Energy

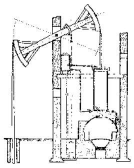
A new abstract building block for mechanism

What makes things work?

- The Industrial Revolution is all about letting machines do work that people or animals did before. How does one understand what makes them work?

Case in point: A steam engine

- A steam engine works by



Burning coal to boil water to make steam to fill a chamber and push against the atmosphere. Then the steam condenses, leaving a vacuum; the pressure of the atmosphere pushes down a piston, which moves a rod which may turn a crank which rotates a wheel which pulls a belt which makes some other machine move and do the desired task.

- Is there a common thread here?

The Heat Engine

- The mechanical part of doing work – push, pull, lift, etc. – was understandable in Newtonian terms:
  - Inertia, momentum and forces.
- The difficult part was understanding the role of heat, which is the essential difference between Industrial Revolution and Medieval machines.

Heat: matter or motion?

- Chemists still found it convenient sometimes to think of heat as a substance, *caloric*, that entered into chemical reactions.
- Heat could be added and subtracted in exact amounts in a chemical reaction, just like any other matter.

Heat makes motion

- The example of the working of the steam engine makes it clear that heat (e.g., burning coal), is the direct cause of motion that does work.
- Can the process be reversed?
  - Can mechanical motion make heat?

Motion makes heat

- Count Rumford’s machine to bore out cannon shafts produced enormous amounts of heat – from the motion of the boring machine.
  - Can this conversion of heat to motion and motion to heat be measured and then expressed precisely?

James Joule

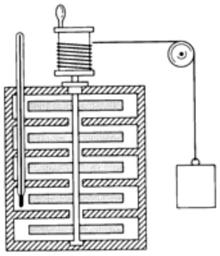
- 1818-1889
- Wealthy amateur scientist. Former student of John Dalton.
- Joule noted that motors of all sorts with moving parts tended to get hot.
- He undertook to find the exact relationship between motion and heat.

Using motion to make heat

- Joule needed a device that would use a precisely measurable amount of mechanical work to cause motion, and a precise way to measure change in temperature of a fixed amount of matter.
- For work, he could use the effort of the force of gravity to move a specified weight over a fixed distance.

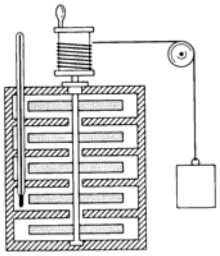
Joule’s churn

- He fixed the weight to a cord looped over a pulley and then wound around a spool.
- The falling weight would turn paddles attached to the spool.



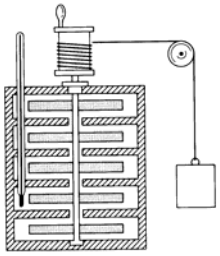
Joule’s churn, 2

- The paddles were arranged inside a tightly fitting canister filled with water, with vanes protruding between the paddles that allowed water to be stirred with difficulty.



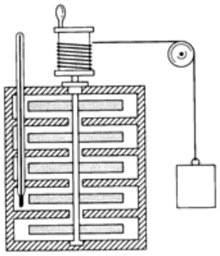
Joule’s churn, 3

- Into the canister he placed a thermometer that was capable of very accurate measurement of small changes in the temperature of the water.



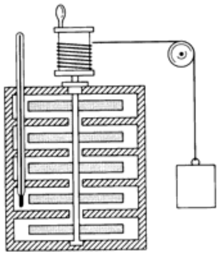
Joule’s churn, 4

- With the weight up near the pulley and the cord wound around the spool, he let gravity pull it down until it rested on the table—a fixed and measured distance.



Joule’s churn, 5

- The mass of the weight X the distance travelled measured the mechanical work done.
- The change in temperature X the weight of the water measured the change in heat (in calories).



The mechanical equivalent of heat

- The resulting measurement gave Joule a fixed relationship between mechanical work done and heat produced.
- This he called the *mechanical equivalent of heat*.

The caloric theory of heat discarded at last.

- Joule’s experiment provided more precise and unambiguous evidence than Rumford’s observation that heat can be produced by mechanical effort.
- This was the final proof that heat was *not* a material, as was implied by the caloric theory.

