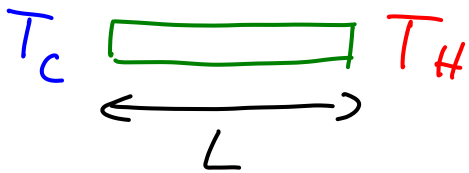
Lecture 31

Recap: Heat Transfer Mechanisms:

① Conduction:

$$P = \kappa \frac{A}{L}(T_H - T_C)$$

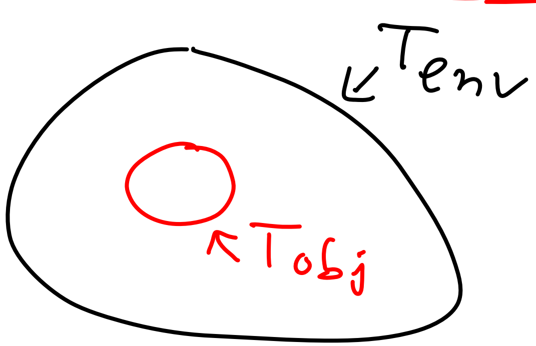


- no transfer of mass!
- R-value = L/κ

② Convection:

- heat transfer by motion of warm fluid to colder region
- usually driven by buoyancy ("convection rolls")

③ Thermal Radiation:



$$P_{net} = \sigma\, \varepsilon\, A_{obj}\,(T_{obj}^4 - T_{env}^4)$$

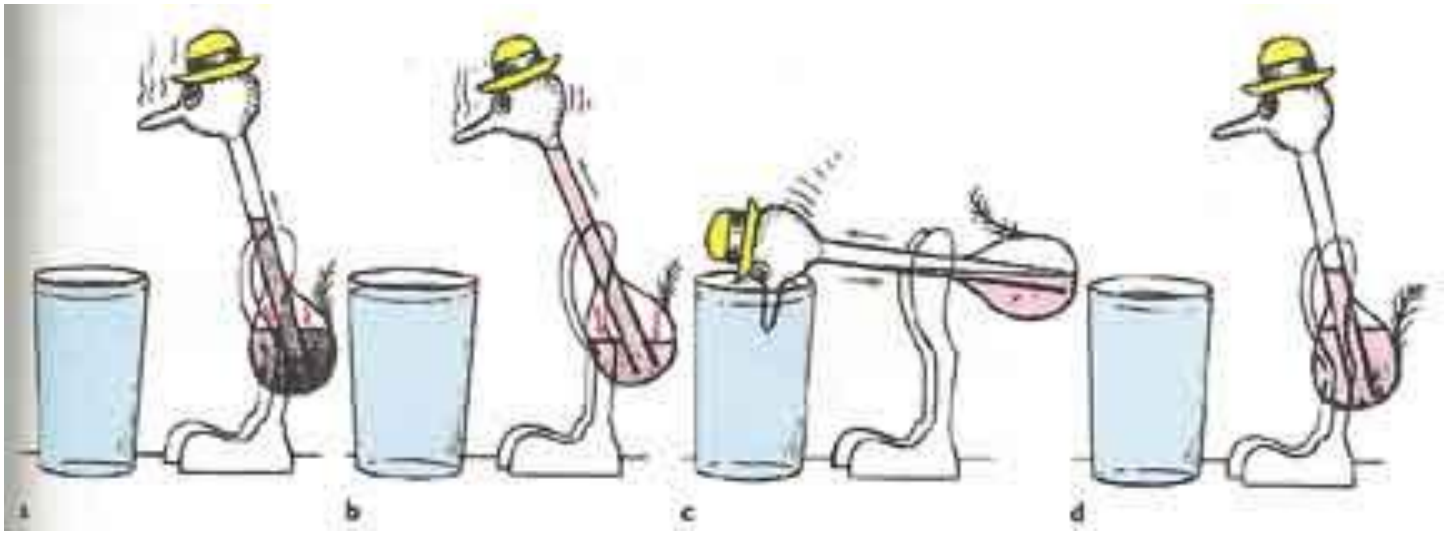
⇐ in Kelvin!

$\sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$

emissivity
$0 \rightarrow 1$
surface property

Today:

- **Heat and work**
- **Heat engines**
- **Refrigerators, heat pumps**
- **The "drinking bird": How does it work???**



What is the typical efficiency of a car petrol engine?

Efficiency ε = (work done) / (total energy used)

ε = ?

