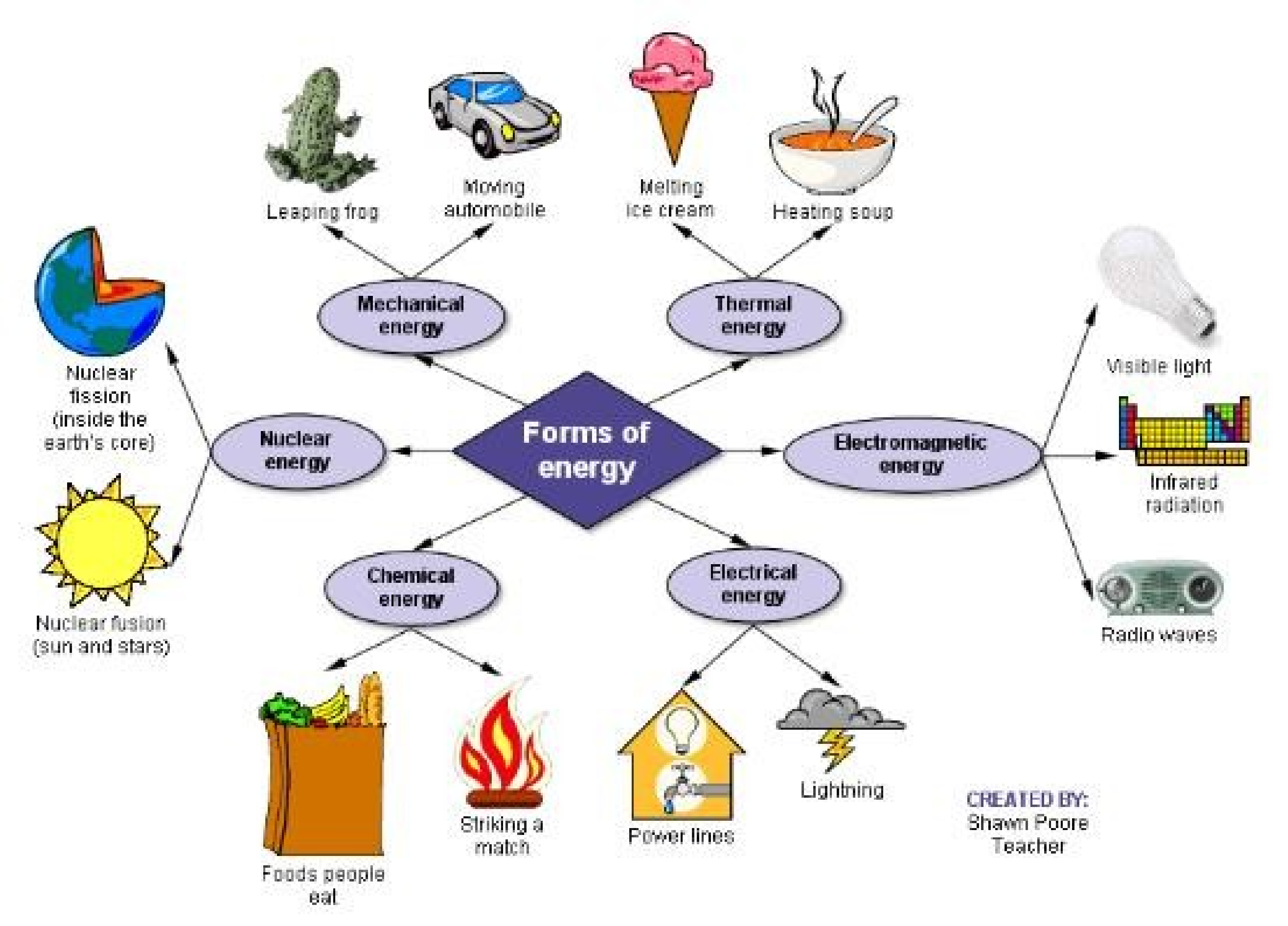
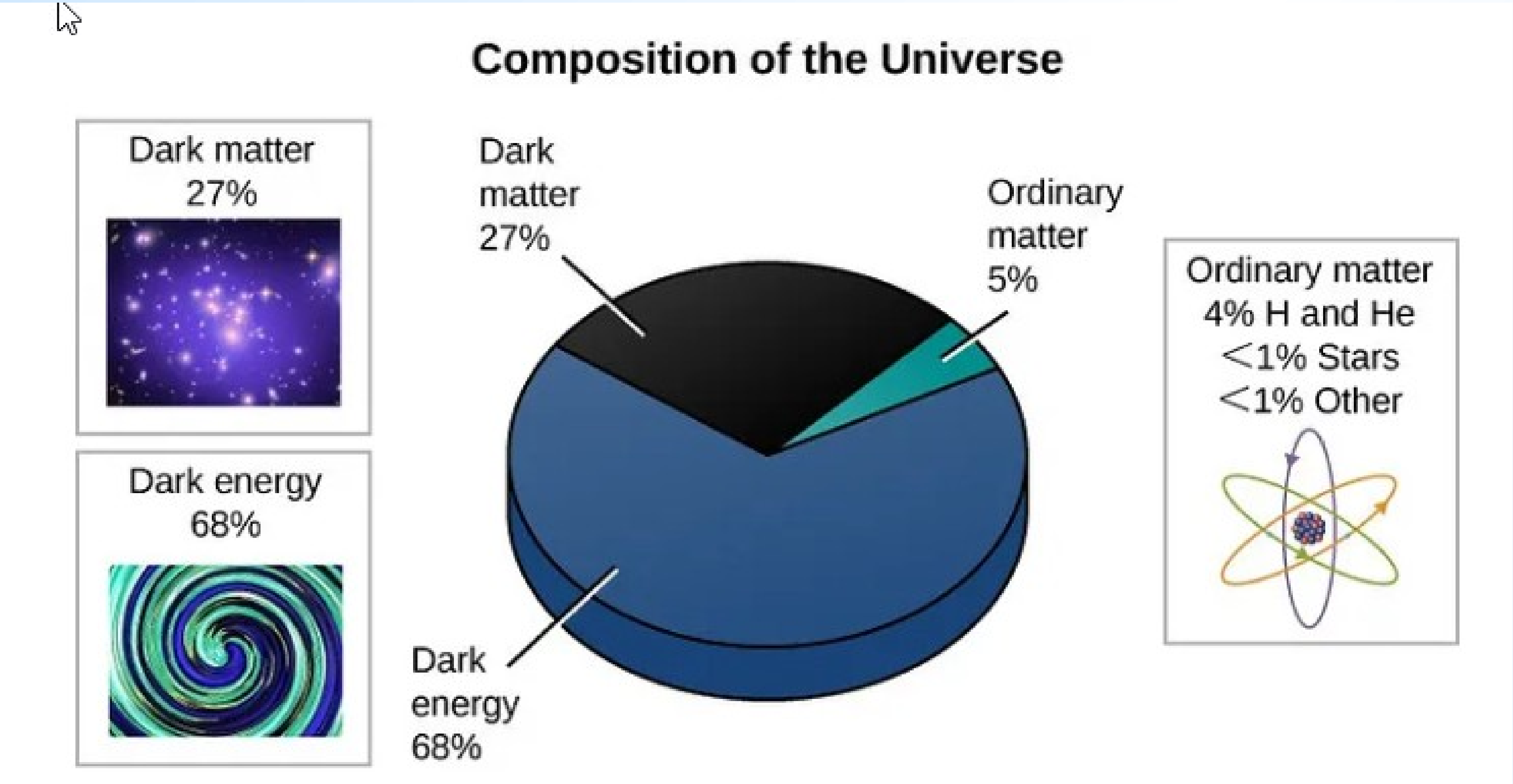
ME – 405 ENERGY CONVERSION SYSTEMS



Dark Energy

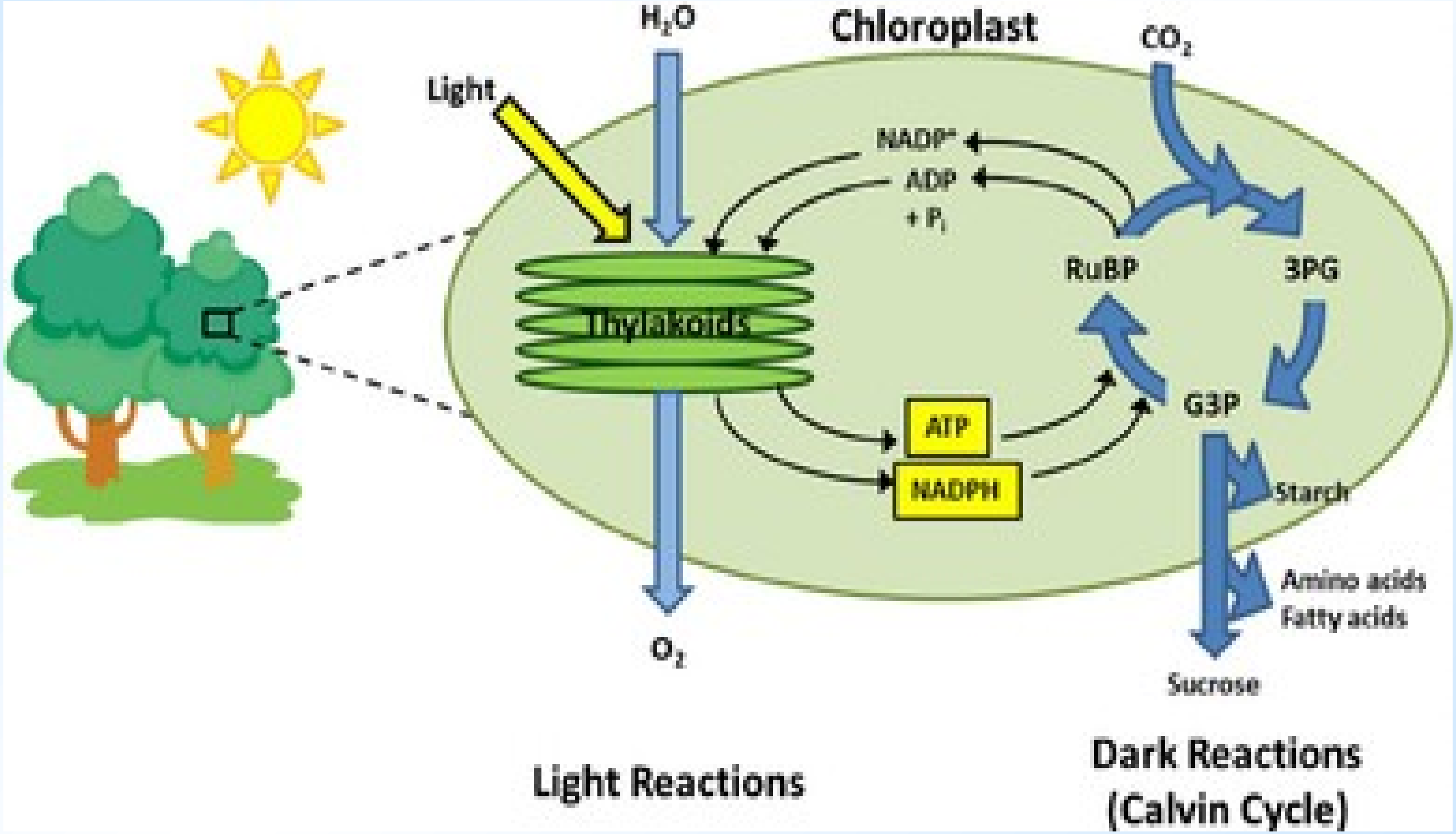
At the end of the 20th century, observations done by NASA of supernovae millions to even billions of light years away using the Hubble Space Telescope showed that the universe's rate of expansion in its earlier days was actually slower than it is today. This was a revolutionary discovery in Astronomy because it contradicts the theories of many astronomers — showing that the universe's rate of expansion has not actually been slowing down due to gravity, but it has been accelerating. Scientists knew that there was an unknown, anti-gravity force causing this, yet to be discovered: Dark Energy.

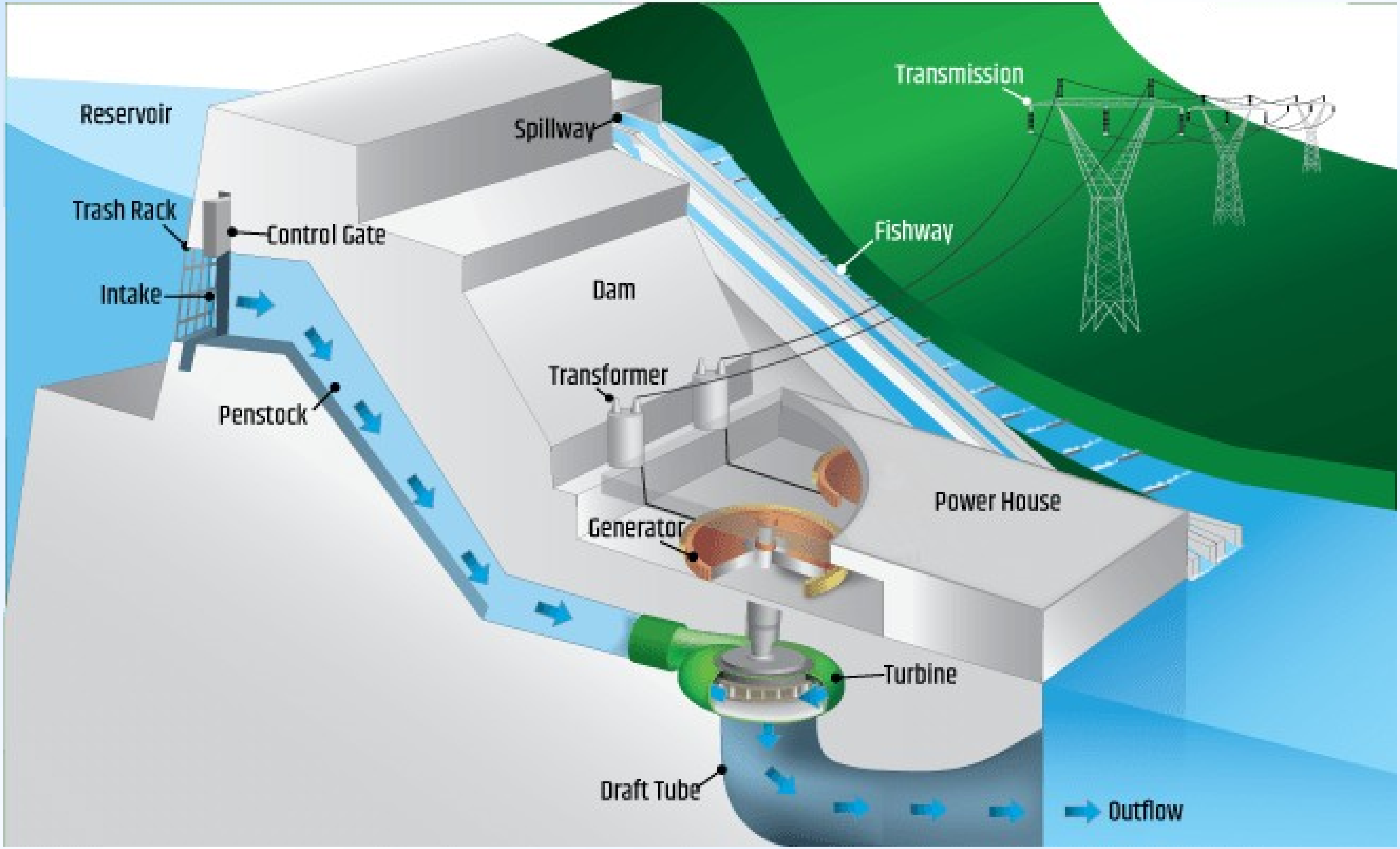
Dark energy is a perplexing form of matter or energy that is accelerating the universe's rate of expansion. Since it does not interact with any type of electromagnetic radiation, it is virtually invisible to us.



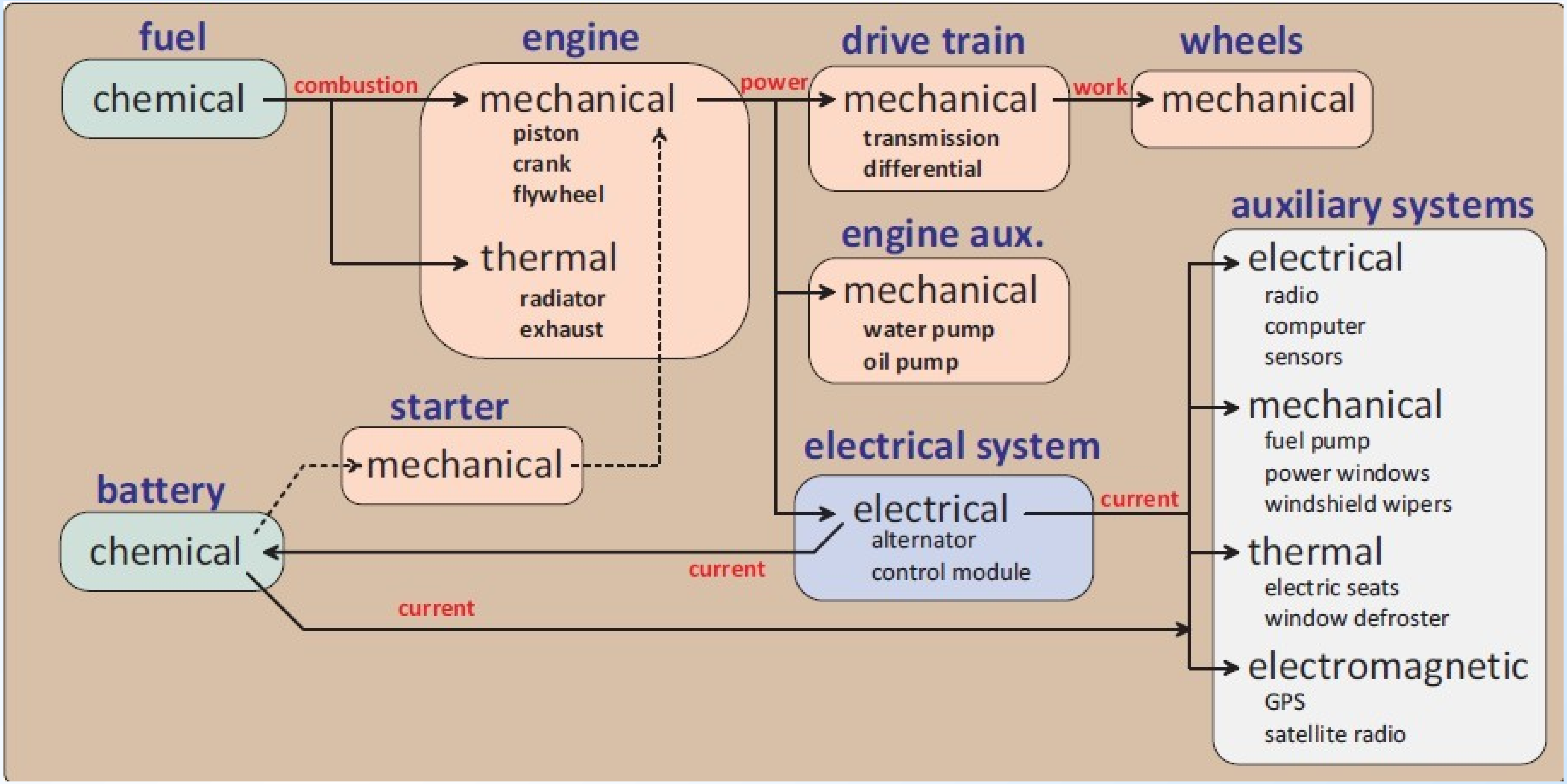
There is a serious discrepancy between old measurements of the Hubble Space Telescope and newer James Webb Space Telescope regarding how fast the expansion is. New measurements show faster rate of expansion.

The most common energy conversion (cyclic process) in the nature is phosynthesis




Reservoir
Spillway
Transmission
Trash Rack
Control Gate
Fishway
Intake
Dam
Transformer
Penstock
Power House
Generator
Turbine
Draft Tube
Outflow

Energy flow in an Internal Combustion Engine Vehicle



fuel
chemical

combustion

engine
mechanical
piston
crank
flywheel

thermal
radiator
exhaust

power

drive train
mechanical
transmission
differential

work

wheels
mechanical

engine aux.
mechanical
water pump
oil pump

starter
mechanical

battery
chemical

electrical system
electrical
alternator
control module

current

current

current

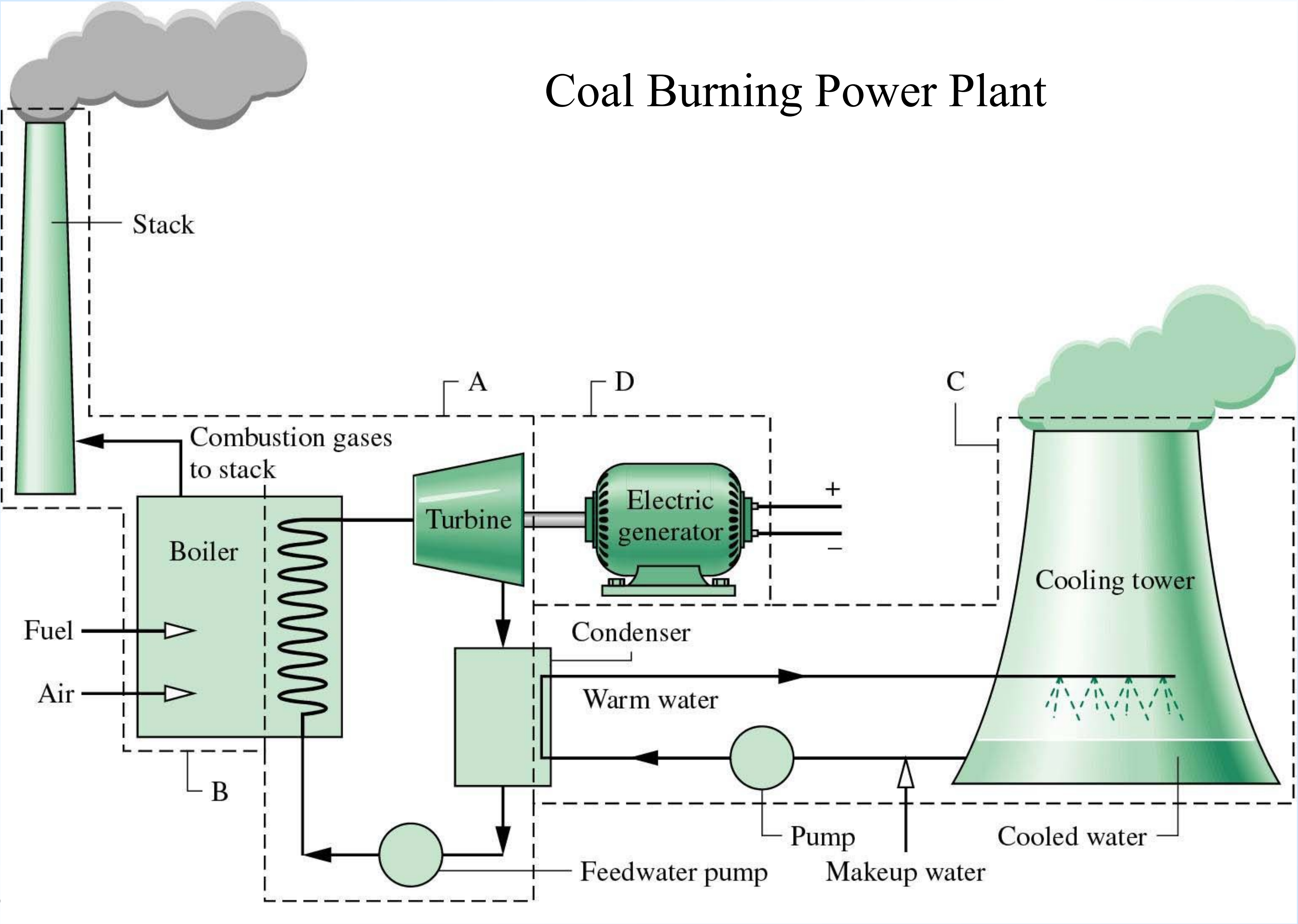
auxiliary systems
electrical
radio
computer
sensors

