Lecture 8

Fundamentals of Physics

Phys 120, Fall 2015

Entropy - the second law of Thermodynamics

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Overview

- Heat flows to equalize temperatures! The Second Law of Thermodynamics.
- Heat engines
- Energy quality - the arrow of time / entropy
- The automobile - energy consuption
- Transportation efficiency
- The steam-electric power plant
- Exponential growth

The History of heat

Early Greek Philosophers like Heraclitus (535BC–475BC) assumed that heat is one of the three elements that everything is made off: earth, water, and fire. Fire was considered closely related to heat. Heraclitus developed the idea of a flowing and ever changing world: "You never step into the same river twice."

Lucretius c.99c.55 BC

Titus Lucretius Carus) was a Roman poet.
Wrote *De Rerum Natura* (On the Nature of Things)

Why? Because I teach great truth, and set out to unknot
The mind from the tight strictures of religion, and I write
Of so darkling a subject in a poetry so bright,
Nor is my method to no purpose — doctors do as much;
Consider a physician with a child who will not sip
A disgusting dose of wormwood: first, he coats the goblet's lip
All round with honey's sweet blond stickiness, that way to lure
Gullible youth to taste it, and to drain the bitter cure,
The child's duped but not cheated — rather, put back in the pink-
That's what I do. Since those who've never tasted of it think
This philosophy's a bitter pill to swallow, and the throng
Recoils, I wished to coat this physic in mellifluous song,
To kiss it, as it were, with the sweet honey of the Muse.

This treaty on Epicureanism is not the usual Roman way of teaching, rather it is a unique (and famous) bit of poetry/science teaching.

Lucretius on random motion of atoms*

If you should think these atoms have the power to stop and stay
At a standstill, and set new motions going in this way,
Then you have rambled far from reason and have gone astray.
Since atoms wander through a void, then they must either go
Carried along by their own weight or by a random blow
Into one another, they bounce apart after the clash
(And no surprise, since they are hard and solid, and they lack
Anything behind them to obstruct their moving back).

All bodies of matter are in motion. To understand this best,
Remember that the atoms do not have a place to rest,
And there's no bottom to the universe, since Space does not
Have limits, but is endless. . . .

*Lucretius, *The Nature of Things*, Penguin Classics, translated by A.E. Stallings

Arabic Science of heat

Al-Biruni (973 – 1048), an outstanding Persian scholar from modern day Afghanistan, is credited with describing the phenomena of getting heat from motion (through friction):

> The earth and the water form one globe, surrounded on all sides by air. Then, since much of the air is in contact with the sphere of the moon, it becomes heated in consequence of the movement and friction of the parts in contact. Thus there is produced fire, which surrounds the air, less in amount in the proximity of the poles owing to the slackening of the movement there.

History of heat

Sir Francis Bacon (1561 – 1626) stated

> *Heat itself, its essence and quiddity is motion and nothing else.*

This idea was, as already hinted at by Lucretius, was developed further by Daniel Bernoulli (1700–1782) who developed the kinetic theory of gases where he assumes a particular nature of matter, and explains that temperature is just the kinetic energy of the particles — and that pressure is just the effect of the particles collision with the wall.

