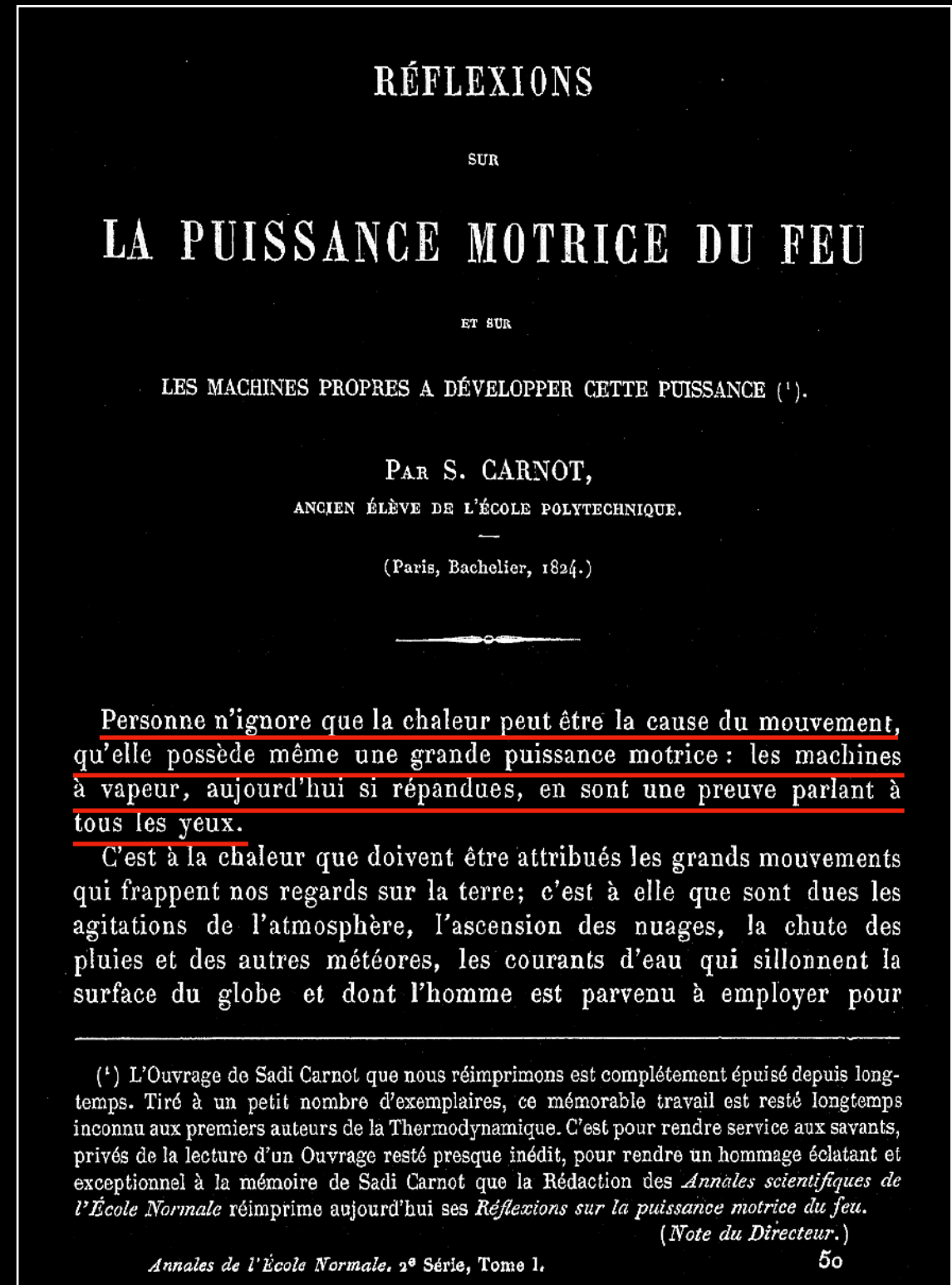
*“Reflections on the motive power of heat, and on machines fitted to develop that power.” (1824)*

# How efficient can a steam engine be?

*“It has often been asked whether the motive power of heat is unbounded, i.e. whether 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, or whether, on the contrary, these improvements may be carried on indefinitely.”*

*“We are seeking to ascertain whether there are in existence agents preferable to the vapor of water for developing the motive power of heat.”*

*“We propose now to submit these questions to a deliberate examination.”*

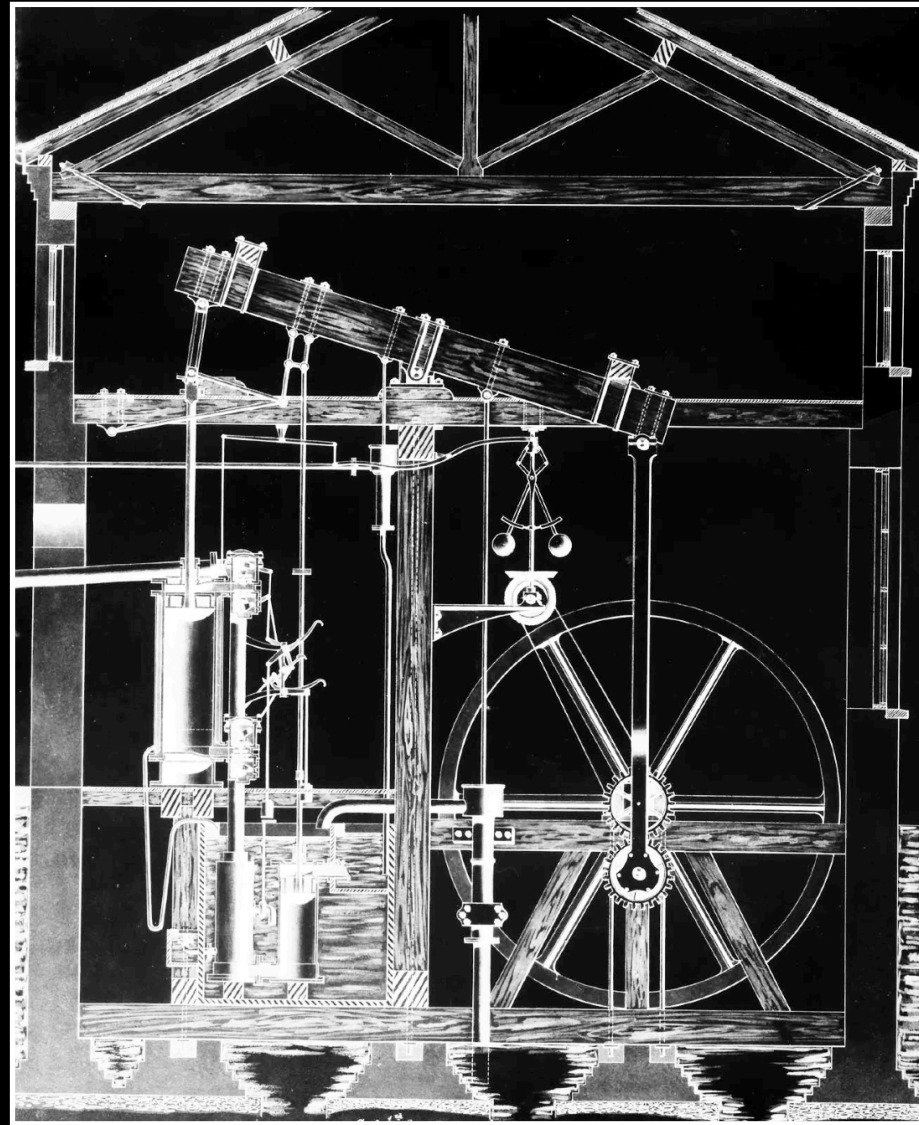


*“Reflections on the motive power of fire, and on machines fitted to develop that power.”*



# Carnot's idealized engine

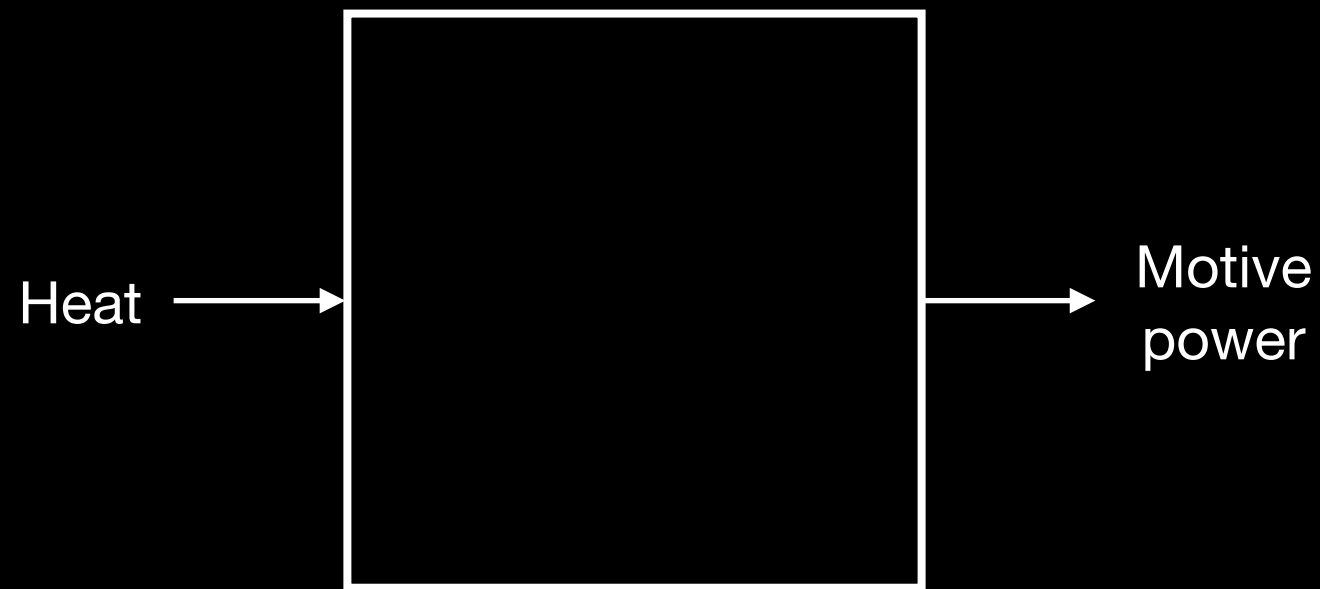
*“The phenomenon of the production of motion by heat has not been considered from a sufficiently general point of view.”*



*“In such machines it becomes difficult to recognize its principles and study its laws.”*

# Carnot's idealized engine

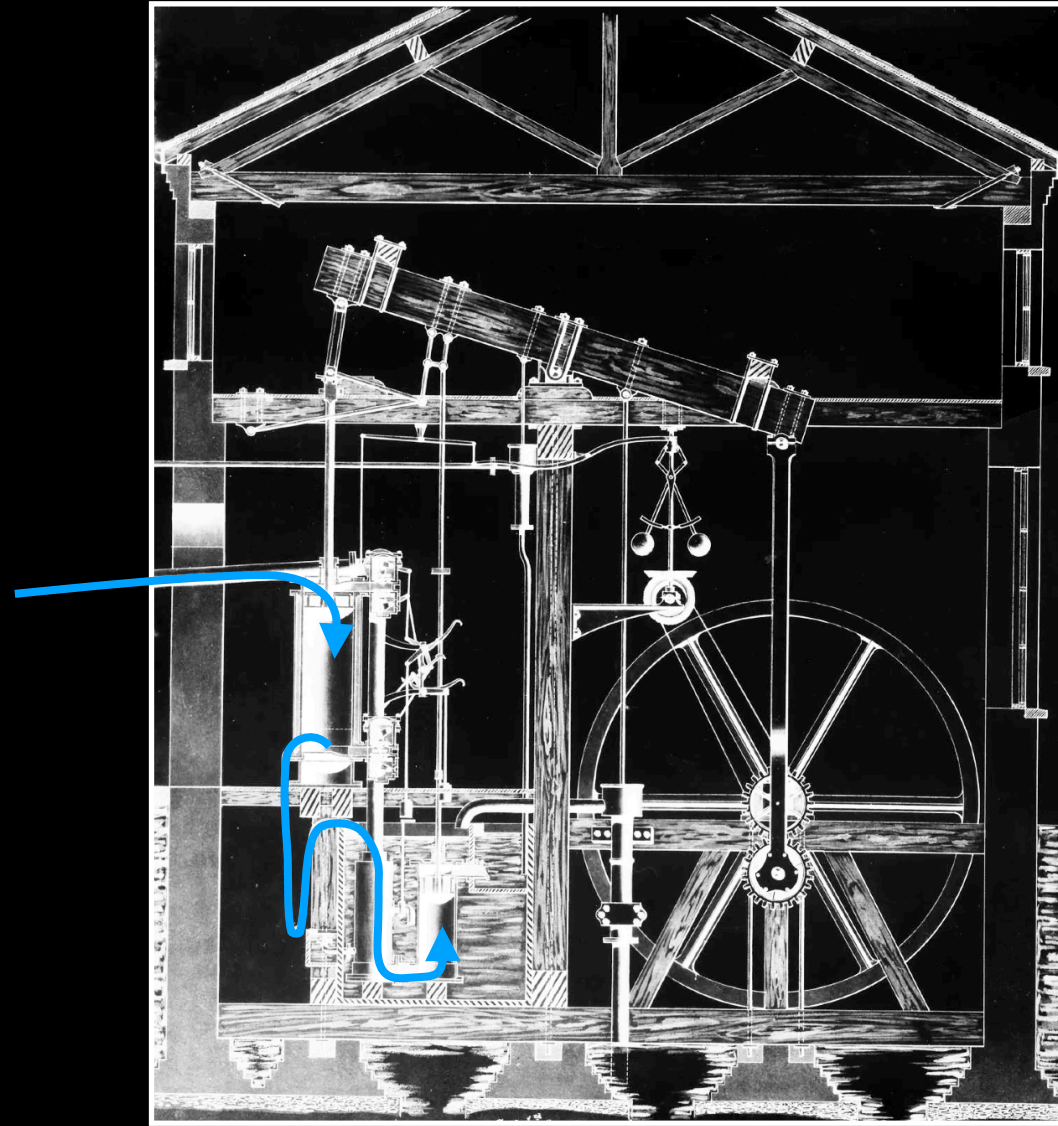
*“It is necessary to establish principles applicable not only to steam engines but to all imaginable heat engines, whatever the working substance and whatever the method by which it is operated.”*





# Carnot's idealized engine

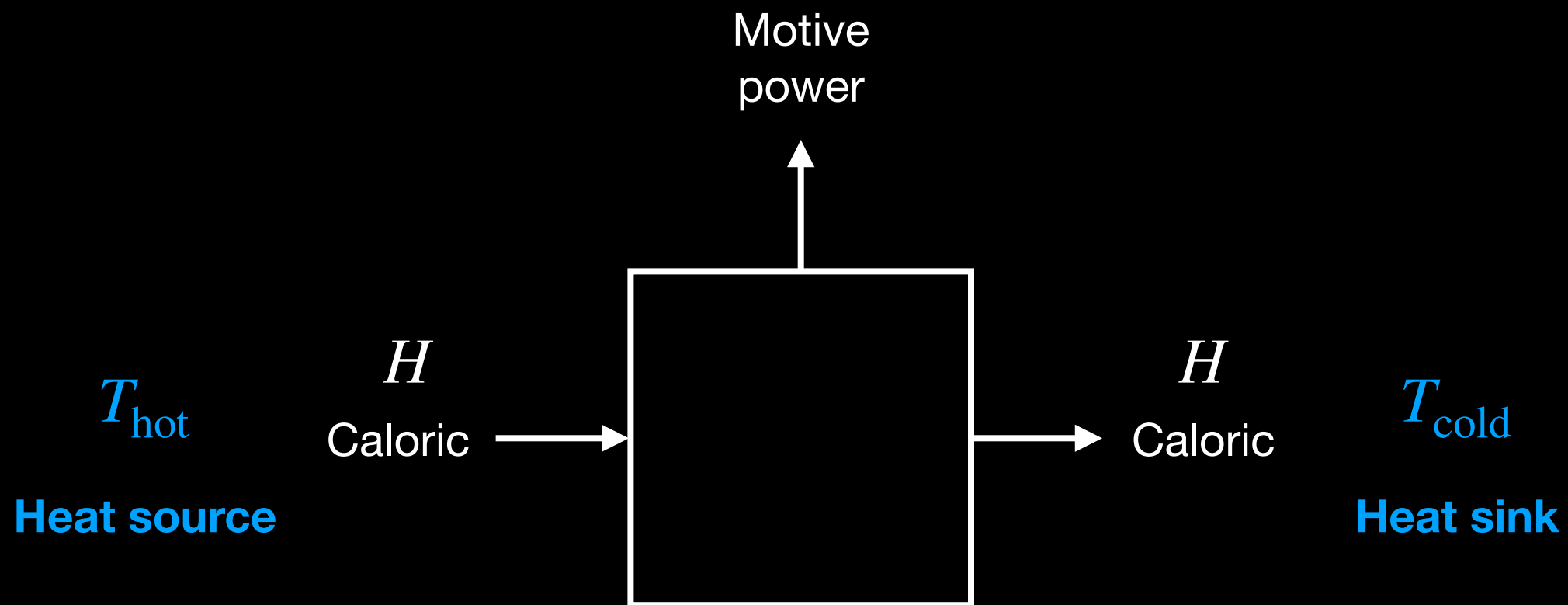
*“What happens in act in a steam engine actually in motion?”*



*“The caloric developed in the furnace produces steam and in some way incorporates itself with it. The latter takes it first into the cylinder, where it performs some function, and from thence into the condenser. The cold water of the condenser takes possession of the caloric developed by the combustion.”*

# Carnot's idealized engine

*“The production of motive power is then due in steam engines not to an actual consumption of caloric, but to its transportation from a warm body to a cold body.”*

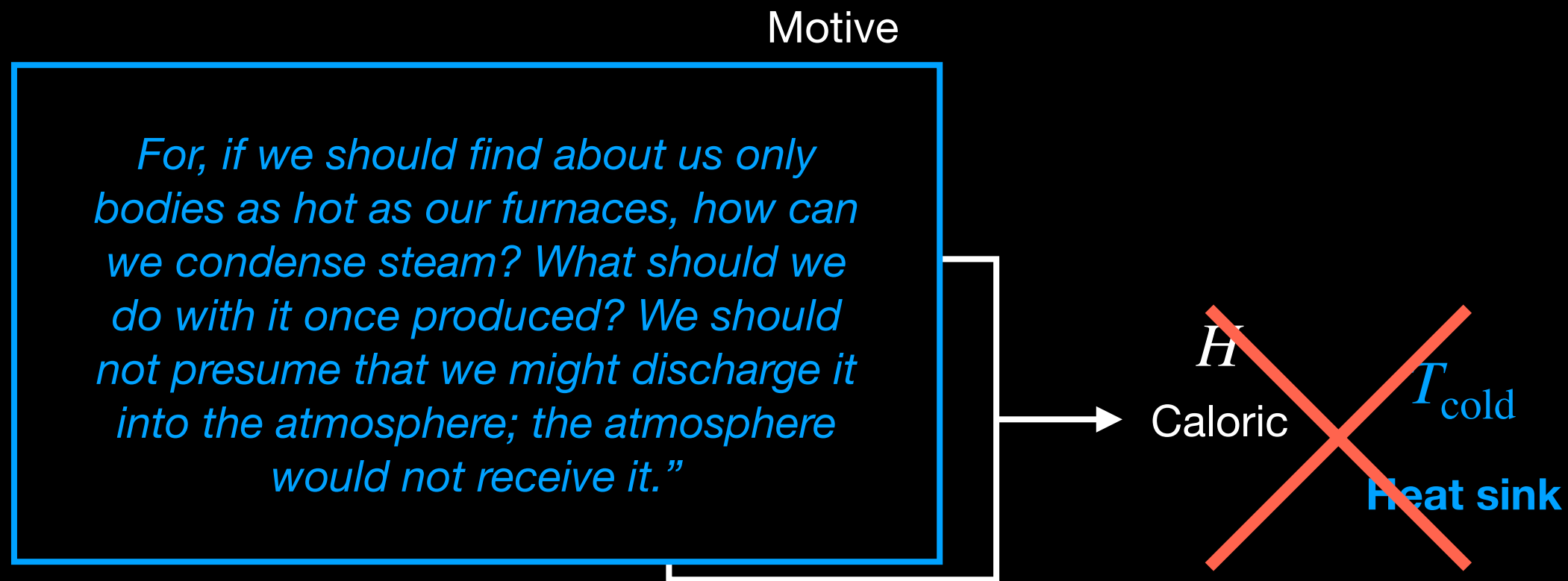


*“The production of heat alone is not sufficient to give birth to the impelling power: it is necessary that there should also be cold; without it, the heat would be useless.”*



# Carnot's idealized engine

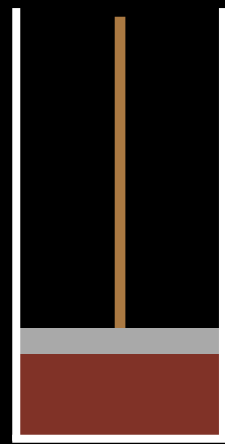
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# How to avoid losses?

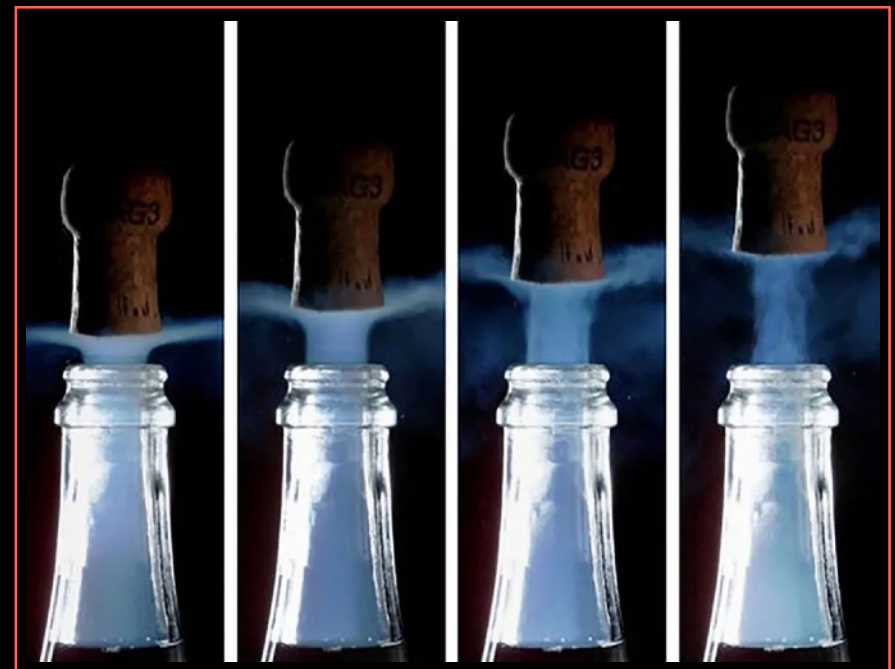
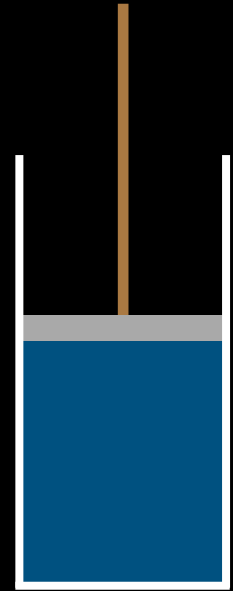
*“In the bodies employed to realize the motive power of heat there should not occur any change of temperature which may not be due to a change of volume.”*



Compressing a gas increases its temperature



Expanding (“rarefying”) a gas decreases its temperature

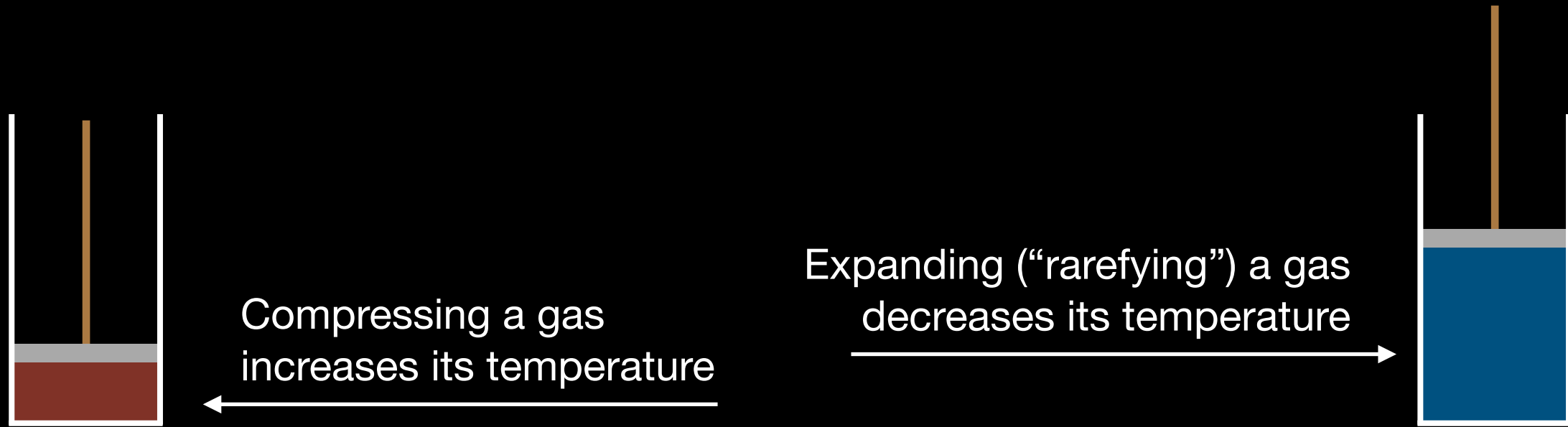


[Smithsonian magazine]



# How to avoid losses?

*“In the bodies employed to realize the motive power of heat there should not occur any change of temperature which may not be due to a change of volume.”*



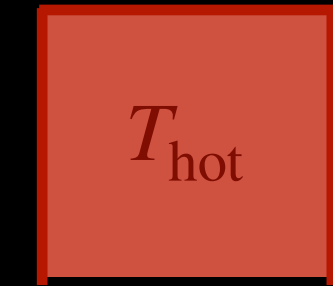
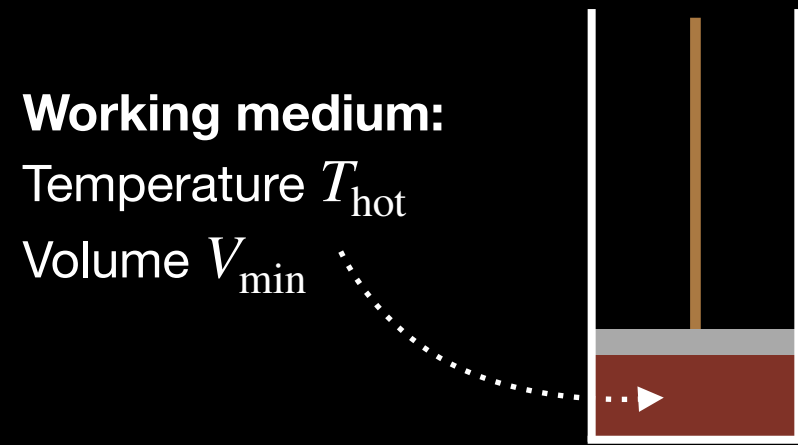
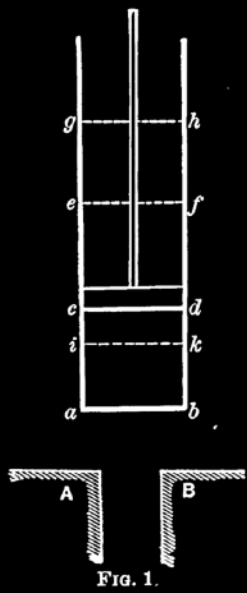
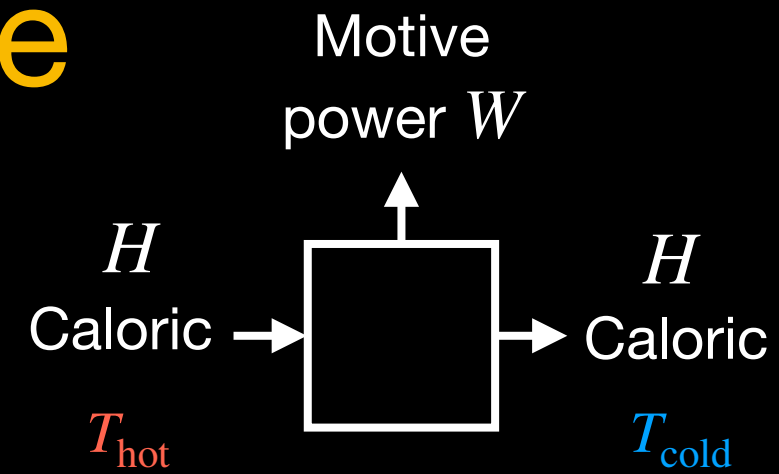
$T_{\text{hot}}$

$T_{\text{cold}}$

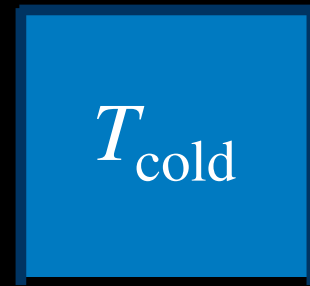
*“This passage occurs mainly by the contact of bodies of different temperatures, hence such contact should be avoided as much as possible.”*