mechanical
fuel pump
power windows
windshield wipers

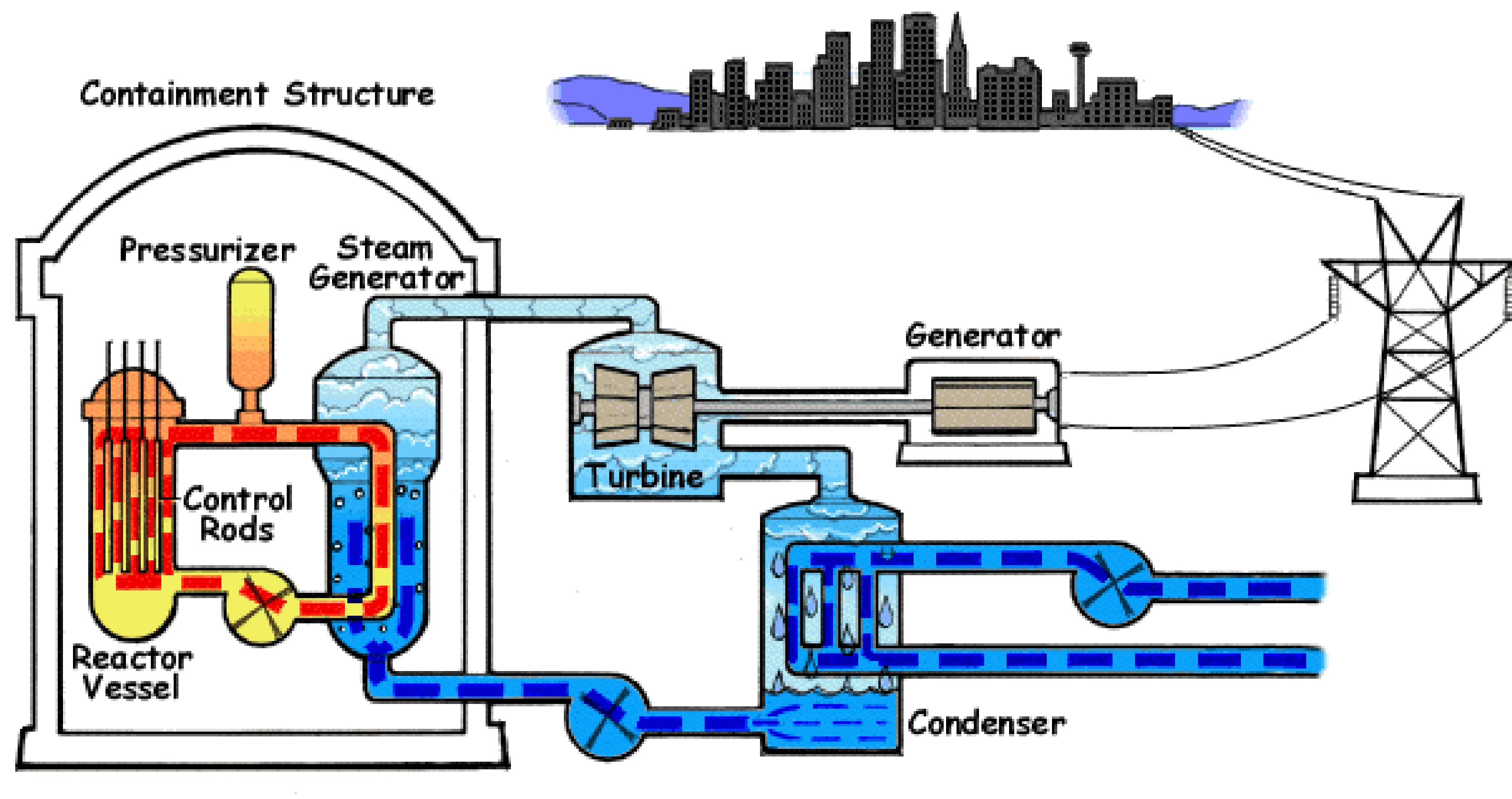
thermal
electric seats
window defroster

electromagnetic
GPS
satellite radio

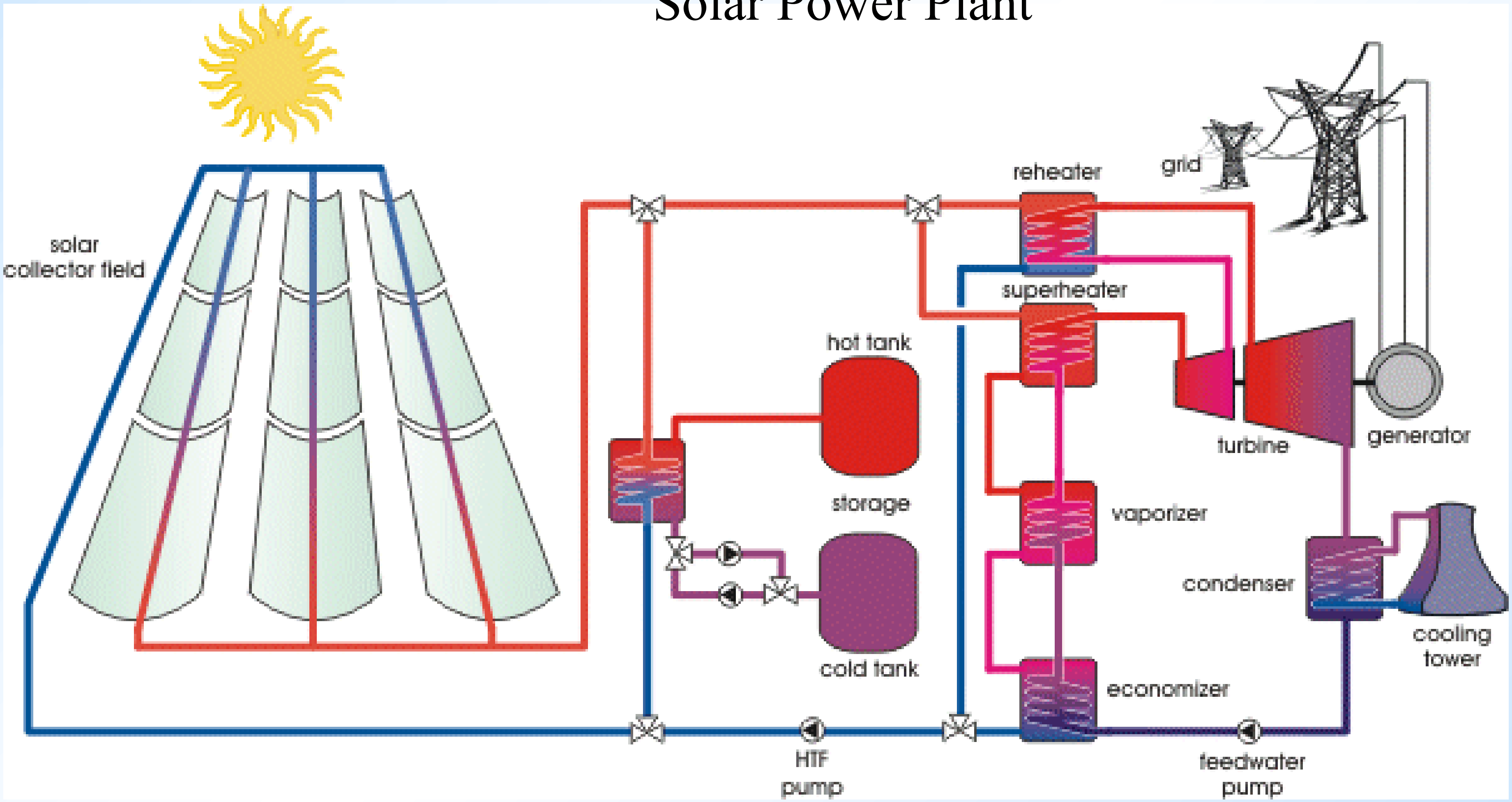
Coal Burning Power Plant



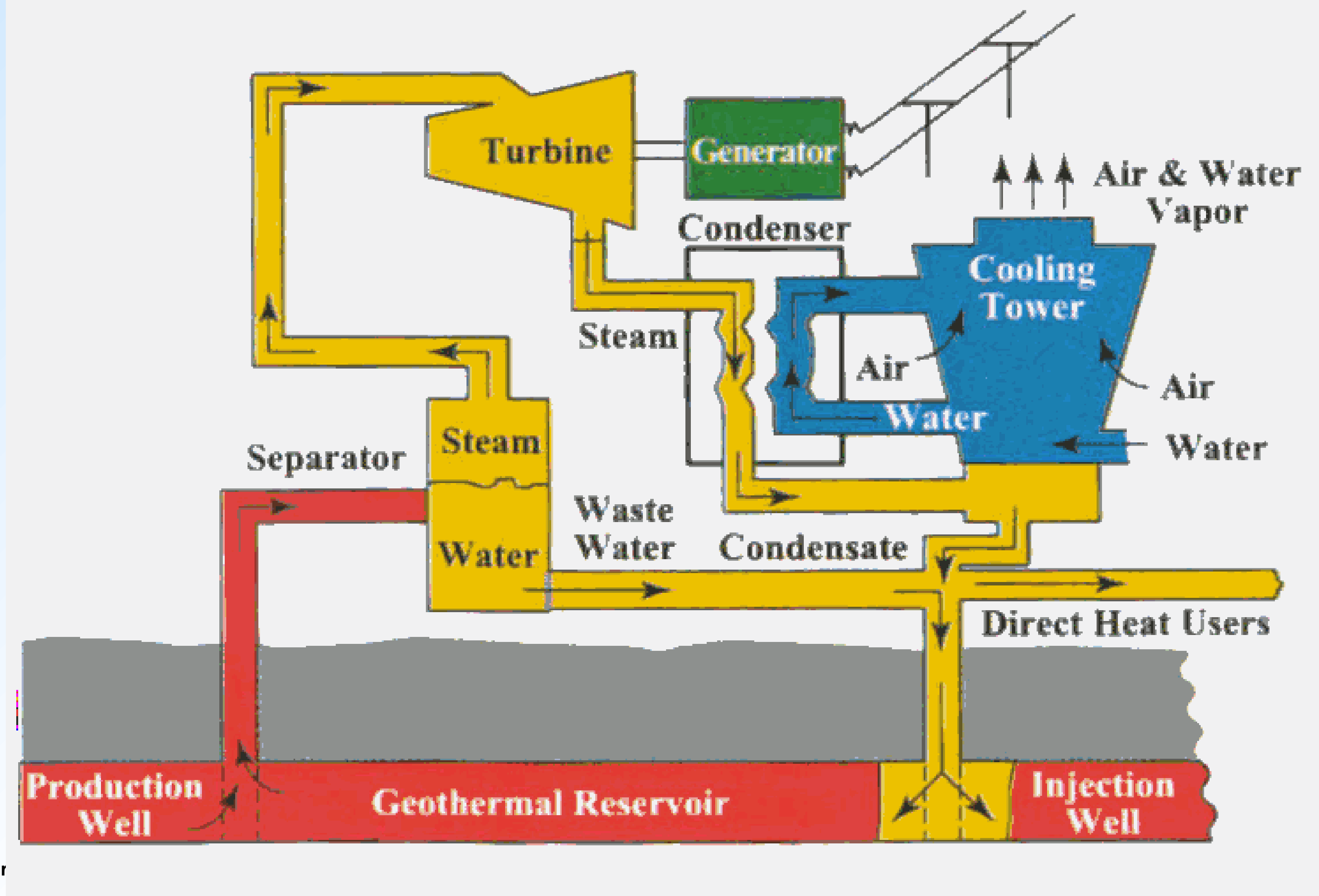
Nuclear Power Plant



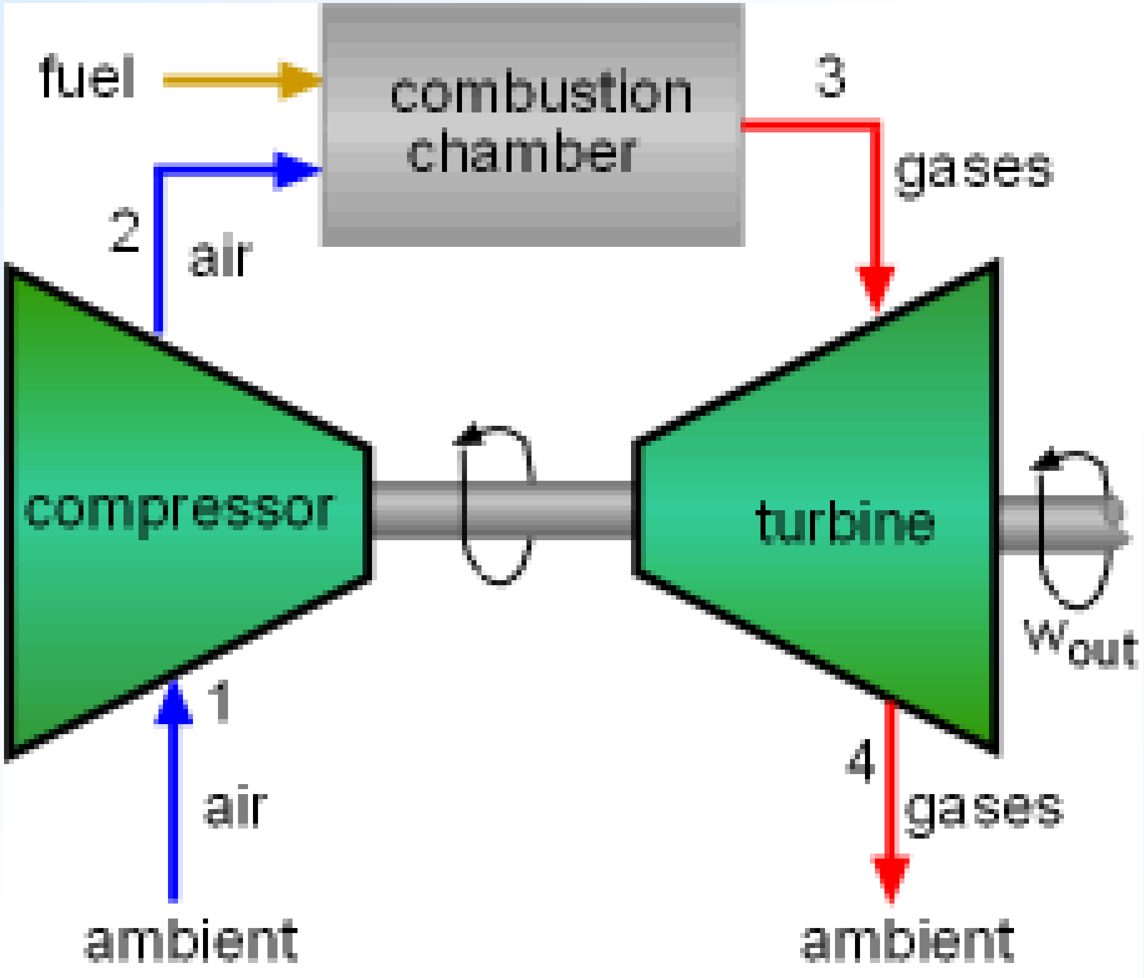
Solar Power Plant



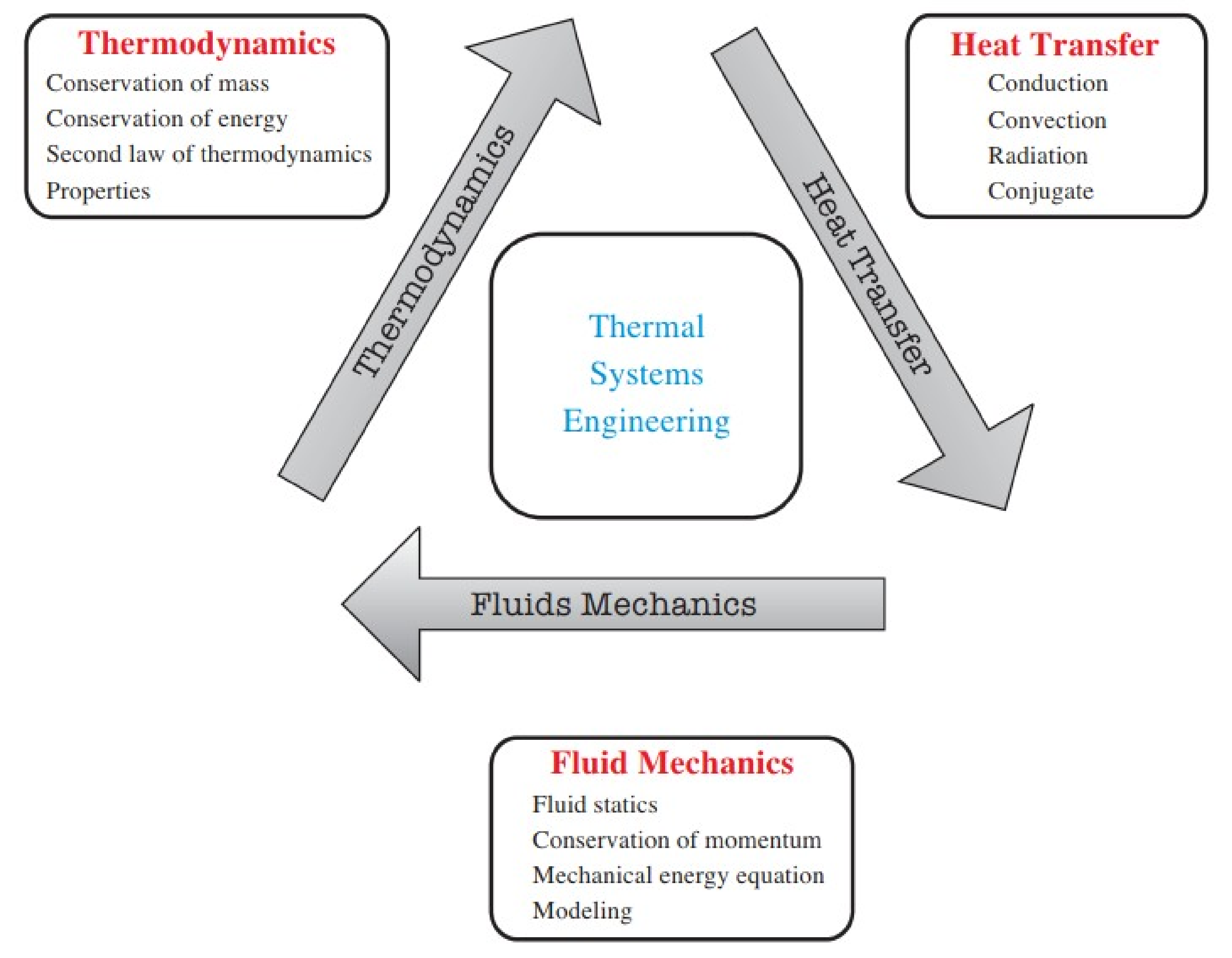
Geothermal Power Plant



Open Ideal Bryton Cycle



THERMAL SCIENCES



Thermodynamics

- Conservation of mass
- Conservation of energy
- Second law of thermodynamics
- Properties

Heat Transfer

- Conduction
- Convection
- Radiation
- Conjugate

Fluid Mechanics

- Fluid statics
- Conservation of momentum
- Mechanical energy equation
- Modeling

Thermodynamics: the study of energy, energy transformations and its relation to matter. The analysis of thermal systems is achieved through the application of the governing conservation equations, namely Conservation of Mass, Conservation of Energy (1st law of thermo), the 2nd law of thermo, and the property relations.

Heat Transfer: the study of energy in transit including the relationship between energy, matter, space, and time. The three principal modes of heat transfer examined are conduction, convection and radiation, where all three modes are affected by the thermophysical properties, geometrical constraints and the temperatures associated with the heat sources and sinks used to drive heat transfer.

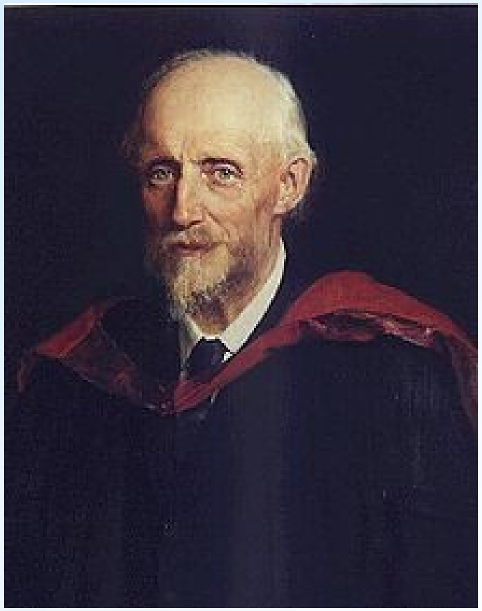
Fluid Mechanics: the study of fluids at rest or in motion. While this course will not deal extensively with fluid mechanics, we will be influenced by the governing equations for fluid flow, namely Conservation of Momentum and Conservation of Mass.

REVIEW OF THERMODYNAMICS

What is Thermodynamics?

Arnold Sommerfeld
German Physicist
1868 - 1951

“Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two points. The third time you go through it you know you don't understand, but by that time you are so used to the subject, it doesn't bother you any more."



Osborn Reynolds
British Engineer
1842 - 1912

“In lecturing on any subject, it seems to be the natural course to begin with a clear explanation of the nature, purpose, and scope of the subject. But in answer to the question “what is thermo-dynamics?' I feel tempted to reply “It is a very difficult subject, nearly, if not quite, unfit for a lecture."

On the General Theory of Thermo-dynamics,

November, 1883

“Thermodynamics" was first used in a publication by Lord Kelvin in 1849. The word thermodynamics comes from the Greek language:

$$\left.\begin{array}{l}\text{Therme = heat}\\[1ex] \text{Dynamis = power}\end{array}\right\}\quad\text{“power of heat”}$$

Standard Engineering Thermodynamic Definitions:

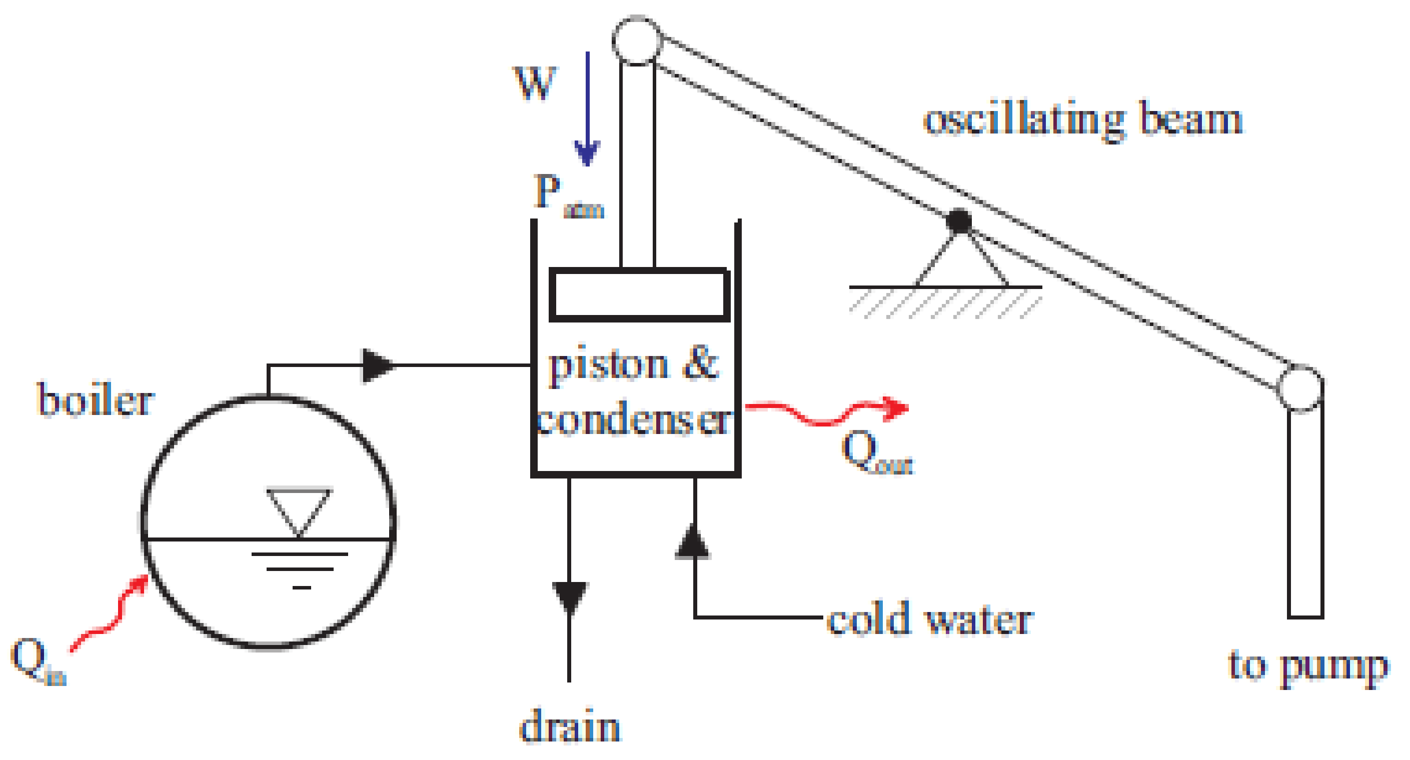
- the science of the relationship between heat and work and the substances related to the interaction of heat and work
- the science of energy and entropy

Our definition:

- conversion of transitional thermal and mechanical energy via energy exchange with a fluid; a subset of the field of energy conversion

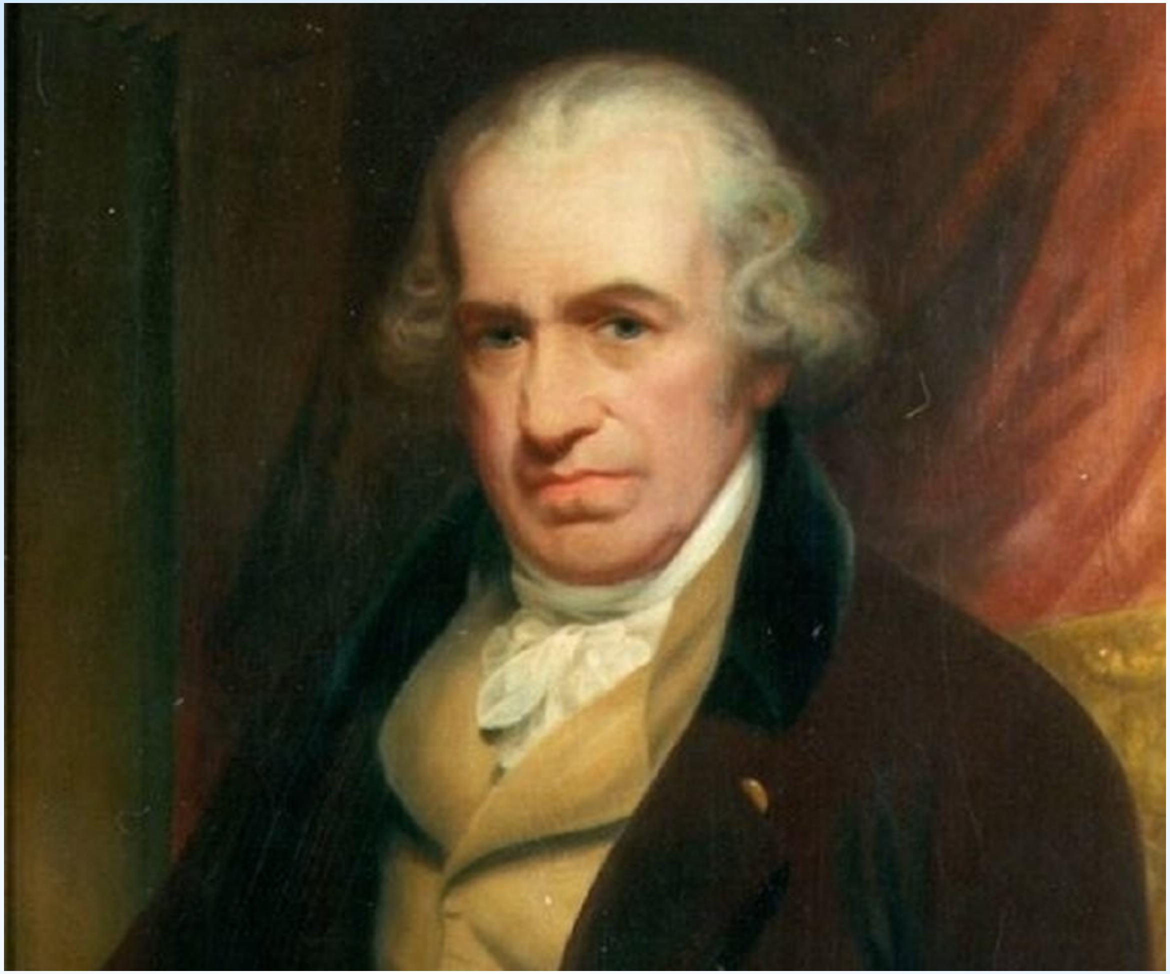
Heat Engines

Newcomen's Atmospheric Engine - 1707



Atmospheric ⇨ works aginst the atmospheric pressure

See: http://www.animatedengines.com/newcomen.html

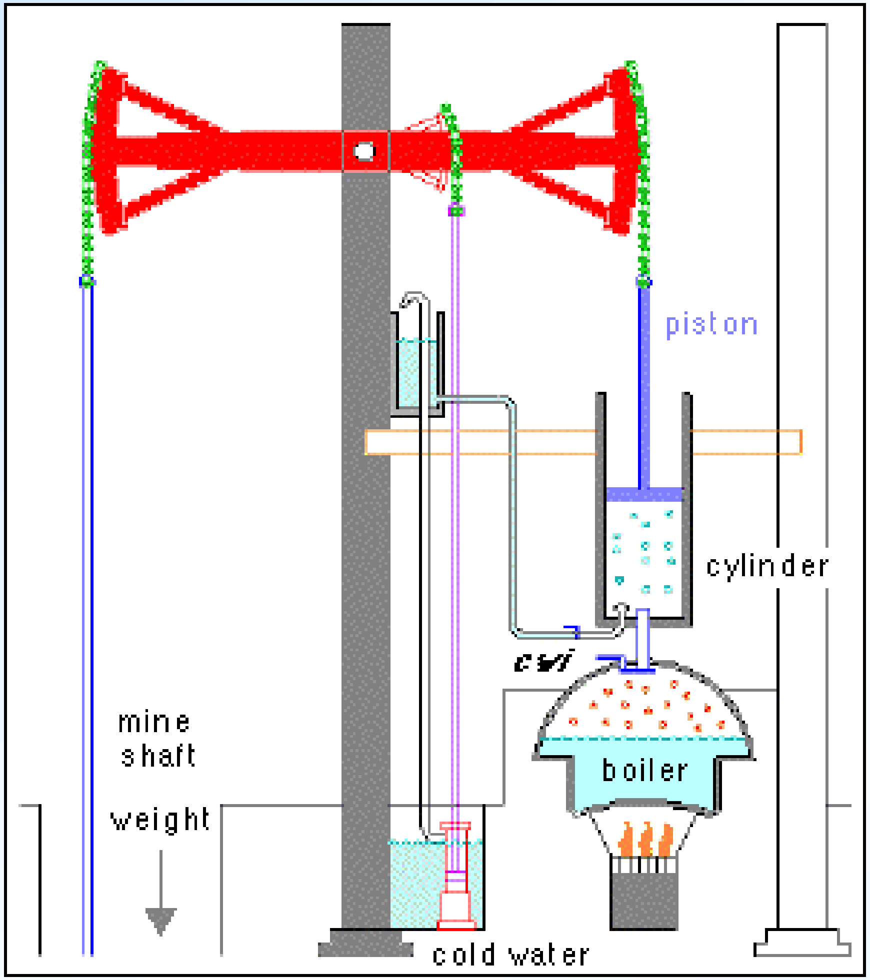


Thomas Newcomen

British Engineer

1663 - 1729

Newcomen's Atmospheric Engine



This magnificent engine was patented in 1705 by Thomas Newcomen, and is generally regarded as the first "modern" steam engine. Unlike later steam engines, the Newcomen works on the *atmospheric* principle.

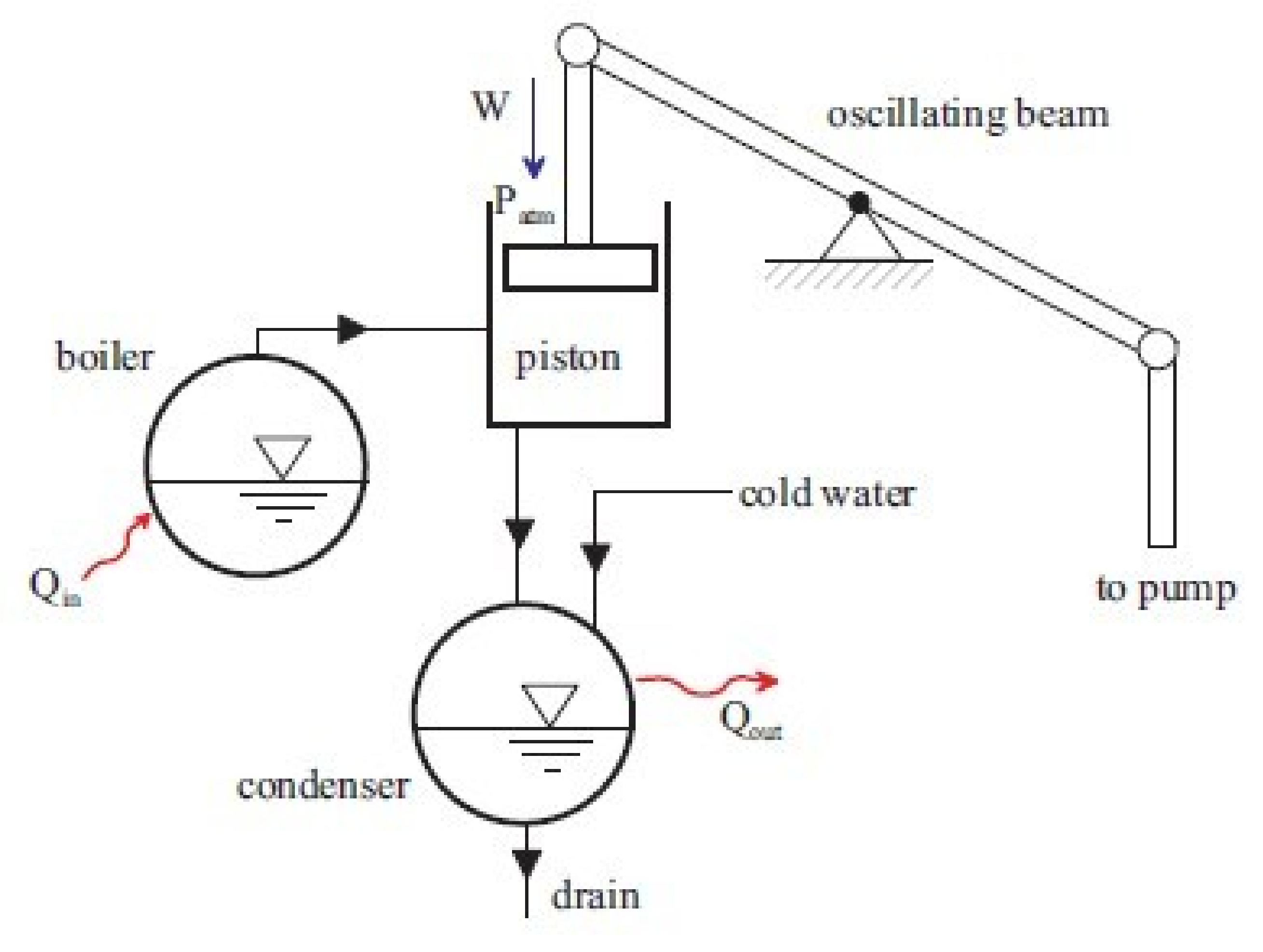
Water is boiled continuously to produce steam. During the piston's upward stroke, this low pressure steam (about 5 p.s.i.) is admitted to the cylinder. The pressure is insufficient to lift the piston on its own—the weight of the pump rod does most of the work.

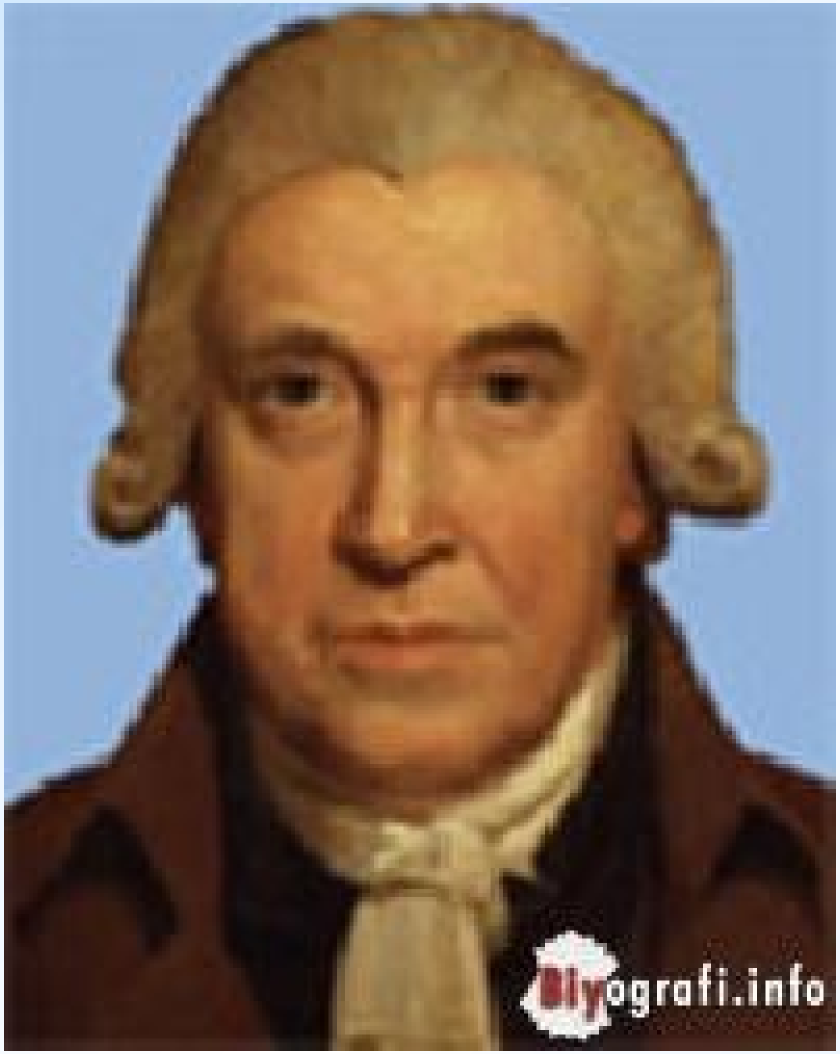
At the top of the stroke, the steam valve is closed and a water jet is briefly turned on, cooling the steam in the cylinder.

The cool steam contracts, sucking the piston downward. In other words, the higher atmospheric pressure drives the piston downward, hence the name *atmospheric* engine. At the end of the stroke, the cooling water is drained from the cylinder by an extra passage not illustrated here.

During the upward stroke, an auxiliary pump fills the cooling water reservoir.

Watt’s Atmospheric Engine - 1764



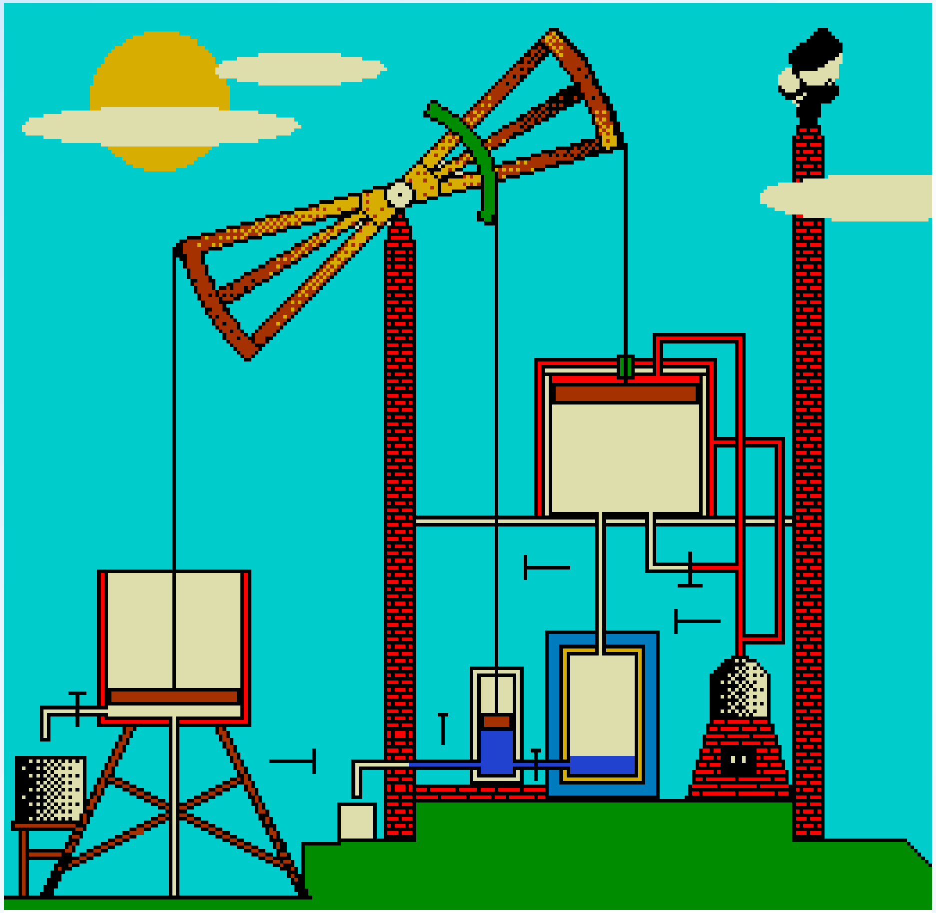


James Watt

Scottish Engineer

1736 -1819

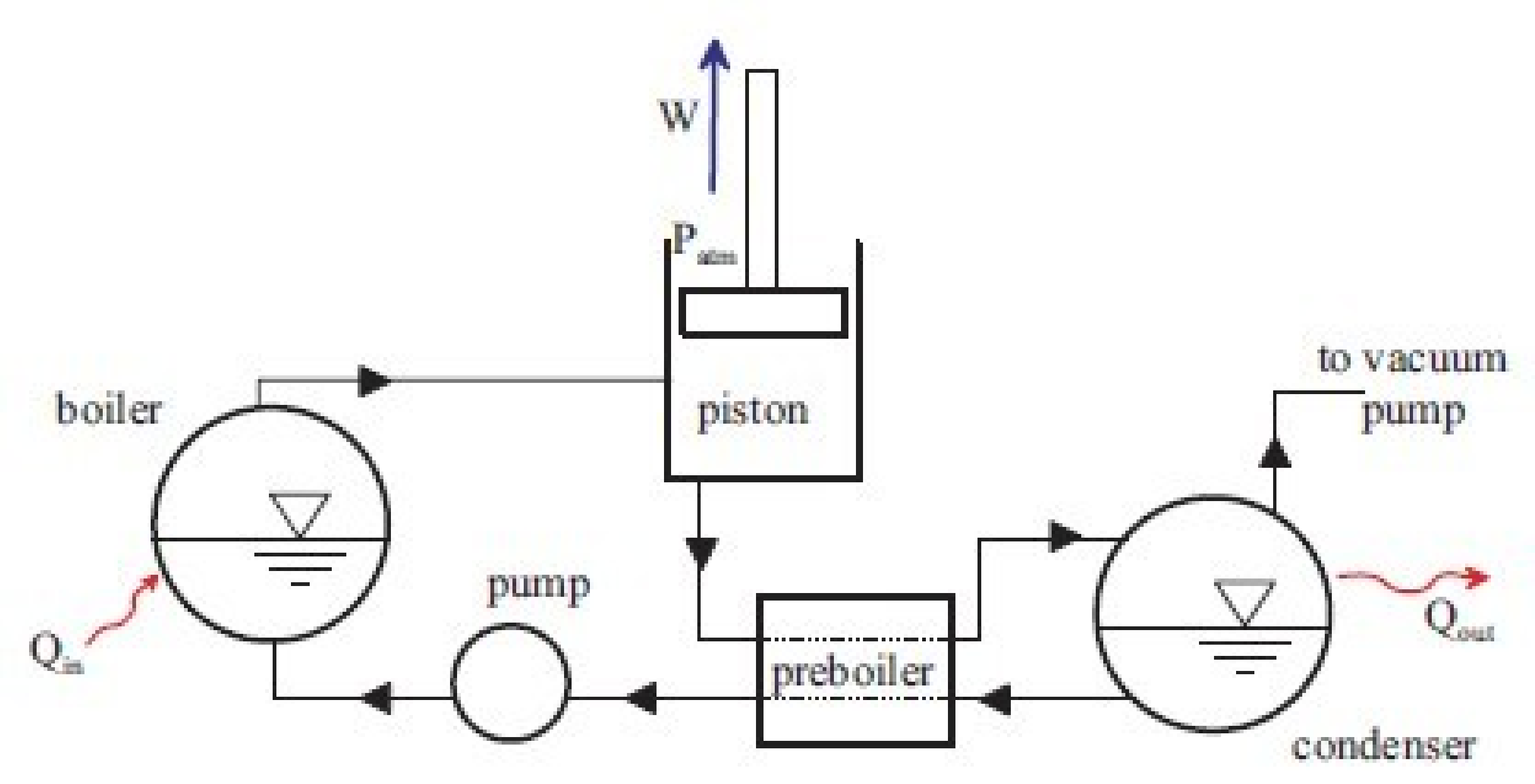
Watt's Atmospheric Engine - 1764



Watt's "improved" atmospheric engine

The engine works by first, steam from the boiler is used to push down the piston in the cylinder, lowering the beam. Secondly the steam is redirected via a series of valves to push the piston back up the cylinder, and so raising the beam. The clever bit is that the steam that was used to raise the piston, is condensed in a separate condenser allowing the engine to be kept above 100 degrees. The movement of the beam is used to operate two pumps the small pump on the same side of the boiler is used to pump the condensed steam back into the boiler the second pump is used to pump out water from the mine.

