Thermodynamics: Introduction

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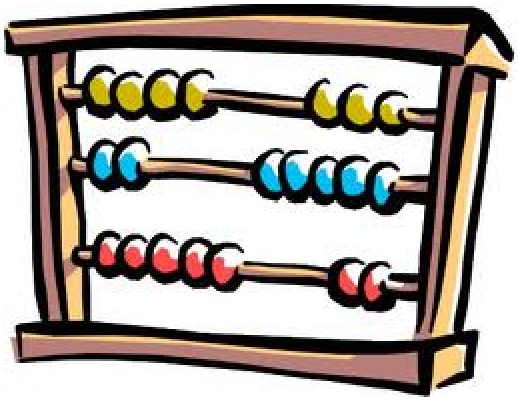
Areas where we can apply our knowledge of thermal engineering

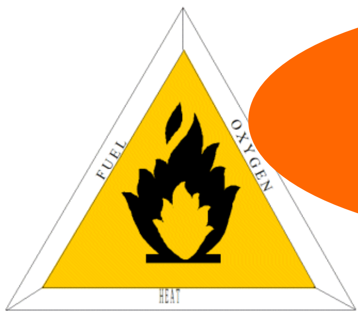
- Power generation
- Automobiles
- Air conditioning
- Propulsion
- Industrial processes
- District heating
- Cooking
- Electronics cooling
- …

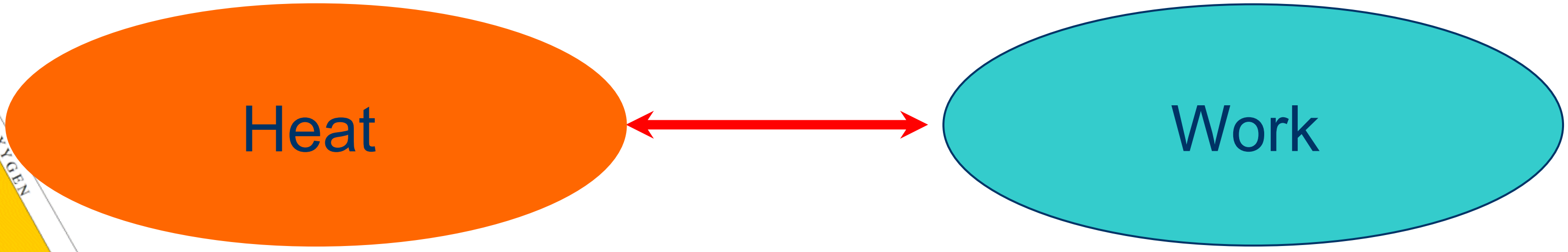


What is Thermodynamics?

Greek root θέρμη (*therme*) = heat and δύναμις (*dynamis*) = power

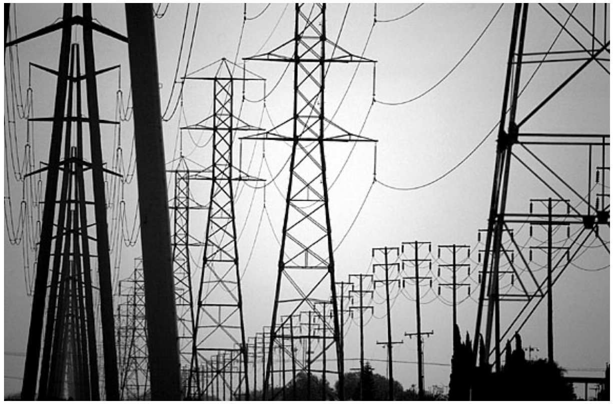
The study of energy in the forms of heat and work and the exchange [redacted]





http://www.hybridmile.com/files/2008/10/engine--1.JPG

Mechanical work– physical movement, e.g. lifting or pushing against friction.



http://www.nearfield.com/~dan/sports/bike/river/coyote/index.htm

Electrical work – flow of current

Where does thermodynamics apply?

- Applies to all forms of matter:
  - solid, liquid, gas, plasma
- Relevant to very large systems (*e.g.* Universe) and small systems (nano-scale)
- *Classical* and *Statistical* approaches are possible

Classical and statistical thermodynamics

- Classical thermodynamics
  - A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles
- Statistical thermodynamics
  - A microscopic approach, based on the average behavior of large groups of individual particles

Sources of Energy (Heat and Work)

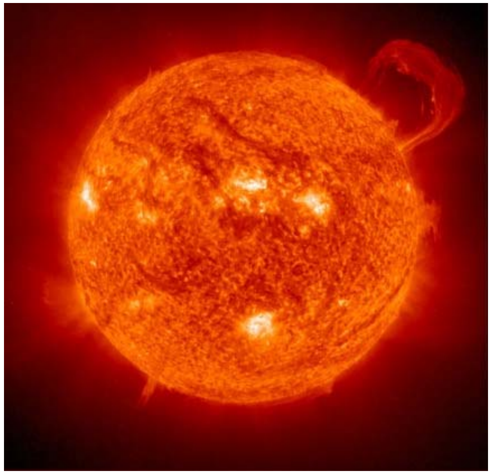
- **Nuclear reactions** are a source of heat (which can then be converted to work).
- **Solar energy** comes in the form of thermal radiation given off by the Sun. (Thermal radiation is a way to transfer heat from a hotter object to a colder object.) The origin of the heat of the Sun is a nuclear reaction.
- **Chemical reactions** are another source of heat (and hence work).
- **Gravitational forces** can likewise be a source of mechanical energy (work), which can be converted to electrical energy.
- **Tidal energy** originates from gravitational forces from the moon; can do work.

Combustion of wood, oil, gas and coal

http://www.dailymail.co.uk/news/article-1043161/Anti-terror-patrols-secretly-stepped-power-stations.html

http://www.nearfield.com/~dan/sports/bike/river/coyote/index.htm

Forms of Solar Energy



http://www.starlight-news.co.uk/StarlightSolarSystemTheSun.html

Form	Explanation and Use
Solar radiation	Direct heating of objects (*e.g.* buildings) by absorption of radiation (in passive syst.)
	Generation of electricity by photovoltaic cells or thermal-energy conversion in the oceans (in active systems)
Photosynthesis	Solar energy is converted to chemical energy in plants and fossil fuels. Solids, liquids and gases are used in combustion.
Wind power	Heating of land, air and seas by solar radiation produces winds. Wind is used as a source of mechanical energy (*e.g*. windmills or sailing ships) or electrical energy (in generators)
Water power	Sun drives water cycle (evaporation, rain) which is converted to mechanical or electrical energy (usually using gravity).

From P.A. Tipler, *Physics*, Ch. 18

Does enough heat come from the Sun to meet human needs?

http://www.stovesonline.co.uk/wood-is-best.html

1 tonne of crude oil (7 barrels) yields 4.2 x10^{10} J of heat.

Humans consume about 1.3x10^{13} W of energy – equivalent to 300 tonnes of crude oil per sec!

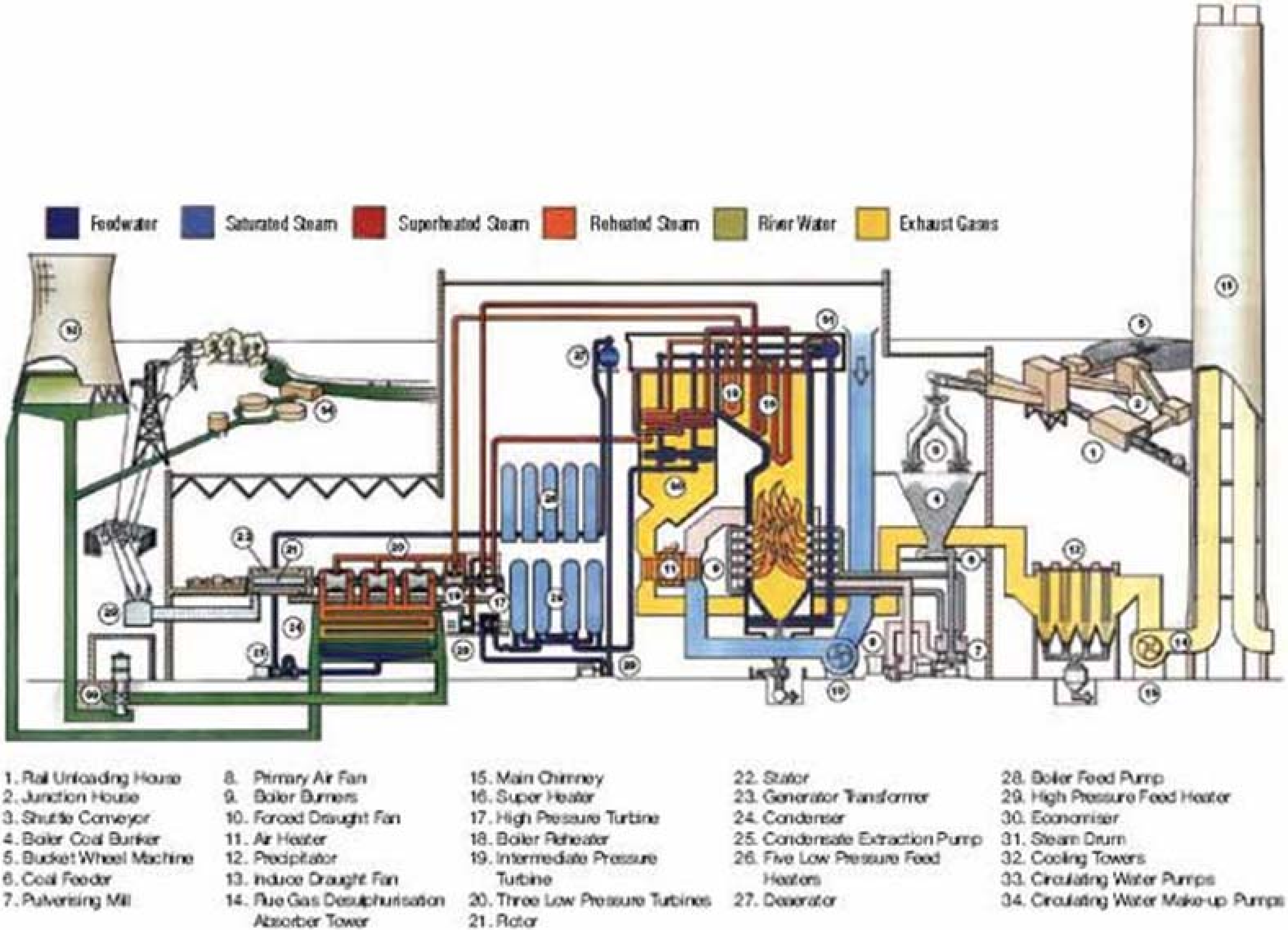
What is a Joule (J)? What is a Watt (W)?

Earth receives: 4.9 x 10^{17} W: Plenty to meet human needs!!