Modus tollens at work

- This is a typical example of the use of *modus tollens* to eliminate false theories.
- Hypothesis: Heat is a form of matter.
- Test implication: If heat is matter, then it cannot be produced by a process that does not alter other matter (i.e. a chemical process).
- Joule’s churn produced heat, therefore the test is false.
- Modus tollens: The hypothesis is therefore false.

A hidden assumption

- The power of *modus tollens* to eliminate the hypothesis of heat as matter depended on another theoretical premise, that matter is neither created nor destroyed in any isolated exchange, only transformed in different ways in, say, chemical reactions.
- This is the principle called *conservation of matter* – a fundamental assumption of chemistry since Lavoisier.

Conservation laws

- Much of science is a search for *invariance* – quantities or relationships that do not change, and which can form the bases of scientific theories.
- Major steps in science occur when statements about what does not change – conservation laws – are proposed or discarded.

Existing implicit conservation laws

- The conservation of matter
  - Assumed by almost all scientific theories in antiquity and the Renaissance. Implied by Newton's theories and explicitly adopted by Lavoisier's chemical theory.
- The conservation of momentum (mv)
  - Essential to Newton's billiard ball characterization of the universe.
- The conservation of *vis viva* (mv^2)
  - In the rival theory to Newton's by Gottfried Leibniz, *vis viva* was assumed to be conserved.

Where is the invariance in heat if it can be produced by motion?

- By showing that heat was not a form of matter, but it could be produced by matter (chemical reaction, e.g. burning), and it could do mechanical work, a hole was left in conservation principles.
  - Motion was clearly not conserved.
    - What, if anything, was?

Energy

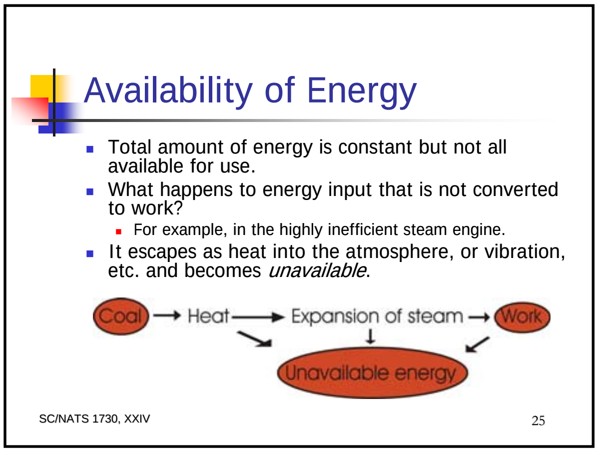
- Julius Mayer, James Joule, and others around the same time proposed that heat, momentum, forces, etc., were all part of a greater whole:
  - *ENERGY*
  - A totally new concept. An abstract entity that describes what all of the above have in common and transcends them.
    - A Platonic form?

The conservation of energy

- And with the new concept, a new principle:
  - *The Total Amount of Energy in any closed system is Constant.*
- This is the principle of **conservation of energy.**
  - A new invariance for science. Now matter and energy are the fundamental unchanging entities, not matter and motion.

Thermodynamics

- With the new concept came a whole new branch of physics, the study of the transformation of energy into different forms.
- The new discipline was called *Thermodynamics.*
- The conservation of energy is its first law.

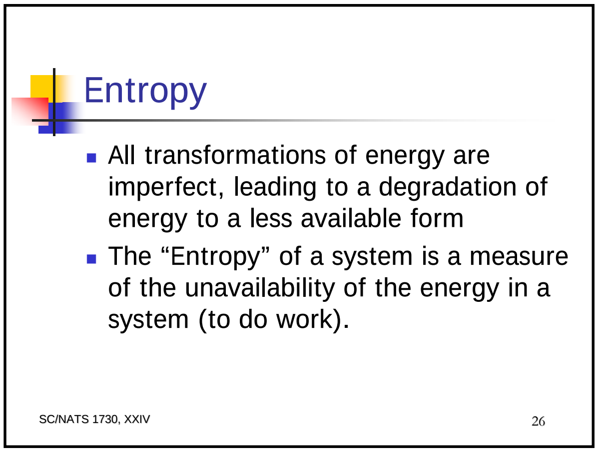


Availability of Energy

- Total amount of energy is constant but not all available for use.
- What happens to energy input that is not converted to work?
  - For example, in the highly inefficient steam engine.
- It escapes as heat into the atmosphere, or vibration, etc. and becomes *unavailable*.

