HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD
A STORY OF INVENTION AND DISCOVERY

Philipp Windischhofer
October 7, 2023
“What changes when cold water is made hot?”
“How many kinds of electricity are there?”

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“What changes when cold water is made hot?”

“If matter is made of atoms, what are the atoms of electricity?”
“How did we get here?”

4th century BC

Ca. 1900
What is heat?
Heat in antiquity

Hero of Alexandria (ca. 70 AD)

Mouseion of Alexandria

“Seat of the muses”
Heat in antiquity

Hero of Alexandria (ca. 70 AD)

“Sounds produced on the opening of a Temple Door”

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Hero’s explanation:

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

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Temperature in antiquity

Galen of Pergamon (ca. 140 AD)
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Coleric
(“yellow bile”)
Temperature in antiquity

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Blood

Maelanc
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Temperature in antiquity

Galen of Pergamon (ca. 140 AD)

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<thead>
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<th>Coleric (&quot;yellow bile&quot;)</th>
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# Temperature in antiquity

Galen of Pergamon (*ca. 140 AD*)

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The choleric
Temperature in antiquity

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**Temperaments**

- Coleric ("yellow bile")
- Blood
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**Bodily fluids**

- The choleric
- The "sanguine"
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Temperature in antiquity

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Bodily fluids

Temperaments

"Temperature"
Temperature in antiquity

Galen of Pergamon (ca. 140 AD)

“For in Celts and Germans […] the skin is cold and wet. However much innate heat there is has fled for refuge to the internal organs, along with the blood, which here is agitated, confined in narrow spaces and itself seething, rendering them high-spirited, rash, and quick to change their opinions.”
Galen’s temperature scale
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“Proceeding from the hottest of all those coming to perception (for example, either fire or boiling water)
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“We divide this precisely in the middle, discovering the moderate which is equally removed from each of the extremes.”
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“But we are also able to prepare this in a certain way when we mix an equal mass of ice with boiling water.”
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Relating Galen’s temperature scale …

... to the latitude of the patient.
The first “thermoscopes”

Letters from Giovanni Sagredo to Galileo:

Giovanni Francesco Sagredo

Mathematician in Venice, diplomat and spy in Syria, treasurer in Palmanova, close friend of Galileo’s
The first “thermoscopes”

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In today’s terminology:

“air thermometer”

Trapped air expands when warmed, contracts when cooled
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Here in the room my instrument showed 130 degrees of heat more than there was two years ago at the time of the very rigorous and extraordinary cold.
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Thus, as the instrument had gone up to 360 degrees in the greatest heat of summer, it appears that salt combined with snow increases the cold by as much as amounts to a third of the difference between the excessive heat of summer and the excessive cold of winter.
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—a thing so wonderful, that I can provide no credible reason for it.”
Measuring temperature

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

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

Santorio Santorre: *Professor of Medicine at Padua*

“Weighing chair” to study his own metabolism for 30 years!
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On thermometers:
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We promise that a book about medical instruments that are not well-known will shortly appear, in which we shall give an illustration of this instrument and describe its construction and use.”
A serious problem
The air thermometer is also a barometer!

The water bucket is open!

*Atmospheric pressure also affects the water level, in the opposite direction that temperature does!*
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A silent inventor: Jean Rey
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Marin Mersenne (a monk from Paris) to Jean Rey:
September 31, 1631

Water bucket
Trapped air
Cooler
Warmer
Water line
Water bucket
A silent inventor: Jean Rey
A physician in the French countryside

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

“Then the thermoscope, making the liquid descend by the rarefaction of its air, bears witness that heat makes air more subtle [..]”
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Jean Rey, in his reply:
January 1, 1632 (before Pascal!)

“There are a variety of thermoscopes, or so it appears. What you say cannot agree with mine, which is nothing more than a little round phial with a very long and slender neck.

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

The heat, expanding the water, makes it rise more or less according to whether the heat is great or small.”
A silent inventor: Jean Rey
A physician in the French countryside

Rey’s thermometer is hermetically sealed

Changes in air pressure do not affect the temperature reading

He did not know of that advantage!
Thermometry as a precision science

Thermometers from Florence, ca. 1660
Thermometry as a precision science

But which scale and which reference points to use?
Thermometry as a precision science

But which scale and which reference points to use?