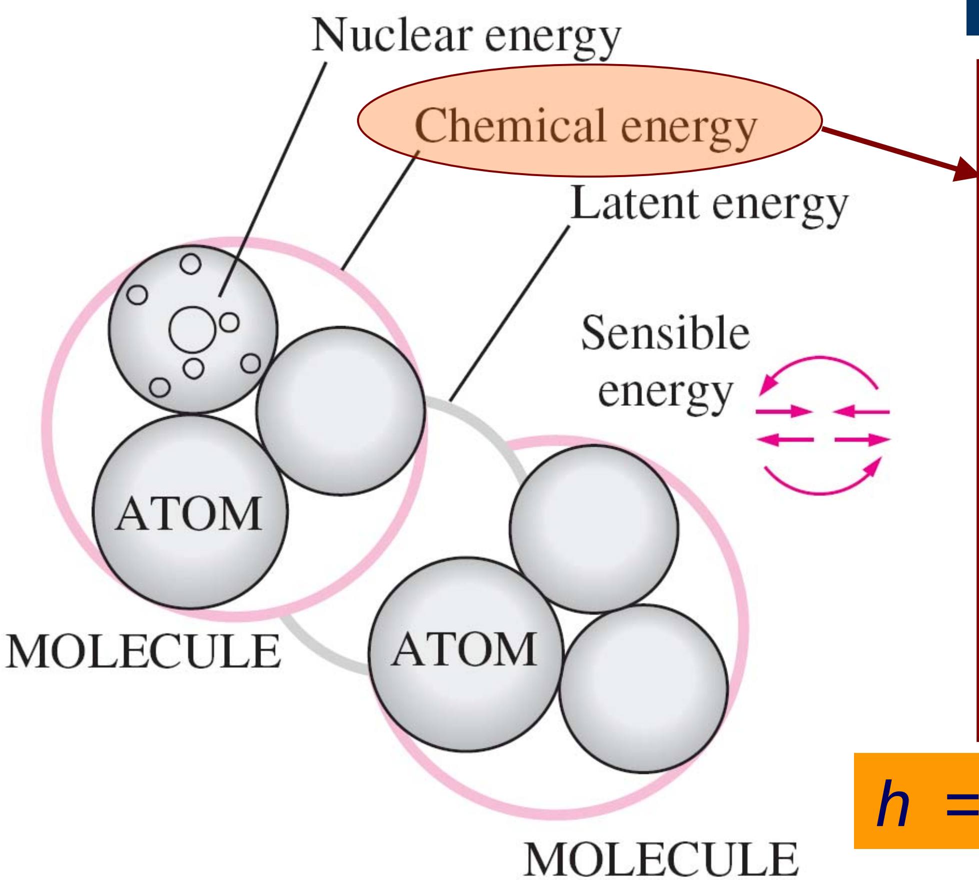
Power Plants

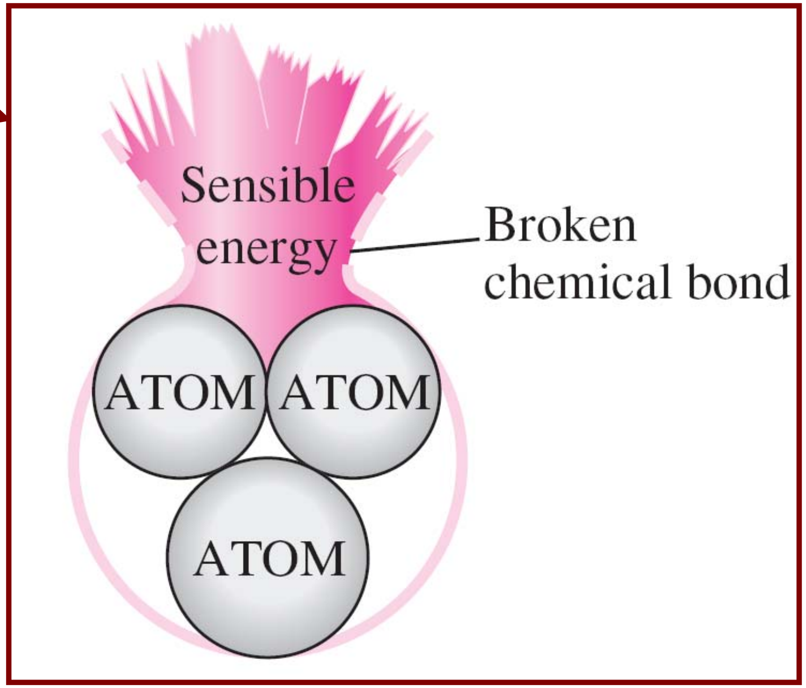
- Thermal Power Plants
  - Coal, oil, natural gas, biomass, etc. as fuel
  - Nuclear power plants
  - Geothermal power plants
- Hydroelectric power plants
- Wind power plant
- Direct energy conversion
  - Solar photovoltaic
  - Thermoelectric
  - MHD
  - Fuel Cell