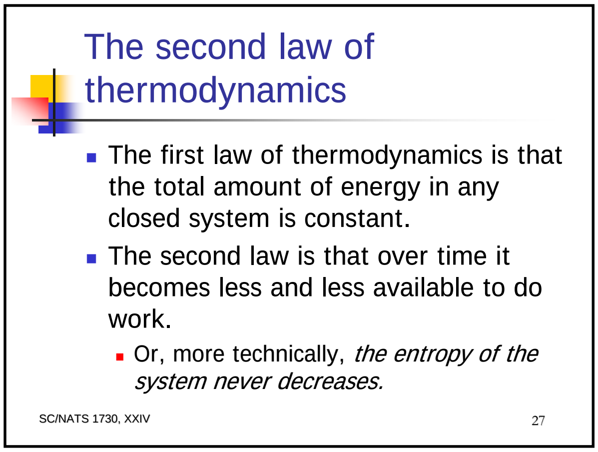
Coal → Heat → Expansion of steam → Work

Unavailable energy



Entropy

- All transformations of energy are imperfect, leading to a degradation of energy to a less available form
- The “Entropy” of a system is a measure of the unavailability of the energy in a system (to do work).



The second law of thermodynamics

- The first law of thermodynamics is that the total amount of energy in any closed system is constant.
- The second law is that over time it becomes less and less available to do work.
  - Or, more technically, *the entropy of the system never decreases.*

Implied irreversibility

- If any process of energy exchange increases entropy, it is therefore not reversible, since the entropy cannot revert to an earlier state.
  - Consequence: A perpetual motion machine cannot work.

Temperature versus Heat

- Heat is one of the forms of energy.
  - It can be transferred from one body to another.
  - It can be measured.
    - The standard unit of measure of heat is the amount of energy required to raise a standard volume of water one degree Celsius.
- But this is not the same as temperature.
  - It takes more or less heat to raise a standard volume of other materials one degree.

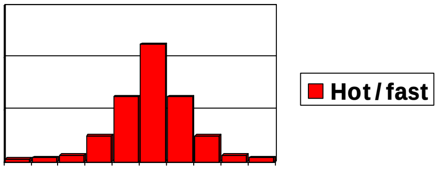
What, then, is temperature?

- If heat is thought of as a form of motion, e.g. molecular vibration, then the *temperature* of that body is the average level of that vibration.
- Air temperature in a room, for example, represents the average speed of the moving particles of air.

The viewpoint of statistical mechanics

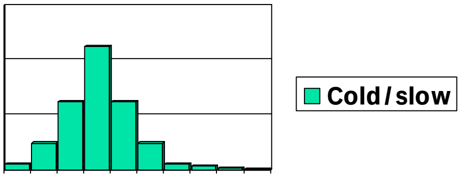
- Statistical mechanics interprets the principles of thermodynamics as the statistical measures of aggregates of individual moving particles.
  - E.g. randomly flying air molecules, or vibrating molecules in a solid or liquid.

Temperature as the average of the molecular speeds



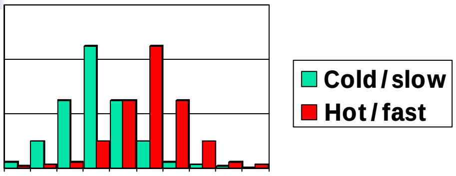
- Imagine a hot room, meaning that the average speed of the randomly moving molecules in the room is high, though some will be very fast and some will be slow.
- If one were to plot the speeds of the molecules on a graph, they would cluster around a mid point, which would represent the temperature of the room.