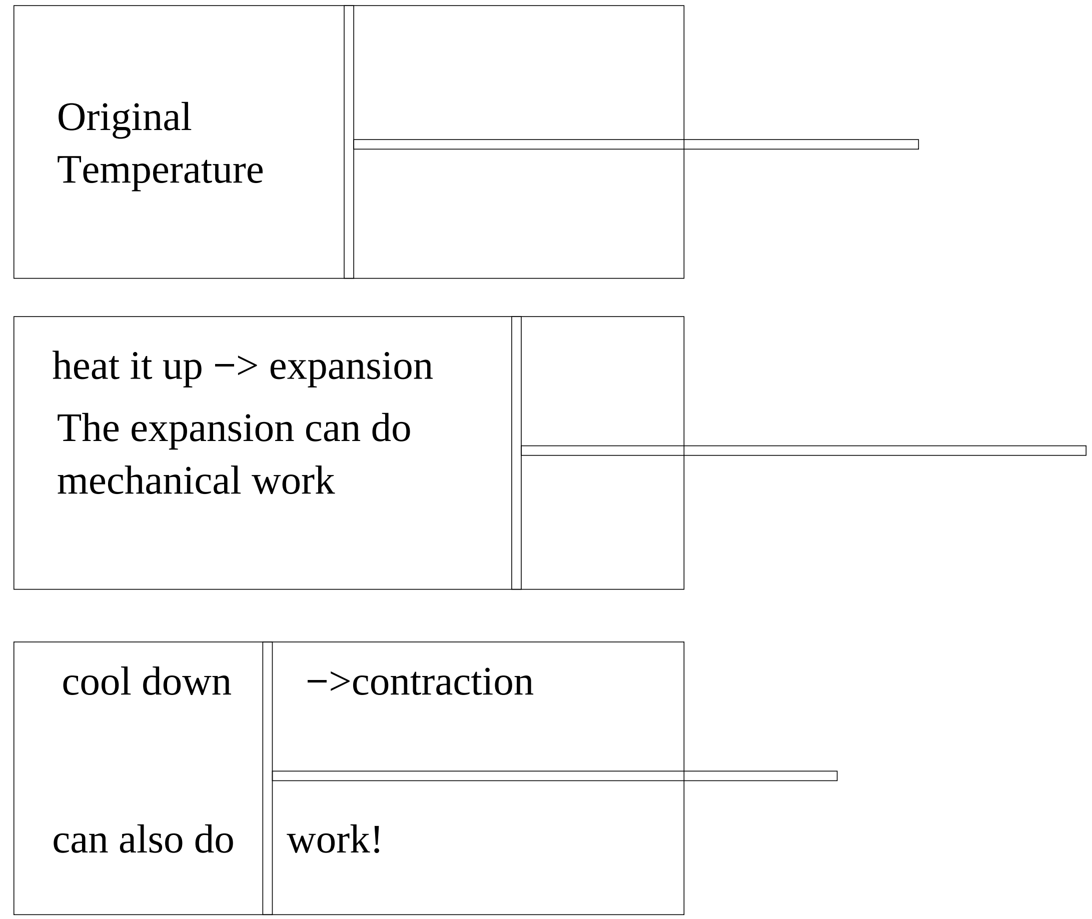
Heat engines

It is easy to construct a simple heat engine. All you need to know is that gases expand as you heat them and contract as you cool them.

To build a useful machine you need to make it work cyclically.

The basic concept then is that you add a certain amount of heat to your system and then you have to remove heat from your system again.

But how much work can be done using such a machine?



What is heat?

In Physics heat is a quantity of energy.

James Prescott Joule (1818–1889) quantified the equivalence of mechanical work and heat by building a paddle machine that lowered a weight while stirring a fluid. He could then measure the change in temperature due to the energy added to the fluid. This he considered a transformation of mechanical energy to heat energy. (Note that it is easy to transform all the mechanical energy to heat energy).

Joule postulated that the total energy of a system is conserved (around the same time as Helmholtz).

Joule's energy conservation: 1847 lecture

You see, therefore, that living force (kinetic energy) may be converted into heat, and that heat may be converted into living force, or its equivalent attraction through space. All three therefore —– namely, heat, living force, and attraction through space (to which I might also add light, were it consistent with the scope of the present lecture) – are mutually convertible into one another. In these conversions nothing is lost . . . . We can therefore express the equivalence in definite language applicable at all times and under all circumstances. Thus the attraction of 817 lb. through the space of one foot is equivalent to, and convertible into, the living force possessed by a body of the same weight of 817 lb. when moving with the velocity of eight feet per second, and this living force is again convertible into the quantity of heat which can increase the temperature of one pound of water by one degree Fahrenheit.

But there is a problem!

While it is easy to transform mechanical energy into heat, the same is not true for the reverse.

This was noticed much earlier by Sadi Carnot (1796–1832) who wrote an ingenious paper on the efficiency of heat engines "Réflexions sur la puissance motrice due feu (Reflections on the Motive power of Fire)" in 1824.