Thermal Power Plants:
the journey from coal to electricity



Energy content in fuels

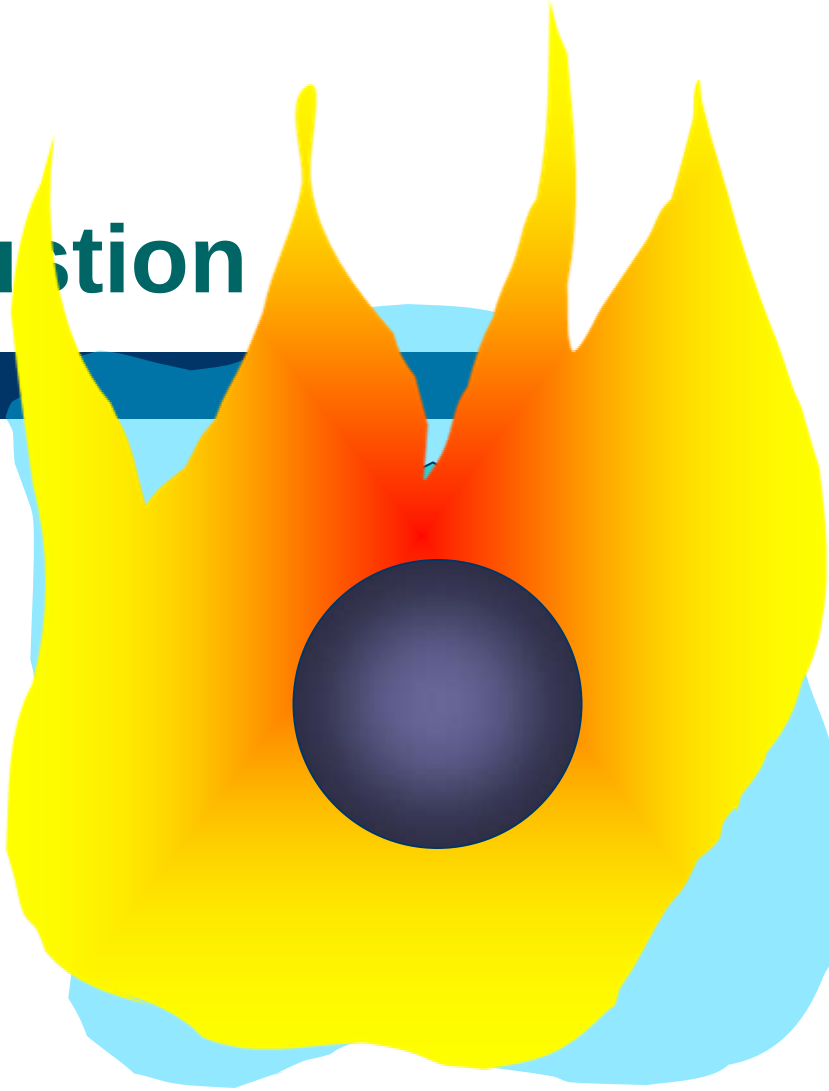




$$h = h_f^o + (h - h^o) + h_{fg}$$

Chemical Sensible Latent

Three Ts of combustion

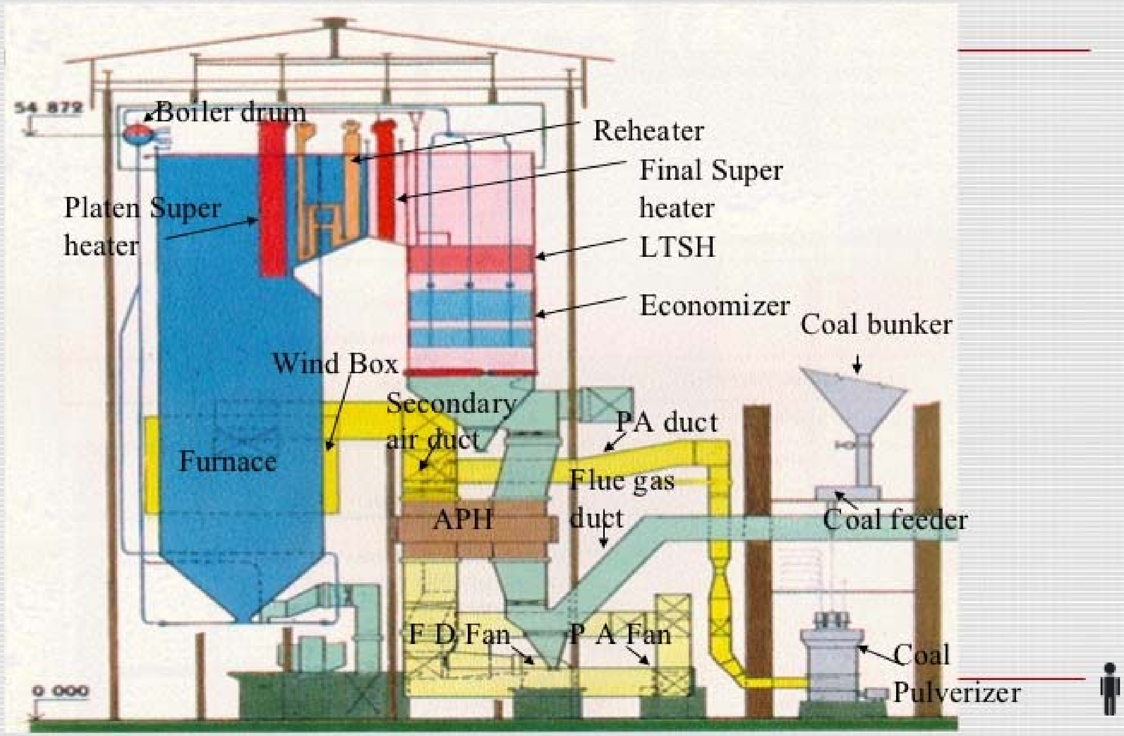


- **T**ime
- **T**emperature
- **T**urbulence

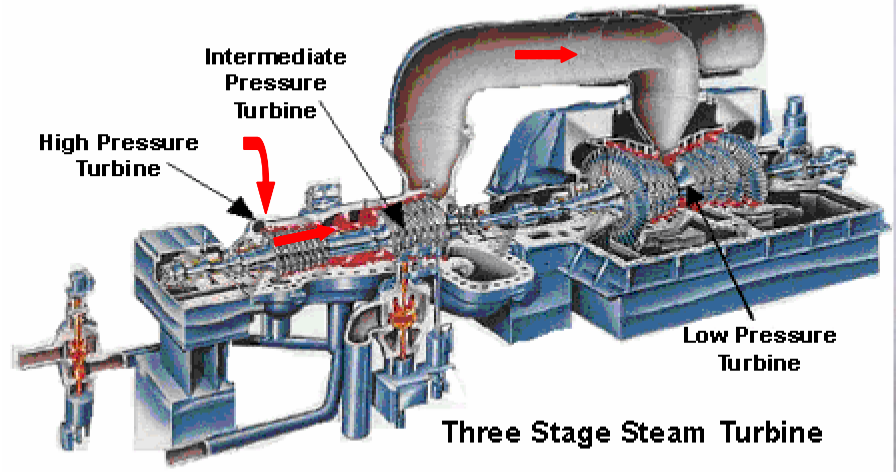
The Boiler

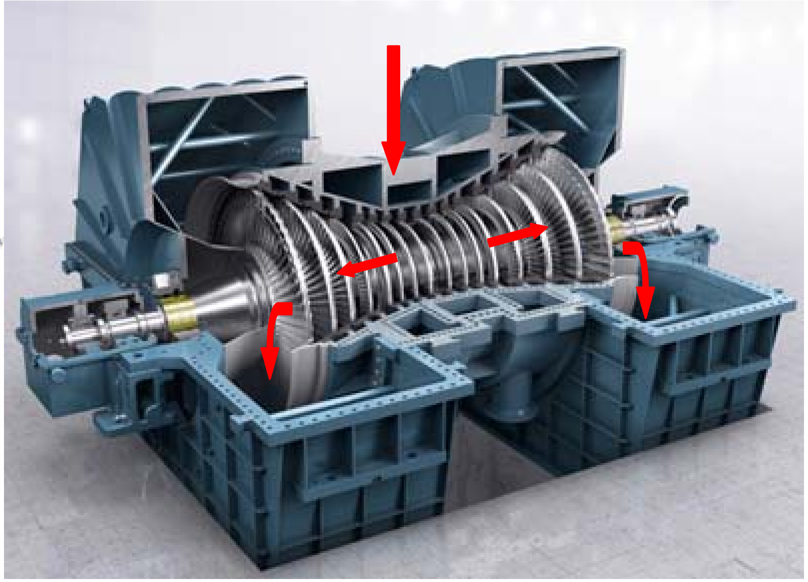
Converts chemical energy to thermal energy (Heat)

BOILER



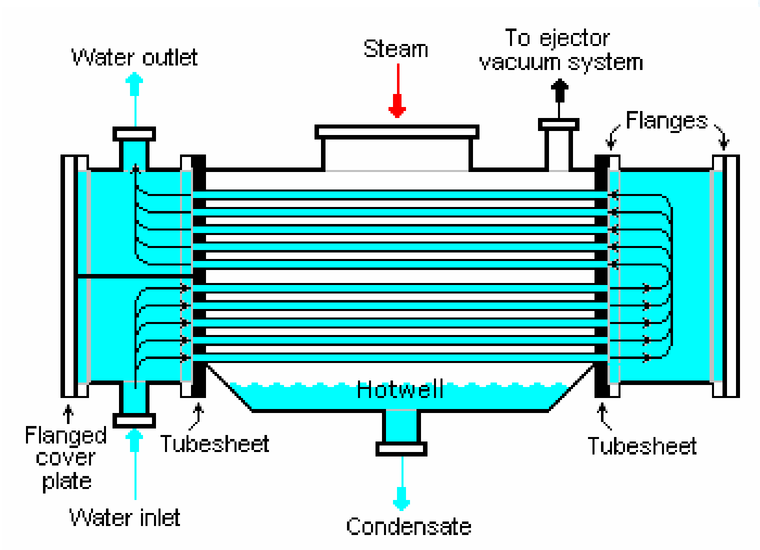
The Turbine

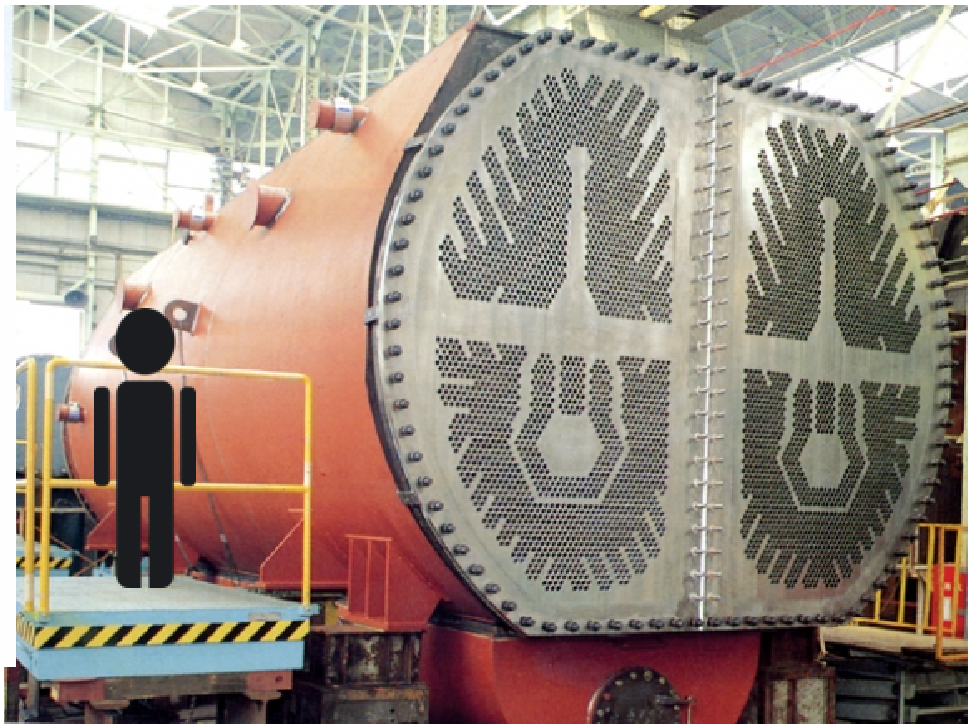

Intermediate Pressure Turbine
High Pressure Turbine
Low Pressure Turbine
Three Stage Steam Turbine