Evans' Atmospheric Engine - 1805

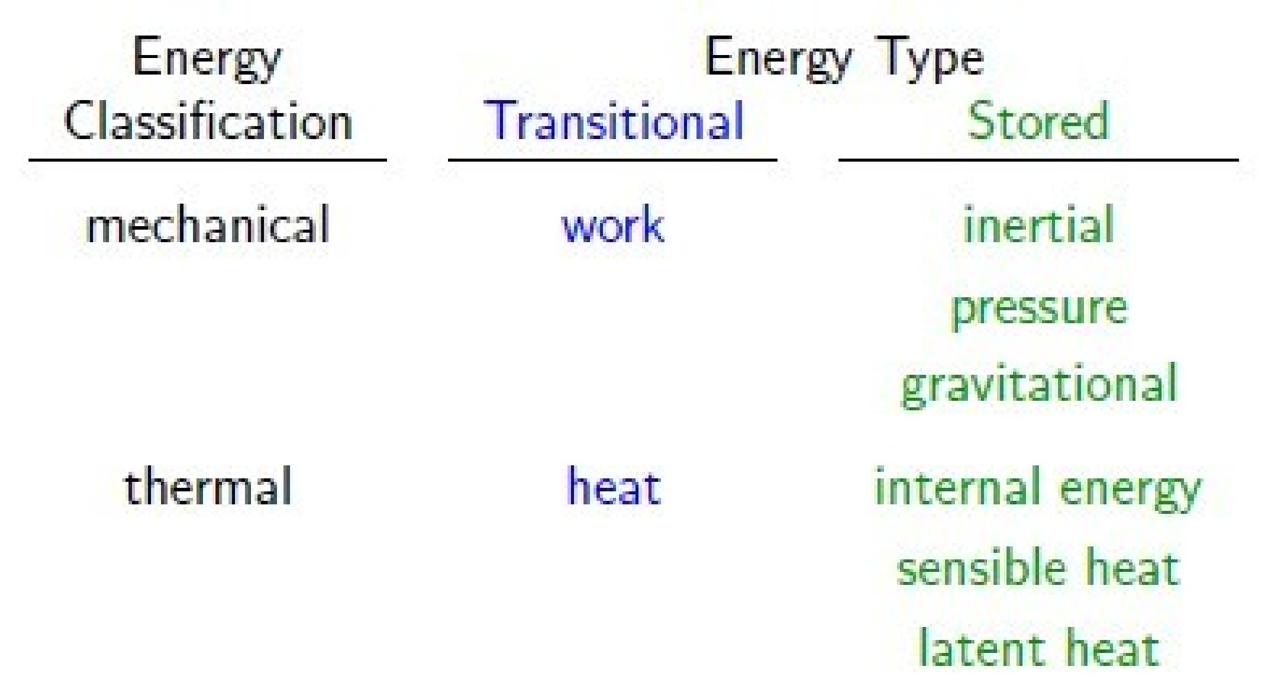


Oliver Evans

US Engineer

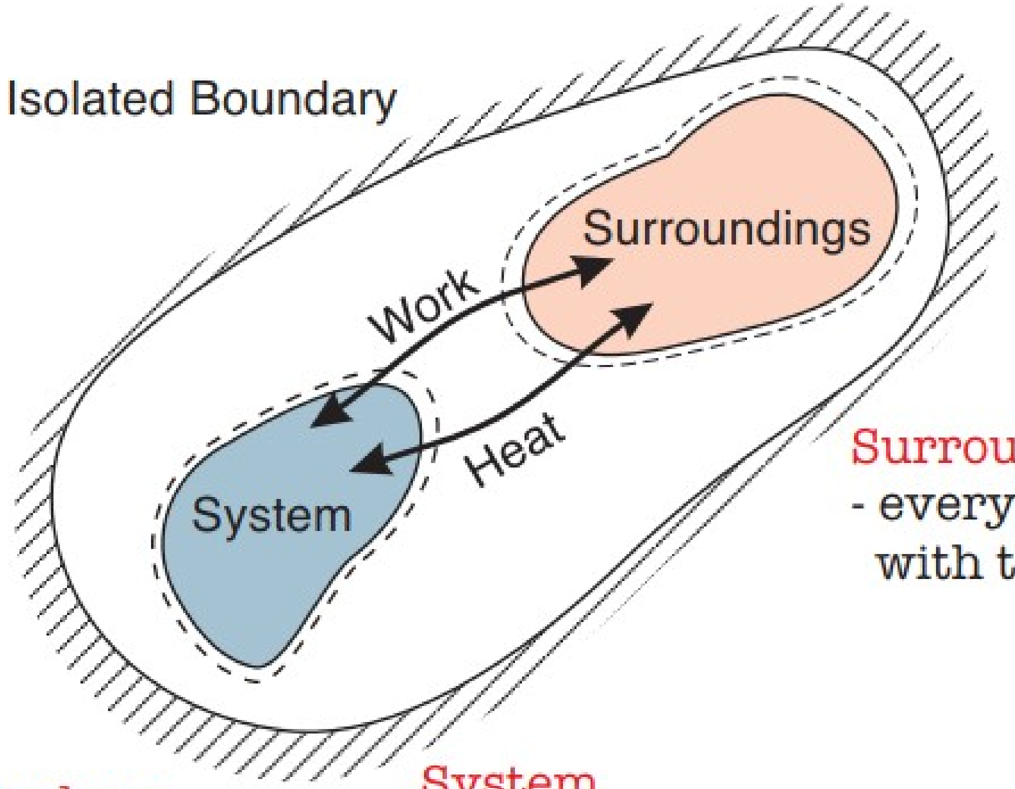
1755 - 1819

Thermodynamic Energy Types & Classifications



Energy Classification	Energy Type	
	Transitional	Stored
mechanical	work	inertial
		pressure
		gravitational
thermal	heat	internal energy
		sensible heat
		latent heat

THERMODYNAMIC SYSTEM

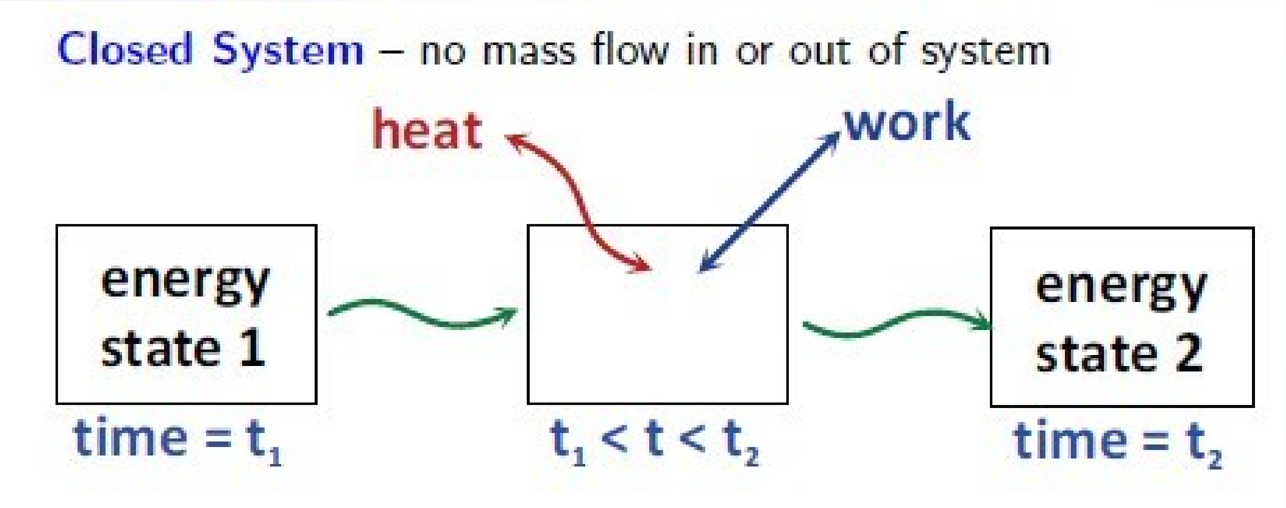


Surroundings
- everything that interacts with the system

System Boundary
(real or imaginary
fixed or deformable)

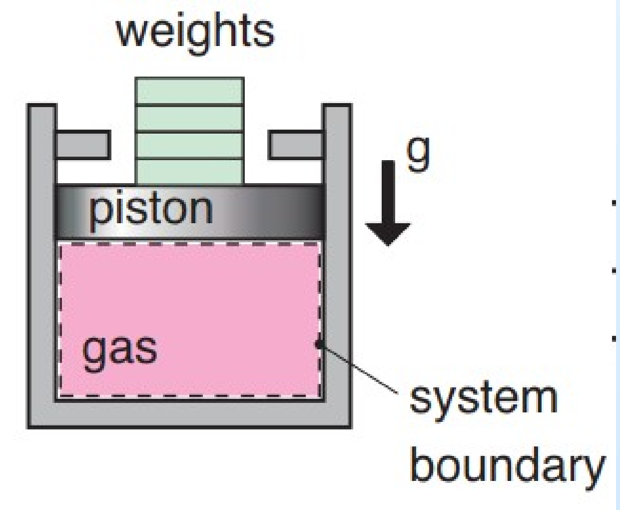
System
- may be as simple as a melting ice cube
- or as complex as a nuclear power plant

Closed System

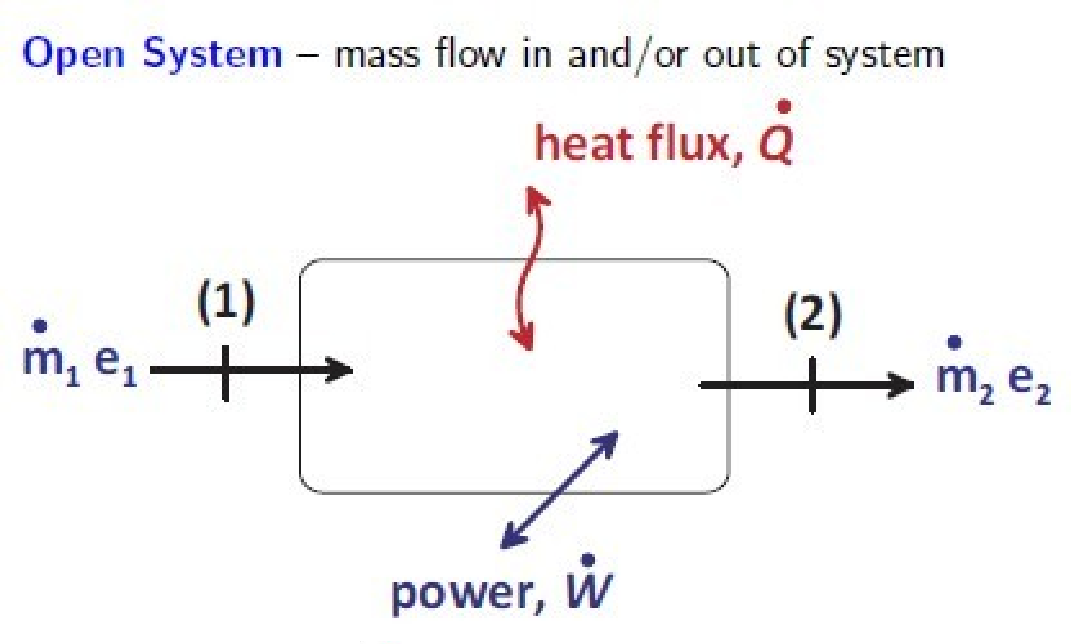


Closed System – no mass flow in or out of system

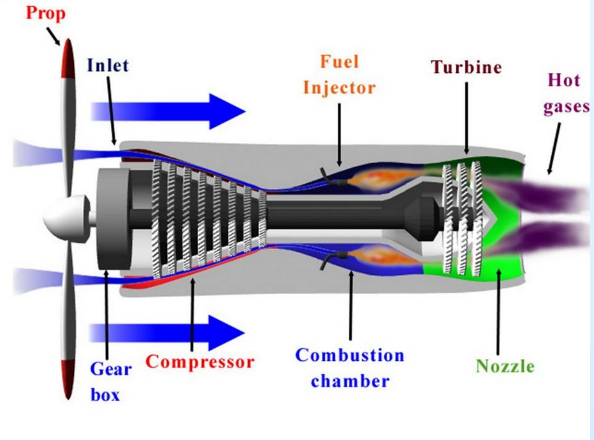
Example: Piston-Cyclinder System



Open System



Example: Turbofan



With a Closed System, we are analyzing a fixed mass.

An Open System, however, is a volume in space with mass passing through.

Conservation Laws are only strictly applicable to a Closed System (fixed mass, inertial frame of reference).

Therefore, Conservation of Energy on an Open System has an extra energy term associated with mass flow in and out of the volume to compensate for the non-fixed mass. The extra energy term will be referred to as flow energy and it looks the same as boundary work. Though not identical, the two are equivalent, mathematically.

Steady Energy Balance

For a steady-state open system:

$$\Delta Q - \Delta W = (E_p + E_k + E_i + E_f)_{out} - (E_p + E_k + E_i + E_f)_{in}$$

ΔQ heat into system

ΔW work produced by system

ΔE change in system energy

E_p potential energy = $m\,g\,z$

E_k kinetic energy = $m\,\dfrac{V^2}{2}$

E_i internal energy = $m\,u$

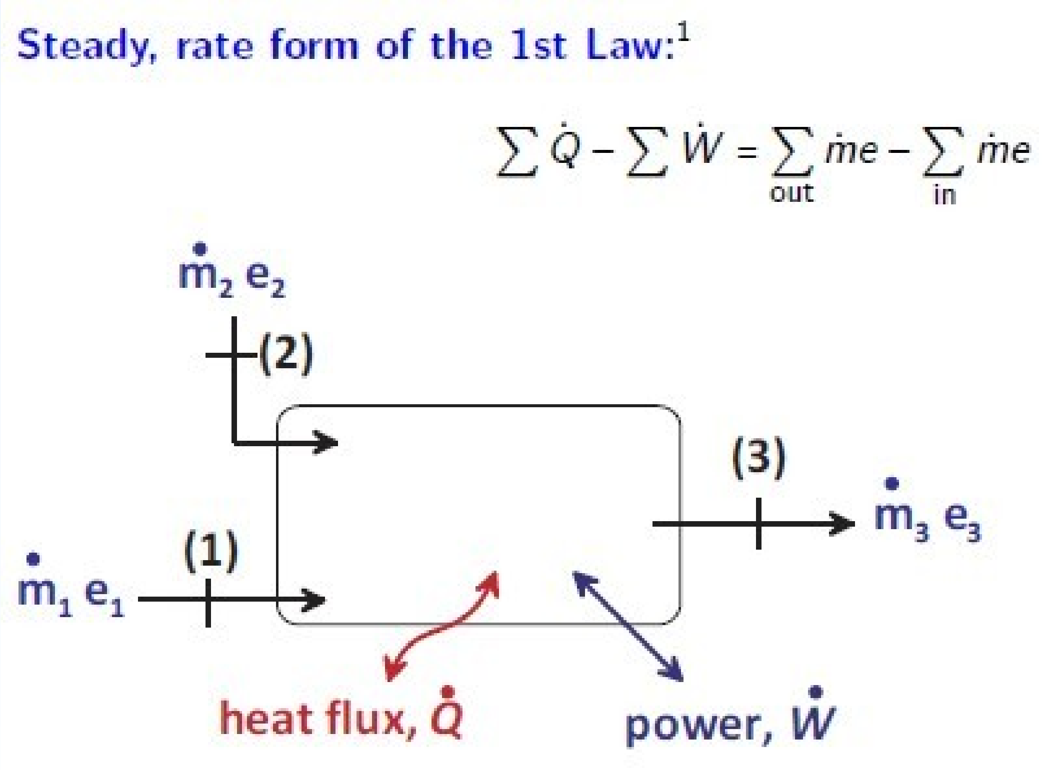
E_f flow energy = $P\,\forall = m\,\dfrac{P}{\rho}$

This is the first law of thermodynamics, which is really:

change in transitional energy = change in stored energy

"Steady" implies that there is no energy or mass accumulation within the system. That is different than the exchange of energy in the mass which passes through the system. The mass which passes through may accumulate energy.

First Law of Thermodynamics



Steady, rate form of the 1st Law:[1]

$$\sum \dot{Q} - \sum \dot{W} = \sum_{\text{out}} \dot{m}e - \sum_{\text{in}} \dot{m}e$$

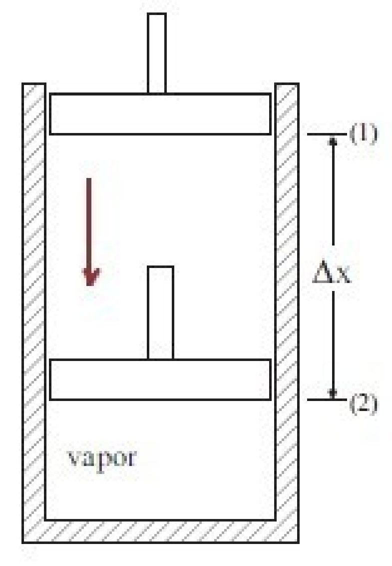
Heat $(\dot{Q})$ & Work $(\dot{W})$: Not the same as useful heat and work

The first law of thermodynamics applies to the working fluid.

Work from Steam

- Work is the expansion (or contraction) of a pressurized gas or vapor. From the perspective of a steam cylinder, work is related to pressure, P, and volume, ∀.

$$\text{Work} = F\,\Delta x = \left(P_{net}\,A_{piston}\right)\left(\frac{\Delta\forall}{A_{piston}}\right) = P_{net}\,\Delta\forall$$



P_{net} is the net pressure difference across the piston. For the atmospheric engines, the pressure difference across the slow moving cylinders was equal to $P_{atmospheric} - P_{saturation}$ which was essentially constant. $P_{saturation}$ is the pressure at which the steam condenses (or evaporates).

$$\text{Work} = \left(P_{atm} - P_{sat}\right)\Delta\forall = \left(P_{atm} - P_{sat}\right)A_{piston}\,\Delta x$$

The work extracted from the atmosphere could be measured by the force F exerted from the piston and the piston displacement Δx during the power stroke.

After Evan's engine development, the work was extracted from pressurized steam instead of the atmosphere. Thus, the net pressure difference, $P_{steam} - P_{atm}$ was not constant during the power stroke and the work during a power stroke required integration of the pressure and volume.

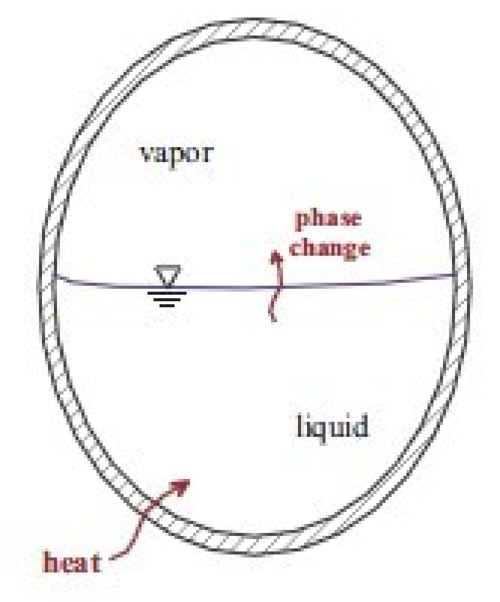
$$W = \int_1^2 P_{net}\ d\forall$$

As engine technology improved, the speed of engines increased; becoming too fast to watch a pressure gauge or manometer and record the pressures as a function of piston position. Some sort of device was needed to measure pressure and volume and correlate the two values. Read about *“Engine Indicators”* (pressure-volume plots).

Steam from Heat

$$\{\text{Heat}\} = \{\text{Change in Fluid Energy}\}$$

$$Q = \Delta E$$



The change in fluid energy, E, was considered different than that which occurred during the work on the piston. The concept of energy and the relationship between heat and work took a long time to become established.

Up until the mid 1800’s, the relationship between heat, work, and the exchange with a fluid (steam) was not understood.

Up until the mid-1800's, the relationship between heat, work, and energy exchange with a fluid (steam or gas) was not understood. Work was known to be related to pressure and volume, but heat added to the fluid from which work was extracted was a mystery.

Two theories were originally put forth to explain heat:

1. Live Force: Heat is a level of randomness of atoms and molecules in a substance; heat is a form of kinetic energy of very small particles. In other words, heat is manifestation of motion at the molecular level.

2. Caloric: Heat is a fluid-like substance that is massless, colorless, odorless, and tasteless. Caloric was a substance that had to be conserved; as such, an important principle of caloric theory is that work can not be converted into heat because work is not a substance.

Caloric theory was proposed by French chemist Antoine Lavosier in 1789 and was the prevailing theory until the mid-1800's.

Caloric is a substance and can be “poured“ from one body to another. Since it is a substance, caloric is subject to conservation laws; i.e., caloric is conserved. When caloric is added to a body, the temperature of that body increases. Remove caloric and the body's temperature decreases. “When a body could not contain any more caloric, much the same way as when a glass of water could not dissolve any more salt or sugar, the body was said to be saturated with caloric. The interpretation gives rise to the terms saturated liquid, saturated vapor, and heat flow that are still in use today."

There were many challenges to caloric theory

American Engineer Benjamin Thompson (Count Rumsford, 1754-1814)

- continuous heating due to friction during boring of cannons “demonstrated categorically" that caloric theory was not valid
- science community remained unconvinced

English Scientist James P. Joule (1818-1889)

- published experimental results in 1843 that “definitively" proved that heat is not a substance subject to laws of conservation
- science community remained unconvinced

German Physician Robert Mayer (1814-1878)

- in 1840's, proposed heat and work were different forms of the same thing
- science community remained unconvinced

Joule and Kelvin performed a series of experiments between 1850 and 1860 which quantified the relationship between heat and work

- took another 50 years for caloric theory to pass

Historical Excerpts

Thermodynamics as a science begins following the first successful atmospheric steam engines in England.

1697: Thomas Savory 1712: Thomas Newcomen	Primarily used for pumping water out of mines

Thermodynamics is based on experimental observations.

- Primarily developed by engineers from observations
- Physicists, philosophers, mathematicians proposed “caloric” theory

The term “energy” was first used by Thomas Young in 1807.

Concept of energy is only 200 years old.

The term “thermodynamics” was first used in a publication by Lord Kelvin in 1849.

The use of “energy” in thermodynamics was first proposed by Lord Kelvin in 1852.

The first and second laws emerged simultaneously in the 1850’s.

The first law for an open system first stated by Gustav Zeuner (University of Dresden) in 1859 – essentially unchanged to date.

The first thermodynamics text book appeared in 1859 by William Rankine.

The term internal energy, denoted as «u», first appeared in the works of Rudolph Clausius and William Rankine in the late 1800’s. “Internal Energy” has replaced such terms as “inner work”, “internal work”, and “intrinsic energy”.

“Enthalpy” – Richard Mollier (University of Dresden)

Historical Milestones

- First century AD: Hero of Alexandria documents many early thermal engines.
- 1593: Galileo develops a water thermometer.
- 1650: Otto von Guericke designs and builds the first vacuum pump.
- 1662: Robert Boyle develops his law for isothermal ideal gases.
- 1679: Denis Papin develops his steam digester, forerunner to the steam engine.
- 1687: Isaac Newton publishes PhilosophiæNaturalis Principia Mathematica.
- 1698: Thomas Savery patents an early steam engine.
- 1710: Thomas Newcomen creates a more practical steam engine.
- 1760s: Joseph Black develops calorimetry.
- 1780s: James Watt improves the steam engine.

Historical Milestones

- 1798: Benjamin Thompson (Count Rumford) considers the mechanical equivalent of heat from cannon boring experiments.
- 1824: Nicolas L`eonard Sadi Carnot discusses idealized heat engines.
- 1840: Germain Henri Hess considers an early version of the first law of thermodynamics for work-free chemical reactions.
- 1840s: Julius Robert von Mayer relates heat and work.
- 1840s: James Prescott Joule relates heat and work.
- 1847: Hermann von Helmholtz publishes his theory of energy conservation.
- 1848: William Thomson (Lord Kelvin) postulates an absolute zero of temperature.
- 1850: Rudolf Julius Emanuel Clausius formalizes the second law of thermodynamics.

Historical Milestones

- 1865: Clausius introduces the concept of entropy.
- 1871: James Clerk Maxwell develops the Maxwell relations.
- 1870s: Josiah Willard Gibbs further formalizes mathematical thermodynamics.
- 1870s: Maxwell and Ludwig Boltzmann develop statistical thermodynamics.
- 1889: Gibbs develops statistical mechanics, giving underlying foundations for classical and statistical thermodynamics.
- 1909: Constantin Carath´eodory publishes a rigorous axiomatic formulation of the laws of thermodynamics.
- 1931: Lars Onsager advances non-equilibrium thermodynamics with his reciprocity relations.

Three Primary Laws of Thermodynamics

1. Conservation of Mass

2. First Law of Thermodynamics: $\sum Q - \sum W = \Delta E$

   - approximated by conservation of energy
   - deals with quantities of energy and conversion, but not efficiency or quality of energy conversion
   - Examples: - punctured aerosol can; - hot object cooling in a room

3. Second Law of Thermodynamics

   - Quality and efficiency of energy conversion

Thermodynamic Properties of Systems

Thermodynamic Property: Any observable or measurable characteristic of a system.

Any mathematical combination of the measurable characteristics of a system

Intensive Properties: Properties which are independent of the size (or mass)

- they are not additive ⇒ $X_{A+B} \neq X_A + X_B$
- examples include: pressure (P), temperature (T), and density (ρ)

Extensive Properties: Properties which are dependent of the size (or mass)

- they are additive ⇒ $X_{A+B} = X_A + X_B$
- examples include: volume (V), energy (E), entropy (S), and surface area (A)

Specific Property: Extensive properties expressed per unit mass to make them intensive properties

Equilibrium: state in which no spontaneous changes are observed with respect to time.

We actually never totally achieve equilibrium, we only approximate it. It takes infinite time to achieve final equilibrium. In this class we will mainly be concerned with two types of equilibrium:

Mechanical equilibrium: characterized by equal pressure, and

Thermal equilibrium: characterized by equal temperature.

A third type of equilibrium is chemical equilibrium, that we will not consider here, and is characterized by equal chemical potentials.

Measurable Properties: P, V, T, and m are important because they are measurable quantities. Many other thermodynamic quantities can only be calculated and used in calculations when they are related to P, V, T, and m:

- Pressure (P) and Temperature (T) are easily measured intensive properties.

  Note: They are not always independent of one another.
- Volume (V) and mass (m) are easily measured extensive properties.

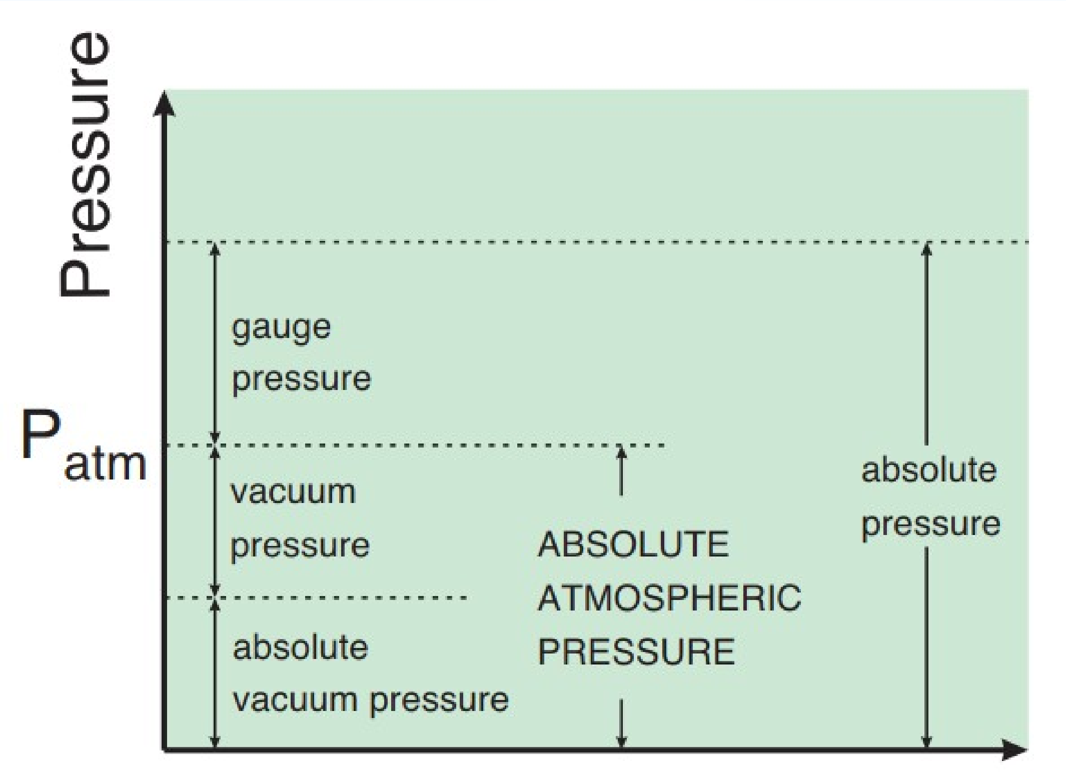
The state of a simple compressible system is completely specified by 2 independent and intensive properties.

Thermodynamic process is any change from one equilibrium state to another.

