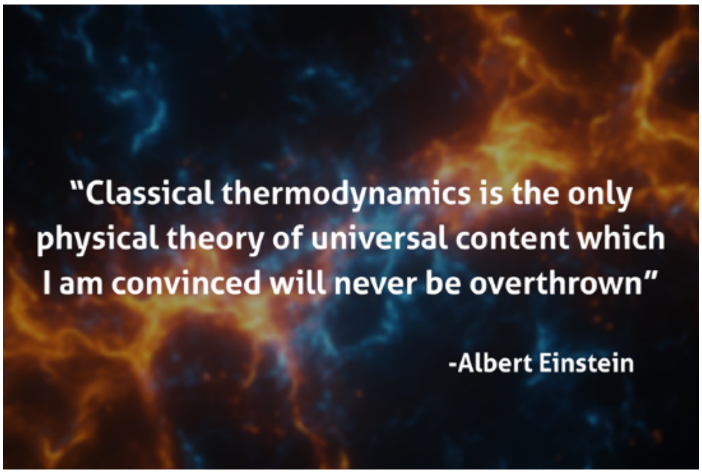
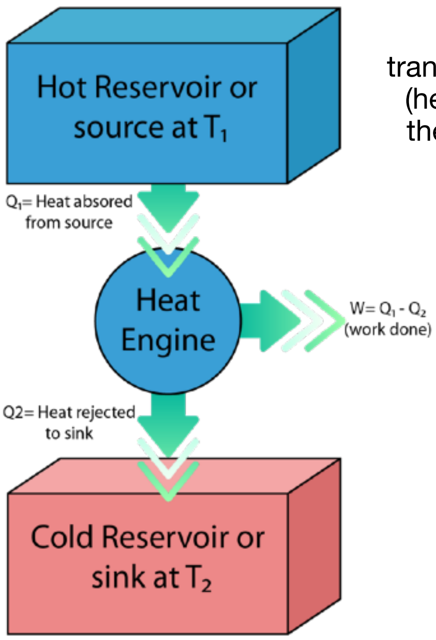
How Laws of Thermodynamics Shape the World and Guide the Complexity of Life.



On the day of February 21, 1804 the world's first ever steam engine locomotive, designed by Richard Trevithick, ran 9 miles from the ironworks at Penydarren to the Merthyr–Cardiff Canal, South Wales. Tradition has it that the owners of local ironworks had a wager of 500 guineas placed as to whether or not the engine could haul ten tons of iron, 5 wagons, and 70 men. The journey took 4 hours and 5 minutes, with an average speed of nearly 5 mph.

Steam engines have become the symbol and the "engine" of the Victorian Industrial Revolution, but its origins can be traced as far back as the 1st century AD in Roman Egypt. Since then, it had a long history of evolution and modifications that greatly improved the efficiency of the process, especially the introduction of a separate condenser by James Watt in 1765. Despite that, by the time young Nicolas Sadi Carnot expressed interest in mechanical systems, the best steam engines converted only a meagre 3% of useful thermal energy into mechanical work.

It took 3 years for the young scientist to research and study the process that culminated in his consequential paper "Reflections on the Motive Power of Fire" in 1824. This seminal work was focused on an ideal heat engine with no friction and no loss to the environment.



Heat engines operate based on the principle that energy can be transformed from one form to another. In a heat engine, thermal energy (heat) is converted into mechanical energy (work) through a series of thermodynamic processes, typically involving heat absorption, work extraction, and heat rejection.

The useful work of a heat engine can be expressed as the heat absorbed by the hot reservoir (Qh) minus the heat rejected to the cold reservoir (Qc).

The efficiency of this process can be expressed as
E = (Qh -Qc) / Qh

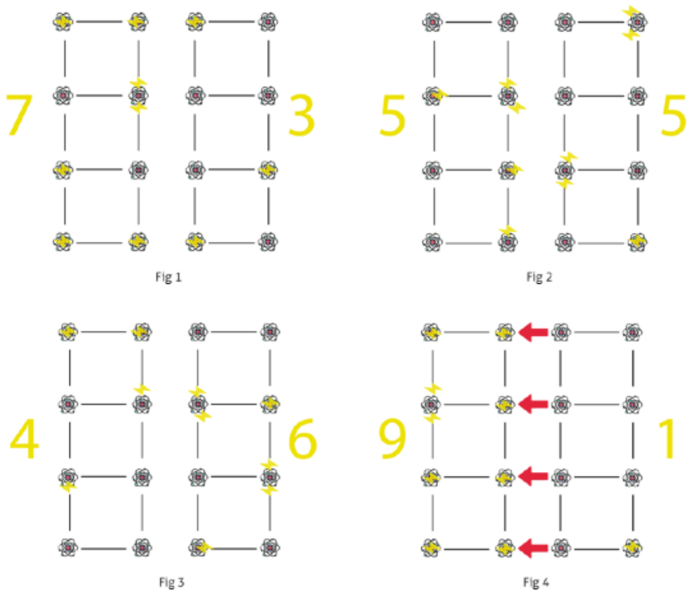
Hence, the difference in energy between the sources affects the efficiency of the ideal heat engine.

