Class 1: Introduction and basic thermodynamic concepts

Navy Shipyard Fire Department Vehicle (1881)

Manufactured in England by Merryweather & Sons – London. The steam which set in motion the water pumps to the fire hose was provided by the coal boiler. In less than 10 minutes it produced the required pressure, which happened while the car was on its way to the fire. The car was pulled either by man or mules.

(Museu de Marinha, Lisbon)

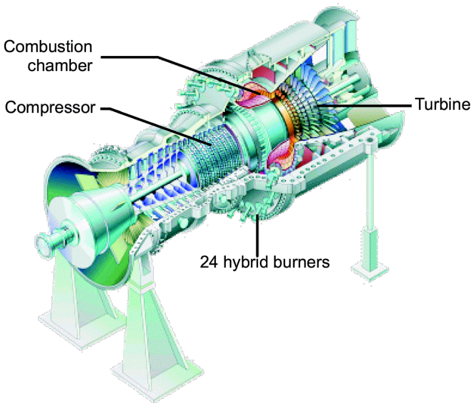
Recap Objectives Eng. Thermodynamics

- **Engineering thermodynamics:** application of thermodynamics to solve technological problems that engineers face

- Analysis of transport and conversion of various forms of energy (work ↔ electricity ↔ heat ↔ cold)

- **The objectives are:**
  1. Conversion of heat into work / electricity (heat engine)
  2. Transportation of heat using work / electricity (cooling / heat pump)

Heat converted into work (electricity) [1]



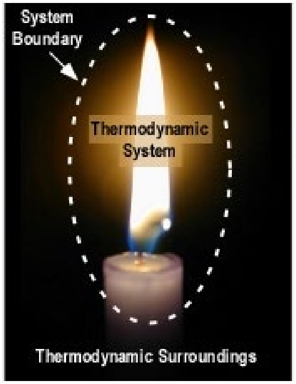
Heat converted into work to generate power [1]

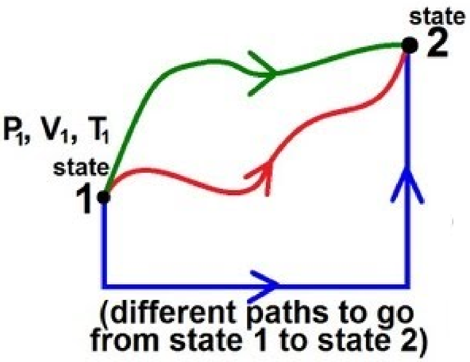
Work (electricity) converted into cold [2]

Roadmap Engineering Thermodynamics

- Using thermodynamics for practical applications requires knowledge of:

Concepts and definitions (Class 1)



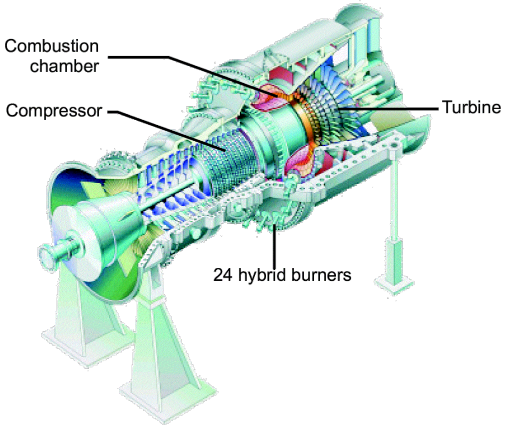


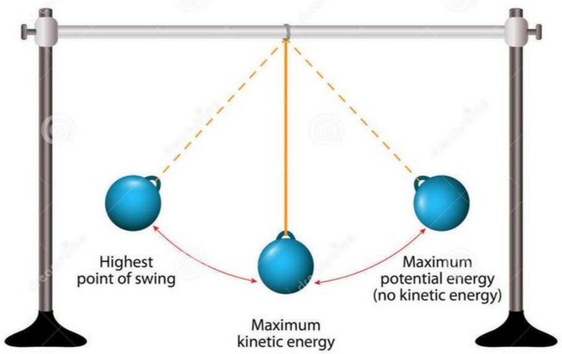
Various forms of energy (Class 2)

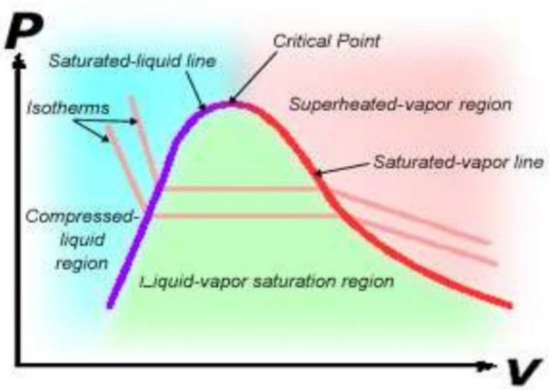
Power cycles
(Class 6 – 11)

Laws of Thermo
(Class 4 and 5)

Properties of Substances
(Class 3, 9)

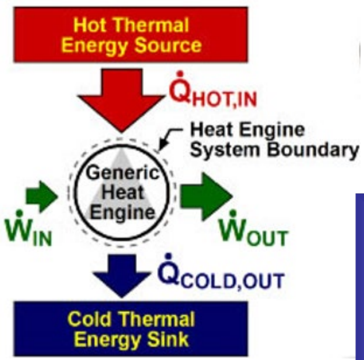




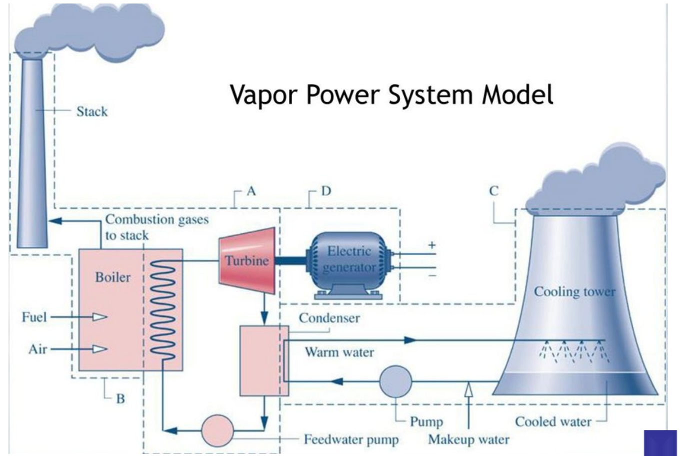


Roadmap Engineering Thermodynamics

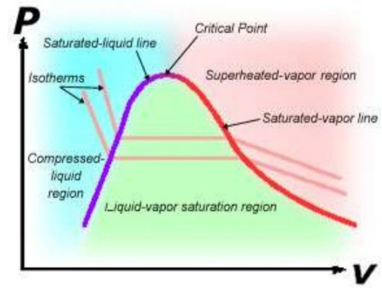
Thermodynamic cycles (Class 6)

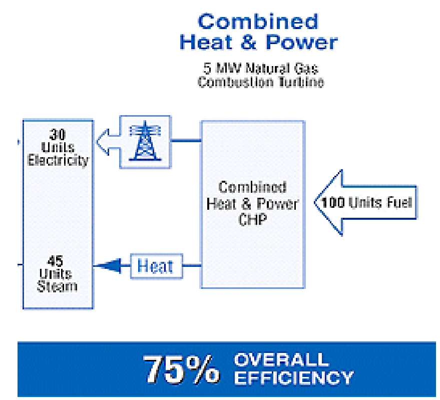


Vapor power cycles – Rankine cycle (Class 7, 8)

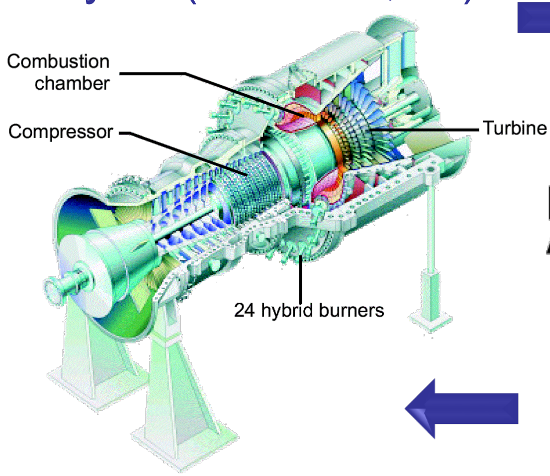


Properties of water (Class 3)

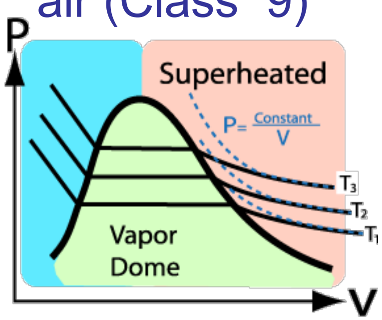




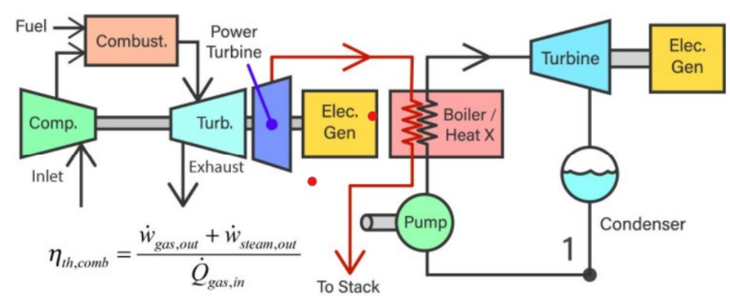
Gas power cycles – Brayton cycle (Class 10, 11)