$T_{\text{hot}}$   $T_{\text{cold}}$

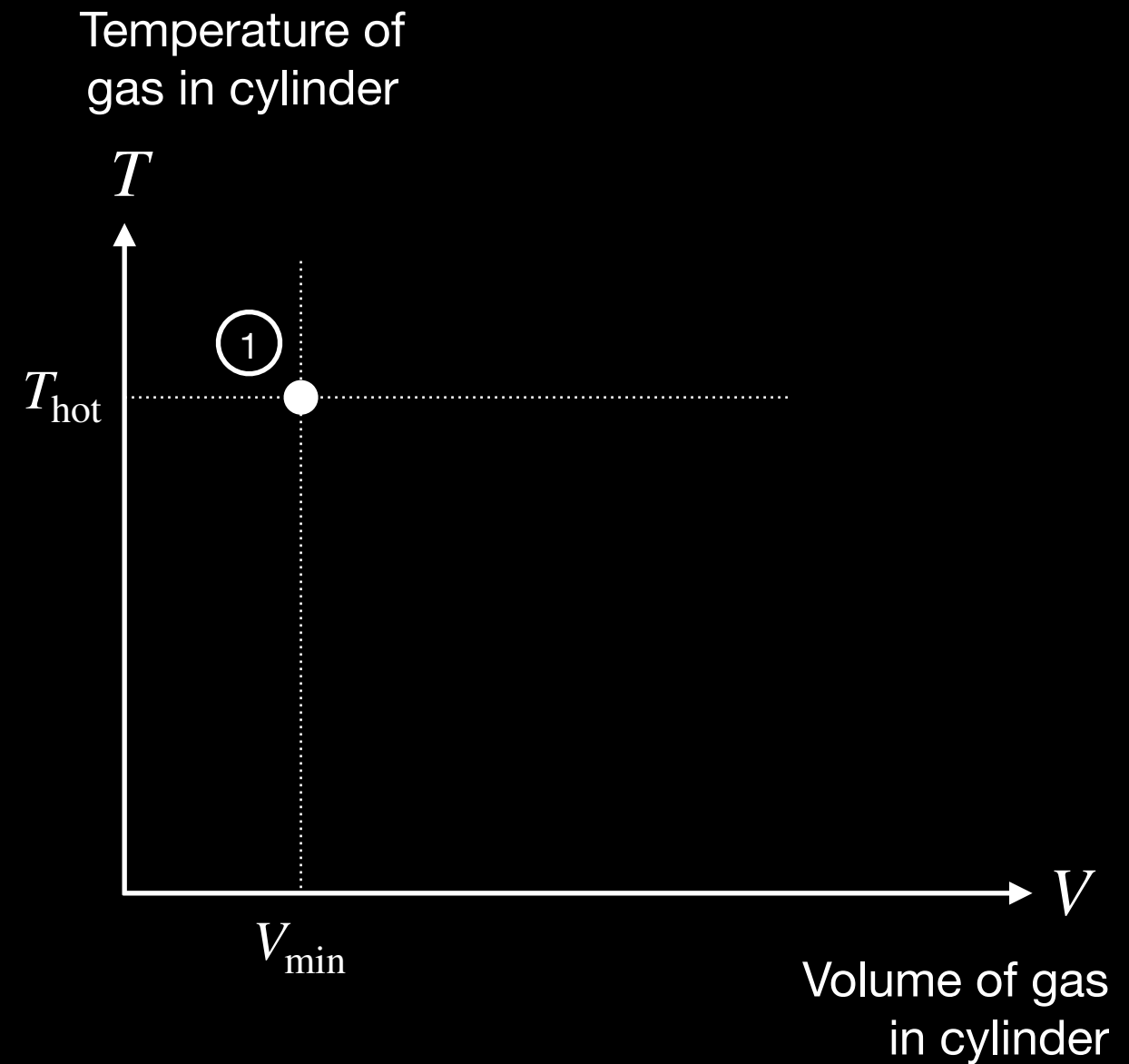
# Carnot's idealized engine



Hot reservoir

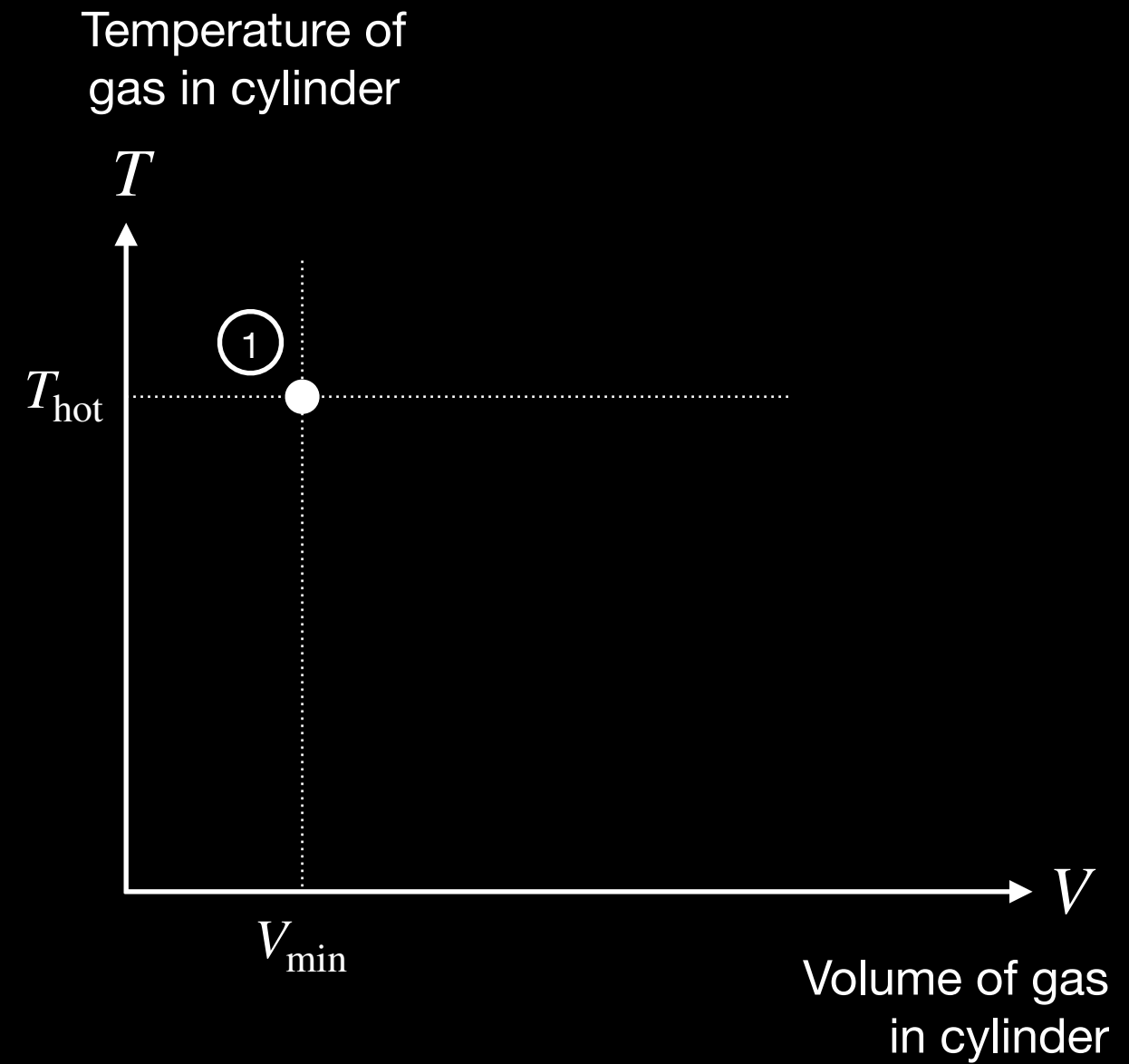
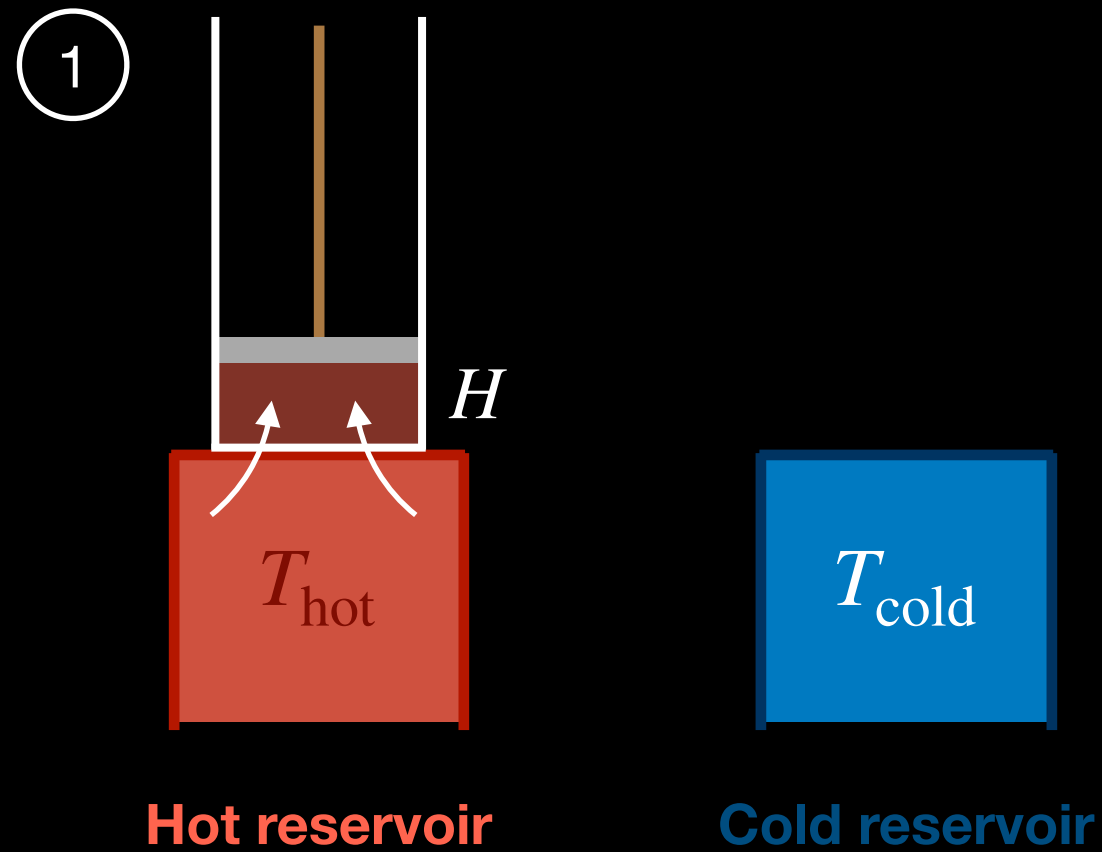
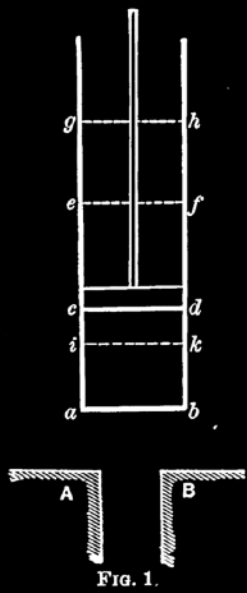


Cold reservoir

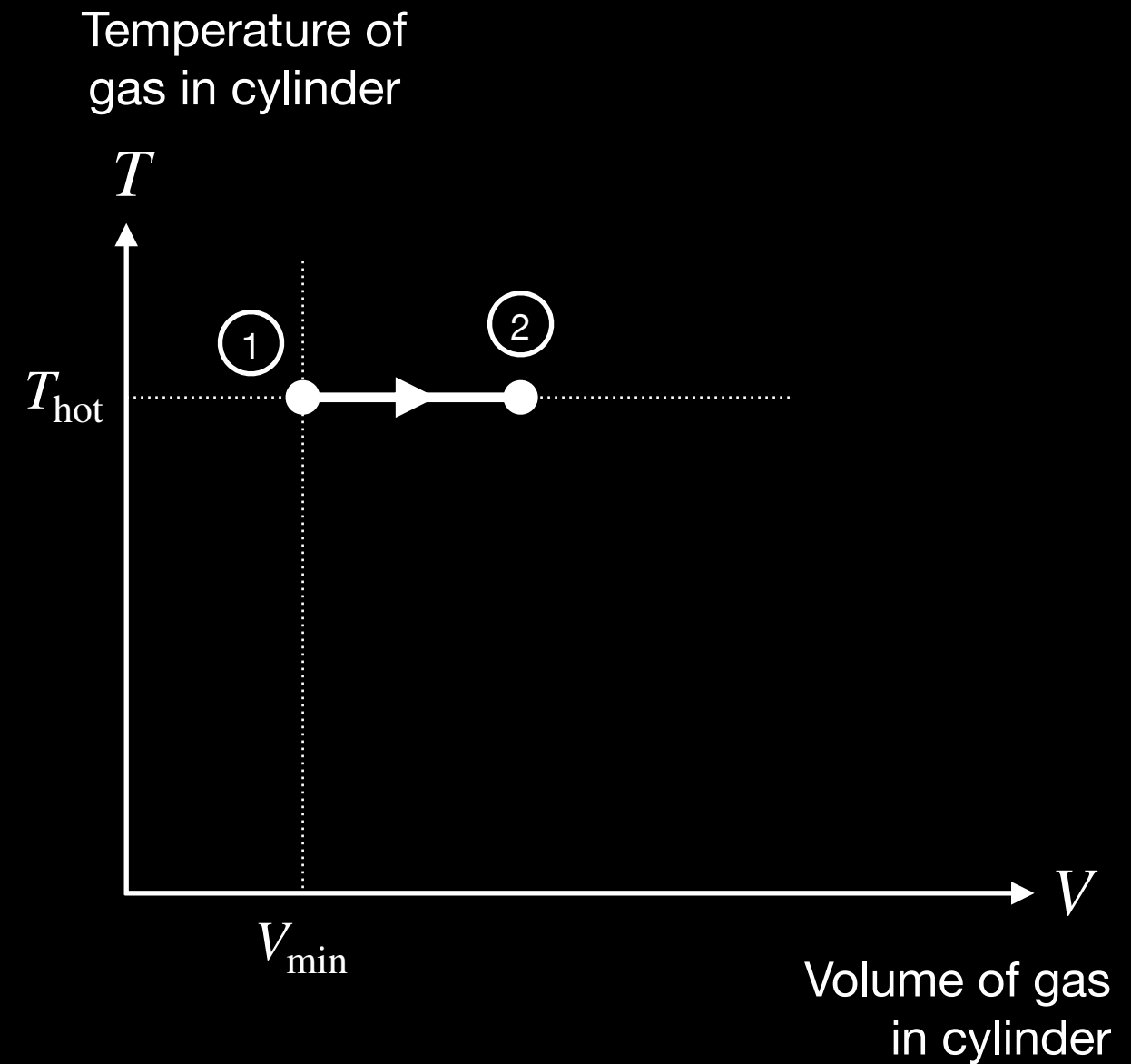
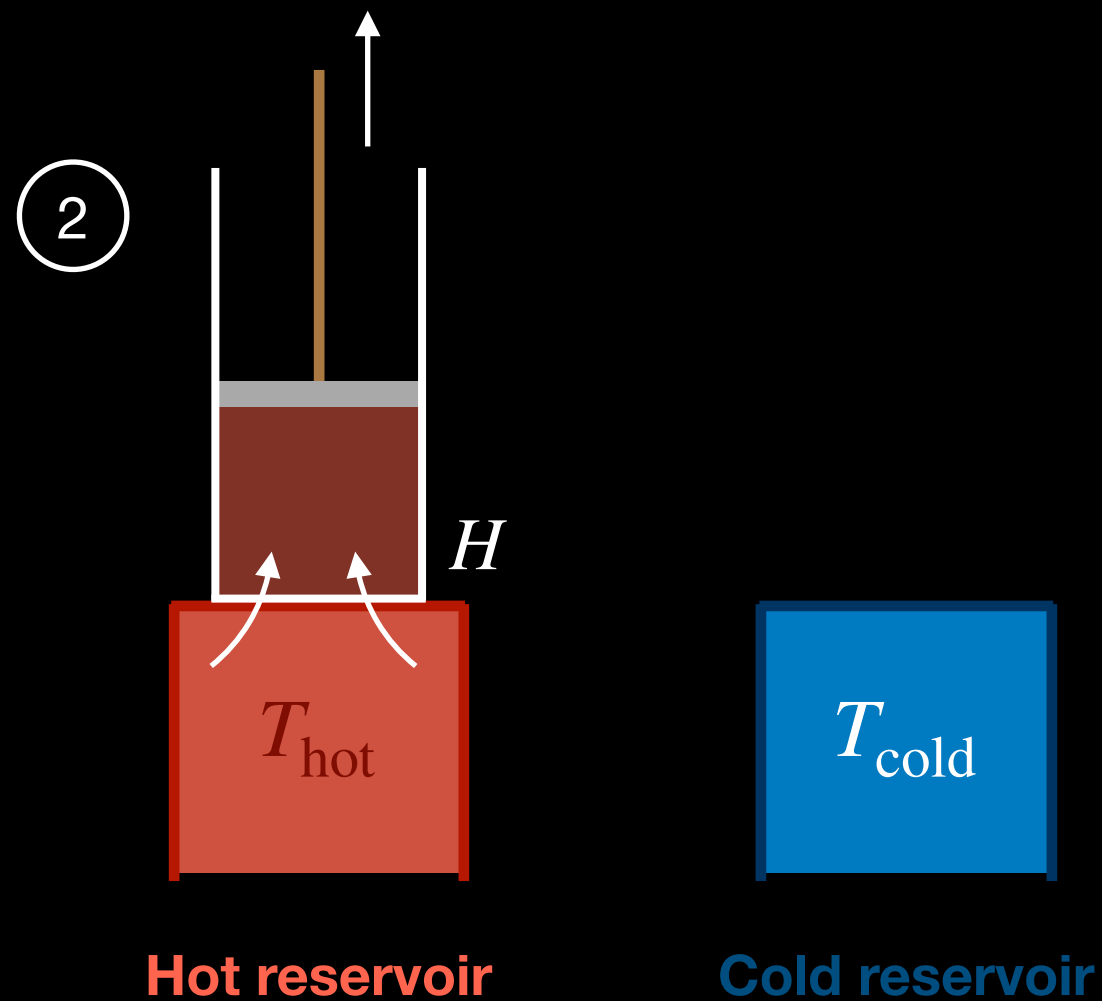
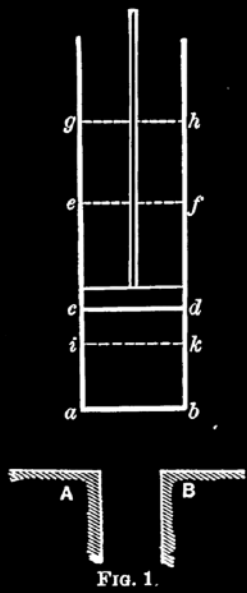




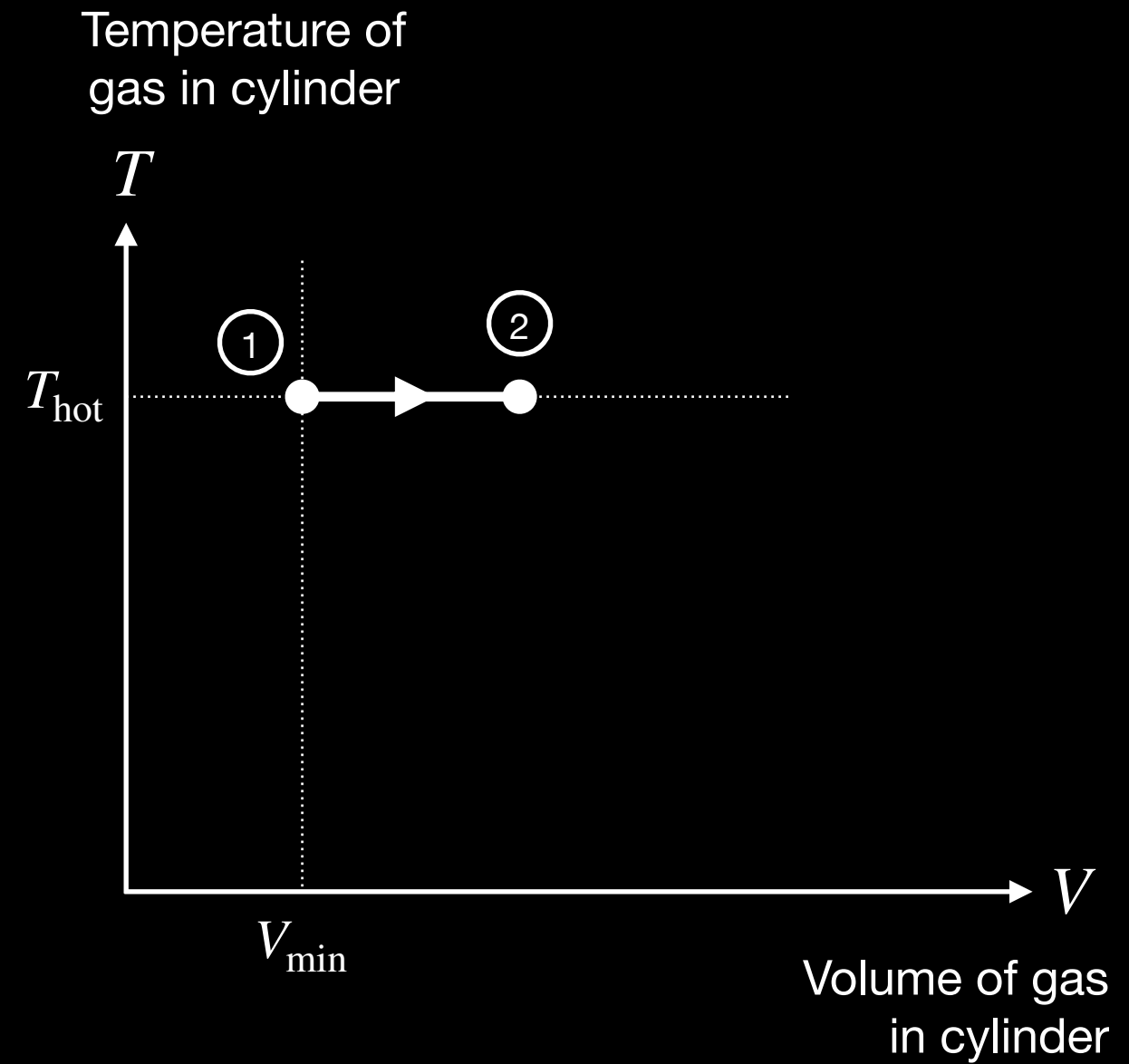
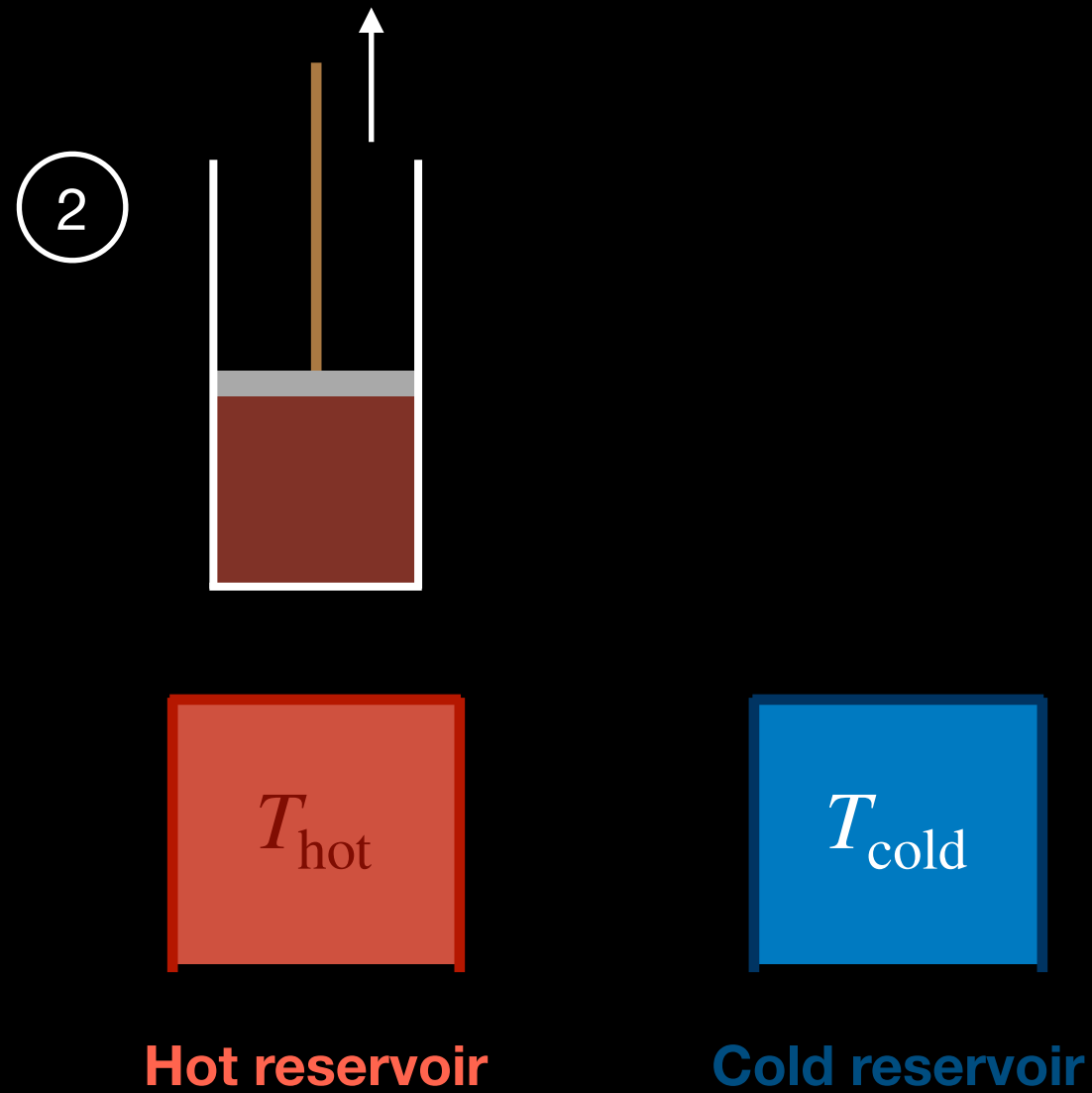
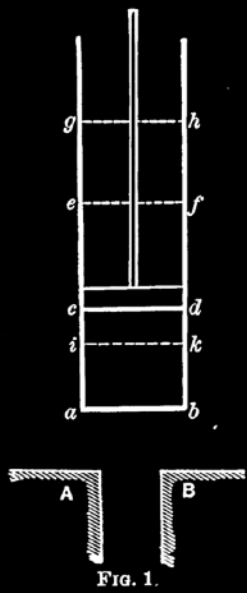
# Carnot's idealized engine



# Carnot's idealized engine

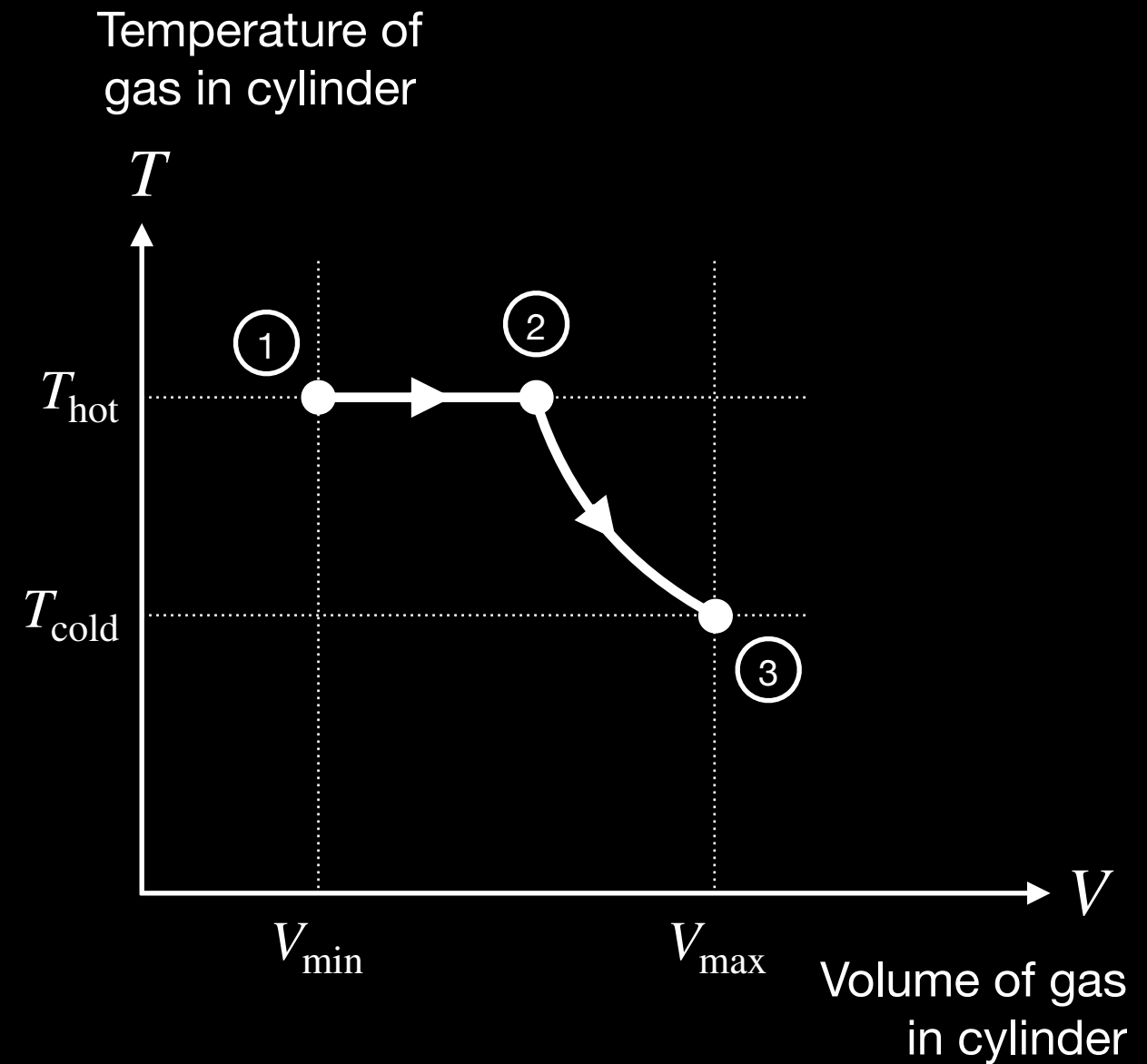
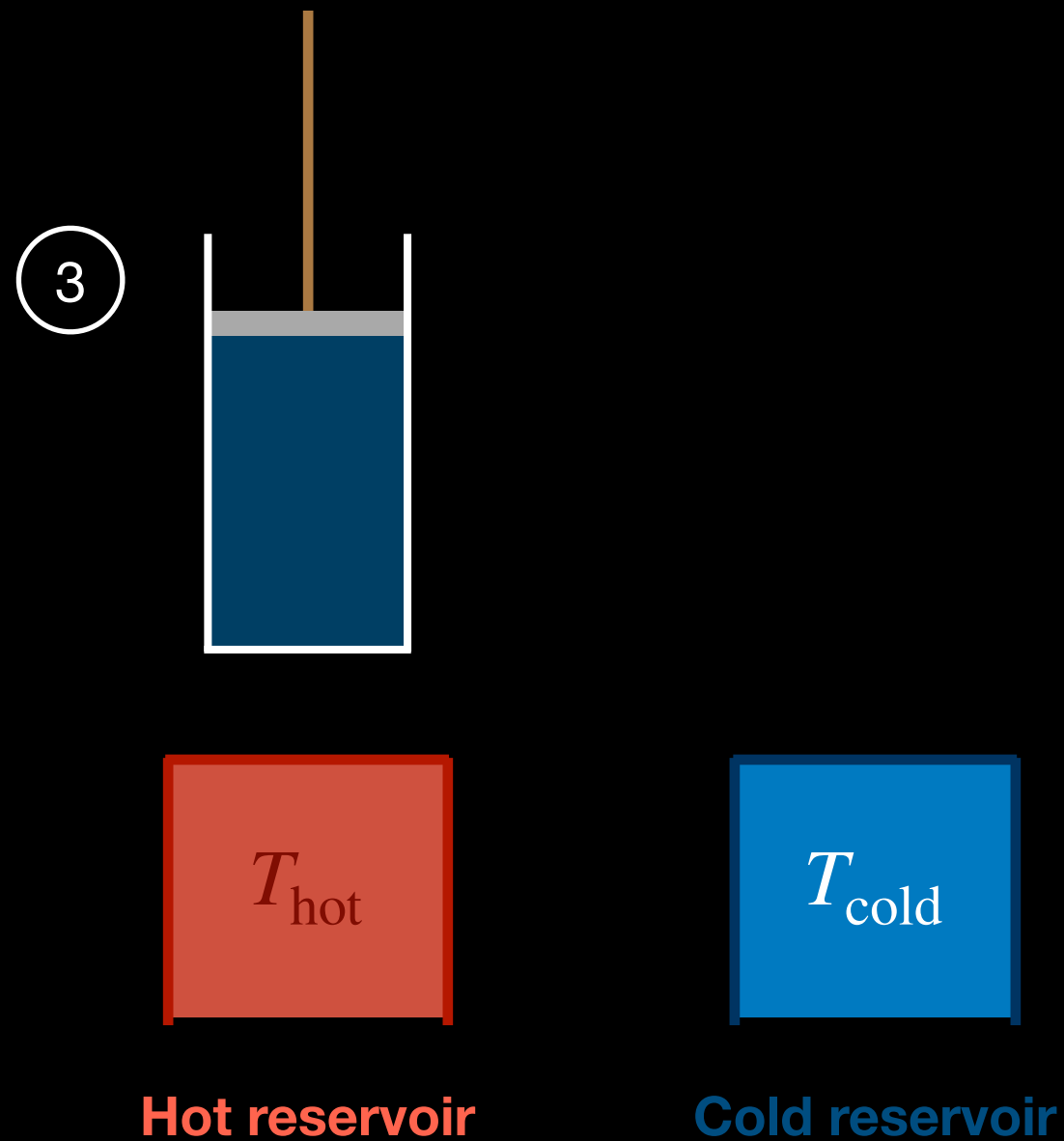
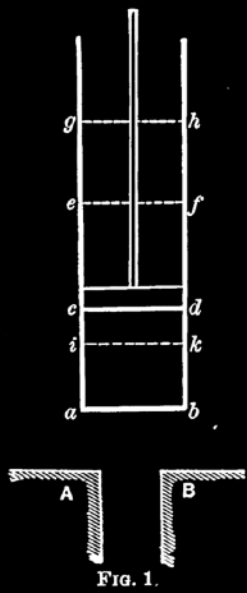


# Carnot's idealized engine

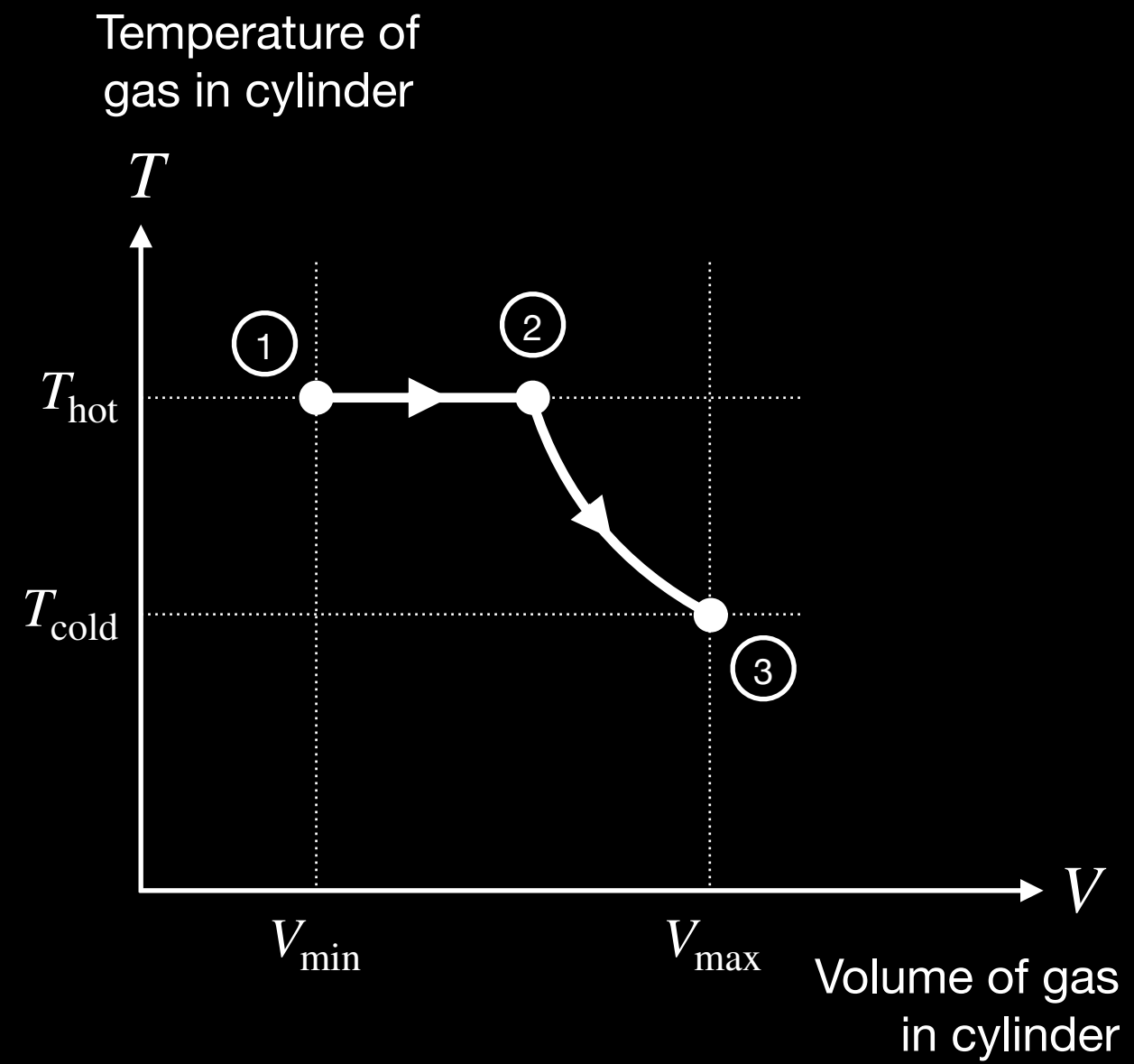
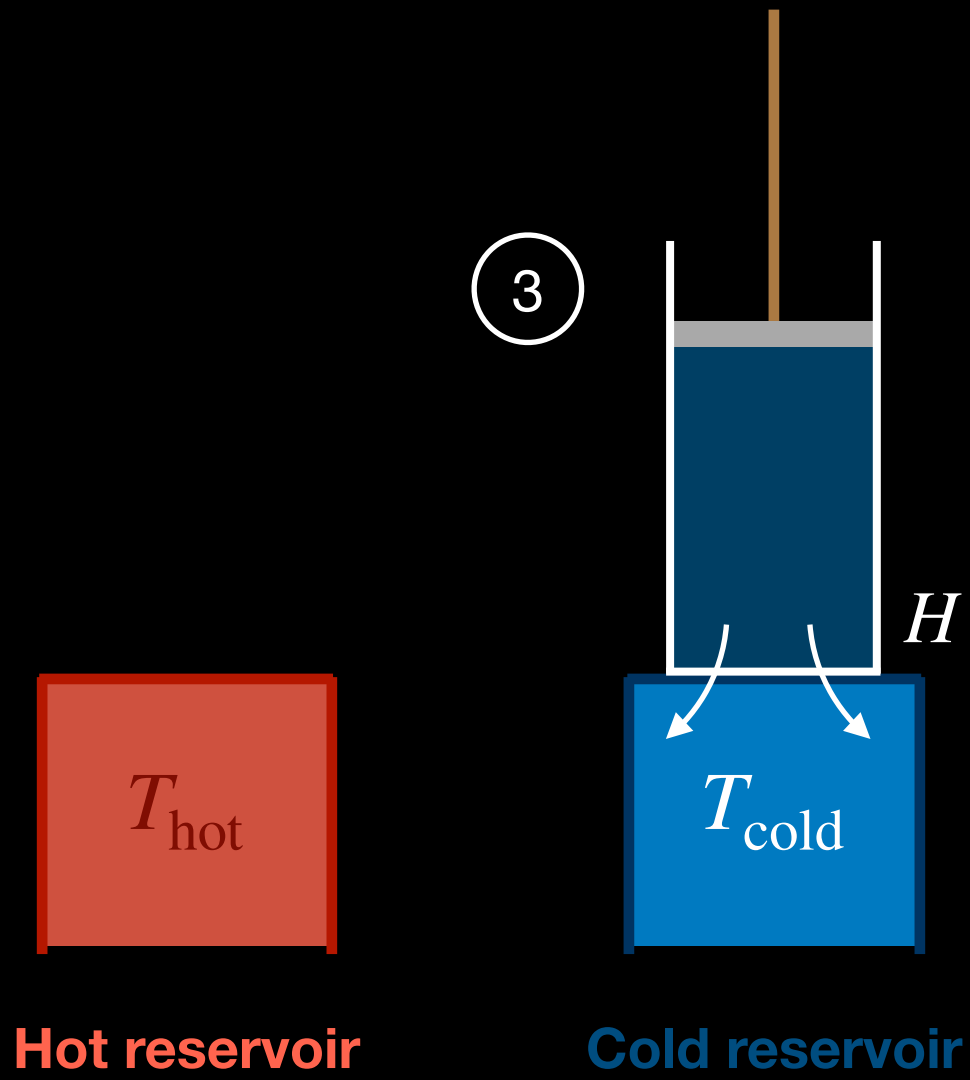
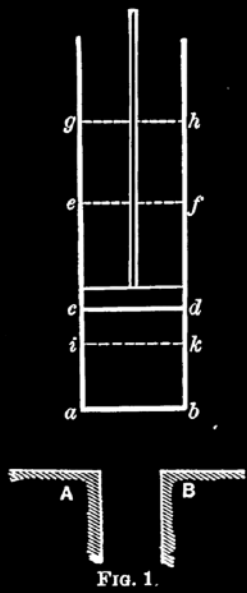