A. ~15 %

B. ~25 %

C. ~35 %

D. ~45 %

E. >=55%

→ Heat and Work:

So far: conservation of mechanical energy E_{mech}

$$E_{mech} = K + U = \text{const}, \text{ if } \underline{\text{no}} \text{ work is done by } \underline{\text{non}}\text{-cons. force}$$

$$\rightsquigarrow \Delta E_{mech} = W_{\text{on system by } \underline{\text{non}}\text{-cons. force}}$$

only considered macroscopic (external) energies of the object (from position, motion)

Now: Internal energy

Internal Energy:

E_{int} = internal energy (thermal, chemical....) from microscopic (thermal) motion and relative positions of atoms/molecules

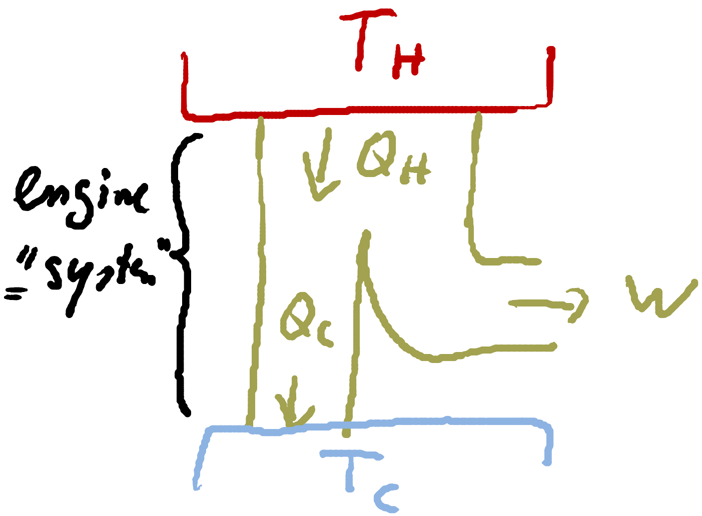
$$\Delta E_{int} = E_{int,f} - E_{int,i}$$

$\Rightarrow$ 1st Law of Thermodynamics:

$$\boxed{\Delta E_{\text{int of system}} = \underbrace{Q_{\text{net added to the system}}}_{\left|Q_{\text{added to system}}\right| - \left|Q_{\text{removed from system}}\right|} - W_{\text{net done by the system}}}$$

Applications (1): Heat Engine

- takes heat energy Q_H from a high T reservoir, converts some of this energy to useful work W and exhausts the rest of the heat energy Q_c to a low T reservoir.



Q_H, Q_c, W: energies in one cycle of heat engine

- assume steady state operation: engine has "warmed up", i.e. all of its parts have reached steady T's
- engine operates in cycles: after each cycle, engine returns to the same state

$\Rightarrow$ no net change in E_{int} after each full cycle!

for 1 cycle: $\Delta E_{\text{int in one cycle}} = 0 = \underbrace{(|Q_H| - |Q_C|)}_{Q_{net}} - W_{\text{by engine in one cycle}}$

$\Rightarrow \boxed{W = |Q_H| - |Q_C|}$ } per cycle of heat engine

Example: Stirling Engine: (closed air chamber)

$\Rightarrow$ converts part of thermal energy Q_H into work

① heat air in air chamber (by warm water)

$\Rightarrow$ air expands

Ideal gas law: $\boxed{pV = NkT}$

$\Rightarrow$ takes Q_H from T_H

$\Rightarrow$ work W done

cycle

② cool air in air chamber (by cold water)

$\Rightarrow$ "exhausts" Q_C to T_C

$\Rightarrow$ air contracts

N = # of molecules

k = Boltzmann constant

p = pressure

V = volume

Define Thermal Efficiency: ε

$$\varepsilon = \frac{\text{useful energy output}}{\text{energy we pay for}}$$

$\Rightarrow$ for heat engine:

$$\underline{\underline{\varepsilon}} = \frac{|W|}{|Q_H|} = \frac{|Q_H| - |Q_c|}{|Q_H|} = \underline{\underline{1 - \left|\frac{Q_c}{Q_H}\right|}}$$

$\rightarrow$ want $\left|\frac{Q_c}{Q_H}\right|$ small for big ε

$\rightarrow$ $Q_c = 0$ (i.e. $W = Q_H$) $\rightarrow$ $\varepsilon = 1$ would be nice...

But $Q_c = 0$, $\varepsilon = 1$ is physical impossible!