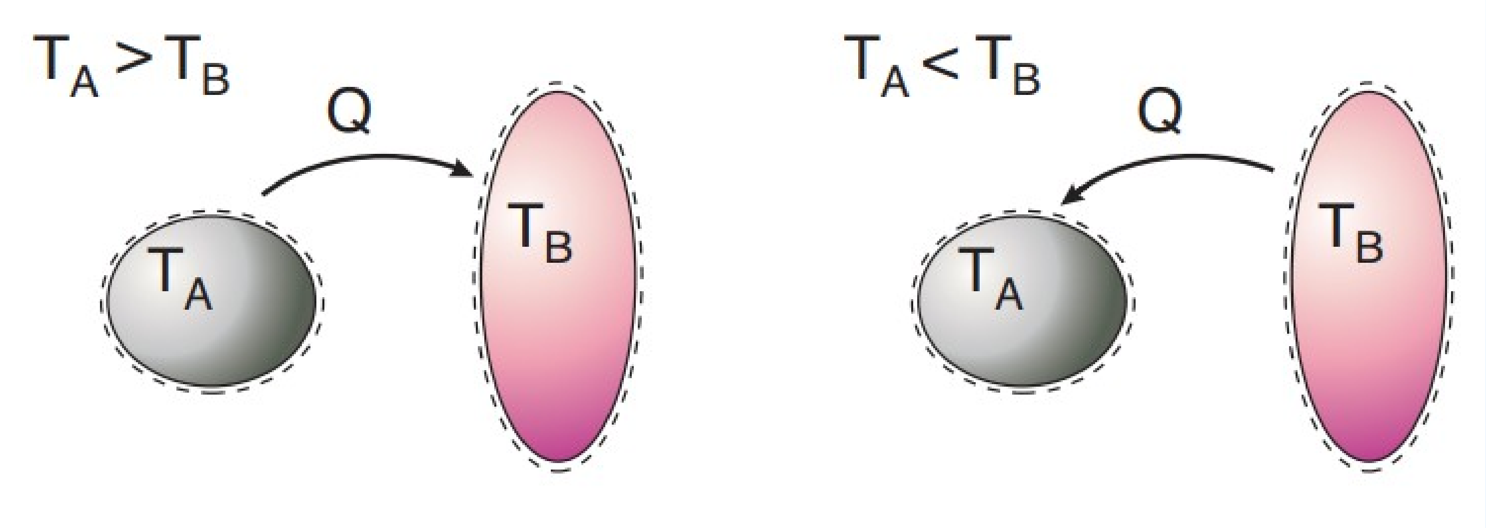
If the end state = initial state, then the process is a cycle

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{\text{N}}{\text{m}^2} = \text{Pa}$$

- In fluids, this is pressure (normal component of force per unit area)
- In solids, this is stress

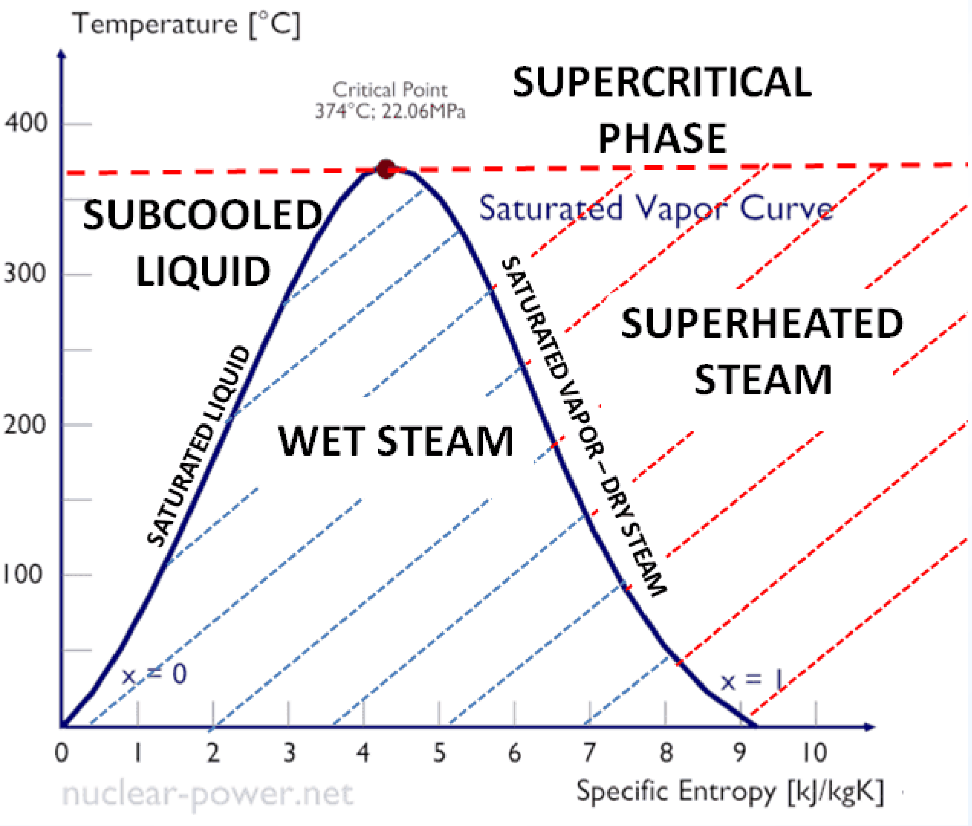


Temperature is a pointer for the direction of energy transfer as heat.

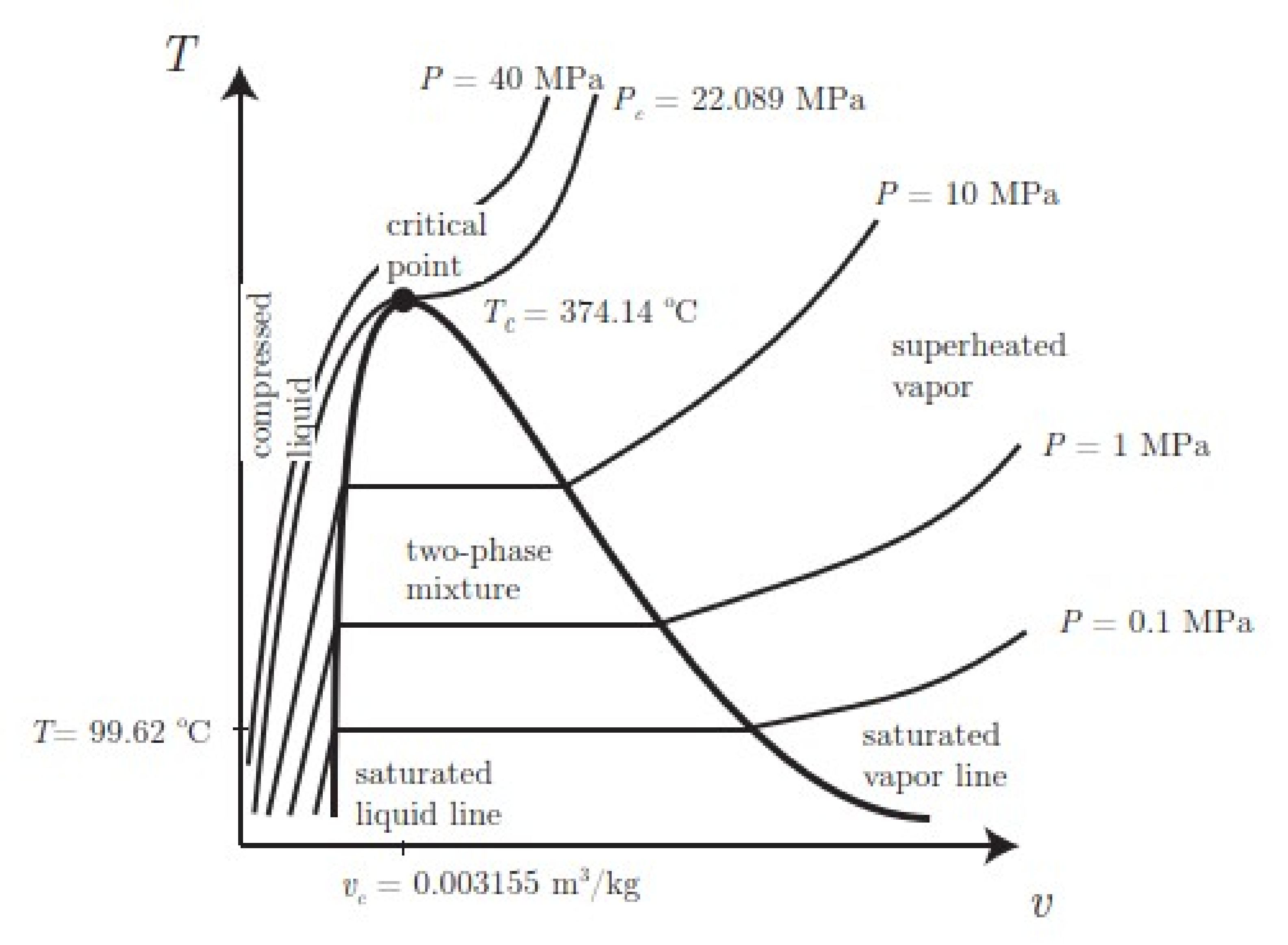


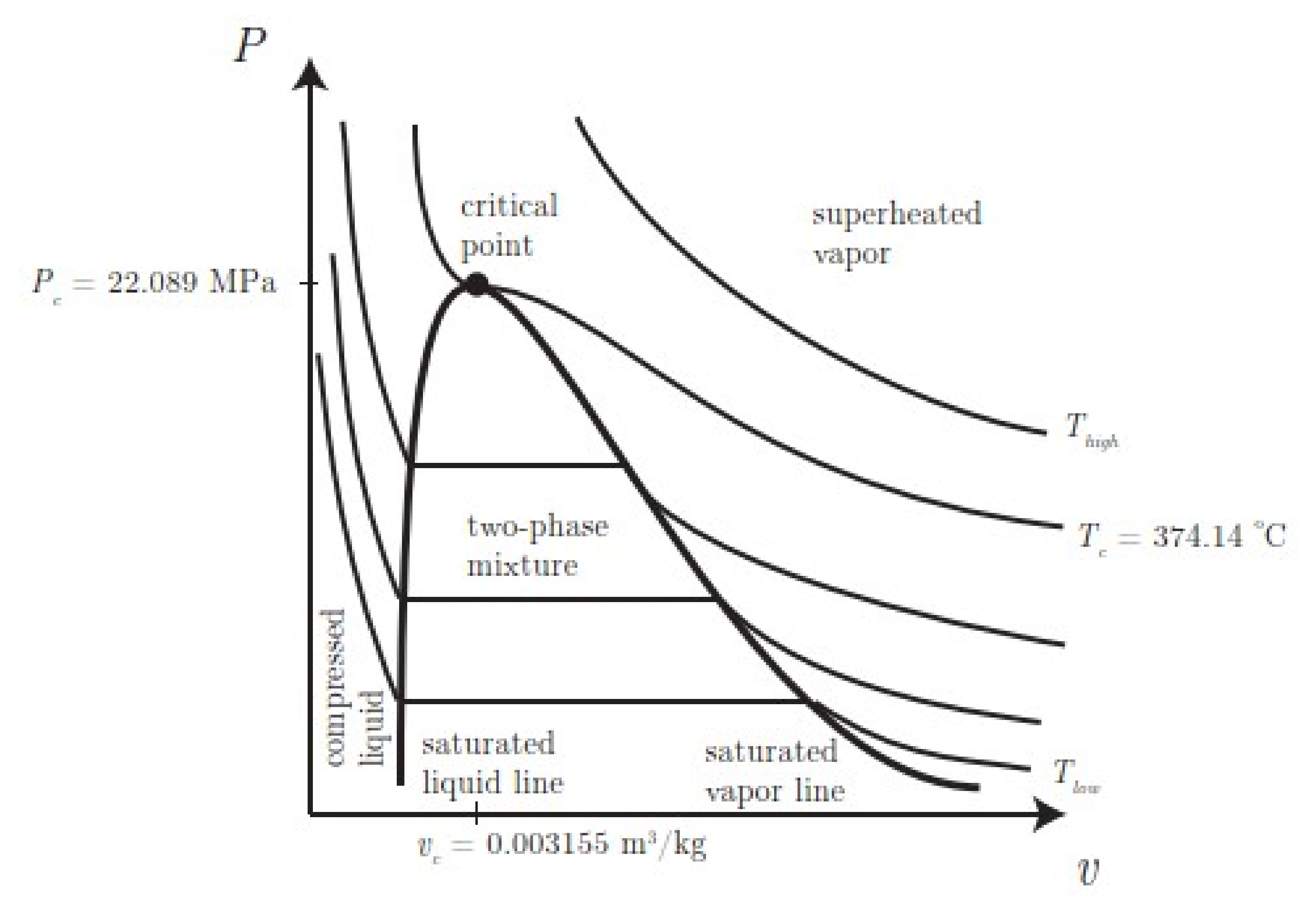
0th Law of Thermodynamics: if system C is in thermal equilibrium with system A, and also with system B, then $T_A = T_B = T_C$

Property Relations

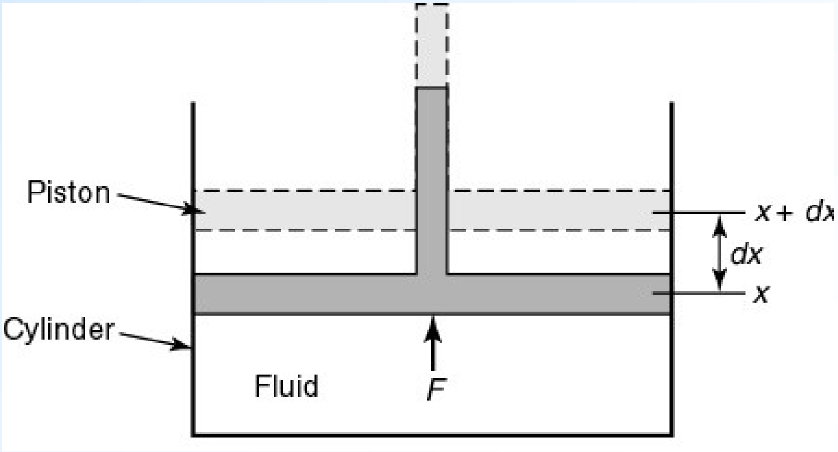


- Incompressible fluid – Incompressible flow
- Saturation pressure curve (steam tables)
- Superheated steam tables (doesn't behave like an ideal gas)
- Subcooled (compressed) liquid tables (steam tables) – least accurate


T
P = 40 MPa
P_c = 22.089 MPa
P = 10 MPa
critical point
T_c = 374.14 °C
superheated vapor
compressed liquid
two-phase mixture
P = 1 MPa
P = 0.1 MPa
T= 99.62 °C
saturated liquid line
saturated vapor line
v_c = 0.003155 m³/kg
v


P
P_c = 22.089 MPa
critical point
superheated vapor
T_{high}
T_c = 374.14 °C
two-phase mixture
compressed liquid
saturated liquid line
saturated vapor line
T_{low}
v_c = 0.003155 m³/kg
v

Boundary Work and Flow Potential



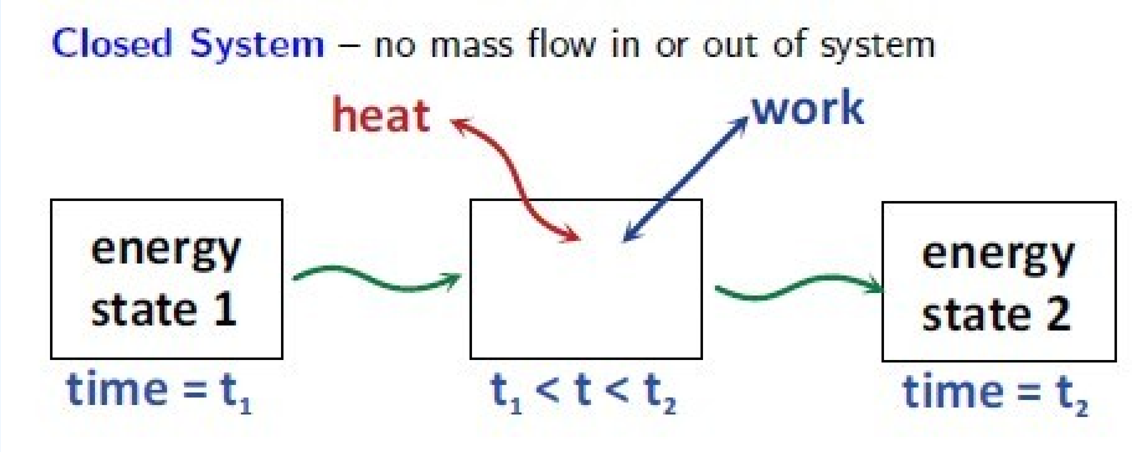
For a closed system, there is no flow potential because no mass crosses through the system boundary. There is, however the possibility of boundary work.

$W = \int P \, d\forall$ boundary work

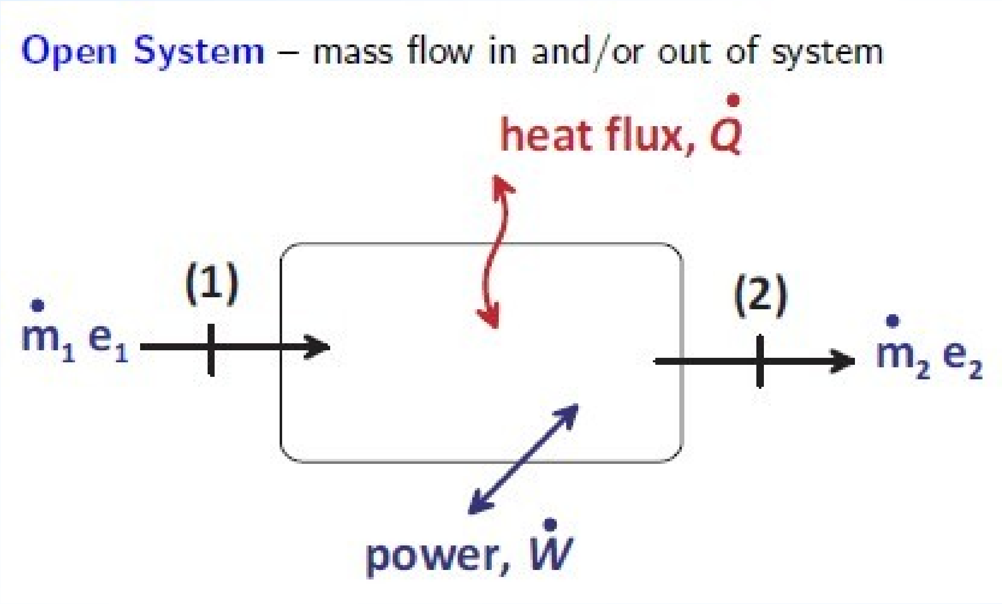
$w = \int P \, dv$ specific boundary work

Flow potential (energy): $P \forall$ or $P v$

Flow potential (energy) occurs when mass crosses a system boundary, which is the definition of an open system

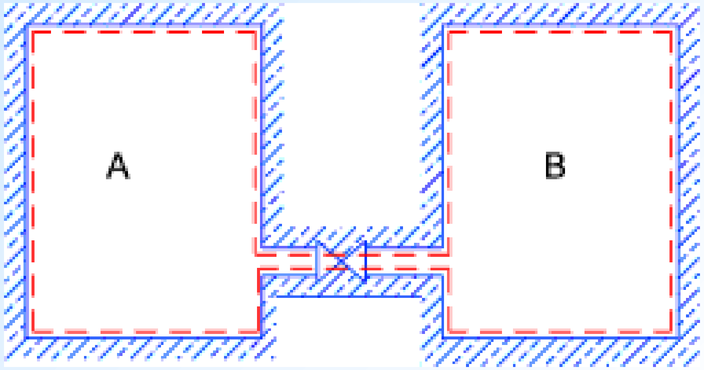


$$Q - W = m\,\Delta e = m\,\Delta u$$



$$\dot{Q} - \dot{W} = \dot{m}\,\Delta e = \dot{m}\,\Delta h$$

Internal Energy, U



Joule's Experiment

- Vessels are isothermal.
- A has air at 2 Atm. pressure
- B has vacuum and the valve is closed
- Open the valve
- Air flows from A to B until each has 1 atm. pressure
- No heat or work to or from gas
- Therefore, $Q – W = 0 = \Delta U$ even though P and $\forall$ have changed
- Conclusion: $U = f(T)$ only - Ideal Gas

Enthalpy, H

In open systems, the combination of internal energy, pressure and volume always appear in the energy balance. (What about closed systems?) For convenience, engineers defined a new property which has come to be called enthalpy.

$$H = U + P \forall$$

On a per unit basis: $h = u + P v$

Enthalpy is from the Greek word “enthalpo” which means “heat within”.

Enthalpy was selected by ASME in the July 1936 issue of Mechanical Engineering “to designate the thermodynamic function define as internal energy plus the pressure volume product of any working substance.

- Replaced “total heat”, “heat content”, and “heat of liquid”
- Originally designated as I, i; still common nomenclature in AVAC industry

Specific Heats (c_v , c_p)

For a simple compressible substance (ideal gas, air, …) and neglecting kinetic and potential energy changes:

$$Q - W = \Delta U = m\,\Delta u$$

$$W = \text{boundary work} = F\,\Delta x = (P\,A)\,\Delta x = P\,\Delta\forall$$

$Q \propto m\,\Delta T$ => Heat transfer is proportional to the mass and temperature difference

On an infinitesimal basis: $\delta Q - \delta W = m\,du$

Not derivatives because these are path-dependent processes and we do not yet know the process

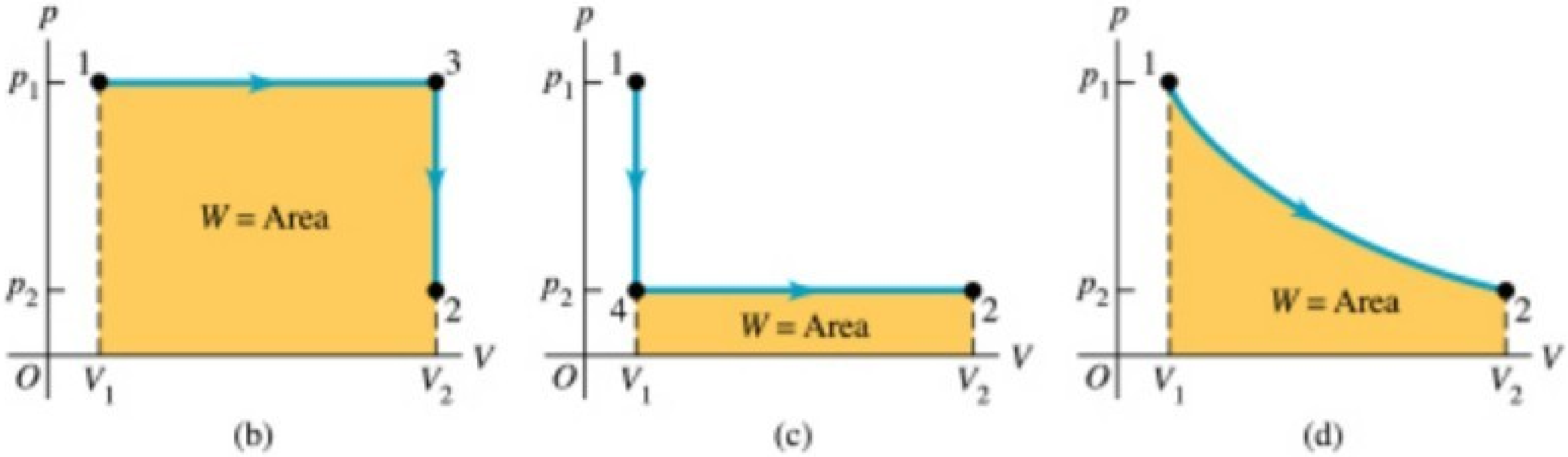
$$\delta W = P\,\Delta\forall$$

$$\delta Q \propto m\,dT$$

Use a constant of proportionality:

$$\delta Q = m\,c\,dT$$

Path dependence of work done by a system:



(b) (c) (d)

$$W = p_1(V_2 - V_1) + 0$$

$$W = 0 + p_2(V_2 - V_1)$$

$$W = \int_{V_1}^{V_2} p\,dV$$

1st law: $\delta Q - \delta W = m\ c\ dT - m\ P\ dv = m\ du$

- For constant volume process: $\delta W = m\ P\ dv = 0 \quad \Rightarrow \quad \boxed{c_v = \left.\frac{du}{dT}\right|_v}$
  - c_v is the slope of u(T)
  - Since c_v is a function of properties, u and T, it too is a property
- For constant pressure process: $\delta Q - \delta W = m\ dU \quad \Rightarrow \quad \delta Q = m\ dU + m\ P\ dv$

Enthalpy is defined as $h = u + P\ v$

$$dh = du + P\ dv + v\ dP = du + P\ dv \quad \text{since } dP = 0$$

Thus $\delta Q = m\ c\ dT = m\ dh \quad \Rightarrow \quad \boxed{c_p = \left.\frac{dh}{dT}\right|_p}$

- c_p is the slope of h(T)
- Since c_p is a function of properties, h and T, it too is a property

- For an ideal gas: $\boxed{P\,v = R\,T}$

$$h = u + P\,v = u + R\,T$$

$$c_v = \left.\frac{du}{dT}\right|_v$$

$$c_p = \left.\frac{dh}{dT}\right|_p = \left.\frac{d(u + R\,T)}{dT}\right|_p = \frac{du}{dT} + R = c_v + R$$

Define $k = \dfrac{c_p}{c_v}$ (also denoted as γ)

$$c_p = c_v + R \quad \text{and} \quad k = \frac{c_p}{c_v}$$

$$c_p = \frac{k\,R}{k - 1} \qquad c_v = \frac{R}{k - 1}$$

- For incompressible substances (solids and liquids), $c_p = c_v = c$

Thermodynamic Properties: P, T, V, m, H, S, c_p and c_v, others

The state of a system is identified by two independent properties.

P and T are **not** independent properties in the two-phase region.

Thermodynamic Laws: 0_{th}, 1_{st}, 2_{nd}, 3_{rd}, ...

Ideal Gas Law

Steam (water vapor) is **not** an ideal gas.

Definitions:

Process: Transitions of a system from one equilibrium state to another

Path: Series of states that that a system passes through during a process

Quasi-equilibrium: process during which the system remains nearly in equilibrium

Iso-processes: process during which one property is constant

- Isochoric → volume is constant
- Isobaric → pressure is constant
- Isothermal → temperature is constant
- Isentropic → entropy is constant
- Adiabatic → no transitional thermal energy conversion

Irreversibilities:

- Friction
- Unstrained expansion – work required to restore state
- Heat transfer through ΔT (as opposed to dT) – cooling required to restore state which rejects heat to surroundings
- Mixing of two substances – work required to separate
- Joule heating (I & R)
- Combustion

External vs Internal Irreversibilities:

- Internal → No irreversibility occurs within the boundary during a process
- External → No irreversibility occurs outside the boundary during a process

2nd law for a process

Transitional forms of energy: Mechanical --> Work

Thermal --> Heat

} Work is the most valuable commodity

- Work can be continuously and completely converted to heat
- Opposite is not true

The portion of heat that cannot be converted to work is ***unavailable energy or unavailability, or exergy***

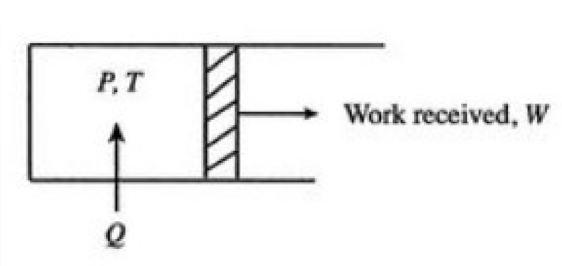
That "*unavailable energy*" has to be rejected as "*low-grade*" heat

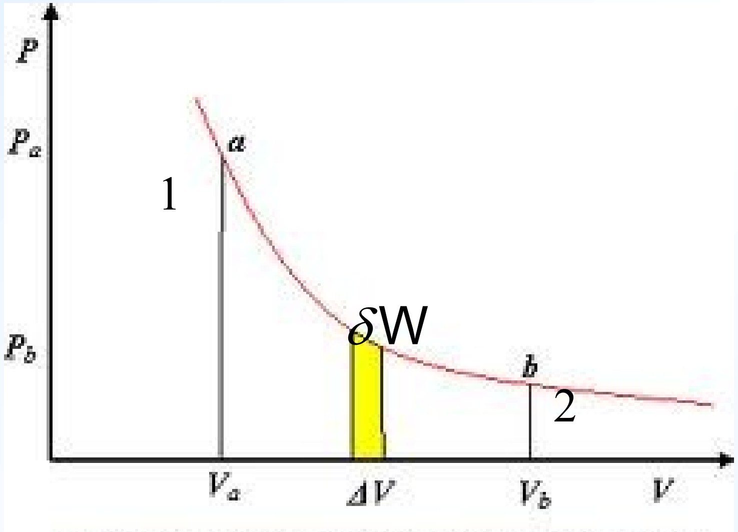
Energy is conserved, but "unavailability" is not.

Entropy

- Introduced and named by Clausius in 1865
- Entropy is a property
- Units of J/K or J/kg.K for specific entropy

Consider a non-flow work (gas expansion against a piston)





Isothermal expansion from a to b along $PV = nRT_H$

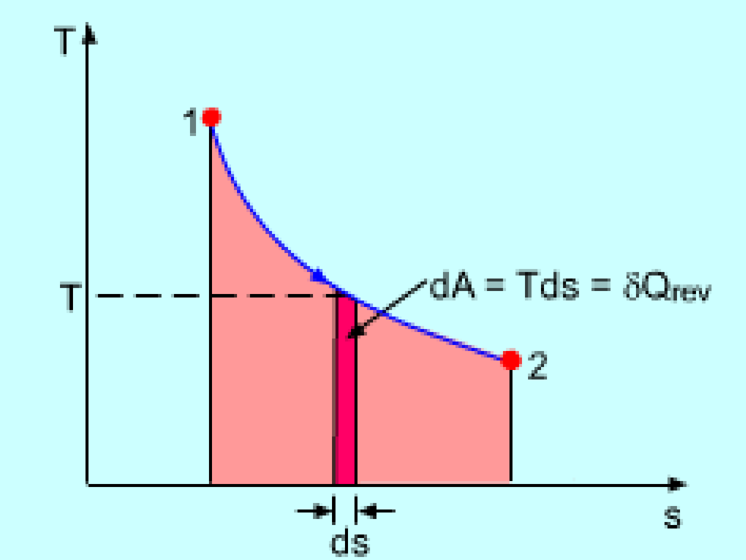
$$_1W_2 = \int_1^2 P \, d\forall$$

Graphically, the total work is the area under the curve.

It would be convenient to have a similar graph where the area under the curve represents the heat transfer during a process.

For the work, the pressure difference is the driving potential.

For heat, temperature difference is the driving potential.



Graphically, the total heat transfer is the area under the curve.

Caveats: The process must be reversible

$$ {}_1Q_2\big|_{rev} = \int_1^2 T\,dS \qquad {}_1Q_2 \leq \int_1^2 T\,dS $$

Reversible, adiabatic process (Q = 0) –> Isentropic process

$$ {}_1Q_2\Big|_{rev} = \int_1^2 T\,dS = 0 $$

Since T is not zero, $\int_1^2 dS = S_2 - S_1 = 0$ => S = constant, isentropic

Isentropic process is reversible and adiabatic.

Definitions:

Entropy = The property which remains constant in an adiabatic, reversible process

Temperature = The property which remains constant in an isothermal process

T dS Relationships

Let’s relate change in entropy to other properties

$$\left.\begin{array}{l} \delta Q\big|_{rev} - \delta W\big|_{rev} = dU \\ T\,dS - P\,d\forall = dU \end{array}\right\}$$

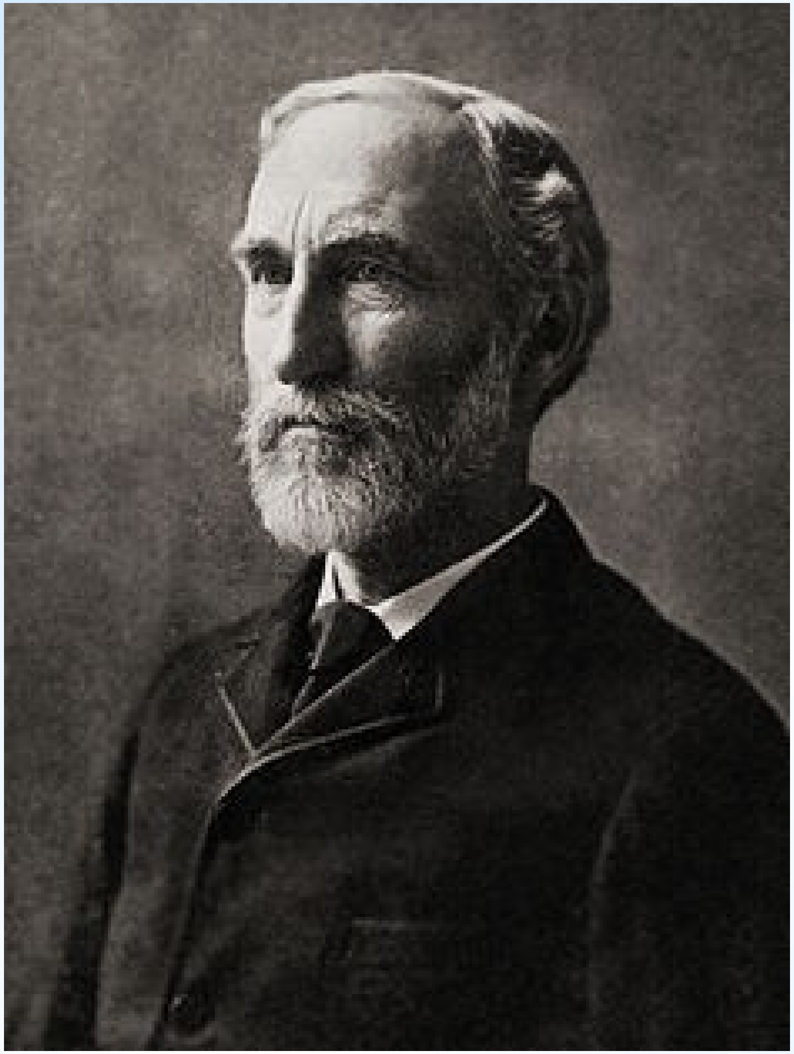
Divide through by mass:

$$\boxed{T\,ds = du + P\,dv \qquad \text{Gibbs Equation}}$$

Recall $h = u + P\,v$ $\quad dh = d(u + P\,v) = du + P\,dv + v\,dP$

$$\boxed{T\,ds = dh - v\,dP}$$

Rearranging $\quad \boxed{ds = \frac{du}{T} + \frac{P\,dv}{T} = \frac{dh}{T} - \frac{v\,dP}{T}}$



Josiah Willard Gibbs

US physicist and chemist

1839 - 1903

For a liquid (incompressible), $dv = 0$

$c_p = c_v = c$ and $du = c\,dT$

Therefore, $\boxed{ds = c\,\dfrac{dT}{T}}$

Integrating: $\boxed{s_2 - s_1 = c\ln\left(\dfrac{T_2}{T_1}\right)}$ Reversible process 1 to 2

If $T_1 = T_2$, then $\Delta s = 0$

The temperature of an incompressible substance remains constant during an isentropic process.