Properties of air (Class 9)



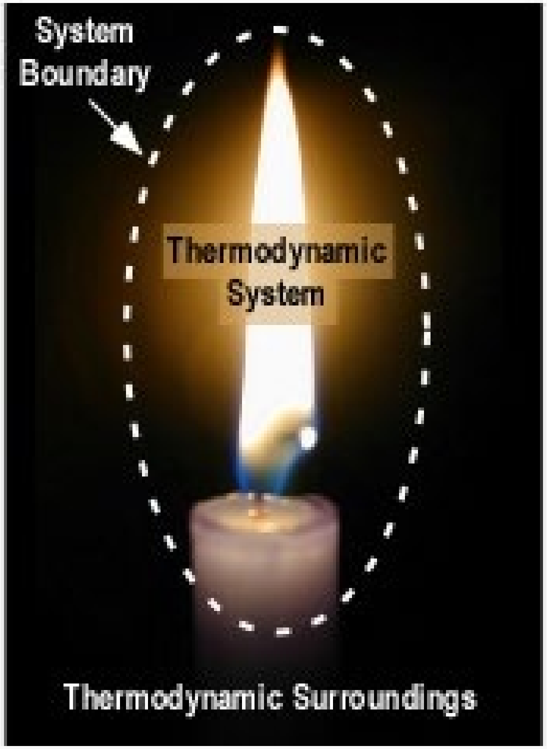
Combined cycles
Combined heat & power (Class 8, 11)



Content Class 1

- **Important definitions, concepts and terminology**

- Systems and boundaries
  - Open / closed / isolated systems
- Properties
  - Extensive / intensive / specific
- States and State Postulate
- Equilibrium and quasi-equilibrium
- Processes and cycles
  - Isobaric / isotherm / isochoric / adiabatic
  - Process diagrams
- Metric system and fundamental units
- Temperature and the zeroth law of thermodynamics
- Pressure (absolute and gauge pressure)



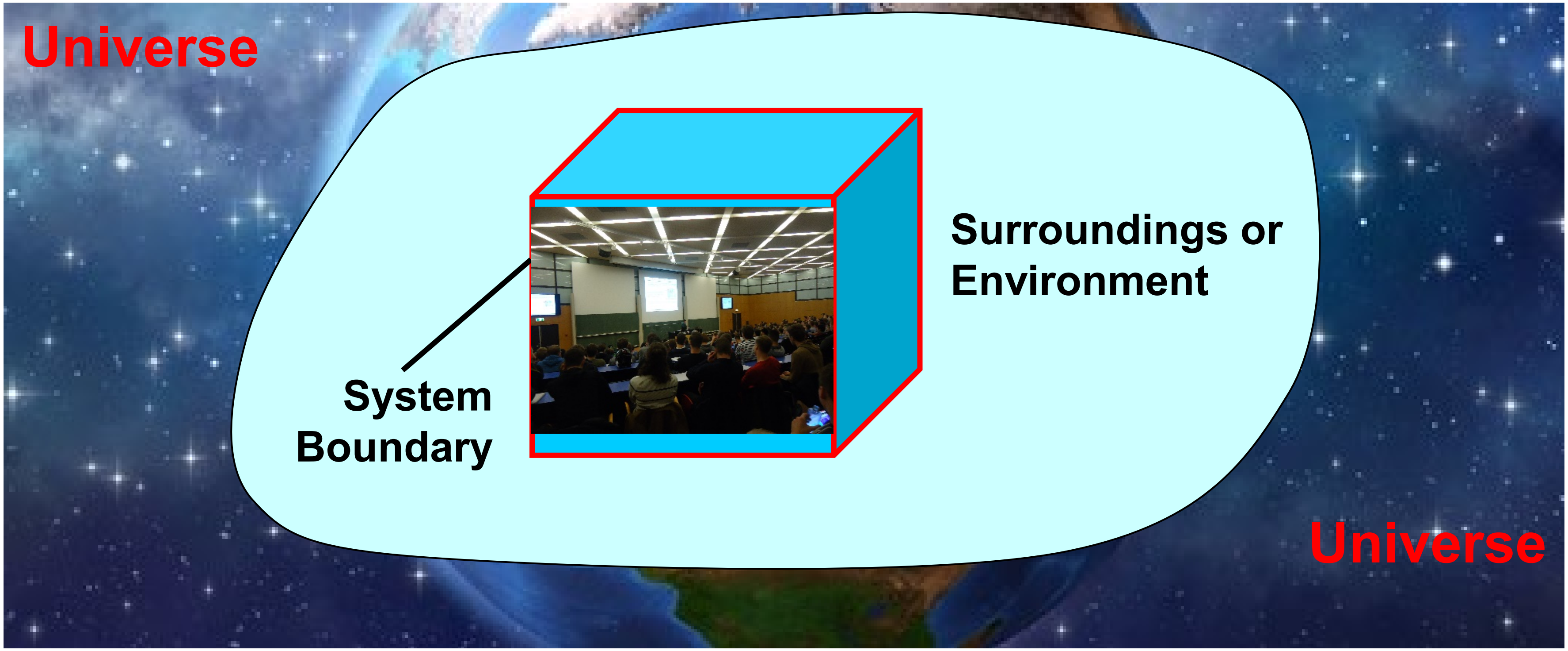
- **Learning goal:** explain thermodynamic concepts, processes & definitions

Systems: Definitions

- **System:** part of the universe that we want to analyze

Systems: Definitions

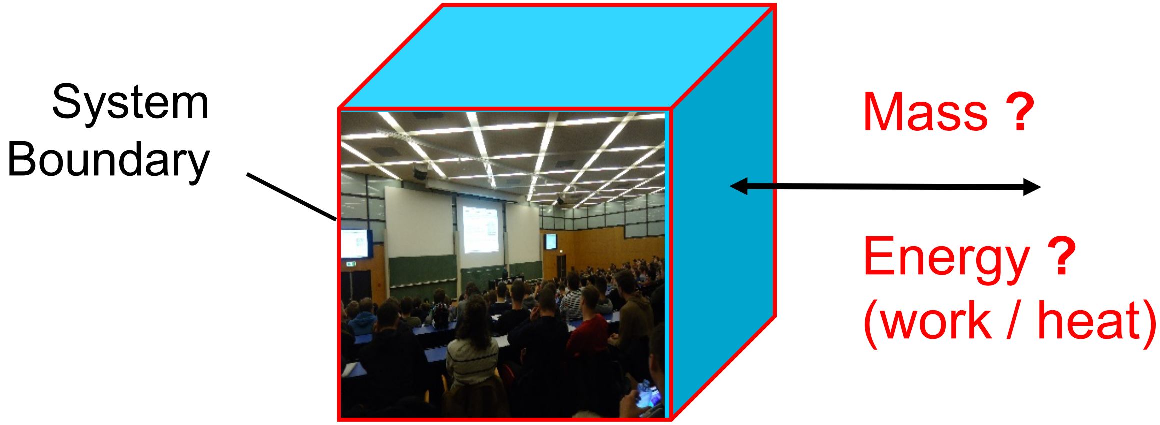
- **System:** part of the universe that we want to analyze
- **Surroundings / Environment:** part of universe that is affected or influenced by the system
- **System boundary:** separates the system from the surround-dings (note: system boundary can be rigid, deformable or move)



Systems: Examples

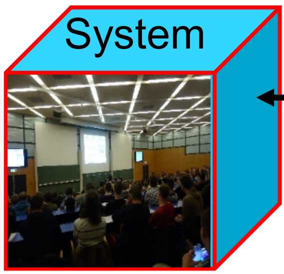
System Types

- **Different types of systems:** difference based on the **transport of mass and energy** across the system boundary



- **Open system:** Mass and energy (work and heat) can cross the boundary
- **Closed system:** Only energy (work and heat) can cross the boundary
- **Isolated system:** No mass or energy (work and heat) can cross the boundary
- **Insulated system:** Mass cannot cross the boundary, heat cannot cross the boundary, but work can

Systems Types

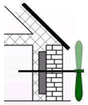
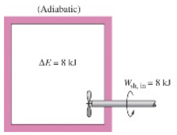


Mass ?