Note: This is not a technical problem!

$\Rightarrow$ From physics: Theoretical maximum efficiency of any heat engine operating between T_H and T_C is set by:

$$\boxed{\left|\frac{Q_C}{Q_H}\right| = \frac{T_C}{T_H}}$$

best one can do (one can always do worse..)

i.e. $\left|\frac{Q_C}{Q_H}\right|_{\text{real engine}} \geq \left|\frac{T_C}{T_H}\right|$

in Kelvin!

$\Rightarrow$ for heat engine:

$$\boxed{\varepsilon_{max} = 1 - \frac{T_C}{T_H}} < 1 \quad \Rightarrow \varepsilon_{\text{real engine}} \leq \varepsilon_{max}$$

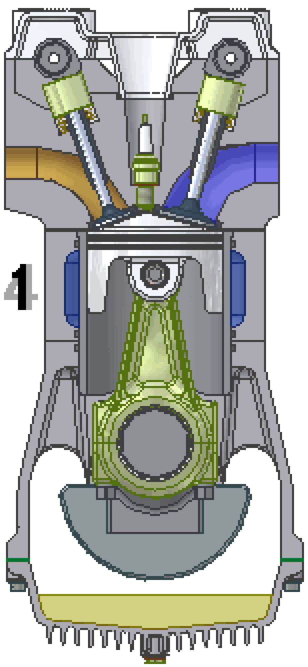
Carnot efficiency

in Kelvin!

Example: Auto Engine

•T_H = 1350°C = 1623 K

•T_C = 300°C = 573 K



⇒ Carnot efficiency = 1 – 573/1623 = 0.65 (65 %)

- But real engine: ε ~ 25 % only!
- Why?

To get Carnot efficiency, you need:

- No friction
- Add and remove heat at constant gas temperature

⇒ Must run cycle very slowly ⇒ low power engine

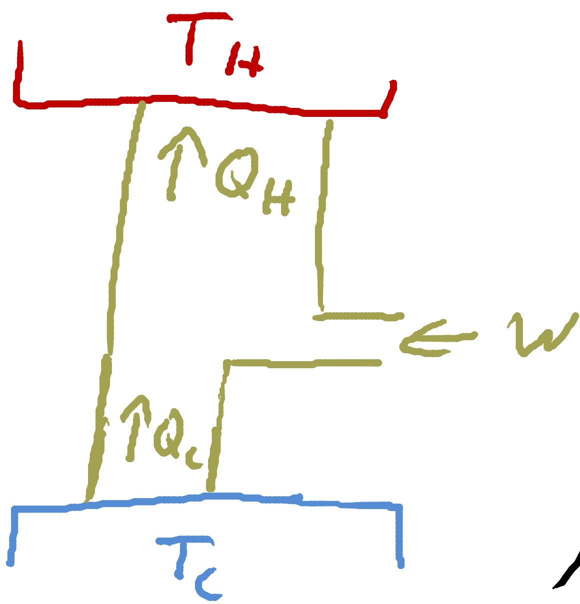
But: car need lots of power!

⇒ efficiency will be low

Application ②:

Refrigerators and Heat Pumps:

- transfer heat energy, using input work, from low T_C to high T_H



- $|Q_H| = |Q_c| + |W|$
- Coefficient of Performance K:

$$K = \frac{\text{useful output}}{\text{energy we pay for}}$$

Refrigerator:

$$K = \frac{|Q_c|}{|W|} = \frac{|Q_c|}{|Q_H| - |Q_c|} \leq K_{max}$$

Carnot

$$\left| \frac{Q_C}{Q_H} \right| = \frac{T_c}{T_H} \implies$$

maximum possible K for refrigerator:

$$K_{max} = \frac{T_c}{\underbrace{T_H - T_c}_{\text{in Kelvin!}}}$$

- carnot K
- ideal performance

Example: Refrigerator

- T_H = 21°C = 294 K
- T_C = 4°C = 277 K

$\Rightarrow k_{max}$ = (useful output) / (energy we pay for)

= 277 / (294-277) = 16 >> 1

Example: Heat Pump

$\Rightarrow k_{max}$ = (useful output) / (energy we pay for)

= $|Q_c|$ / $|W|$ if operated as AC in summer

$\Rightarrow k_{max}$ = (useful output) / (energy we pay for)

= $|Q_H|$ / $|W|$ if operated as heater in winter

A **heat pump** is used to heat a building during the **winter**. The outside temperature is **0ºC** and the inside temperature **20ºC**.