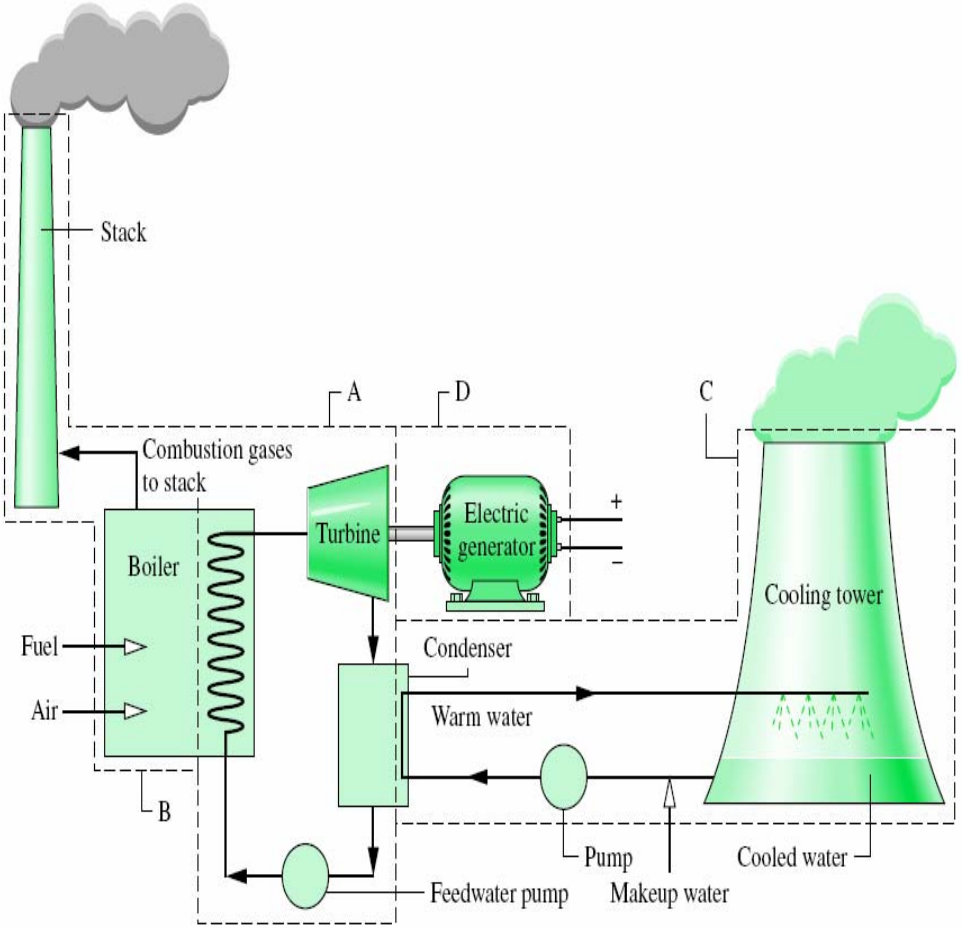
The Turbine Generator floor

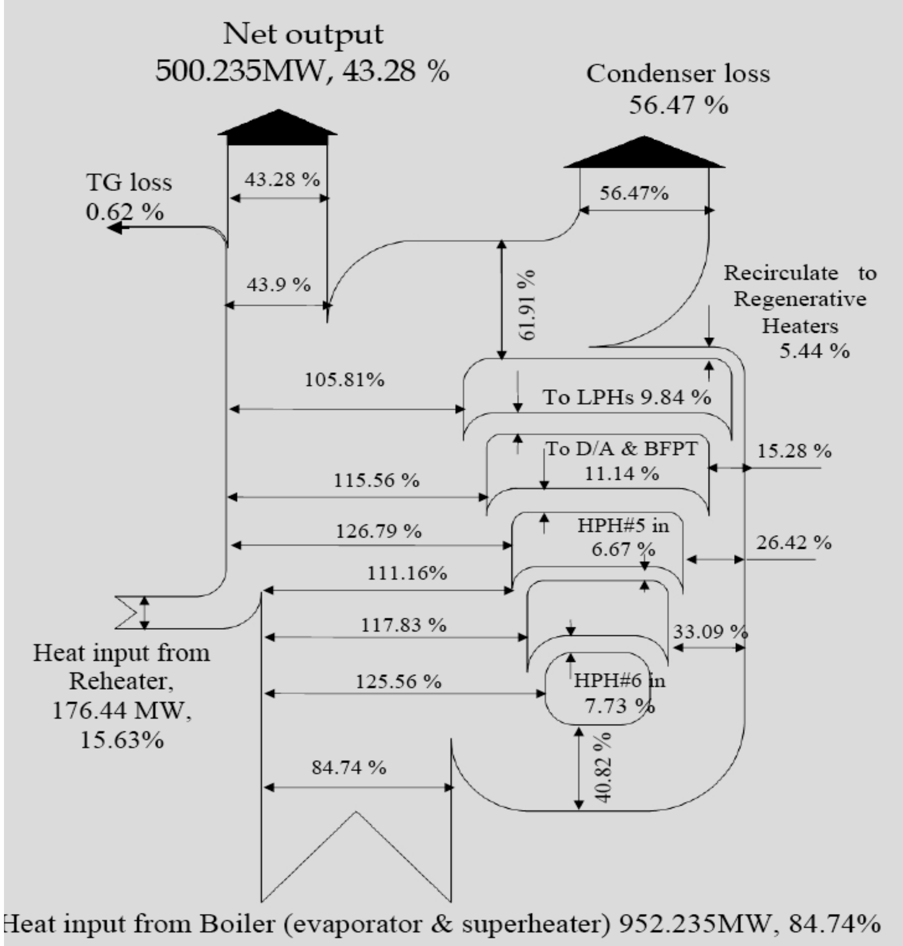
The Condenser





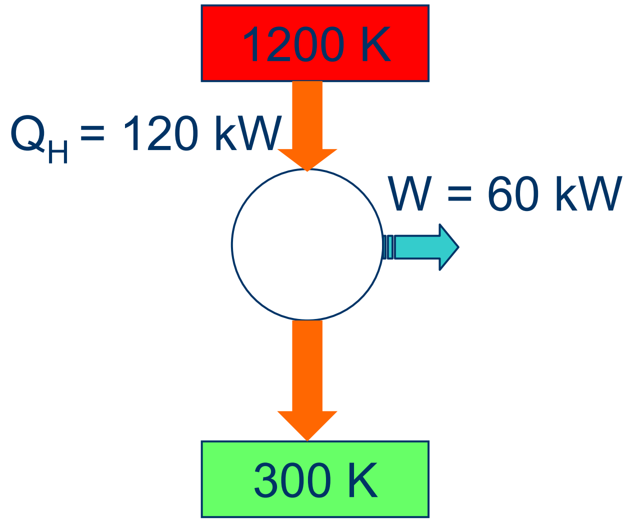
What are the losses in a power plant? Which parameters must we measure? Were should we impose better control?





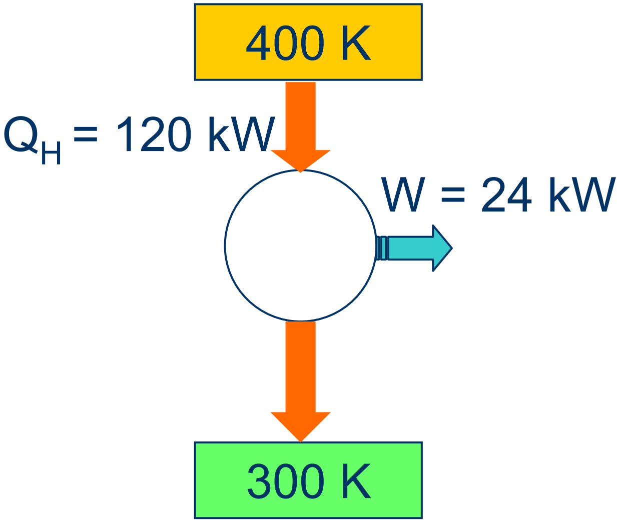
Which cycle is better?

Gas Turbine plant

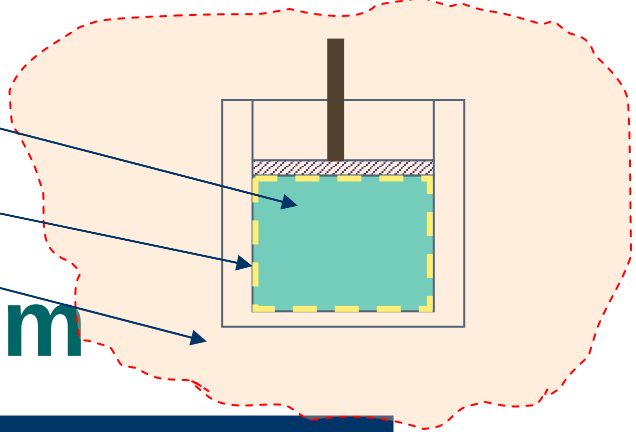


$\eta = 50\%$

Organic Rankine Cycle plant



$\eta = 20\%$

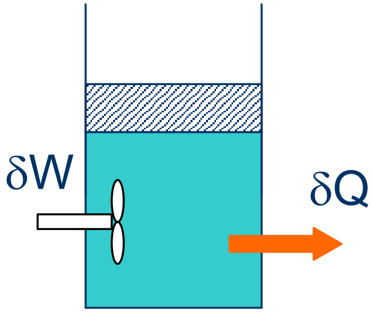


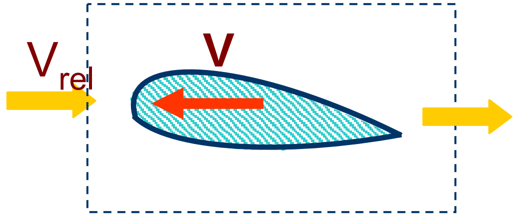
Thermodynamic system

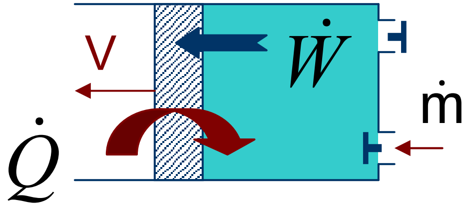
- A fixed region in space where attention is focused:
  - stationary or moving
  - fixed or deformable
- Surrounded by a control surface (system boundary)
  - Mass and energy transfer takes place across the system boundary
- Surrounding: Anything outside the system boundary
- System + Surrounding = Universe

Concept of closed and open system

- Control mass/ Closed system
  - A fixed region in space surrounded by a control surface enclosing a specific, identifiable quantity of matters
    - No mass transfer across the control surface
    - Energy transfer may take place across the control surface
- Control volume/ Open system
  - A fixed region in space surrounded by a control surface across which transfer of mass, momentum, energy and chemical species may take place
    - Can be fixed or moving
    - Can be non-deformable or deformable