Energy ? (Work / heat)

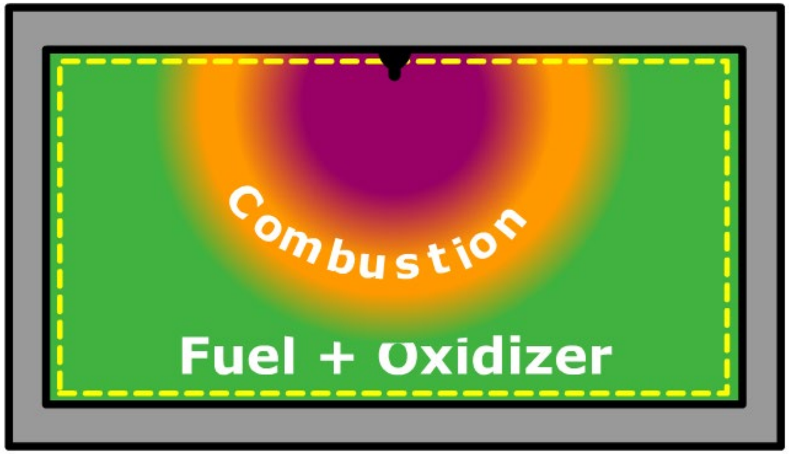
Transferred across system boundary

Note: a boundary can be rigid, deformable or move

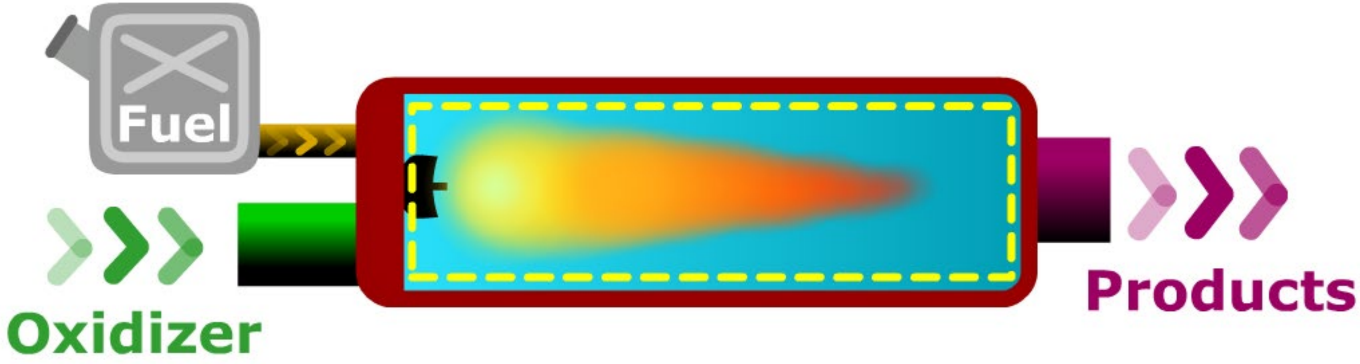
Type of System	Mass	Energy	Example
Open System / Control Volume (CV)	Yes	Yes	   
Closed System / Control Mass (CM)	No	Yes	   
Isolated System	No	No	 
Insulated System	No	Work yes Heat no	 

- Thermodynamic relations for closed or open systems are different

Combustion in Open & Closed Systems



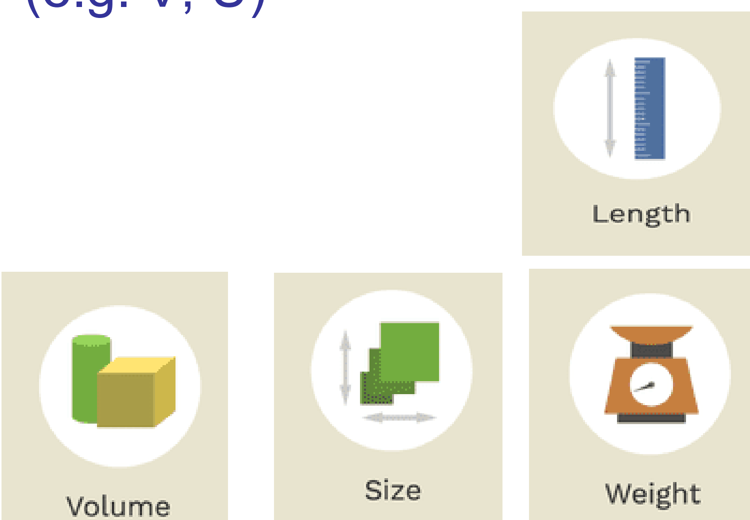
- **Closed system:** Combustion in a closed system, only heat can cross the system boundary mass stays inside the system
- **Open system:** Combustion in an open system, also mass (fuel, oxidizer and combustion products) can cross the system boundary



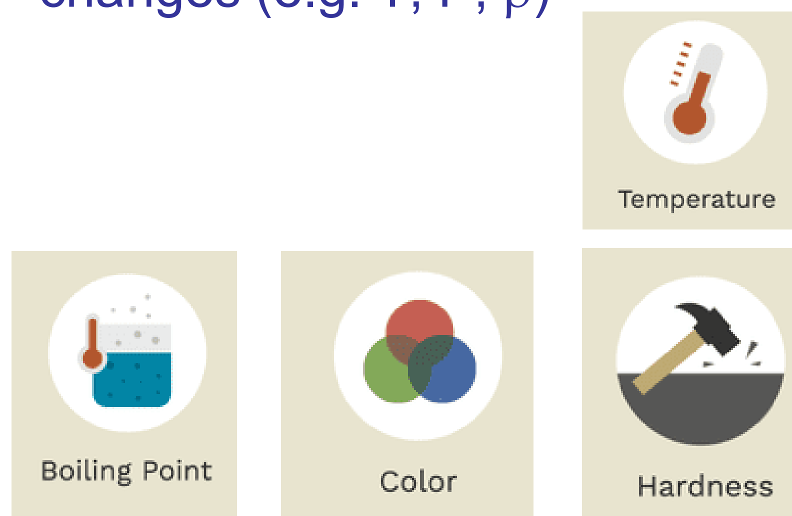
Properties: Definitions

- **Property:** any defining characteristic of a system
- **Thermodynamic properties:** properties that describe mass and energy of systems (e.g. T, P, v, ρ and U)

- **Extensive properties**
  Depend on system size, vary if the size of the system changes (e.g. V, U)



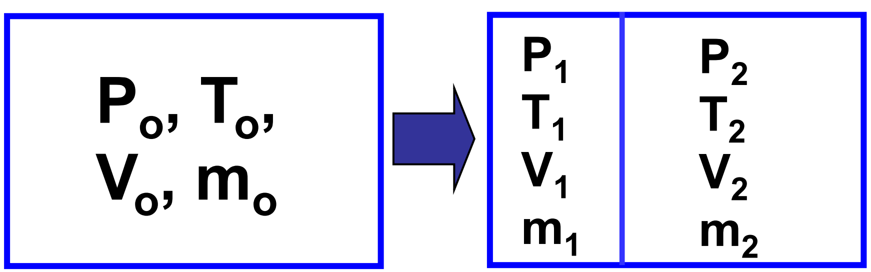
- **Intensive properties**
  Independent of system size, do not vary if the size of the system changes (e.g. T, P, ρ)



Intensive and Extensive Properties

- The value of an **extensive property** is dependent of the mass / size of the system
- The value of an **intensive property** is independent of the mass / size of the system

- The box will be divided in two parts
- How will the properties change?



$P_0 = P_1 = P_2 \rightarrow$ Intensive prop

$T_0 = T_1 = T_2 \rightarrow$ Intensive prop

$V_0 \neq V_1 \neq V_2 \rightarrow$ Extensive prop

$m_0 \neq m_1 \neq m_2 \rightarrow$ Extensive prop

Total and Specific Properties

- Besides **intensive** and **extensive** properties, **total** and **specific** properties can be distinguished

- **Total properties**
  - Describe the total value of a system
  - Depend on the size of the system, i.e. extensive properties
  - Denoted by upper case letter

- **Specific properties**
  - Dividing an extensive property by mass gives a specific one
  - Specific properties are intensive properties as they are not dependent on the size of the system
  - Denoted by lower case letter

- Total volume: V [m^3]
- Specific volume: $v = V/m$ [m^3/kg]

V = 3 liters = 0.003 m^3
m = 2.76 kg
v = 0.003/2.76 = 0.00109 m^3/kg

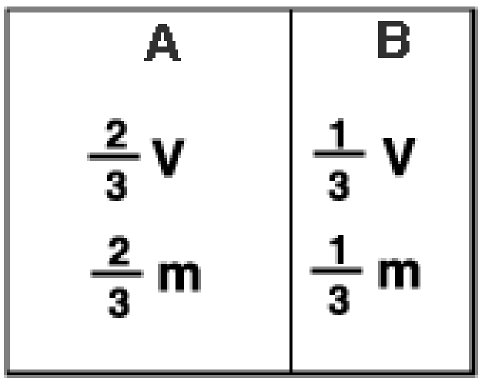
Specific Properties

- **Why we use specific properties?**
  - The size of the system is not important to know something of it
  - Everyday life example: shopping

- Fresh fruit, vegetables and meat are priced in Euro per kg
  - you buy Y kg and you pay Y kg x euro/kg (price is independent of the amount of vegetables or meat that the shopkeeper has)
  - You don’t want to know the total price of a big piece but you need to know what to pay if you buy 200 grams.