Florence (~1660)

“The most severe winter cold”

“The greatest summer heat”

Thermometers from Florence, ca. 1660
## Thermometry as a precision science

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

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**“The greatest summer heat”**

**Thermometers from Florence, ca. 1660**
Thermometry as a precision science

But which scale and which reference points to use?

**Florence**
- (~1660) “The most severe winter cold”
- (1669) Melting snow
  - “The greatest summer heat”

**Dalencé**
- (1688) Melting snow: -10 degrees
  - Melting butter: +10 degrees

Thermometers from Florence, ca. 1660
### Thermometry as a precision science

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Thermometry as a precision science

But which scale and which reference points to use?

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*Thermometers from Florence, ca. 1660*
Thermometry as a precision science

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Science
Science

Engineering
Captain Thomas Savery
Military engineer, trench-master, hobbyist
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Military engineer, trench-master, hobbyist

Navigation improv’d (1698):
Or, the art of Rowing Ships of all Rates, in Calms, with a more easy, swift, and steady Motion than Oars can.
Captain Thomas Savery
Military engineer, trench-master, hobbyist

**Navigation improv’d (1698):**

Or, the art of Rowing Ships of all Rates, in Calms, with a more easy, swift, and steady Motion than Oars can.

Surveyor of the Royal British Navy: “And have interloping people, that have no concern with us, pretend to contrive or invent things for us?”
His second try: a steam pump

Patented on 2 July 1698:

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

to hold for 14 years; with usual clauses”

(Published right around Rømer’s proposal for his temperature scale)
His second try: a steam pump

(Published right around Rømer’s proposal for his temperature scale)
His second try: a steam pump

“The force used in my engine is in a matter infinite and unlimited …”

(Published right around Rømer’s proposal for his temperature scale)
His second try: a steam pump

“The force used in my engine is in a matter infinite and unlimited …”

“It will raise your water five hundred or one thousand feet high, were any pit so deep.”

(Published right around Rømer’s proposal for his temperature scale)
The “Savery Engine”
The “Savery Engine”
The “Savery Engine”

Pumping cycle:

1.) Pumping vessel connected to boiler; filled with steam
The “Savery Engine”

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2.) Pumping vessel isolated from boiler; connected to intake
The “Savery Engine”

Pumping cycle:

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→ Steam condenses and contracts, water sucked into pumping vessel
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4. Dousing water turned off, pumping vessel reconnected to boiler and to outflow pipe
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→ Steam pressure pushes water out of the pumping vessel
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The Savery Engine in action

Never became the “Miner’s friend”

High-pressure steam

 boiler explosions

Used in two London waterworks
Thomas Newcomen
Ironmonger in Devonshire, phantom

“A man from Dartmouth, without any knowledge whatever of the speculations of Captain Savery, had also made up his mind to invent a fire-machine for drawing water from the English tin mines.”

From the records of Marten Triewald
Newcomen’s “atmospheric engine”

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

Marten Triewald
Newcomen’s “atmospheric engine”

Pumping cycle:
Newcomen’s “atmospheric engine”

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1.) Piston connected with boiler, filled with steam
Newcomen’s “atmospheric engine”

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Newcomen’s “atmospheric engine”

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1.) Piston connected with boiler, filled with steam
   → Piston extends, counterweight is lowered

2.) Piston disconnected from boiler, cold water injected
   → Steam condenses, atmospheric pressure pushes piston back in, counterweight is raised

Up- and downward movement of shaft drives pump

No need for high-pressure steam → more reliable
The first Newcomen engine in operation

“The steam engine near Dudley castle.

Invented by Capt. Savery & Mr. Newcomen, Erected by ye later 1712”
The Newcomen engine spreads …

… under Savery’s patent!