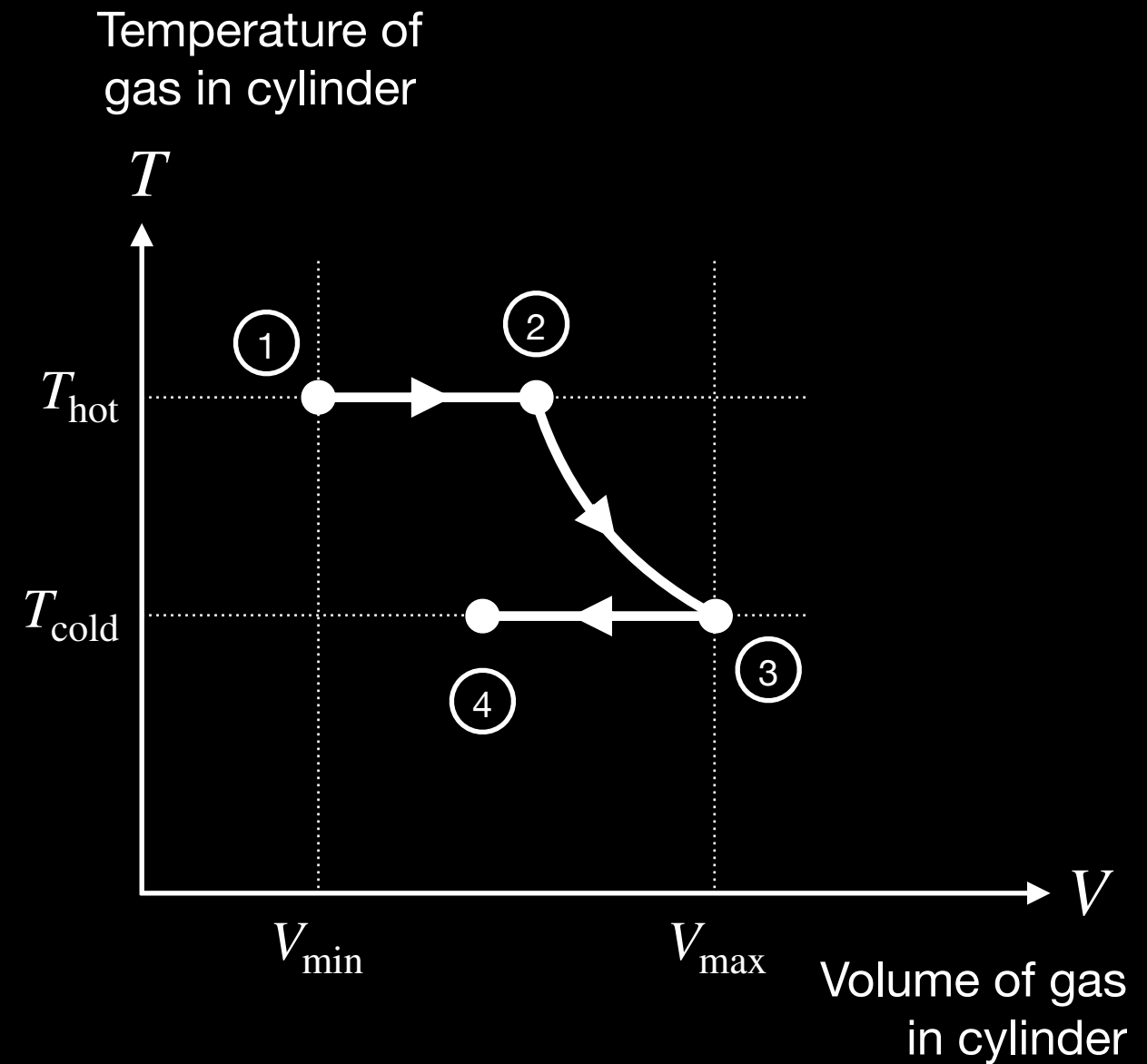
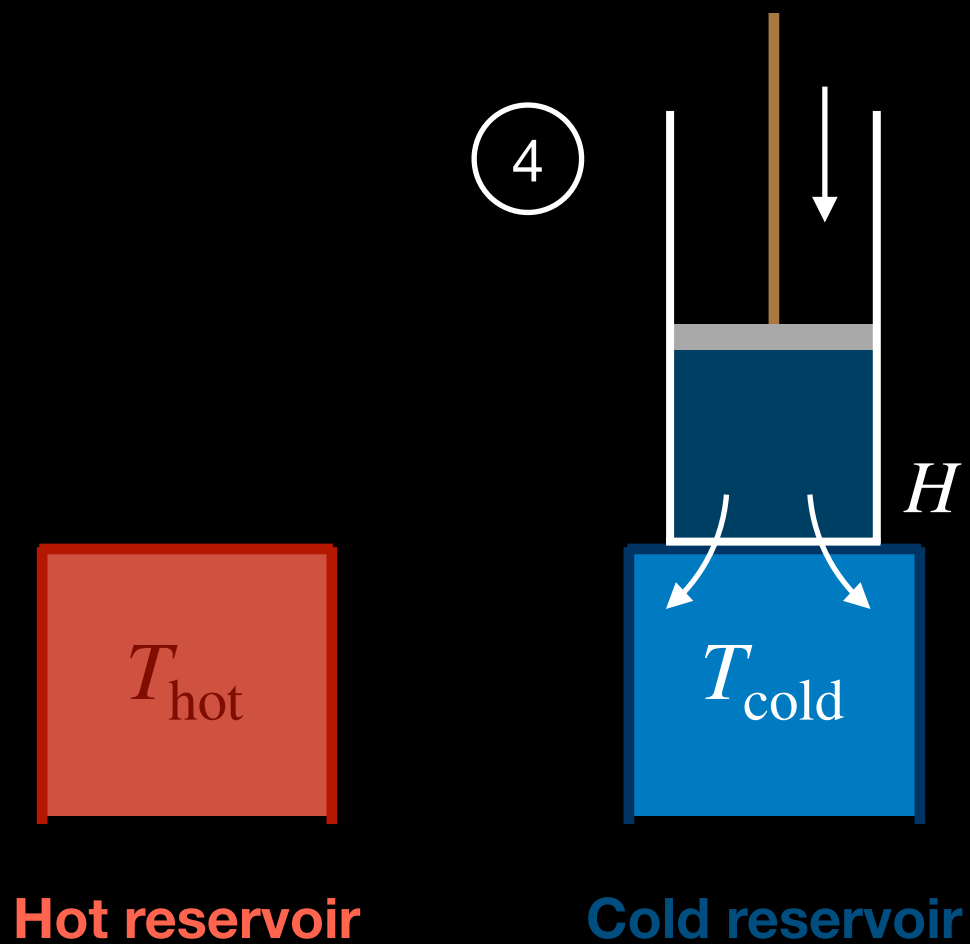
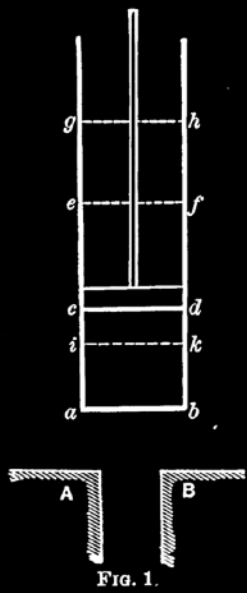
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# Carnot's idealized engine

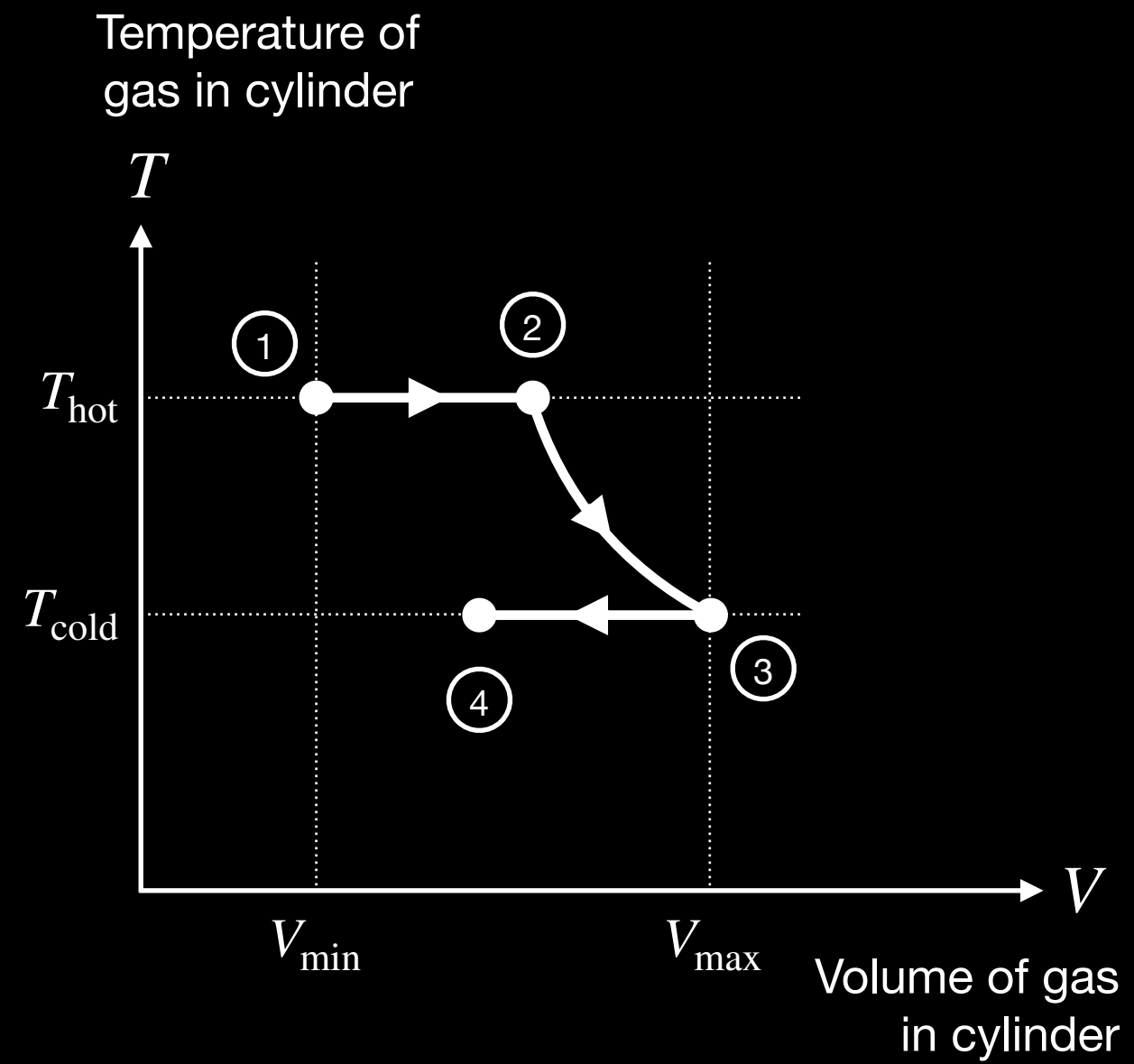
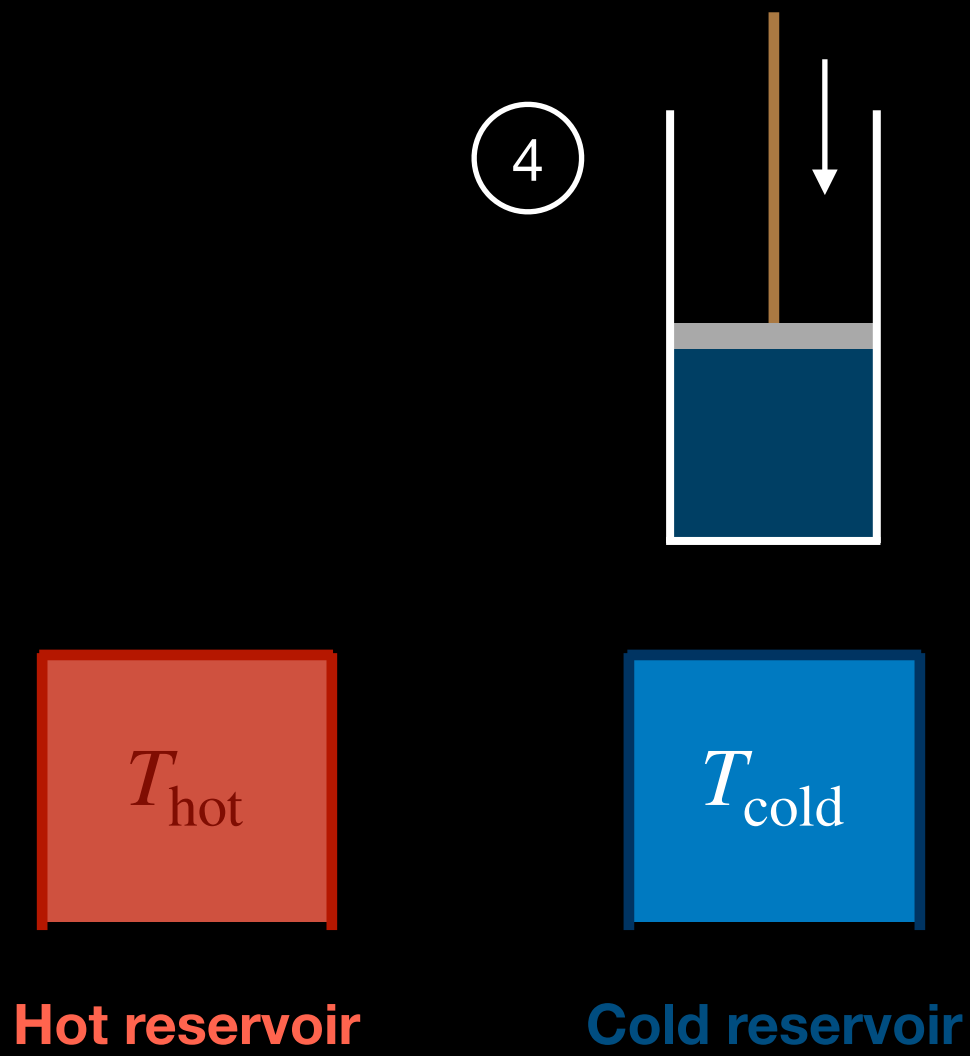
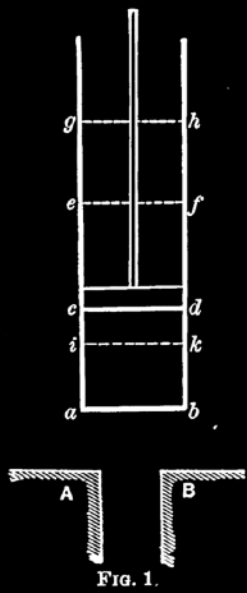


# Carnot's idealized engine

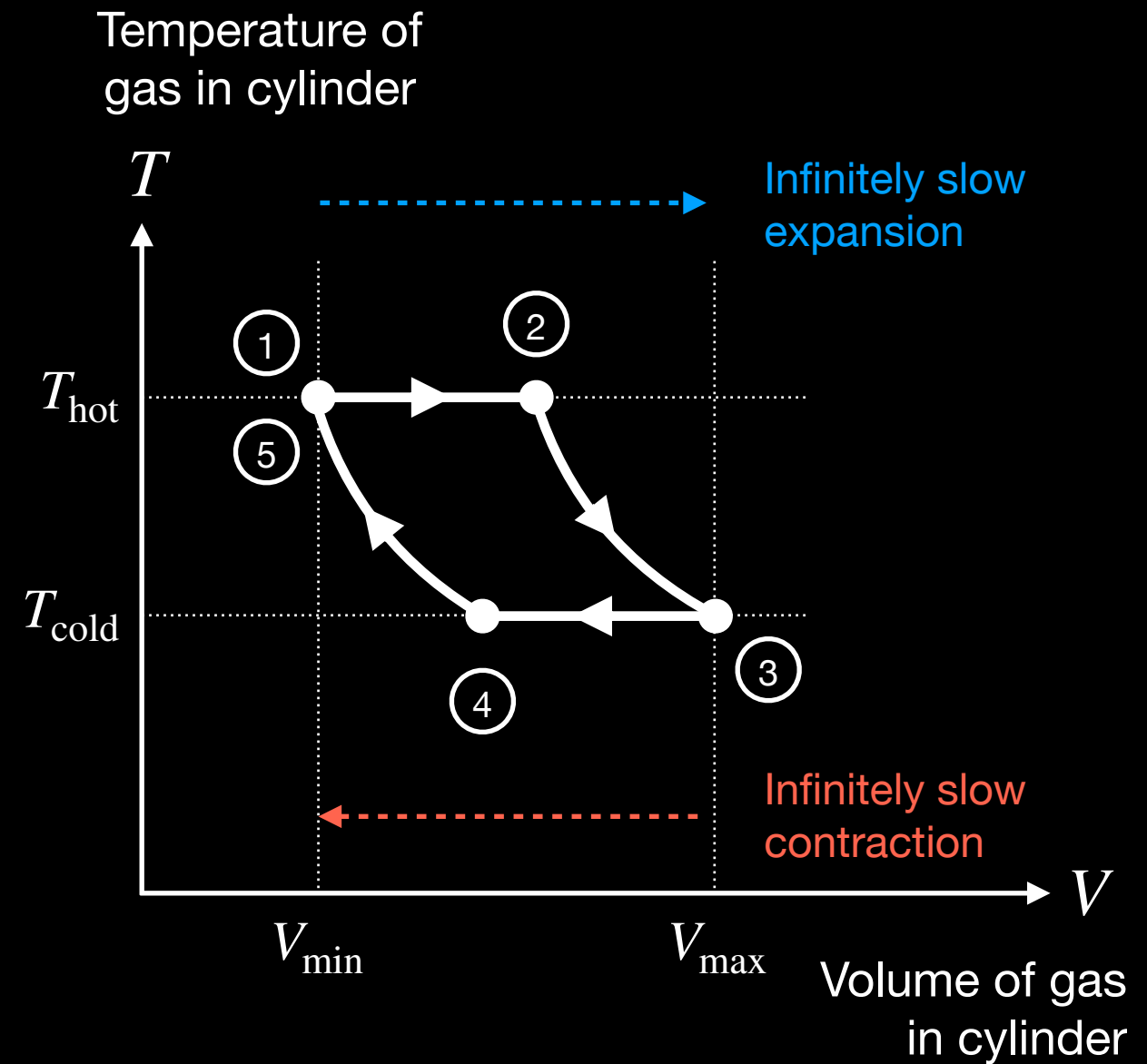
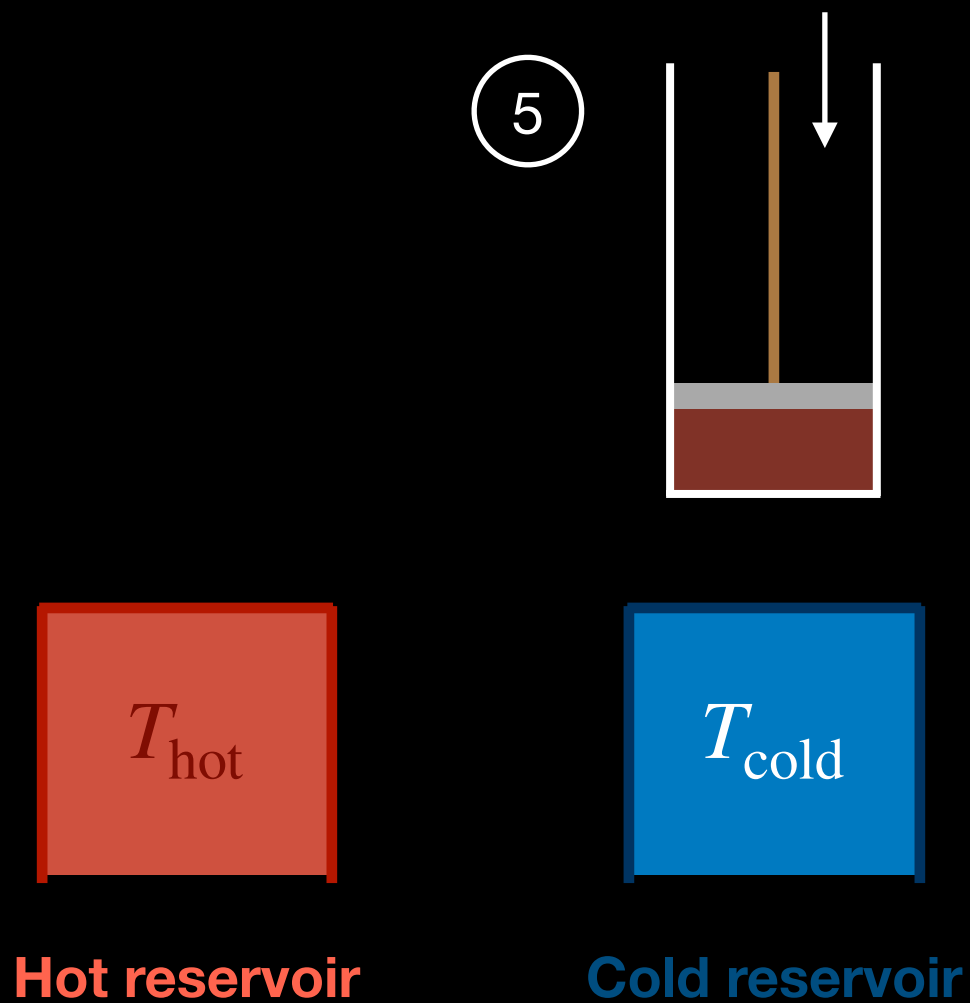
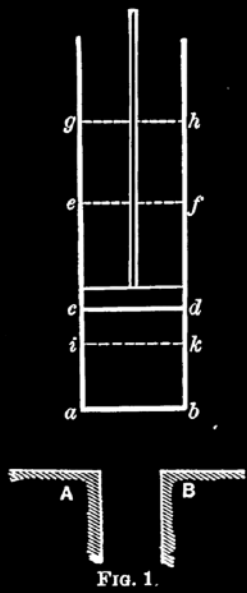




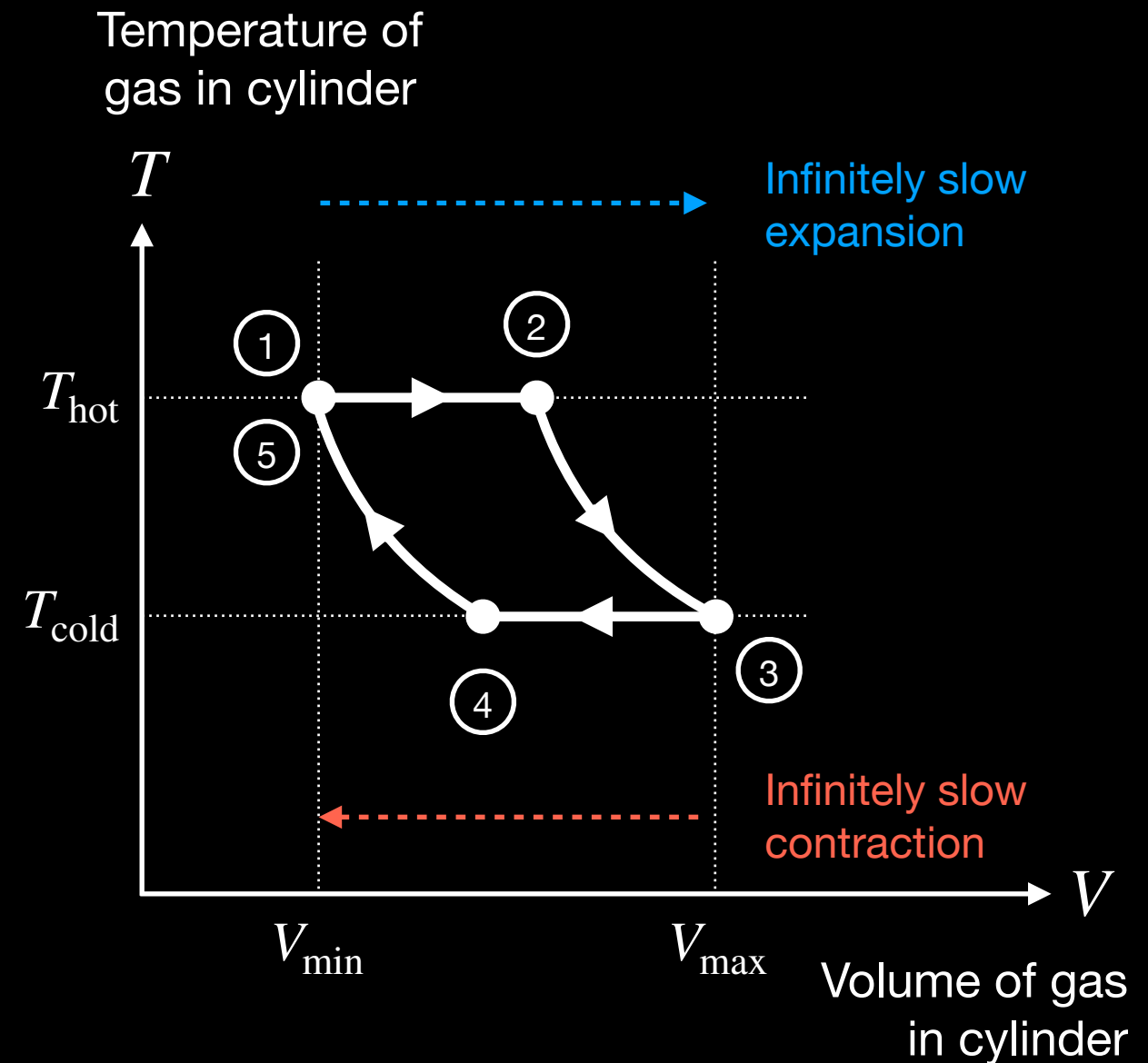
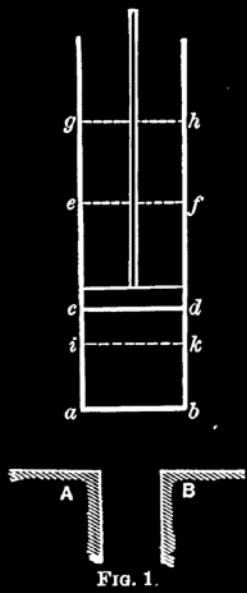
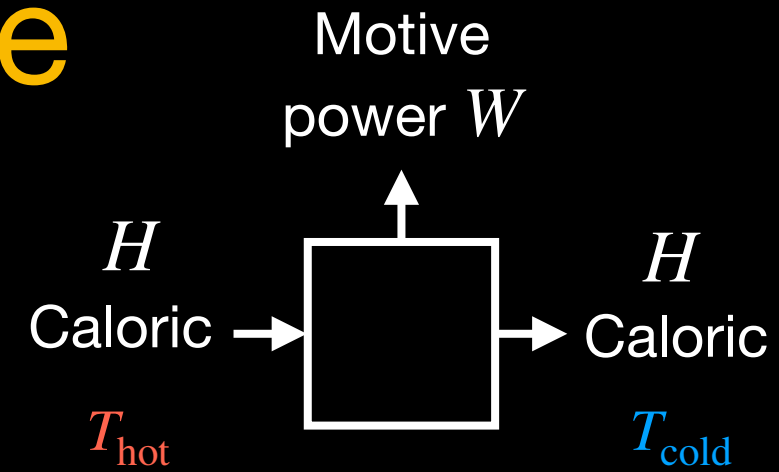
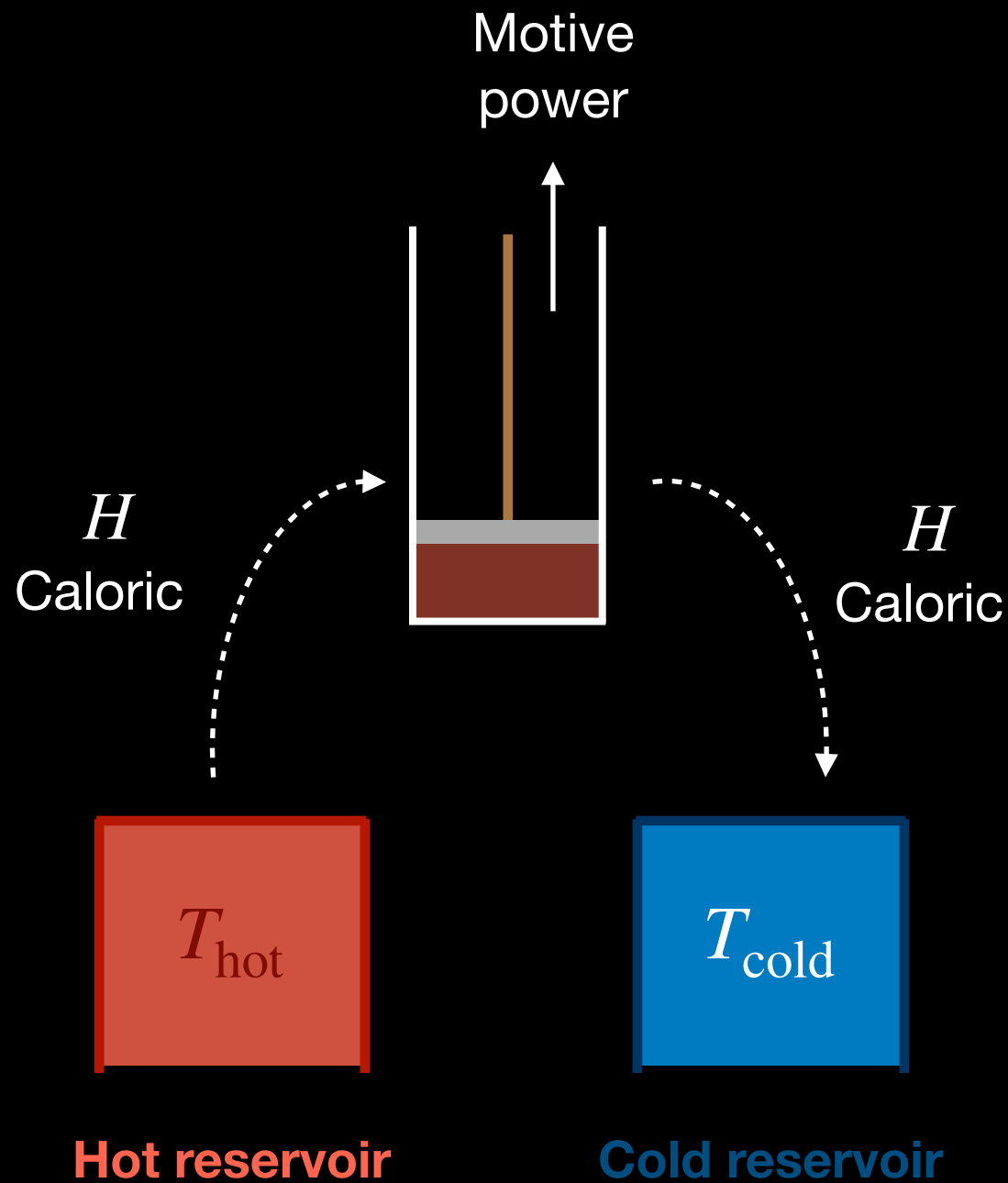
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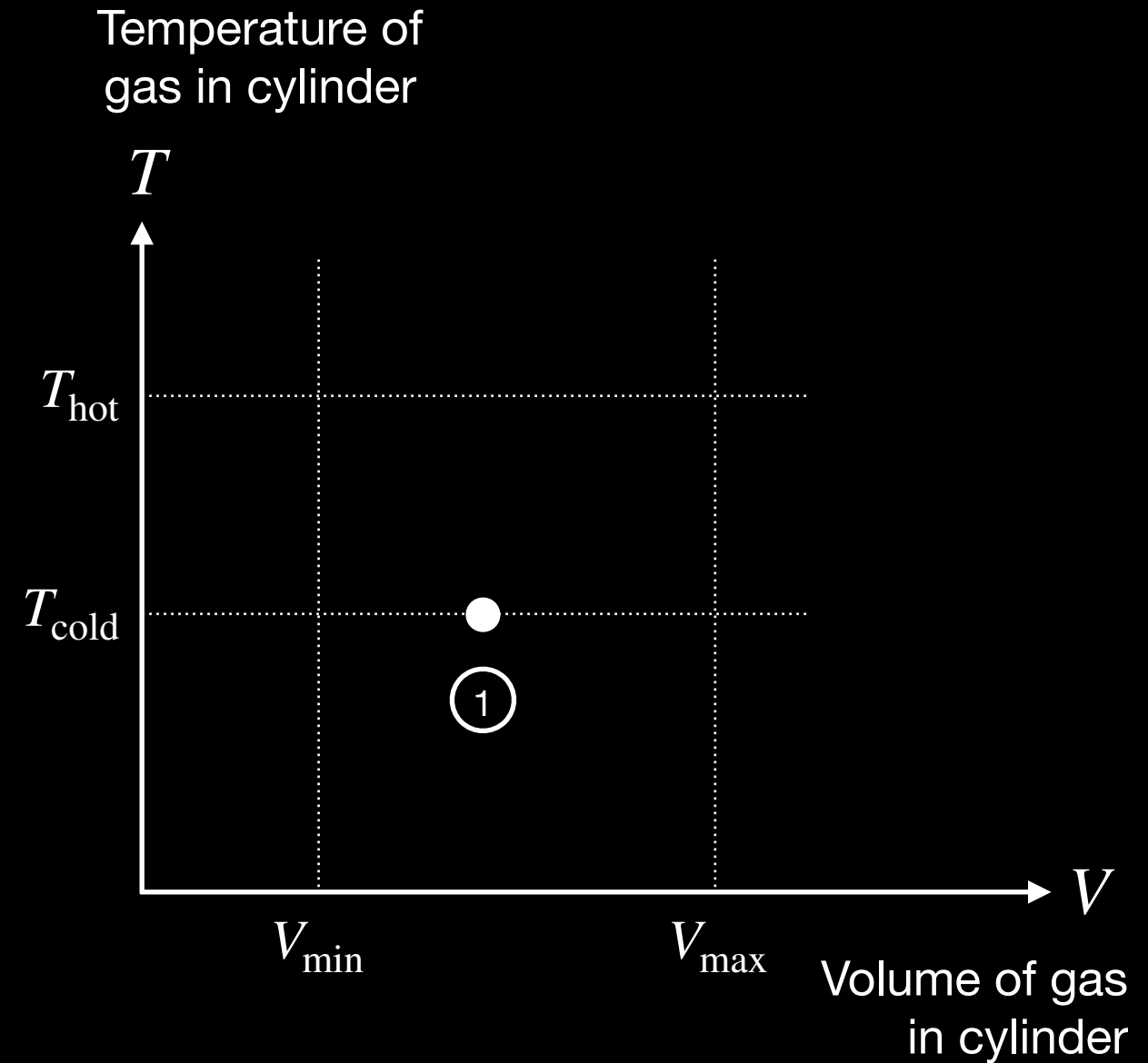
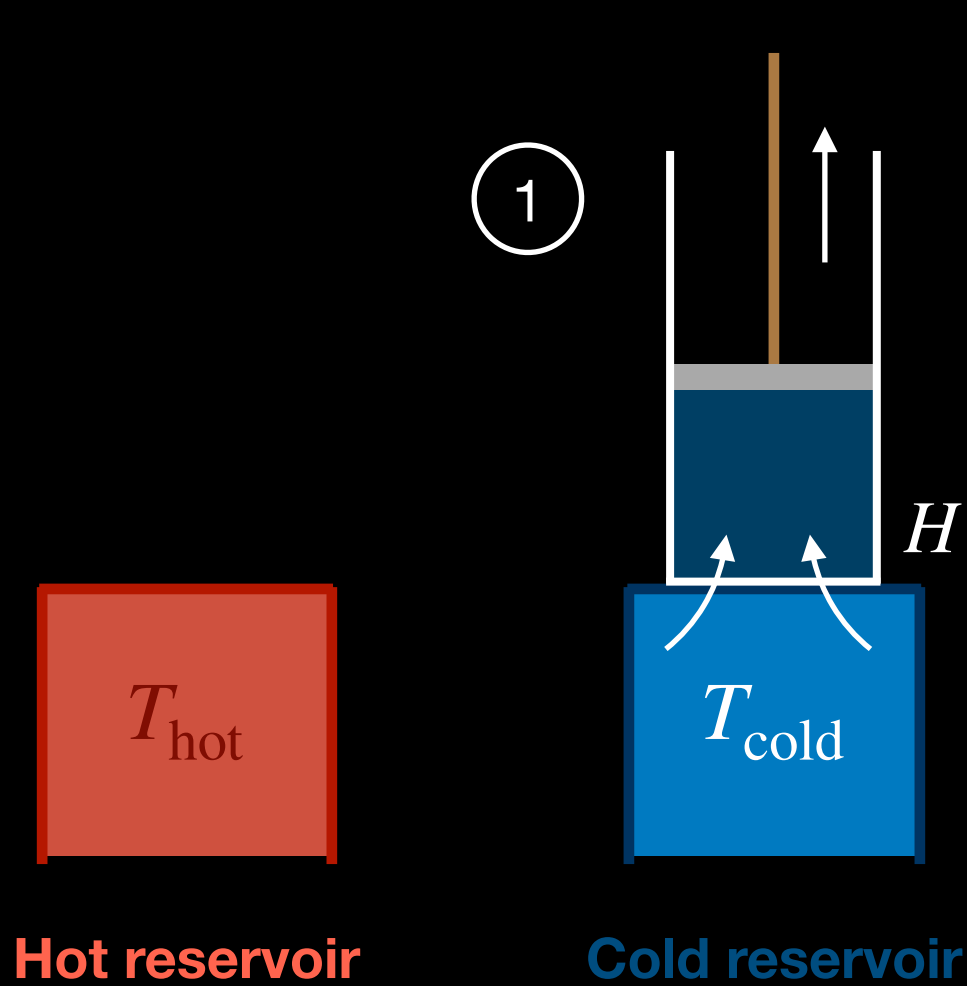
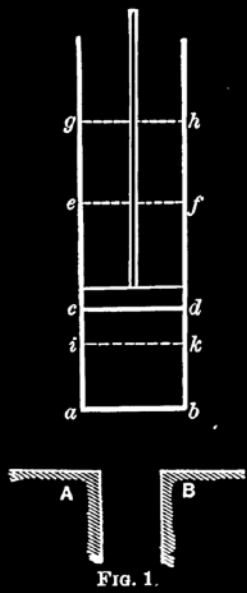
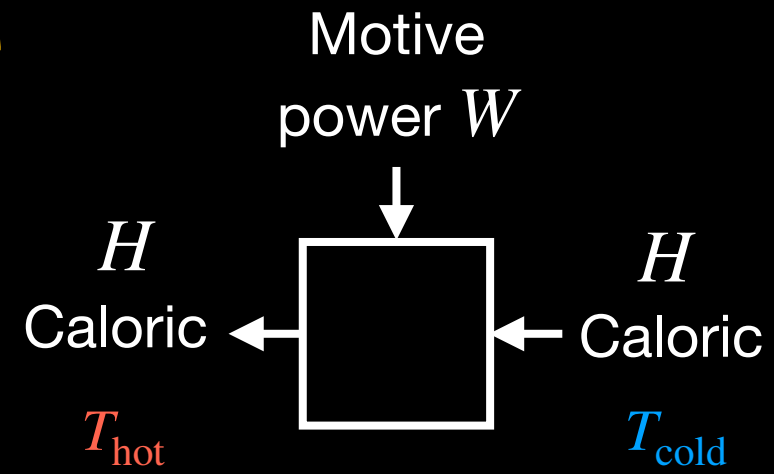
# Carnot's idealized engine