Total and Specific Properties

- **Example for volume**
- Total volume: V [m^3]
- Specific volume: v = V/m [m^3/kg]
  (note: v = 1/ρ)



$$V_{A+B} = V_A + V_B$$

$$m_{A+B} = m_A + m_B$$

$$v = \frac{V_{A+B}}{m_{A+B}} = \frac{V_A}{m_A} = \frac{V_B}{m_B}$$

- Specific volume, v = V/m = 1/ρ is the same for A and B
- This also holds for energy properties
  - Total energy: E [J]
  - Specific Energy: e = E/m [J/kg]

Note: in handwriting the difference between upper and lower case is not always clear

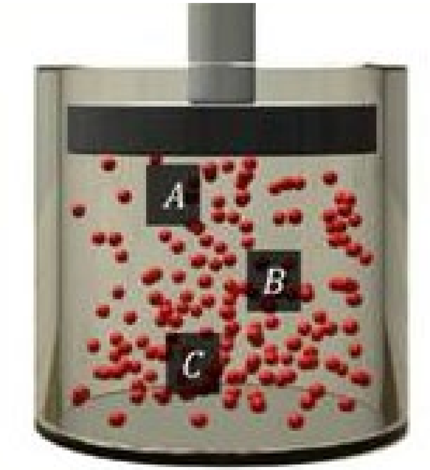
Intensive, Extensive and specific properties

Property	Extensive	Intensive
Mass	m	-
Temperature	-	T
Volume	V	v = V/m (specific volume)
Pressure	-	P
Internal Energy	U	u = U/m (specific internal energy)
Enthalpy	H	h = H/m (specific enthalpy)

- Any extensive property can be made intensive by dividing by mass
- This is a **specific property**

Thermodynamic State

- A set of thermodynamic properties that describe the condition of a system
- At a given state all the properties of the system have fixed values
- The ability to define the state of a system is essential in thermodynamics
- Using the state postulate, only a limited set of property data is needed to determine all property data of a thermodynamic state



T, P, v, m, e, ….

State Postulate

- Knowing any two independent properties of a state one can determine any other property of the state (more in class 3)

> State postulate: The state of a simple compressible system is completely specified by two independent, intensive properties

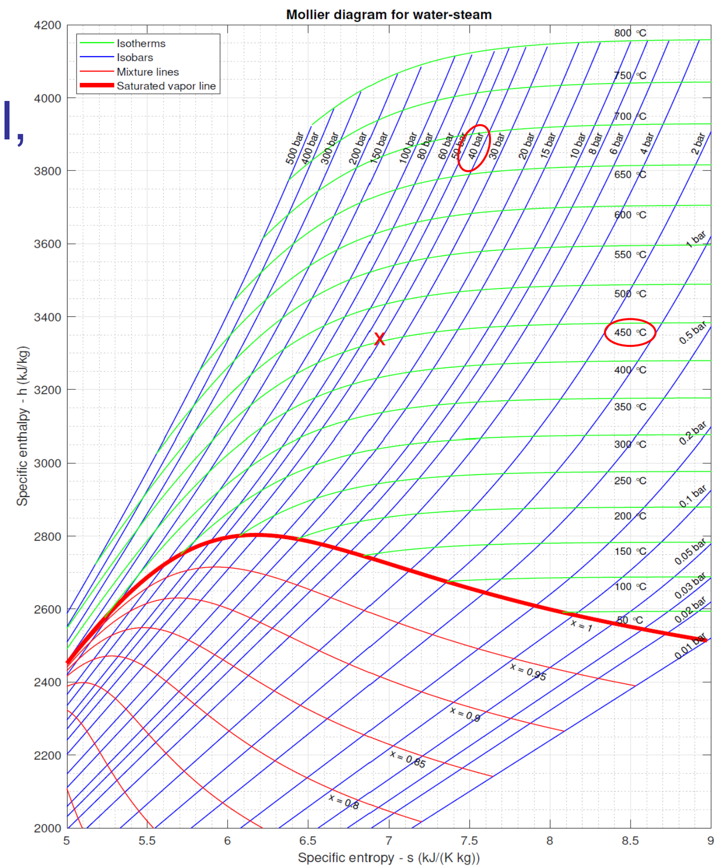
- Simple compressible system: If a system involves no electrical, magnetic, gravitational, motion and surface tension effects

Table of Steam Properties

P (kPa)	T (^{0}C)	v (m^3/kg)
100	100	1.696
100	120	1.793
100	160	1.984

ThermoNet: John Wiley Publishers

The state of nitrogen is fixed by two independent properties



Changing the state of a system: Processes

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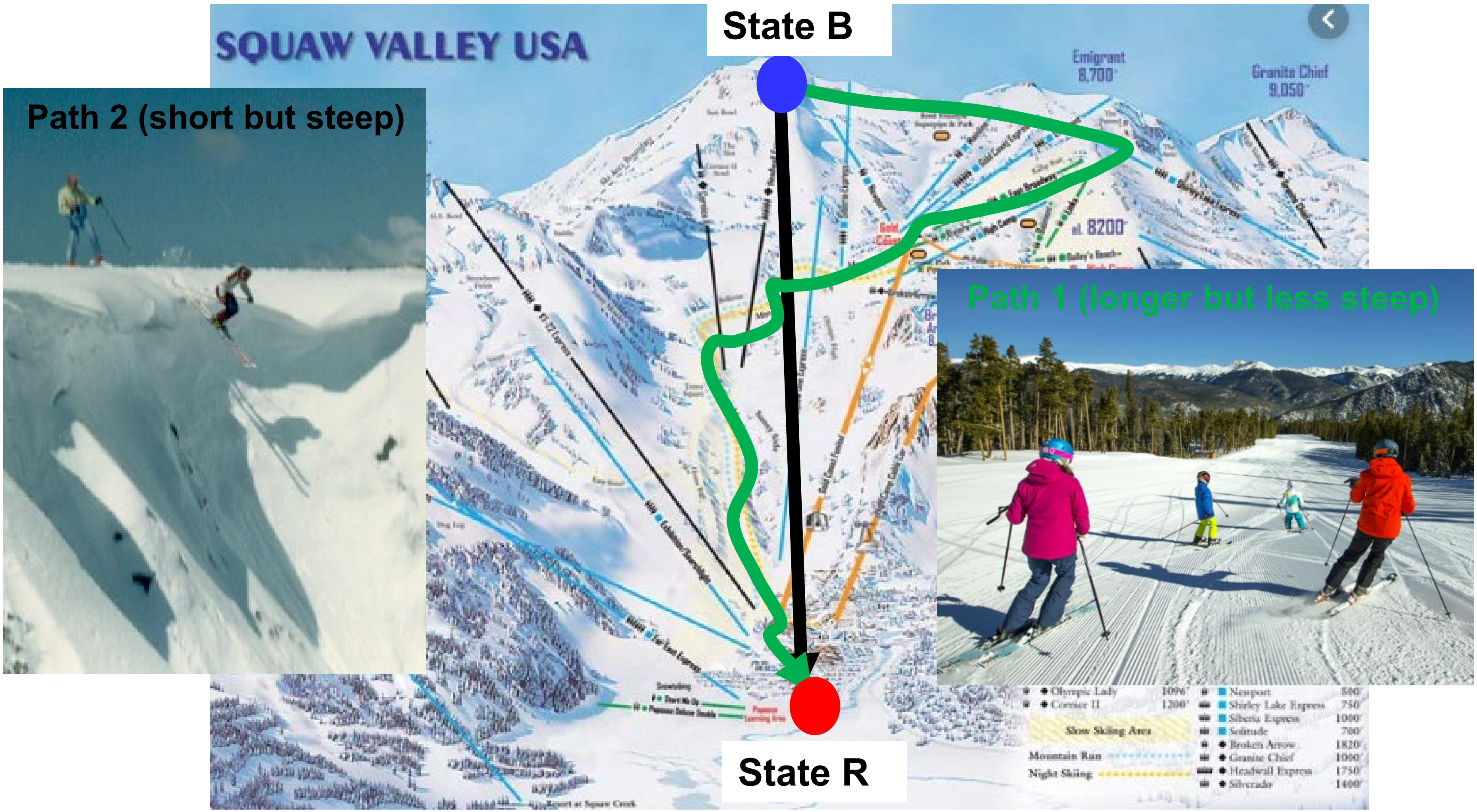
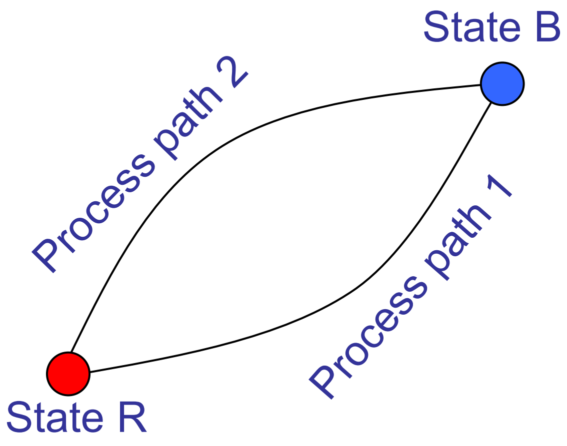


- A change of the system, state B to R is also a change of its properties (T, P, ..)
- The process, the way the change is accomplished, can differ (different the paths) but the change in the state (properties) will be the same

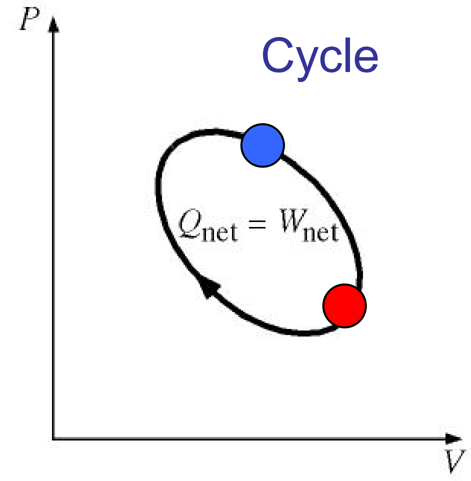
Changing the state of a system: Processes

- Change of the **state** of the system is reflected in a change of the properties of the system