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

Landgoed Groenendaal, Netherlands (shown in 1780s)

Now at Henry Ford museum in Dearborn, MI

~1500 Newcomen engines had been built by 1800
The Newcomen engine spreads …

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

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

“And did those feet in ancient time”,  
William Blake, 1804

Bernissart, Belgium (built 1781)  
~1500 Newcomen engines had been built by 1800  
Extremely inefficient workhorse of the early industrial revolution: deep coal mines, blast furnaces, …

Fairbottom Bobs” at a coal mine in Lancashire, England (operating 1760-1827)  
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Landgoed Groenendaal, Netherlands (shown in 1780s)
Science

Engineering
Joseph Black
Professor of anatomy and chemistry in Glasgow

University of Glasgow (1756–1766)

*Newcomen’s machine already well-established!*
Joseph Black
Professor of anatomy and chemistry in Glasgow

University of Glasgow (1756–1766)

Newcomen’s machine already well-established!

Lecture notes:
published posthumously by his friend John Robison
Black’s “equilibrium”

“If we take a thousand different kinds of matter and put them together in a room without a fire …”
Black’s “equilibrium”

“If we take a thousand different kinds of matter and put them together in a room without a fire …”

“… if we apply a thermometer to them all in succession, it will give precisely the same reading.”
Black’s “equilibrium”

“If we take a thousand different kinds of matter and put them together in a room without a fire …”

The thermometer has been critical for this observation to be made! A piece of metal and feathers at the same temperature feel very different.
Black’s “equilibrium”

“I call it the equilibrium of heat. Its nature was not well understood until I pointed out a method of investigating it.”
Black’s “equilibrium”

“I call it the equilibrium of heat. Its nature was not well understood until I pointed out a method of investigating it.”

Dr. Boerhaave:
Black’s “equilibrium”

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Dr. Boerhaave:
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“*I call it the equilibrium of heat.* Its nature was not well understood until I pointed out a method of investigating it.”

Dr. Boerhaave:

“In equilibrium there is an equal quantity of heat in every equal volume of space, however filled up with different bodies.”
Black’s “equilibrium”

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Dr. Boerhaave:

“In equilibrium there is an equal quantity of heat in every equal volume of space, however filled up with different bodies.”

“The reason is that, to whichever of these bodies the thermometer be applied, it gives the same reading.”
Black’s “equilibrium”

“In equilibrium there is an equal quantity of heat in every equal volume of space, however filled up with different bodies. The reason is that, to whichever of these bodies the thermometer be applied, it gives the same reading.”

“Father of physiology” together with Santorio
Black’s “equilibrium”

“But [Boerhaave] is taking a very hasty view of the subject.”
Black’s “equilibrium”

“But [Boerhaave] is taking a very hasty view of the subject.”

“He is confounding the quantity of heat in different bodies with its intensity [temperature], though it is plain that these are two different things, and should always be distinguished.”
Black’s “equilibrium”

“But [Boerhaave] is taking a very hasty view of the subject.”

“He is confounding the quantity of heat in different bodies with its intensity [temperature], though it is plain that these are two different things, and should always be distinguished.”

Is it really “plain”?
“He is confounding the quantity of heat in different bodies with its intensity [temperature], though it is plain that these are two different things, and should always be distinguished.”

Is it really “plain”?

“But [Boerhaave] is taking a very hasty view of the subject.”
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“But [Boerhaave] is taking a very hasty view of the subject.”

“He is confounding the quantity of heat in different bodies with its intensity [temperature], though it is plain that these are two different things, and should always be distinguished.”

Is it really “plain”?

*Temperature* is measured by a thermometer, but *heat* flows between bodies.
Interpreting second-hand experiments

Experiment performed by Fahrenheit, described by Boerhaave, analyzed by Black

Mixing warm water with cold water

![Diagram showing a thermometer at 150°F in a vessel labeled 'Hot water' and a thermometer at 100°F in a vessel labeled 'Cold water']
Interpreting second-hand experiments

Experiment performed by Fahrenheit, described by Boerhaave, analyzed by Black

Mixing warm water with cold water

Cold water

Hot water

100°F

150°F

Luke-warm water

125°F
Interpreting second-hand experiments

Experiment performed by Fahrenheit, described by Boerhaave, analyzed by Black

Mixing warm water with cold water

“The temperature of the warm water is lowered by 25 degrees while that of the cold is raised just as much.”
Interpreting second-hand experiments

Experiment performed by Fahrenheit, described by Boerhaave, analyzed by Black

Mixing warm mercury with cold water

[Diagram showing a thermometer in mercury at 150°F and another in water at 100°F]
Interpreting second-hand experiments