This is closely approximated by liquids and solids.

Example 1

A block of iron weighing 100 kg and having a temperature of 100 C is immersed in 50 kg of water at a temperature of 20 C. What will be the change in entropy of the combined system of iron and water?

Specific heats of iron and water are 0.45 kJ/kg.K and 4.18 kJ/kg.K, respectively.

Let T_f be the final temperature of the system after it reaches thermal equilibrium.

Energy balance: $$\left[m\, c_p\, (T - T_f)\right]_{iron} = \left[m\, c_p\, (T - T_f)\right]_{water}$$

$$(100)\,(0.45)\,(373 - T_f) = (50)\,(4.18)\,(T_f - 293) \quad \Rightarrow \quad T_f = 307.3\ \text{K}$$

$$\Delta S_{total} = \Delta S_{iron} + \Delta S_{water}$$

For solids and liquids: $d\forall = 0$ and $\Delta S = m\, c_p\, \ln\left(\dfrac{T_f}{T}\right)$

Why negative?

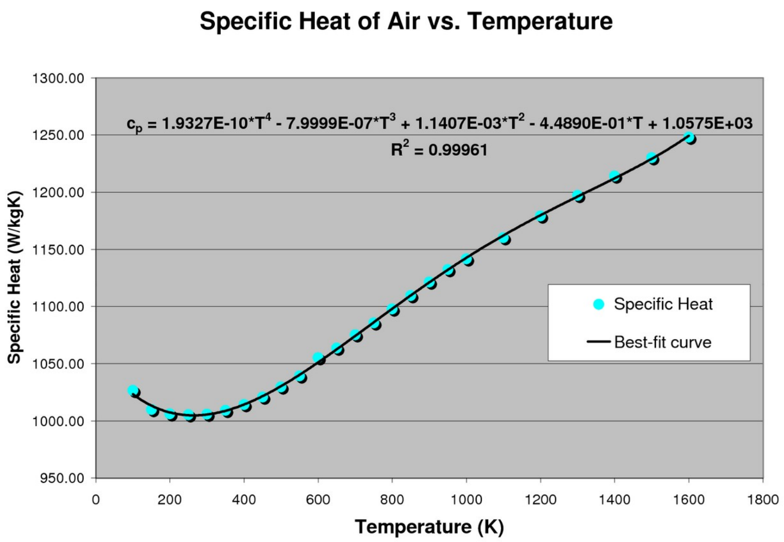
$$\left.\begin{aligned} \Delta S_{iron} &= (100)\,(450)\,\ln\left(\frac{307.3}{373}\right) = -\,8.7189\ \text{kJ/K} \\ \Delta S_{water} &= (50)\,(4180)\,\ln\left(\frac{307.3}{273}\right) = 9.9592\ \text{kJ/K} \end{aligned}\right\} \quad \begin{aligned} \Delta S_{total} &= -\,8.7189 + 9.9592 \\ &= 1.2403\ \text{kJ/K} \end{aligned}$$

Entropy Change of an Ideal Gas

$$\left.\begin{array}{l} P\,v = R\,T \\ du = c_v\,dT \\ T\,ds = du + P\,dv \end{array}\right\}$$

$$ds = c_v \frac{dT}{T} + R \frac{dv}{v}$$

$$s_2 - s_1 = \int_1^2 c_v(T) \frac{dT}{T} + R \ln\left(\frac{v_2}{v_1}\right)$$



Assuming constant specific heat:

$$s_2 - s_1 = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2}{v_1}\right)$$

Similarly, using enthalpy:

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

Isentropic Process with an Ideal Gas

$$s_2 - s_1 = 0 = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2}{v_1}\right) \qquad \ln\left(\frac{T_2}{T_1}\right) = -\frac{R}{c_v} \ln\left(\frac{v_2}{v_1}\right) = \ln\left(\frac{v_1}{v_2}\right)^{R/c_v}$$

Combine : $P\,v = R\,T$ and $P_1\,v_1^n = P_2\,v_2^n$ => $R = c_p - c_v$ and $k = \frac{c_p}{c_v}$

$$\left.\begin{aligned} \left.\frac{T_2}{T_1}\right|_{ds=0} &= \left(\frac{v_1}{v_2}\right)^{k-1} \quad \text{(ideal gas)} \\ \left.\frac{T_2}{T_1}\right|_{ds=0} &= \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \quad \text{(ideal gas)} \\ \left.\frac{P_2}{P_1}\right|_{ds=0} &= \left(\frac{v_1}{v_2}\right)^{k} \end{aligned}\right\}$$

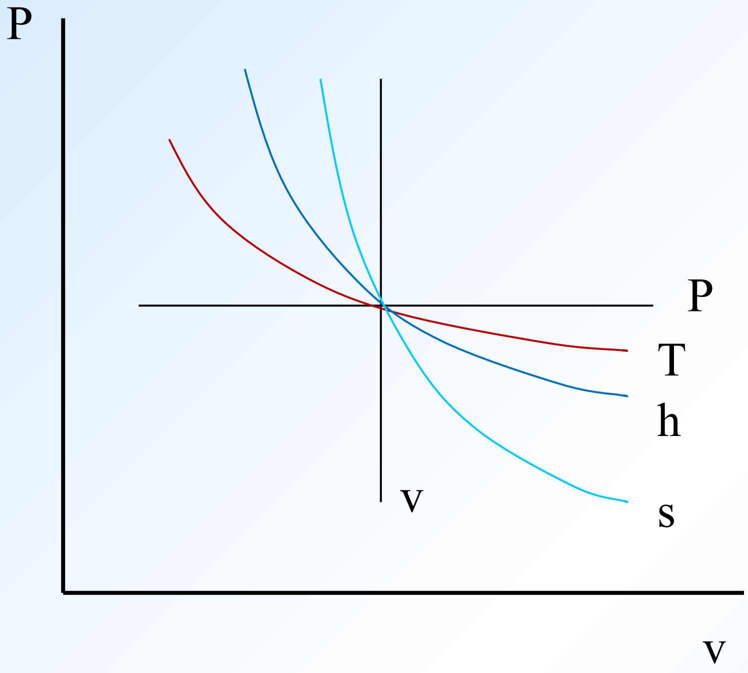
Or

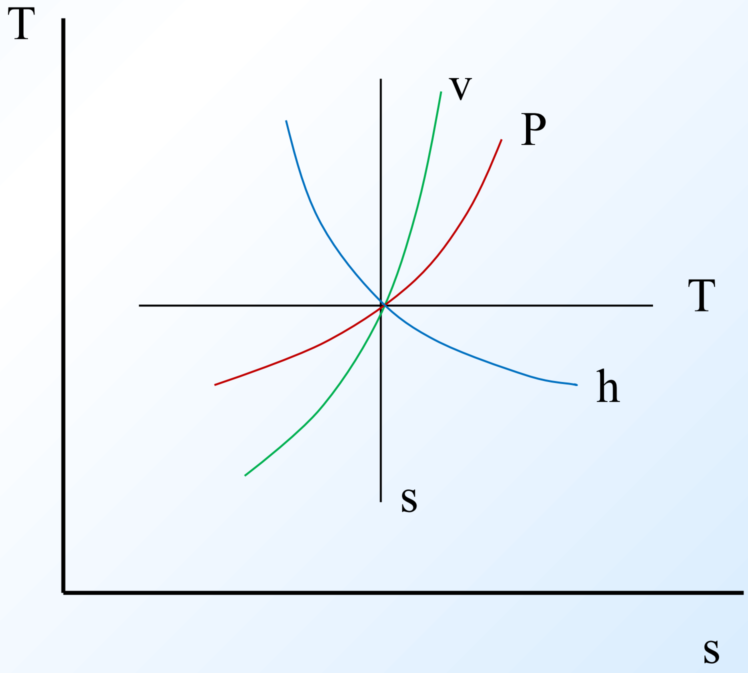
$T\,v^{k-1} = \text{constant}$

$T\,P^{\frac{1-k}{k}} = \text{constant}$

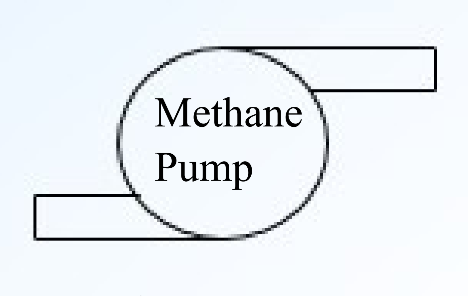
$P\,v^{k} = \text{constant}$

Iso-processes on P-v and T-s diagrams





Example 2 – Cryogenic Methane Pump



$P_2 = 5$ MPa
$T_2 = 120$ K

$P_1 = 1$ MPa
$T_1 = 110$ K

Liquid methane is used in cryogenic applications. Determine the entropy change in the liquid methane as it passes through a pump

(a) From property data

(b) Assuming totally incompressible liquid. Error using this?

Note that the critical temperature of methane is 191 K (- 82 °C) temperature below which methane remains liquid.

State 1: P_1 = 1 Mpa

T_1 = 110 K

s_1 = 4.875 kJ/kg.K

c_{p1} = 3.471 kJ/kg.K

State 2: P_2 = 5 Mpa

T_2 = 120 K

s_2 = 5.145 kJ/kg.K

c_{p2} = 3.486 kJ/kg.K

$s_1 – s_2$ = 0.270 kJ/kg.K

Note that c_p has 0.43+ change

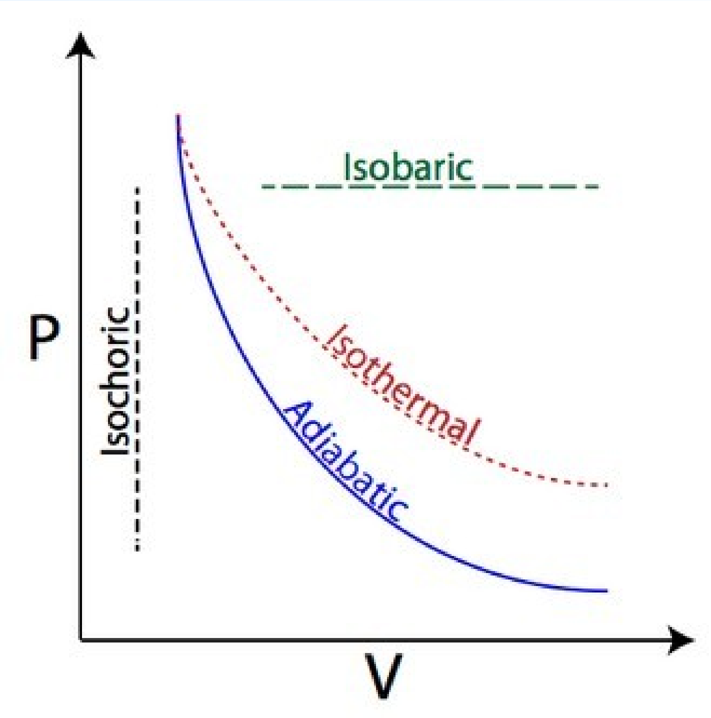
$$s_2 - s_1 = c \ln\left(\frac{T_2}{T_1}\right) \quad , \quad c_{p,avg} = 3.4785 \text{ kJ/kg.K}$$

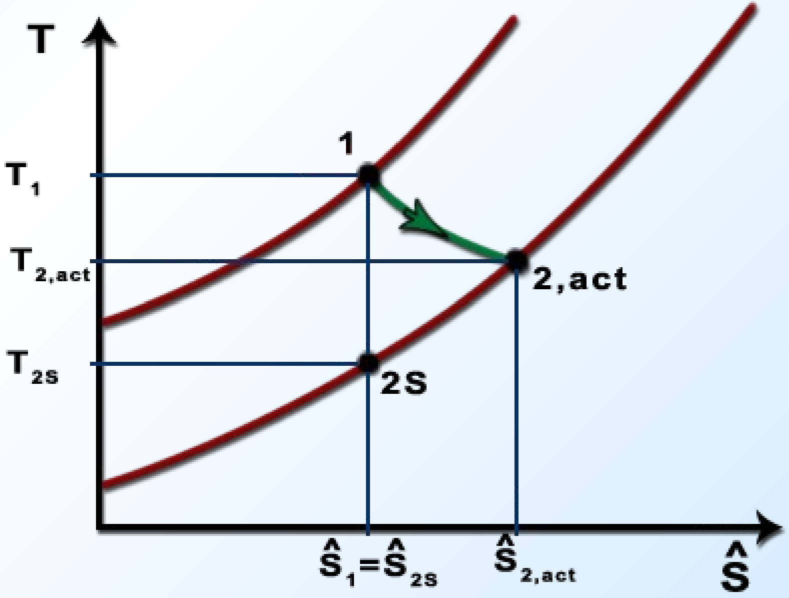
$$s_2 - s_1 = (3.4785 \text{ kJ/kg.K}) \ln\left(\frac{120 \text{ K}}{110 \text{ K}}\right) = 0.303 \text{ kJ/kg.K}$$

$$\text{Error} = \left(\frac{\Delta s_{actual} - \Delta s_{ideal}}{\Delta s_{actual}}\right) = 0.122 \quad \Rightarrow \quad 12.2\ \%$$

Expansion of and Ideal Gas

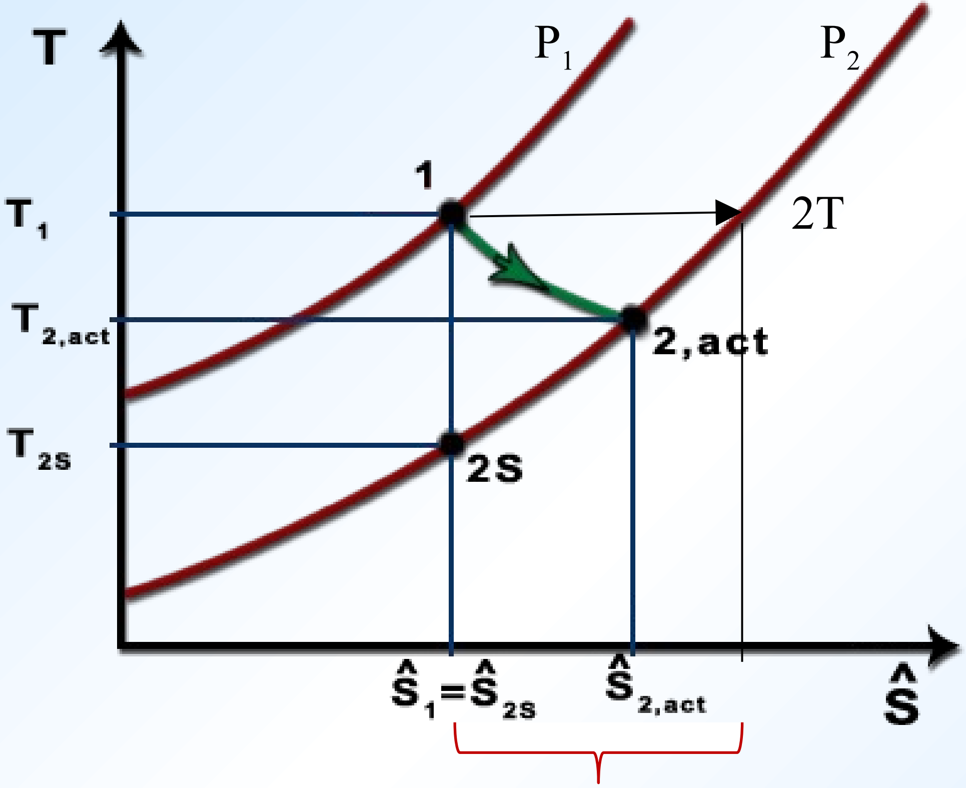
Adiabatic Expansion, Q = 0





$$\Delta s = c_p \ln\left(\frac{T_2}{T_1}\right) \qquad T_2 = T_1\, e^{\Delta s / c_p}$$

Adiabatic Expansion of an Ideal Gas, Q = 0



Irreversibility in expansion

1 –> 2 s

Reversible, adiabatic => isentropic

$$\frac{T_1}{T_{2s}} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

1 –> 2 T

Unstrained expansion => throttling

Most irreversible process

Energy is dissipated in fluid friction

1 –> 2_{act}

Irreversible expansion

First Law for a Turbine

$$- \dot{W} = \dot{m} \left(e_{out} - e_{in} \right) \qquad e = u + P v + \boxed{\frac{1}{2} V^2 + g z} \rightarrow \text{Small change}$$

$$- \dot{W} = \dot{m} \left(e_{out} - e_{in} \right) = \dot{m} \left[\left(u + P v \right)_{out} - \left(u + P v \right)_{in} \right] = \dot{m} \left(h_{out} - h_{in} \right)$$

For Process 1 -> 2s: $_1\dot{W}_{2s} = \dot{m} \left(h_1 - h_{2s} \right)$ Reversible

For Process 1 -> 2: $_1\dot{W}_2 = \dot{m} \left(h_1 - h_2 \right)$ Irreversible

The degree of irreversibility is given by adiabatic turbine efficiency, η_T

also known as polytropic turbine efficiency and isentropic turbine efficiency

$$\eta_T = \frac{\text{energy sought}}{\text{energy cost}} = \frac{\text{actual work}}{(\text{actual work}) + (\text{lost work})} = \frac{\text{actual work}}{\text{ideal work}}$$

$$\eta_T = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

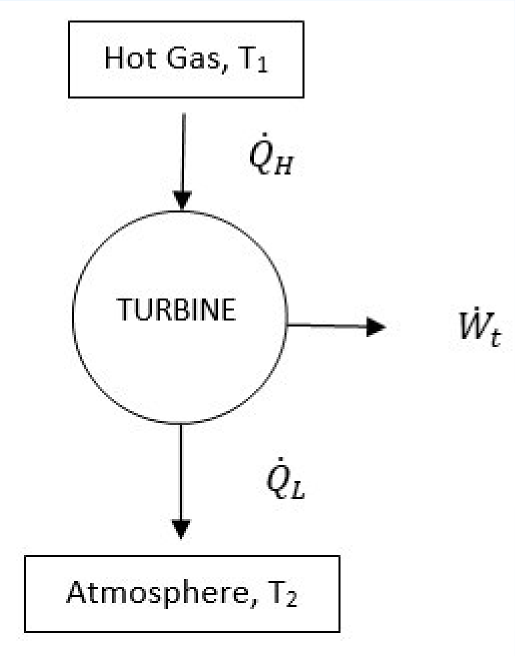
For an Ideal Gas with constant specific heats: $h_1 - h_2 = c_p\,(T_1 - T_2)$

$$\eta_T = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{T_1 - T_2}{T_1 - T_{2s}}$$

We can now state that the change in entropy is a measure of available energy (or exergy), e.g., the portion of heat that cannot be converted to work.

Example 3

Air expands in a gas turbine from 10 atm and 2000 °F to 1 atm and 1050 °F at the exhaust. Assuming a constant specific heat of 0.24 Btu/lbm.°F, find the turbine work and adiabatic turbine efficiency.



First law for a turbine:

$$\cancel{\dot{Q}} - \dot{W} = \frac{\partial}{\partial t}\cancel{\int_{C\forall} e\,\rho\, d\forall} + \int_{CS} e\,\rho\,(\vec{V}\cdot\hat{n})\, dA$$

= 0, adiabatic   = 0, steady state

$$-\dot{W} = \int_{Out} e\,\rho\,|V|\, dA - \int_{In} e\,\rho\,|V|\, dA$$

Recall: $\vec{V}\cdot\hat{n} < 0$ for in flow

$\vec{V}\cdot\hat{n} > 0$ for exit flow

Conservation of mass: $\dot{m} = \text{constant} = \int_{CS} e\, \rho\, (\underset{\sim}{V} . \vec{n})\, dA$

Assume uniform flow; that is, we can use the average value of the properties on the control surface (CS) inlet and outlet areas.

$$\int_{CS} e\, \rho\, (\underset{\sim}{V} . \vec{n})\, dA = \rho\, (\underset{\sim}{V} . \vec{n}) \int_{CS} dA = \rho\, (\underset{\sim}{V} . \vec{n})\, A = \mp\, \rho\, V\, A = \mp\, \dot{m}$$

First law again: $- \dot{W} = \dot{m}\, \left(e_{out} - e_{in}\right)$

neglect; little change in velocity
in and out of turbine

$$e = \tilde{u} + \underbrace{\frac{1}{\rho}\, P}_{P\,v} + \cancel{\frac{1}{2} V^2} + \cancel{g\, z} = \tilde{u} + P\, v = \tilde{h}$$

internal energy

neglect

enthalpy

$$-\dot{W}_T = \dot{m}\left(e_{out} - e_{in}\right) = \dot{m}\left(h_{out} - h_{in}\right) \longleftarrow$$

since we are extracting work,
$h_{out} < h_{in}$

Therefore, $\dfrac{\dot{W}_T}{\dot{m}} = w_T = \Delta h$

For an ideal gas, $w = \Delta h = c_p\ \Delta T$ adiabatic expansion

$$w_T = (0.24\ \text{Btu/lbm.F})\ (2000\ \text{F} - 1050\ \text{F}) = 228\ \text{Btu/lbm}$$

The adiabatic turbine efficiency is defined as: $\eta_T = \dfrac{h_1 - h_2}{\underbrace{h_1 - h_{2s}}_{\text{Adiabatic, reversible process}}}$

For an ideal gas: $\Delta h = c_p \, \Delta T$, and

for constant specific heat:

$$\eta_T = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{T_1 - T_2}{T_1 - T_{2s}}$$

Need to calculate the adiabatic, reversible, expansion temperature, T_{2s}

For an ideal gas and polytropic process

Equation of state: $P \, \forall = R \, T$

Equation of process: $P \, \forall^n = \text{constant}$

$$\frac{P_1 \, \forall_1}{T_1} = \frac{P_2 \, \forall_2}{T_2} \quad \Rightarrow \quad \frac{\forall_1}{\forall_2} = \frac{P_2 \, T_1}{P_1 \, T_2}$$

$$P_1 \, \forall_1^n = P_2 \, \forall_2^n \quad \Rightarrow \quad \frac{\forall_1}{\forall_2} = \left(\frac{P_2}{P_1}\right)^{1/n}$$

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{(n-1)/n}$$

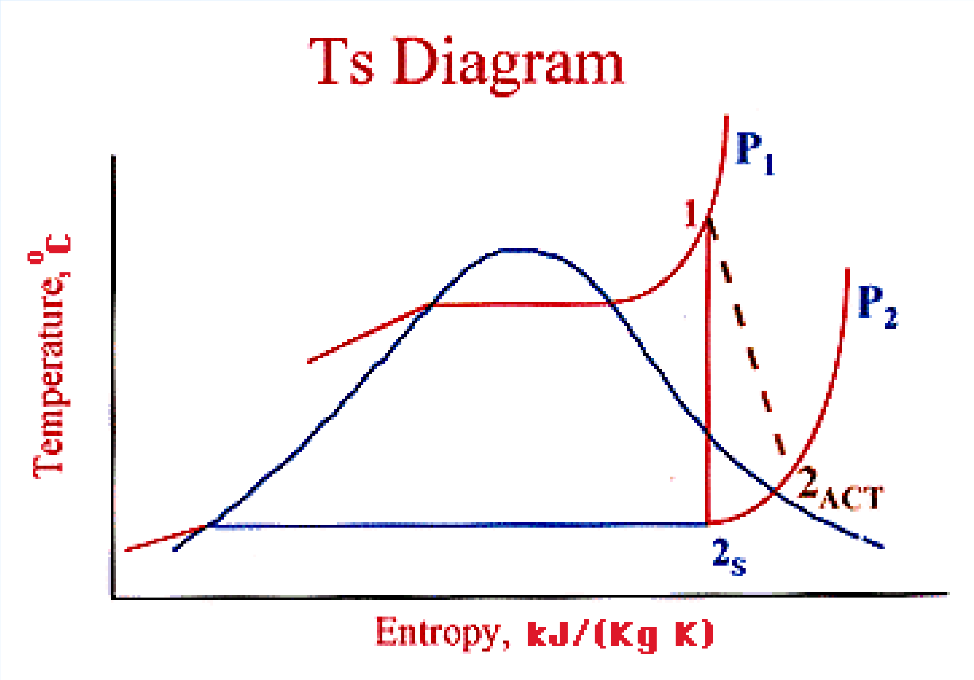
For a reversible, adiabatic expansion: $T_2 = T_{2s}$ and $n = k = c_p/c_v$

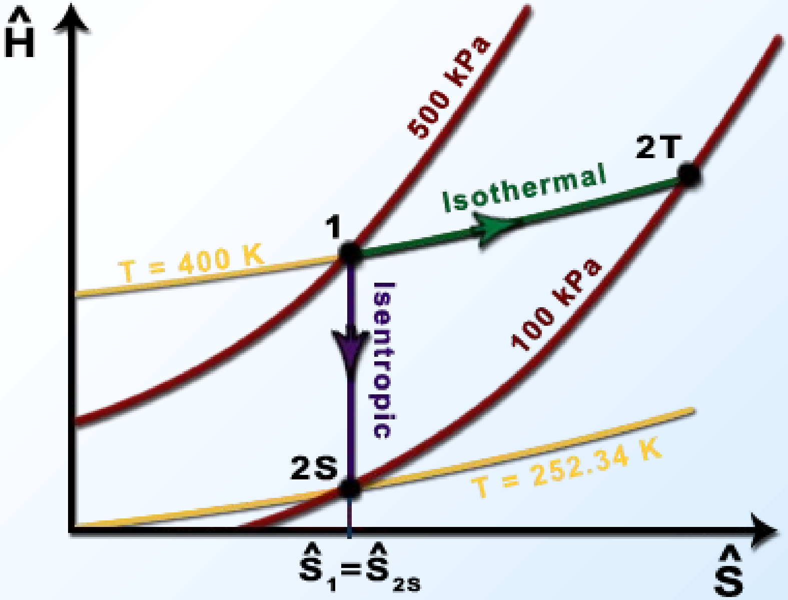
For air: $k = 1.4$

$$T_{2s} = T_1 \left(\frac{P_1}{P_2}\right)^{(k-1)/k} = (2000 + 460\ \text{R}) \left(\frac{1\ \text{atm}}{10\ \text{atm}}\right)^{(1.4-1)/1.4} = 814\ \text{F}$$

$$\eta_T = \frac{T_1 - T_2}{T_1 - T_{2s}} = \frac{2000 - 1050}{2000 - 814} = 0.801 \quad \Rightarrow \quad 80.1\ \%$$

Vapor (Steam) Expansion

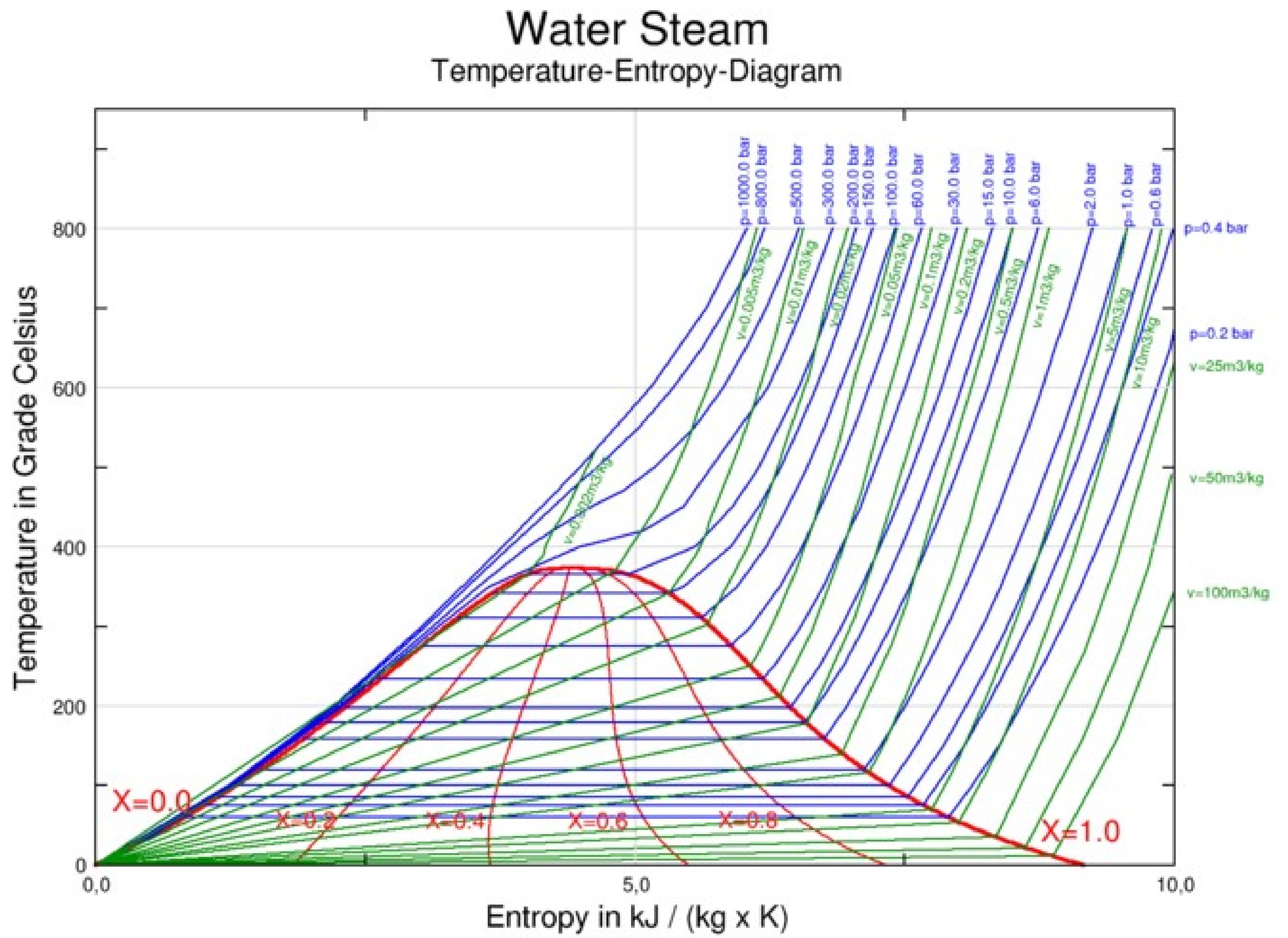


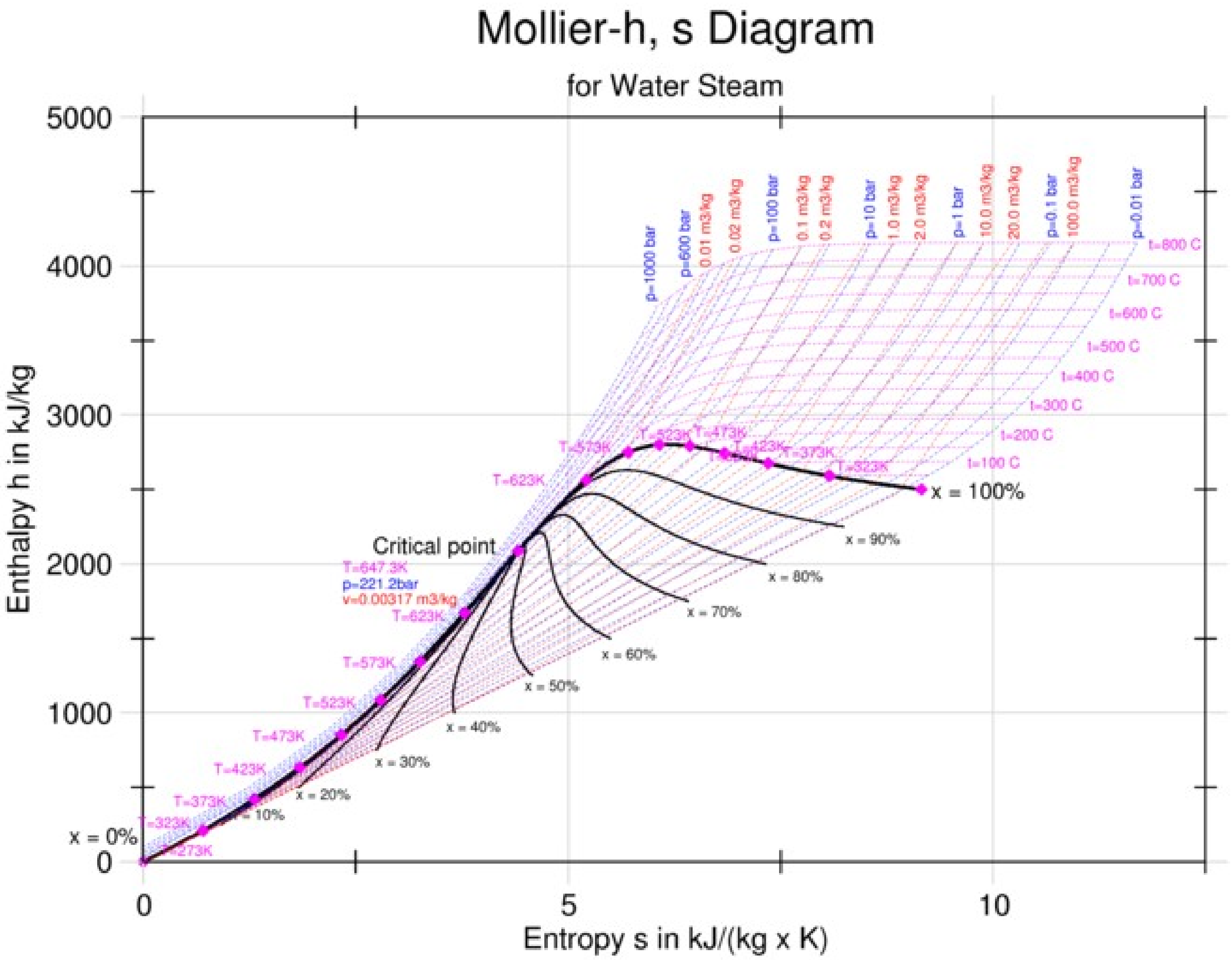


$T_{2s} = T_{act}$ if in the two-phase region

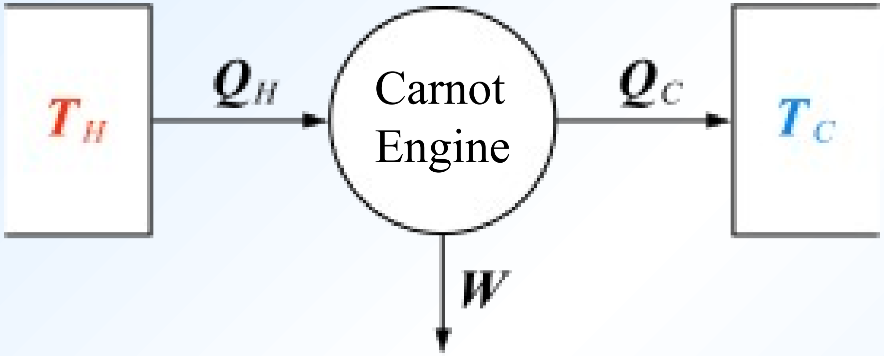
$h_2 > h_{2s}$ exit enthalpy is greater in the irreversible case

$$\eta_T = \frac{h_1 - h_2}{h_1 - h_{2s}}$$ degree of irreversibility


Water Steam
Temperature-Entropy-Diagram
Temperature in Grade Celsius
Entropy in kJ / (kg x K)
0
200
400
600
800
0,0
5,0
10,0
p=1000.0 bar
p=800.0 bar
p=500.0 bar
p=300.0 bar
p=200.0 bar
p=150.0 bar
p=100.0 bar
p=60.0 bar
p=30.0 bar
p=15.0 bar
p=10.0 bar
p=6.0 bar
p=2.0 bar
p=1.0 bar
p=0.6 bar
p=0.4 bar
p=0.2 bar
v=0.002m3/kg
v=0.005m3/kg
v=0.01m3/kg
v=0.02m3/kg
v=0.05m3/kg
v=0.1m3/kg
v=0.2m3/kg
v=0.5m3/kg
v=1m3/kg
v=5m3/kg
v=10m3/kg
v=25m3/kg
v=50m3/kg
v=100m3/kg
X=0.0
X=0.2
X=0.4
X=0.6
X=0.8
X=1.0