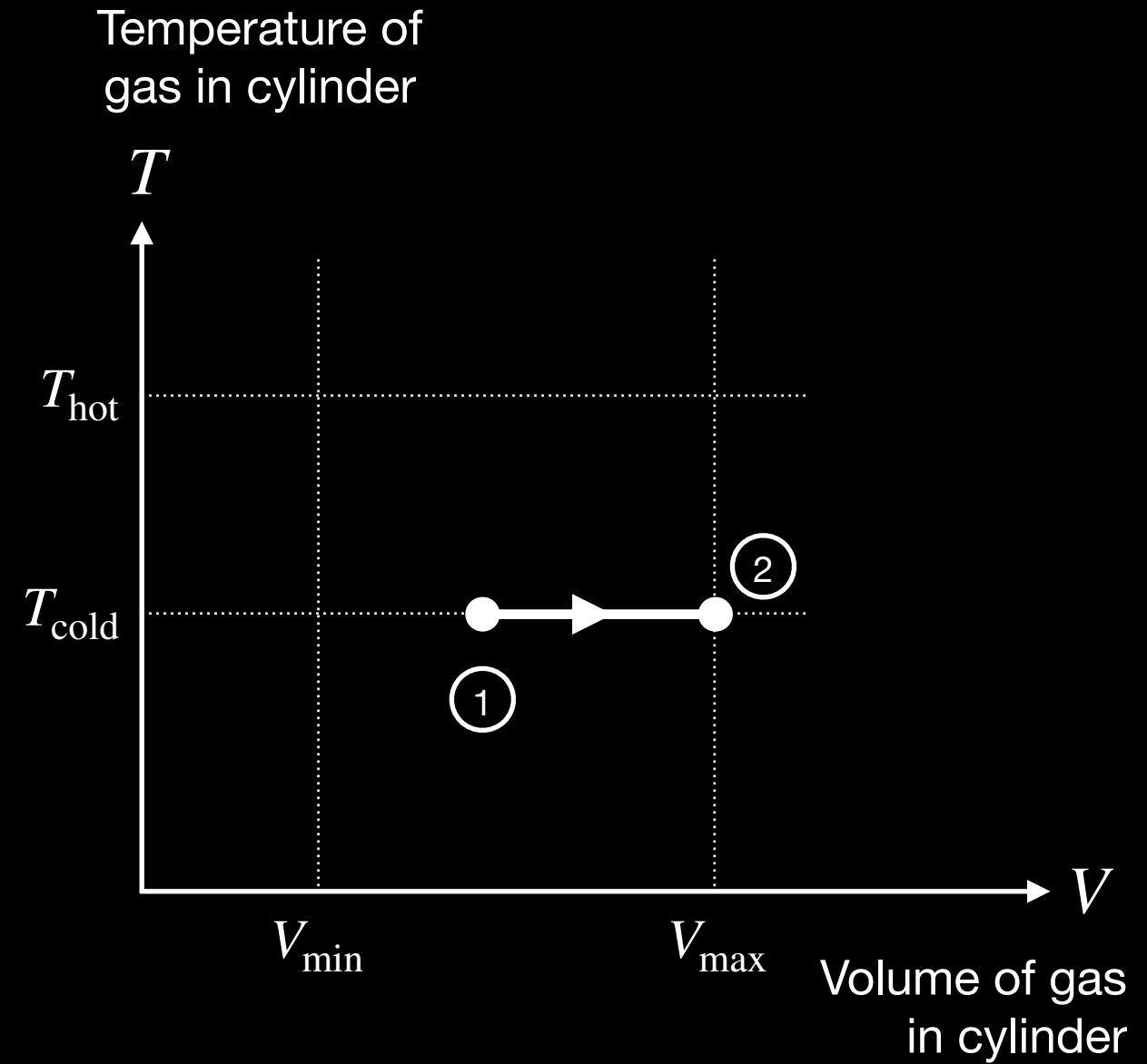
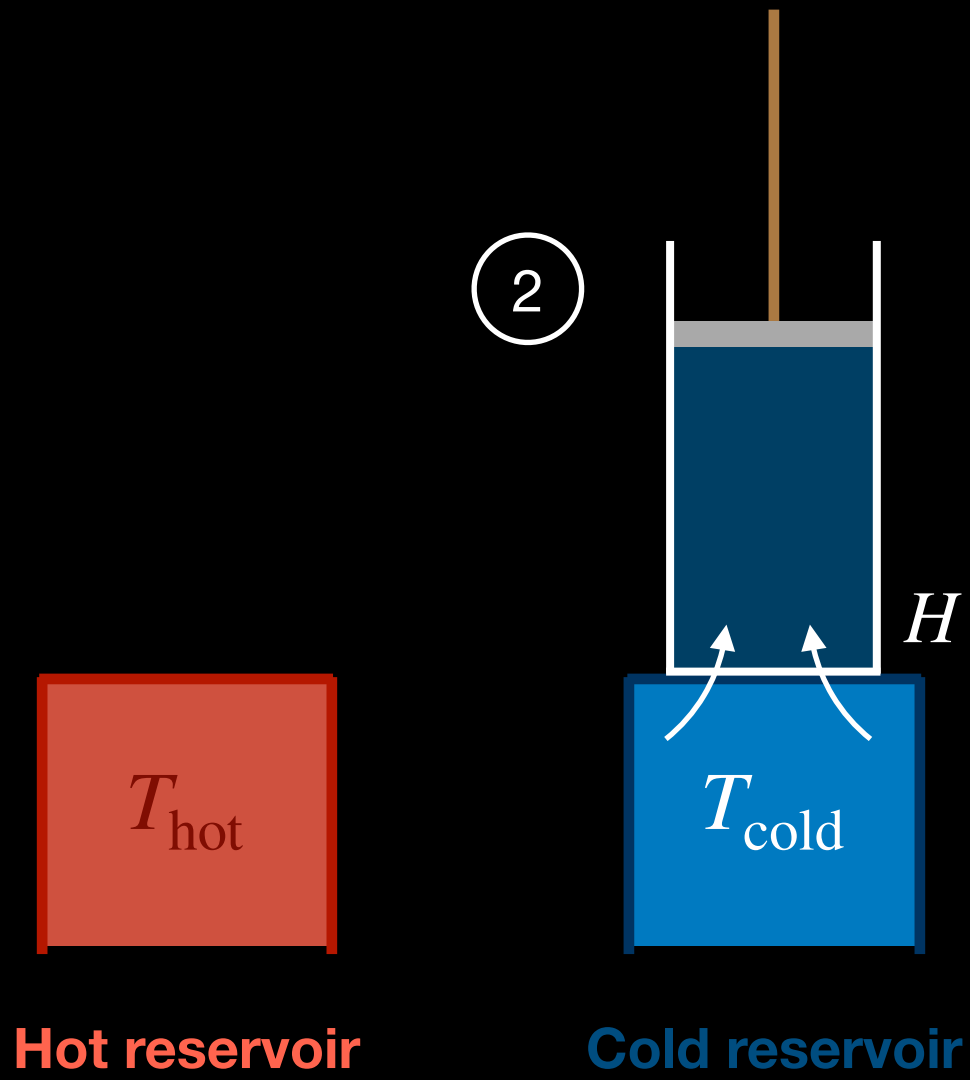
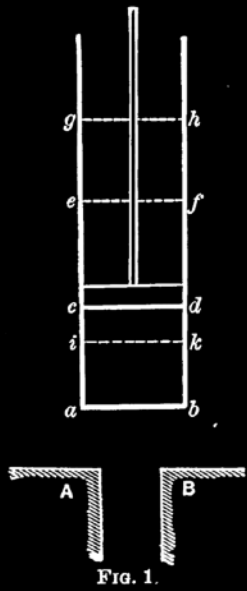
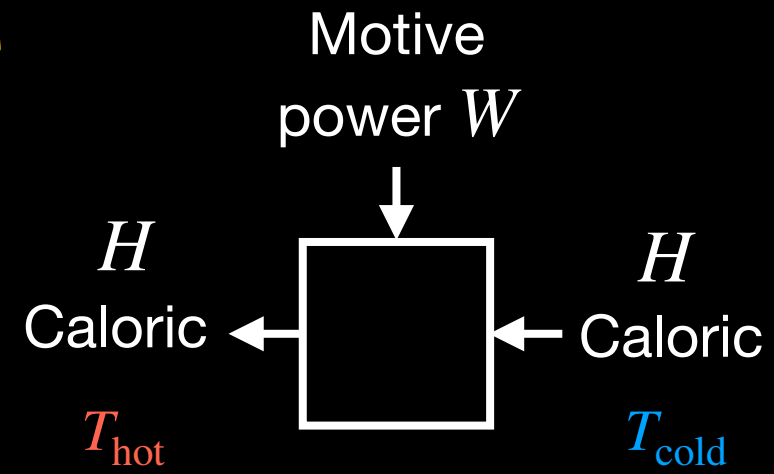
**This is the most efficient heat engine of any kind!**



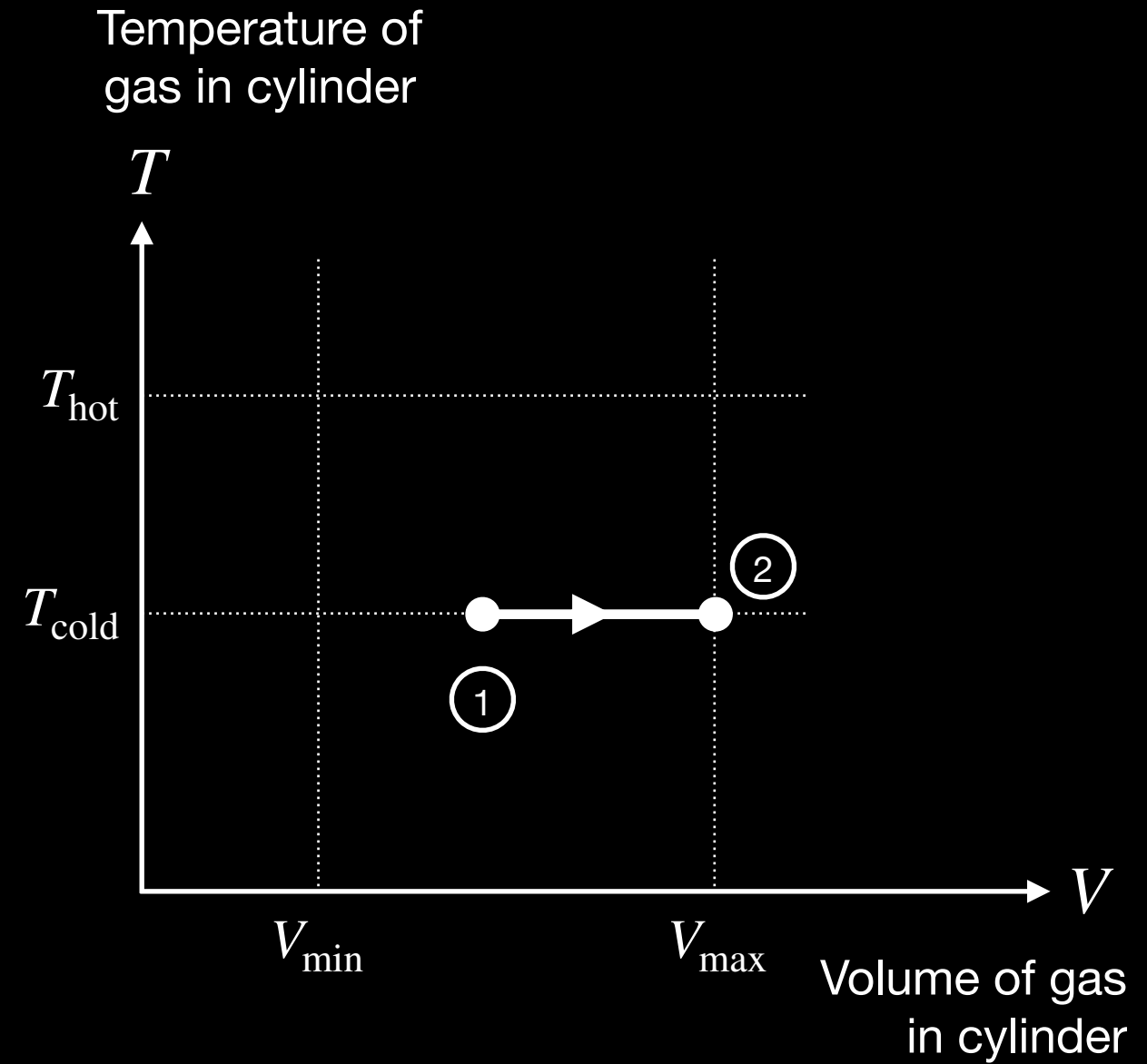
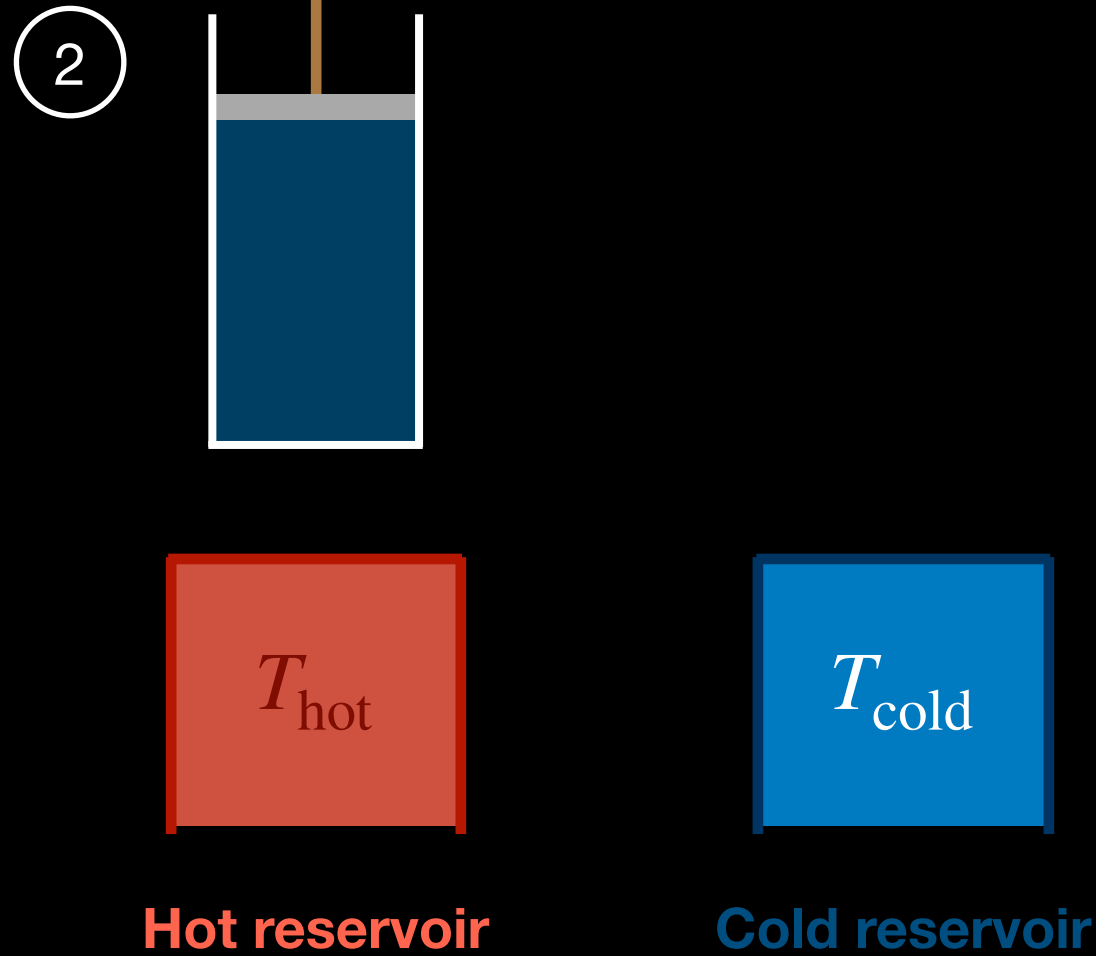
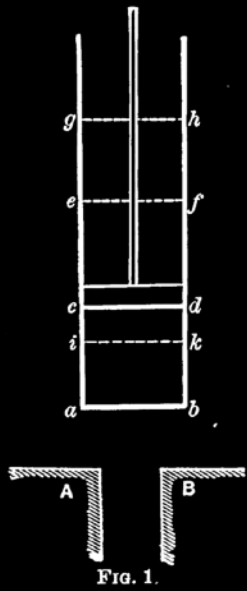
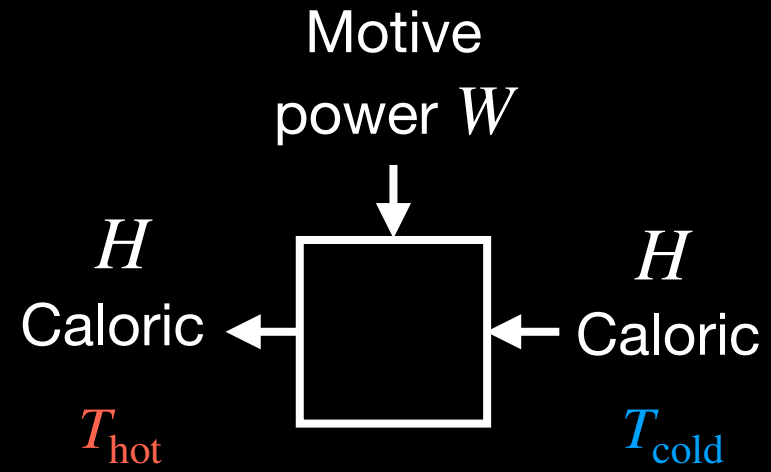
# Carnot's idealized fridge



# Carnot's idealized fridge

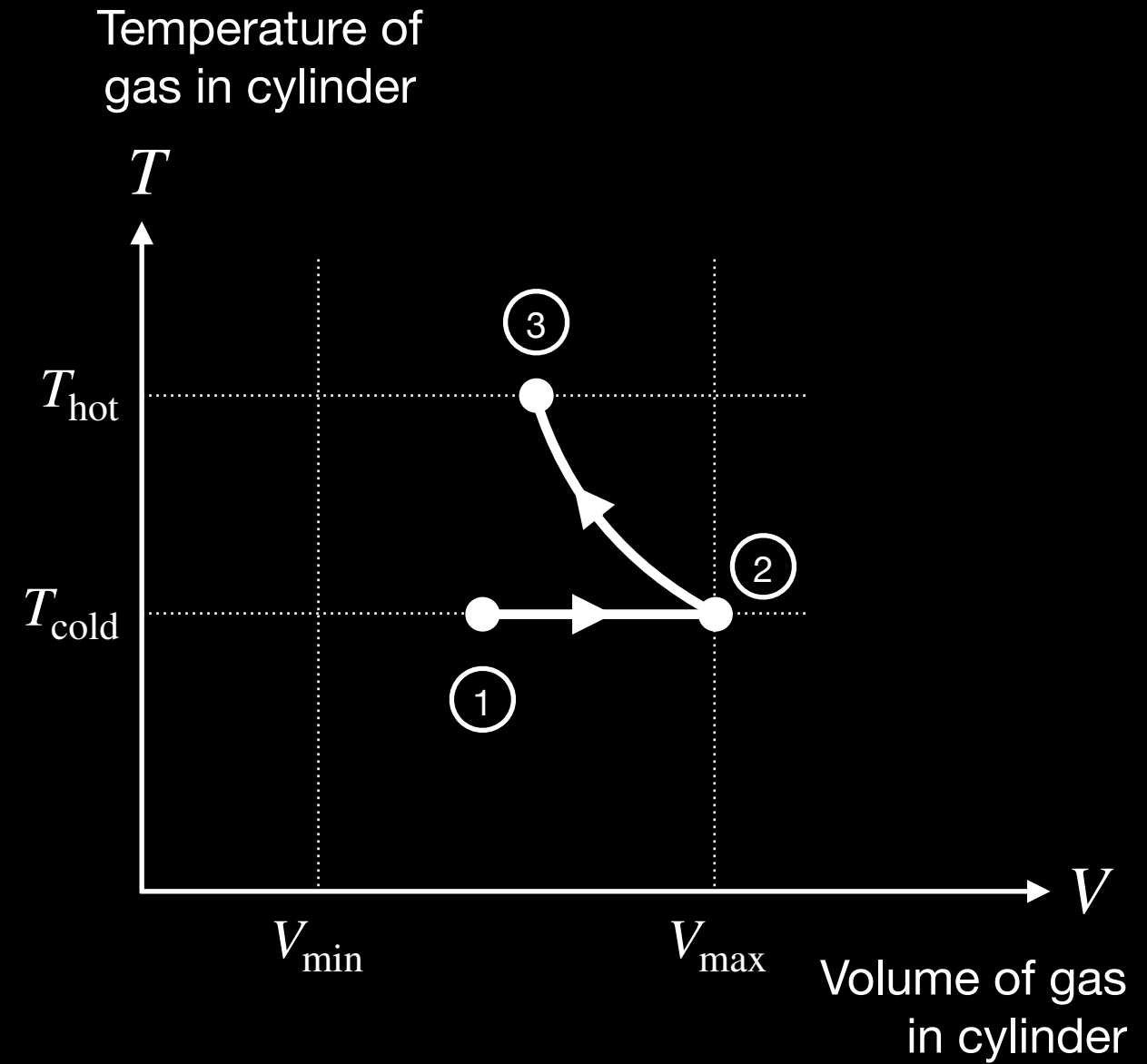
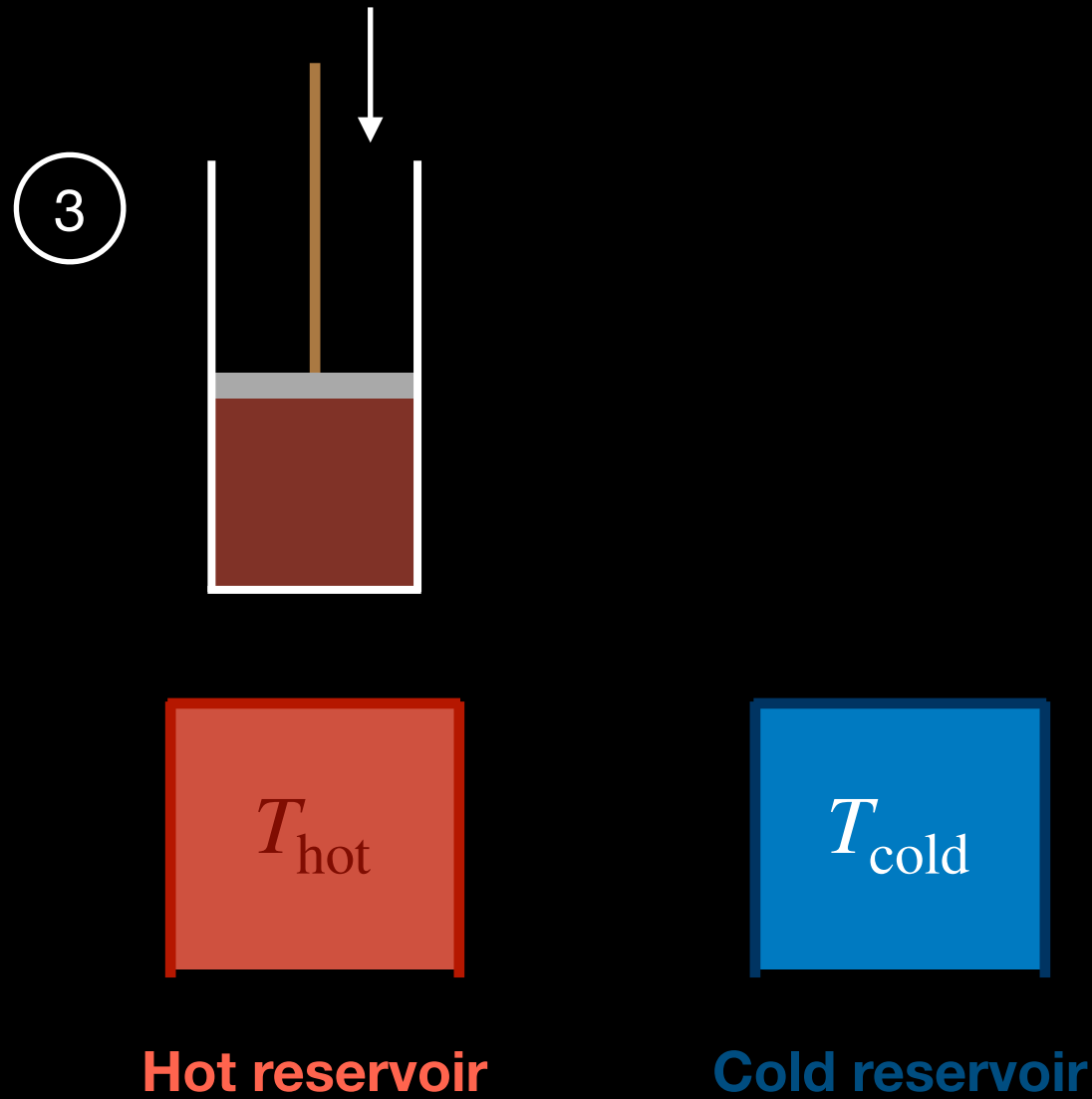
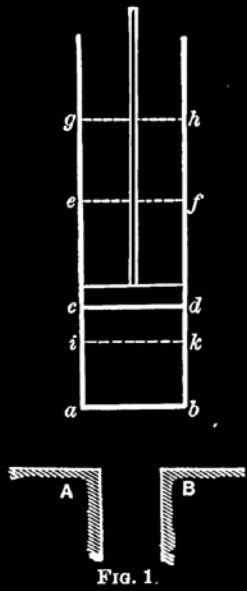
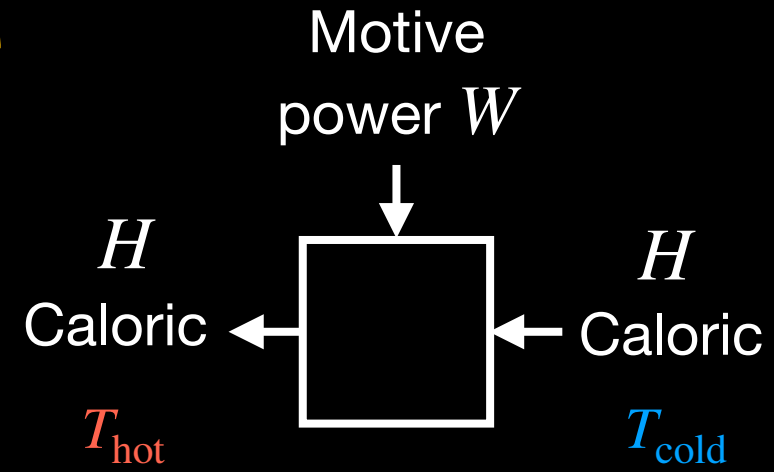