Experiment performed by Fahrenheit, described by Boerhaave, analyzed by Black

Mixing warm mercury with cold water
Interpreting second-hand experiments

Experiment performed by Fahrenheit, described by Boerhaave, analyzed by Black

Mixing warm mercury with cold water

“The quicksilver, therefore, has cooled through 30 degrees, while the water has become warmer by 20 degrees only …”
Interpreting second-hand experiments

Experiment performed by Fahrenheit, described by Boerhaave, analyzed by Black

Mixing warm mercury with cold water

“The quicksilver, therefore, has cooled through 30 degrees, while the water has become warmer by 20 degrees only …”

“… and yet the quantity of heat which the water has gained is the very same as that which the quicksilver has lost.”
Interpreting second-hand experiments
Interpreting second-hand experiments

Experiment performed by Dr. Martine, analyzed by Black

“Dr. Martine found that the quicksilver was warmed by the fire almost twice as fast as the water.”
Interpreting second-hand experiments

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Mercury reacts “faster” to heat!
Interpreting second-hand experiments

Experiment performed by Dr. Martine, analyzed by Black

“Dr. Martine found that the quicksilver was warmed by the fire almost twice as fast as the water.”

This is not obvious!

Mercury weighs 13-14 times as much as the same volume of water!

by 20 degrees only …”

Mercury reacts “faster” to heat!
Black’s “capacity for heat”

1) Expose tested substance to constant heat source

2) Measure time needed to produce a certain temperature increase
Black’s “capacity for heat”

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\[ H \propto w \cdot \Delta T \]
Black’s “capacity for heat”

1) Expose tested substance to constant heat source

2) Measure time needed to produce a certain temperature increase

\[ H \propto w \cdot \Delta T \]

“Sensible heat” provided
Black’s “capacity for heat”

1) Expose tested substance to constant heat source

2) Measure time needed to produce a certain temperature increase

$H \propto w \cdot \Delta T$

“Sensible heat” provided

Weight of tested substance
Black’s “capacity for heat”

1) Expose tested substance to constant heat source

2) Measure time needed to produce a certain temperature increase

\[ H \propto w \cdot \Delta T \]

“Sensible heat” provided

Rise in temperature

Weight of tested substance

Temperature increase \( \Delta T \)

Constant heat source

Weight \( w \)

Tested substance
Black’s “capacity for heat”

1) Expose tested substance to constant heat source

2) Measure time needed to produce a certain temperature increase

\[ H \propto w \cdot \Delta T \]

“Sensible heat” provided

“Rise in temperature

Weight of tested substance

“Heating twice as much material takes twice the heat”
Black’s “capacity for heat”

1) Expose tested substance to constant heat source

2) Measure time needed to produce a certain temperature increase

\[ H \propto w \cdot \Delta T \]

“Sensible heat” provided

“Doubling the temperature increase takes twice the heat”

“Heating twice as much material takes twice the heat”

Tested substance

Constant heat source

Temperature increase $\Delta T$

Weight $w$
Black’s “capacity for heat”

1) Expose tested substance to constant heat source

2) Measure time needed to produce a certain temperature increase

\[ H = s \cdot w \cdot \Delta T \]

“Sensible heat” provided

Rise in temperature

Weight of tested substance

Weight \( w \)

Temperature increase \( \Delta T \)
Black’s “capacity for heat”

1) Expose tested substance to constant heat source

2) Measure time needed to produce a certain temperature increase

\[ H = s \cdot w \cdot \Delta T \]

“Sensible heat” provided

“Capacity for the matter of heat”

Weight of tested substance

Weight \( w \)

Rise in temperature

Temperature increase \( \Delta T \)
Black’s “capacity for heat”

Martine’s mercury experiment:

“Mercury is 13-14 times heavier than water, but heated up twice as fast.”

\[ H = s \cdot w \cdot \Delta T \]

“Sensible heat” provided

“Capacity for the matter of heat”

Rise in temperature

Weight of tested substance

Water

Mercury
Black’s “capacity for heat”

Martine’s mercury experiment:

“Mercury is 13-14 times heavier than water, but heated up twice as fast.”