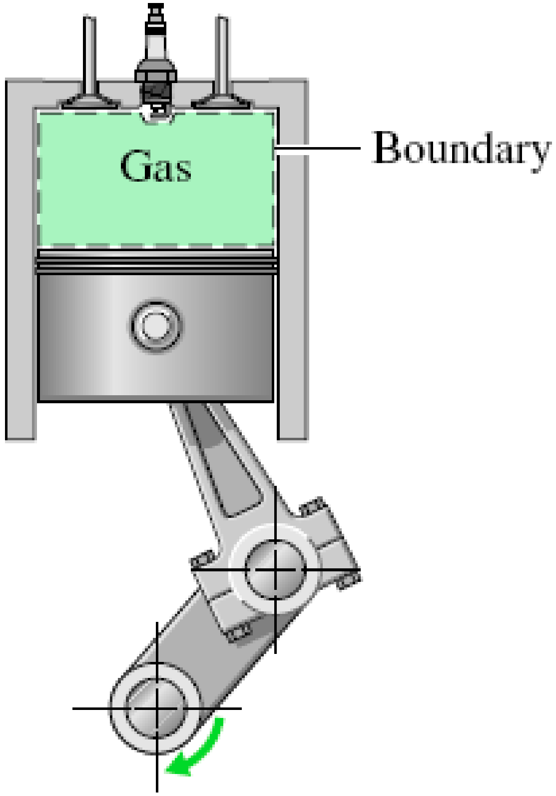


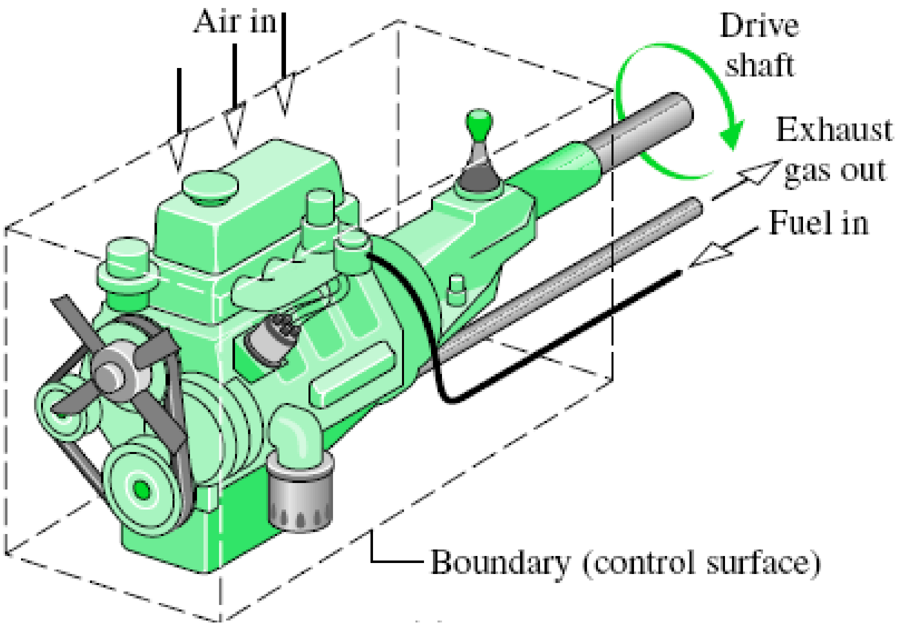




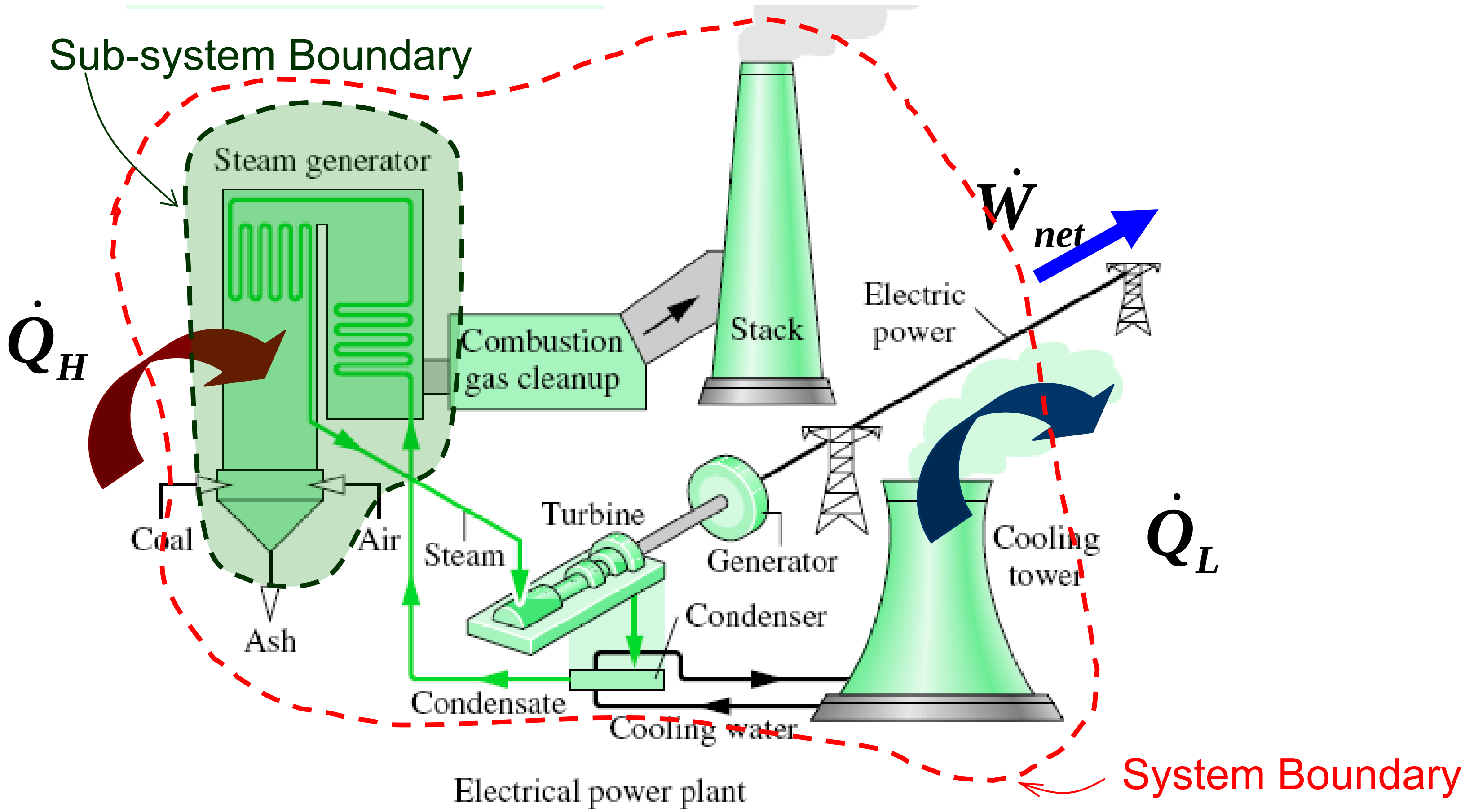
ISOLATED SYSTEM: No energy or mass interaction across the system boundary

Choice of system boundary





Power plant: a combination of open sub-systems

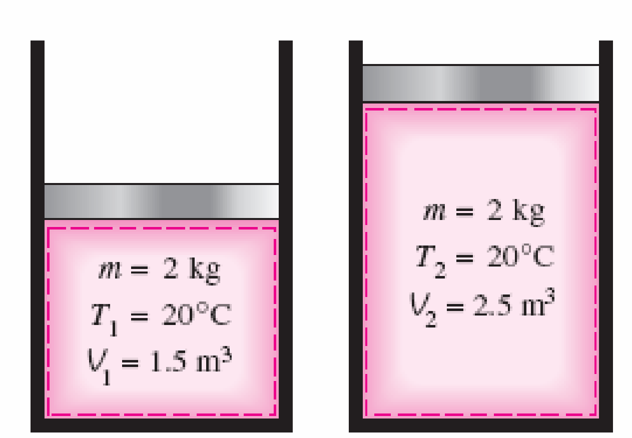


Property of a system

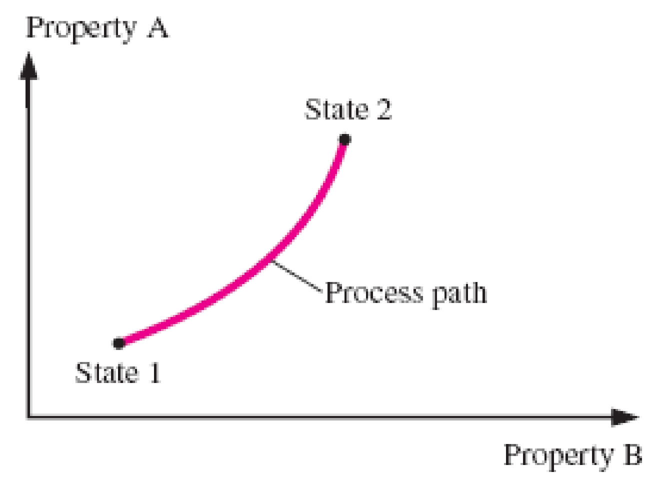
- Property is a macroscopic characteristic of a system such as mass, volume, energy, pressure, and temperature to which a numerical value can be assigned at a given time without knowledge of the previous behavior (history) of the system
  - *Intensive property: Independent of the extent/mass/size of the system (e.g., pressure, temperature, density, specific energy, etc.)*
  - *Extensive property: Depends on the extent/mass/size of the system (e.g., volume, mass, total energy, total charge)*

State and process

- State: Set of measurable or calculated properties by which the condition of a system is uniquely identified
  - State of a gas specified by (p,T)
- Process: Transformation from one state to another



(a) State 1 (b) State 2



●Process: Transformation from one state to another

Brief discussion on the properties

- Pressure
- Temperature
- Density
- Internal energy (kJ)
  - Specific internal energy (kJ/kg)
- Enthalpy (kJ)
  - Specific enthalpy (kJ/kg)
- Entropy (kJ/K)
  - Specific entropy (kJ/kgK)

Other thermophysical properties

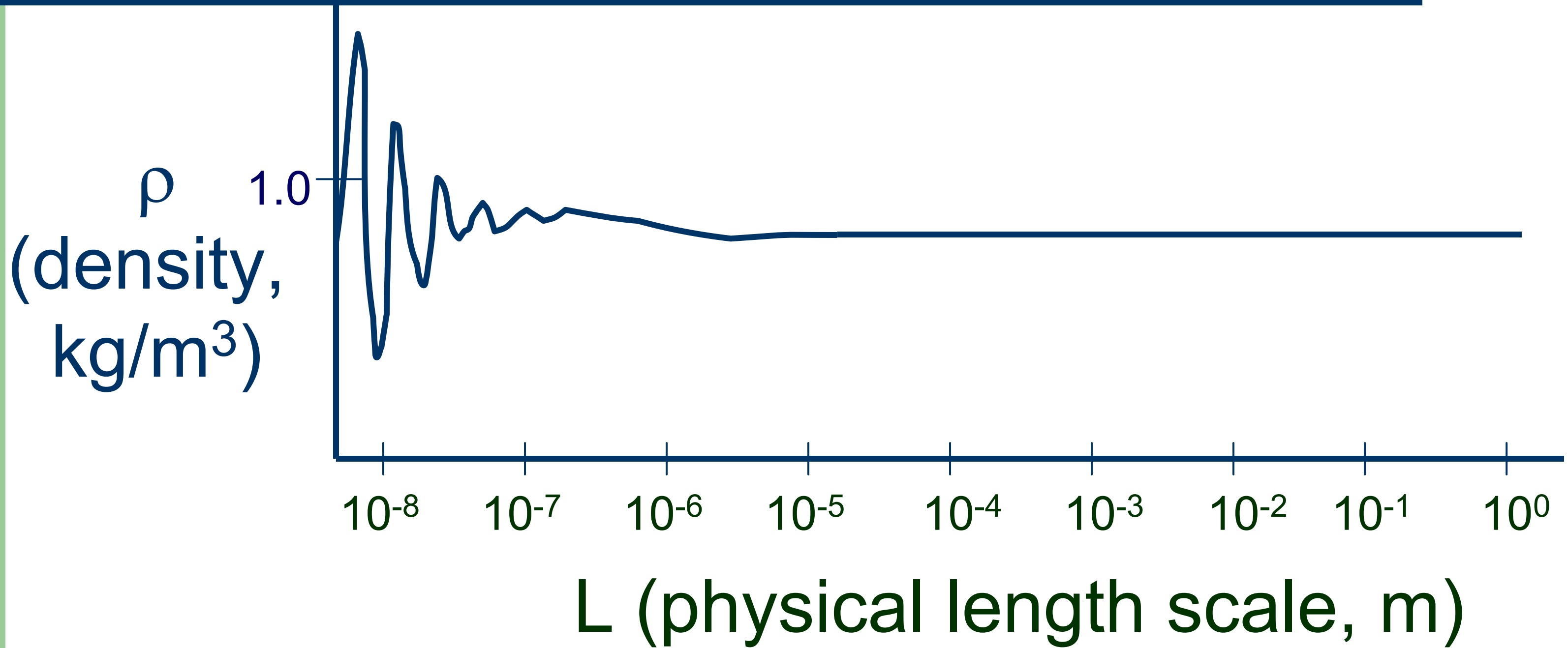
- **Specific heat**
- **Viscosity**
- **Thermal conductivity**
- **Bulk modulus**
- **Joule Thomson coefficient**
- **….**

Concept of Continuum

Knudsen Number

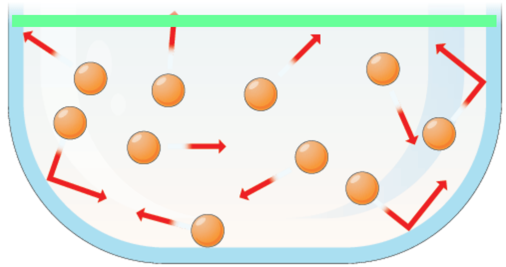
$$Kn = \lambda/L$$

λ = molecular mean free path
L = physical length scale



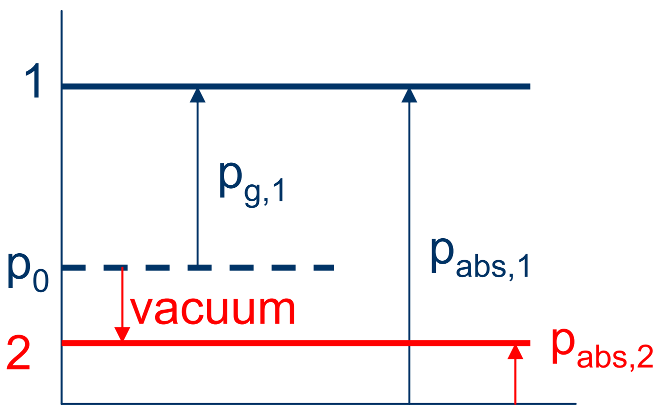
Continuum hypothesis is valid when the length sale of the problem >> λ, i.e., Kn<<1