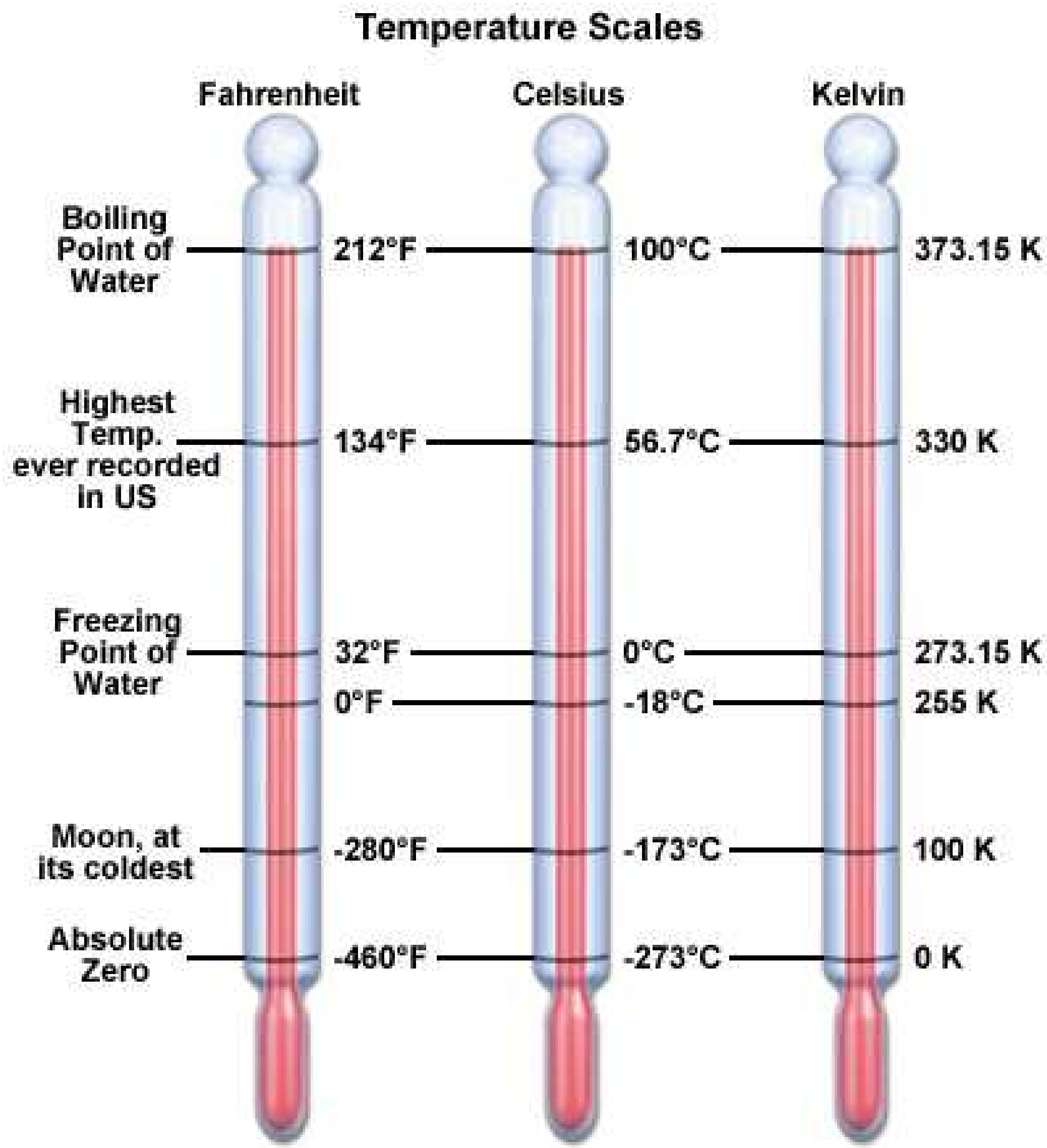
The consequence of this paper was the discovery of the second law of thermodynamics. In its own way it is a paper as important as Einstein's discover of relativity and the discovery of Quantum Mechanics.

The second law of thermodynamics

> **The second law of thermodynamics, stated as the law of heating**
> Thermal energy flows spontaneously from higher to lower temperature, but now from lower to higher temperature.

You might think that this is a trivial observation — but we will see that it has far reaching consequences. This also means that you cannot build a machine that does nothing else but transfer heat from a cold object to a warmer object. **The first law** states that the total energy is conserved.