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

(The modern value is ~30 times smaller than water.)

\[ H = s \cdot w \cdot \Delta T \]

“Sensible heat” provided

“Capacity for the matter of heat”

Weight of tested substance

Rise in temperature

Water

Mercury
A thought experiment

Just below freezing point
Ice cubes

Just above freezing point
Water
A thought experiment

\[ H = s \cdot w \cdot \Delta T \]

*Just below freezing point*

Ice cubes

*Just above freezing point*

Water

“Sensible heat” provided

Rise in temperature

“Capacity for the matter of heat”

Weight of tested substance
A thought experiment

Just below freezing point

Ice cubes

Just above freezing point

Water

If this were true, ice would melt almost instantaneously!

\[ H = s \cdot w \cdot \Delta T \]

“Sensible heat” provided

Rise in temperature

“Capacity for the matter of heat”

Weight of tested substance
A thought experiment
A thought experiment

“Were this really the case, the consequences of it would be dreadful in many cases.”
A thought experiment

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“Were this really the case, the consequences of it would be dreadful in many cases.

Were the ice and snow to melt suddenly, the torrents and inundations would be irresistible and dreadful.
A thought experiment

“Were this really the case, the consequences of it would be dreadful in many cases.

Were the ice and snow to melt suddenly, the torrents and inundations would be irresistible and dreadful.
“Were this really the case, the consequences of it would be dreadful in many cases.

Were the ice and snow to melt suddenly, the torrents and inundations would be irresistible and dreadful.

They would tear up and sweep away everything, and this so suddenly that mankind would have great difficulty in escaping from their ravages.”
A new “type” of heat

\[ H = s \cdot w \cdot \Delta T \]

“Sensible heat” provided
Rise in temperature
“Capacity for the matter of heat”
Weight of tested substance

Just below freezing point
Ice cubes

Just above freezing point
Water
A new “type” of heat

“When ice or any other solid substance is melted, it receives a much larger quantity of heat than what is perceptible by a thermometer.

\[ H = s \cdot w \cdot \Delta T \]

- **Just below freezing point**
  - Ice cubes

- **Just above freezing point**
  - Water

“Sensible heat” provided

“Capacity for the matter of heat”

Rise in temperature

Weight of tested substance
A new “type” of heat

“When ice or any other solid substance is melted, it receives a much larger quantity of heat than what is perceptible by a thermometer.

\[ H = s \cdot w \cdot \Delta T \]

- **Just below freezing point**
  - Ice cubes

- **Just above freezing point**
  - Water

“Sensible heat” provided

Rise in temperature

“Capacity for the matter of heat”

Weight of tested substance
A new “type” of heat

“When ice or any other solid substance is melted, it receives a much larger quantity of heat than what is perceptible by a thermometer.

This heat must be added to give it the form of a liquid.”

\[ H = s \cdot w \cdot \Delta T \]

- **Just below freezing point**
  - Ice cubes
- **Just above freezing point**
  - Water

- “Sensible heat” provided
- Rise in temperature
- “Capacity for the matter of heat”
- Weight of tested substance
A new “type” of heat

“When ice or any other solid substance is melted, it receives a much larger quantity of heat than what is perceptible by a thermometer.

This heat must be added to give it the form of a liquid.”

This “new” type of heat is not “sensible heat”
Black called it “latent heat”


\[ H = s \cdot w \cdot \Delta T \]

“Capacity for the matter of heat”

“Sensible heat” provided

Rise in temperature

Weight of tested substance

Just below freezing point
Ice cubes

Just above freezing point
Water
“Another peculiarity attends the boiling of liquids.”

“Just below boiling point
Water

Just above boiling point
Steam

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

Bodies react differently to the same amount of “sensible” heat

\[ H = s \cdot w \cdot \Delta T \]

“Capacity for the matter of heat”
Bodies react differently to the same amount of “sensible” heat

\[ H = s \cdot w \cdot \Delta T \]

“Capacity for the matter of heat”

Sometimes, heat is not sensible, but “latent”

“Its effect consists, not in warming the bodies, but in converting the ice into water, or the water into steam.”
We have already come a long way!
We have already come a long way!
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We have already come a long way!
What is heat?
HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD
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