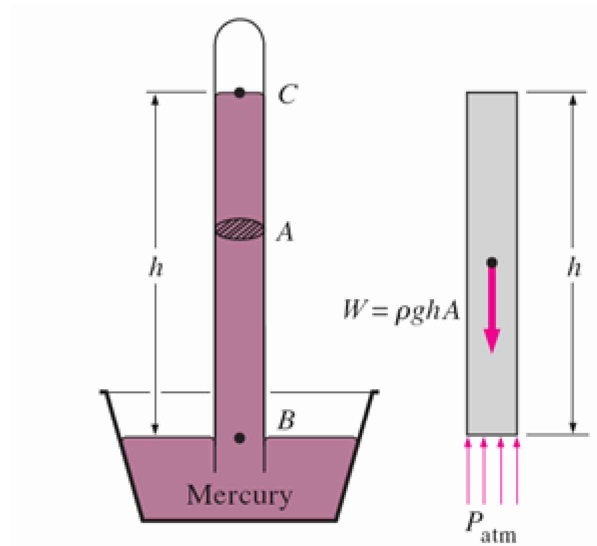
Pressure



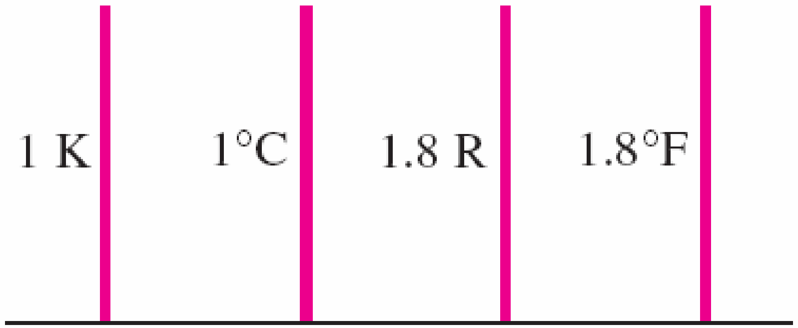
Bourdon tube

- Different units
  - 1 N/m^2 = 1 Pa =1.450377×10^{-4} psi
  - 1 bar = 10^5 Pa
  - 1 atm = 1.0325 × 10^5 Pa
  - 1 Torr = 1 mm Hg





Barometer to measure p_0



Temperature

- Temperature denotes the state of stored energy for an ideal gas
  - T $\propto$ Molecular kinetic energy (for gases), molecular vibration energy (for solids), or both (for liquids)
- Temperature scales
  - Absolute (Kelvin, Rankine)
  - Relative (^oC, ^oF)

Absolute Zero: 0 K = -273.15 ^oC = -459.67 F = 0 R

$$T(\text{K}) = T(^\circ\text{C}) + 273.15$$
$$T(\text{R}) = T(^\circ\text{F}) + 459.67$$

Thermodynamic equilibrium

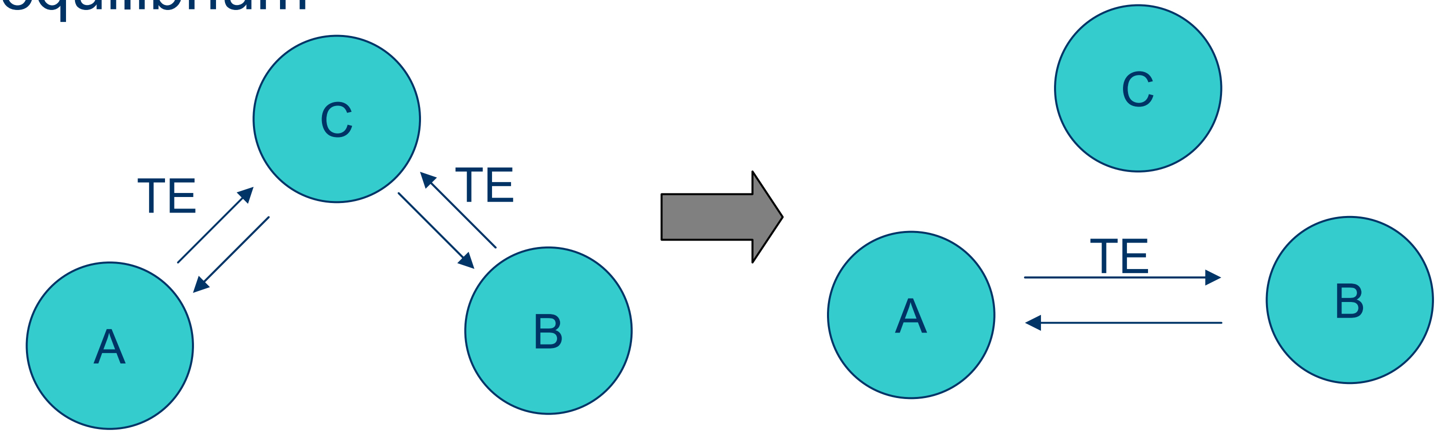
- Equilibrium: state of balance

A system is said to be in an equilibrium state if its properties do not change without some perceivable effect in the surroundings.

- Mechanical equilibrium
  - No unbalanced force
- Thermal equilibrium
  - Homogeneity of T
- Chemical equilibrium
  - No net change in chemical composition
- Phase equilibrium
  - No net change of phase constituents (e.g., liquid & vapor)

Zeroth law of thermodynamics

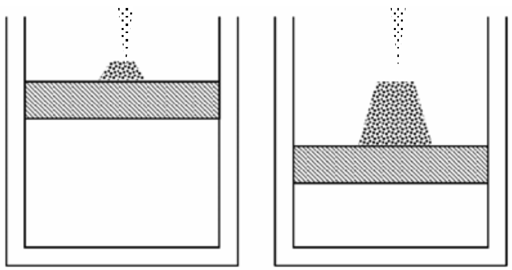
- If two systems (say A and B) are in thermal equilibrium with a third system (say C) separately (that is A and C are in thermal equilibrium; B and C are in thermal equilibrium) then they are in thermal equilibrium themselves (that is A and B will be in thermal equilibrium



TE = Thermal Equilibrium

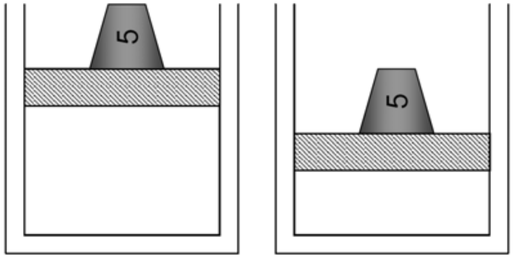
Reversible and irreversible processes

- Gradual compression



1 2

- Sudden compression



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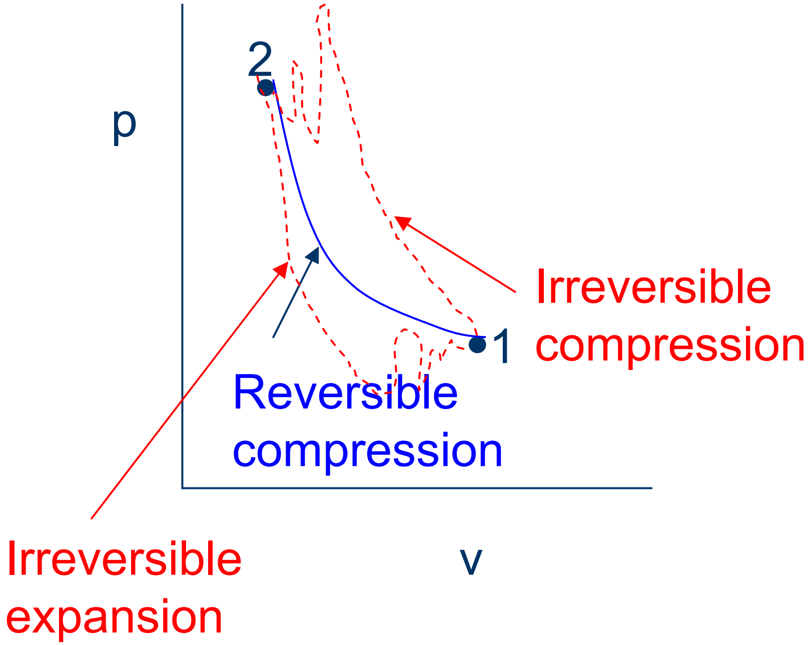


Reversible process

- A process that, once having taken place, can be retraced without leaving any changes in the system or the surrounding
  - The process must have passed through a series of equilibrium states
  - The process can exactly be retraced by reverting the conditions of the surrounding

“Reversible” and “reversible in the limit”

- Perfectly reversible: occurs with $\Delta F=0$, $\Delta T=0$, $\Delta C=0$, Δ(chem. pot)=0
- Reversible in the limit: occurs with $\Delta F\rightarrow 0$, $\Delta T\rightarrow 0$, $\Delta C\rightarrow 0$, Δ(chem. pot)$\rightarrow 0$ (i.e., work transfer with fully resisted expansion/ compression, heat transfer with infinitesimal temperature difference, mass transfer with infinitesimal concentration difference, etc.)

Irreversibility occurs due to

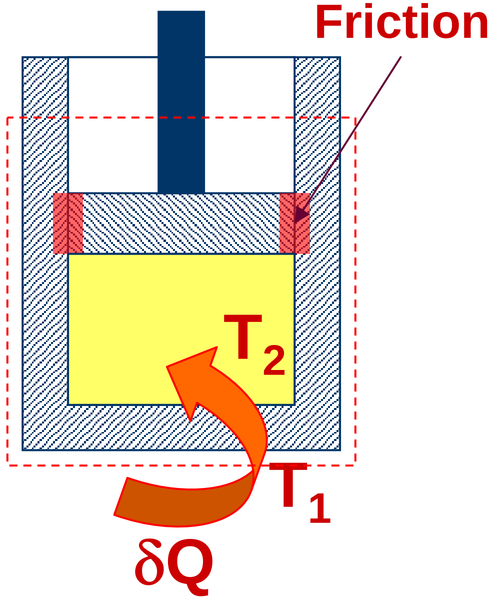
Departure from equilibrium → Dissipative effects

Irreversible process

- Any process that deviates from the state of equilibrium during its occurrence, and incurs dissipative effects
  - Un-resisted expansion or compression
  - Friction (fluid-fluid, fluid-solid or solid-solid)
  - Heat transfer with finite temperature difference
  - I^2R heating (Joule heating)
  - Magnetization with hysteresis
  - Spontaneous mixing in finite concentration difference
  - Spontaneous chemical reaction
  - Inelastic deformation

Internal and external irreversibilities

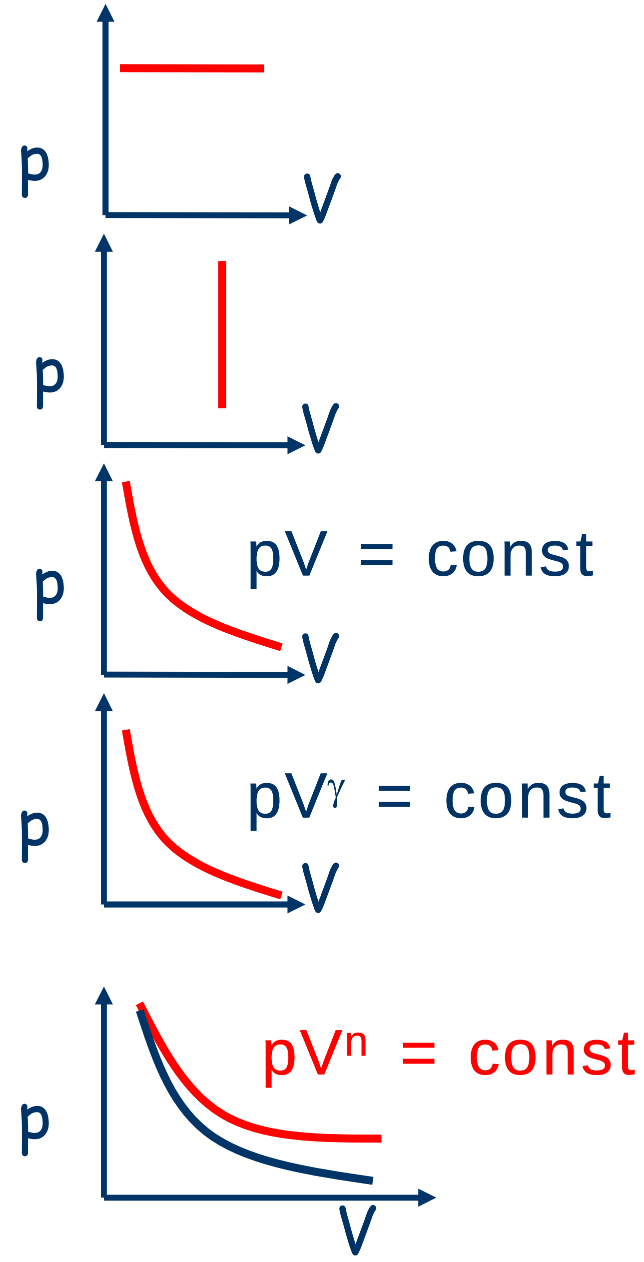
- Internal irreversibility:
  - Any irreversibility occurring within the system boundary
  - Fluid friction, chemical reaction, etc.
- External irreversibility
  - Any irreversibility outside the system boundary
  - Heat transfer with finite temperature difference