- **Process:** Changing the state of a system

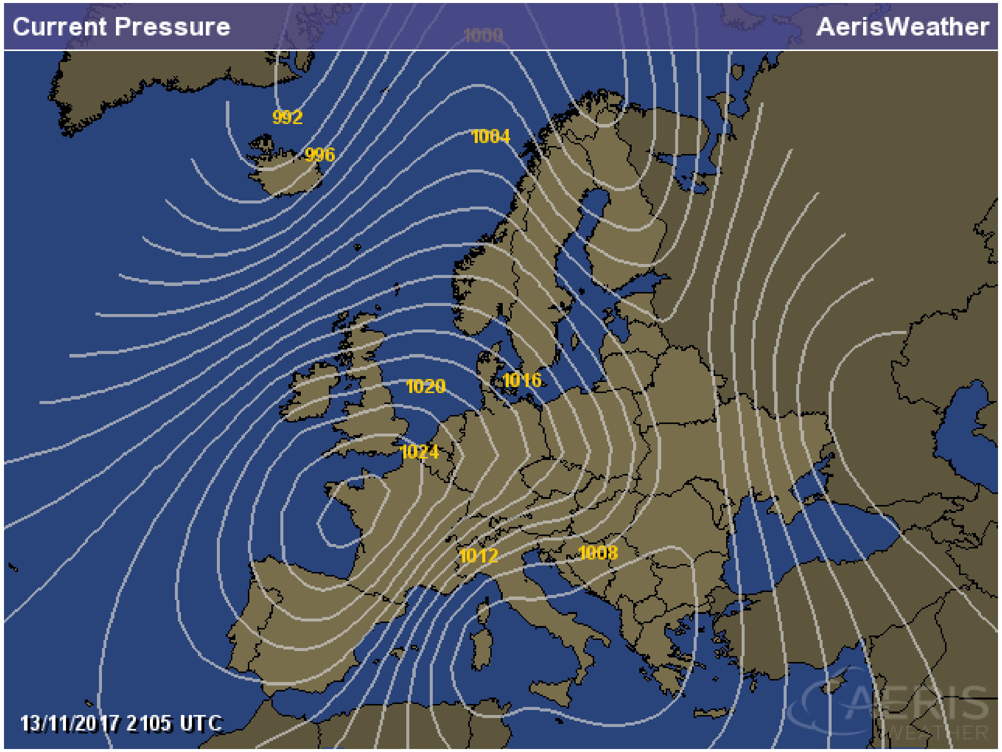
- The system undergoes a **cycle** if it undergoes a process to a different state and returns to the original state via a different process path



Types of Processes

- **Isothermal:** constant temperature
- **Isobaric:** constant pressure
- **Isometric or isochoric:** constant volume
- **Adiabatic:** no heat transfer

This does not imply that the temperature is constant, the temperature can still change by heating up or cooling down as a result of work added or subtracted to the system

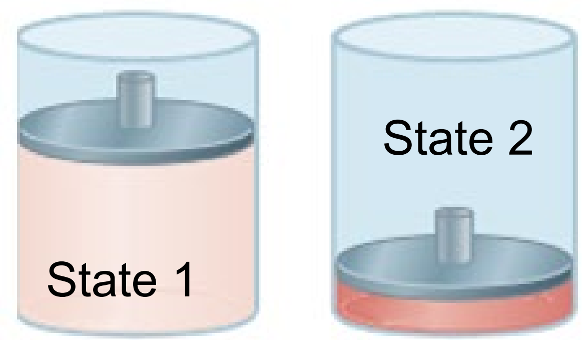


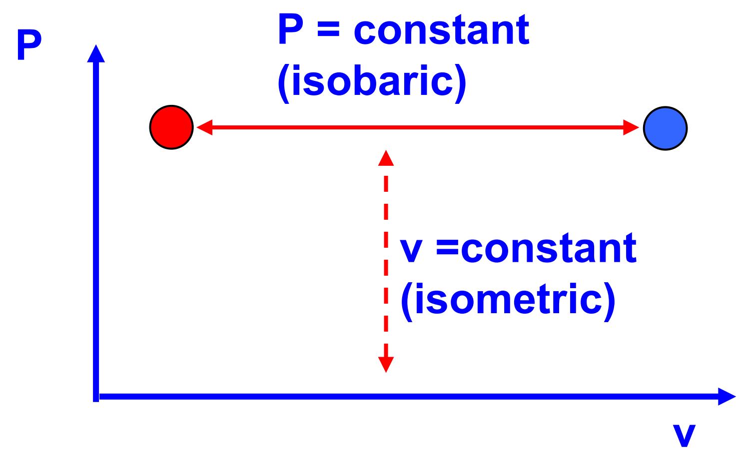
Isobars, lines of constant pressure on a weather map

Processes: property diagrams

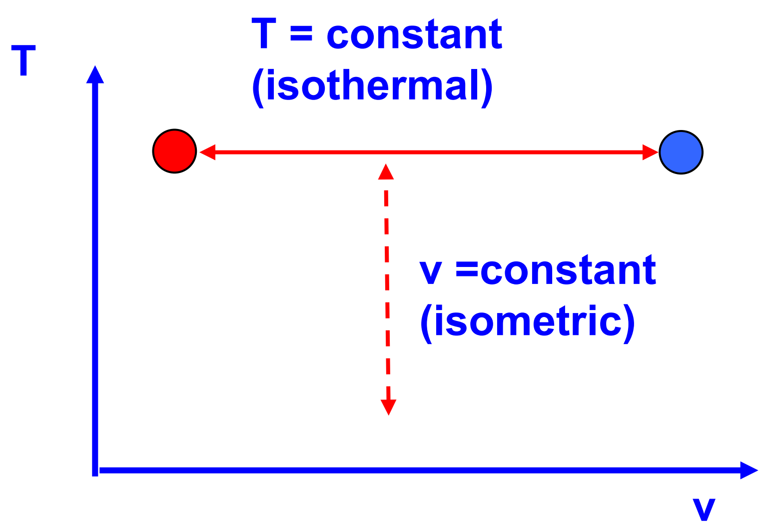
- Thermodynamic processes displayed in property diagrams

- Pv-diagram

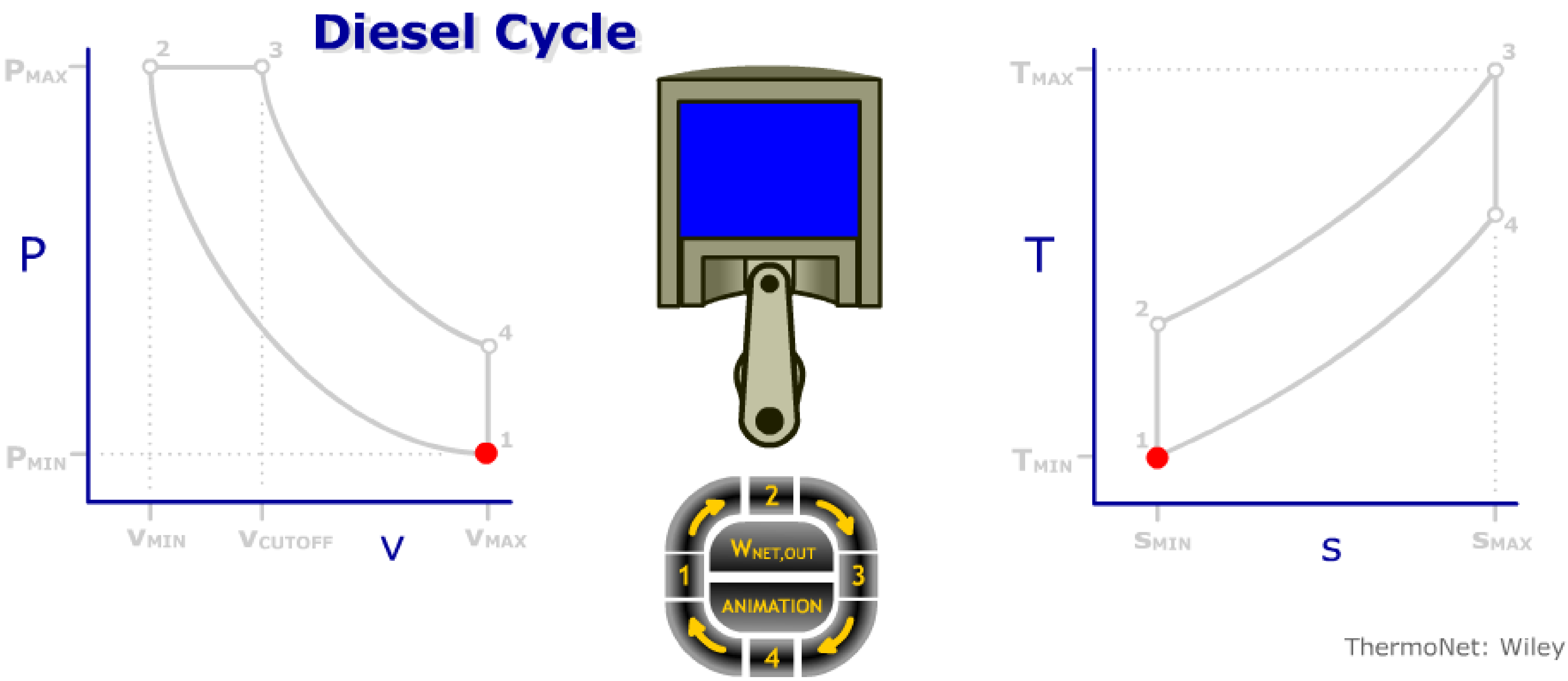




- Tv-diagram



Example: Isobaric, Isentropic & Isometric Processes

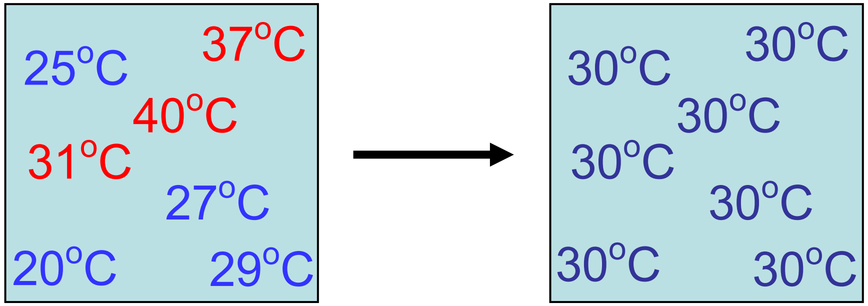


- Isobaric process (2-3) and isochoric (isometric) (1-4) process
- Processes (1-2) and (3-4) are isentropic (class 5)
- The four processes together make a complete cycle