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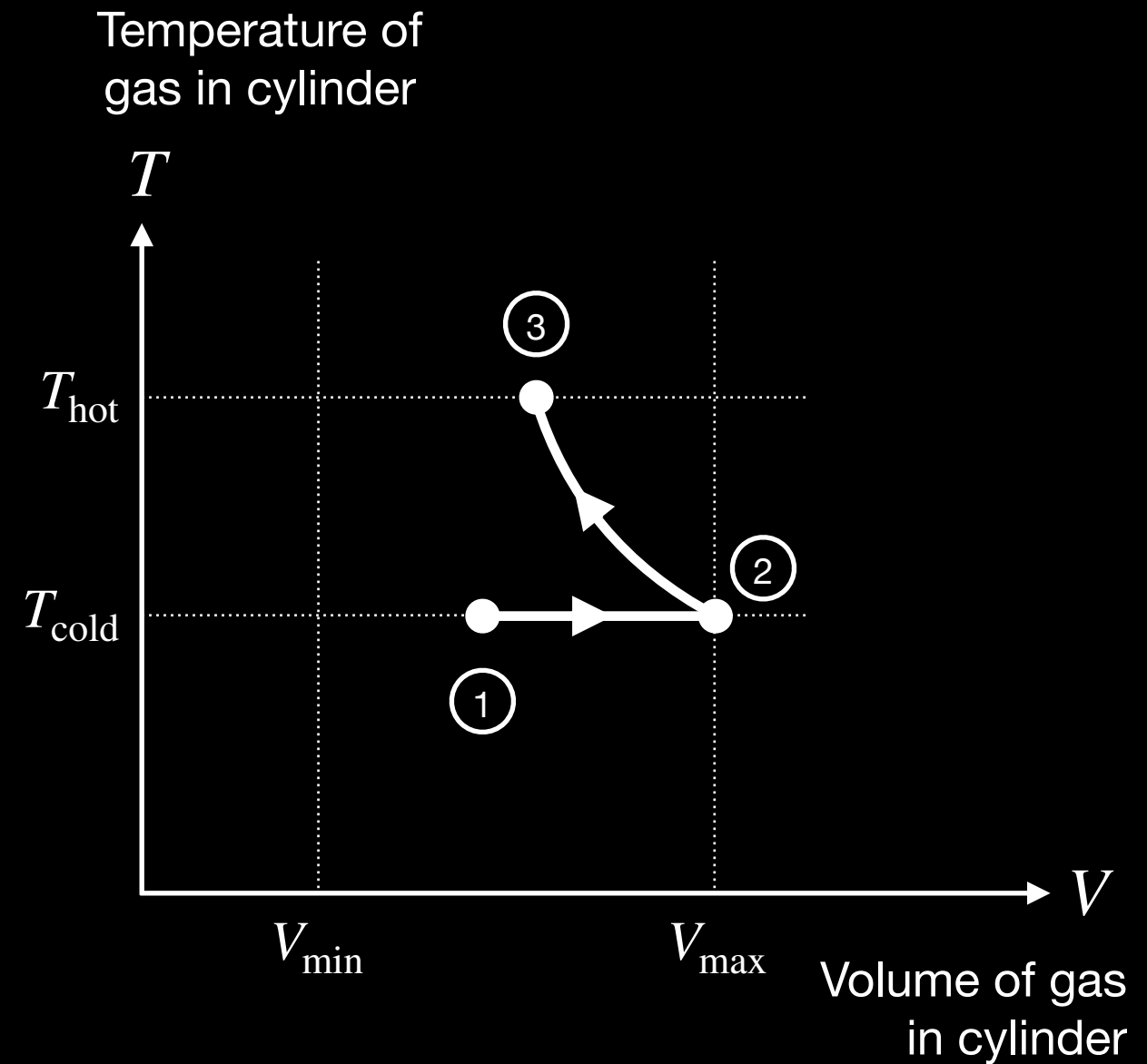
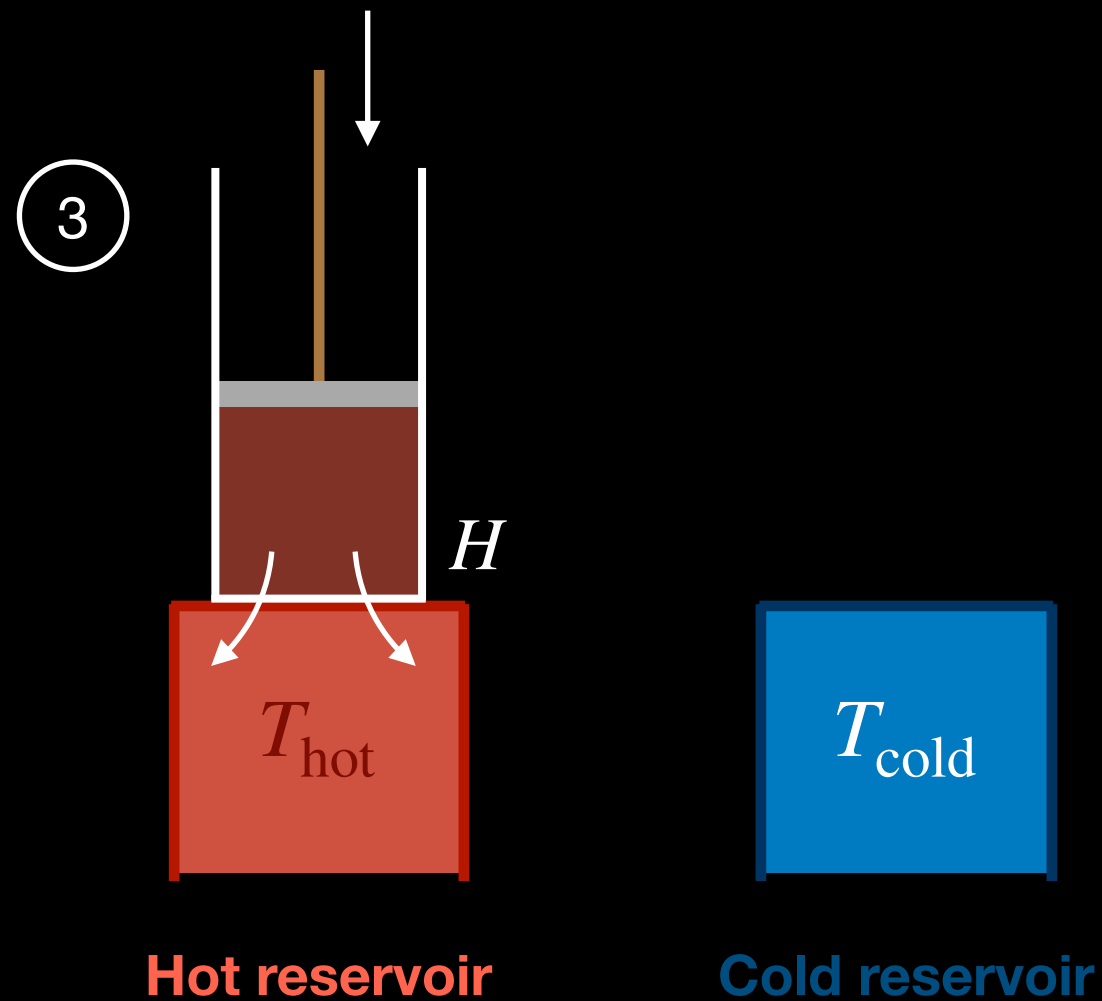
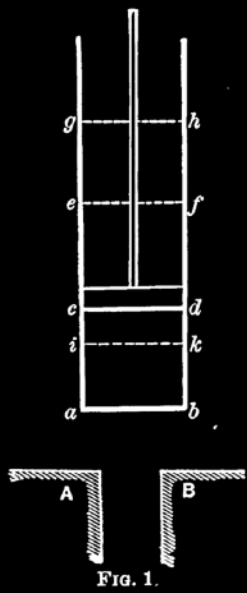
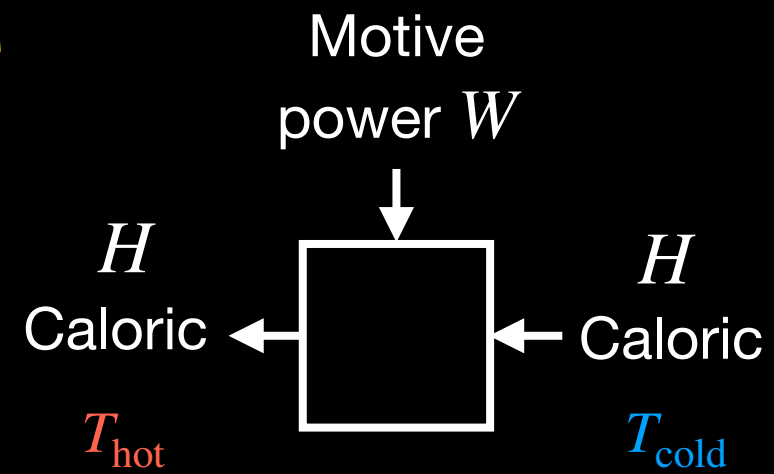




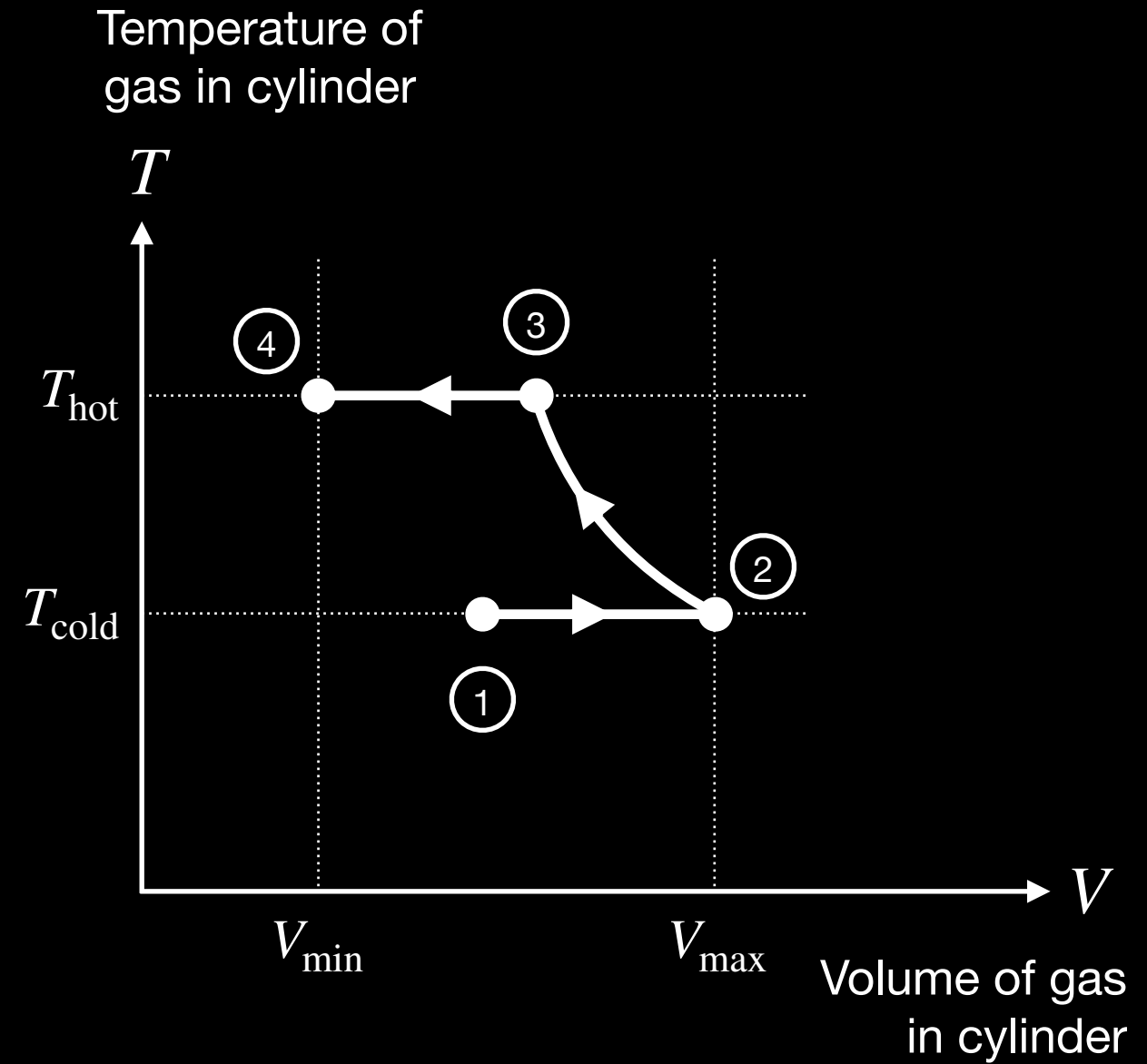
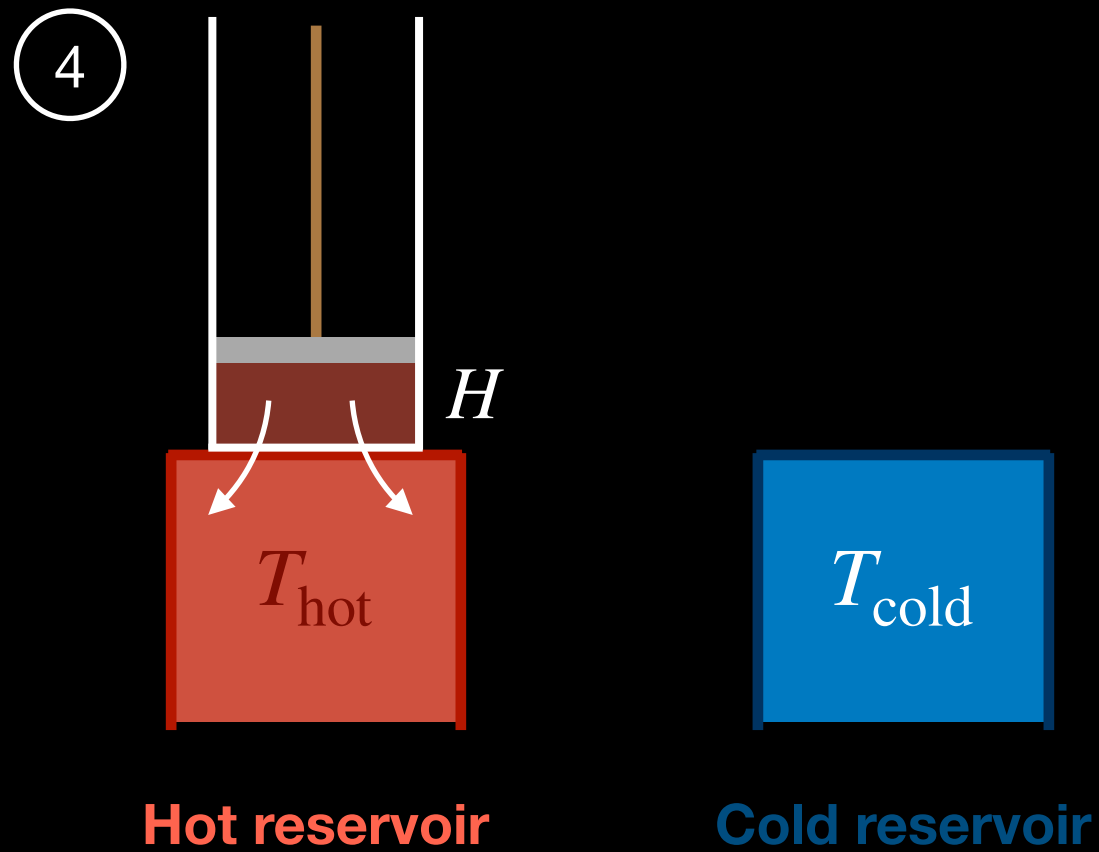
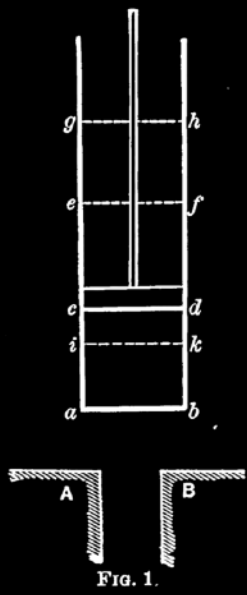
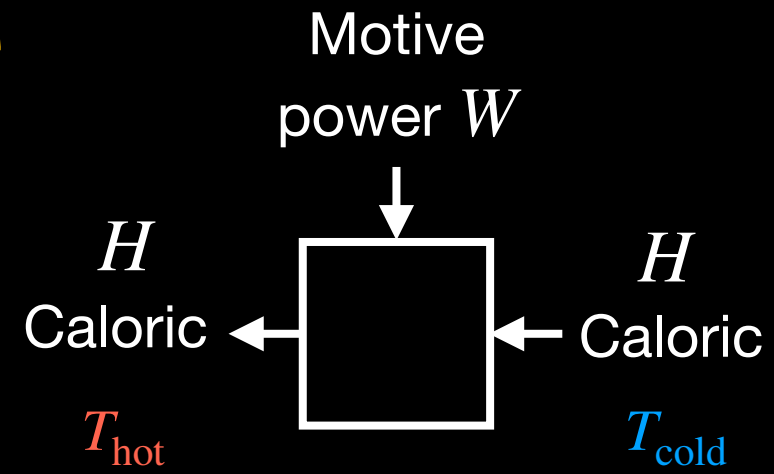
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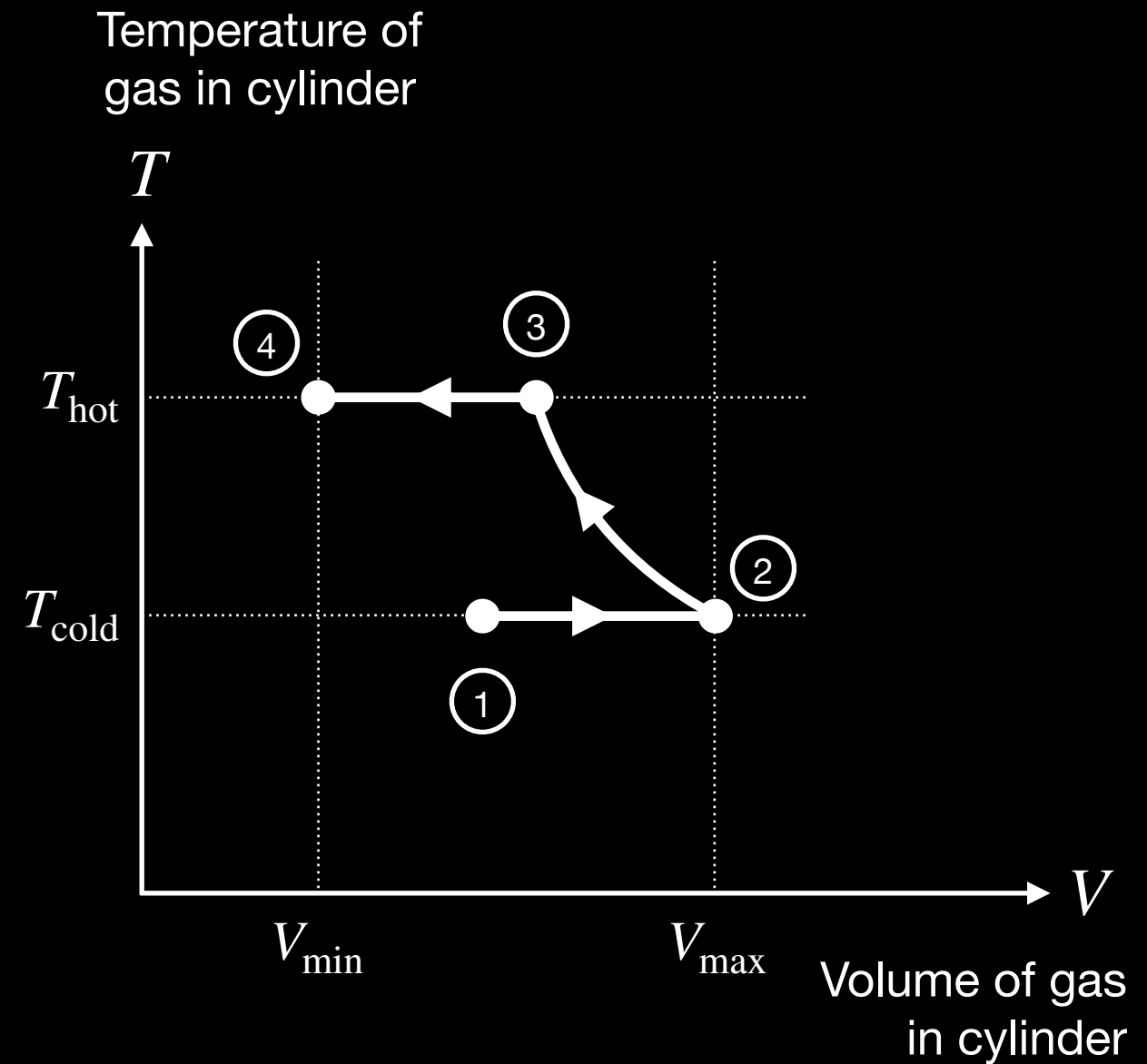
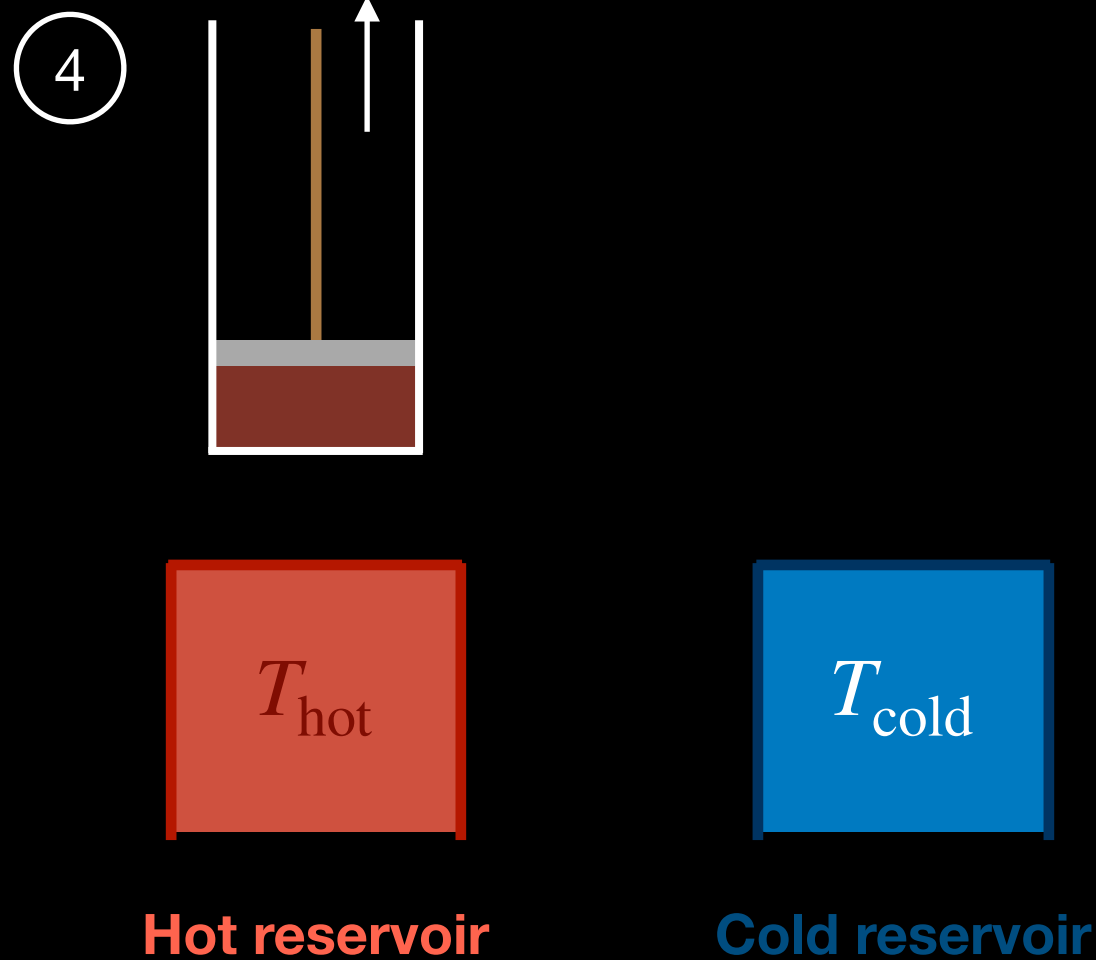
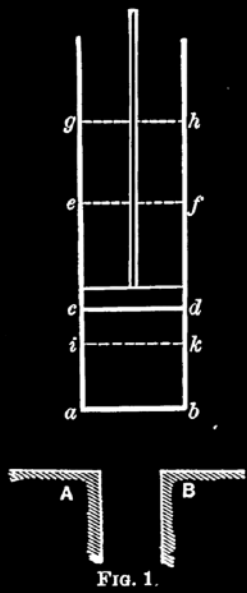
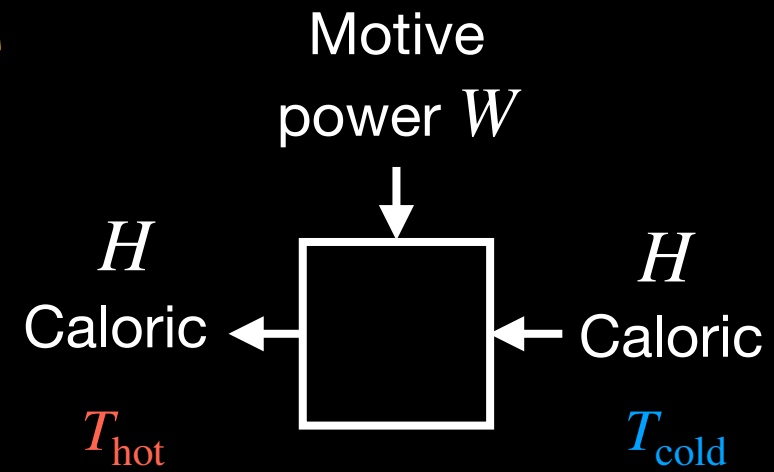
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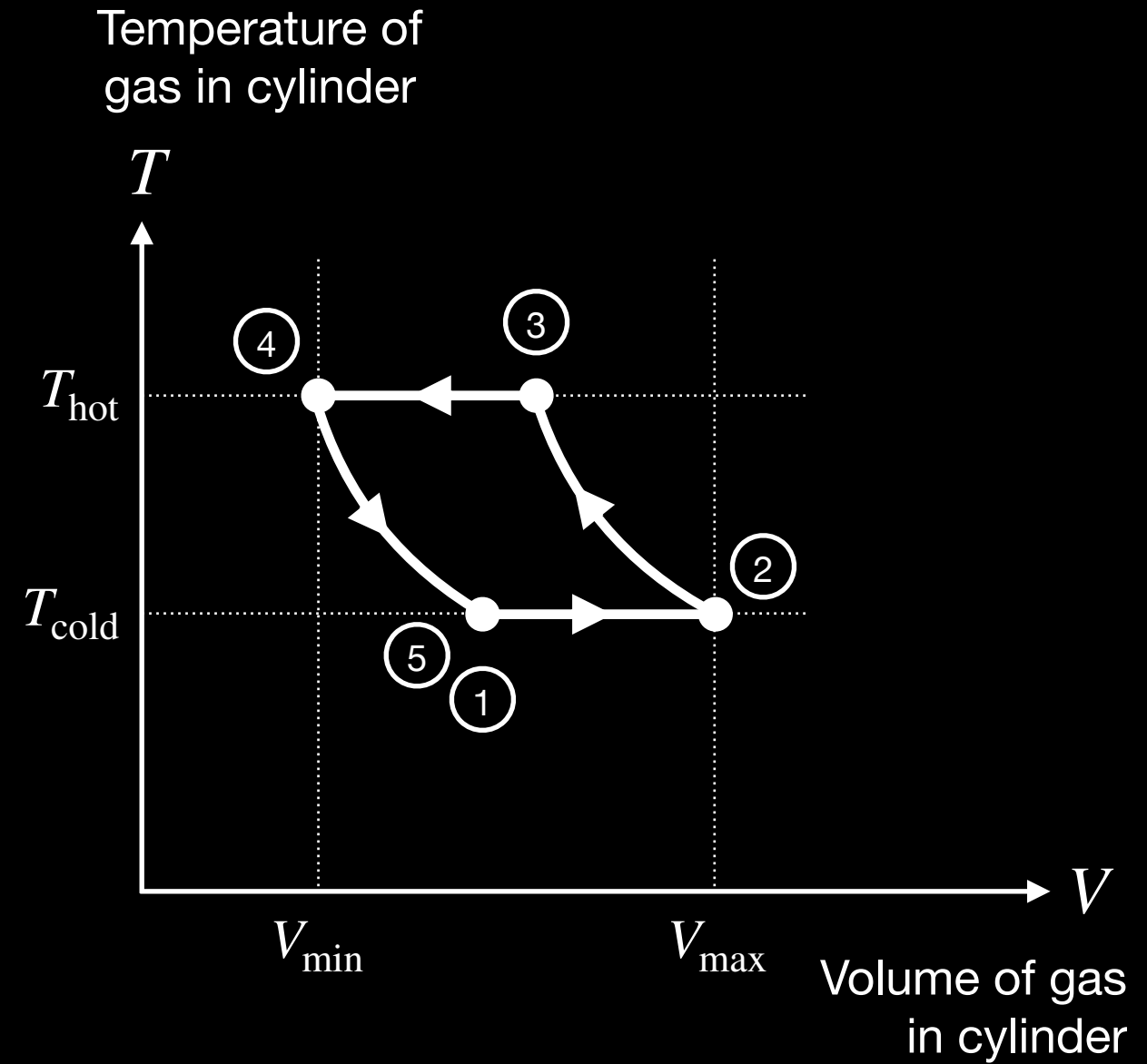
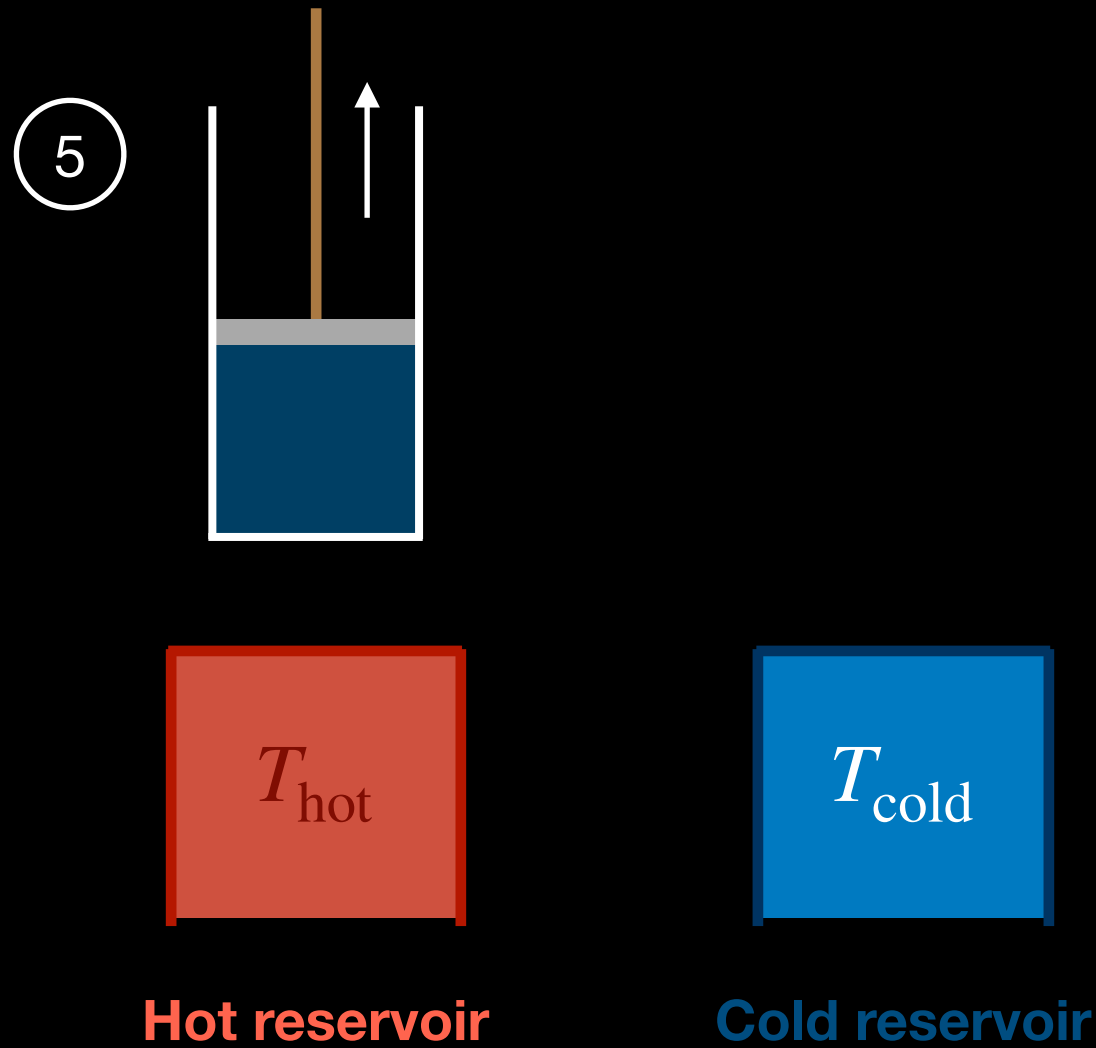
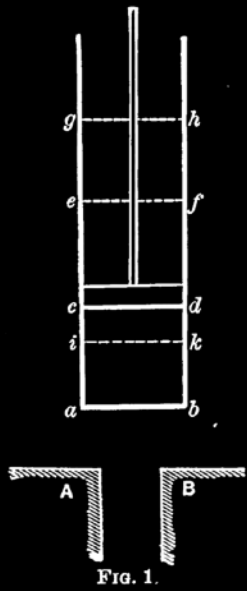
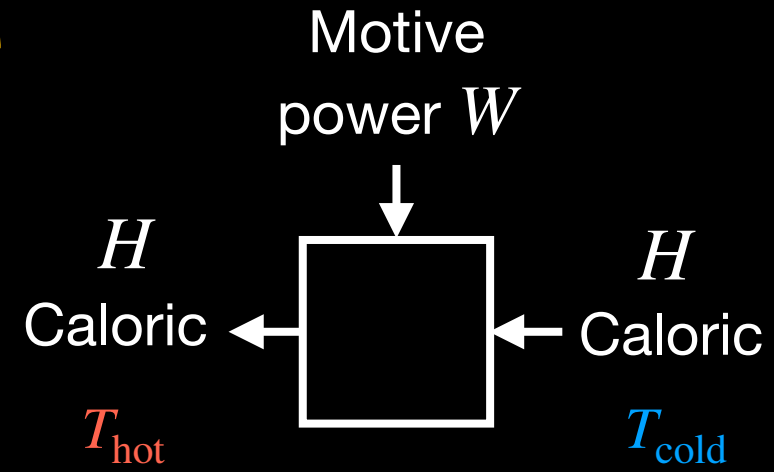