Mollier-h, s Diagram
for Water Steam
5000
4000
3000
2000
1000
0
0
5
10
Enthalpy h in kJ/kg
Entropy s in kJ/(kg x K)
p=1000 bar
p=600 bar
0.01 m3/kg
0.02 m3/kg
p=100 bar
0.1 m3/kg
0.2 m3/kg
p=10 bar
1.0 m3/kg
2.0 m3/kg
p=1 bar
10.0 m3/kg
20.0 m3/kg
p=0.1 bar
100.0 m3/kg
p=0.01 bar
t=800 C
t=700 C
t=600 C
t=500 C
t=400 C
t=300 C
t=200 C
t=100 C
x = 100%
x = 90%
x = 80%
x = 70%
x = 60%
x = 50%
x = 40%
x = 30%
x = 20%
x = 10%
x = 0%
Critical point
T=647.3K
p=221.2bar
v=0.00317 m3/kg
T=623K
T=573K
T=523K
T=473K
T=423K
T=373K
T=323K
T=273K

Revisiting Carnot Cycle



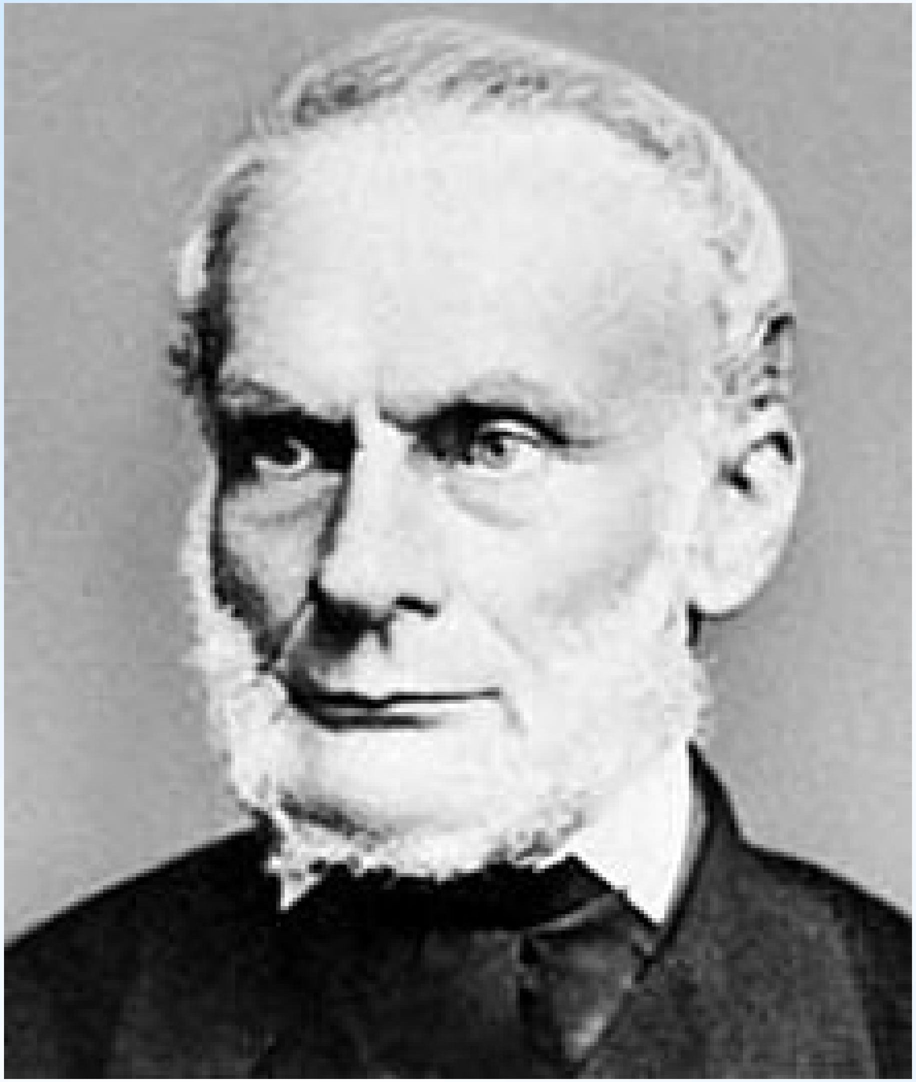
Carnot's theorem: *No engine operating between two heat reservoirs can be more efficient than a Carnot engine operating between the same reservoirs.*

This maximum efficiency can be defined as: $\eta_{Carnot} = \dfrac{W}{Q_H} = 1 - \dfrac{T_C}{T_H}$

Nicolas Léonard Sadi Carnot

French Mechanical Engineer

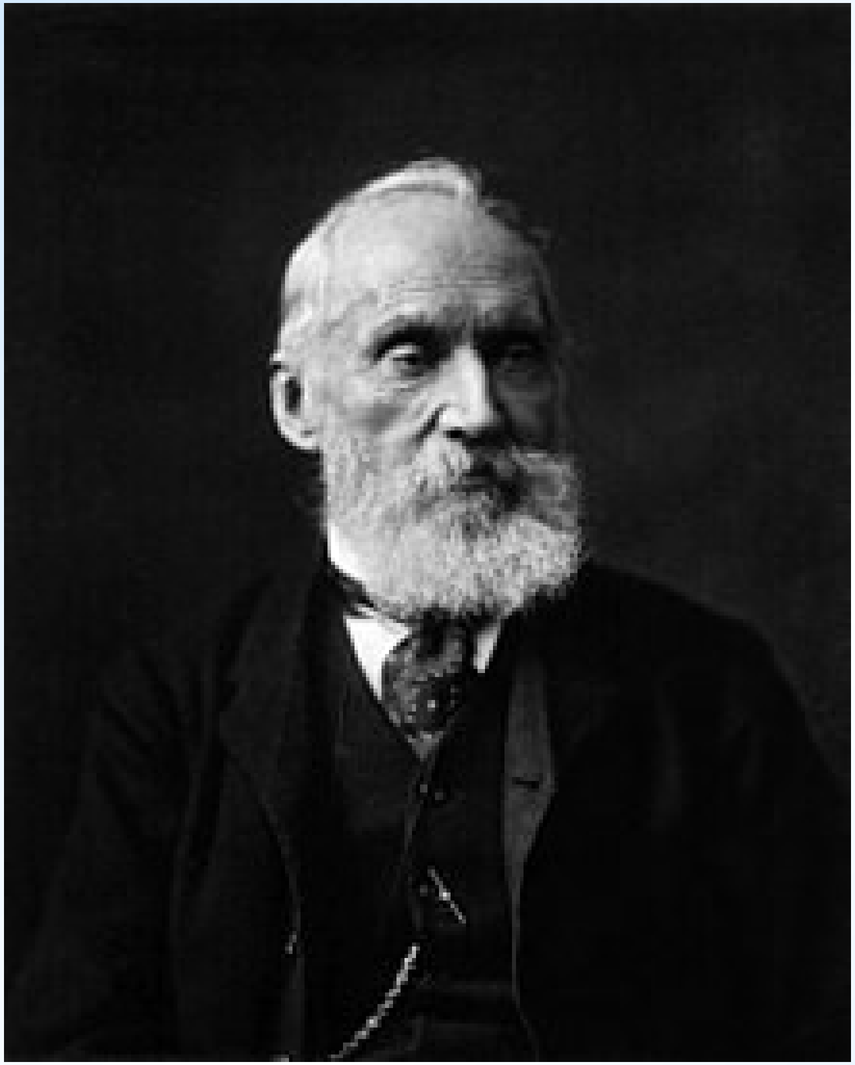
1796 - 1832



Rudolf Julius Emanuel Clausius

German Physicist

1822 - 1888



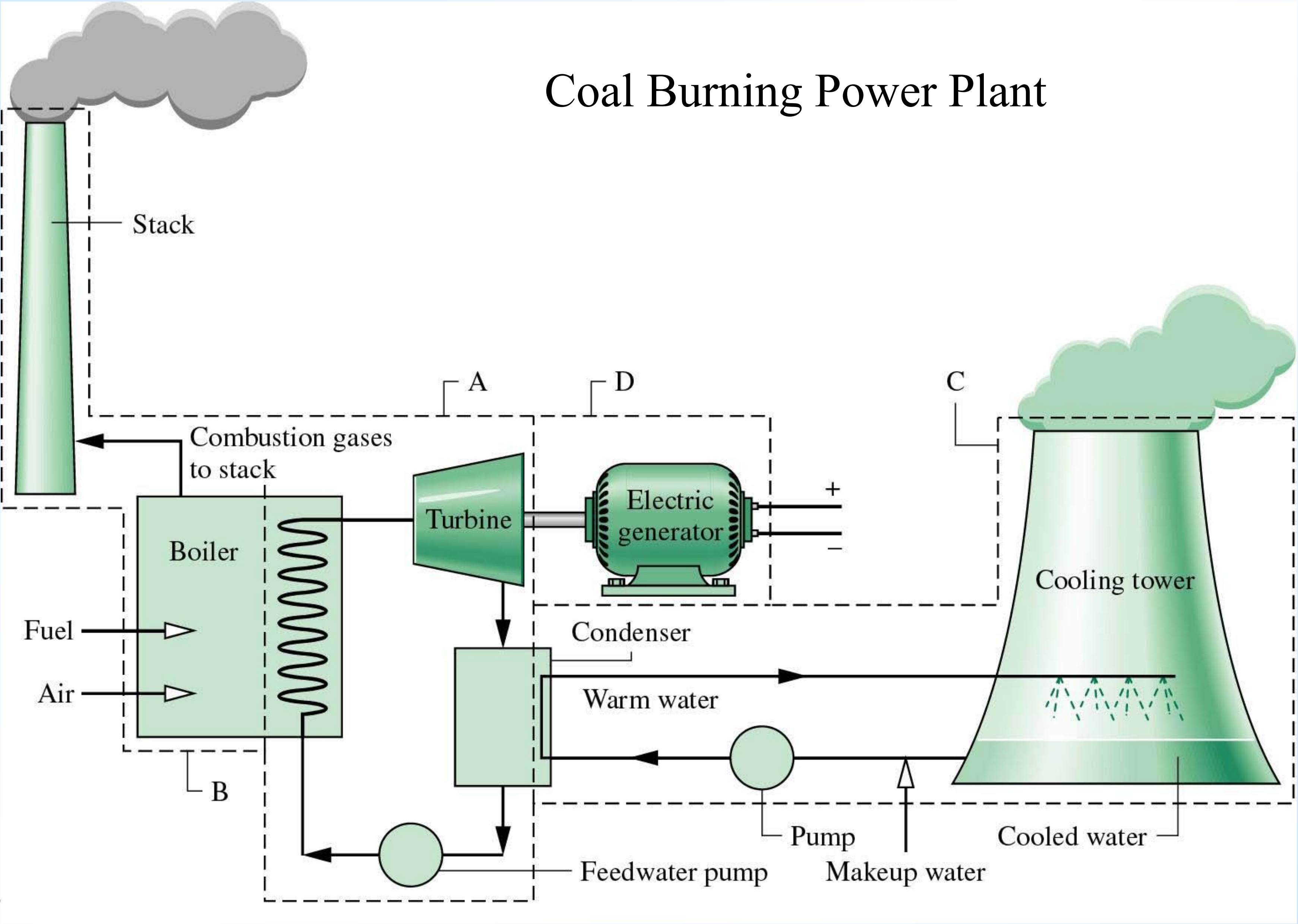
William Thomson

(Lord Kelvin)

British Mathematical Physicist

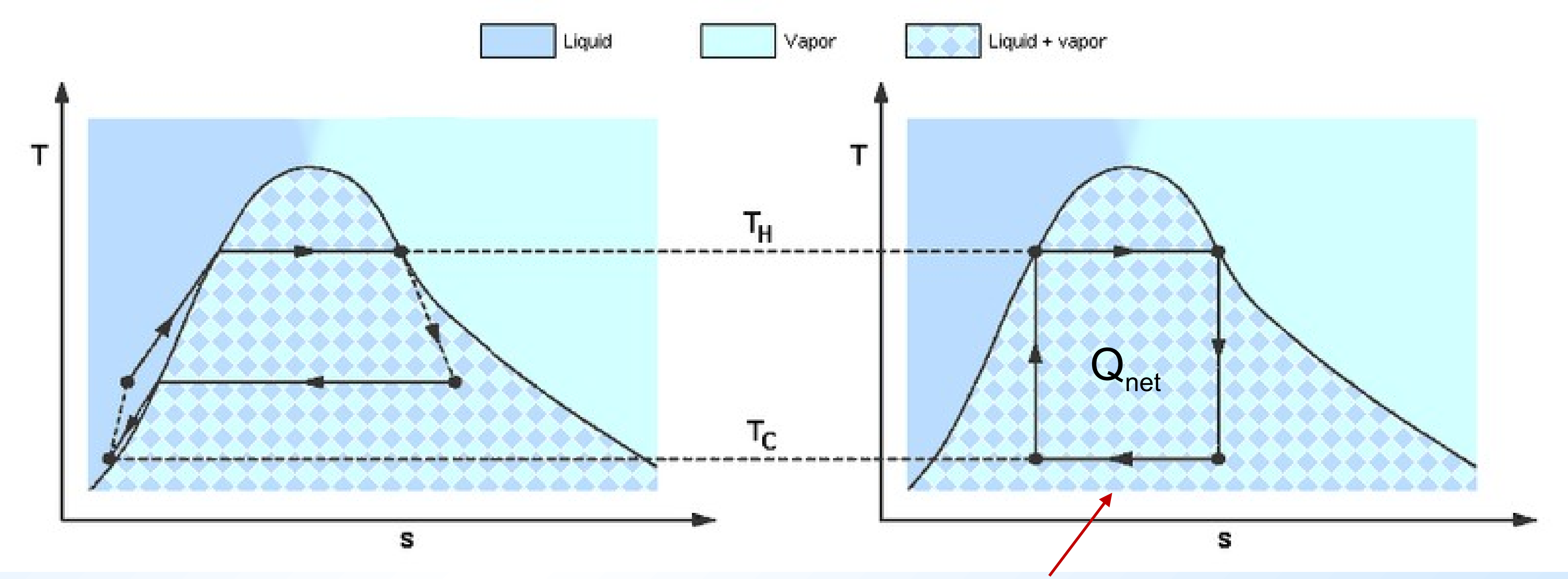
1824 - 1907

Coal Burning Power Plant



Real, ideal engine

Carnot cycle



Heat which is not available

for conversion to work

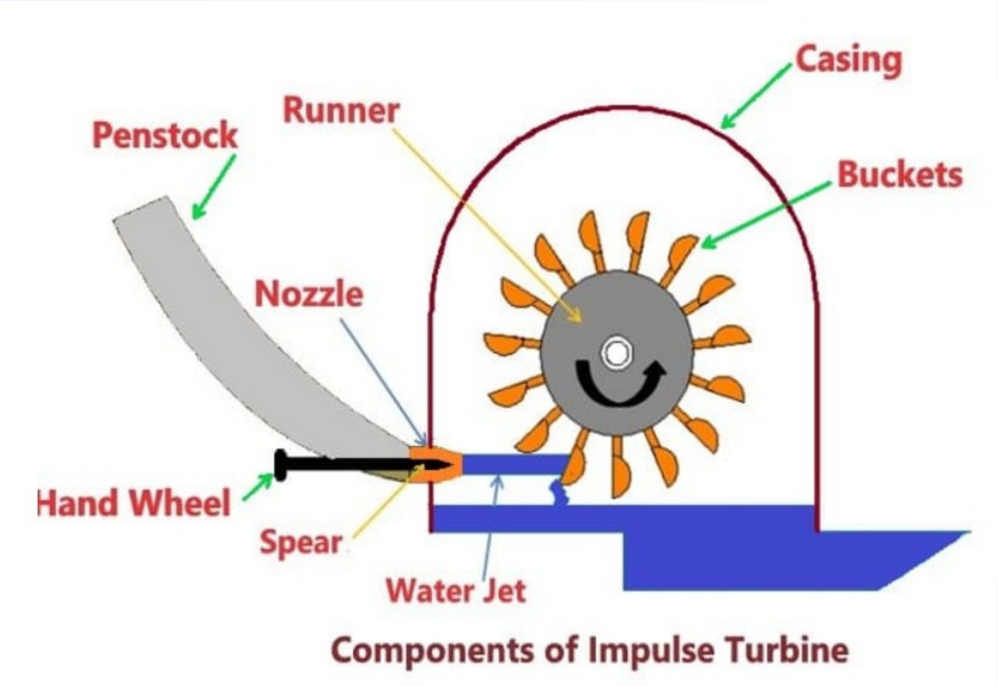
Example 4

A cryogenic manufacturing facility handles liquid methane at 115 K and 5 MPa at a rate of 0.280 m^3/s. A process requires dropping the pressure of the liquid methane to 1 MPa, which is accomplished by throttling the liquid methane by passing it through a valve (flow restrictor).

A recently hired engineer proposes to replace the throttling valve with a turbine in order to produce power while dropping the pressure to 1 MPa.

(a) Determine the maximum power that the turbine can produce

(b) Determine how much this turbine could save the facility in electricity costs per year if the turbine operates continuously and if the facility pays 0.15 TL/kWh on average for electricity.



Assumptions:

- Adiabatic
- Reversible
- Steady flow
- Uniform flow
- Negligible change in KE
- Negligible change in PE

State 1: $P_1 = 5$ Mpa

$T_1 = 115$ K

$h_1 = 232.2$ kJ/kg

$s_1 = 4.9945$ kJ/kg.K

$\rho_1 = 422.15$ kg/m^3

State 2: $P_2 = 1$ Mpa

$s_2 = s_1$

$h_2 = 222.8$ kJ/kg

■ =

First Law: $${}_1\cancel{\dot{Q}}_2 - {}_1\dot{W}_2 = \dot{m}\,(e_2 - e_1) = \dot{m}\,(h_2 - h_1)$$

$$\dot{m} = \rho_1\,\dot{\forall}_1 = (422.15)\,(0.280) = 118.2 \text{ kg/s}$$

$$-\dot{W}_t = (118.2 \text{ kg/s})\,(222.8 \text{ kJ/kg} - 232.2 \text{ kJ/kg})$$

$$\dot{W}_t = 1123 \text{ kW}$$

Annual power production:

$$\left(\dot{W}_t\right)(\Delta t) = (1123 \text{ kW})\,(8760 \text{ hr/year})$$

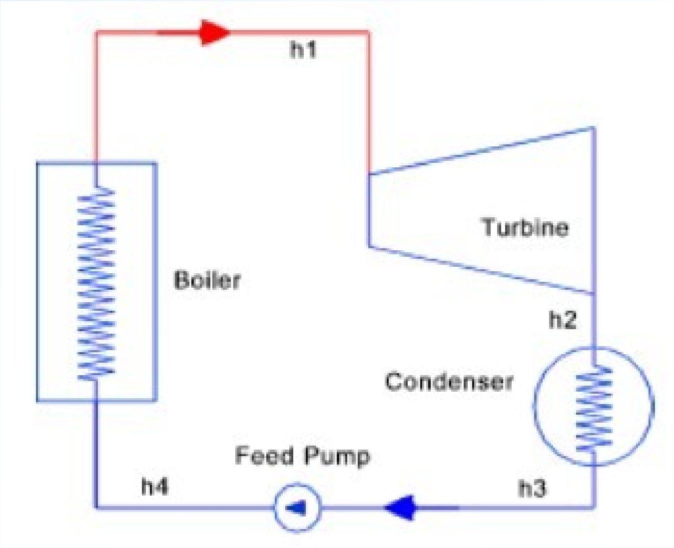
$$= 9.837\ 10^6 \text{ kWh/year}$$

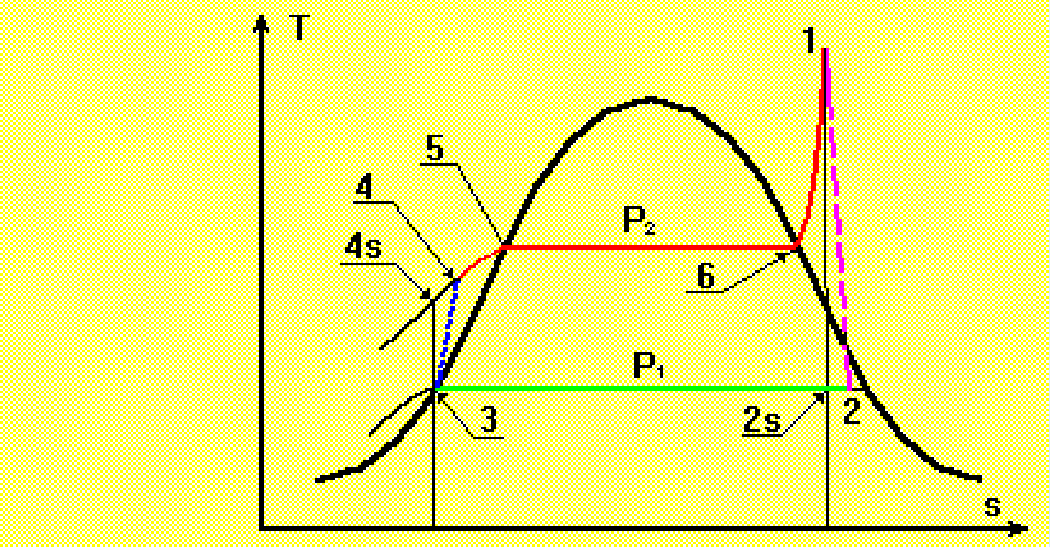
At \$0.075 kWh, annual saving = \$ 737 800 per year

Actual turbine about 80 % efficient => 900 kW => save \$ 600 000 per year

Example 5

A steam turbine is used to drive a feed water pump of a large utility boiler. A 17.78 kg/s flow of supercritical steam enters the turbine at 808.3 K and 23.26 MPa. The steam exits the turbine at 5.249 kPa with a quality of 0.9566. Determine the power produced by the turbine and the turbine isentropic efficiency.





T-s diagram for a Rankine cycle.

State 1 – Supercritical steam: $T_1 = 808.3$ K, $P_1 = 23.26$ MPa $\rightarrow$ $h_1 = 3312.1$ kJ/kg, $s_1 = 6.1762$ kJ/kg.K

State 2 – Saturated liquid & vapor: $x_2 = 0.9566$, $P_2 = 5.249$ kPa $\rightarrow$ $h_{f2} = 141.38$ kJ/kg, $h_{g2} = 2562.3$ kJ/kg, $s_{f2} = 0.48803$ kJ/kg.K, $s_{g2} = 8.3765$ kJ/kg.K

$$h_2 = (1 - x_2)\, h_{f2} + x_2\, h_{g2} = 2457.2 \text{ kJ/kg}$$

$$s_2 = (1 - x_2)\, s_{f2} + x_2\, s_{g2} = 8.0341 \text{ kJ/kg.K}$$

$$s_{2s} = s_1 = 6.1762 \text{ kJ/kg.K}$$

$$x_{2s} = \frac{s_{2s} - s_{2f}}{s_{2g} - s_{2f}} = 0.721$$

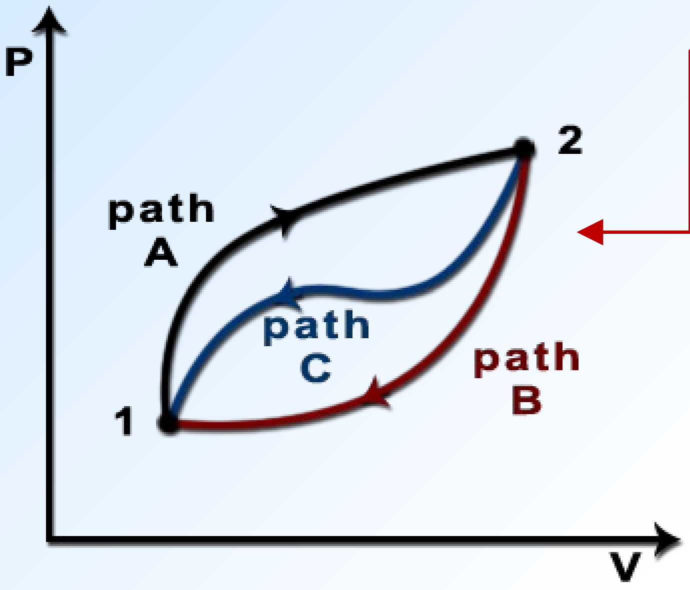
$$h_{2s} = (1 - x_{2s})\, h_{f2} + x_{2s}\, h_{g2} = 1887.0 \text{ kJ/kg}$$

Specific work: $w_T = h_1 - h_2 = 3312.1 - 2457.2 = 854.9$ kJ/kg

Power: $\dot{W}_T = \dot{m}\, w_T = (17.78 \text{ kg/s})\,(854.9 \text{ kJ/kg}) = 15\,200$ kW

Isentropic efficiency: $$\eta_T = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{3312.1 - 2457.2}{3312.1 - 1887.0} = 0.60 \quad \Rightarrow \quad 60\ \%$$

Polytropic Work



Work is different for each process

$$\text{Work} = \int_1^2 F\,dx$$

For a moving boundary:

$$\delta W = P\,d\forall \quad \Rightarrow \quad {}_1W_2 = \int_1^2 P\,d\forall$$

Polytropic process: $P\,\forall^n = \text{constant} = P_1\,\forall_1^n = P_2\,\forall_2^n = C$

$$\boxed{{}_1W_2 = \int_1^2 P\,d\forall = \frac{P_2\,\forall_2 - P_1\,\forall_1}{1-n}\,, \quad n \neq 1}$$

$$ {}_1W_2 = \int_1^2 P\, d\forall = \frac{P_2\, \forall_2 - P_1\, \forall_1}{1 - n} \quad , \quad n \neq 1 $$

When n = 1 (isothermal ideal gas):

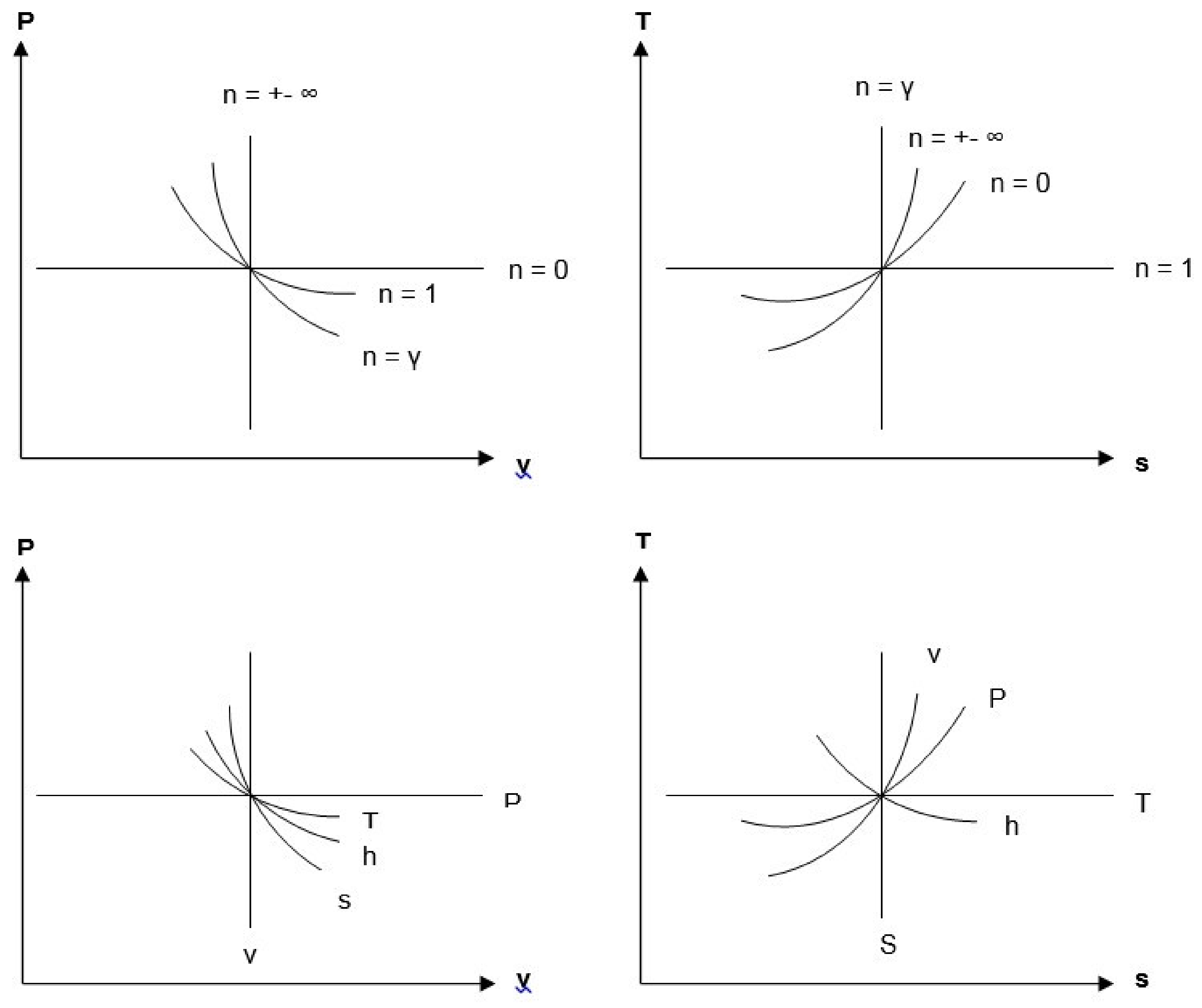
$$ {}_1W_2 = \int_1^2 P\, d\forall = C \int_1^2 \frac{d\forall}{\forall} = C\, \ln\left(\frac{\forall_2}{\forall_1}\right) = P_1\, \forall_1\, \ln\left(\frac{\forall_2}{\forall_1}\right) = P_2\, \forall_2\, \ln\left(\frac{\forall_2}{\forall_1}\right) $$

Process	**n**	**C**	$\int_1^2 P\, d\forall$
Constant temperature (Isothermal)	1	0	$P_1\, \forall_1\, \ln\left(\frac{\forall_2}{\forall_1}\right)$
Constant pressure (isobaric)	0	c_p	$P\, \Delta\forall$
Constant volume (isochoric)	∞	c_v	0

Polytropic Processes $P\,\forall^{n} = P_1\,\forall_1^{n} = P_2\,\forall_2^{n} = \text{constant}$

$$\delta Q = c\ m\ dT$$

Process	c	n
Constant Volume (Isochoric)	c_v	∞
Constant Pressure (Isobaric)	c_p	0
Constant Temperature (Isothermal)	∞	1
Adiabatic, Reversible (Isentropic)	0	$\gamma = c_p / c_v$
Polytropic	$c_v \left(\frac{\gamma - n}{1 - n} \right)$	0 to ∞


P
n = +- ∞
n = 0
n = 1
n = γ
v
T
n = γ
n = +- ∞
n = 0
n = 1
s
P
P
T
h
s
v
v
T
v
P
T
h
S
s