Thermodynamic Equilibrium

- **Equilibrium** of a system implies a state of balance of the system, where there are no driving forces within the system

- **Types of equilibrium**
  - Thermal equilibrium
  - Mechanical equilibrium
  - Phase equilibrium
  - Chemical equilibrium



Closed system reaching thermal equilibrium

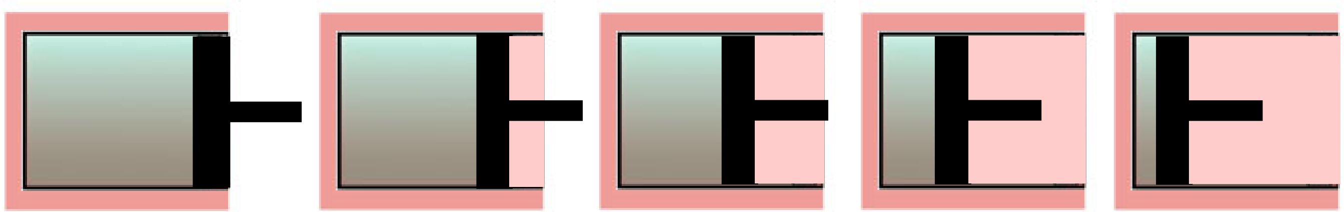
- A system is only in

equilibrium when all relevant equilibrium criteria are satisfied

- If the properties of a system (like pressure and temperature) are not changing with time the system is in **thermodynamic equilibrium**

Quasi-Equilibrium

- A system's equilibrium changes during a process
- During the process, the system passes a series of states
- Describe the system at any point in time ⟶ always consider a system to be in quasi-equilibrium
- Quasi-equilibrium
  - Idealized process, not a true representation of an actual process
  - Modeling tool



Slow compression: every step quasi-equilibrium is reached

- All steps can be considered infinitesimal small and the process occurs between the upper and lower limit
- Mathematics: differentials and integrals

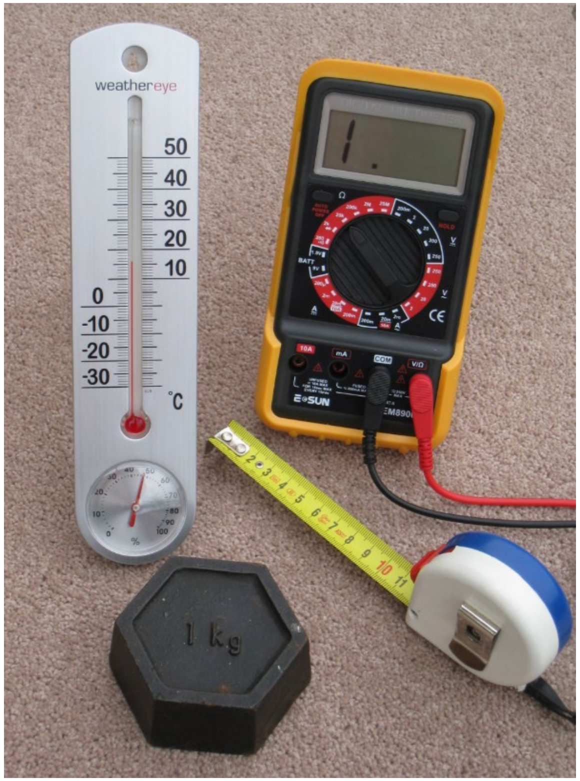
Unit Systems / Dimensions

- **Fundamental units or dimensions:** defined by reproducible physical measurements
  - SI: metric international system
  - Base units: time (s), length (m), temperature (K), mass (kg)

- **Derived units or dimensions:** derived from base units
  - Force (N) is a derived unit from mass via:

    Newton's Law: $F = m.a$ $[N] = [kg.m/s^2]$

- Always give units with values, without a unit the answer is useless



- Note: Other unit system, U.S. Conventional System or English System (USCS)
  - Base Units: time (s), length (ft), force (lbf)
  - Mass (lbm) is a derived unit from force
- Although it is handy to know how to convert units, it not part of this course

Property Units: Time (t)

- **Time (t) in seconds (s)**

  - Since 1967 the second is defined as the time required for cesium-133 atoms to resonate 9.192.631.770 cycles in a cesium resonator

1 second is 9.192.631.770 trillingen in cesium-133

https://www.youtube.com/watch?v=oPLirFEFflY&feature=youtu.be

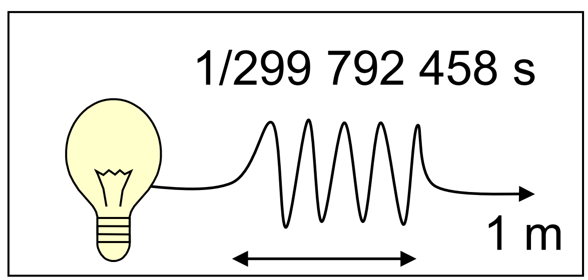
Property Units: Time (t)

Some Dutch culture

Time is one of the fifty subjects in the beta canon (http://www.foksuk.nl/betacanon en http://extra.volkskrant.nl/betacanon/)

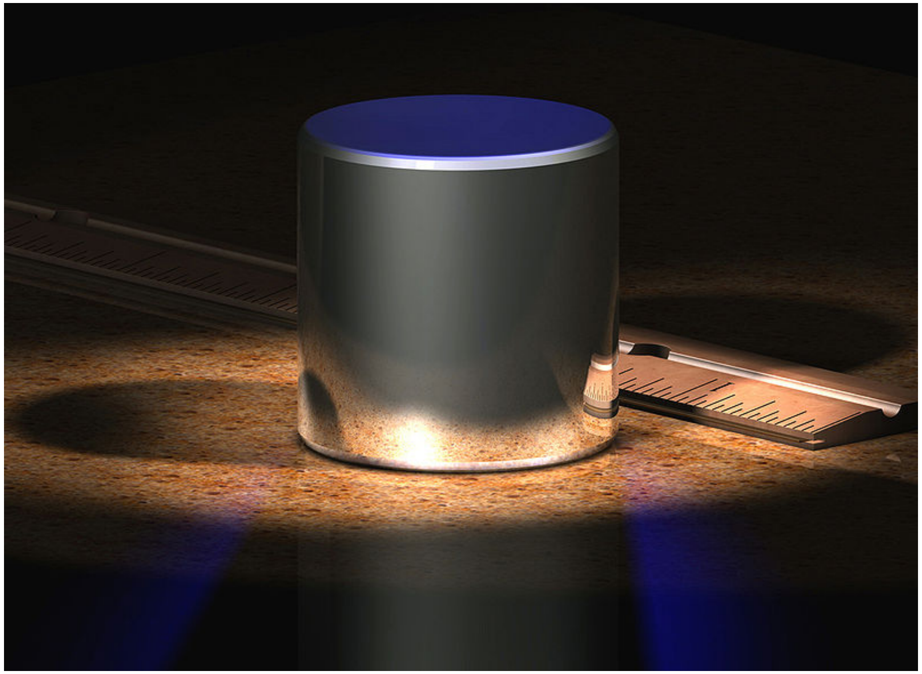
Property Units: Length (L)

- **Length (L) in meters (m)**
  - 1875 International Prototype Meter, the distance between two marks on a platinum-iridium bar under certain prescribed circumstances (the bar is in the International Bureau of Weights and Measures in Serves in France)
  - In 1960 a meter is a length equal to 1 650 763.73 wave-lengths in a vacuum of the orange-red line of krypton-86
  - In 1983 the meter is the length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 (1/c) of a second



Property Units: Mass (M)

- **Mass (M) in kilograms (kg)**
  - Defined in 1889/1901 as the mass of a platinum-iridium cylinder maintained under prescribed conditions. The International Prototype Kilogram is kept at the *Bureau International des Poids et Mesures* (International Bureau of Weights and Measures) in Sèvres on the outskirts of Paris.