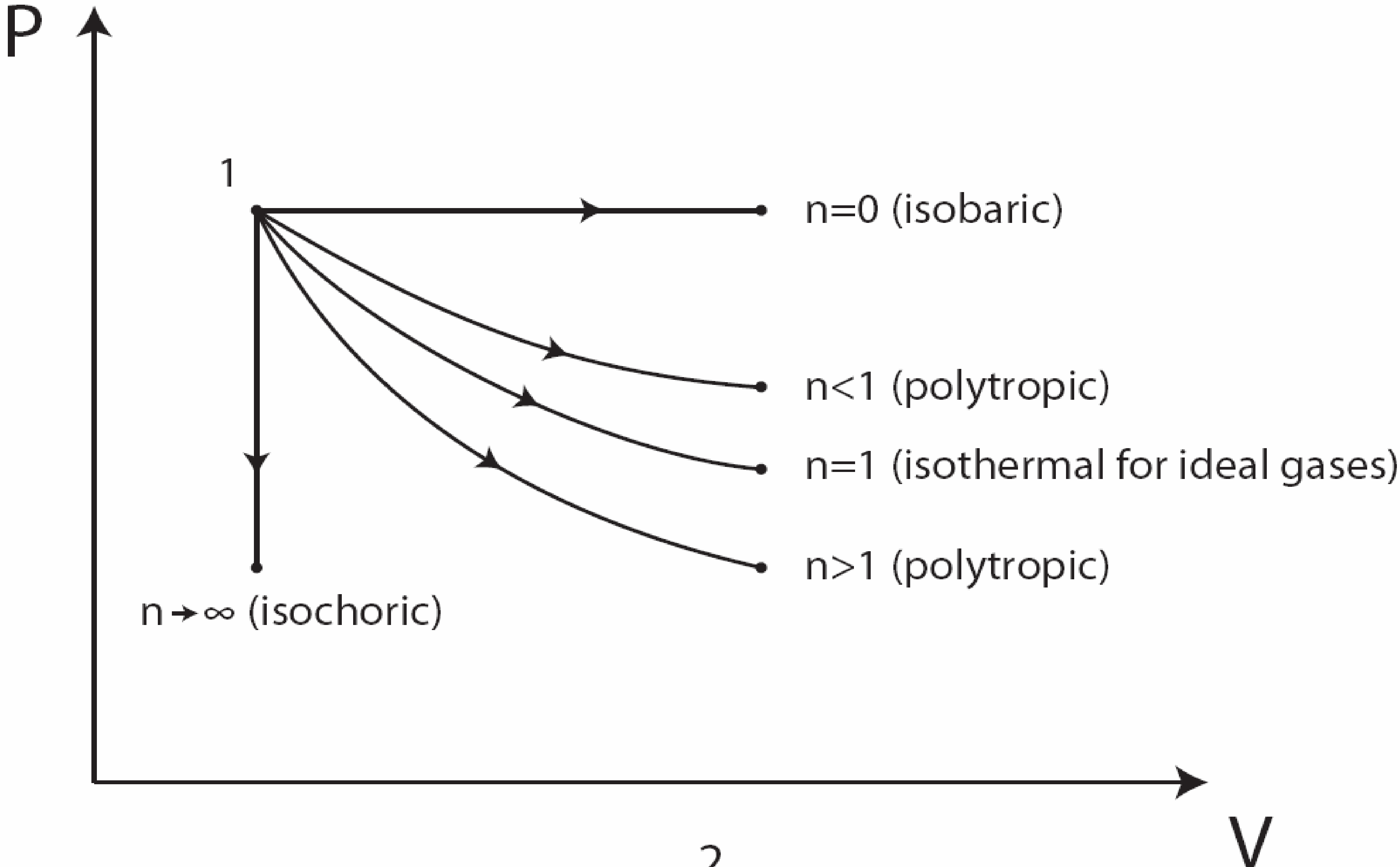


Friction: **internal** irreversibility
δQ with ($T_2 - T_1$): **external** irrev.

A few processes

- Isobaric: p = constant
- Isovolumetric (Isochoric)
  V = constant
- Isothermal: T = constant
- Adiabatic: $Q = 0$
- Polytropic process: $Q \neq 0$





$$ {}_1W_2 = \int_1^2 P\, dV $$

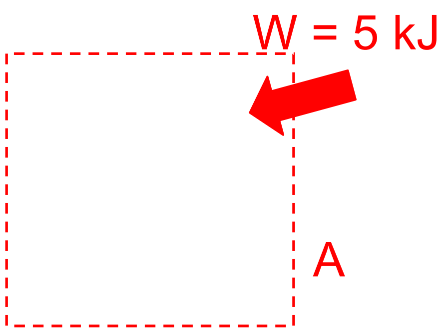
☠ Valid only for reversible processes!!!! NEVER try this on an irreversible one!

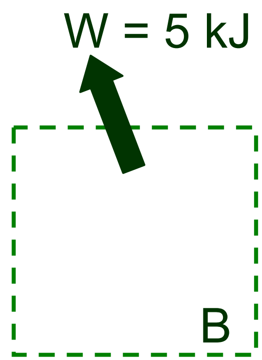
Concept of energy

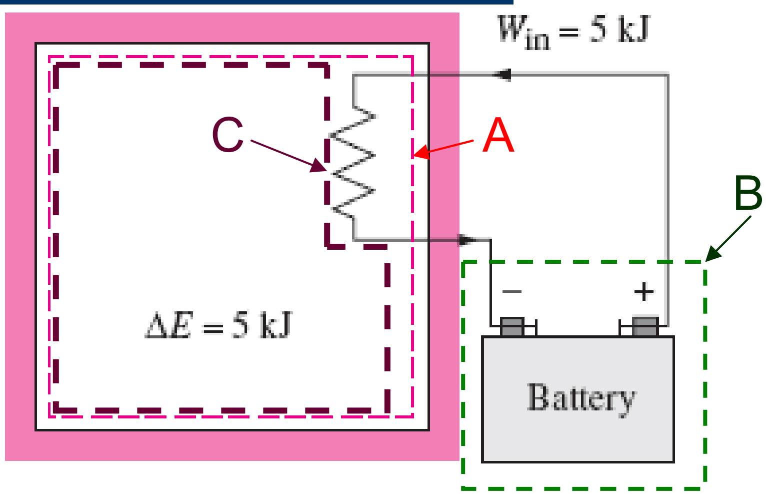
- Energy: ability to do work
- Stored energy: Ability of a system by virtue of its state: *internal energy, nuclear energy, mechanical energy (potential and kinetic), chemical energy, electrical energy (electrostatic, magnetostatic, electrodynamic)*
- Energy in transit:
  - **Heat**: Energy that crosses the system boundary due to temperature difference (finite or infinitesimal) across the system boundary
  - **Work**: Energy in transit, whose sole effect external to the system can be reduced to “raising of weight”

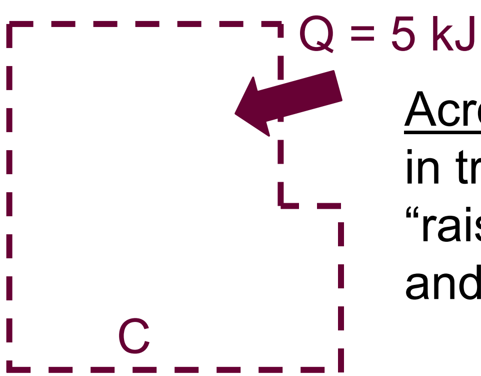
$$W = \int_{s_1}^{s_2} \mathbf{F} \cdot d\mathbf{s}$$

What crosses the boundary, heat or work?



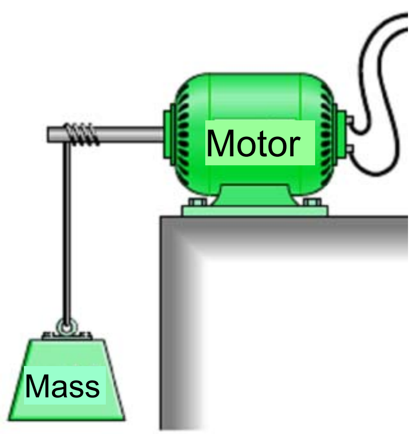






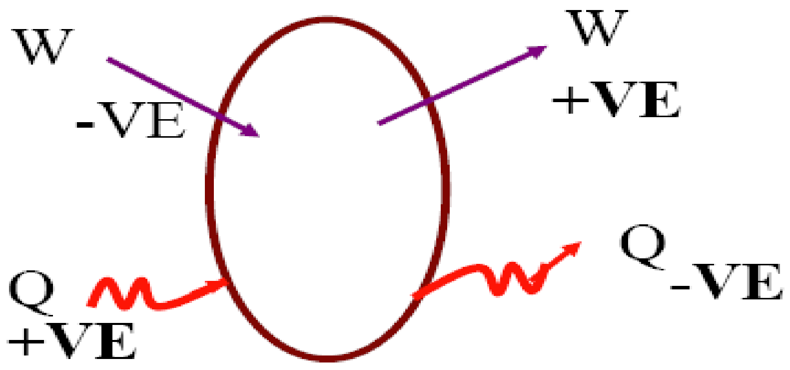
<u>Across boundaries A and B:</u> the energy in transit could have been converted to “raising of weight only” by using a motor and a pulley: both are **WORK**