Perfect Gas Relationships – Constant Specific Heat

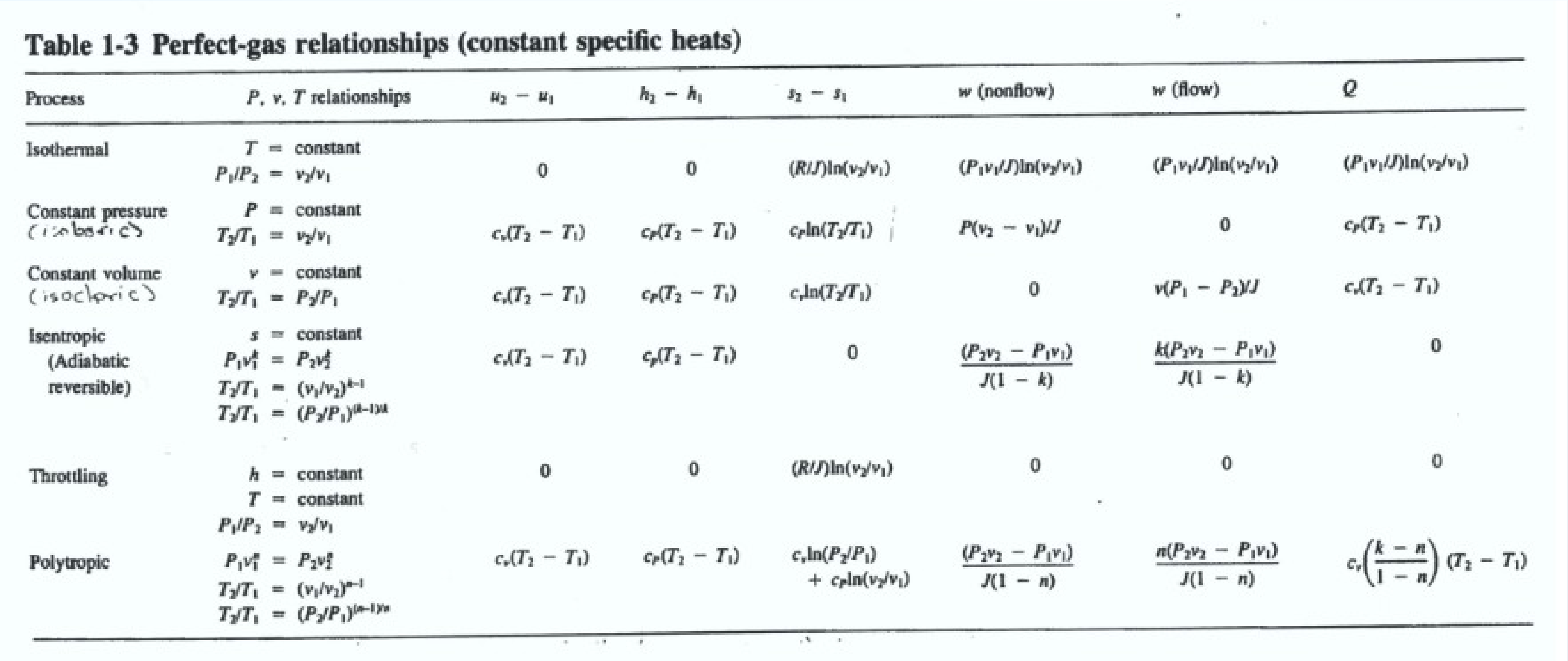


Table 1-3 Perfect-gas relationships (constant specific heats)

Process	P, v, T relationships	$u_2 - u_1$	$h_2 - h_1$	$s_2 - s_1$	w (nonflow)	w (flow)	Q
Isothermal	$T = \text{constant}$ $P_1/P_2 = v_2/v_1$	0	0	$(R/J)\ln(v_2/v_1)$	$(P_1v_1/J)\ln(v_2/v_1)$	$(P_1v_1/J)\ln(v_2/v_1)$	$(P_1v_1/J)\ln(v_2/v_1)$
Constant pressure (isobaric)	$P = \text{constant}$ $T_2/T_1 = v_2/v_1$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	$c_p\ln(T_2/T_1)$	$P(v_2 - v_1)/J$	0	$c_p(T_2 - T_1)$
Constant volume (isochoric)	$v = \text{constant}$ $T_2/T_1 = P_2/P_1$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	$c_v\ln(T_2/T_1)$	0	$v(P_1 - P_2)/J$	$c_v(T_2 - T_1)$
Isentropic (Adiabatic reversible)	$s = \text{constant}$ $P_1v_1^k = P_2v_2^k$ $T_2/T_1 = (v_1/v_2)^{k-1}$ $T_2/T_1 = (P_2/P_1)^{(k-1)/k}$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	0	$\dfrac{(P_2v_2 - P_1v_1)}{J(1 - k)}$	$\dfrac{k(P_2v_2 - P_1v_1)}{J(1 - k)}$	0
Throttling	$h = \text{constant}$ $T = \text{constant}$ $P_1/P_2 = v_2/v_1$	0	0	$(R/J)\ln(v_2/v_1)$	0	0	0
Polytropic	$P_1v_1^n = P_2v_2^n$ $T_2/T_1 = (v_1/v_2)^{n-1}$ $T_2/T_1 = (P_2/P_1)^{(n-1)/n}$	$c_v(T_2 - T_1)$	$c_p(T_2 - T_1)$	$c_v\ln(P_2/P_1)$ $+ c_p\ln(v_2/v_1)$	$\dfrac{(P_2v_2 - P_1v_1)}{J(1 - n)}$	$\dfrac{n(P_2v_2 - P_1v_1)}{J(1 - n)}$	$c_v\left(\dfrac{k - n}{1 - n}\right)(T_2 - T_1)$

$J = 1$ in SI system

See the Web site – Print a copy for yourself

Definitions:

Process: Transitions of a system from one equilibrium state to another

Path: Series of states that that a system passes through during a process

Quasi-equilibrium: process during which the system remains nearly in equilibrium

Iso-processes: process during which one property is constant

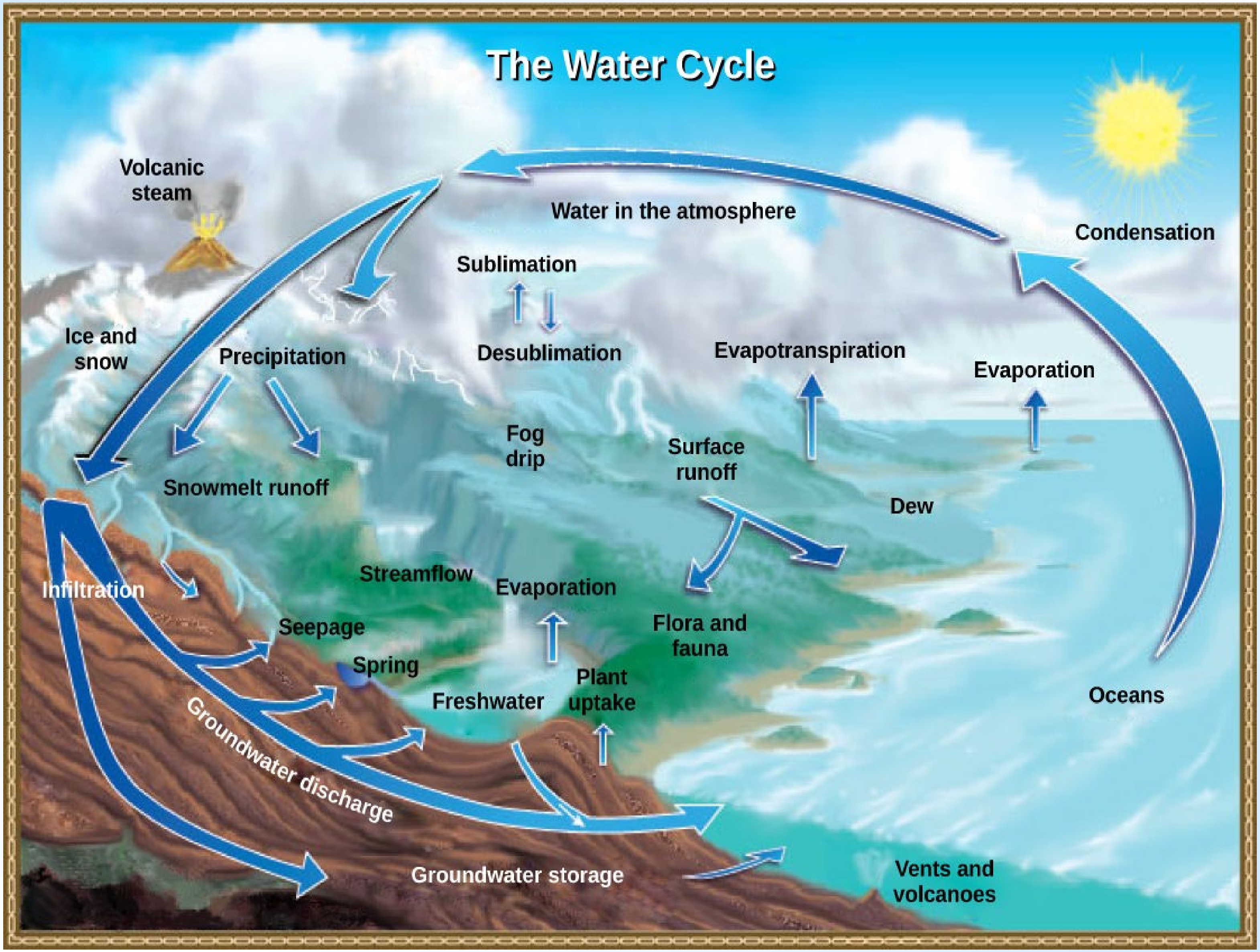
- Isochoric → volume is constant
- Isobaric → pressure is constant
- Isothermal → temperature is constant
- Isentropic → entropy is constant
- Adiabatic → no transitional thermal energy conversion

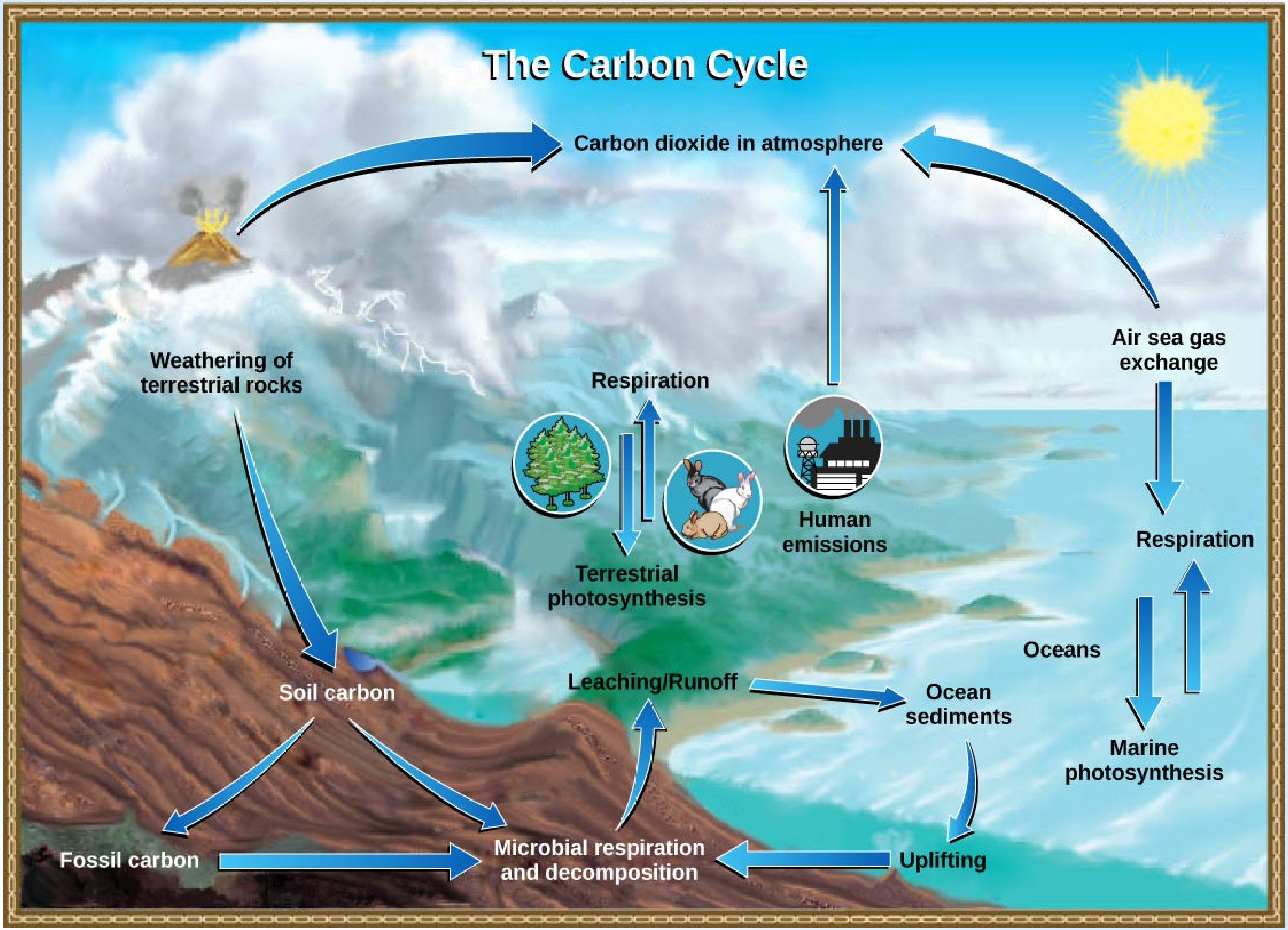
Cycle: succession of states in which the system ultimately returns to the initial state

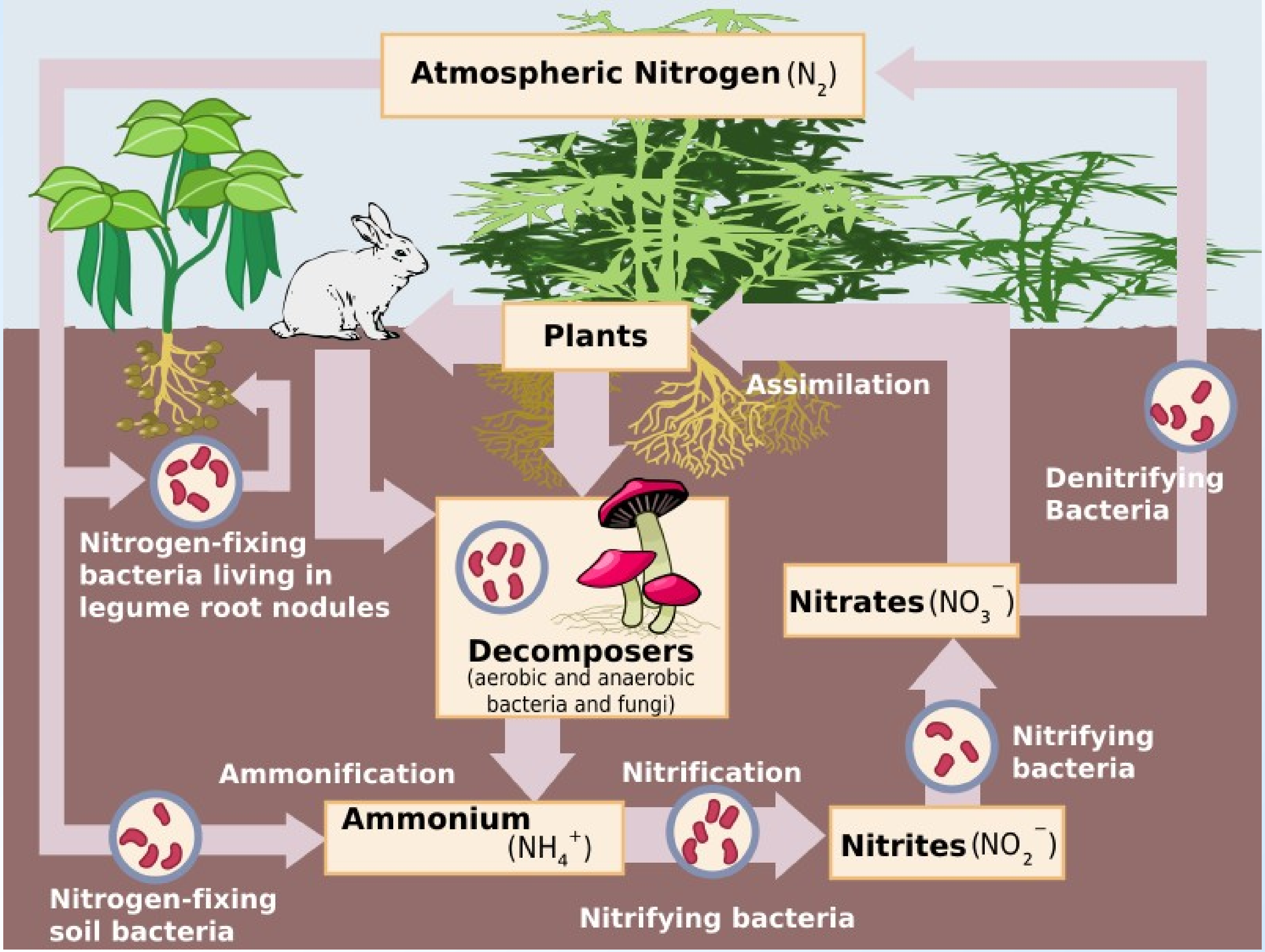
In order to convert forms of energy, particularly heat to work, on an extended and continuous basis, one needs to operate on a cycle.

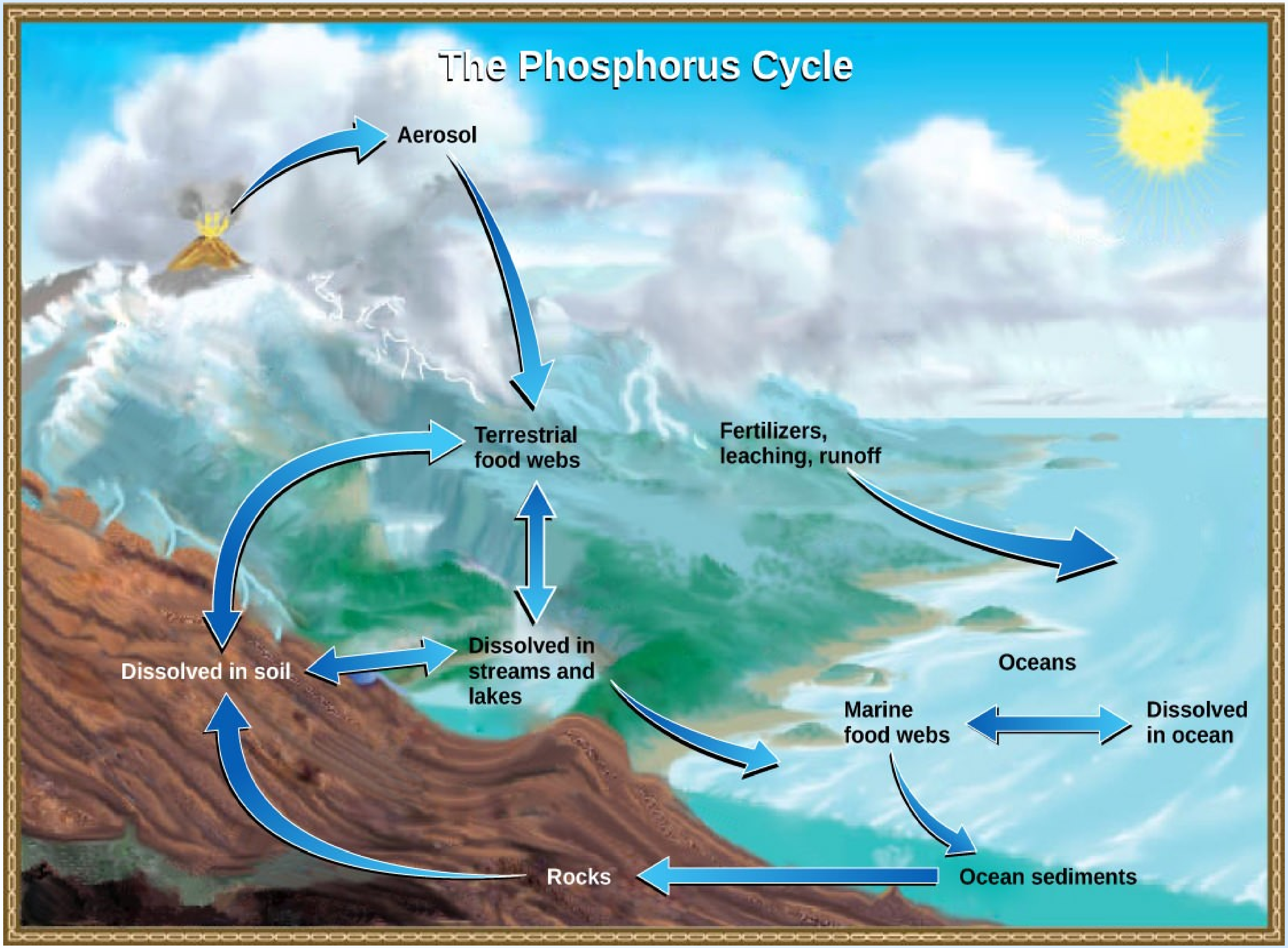
A cycle is a series of processes that begins and ends at the same state, thus can repeat indefinitely, or as long as needed.

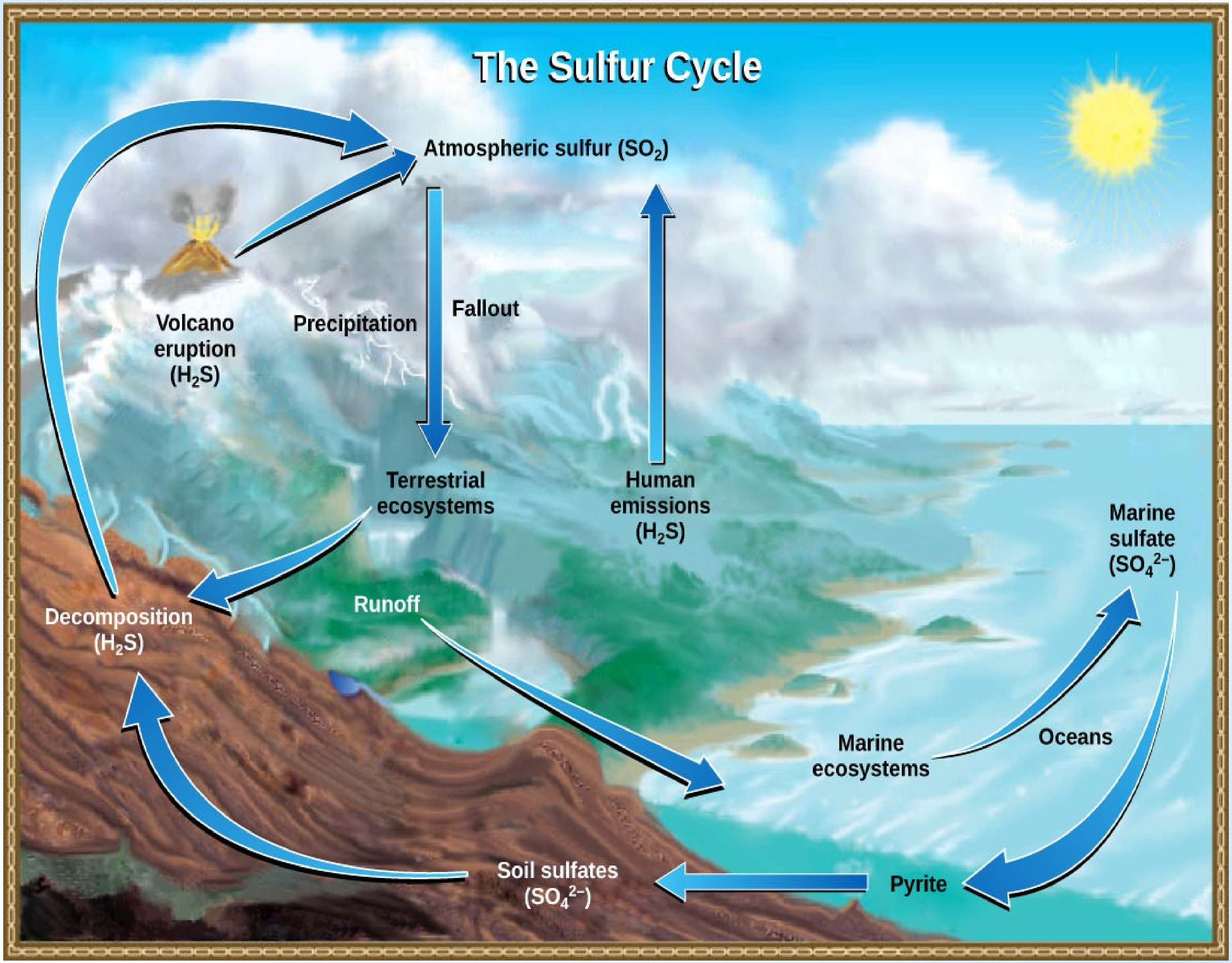
- Rankine cycle (steam)
- Bryton cycle (gas)
- Combined cycle (combination of Rankine and Bryton cycles)
- Co-generation cycle (generate both electricity and heat)
- Others (Otto, Diesel, Refrigeration, ...)


The Water Cycle
Volcanic steam
Water in the atmosphere
Condensation
Sublimation
Desublimation
Ice and snow
Precipitation
Evapotranspiration
Evaporation
Fog drip
Surface runoff
Snowmelt runoff
Dew
Streamflow
Evaporation
Infiltration
Seepage
Flora and fauna
Spring
Plant uptake
Freshwater
Oceans
Groundwater discharge
Groundwater storage
Vents and volcanoes


The Carbon Cycle
Carbon dioxide in atmosphere
Weathering of terrestrial rocks
Respiration
Human emissions
Air sea gas exchange
Respiration
Terrestrial photosynthesis
Oceans
Soil carbon
Leaching/Runoff
Ocean sediments
Marine photosynthesis
Fossil carbon
Microbial respiration and decomposition
Uplifting


Atmospheric Nitrogen (N_2)
Plants
Assimilation
Denitrifying Bacteria
Nitrogen-fixing bacteria living in legume root nodules
Decomposers
(aerobic and anaerobic bacteria and fungi)
Nitrates (NO_3^-)
Nitrifying bacteria
Ammonification
Nitrification
Ammonium (NH_4^+)
Nitrites (NO_2^-)
Nitrogen-fixing soil bacteria
Nitrifying bacteria


The Phosphorus Cycle
Aerosol
Terrestrial food webs
Fertilizers, leaching, runoff
Dissolved in soil
Dissolved in streams and lakes
Oceans
Marine food webs
Dissolved in ocean
Rocks
Ocean sediments


The Sulfur Cycle
Atmospheric sulfur (SO_2)
Volcano eruption (H_2S)
Precipitation
Fallout
Terrestrial ecosystems
Human emissions (H_2S)
Marine sulfate (SO_4^{2-})
Decomposition (H_2S)
Runoff
Marine ecosystems
Oceans
Soil sulfates (SO_4^{2-})
Pyrite

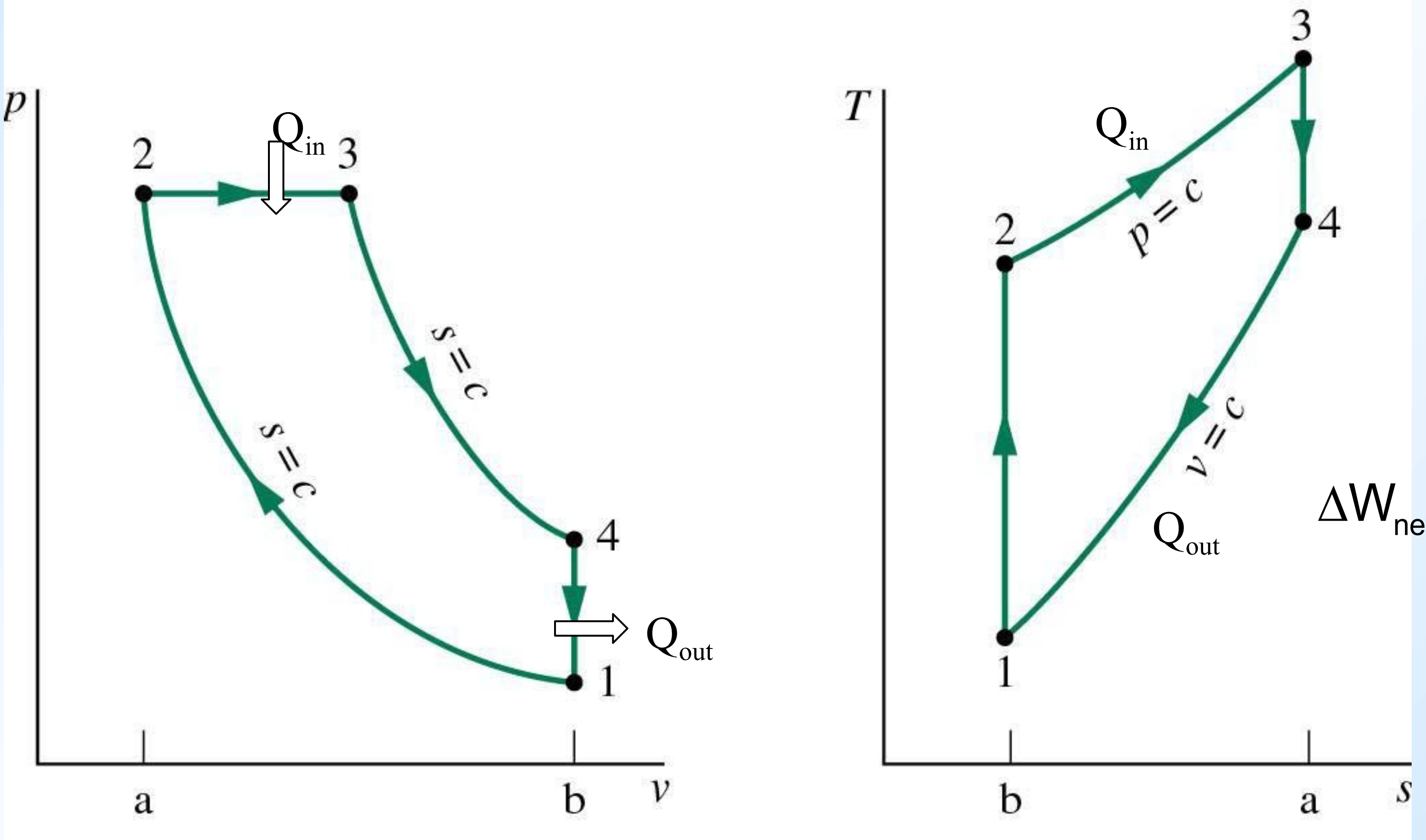
Ideal Diesel Cycle

1 – 2: Isentropic compression (compression stroke)

2 – 3: Isobaric heat addition

3 – 4: Isentropic expansion (power stroke)

4 – 1: Isochoric heat rejection (exhaust)



$$\Delta W_{net} = \Delta Q$$
$$= Q_{in} - |Q_{out}|$$

Ideal

Otto Cycle

1 – 2:Isentropic compression (compression stroke)

2 – 3: Isochoric heat addition

3 – 4: Isentropic expansion (power stroke)

4 – 1: Isochoric heat rejection (exhaust)

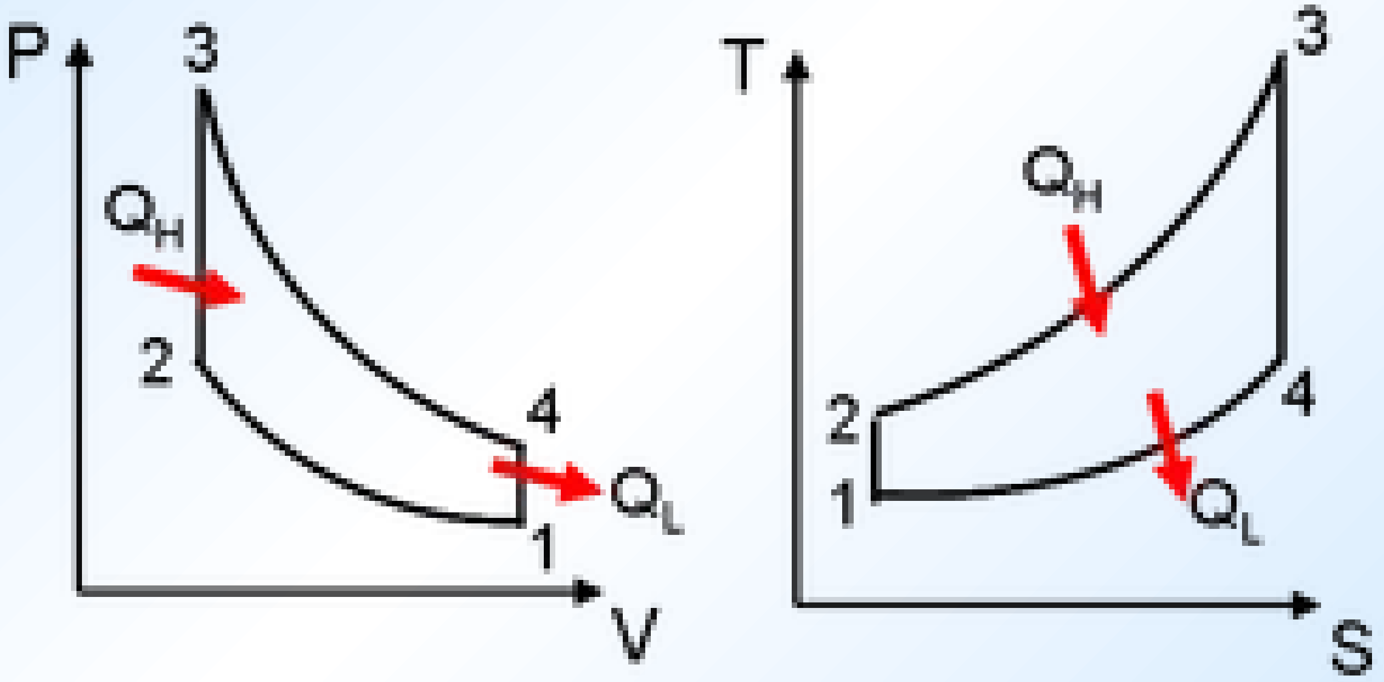


Fig.2. P-V and T-S diagrams of Ideal Otto Cycle

Second Law

First law for a cycle: $\Delta Q = \Delta W$

- Precludes heat rejection, friction, etc
- Given a conversion efficiency, can analyze a real system

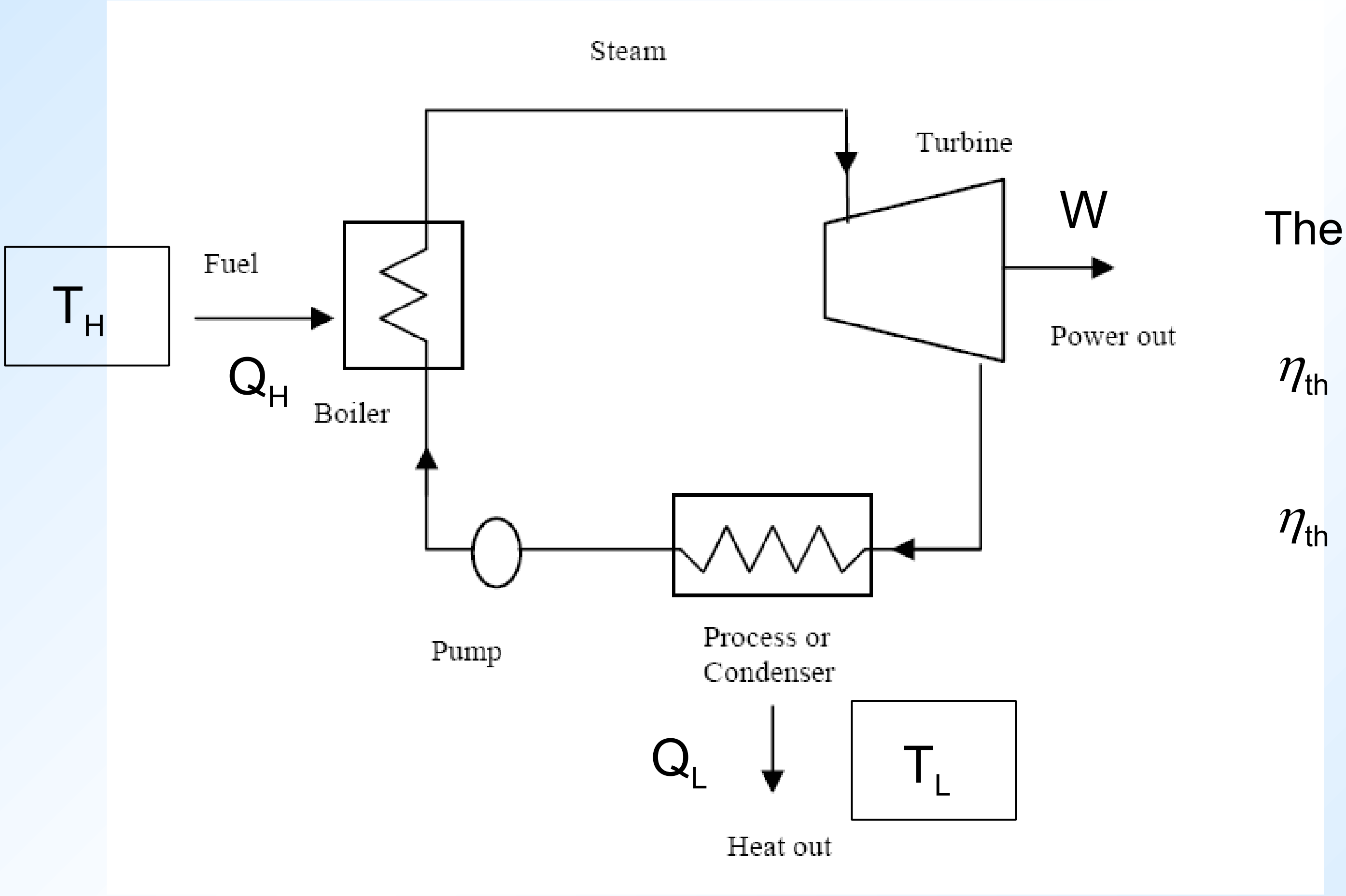
Second law is based on the heat engine → really only applies to a heat engine

Heat Engine: conversion of translational thermal energy (heat) to/from translational mechanical energy (work) using two thermal reservoirs.