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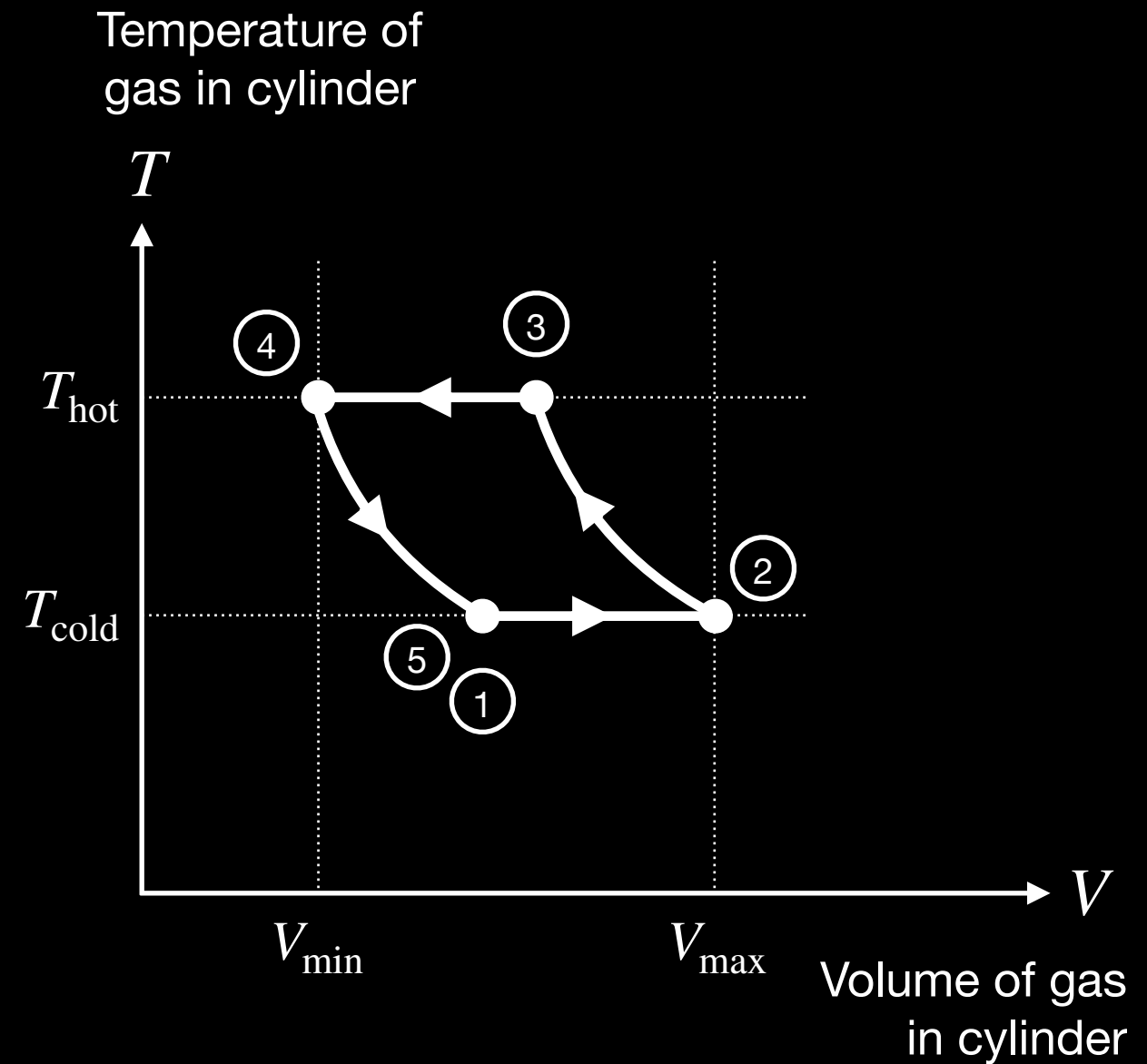
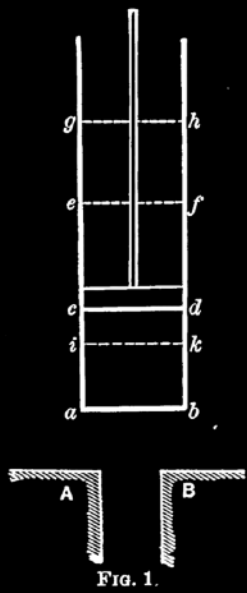
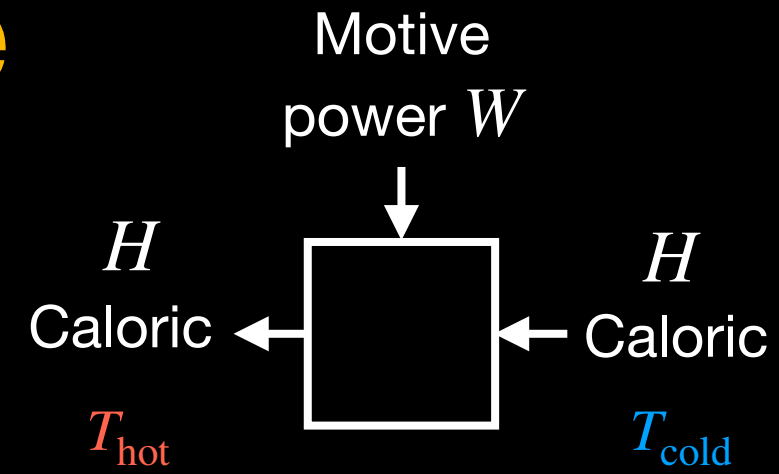
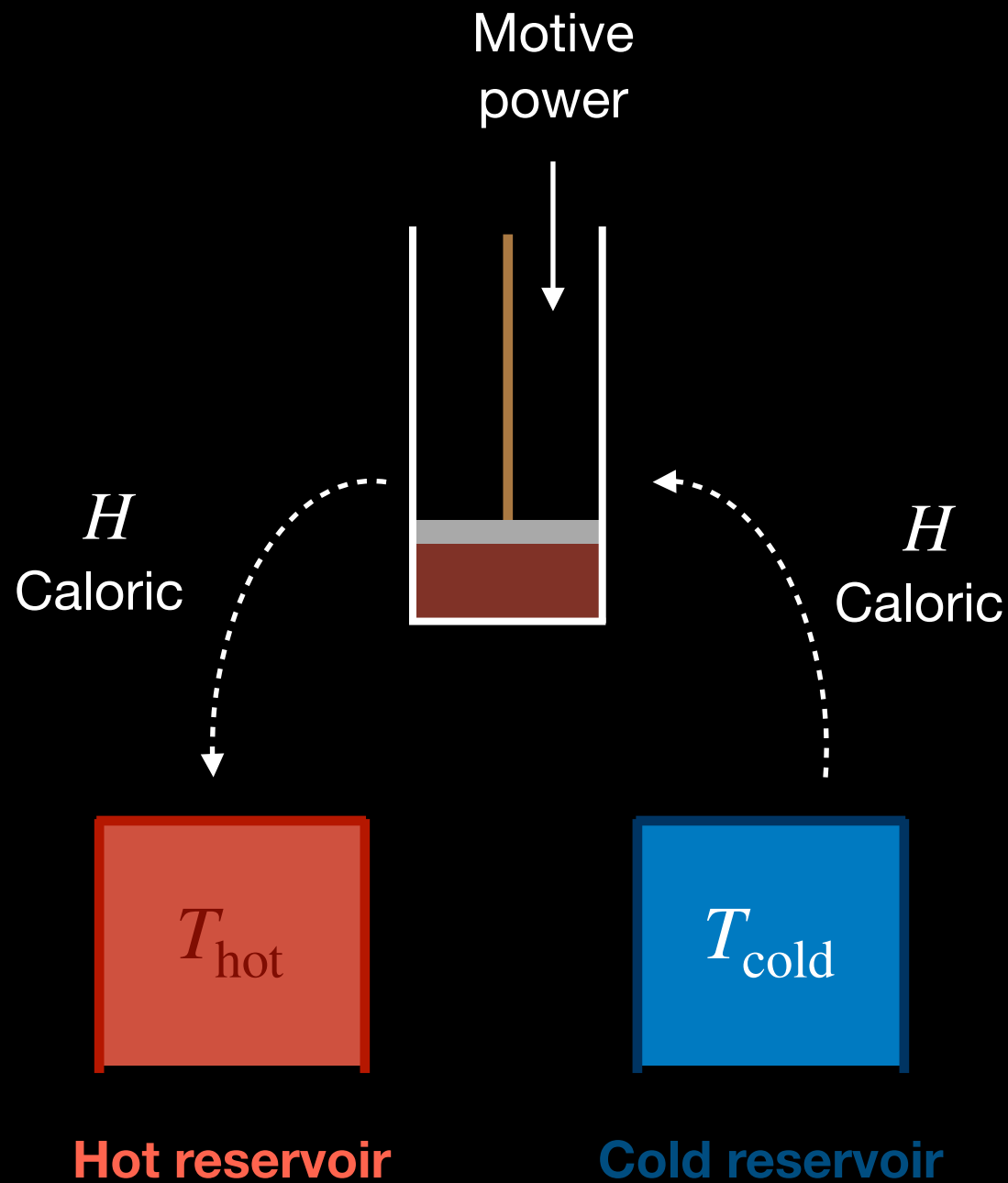




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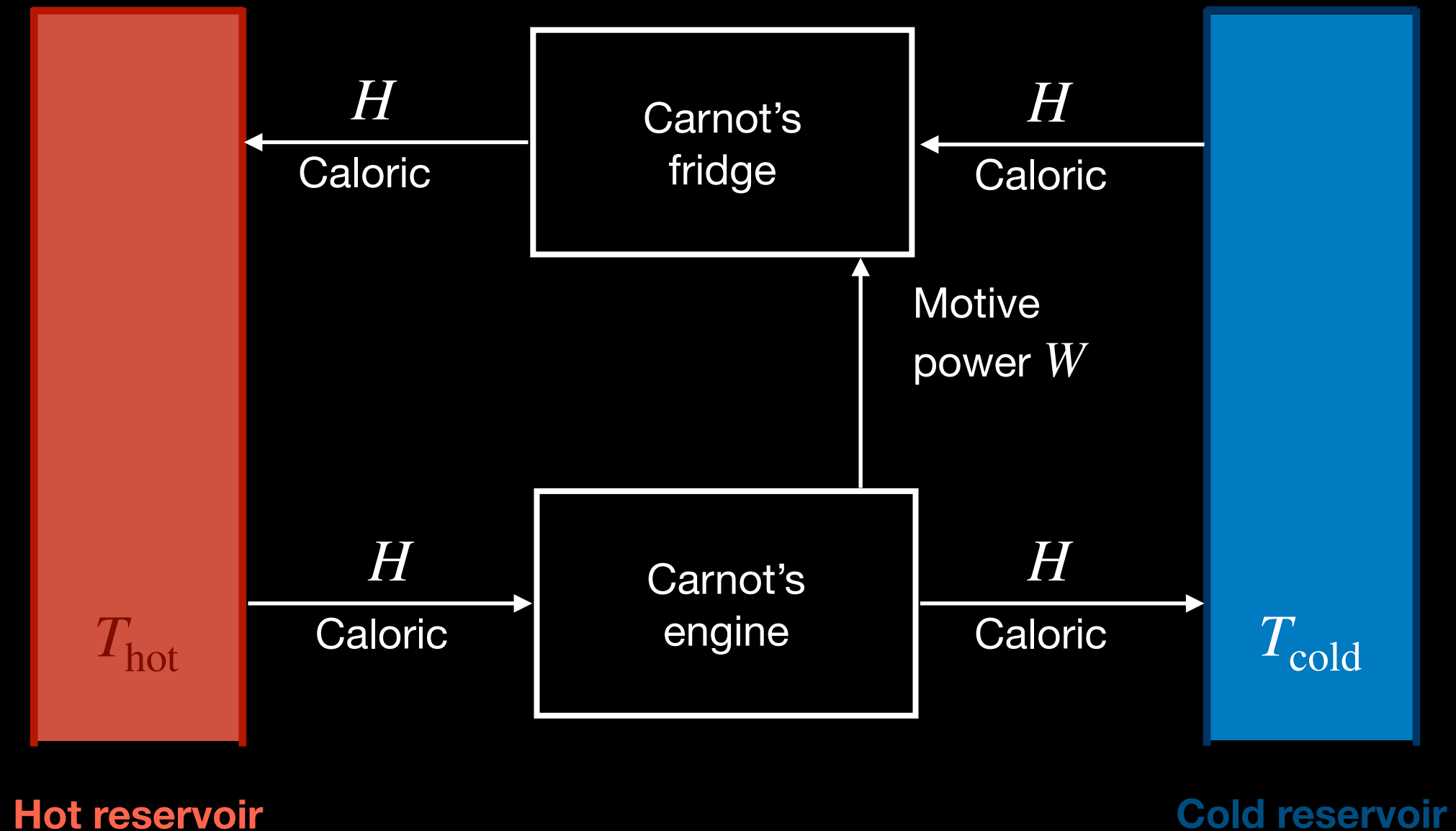


# Carnot's idealized fridge



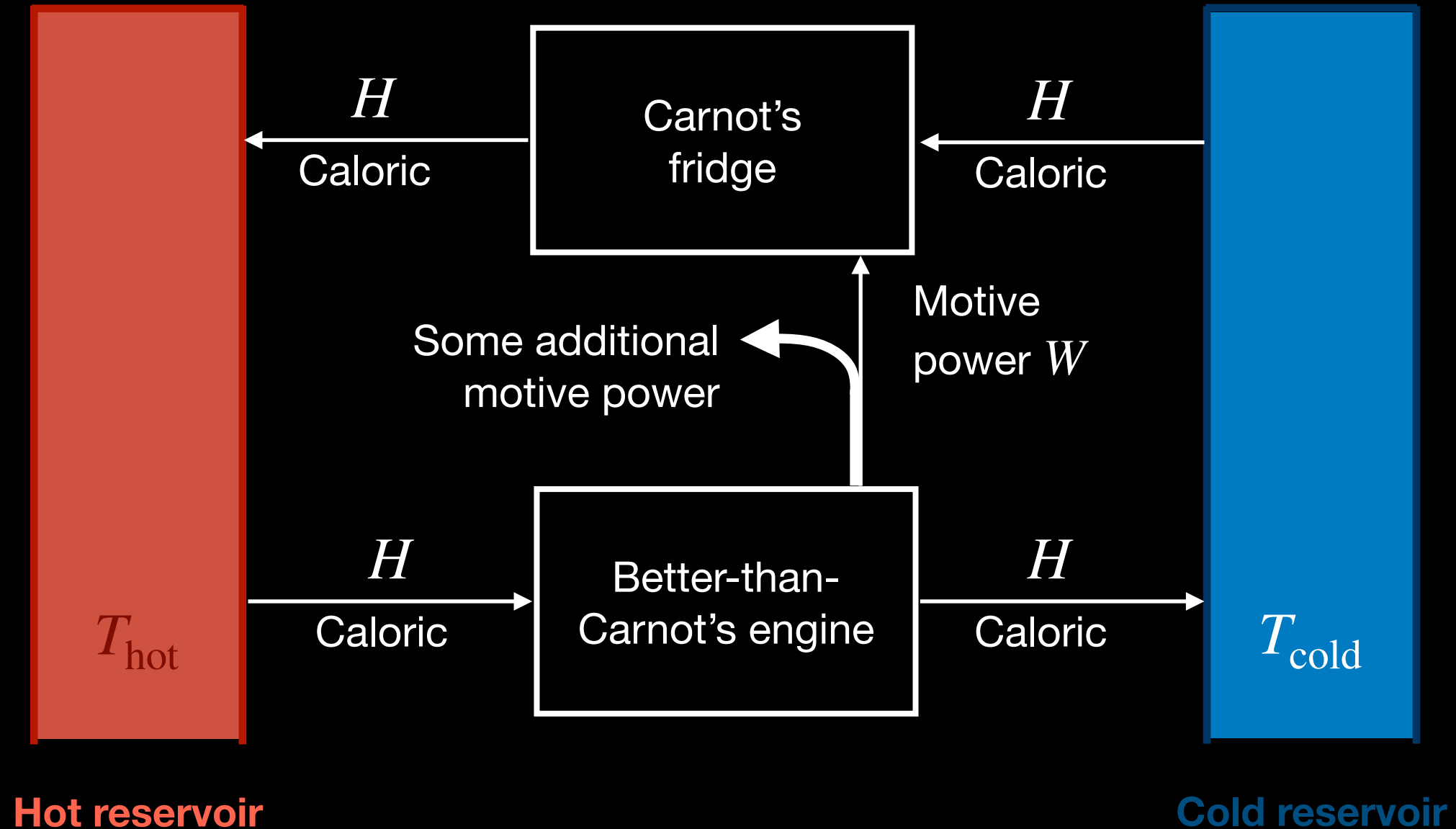
# A thought experiment

This is “entirely contrary to ideas now accepted, to the laws of mechanics and of sound physics.”



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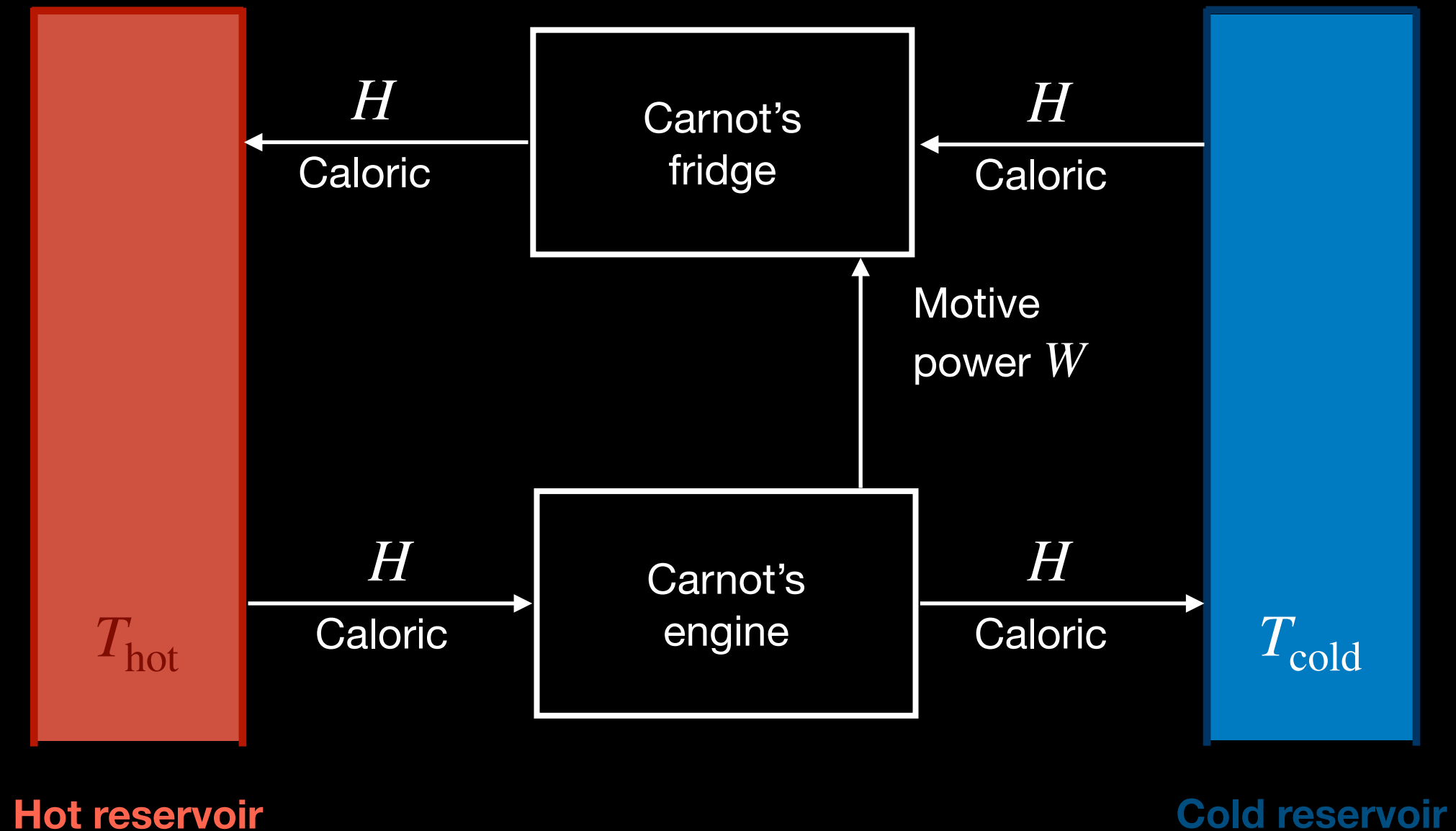


There is no heat engine of any kind more efficient than Carnot's!



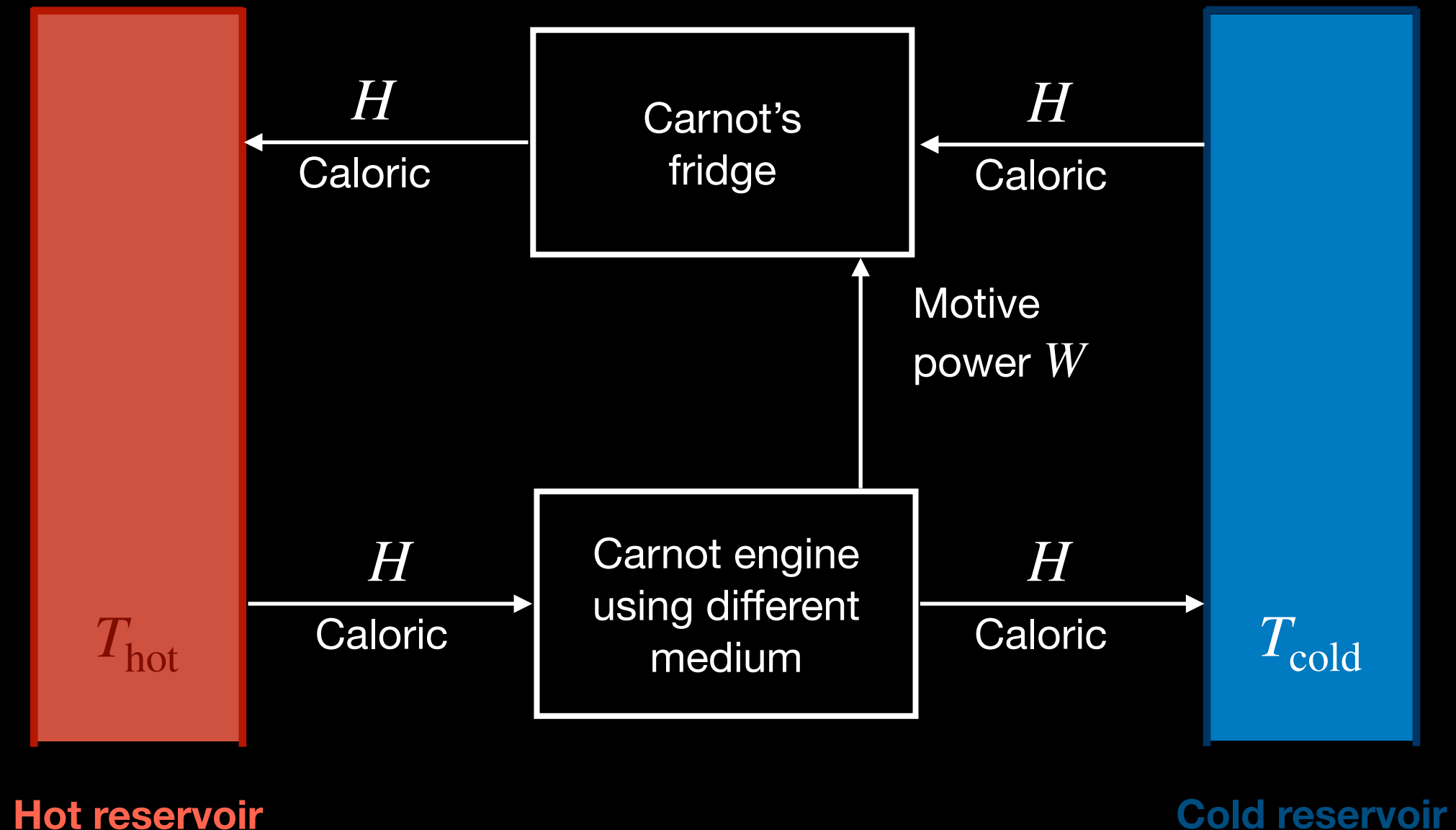
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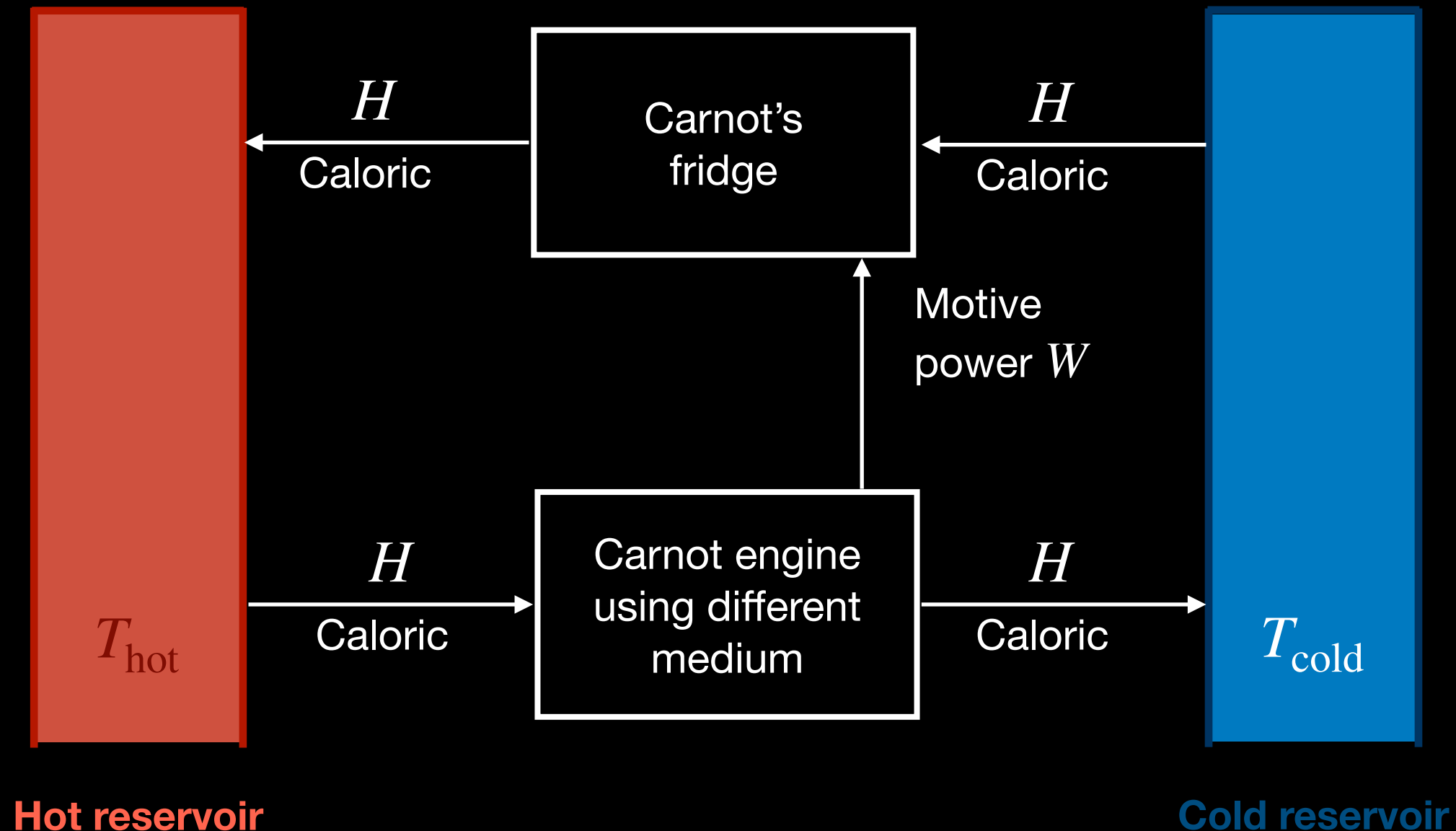
This is “entirely contrary to ideas now accepted, to the laws of mechanics and of sound physics.”



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

# A thought experiment

This is “entirely contrary to ideas now accepted, to the laws of mechanics and of sound physics.”

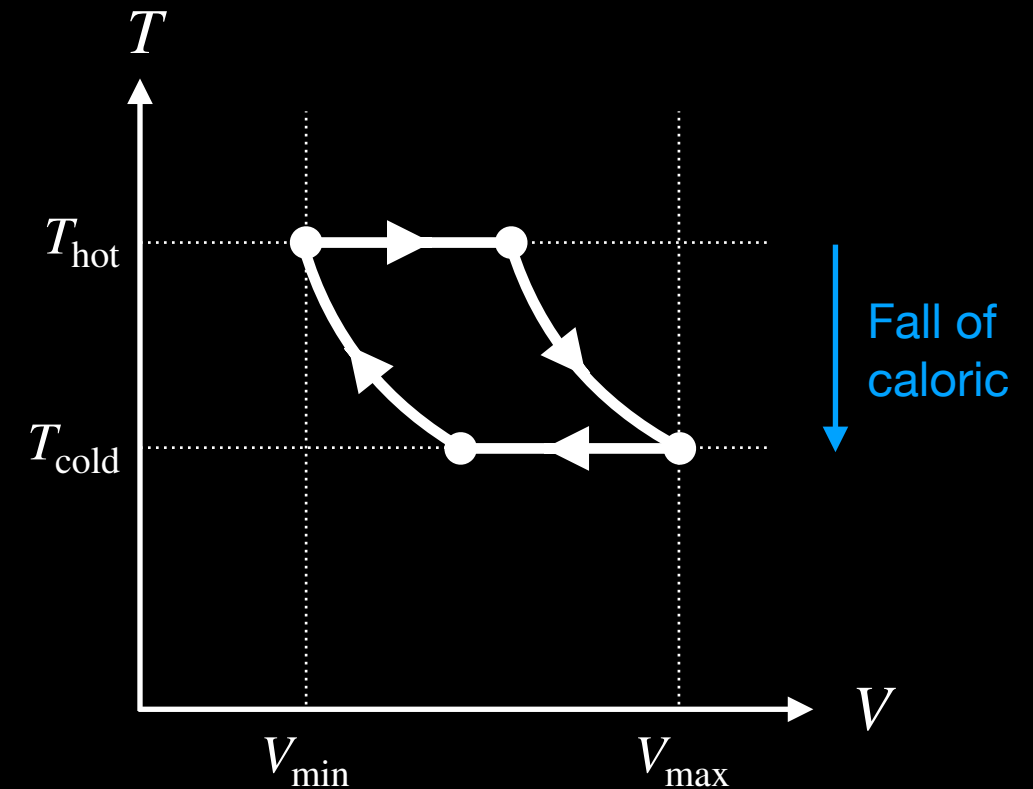


“The motive power of heat is independent of the agents employed to realize it; its quantity is fixed solely by the temperatures of the bodies between which caloric is transferred.”