The works of Carnot intrigued Lord Kelvin and gave him an idea to form the basis for the absolute temperature scale. The efficiency of an ideal steam engine will approach 100% if the temperature of the cold source was so low that the gas particles will stop moving, then it will take no work to compress it and no heat will be lost. This is the idea of "Absolute Zero" (-273C), which makes an ideal heat engine 100% efficient.

He formulated that the efficiency of the process can also be expressed as $E = (Th-Tc)/Th$ or $E= 1 - Tc/Th$, which led to a conclusion that 100% efficiency of an **ideal engine** can be achieved by having either infinitely high temperature on the hot side or an absolute zero on the cold side, and neither is possible.

In the actual heat engine process, the energy is lost to the friction and the heat is dissipated to the environment, which is, in other words, lost**.** The total amount of energy does not change, but it becomes less usable.

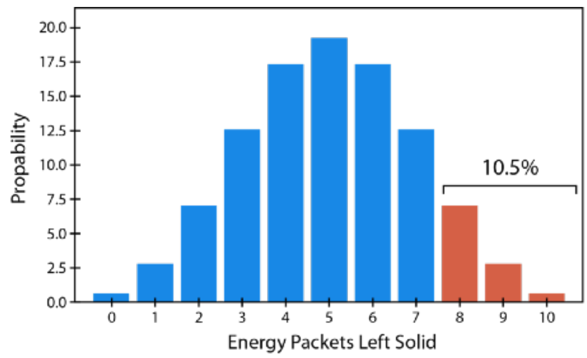
Enter the concept of **Entropy** (Greek for en - inside and trope - transformation). In 1865, Rudolf Clausius formulates the first two laws of thermodynamics. Though the energy of the universe is constant (**the1st law of thermodynamics**), it spreads out over time, and the amount of usable energy in a closed system is always decreasing (**the 2nd law**), which explains many phenomena and makes perpetuum mobile unattainable. This was a counterintuitive assertion, since most of the laws of physics work the same way forward or backwards, while the concept of entropy displays an irreversible time dependency.



To explain this phenomenon, we can use hot and cold metal bars with a lattice containing 8 atoms each. The hot bar has 7 energy pockets in the original state and the cold bar has only 3 energy pockets (Fig.1).

The energy pockets are free to move around both latices creating a variety of states with different combination of energy pockets (Fig. 2-4). Each unique combination is equally potential, including the combination where there is more energy pockets on the hot bar than in its original state (Fig.4). It appears that the energy (heat) has flown from cold to hot (decreasing entropy), which seemingly violates the 2nd law. (This example is borrowed from a Veritasium video)

The insight of this contradiction came from Ludwig Boltzmann, who postulated that spontaneous decrease of energy is not impossible, but improbable. The 8-atom example is based on a micro scale, where the chance of heat flowing from cold to hot has a reasonable 10.5% chance . However, on a macro scale there are over **6E+23** (Avogadro's number) constituent particles in each mole of a substance, making the chance of heat flowing from cold to hot infinitely small.



Air-Conditioning.

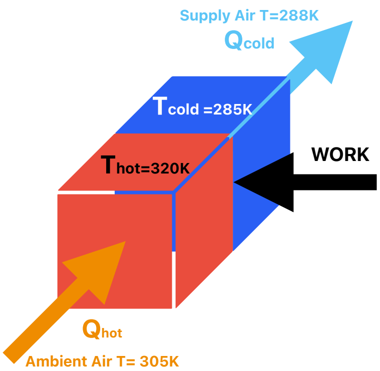
In the case of air-conditioning and refrigeration, heat is evidently moving from a cold source to a hot source. Does it violate the 2nd law? Not if the decrease of entropy in the space that is being cooled is offset by increasing entropy elsewhere by a greater amount.

AC or Refrigeration principles are based on the reverse Carnot cycle and consist of four processes: heat rejection, heat absorption, expansion, and compression. The latter requires work, a lot of work in a form of **concentrated energy** that is either stored in a fossil fuel, a result of nuclear reaction of fission by splitting atom, fusion by merging atoms, or captured from the sun where light hydrogen nuclei are combined to form a heavy element of helium. A large portion of this useful concentrated energy is dissipated (lost) to the ambient environment during power generation, transmission, and manufacturing of the equipment, increasing the entropy state.

In advanced HVAC and data center cooling systems, like those developed by Air^{2}O optimizing energy efficiency under thermodynamic constraints is critical.

When we say that the Coefficient Of Performance (COP) of an air-conditioning cycle is 3, it does not mean that for every unit of energy we exert, three units of energy are generated: it would be a violation of the 2nd law. The efficiency of an **ideal** residential air-conditioning is only

Eff = Tcold/Thot = 1- (285K/320K)* = 0.11 (11%)**
Since COP = 1/Eff, then COP of an AC = 1/0.11 = 9 ***



*Typical evaporator and condenser temperatures of a residential AC when the ambient T= 32C / 305K.