<u>Across boundary C:</u> **Heat**

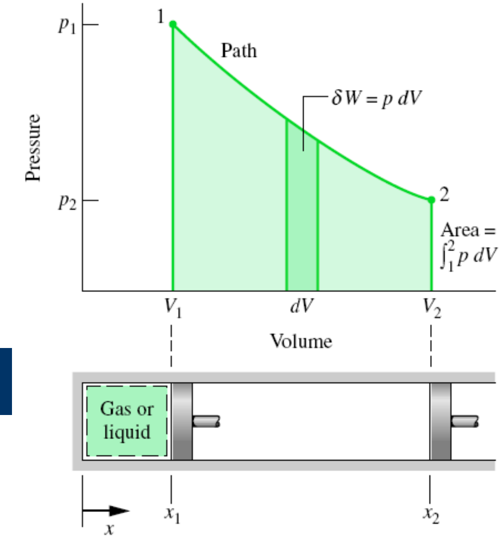


Heat and work: sign convention

- Work done BY the system is +ve
- Obviously work done ON the system is –ve
- Heat given TO the system is +ve
- Obviously Heat rejected by the system is -ve



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



Different forms of work

- Boundary work
- Shaft work (angular rotation against a torque)
- Work done in sending charge across a voltage
- Work done in deforming elastic solid or membrane
- Work done due to electric polarization or magnetization
- Work done due to reversible chemical reaction…

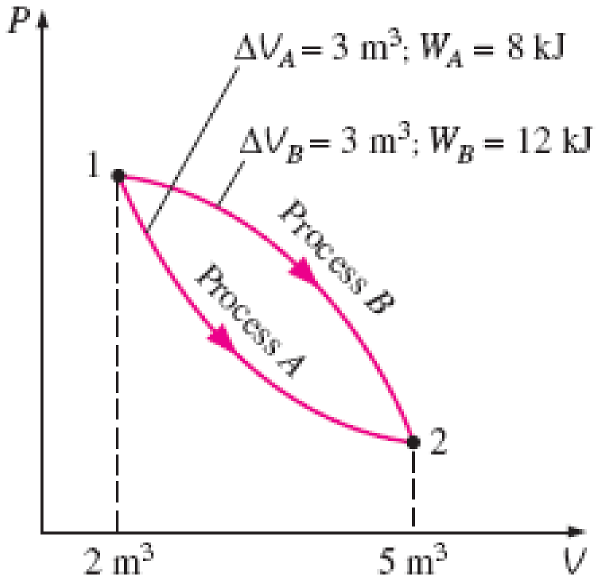
$$\delta W = pdV + \Gamma d\theta + \mathrm{V} dq - \sigma d\left(Ax\right) - \Xi \cdot d\left(V\mathbf{P}\right) - \gamma dA + \ldots$$

Boundary work | Shaft work | Electric work | Elastic work | El/mag Polarization work | Surface tension work

Γ=Torque (Nm), θ=Angular displ., σ=Elastic stress (Nm^{-2}), γ=Surface tension (Nm^{-1}), Ξ=Electric/magnetic field, V =Vol (m^3) P=Dielectric / magnetic polarization

Attributes of work and heat

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are boundary phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state.
- Both are path functions (i.e., their magnitudes depend on the path followed during a process as well as the end states).



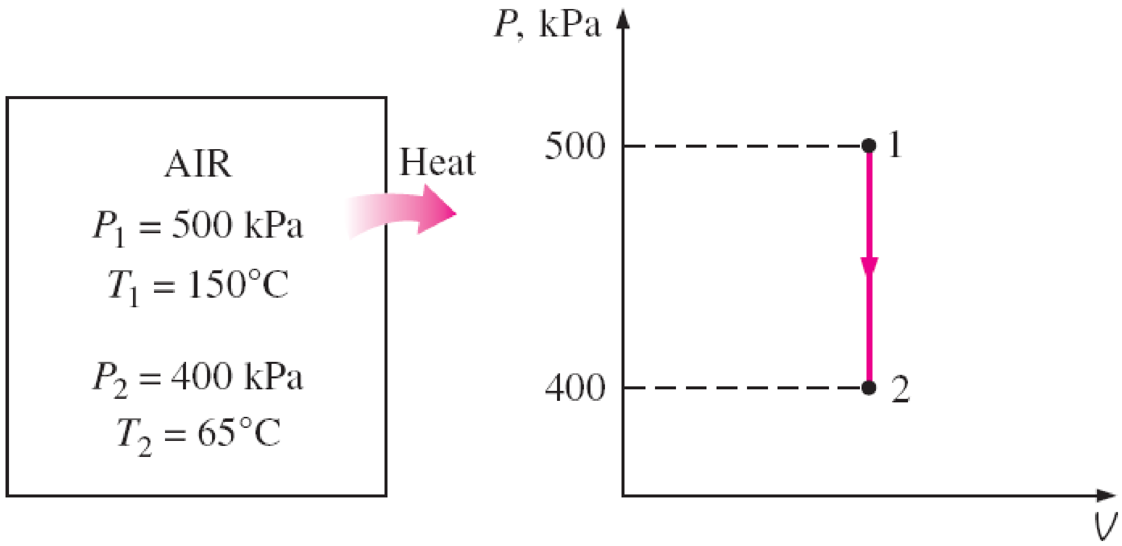
$$ {}_1W_2 = \int_{x_1}^{x_2} F\mathrm{d}x = \int_1^2 p\mathrm{d}V $$

Calculation of work transfer

- Do sample problems
  - Remember, you can calculate work transfer using $W = \int p dv$ only if the process follows a equilibrium or quasi-equilibrium path (i.e., you know precisely how *p* varies with *v*.
  - You **cannot** calculate work done using the above expression if the process is internally irreversible

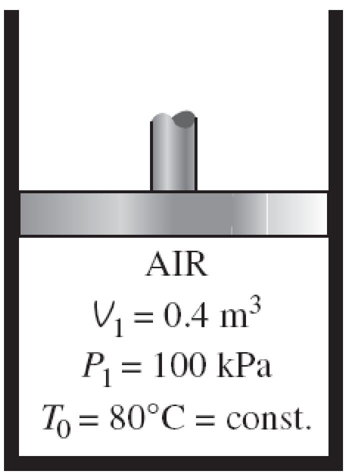
Example 1:

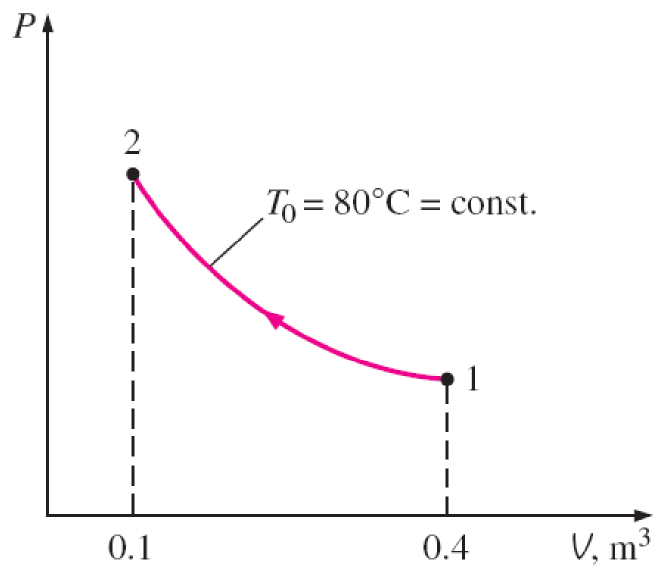
A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.



Example 2:

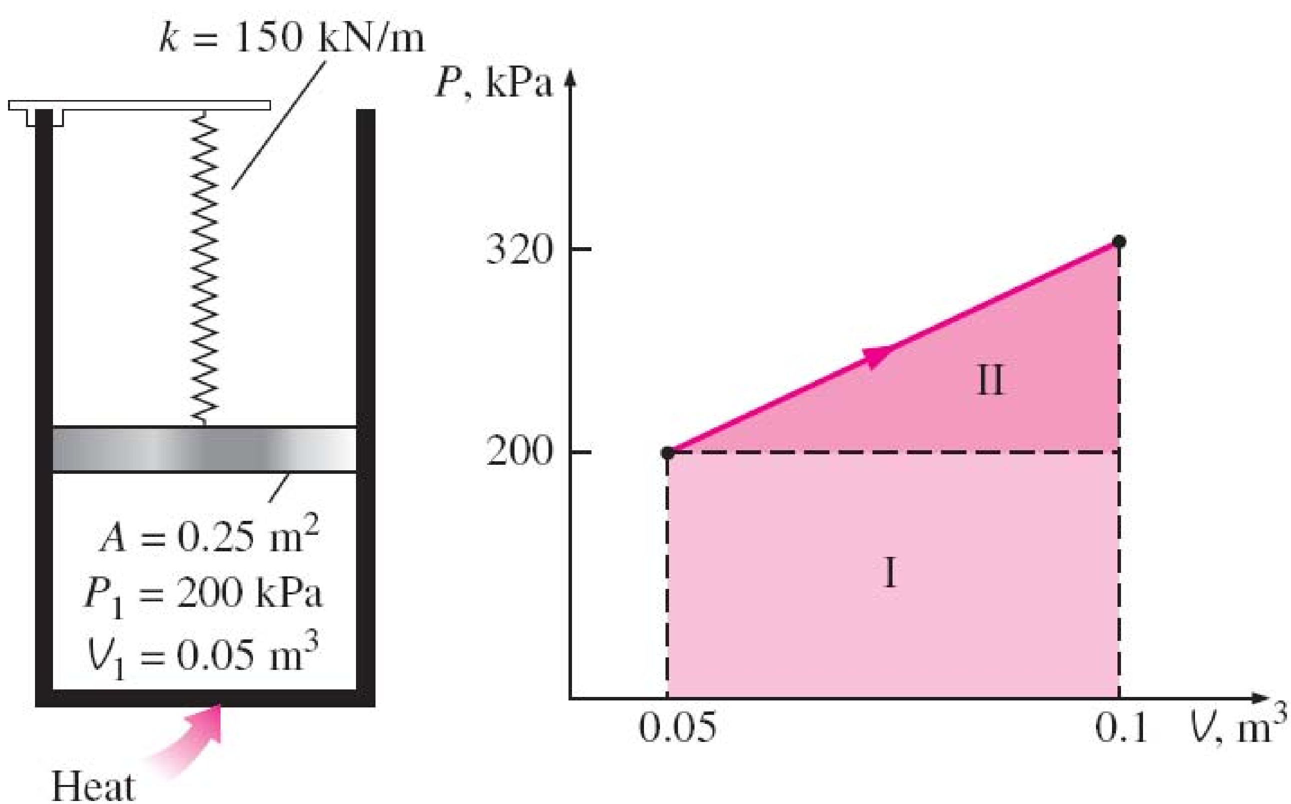
A piston–cylinder device initially contains 0.4 m^3 of air at 100 kPa and 80°C. The air is now compressed to 0.1 m^3 in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.





$= -55.5$ kJ

3 A piston–cylinder device contains 0.05 m^3 of a gas initially at 200 kPa. At this state, a linear spring that has a spring constant of 150 kN/m is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is 0.25 m^2, determine (*a*) the final pressure inside the cylinder, (*b*) the total work done by the gas, and (*c*) the fraction of this work done against the spring to compress it.



Ans: (a) 320 bar
(b) 13 kJ
(c) 3/13