# Carnot's conclusions

## How to build an good heat engine:

- 1) *“The temperature of the fluid should be made as high as possible, in order to obtain a great fall of caloric, and consequently a large production of motive power.”*
- 2) *For the same reason the cooling should be carried out as far as possible.*
- 3) *It should be so arranged that the passage of the elastic fluid from the highest to the lowest temperature should be due to increase of volume.”*



*“[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.”*



# Benjamin Thompson — Count Rumford

Personal assistant, jack of all trades



Planter of trees in the  
English Garten



[source]

844. Rumford'sche Suppe.

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

Erbsen und Erbsen jedes	- -	22	Loth
Stoffeln, (Erdbirn)	- -	2 Pf.	10 Loth
Wein; Fleisch	- - - -	8	Loth
z, wenn es nicht sehr scharf ist	- -	6	Loth
er (nicht Wein:) Essig	- -	16	Loth
ffer 6 bis 7 Quart oder 10 Pf.	- -		

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

Designer of military uniforms

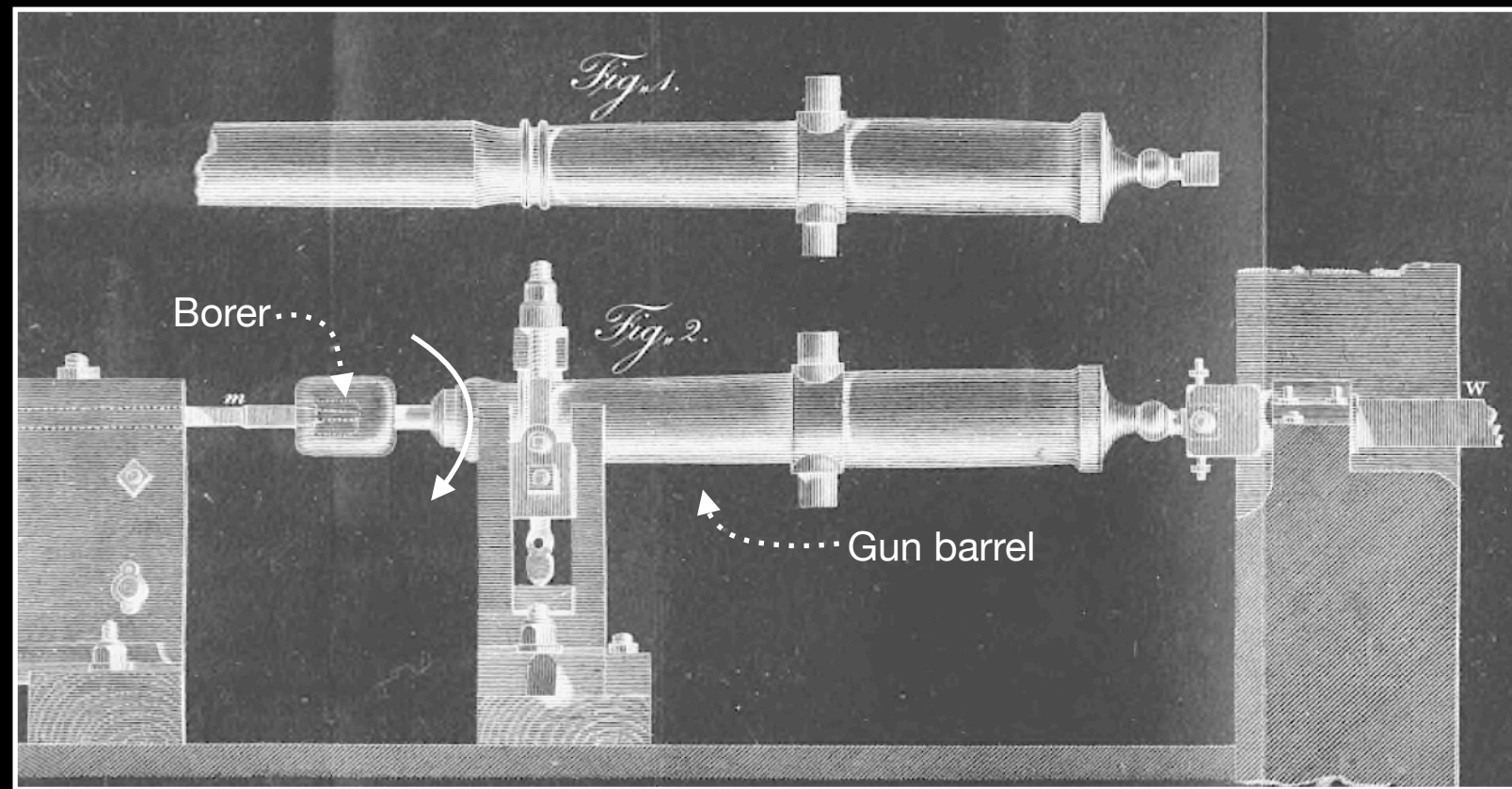
*“I am persuaded that a habit of keeping the eyes open to everything that is going on in the ordinary course of the business of life has oftener led to useful doubts and sensible schemes for investigation and improvement than all the more intense meditations of philosophers in the hours expressly set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



# The cannon boring experiments

*“It was by accident that I was led to make the experiment of which I am about to give an account.”*

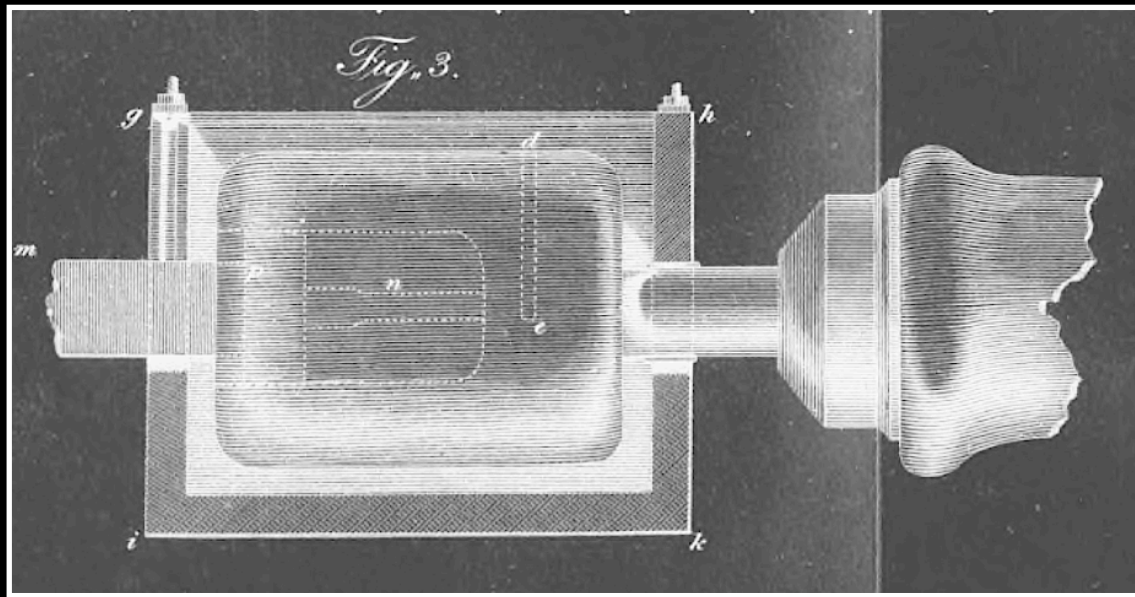
*“Being engaged lately in superintending the boring of cannon in the workshops of the military arsenal at Munich, I was struck with the very considerable degree of heat that a brass gun acquires in a short time in being bored [...]”*



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

# The cannon boring experiments

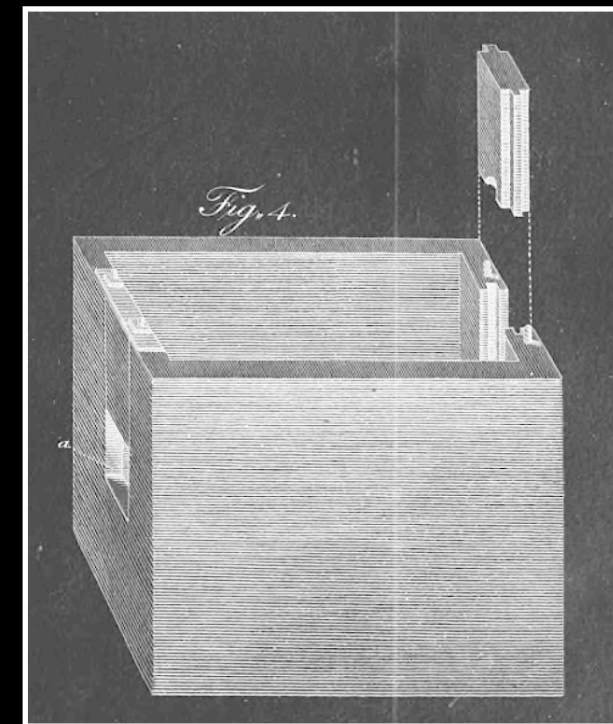
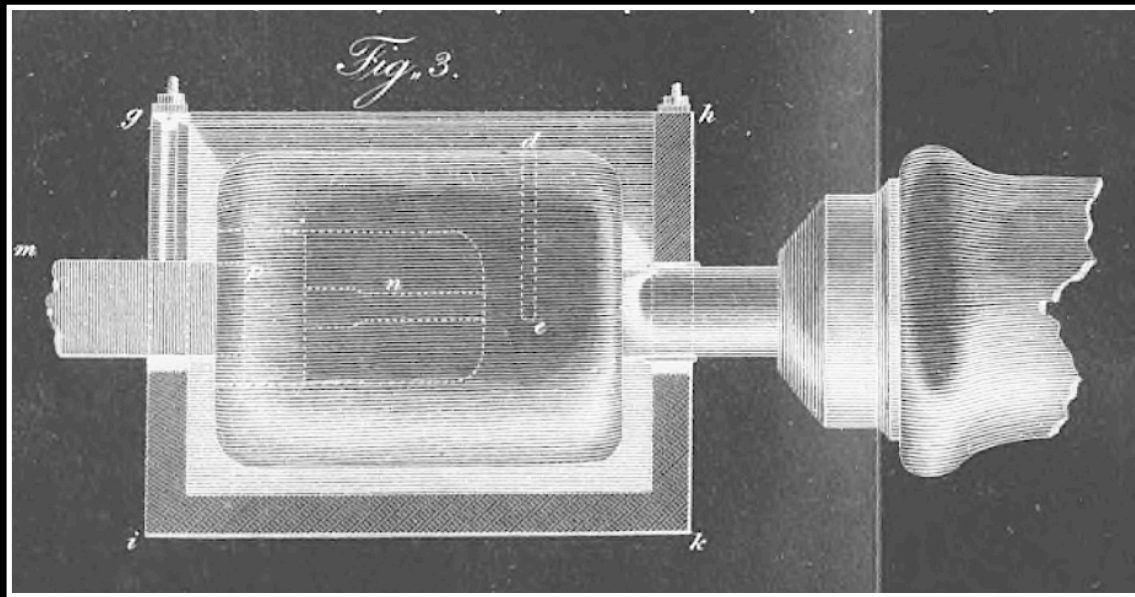
*“I caused the extremity of the cannon to be cut off and the metal in that part to be turned down to form a hollow cylinder, which could be turned round its axis by means of the neck that united it with the cannon.”*



*“This cylinder was designed for the express purpose of generating heat by friction, by forcing a blunt borer against the solid bottom of the cylinder at the same time that the latter was turned round its axis by the force of horses.”*

# The cannon boring experiments

*“A quadrangular box, watertight, was provided with holes or slits in the middle of each of its ends. The hollow metal cylinder occupied the middle of the box. On pouring water into the box and filling it to the brim, the cylinder was completely covered on every side.”*



*“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.”*



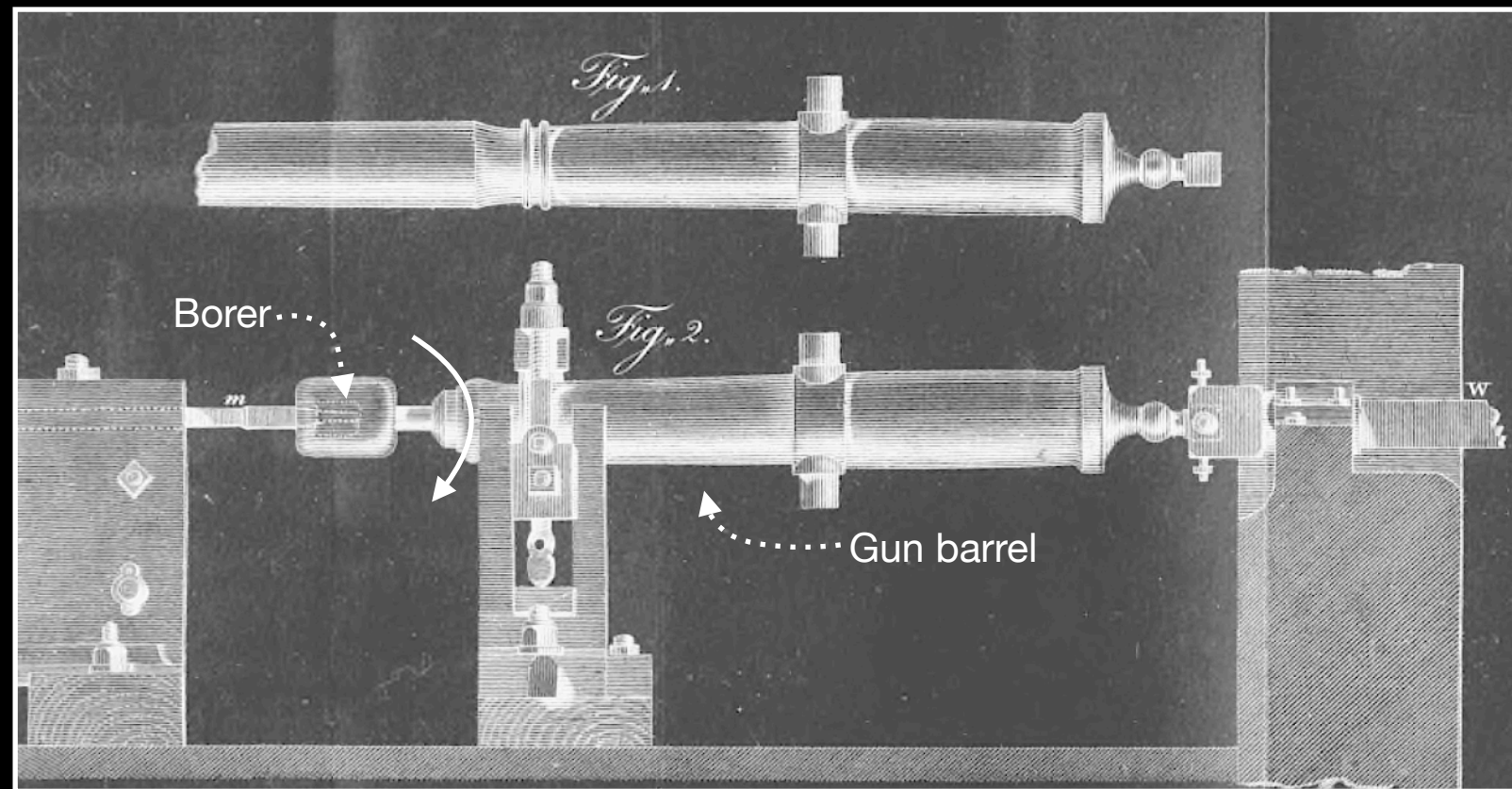
# The cannon boring experiments

*“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.*

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

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

*At 2½ hours it ACTUALLY BOILED!”*

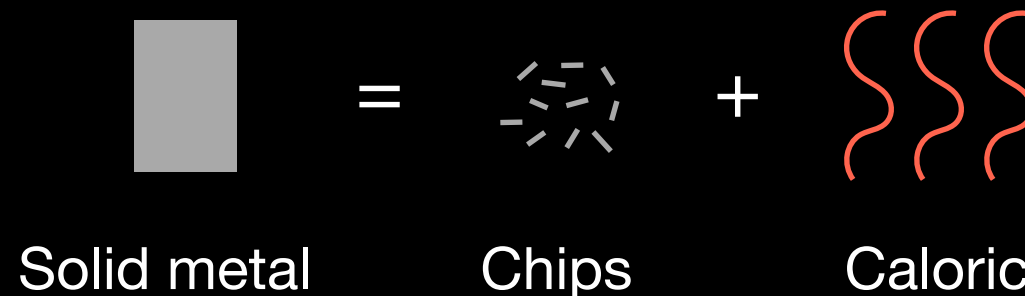


# The cannon boring experiments

“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?”*

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



**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

*“But no such change had taken place [...]”*

# The cannon boring experiments

“From whence came this heat?”

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

*“That this could not have been the case is evident:*

*First, because this water continually receiving heat from the machinery,  
and could not at the same time be giving heat to it;*

*Second, because there was no chemical decomposition of any part of this water.”*

Caloric (thus heat) is liberated in the combustion (“decomposition”) of coal, so why could the same not happen for water?

*“I frequently examined the water to see if any bubbles rose up through it.”*

# The cannon boring experiments

“From whence came this heat?”

***“Was it furnished by means of the iron bar to the end of which the blunt steel borer was fixed? Or by the small neck of metal by which the cylinder was united to the cannon?”***

*“These suppositions appear more improbable even than those mentioned before, for heat was continually going off by both these passages.”*

***“We must not forget to consider that most remarkable circumstance, that the source of heat generated by friction in these experiment appeared to be inexhaustible.”***

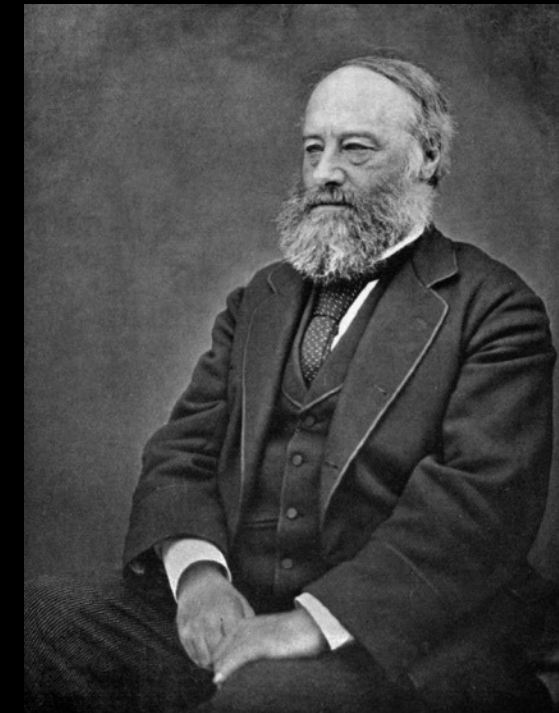
*“It is hardly necessary to add that anything which any insulated body can continue to furnish without limitation, cannot possibly be a material substance.*

***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.”***



# James Prescott Joule

Physicist and brewer



BARRELS TO BE RETURNED WHEN EMPTY BEING NEVER SOLD

*Salford Jan 10 1854*  
*Mr. Wm. Joseph Thompson*  
*Bought of Benjamin Joule*

COPIES	CALLED FOR	PRICE	2	3	30
1853					
Oct. 31	<i>In Account</i>				
	<i>Handed</i>				

*See dividend to be sent to*

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

... while conducting experiments with electricity

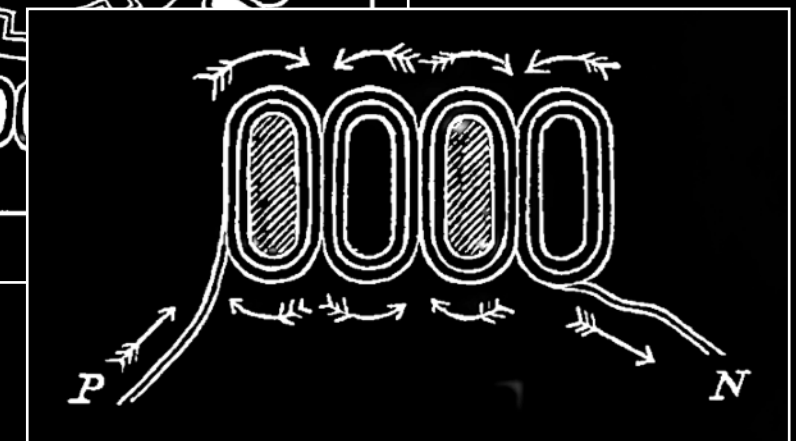
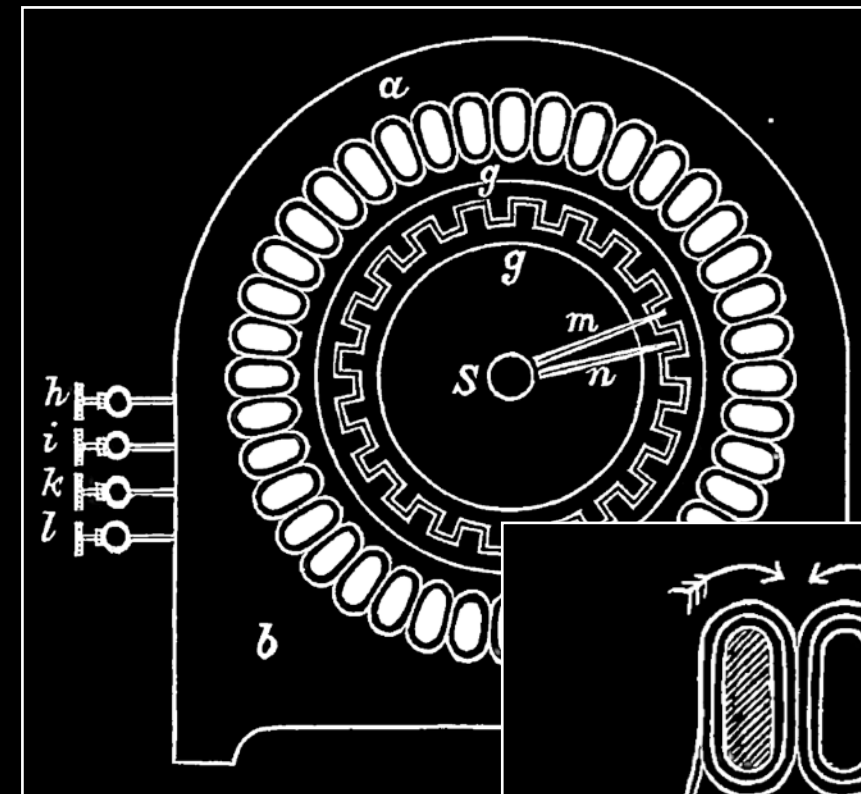
**Ale and Porter Stores,  
 No. 74, MILL STREET, MACCLESFIELD.**

**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.

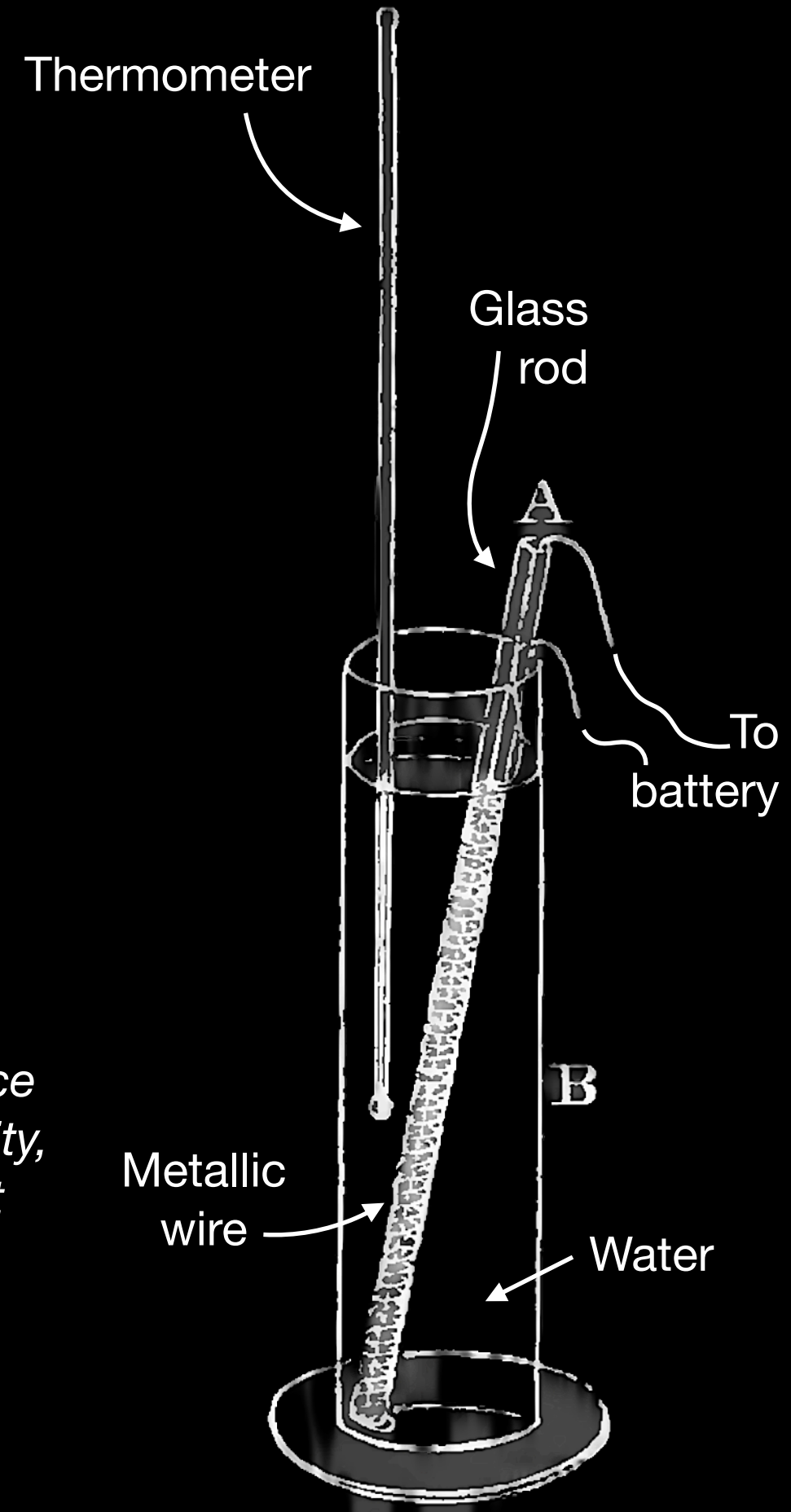


# Heat and electricity

Mean Deviations of the Needle of the Galvanometer.	Quantities of Current Electricity expressed in Degrees (5).	Quantities of Heat produced in half an hour by the Intensities in Column 2.	Proportional to the Squares of the Intensities in Column 2.
16°	0.43 Q	....	....
31½°	0.92 Q	3	2.9
55°	2.35 Q	19.4	18.8
57⅔°	2.61 Q	23	23.2
58½°	2.73 Q	25	25.4

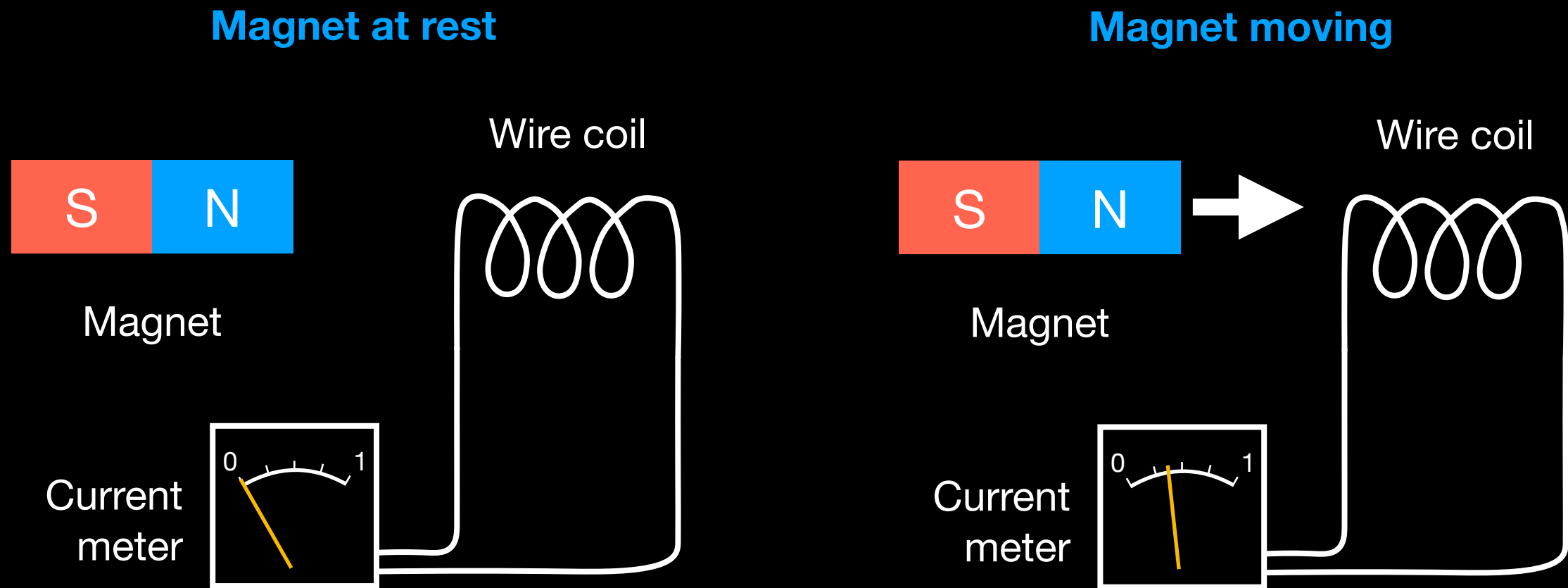
*“We see, therefore, that when a current of voltaic electricity is propagated along a metallic conductor, the heat evolved in a given time is proportional to the resistance of the conductor multiplied by the square of the electric intensity, whatever may be the length, thickness, shape, or kind of that metallic conductor.”*

***“The above law is of great importance.”***



# Heat and induction

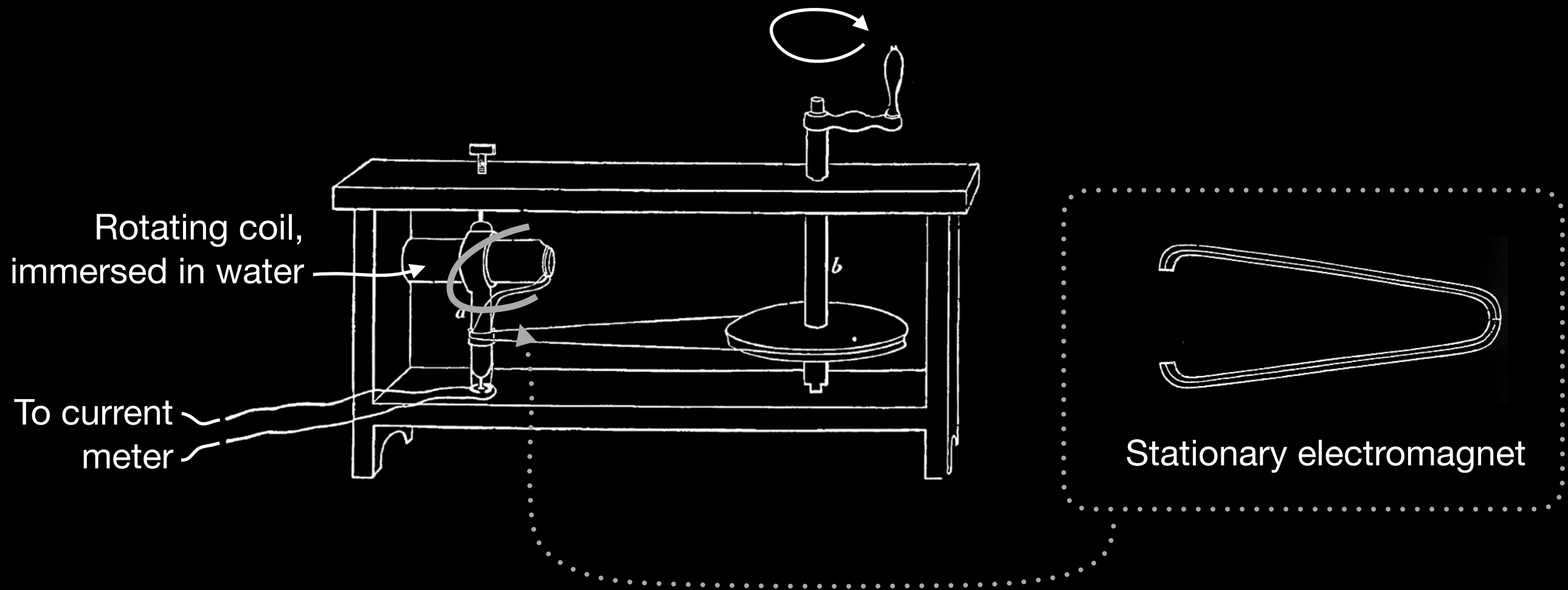
*“It is pretty generally, I believe, taken for granted that the electric forces which are put into play by the magneto-electrical machine possess, throughout the whole circuit, the same calorific properties as currents arising from other sources.”*



*“At the same time it must be admitted that hitherto no experiments have been made decisive of this very interesting question ...”*

# Heat and electricity

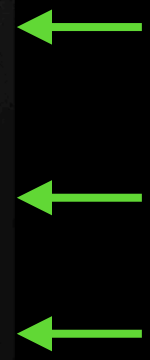
*“... leaving it a matter of doubt whether the heat observed was generated or merely transferred from the coils in which the magneto-electricity was induced, the coils themselves becoming cold.”*





# Heat and electricity

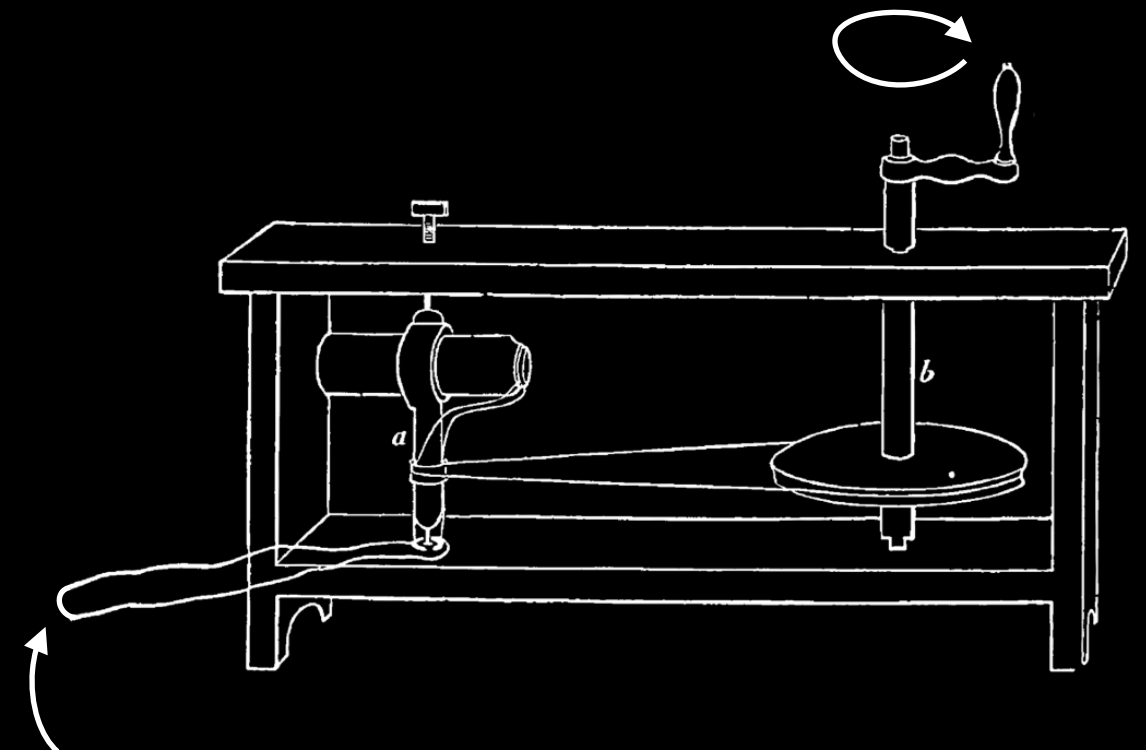
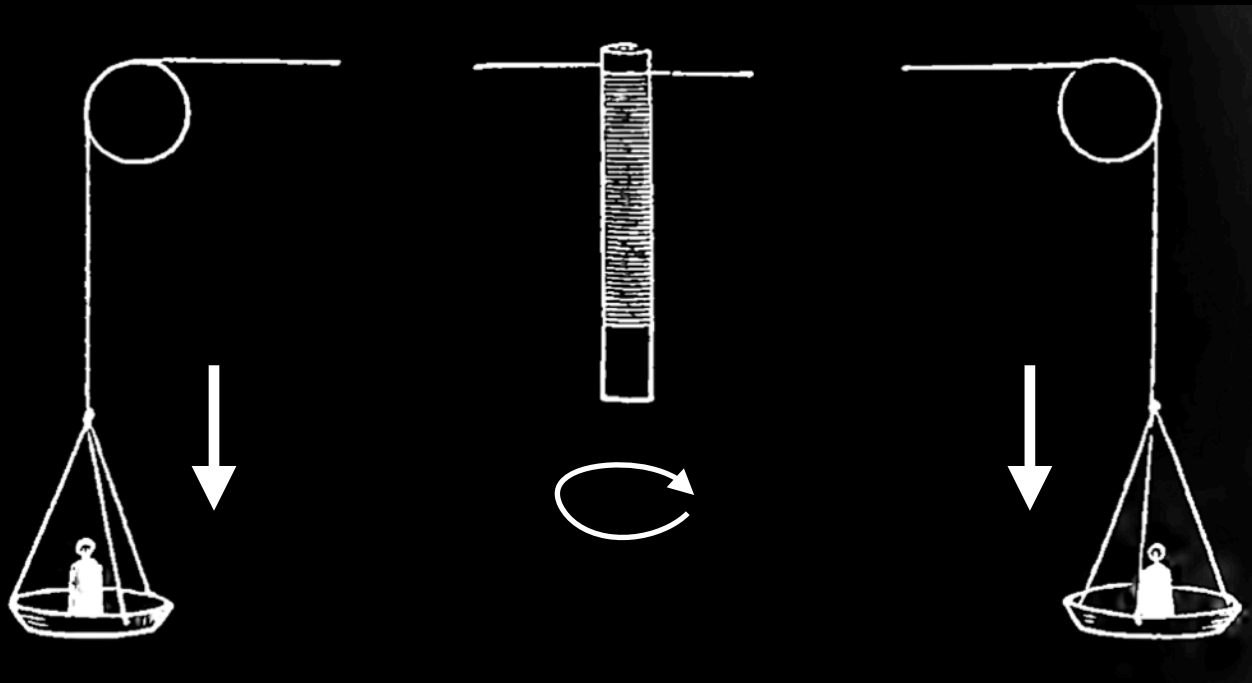
	Revolutions of Electro-Magnet per minute.	Deflections of Galvanometer of 5 turns.	Mean Temperature of Room.	Mean Difference.	Temperature of Water.		Loss or Gain.	
					Before.	After.		
April 15, P.M.	Battery contact broken.	600	0 0	54.69	0.19+	54.90	54.85	0.05 loss
	Battery in connexion.	600	21 0	54.67	0.20+	54.85	54.88	0.03 gain
	Battery contact broken.	600	0 0	54.61	0.24+	54.88	54.83	0.05 loss
	Battery in connexion.	600	24 0	54.65	0.23+	54.85	54.92	0.07 gain
	Mean, Battery in connexion.	600	22 30	..	0.21+	..	..	0.05 gain
	Mean, Battery contact broken.	600	0 0	..	0.21+	..	..	0.05 loss
	Corrected Result.	} 600 22° 30' = 0.177* of cur. mag.-elect. 0.10 gain						



“Having proved that heat is generated by the magneto-electrical machine [...], it became an object of great interest to inquire whether a constant ratio existed between it and the mechanical power gained or lost.”