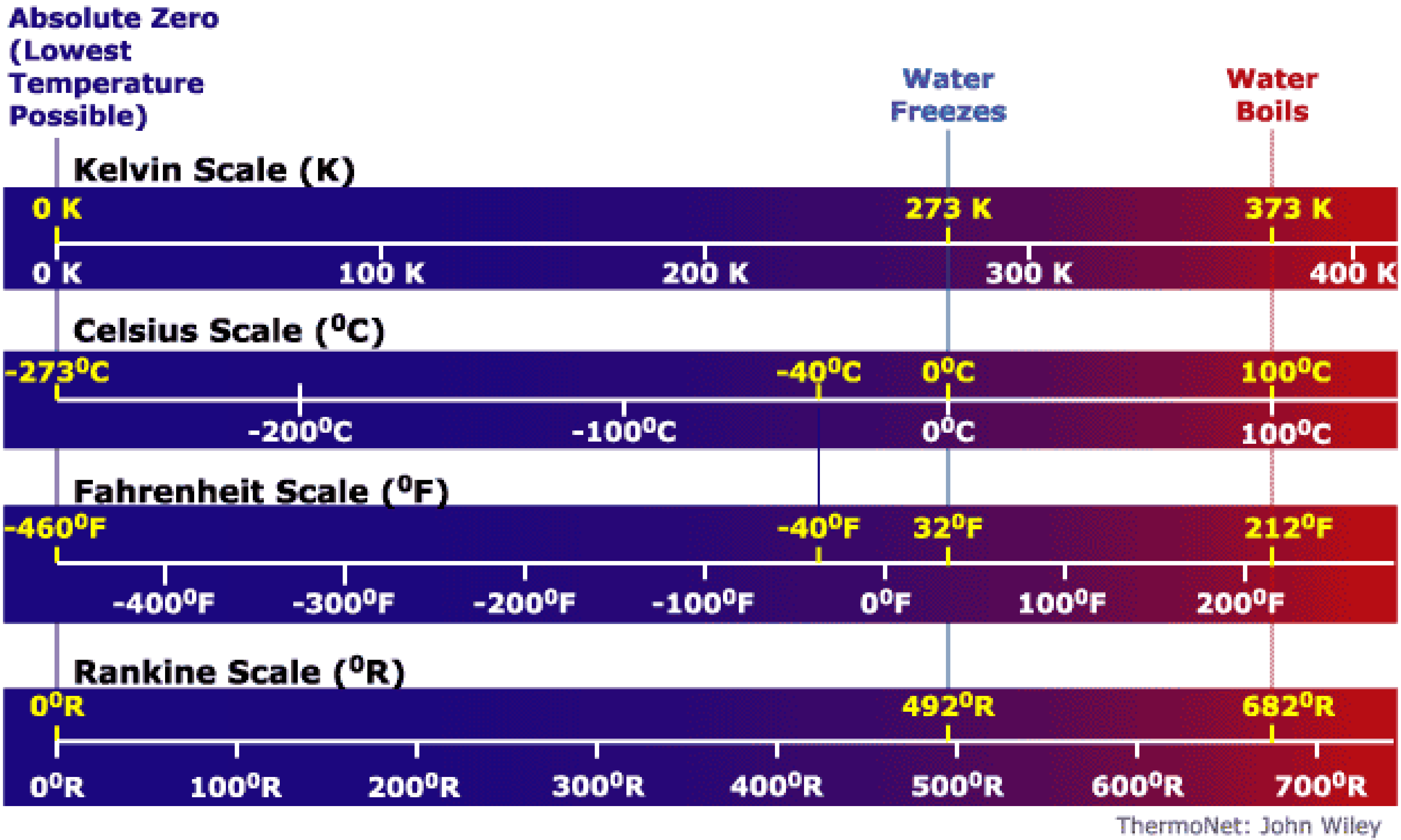
A computer-generated image of the **International Prototype kilogram** (IPK), which is made from an alloy of 90% platinum and 10% iridium (by weight) and machined into a right-circular cylinder (height = diameter) of 39.17 mm (the inch ruler is for scale), its edges have a four-angle chamfer to minimize wear.

Property Units: Temperature (T)

- **Temperature (T) in Kelvin (K)**
  - **Absolute zero temperature**
    - Lowest possible temperature
    - Units: Kelvin (K)   (T = 0 K)
    - Can never be negative
  - **Relative temperature**
    - Temperature measured relative to non-absolute zero temperature
    - Freezing point of water at atmospheric pressure (273.15 K)
    - Units: Degrees Celsius (^{0}C)
  - T(K) = T(^{0}C) + 273.15
- The **Kelvin** is defined as the 1/273.16 part of the thermodynamic temperature of the triple point (freezing point) of water

Lord Kelvin (William Thomson)
(1824-1907)

Temperature Scales



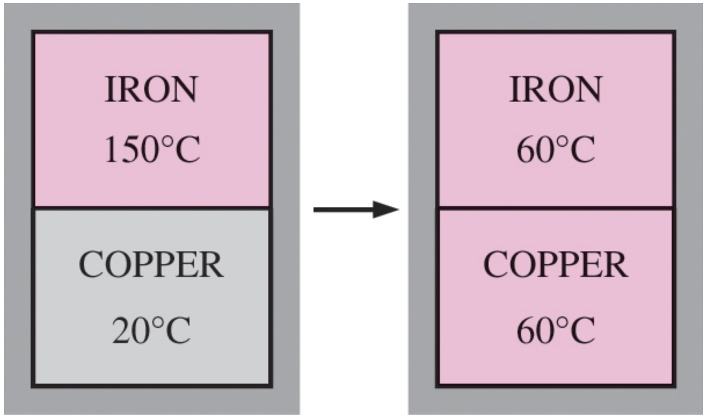
Zeroth law of thermodynamics

- **The zeroth law of thermodynamics** states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other

- By replacing the third body by a thermometer it can be restated as, two bodies are in thermal equilibrium if both have the same temperature even if they are not in contact

- It may seem silly that such an obvious fast is called one of the basic laws, however it cannot be concluded from the other laws and serves as a basis for the validity of temperature measurements

- Its value as a fundamental physical principle was recognized after formulation of the first and the second law and therefore called the zeroth law



Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure

- The zeroth law was formulated by Fowler in 1931

Property Units: Volume (V) – Density (ρ)

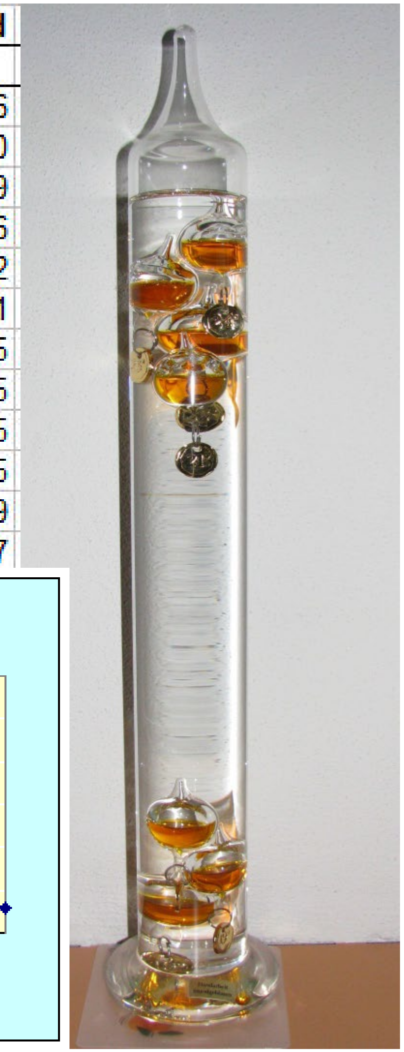
- **Volume, specific volume and density**
  - Volume, V [m^3]
    - Related to meter
  - Specific volume, v [m^3/kg]

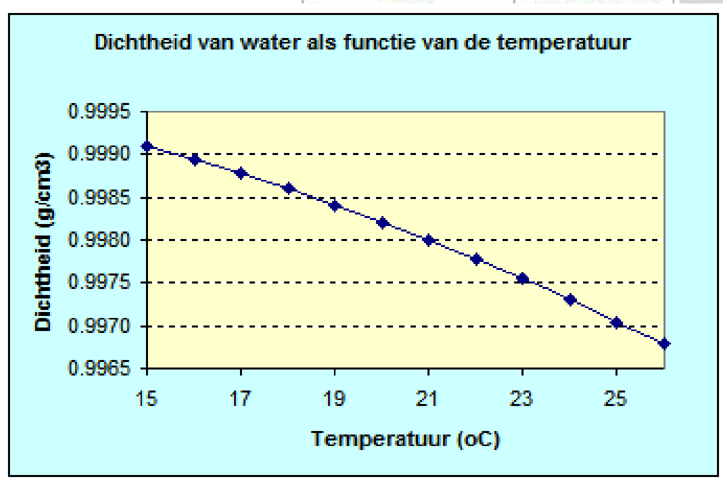
$$v = \frac{V}{m}$$

  - Density, ρ [kg/m^3]

$$\rho = \frac{1}{v} = \frac{m}{V}$$

Temperatuur	Dichtheid
oC	kg/m3
15	999.1026
16	998.9460
17	998.7779
18	998.5986
19	998.4082
20	998.2071
21	997.9955
22	997.7735
23	997.5415
24	997.2995
25	997.0479
26	996.7867