What is the **maximum possible coefficient of performance**?

K_{max} = ?

A. 1/20

B. 1

C. 13.65

D. 14.65

E. 20

Heat pump during winter:

$$K = \frac{\text{useful output}}{\text{energy we pay for}} = \frac{|Q_H|}{|W|}$$

want heat

to run heat pump

$$\Rightarrow K = \frac{|Q_H|}{|Q_H| - |Q_C|}$$

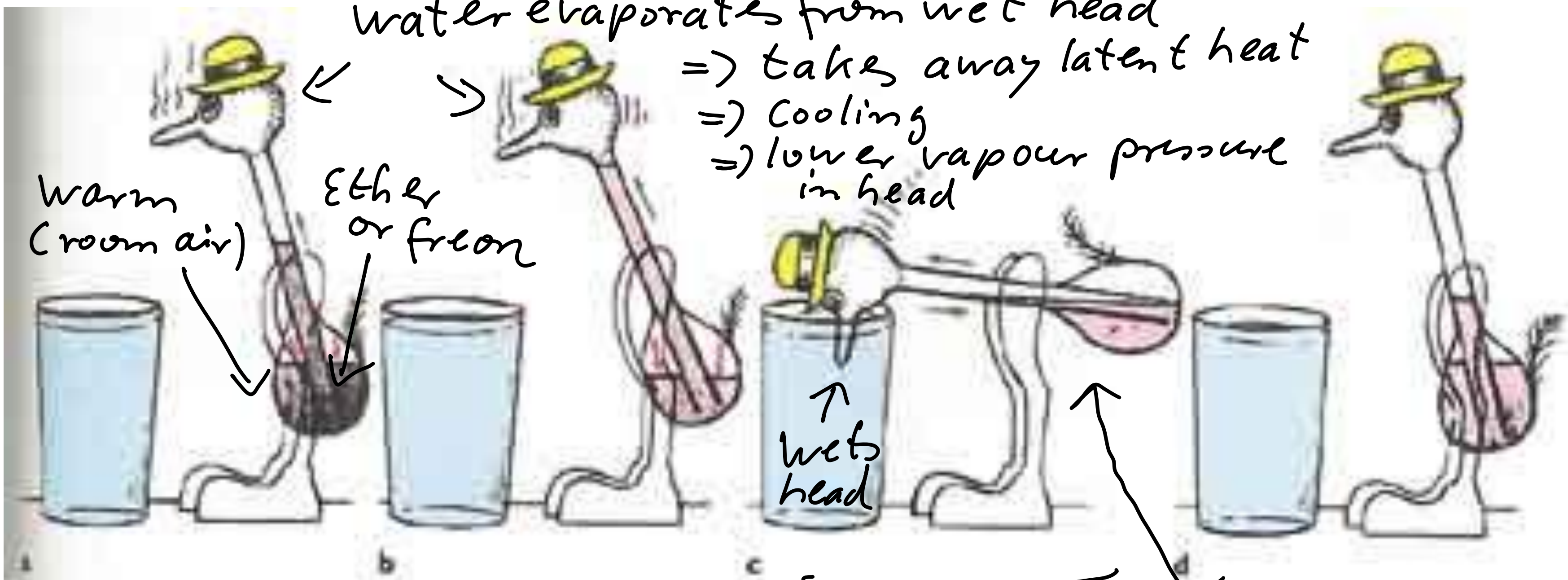
$\Rightarrow$ carnot: (best possible)

$$\left|\frac{Q_C}{Q_H}\right| = \frac{T_C}{T_H}$$

$$\Rightarrow K_{max} = \frac{|Q_H|/|Q_C|}{\frac{|Q_H|}{|Q_C|} - 1} = \frac{T_H/T_C}{\frac{T_H}{T_C} - 1} = \frac{T_H}{T_H - T_C} = \frac{(273+20)K}{20K} = 14.65$$

Heat engine: The "Drinking Bird"

water evaporates from wet head
$\Rightarrow$ takes away latent heat
$\Rightarrow$ cooling
$\Rightarrow$ lower vapour pressure in head



a: ether evaporates rapidly at room temperature

b: vapour pressure difference pushes ether up the tube

c: $\Sigma \tau$ becomes $\neq 0$ as weight of ether in head becomes sufficient $\Rightarrow$ loses balance

d: ether runs back into belly; unbalance in vapour pressure vanishes $\Rightarrow$ bird stands straight again...