Temperature as the average of the molecular speeds, 2



- In a cold room, the speeds of the molecules would also vary from slow to fast, but a greater number of them would be slower, the average speed would be less, and the resulting temperature would be lower.

Temperature as the average of the molecular speeds, 3



- If the two rooms were adjacent, and a door left open between them, the air molecules from each room would mix together and their average speed would be somewhere between that of the two rooms separately. Likewise, the temperature of the joined rooms would be something between that of each room before the door was opened.

A new kind of physical law

- The laws of thermodynamics are quite different from those of classical, Newtonian physics.
- Newton’s laws were applicable to every single particle in the universe in the same way.
- The laws of thermodynamics are about statistical measures: averages, tendencies.
- If science is about true and complete knowledge of the physical world, how can its laws be merely statistically true?

James Clerk Maxwell

  - 1831-1879
- Scottish mathematical physicist. One of the great minds of science in the 19th century.
- Maxwell objected to this change in the nature of physical laws that was represented by thermodynamics.

The problem with the 2nd law

- The 2nd law of thermodynamics implies that *some* energy becomes unavailable after every interaction, but which “energy” is not specified.
- This seems to imply a law within a mechanist system that does not have a mechanism specified.

The case of the hot and cold rooms again

- In the case of the two chambers, one hot and the other cold, when the door was closed between them, the temperature difference itself represented available energy.
  - For example, if the connecting wall was movable (like a piston) the hot air would press on it more than the cold air and would cause it to move.
    - This is how the (high pressure) steam engines work.

The case of the hot and cold rooms again, 2

- In the actual case, when the door was opened, the gases mixed and both rooms moved to a common temperature. The energy that could have moved that wall became unavailable.
- According to the 2nd law, the procedure would not be reversible.

Maxwell's Demon

- Maxwell questioned the universality of this edict by proposing the following paradoxical thought experiment:
  - Suppose, he said, that you start with two adjacent rooms at the same temperature, with the connecting door open.
  - Air will freely move back and forth. Some air molecules will be faster (hotter) than others, and others will be slower, but they will randomly migrate back and forth from room to room.

Maxwell's Demon, 2

- Now, says Maxwell, suppose you position a "demon" at the door, whose eyesight is capable of distinguishing fast from slow molecules. He is also capable of opening and closing the door quickly in order to allow, or prevent molecules from passing through it.

Maxwell's Demon, 3

- When fast moving molecules appear headed toward the door from the left room, the demon swings the door open.
- He also lets slow molecules from the right room move to the left room.
- Otherwise, he keeps the door shut.

Maxwell's Demon, 4

- Over time, the fast moving molecules will be a greater proportion of those in the room on the right and the slow moving molecules will predominate on the room on the left.
- He will have reversed the direction of the energy exchange, made a temperature difference, and *lowered* the entropy of the system—all held to be impossible by the 2nd law.

Absolute Zero

- Temperature measures molecular motion.
- It therefore has a theoretical lowest limit where all motion stops.
- The lowest possible temperature is that theoretical limit:
  - Found by William Thomson (Lord Kelvin) to be –273°Celsius
  - The *Kelvin* scale of temperature starts at this point (as zero) and has degrees of the same size as Celsius degrees.

The Third Law of Thermodynamics

- Absolute zero represents a temperature at which there is no molecular motion at all.
- Any process to slow down that motion (make things colder) has to absorb some of it, causing some motion.
- Consequently, zero motion—absolute zero temperature—cannot ever be reached.
  - This is the *Third Law of Thermodynamics.*

The Universe and thermodynamics

- The laws of thermodynamics apply to all closed systems.
  - The universe itself is a closed system.
  - Therefore, the laws of thermodynamics apply.
- Energy is unevenly distributed in the universe.
  - E.g. stars versus empty space.
- Entropy is constantly increasing, making the energy more evenly distributed.
  - Stars constantly radiate their energy and eventually die.

The Heat Death of the Universe

- Eventually all the universe will be the same temperature.
- 19th century physicists calculated that this ultimate maximum entropy state would bring the universe altogether to a temperature of something less than 10 degrees Kelvin. (I.e., lower than -263° C)
- This they called the *"Heat Death of the Universe."*