** Based on the ambient air supply.
In reality, the efficiency of residential AC units is higher since they partially recirculate the interior space/room air, resulting in lower condensing temperature and higher COP.

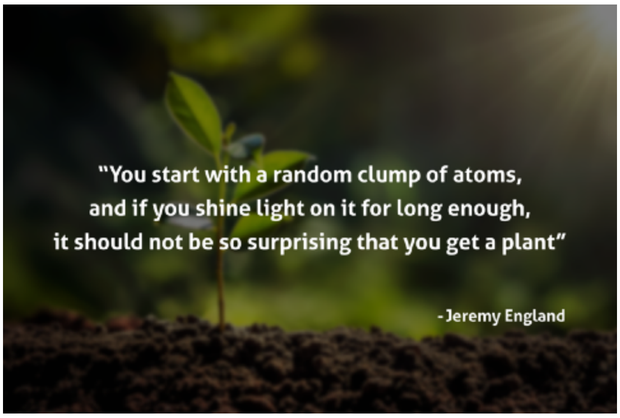
Eff = 1- 285/310 = 9%
COP = 1/0.09 = 11

The smaller the temperature difference, the greater COP

*** The COP of an ideal AC unit at these specific conditions.
COP of an actual AC unit is usually closer to 3.

At Air^{2}O we understand the fundamentals of thermodynamics, and we are well versed in the processes and the limitations related to the Thermal Management of Mission Critical Applications. Air^{2}O applies a full spectrum of energy saving and recovery technologies to improve the overall efficiency and performance of Air-Conditioning systems.

“Every Life is on Fire: How Thermodynamics Explains the Origins of Living Things”

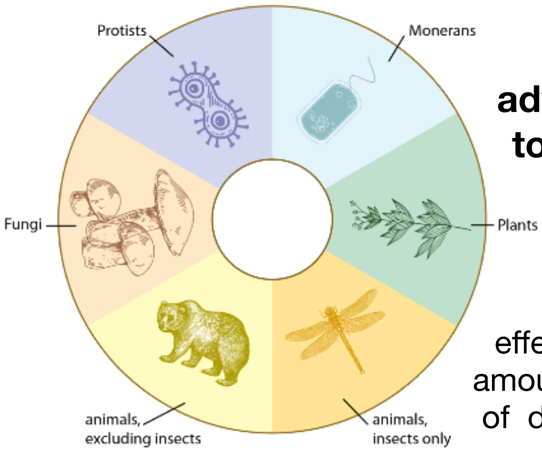


Jeremy England, a physicist at MIT, proposes that when a random clump of atoms is driven by an external concentrated energy source, such as sunlight, and surrounded by a heat sink in a form of water or atmosphere will naturally evolve to dissipate more energy.

England's theory suggests that under certain conditions, matter will acquire life-like physical properties as a consequence of the **2nd law of thermodynamics**. He argues that this does not replace Darwin's theory of evolution by natural selection but complements it.

The 2nd law postulates that the entropy of a closed system always increases, while an open system can keep its entropy low, by doing work - exerting energy - that greatly raises the entropy of its surroundings. In the influential 1944 monograph “What Is Life?” the eminent quantum physicist Erwin Schrödinger argued that this is what living things ought to do. A plant, for example, absorbs concentrated energy from the Sun, uses it to build sugars, and emit infrared light (**Stefan-Boltzmann law**), a much less useful form of energy.

The concentrated energy created by the sun fusing hydrogen into helium radiates outwards gradually increasing its entropy. Interestingly, in 5-8 billion years, the sun will exhaust the hydrogen at its core and will expand and transform into a red giant. The hydrogen on the shell will continue burning, making them look bright red. Despite that, the red giant will have less energy and greater entropy than the sun, thus the orderly internal structure of the universe will be maintained.



All living organisms are open systems with advanced heat dissipation properties that lead to increase in entropy.

The evolutionary process of self-replication is a highly effective mechanism for dissipating progressively increasing amount of energy over time. As England put it, “A great way of dissipating more is to make more copies of yourself.”

“Besides self-replication, greater structural organization is another means by which strongly driven systems ramp up their ability to dissipate energy. A plant, for example, is much better at capturing and routing solar energy through itself than an unstructured heap of carbon atoms. **Thus, England argues that under certain conditions, matter will spontaneously self-organize**. This tendency could account for the internal order of living things and of many inanimate structures as well. “Snowflakes, sand dunes and turbulent vortices all have in common that they are strikingly patterned structures that emerge in many-particle systems driven by some dissipative process,” he said. Condensation, wind and viscous drag are the relevant processes in these particular cases.” - Quanta Magazine.

Ironically, we are all contributing to the ultimate heat death of the universe, a theoretical end where the universe reaches a state of maximum entropy where nothing will move and nothing will be.

Credits and Acknowledgements.

The article is drawn from Veritasium recordings by Derek Muller, on works of Jeremy England, and from Quanta Magazine publications.