Thermal Reservoir:

- Constant temperature source or sink
- Heat transfer to/from a thermal reservoir does not change its temperature.

Steam Cycle - Rankine Cycle

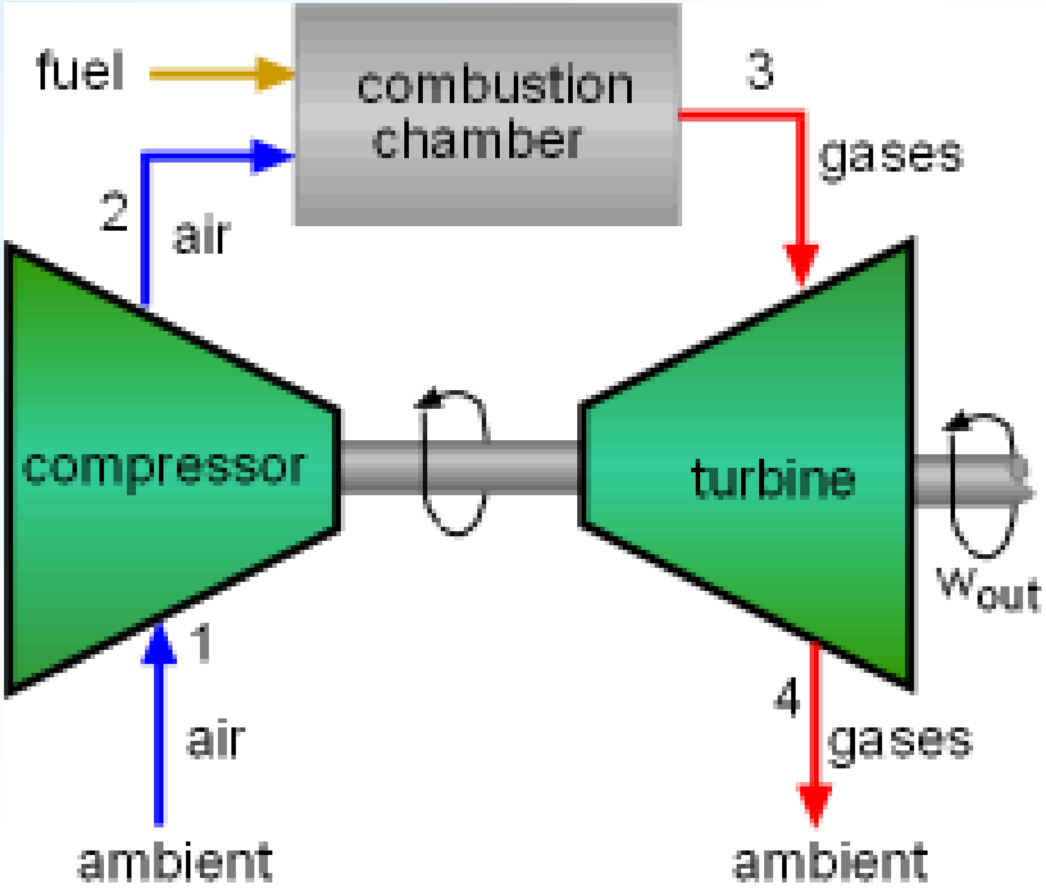


Thermal efficiency:

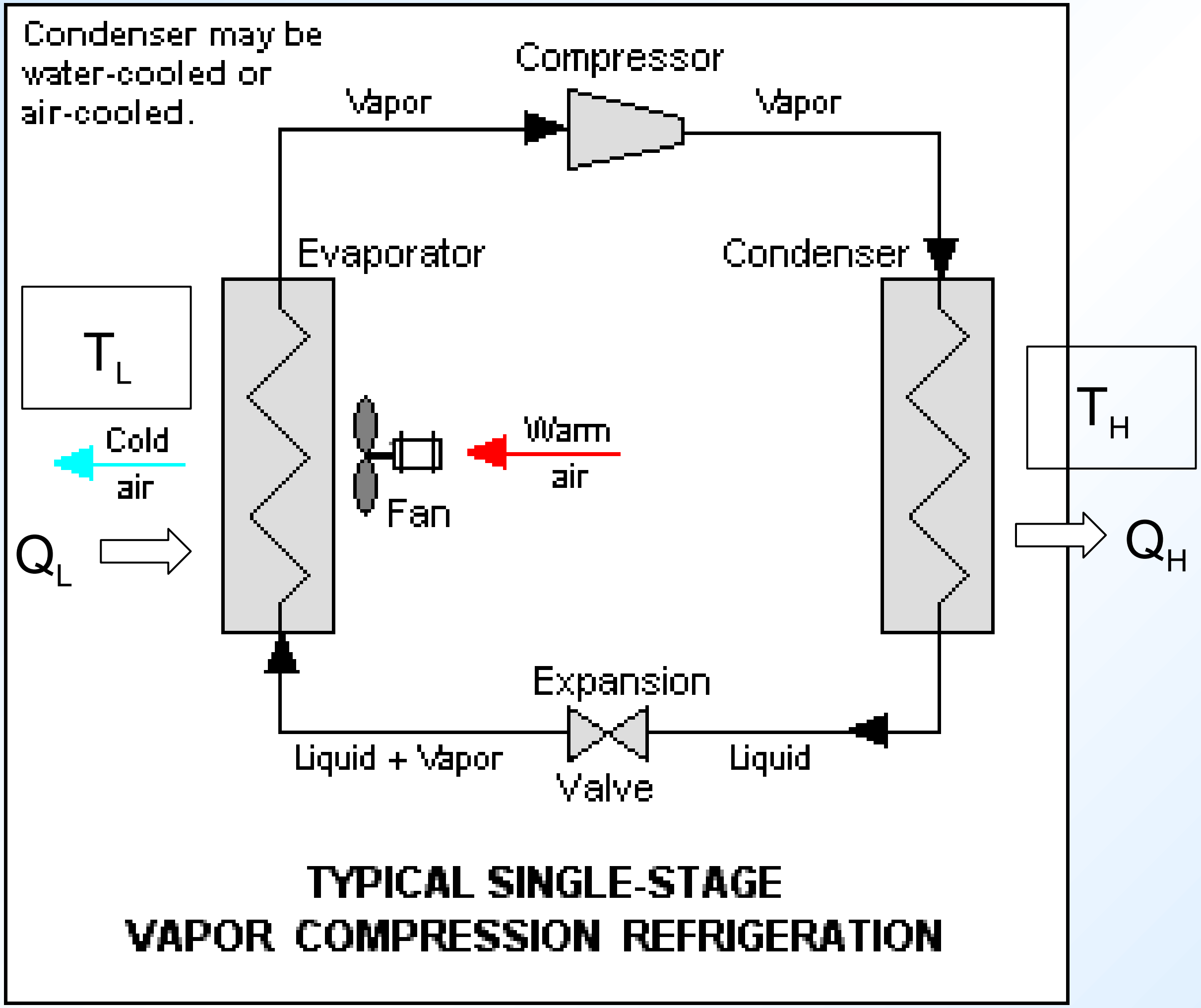
$$\eta_{th} = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H}$$

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

Gas Cycle - Ideal Bryton Cycle



Refrigeration Cycle



Coefficient of performance (COP)

$$\beta = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L}$$

$$\beta = \frac{1}{Q_H / Q_L - 1}$$

Second Law Statements

Kelvin – Planck: It is impossible to build a 100 % efficient heat engine. $W < Q_H$

Clausius: It is impossible to transfer heat from a clod body to a hot body without heat input. $Q_L \neq Q_H$

Cannot prove "negative" postulates. Proof rests on experimental evidence.

Reversible Process: Deviation from equilibrium is infinitesimal and occurs at an infinitesimal rate

Irreversibilities:

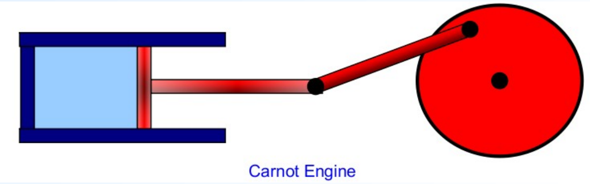
- Friction
- Unstrained expansion – work required to restore state
- Heat transfer through ΔT (as opposed to dT) – cooling required to restore state which rejects heat to surroundings
- Mixing of two substances – work required to separate
- Joule heating (I & R)
- Combustion

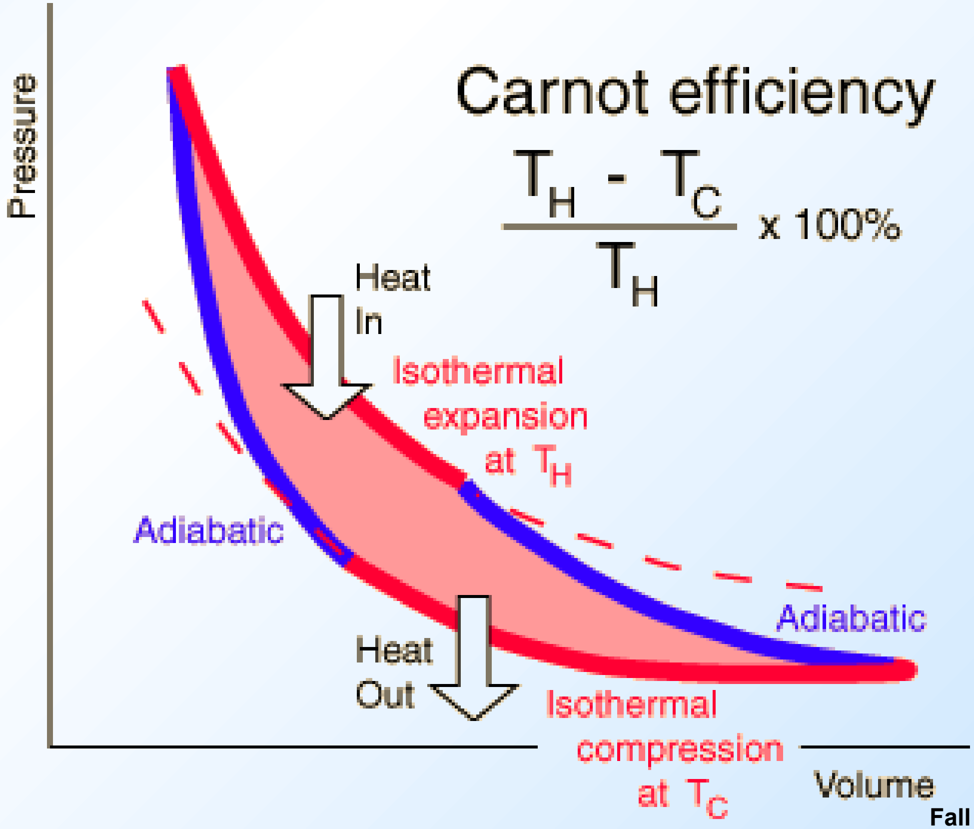
External vs Internal Irreversibilities:

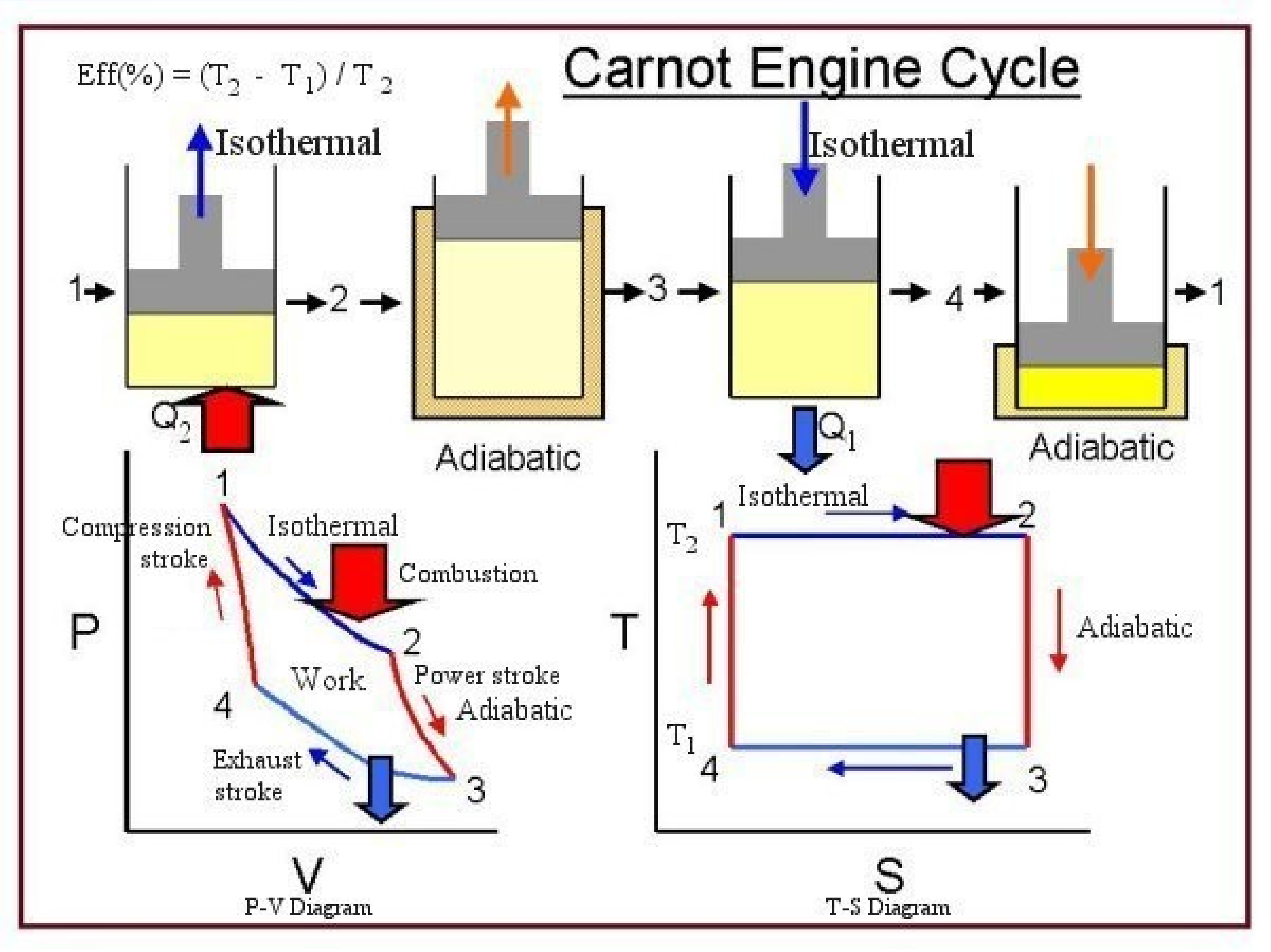
- Internal → No irreversibility occurs within the boundary during a process
- External → No irreversibility occurs outside the boundary during a process

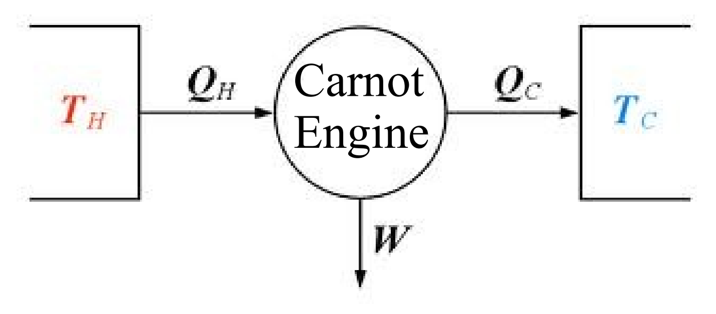
Carnot Cycle – Proposed in 1824 by Sadi Carnot (1796 - 1832)

Carnot Heat Engine: Cycle composed of 4 reversible processes, 2 isothermal and 2 adiabatic (closed or steady-flow system)






Carnot Engine Cycle
Eff(%) = (T2 - T1) / T 2
Isothermal
Isothermal
1
2
3
4
1
Q2
Adiabatic
Q1
Adiabatic
P
1
Compression
stroke
Isothermal
Combustion
2
Work
Power stroke
Adiabatic
4
Exhaust
stroke
3
V
P-V Diagram
T
Isothermal
T2
1
2
Adiabatic
T1
4
3
S
T-S Diagram

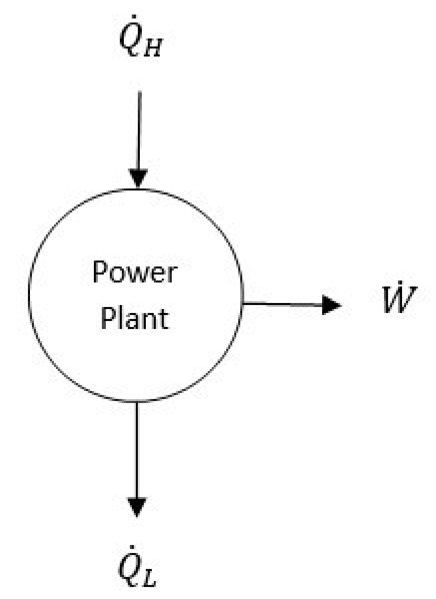


- Cycle reversed is a refrigerator
- Cycle is independent of the working fluid. It is only dependent on heat input and heat output

1st Proposition: It is impossible to construct a heat engine that is more efficient than a reversible engine.

2nd Proposition: All engines that operate on a Carnot cycle between two given constant-temperature reservoirs have the same efficiency.

Example 6



A steam power plant rated at a power output of 150 MWe consumes coal at a rate of 60 tonnes per hour. If the lower heating value of coal is 30 000 kJ/kg, determine the overall efficiency of the plant assuming steady operation.

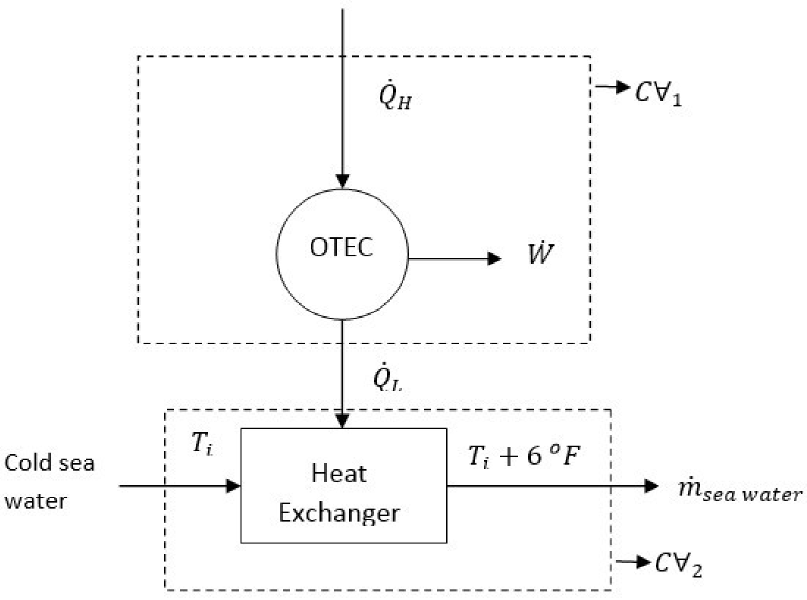
$$\eta_{th} = \frac{\dot{W}}{\dot{Q}_H} \qquad \dot{W} = 150\ \text{MW}_e$$

$$\dot{Q}_H = \dot{m}_{coal}(\text{LHV}) = \frac{(60\ \text{tonnes/hr})\ (1000\ \text{kg/tonne})}{3000\ \text{s/hr}}\ (30\ 10^6\ \text{J/kg})$$

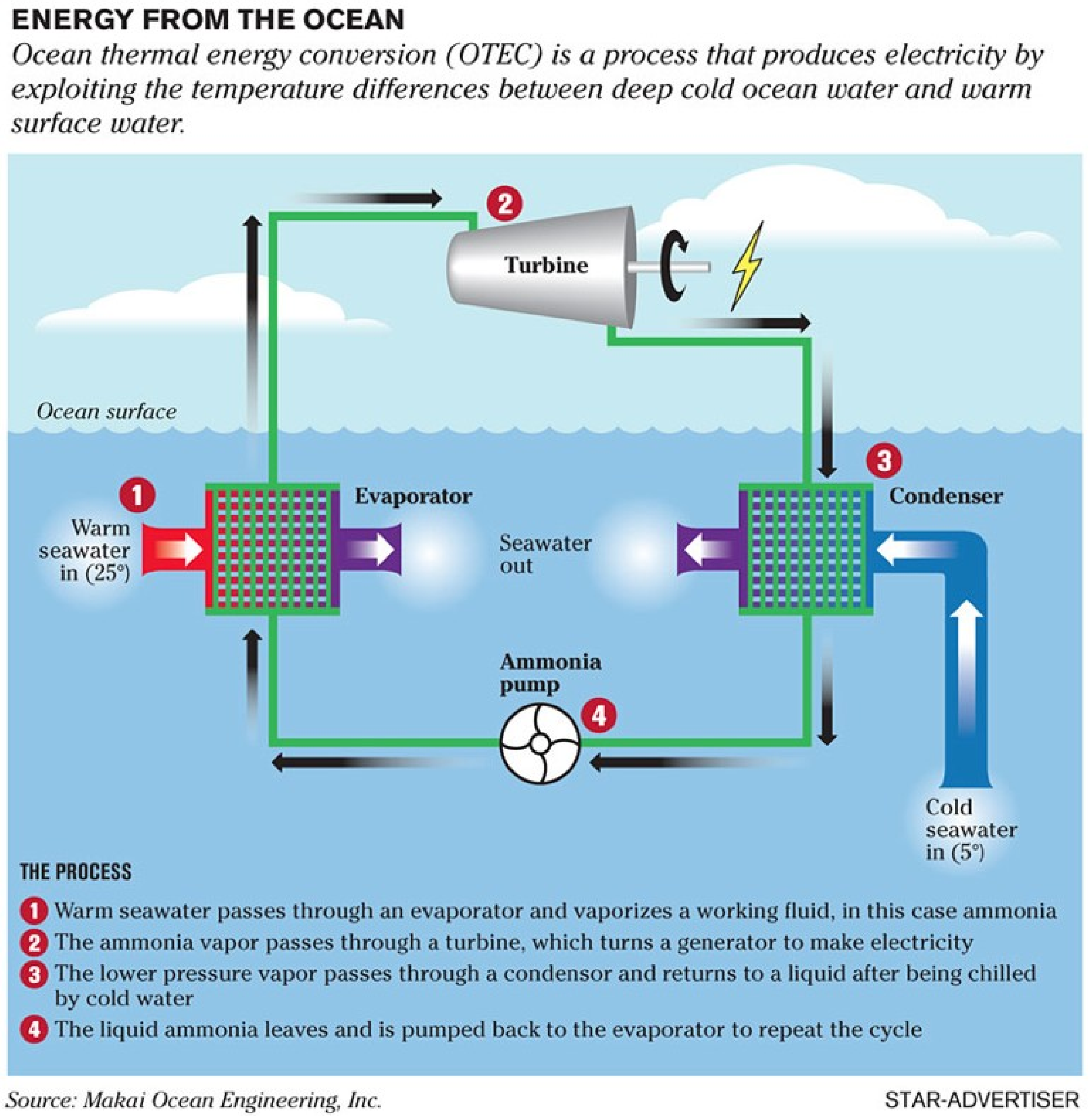
$$= 500\ \text{MW}$$

$$\eta_{\substack{\text{overall}\\ \text{total}}} = \frac{\dot{W}}{\dot{Q}_H} = \frac{150\ \text{MW}_e}{500\ \text{MW}_{th}} = 0.30 \quad \Rightarrow \quad 30\ \%$$

Example 7



An Ocean Thermal Energy Conversion (OTEC) power plant, built in Hawaii in 1987 was designed to operate between the temperature limits of 86 °F at the ocean surface and 41 °F at a depth of 2100 ft. Approximately 13300 gpm (gallons per minute) cold sea water was to be pumped from the deep ocean through a 40-in-dia. pipe to serve as a cooling medium, or heat sink. If the thermal efficiency is 2.5 % and the temperature rise of the cooling water from inlet to outlet of the heat exchanger is 6 °F, determine the power generated. The density of sea water can be assumed constant at 64 lbm/ft^3. (See http://www.explainthatstuff.com/how-otec-works.html)



ENERGY FROM THE OCEAN

Ocean thermal energy conversion (OTEC) is a process that produces electricity by exploiting the temperature differences between deep cold ocean water and warm surface water.

THE PROCESS

1. Warm seawater passes through an evaporator and vaporizes a working fluid, in this case ammonia
2. The ammonia vapor passes through a turbine, which turns a generator to make electricity
3. The lower pressure vapor passes through a condensor and returns to a liquid after being chilled by cold water
4. The liquid ammonia leaves and is pumped back to the evaporator to repeat the cycle

Source: Makai Ocean Engineering, Inc.

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Assume steady, incompressible flow with constant properties.

Control volume 1: $\dot{W} = \dot{Q}_H - \dot{Q}_L$

$$\eta_{th} = \frac{\dot{W}}{\dot{Q}_H} = \frac{\dot{W}}{\dot{W} - \dot{Q}_L} = \frac{1}{1 - \frac{\dot{Q}_L}{\dot{W}}} \quad => \quad \dot{W} = \frac{\dot{Q}_L}{\frac{1}{\eta_{th}} - 1}$$

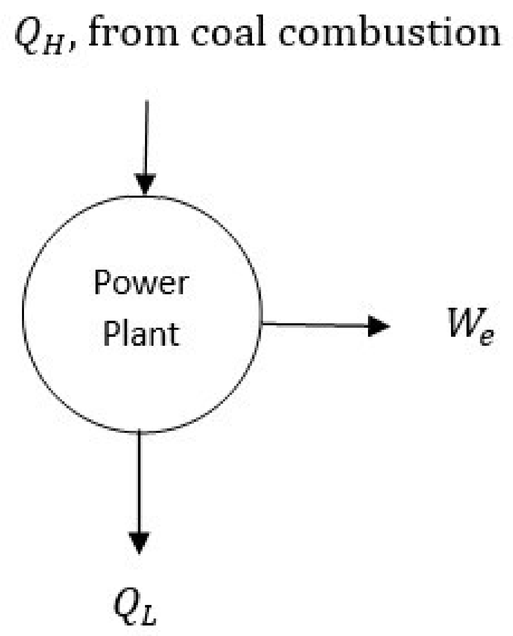
Control volume 2: $\dot{Q}_L = \dot{m}\, c \left[\left(T_i + 6\text{ F}\right) - T_i\right]$

$$\dot{m} = \frac{13300\text{ gal/min})\ (64\text{ lbm/ft}^3)}{(7408\text{ gal/ft}^3)\ (60\text{ s/min})} = 1915\text{ lbm/s}$$

$$\dot{Q}_L = (1915\text{ lbm/s})\ (1.0\text{ Btu/lbm.F})\ (6\text{ F}) = 11\,490\text{ Btu/s}$$

$$\dot{W} = \frac{\dot{Q}_L}{\frac{1}{\eta_{th}} - 1} = \frac{11490}{\frac{1}{0.025} - 1} = 295\text{ Btu/s} = \frac{295\text{ Btu/s}}{0.9478\ \frac{\text{Btu/s}}{\text{kW}}} = 311\text{ kW}_e$$

Example 8



A coal burning steam power plant produces a net power of 300 MWe with an overall thermal efficiency of 32 %. The actual gravimetric air-fuel ratio (AF) in the furnace is calculated to be 12 kg of air / kg fuel.

The heating value of the coal is 28000 kJ/kg. Determine

(a) The amount of coal consumed during a 24-hour period, and

(b) The rate of air flowing through the furnace

See the property tables on the Web site.

Heat input to power plant: $\dot{Q}_{in} = \dfrac{\dot{W}_{net,out}}{\eta_{th}} = \dfrac{300 \text{ MW}}{0.32} = 937.5 \text{ MW}$

During 24 hours: $Q_{in} = \dot{Q}_{in}\ \Delta t = (937.5 \text{ MJ/s})\ (3600 \text{ s/h})\ (24 \text{ h/day})$

$= 8.1\ 10^{7} \text{ MJ/day}$

Coal consumed: $m_{coal} = \dfrac{Q_{in}}{HV} = \dfrac{8.1\ 10^{7} \text{ MJ/day}}{28 \text{ MJ/kg}} = 2.893 \text{ kg/day}$

$\dot{m}_{coal} = \dfrac{2.893 \text{ kg/day}}{(24)\ (3600)} = 33.48 \text{ kg/s}$

Rate of air flow: $\dot{m}_{air} = (\dot{m}_{coal})\ (AF) = (33.48 \text{ kg coal/s})\ (12 \text{ kg air/kg coal})$

$= 401.8 \text{ kg air/s}$

See ‘’odtuclass’’ for the article, «Founders of Thermodynamics» by S. Kakaç

See ‘’odtuclass’’ for the article, «Solving Thermodynamics Problems»

See ‘’odtuclass’’ for «Thermodynamics Property Tables», by Y. Çengel

See ‘’odtuclass’’ for «Lecture Notes on Thermodynamics», by J. J. Powers

See ‘’odtuclass’’ for more problems on Thermodynamics