# The mechanical equivalent of heat

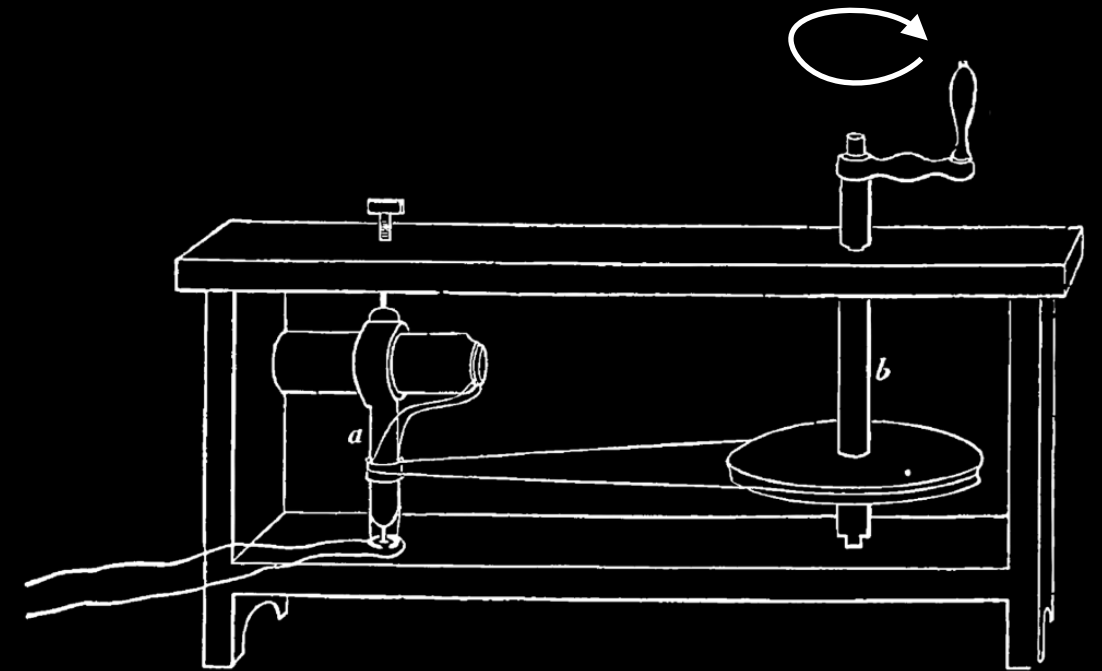
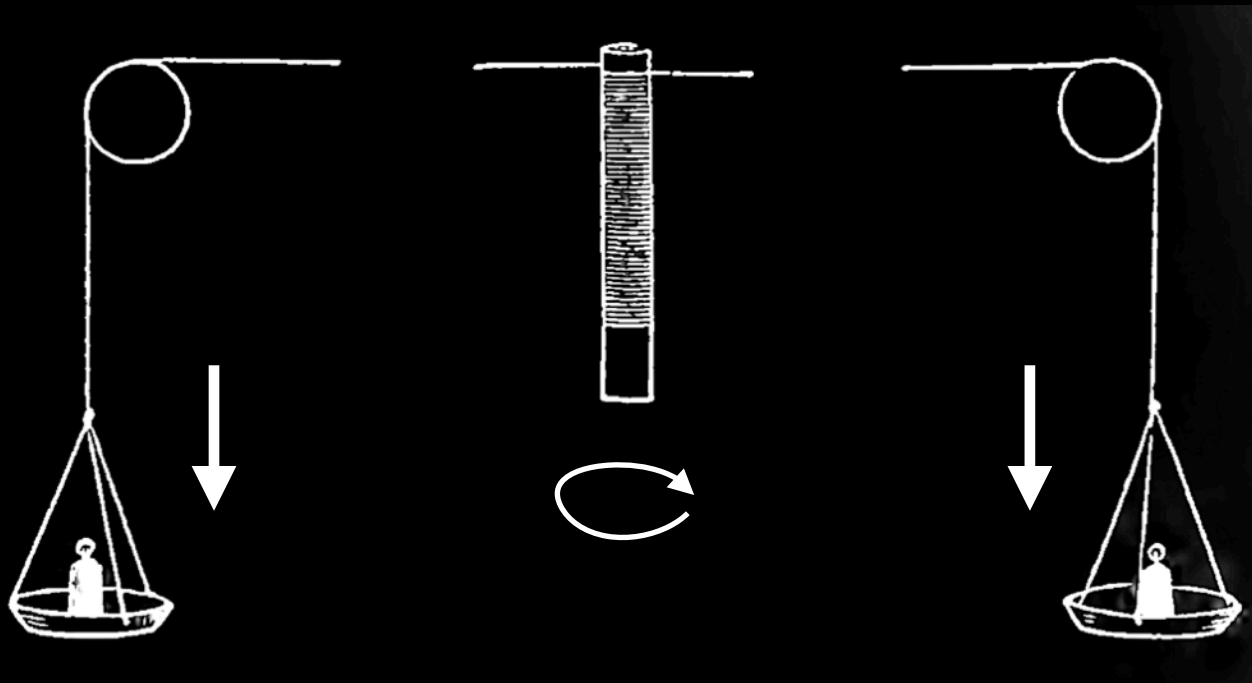
“For this purpose it was only necessary to repeat the previous experiments, and to ascertain, at the same time, the mechanical force necessary in order to turn the apparatus.”



“In order to obtain the full calorific effect, I now connected the terminal wires of the revolving coil.”

# The mechanical equivalent of heat

*“I found [...] a change of  $2.74^{\circ}\text{F}$ , and this has been obtained by the power which can raise 4 lb. 12 oz. to the perpendicular height of 517 feet.”*

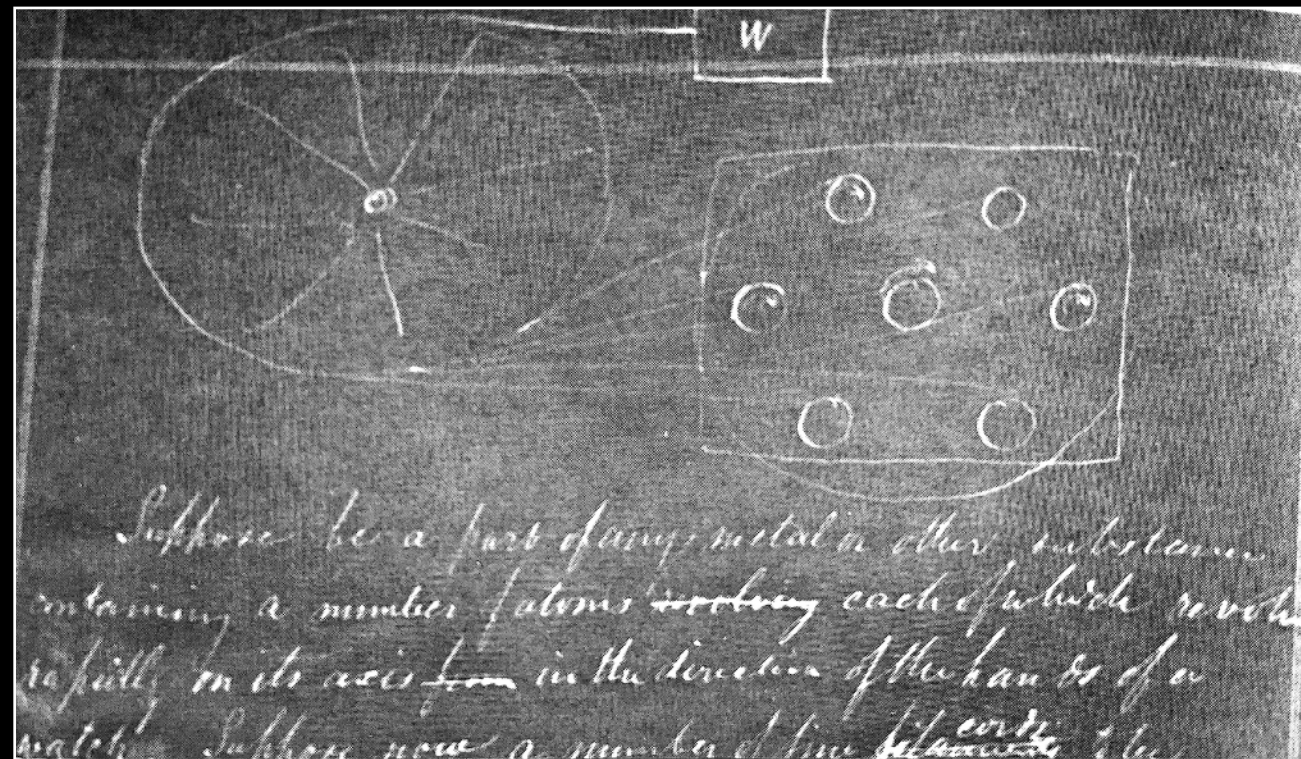


***“ $1^{\circ}\text{F}$  of heat per lb. of water is therefore equivalent to a mechanical force capable of raising a weight of 896 lb. to the perpendicular height of one foot.”***

# The mechanical equivalent of heat

*“PS: We shall be obliged to admit that Count Rumford was right in attributing the heat evolved by boring cannon to friction, and not (in any considerable degree) to any change in the capacity of the metal.”*

*“I have lately proved experimentally that heat is evolved by the passage of water through narrow tubes.”*



From Joule's laboratory notebook.

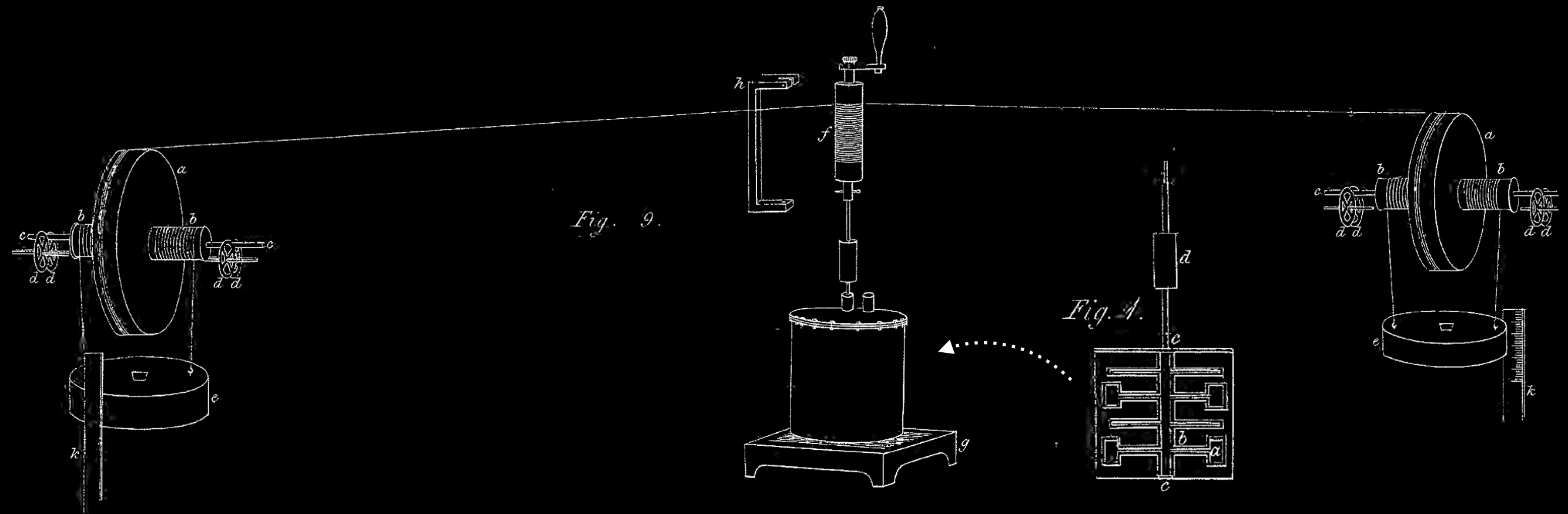
*“I thus obtained one degree of heat per lb. of water from a mechanical force capable of raising about 770 lb. to the height of one foot.”*



# The mechanical equivalent of heat

*“In accordance with the pledge I gave the Royal Society some years ago, I have now the honor to present it with the results of the experiments I have made in order to determine the mechanical equivalent of heat with exactness.”*

*“From the explanation given by Count Rumford of the heat arising from the friction of solids, one might have anticipated, as a matter of course, that the evolution of heat would also be detected in the friction of liquids.”*

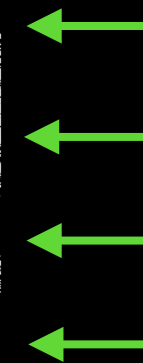


“Paddle-wheel” in water

# The mechanical equivalent of heat

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

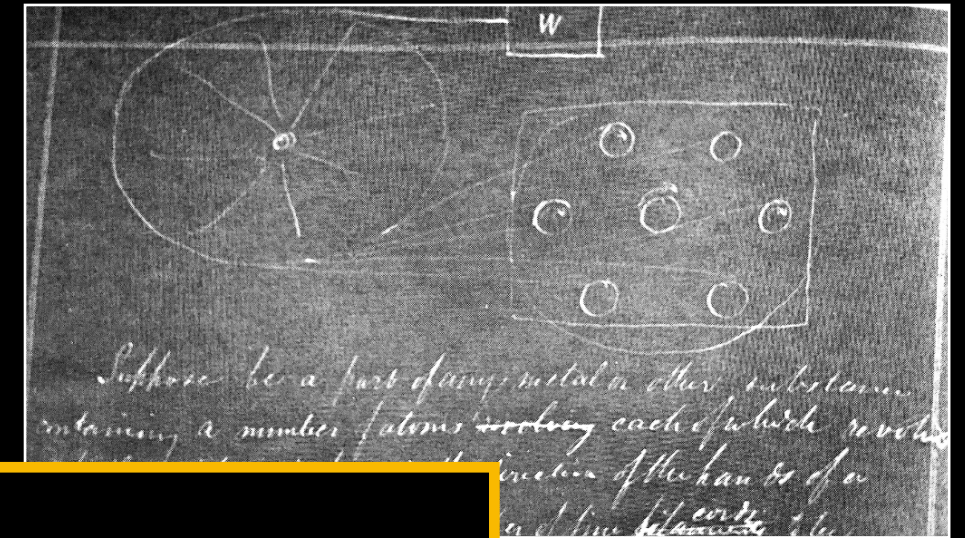
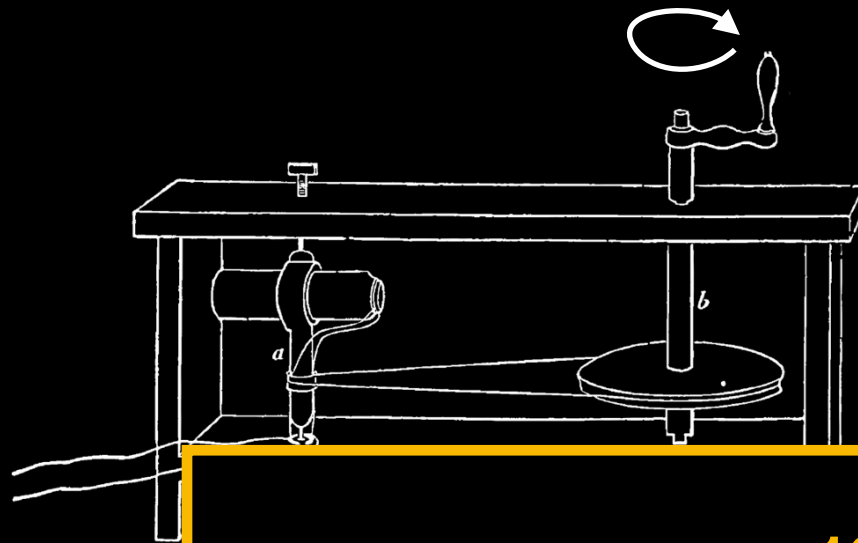
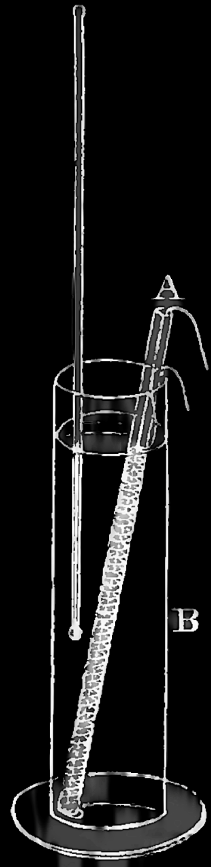


*“I will therefore conclude by considering it as demonstrated by the experiments contained in this paper,*

*1st. That the quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of force expended.*

*2nd. That the quantity of heat capable of increasing the temperature of a pound of water by 1°F, requires for its evolution the expenditure of a mechanical force represented by the fall of 772 lbs. through the space of one foot.”*

# The true nature of heat



**1849:**  
**“Heat is simply a mechanical effect,  
not a substance.”**

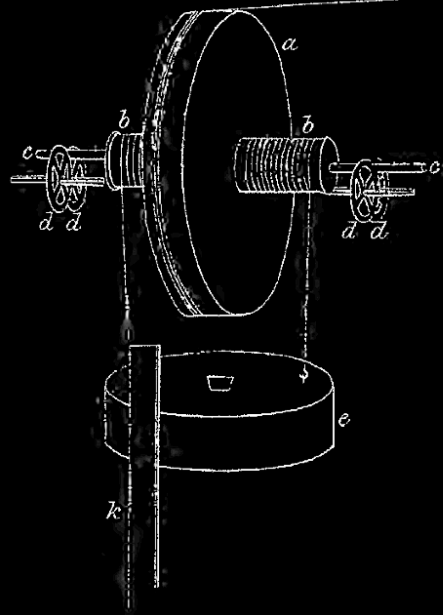


Fig. 9.

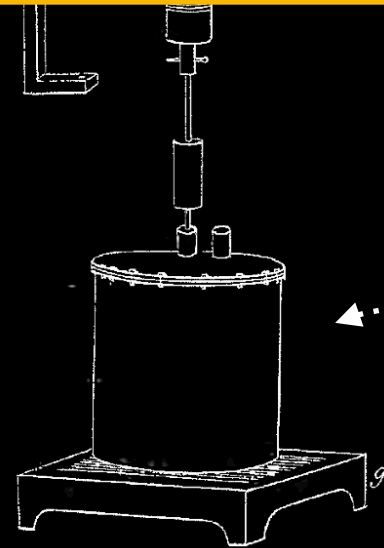
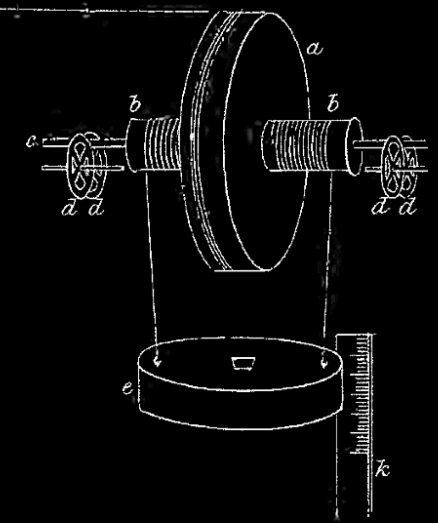
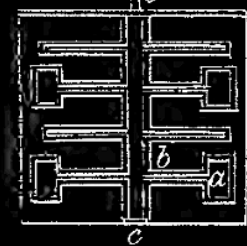
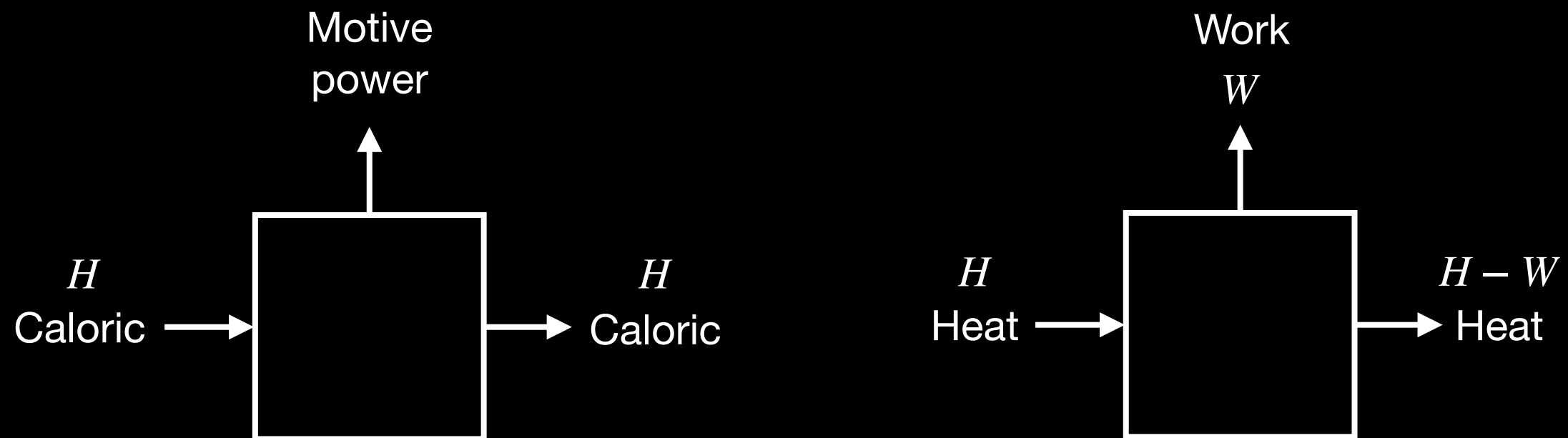


Fig. 4.



# A correction to Carnot's theory

Heat is not conserved, but energy is!



*(Steam engines too inefficient for the discrepancy to be noted!)*

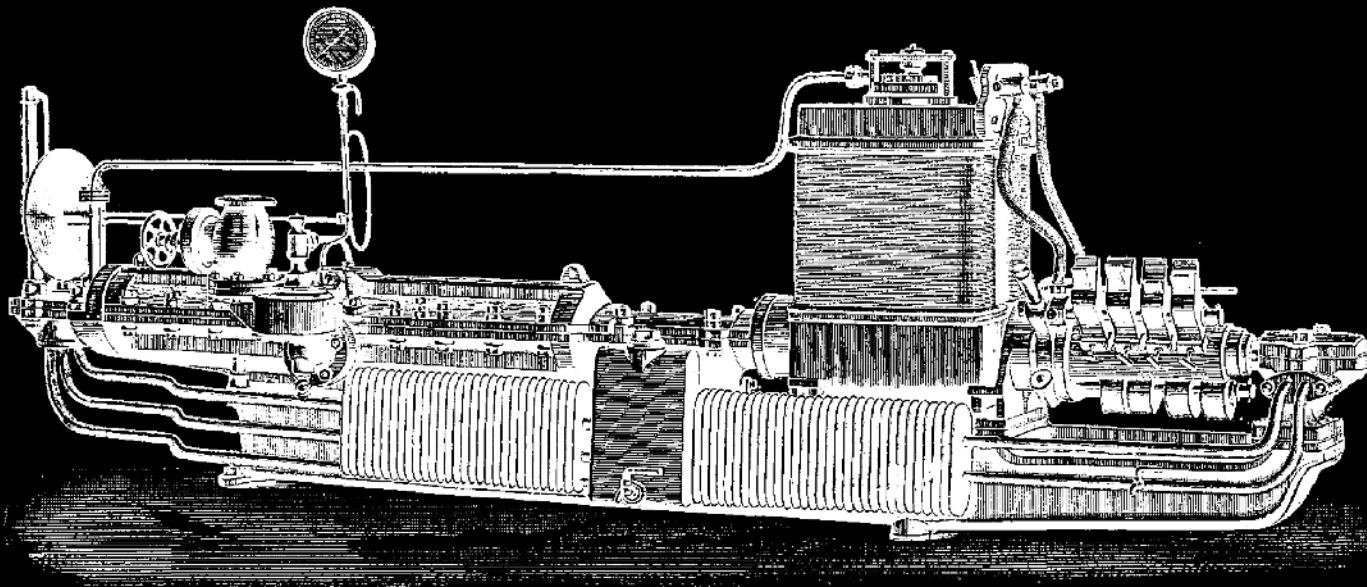


# ... and the rest is history

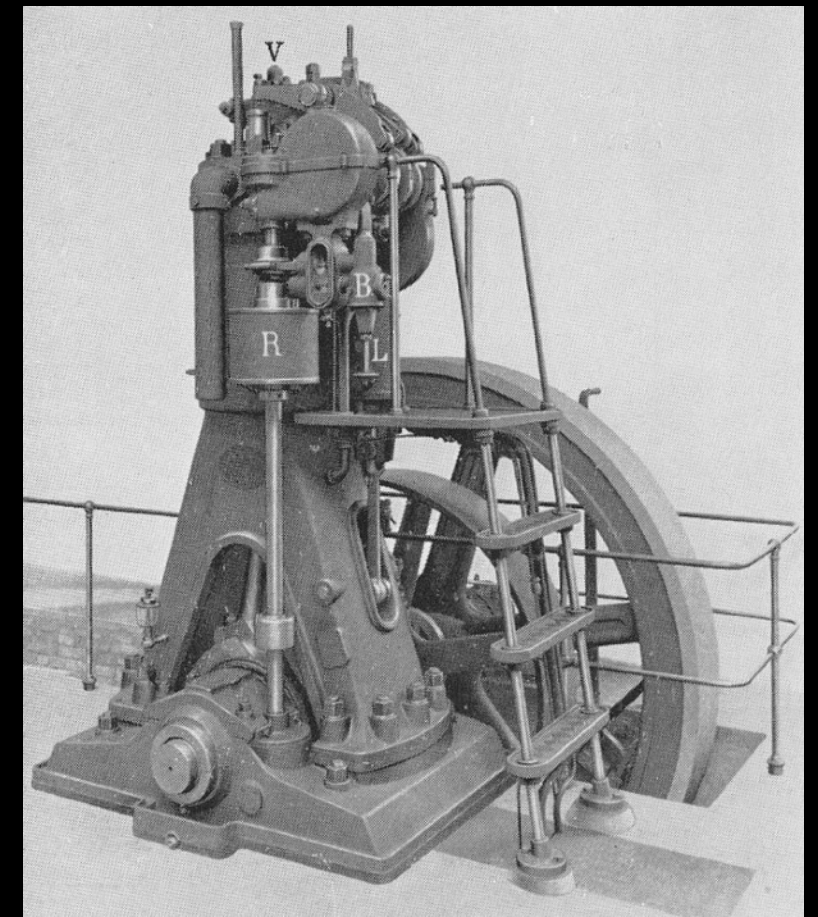
**1857:** Rudolf Clausius: “Heat is the average kinetic energy of molecules”

**1866:** James Clerk Maxwell calculates the velocity distribution in a gas  
→ kinetic theory of heat is now on solid foundations

**1887:** Charles Parsons builds the first compound steam turbine



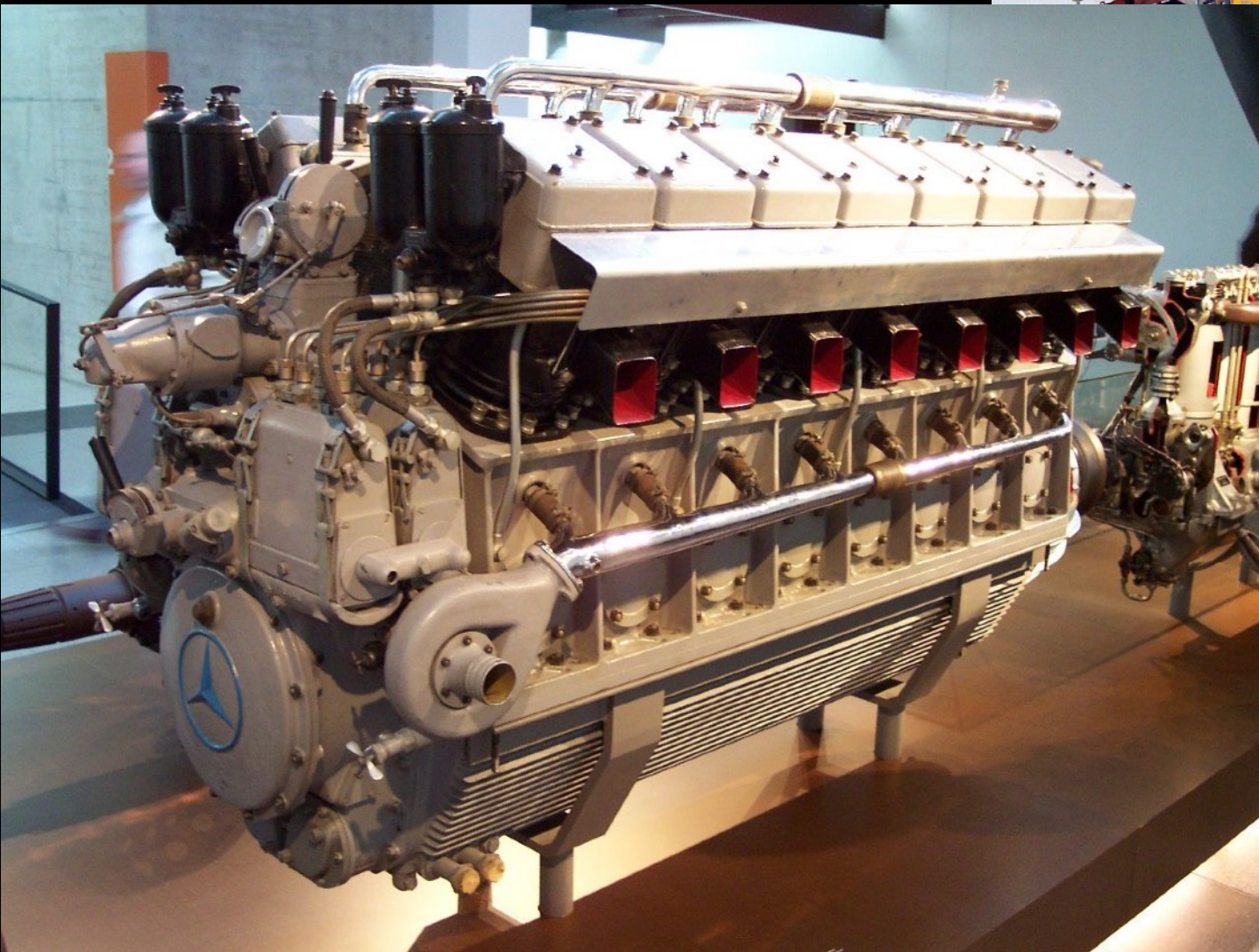
**1892:** Rudolf Diesel: “Theory and construction of a rational heat motor with the purpose of replacing the steam engine”  
→ inspired by Carnot’s theory





# Today

Steam turbines provide the vast majority of today's electricity



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





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