Temperature scales



Concept check

Suppose you put a cold ice-cube in your hand and you observed that the ice-cube cooled down further while your hand warmed up. This would violate

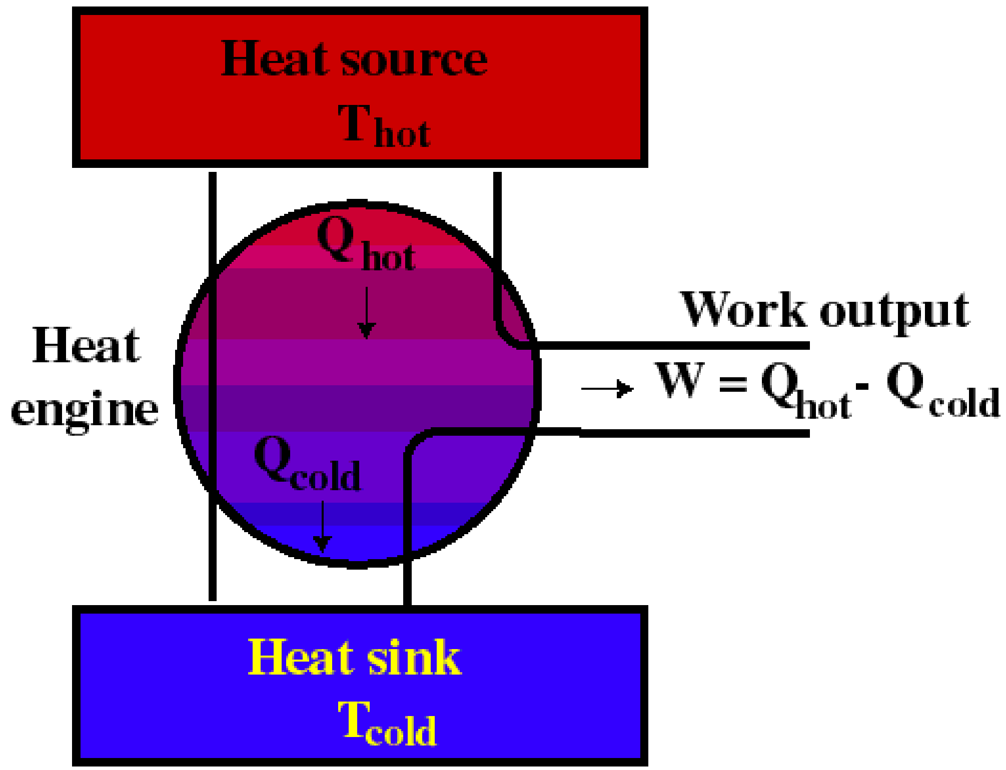
a) conservation of energy

b) the second law of thermodynamics

c) neither of the above, but other physical laws

d) no known physical laws

Heat engines: using thermal energy to do work



How much heat can you transform?

It can't be all, otherwise I could use that work to heat up a warmer object violating the second law!

$$\text{energy efficiency} = \frac{\text{work output}}{\text{thermal energy input}}$$

> **The second law of thermodynamics, stated as the law of heat engines**
> Any cyclic process that uses thermal energy to do work must also have a thermal energy exhaust. In other words, heat engines are always less than 100% efficient at using thermal energy to do work.

Theoretical limit (just a footnote): Eff $= (T_{in} - T_{out})/T_{in}$, where temperature is measured in Kelvin.

Efficiencies of heat engines

Engine type	$T_{in}(^\circ C)$	$T_{out}(^\circ C)$	Max. eff.	Act. eff.
Gasoline auto/truck	700	340	37	20
Diesel auto/truck	900	340	48	30
Steam locomotive	180	100	20	10
Fossil fuel plant	550	40	60	40
Nuclear plant	350	40	50	35
Solar plant	225	40	40	30
Ocean-thermal plant	25	5	7	???

As you see you get the best efficiency if you burn hot and exhaust cold.

Concept check

A typical large coal-fired electric-generating plant burns about 1 tonne (1000 kg) of coal every 10 seconds. How much of the tonne goes into producing electric energy?
(a) 600 kg; (b) 60 kg; (c) 500 kg; (d) 400 kg

Energy Quality: things run down

Look at a swinging pendulum. It slows down. What happens with the energy? Can it be recovered?

First law: Energy is conserved
Second law: Energy is degraded to heat

Entropy

The measure of microscopic disorder is called **entropy***.

> **The second law of thermodynamics, stated as the law of entropy**
> The total entropy (or microscopic disorganization) of all the participants in any physical process cannot decrease during that process, but it can increase.

This is the underlying reason for the arrow of time (i.e. how the future is different from the past).