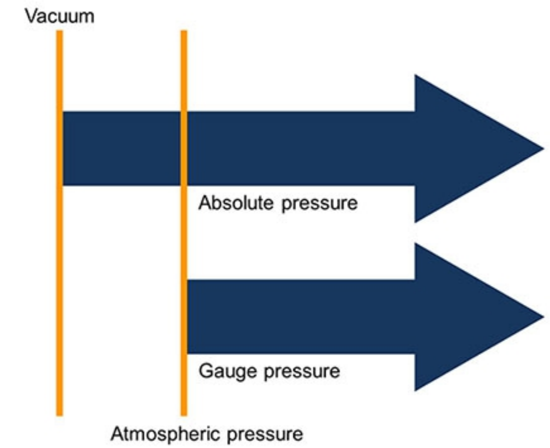




Density and specific volume depend on temperature

Property Units: Pressure (P)

- **Pressure (P)**
  - P = Force divided by area (F / area)
  - Units: Pa = N/m^2 (1 bar = 10^5 Pa)

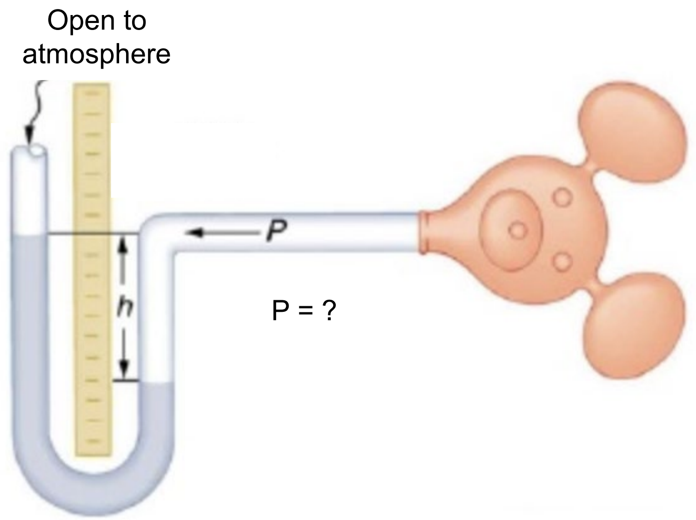


- Two types of pressure
  - **Gauge pressure** (P_{gauge}) measured relative to atmospheric pressure (P_{atm})
  - **Absolute pressure** ($P_{absolute}$) measured relative to zero pressure (vacuum)

- Measuring pressure with manometer

$$P_{gauge} = \rho g h$$
$$P_{absolute} = P_{atm} + P_{gauge}$$

  - P_{atm} = 1 bar = 10^5 Pa



Problem Solving (in Thermodynamics)

- **Problem Statement**

- **Analysis**
  - Given
  - Diagram of system and process
  - Assumptions
  - Governing relations

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{Q}_{in}}$$

$$= \frac{\dot{m}_3(h_5 - h_6) + \dot{m}_7(h_6 - h_7)}{\dot{m}_3(h_5 - h_4)}$$

$$- \frac{\dot{m}_7(h_2 - h_1) + \dot{m}_3(h_4 - h_3)}{\dot{m}_3(h_5 - h_4)}$$

- **Solution**
  - Derive the answer in symbols → e.g.:
  - Fill in the data for a quantitative solution (unit!)

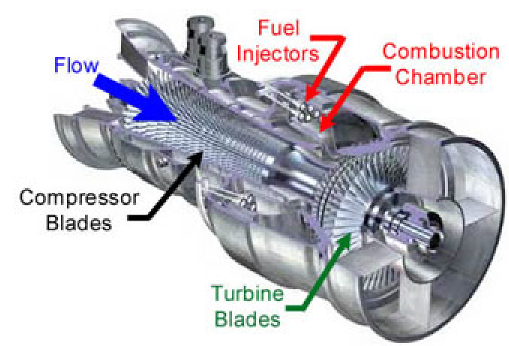
- **Discussion of Results**
  - Does the answer make sense?
  - What are implications? → this follows from the symbolic solution
  - Interpretation and discussion is the most important part for an engineer

Recapitulate Class 1

- What is thermodynamics? ⟶ science on using heat and power, conversion of different forms of energy
- Systems and boundaries
  - Open / closed / isolated systems
- Properties
  - Extensive / intensive / specific
- States and State Postulate
- Equilibrium and quasi-equilibrium
- Processes and cycles
  - Isobaric / isotherm / isochoric / adiabatic
  - Process diagrams
- Metric system and fundamental units
- Temperature and the zeroth law of thermodynamics
- Pressure (absolute and gauge pressure)

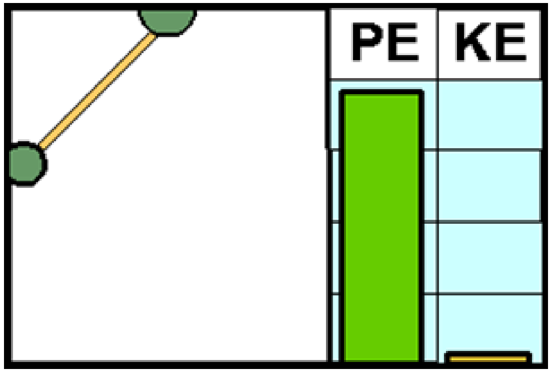




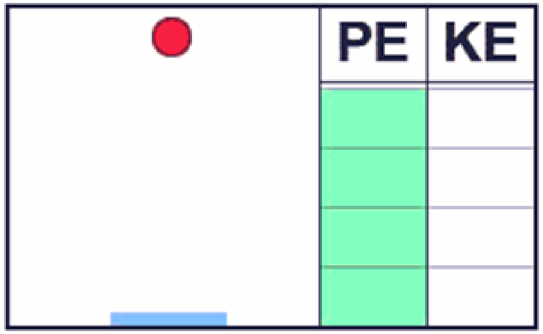


Next Class 2: Energy, work, heat, enthalpy, entropy

- Concept of energy and various forms of energy
  - Internal, kinetic and potential energy
- State and path functions
- Mechanisms of energy transfer
  - Heat and heat transfer
  - Work
  - Flow Work (Pv)
- The rate of doing work, heat & mass transfer
- The first law of thermodynamics
- Energy balance
- New properties
  - Enthalpy
  - Entropy
- Efficiencies of energy conversion processes



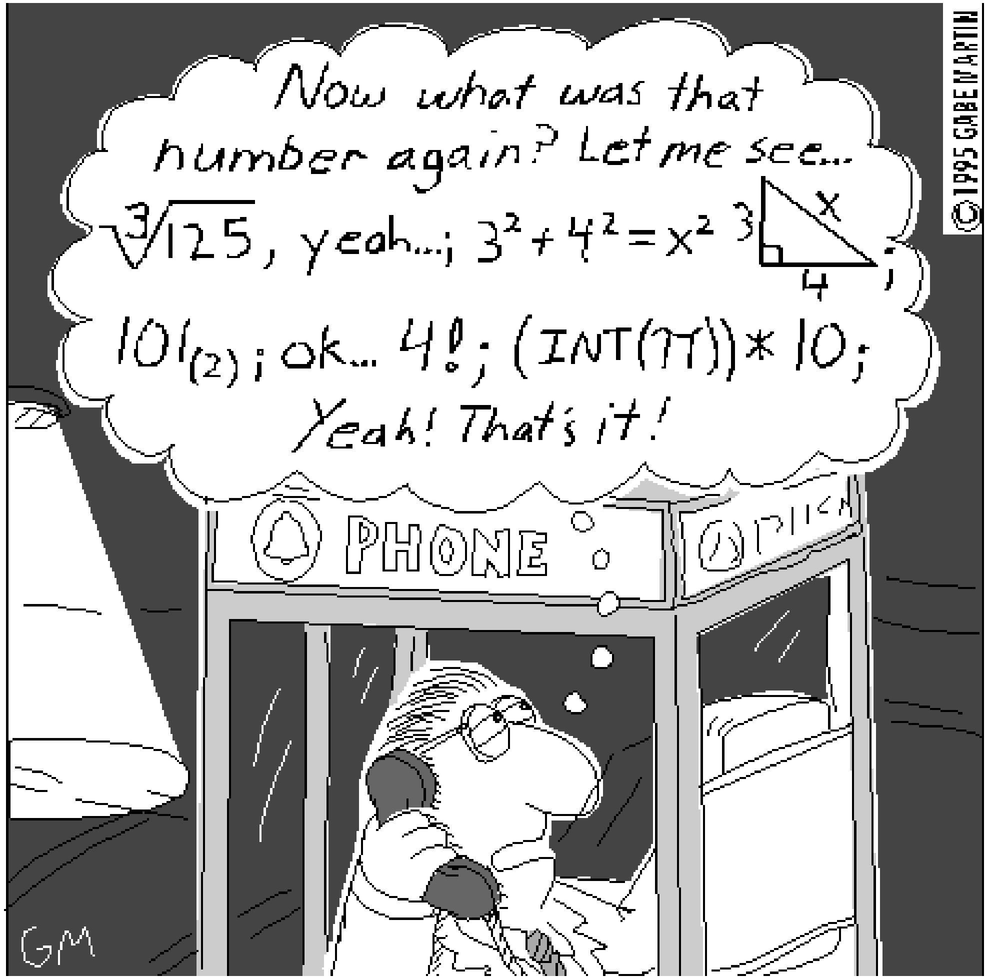
Conservation of mechanical energy, potential energy transforms into kinetic energy and visa versa



But where does the potential energy go in this case? Is the energy not conserved?

Keep in mind: Important Formulas

- Total volume: V [m^3]
- Specific volume: $v=V/m$ [m^3/kg]
- Density: $\rho = 1/v = m/V$ [kg/m^3]



- New formulas will be added every lecture class