*We won't give an exact mathematical definition in this course

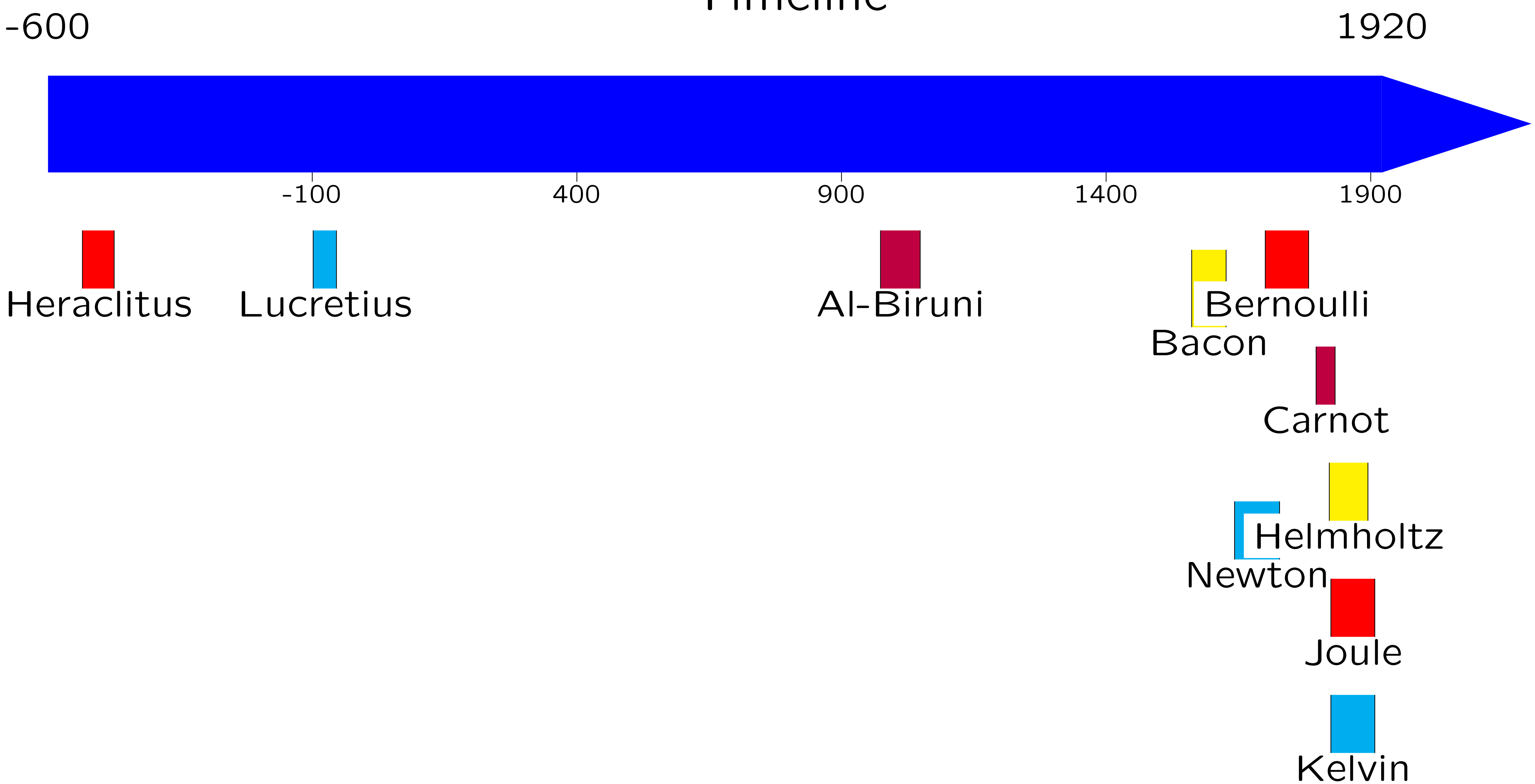
Arrow of time

All microscopic theories (like Newton's laws) are *timereversible*, i.e. if you turn the velocities of all parts of the system around, it will go back to where it came from. Therefore playing a movie forward and playing it backwards are equally correct Physics.

But we know that is now true: If I show you a movie of an egg that drops and breaks, and then show it backwards, you know immediately which version is forward and which version is backward. But how do you know?

This is because of the law of entropy: in one direction entropy increases (when the egg breaks) and that is the only way consistent with the second law of thermodynamics.

Timeline


-600
1920
-100
400
900
1400
1900
Heraclitus
Lucretius
Al-Biruni
Bernoulli
Bacon
Carnot
Helmholtz
Newton
Joule
Kelvin

Summary

- History of Heat
- Heat as motion
- Heat engines
- Entropy
- The arrow of time