Sustainability in Civil Engineering

II. Power & Heat: Thermodynamics

What is sustainability?

What are some manifestations of un***sustainability?***

How does engineering practice need to change?

- A useful starting point is to think about energy...

Energy in physics

- Motion or the ability to cause motion
- This definition is so that the total amount stays the same (conservation; First Law of Thermodynamics)
- Many different forms
- Conversion between forms is at least partially possible
- Unit: joule (J)
- Power: energy per unit time, unit: watt (W)

Example energy forms and expressions

- Kinetic (or mechanical): $\frac{1}{2}mv^2$, $\frac{1}{2}I\omega^2$
- Gravitational potential: mgh
- Thermal: 3/2nkT (ideal gas), mcT (generic substance with heat capacity c)
- Chemical potential: $\Sigma_i \mu_i N_i$
- Electrostatic potential: $q_1 q_2/(4\pi\varepsilon_0 r)$
- Blackbody radiation: $\sigma T^4 \cdot A\Delta t$
- Nuclear potential: $c^2\Delta m$

Energy conversion examples

- Steam turbine (thermal → mechanical)
- Wind generator (kinetic → electric)
- Solar water heater (radiative → thermal)
- Air conditioner (electrical → thermal)
- Tree (radiative → chemical)
- Hydroelectric plant (gravitational → electric)
- Wood stove (chemical → thermal)

Energy conversion toward a particular direction and at a particular speed typically requires *apparatus* (which itself takes energy to construct)

Energy quality

- Energy in a given form can only be wholly converted to energy of *lower* quality
- It can be partly converted to to energy of higher quality if the rest of it is converted to energy of lower quality, so that the average energy quality deteriorates
- The Second Law of Thermodynamics: energy dissipates (loses quality)

Exergy and Entropy

- *Exergy* is energy multiplied by a quality factor that quantifies the extent to which it can be converted to other forms: this factor ranges from 0 (lowest quality) to 1 (highest quality)
- *Entropy* is a measure of how disorganized (diffuse) a system is, with different units than energy
- High quality = high exergy = low entropy
- Unlike energy, exergy and entropy are *not* conserved (exergy decreases, entropy increases)

Other statements of the Second Law

- Heat will not flow spontaneously from a cold object to a hot object
- The entropy of a closed system does not decrease
- A given amount of heat energy cannot all be converted to useful work

Temperature

- A measure of how much energy is evenly, incoherently dispersed among the particles of a system (for example, as random motion) [internal energy]
- Heat flows from high to low temperature
  - Basis for many of our energy conversion systems
  - Major cause of exergy demand
- Zeroeth law of thermodynamics: the concept of thermal equilibrium
- With absolute scale (K), can say that *A* is twice as hot as *B* (has twice as much dispersed energy per mode)

Entropy and heat transfer

- When a quantity of heat energy Q is transferred at a temperature T, the entropy change is Q/T
- Thus, if heat flows from a hot object (T_H) to a cold object (T_C), the entropy changes are $-Q/T_H$ and $+Q/T_C$ respectively
- By the Second Law, $T_H > T_C$ – *total* entropy won't decrease ($T_H = T_C$ is the reversible limit, but then the heat transfer would be infinitely slow)
- Cf. the sun-earth-space system

Entropy and disorder

- Entropy can also change without heat transfer
  - Entropy of mixture containing n_A molecules of gas A and n_B molecules of gas B: $-k(n_A \cdot \ln(x_A) + n_B \cdot \ln(x_B))$, where x_A, x_B are the respective number fractions (cf. ore extraction, desalination)
  - Chemical reactions progress in the direction that increases the entropy of the system (chemical entropies [or exergies] under standard conditions can be found in tables)

Quality of common forms of energy (multiplier for exergy)

- Kinetic energy, gravitational potential energy, electricity, chemical energy: ~1
- Sunlight: 0.93
- Thermal, hot steam: ~0.5
- Thermal, hot water: ~0.1
  - *In general, the quality of the thermal energy for a hot object at (absolute) temperature T in an environment at temperature T_E is given by*

    $(T - T_E) / T$

Car travel as an example of energy conversion

- Internal-combustion engine converts high-quality chemical energy in gasoline + oxygen to medium-quality thermal energy, and in turn to high-quality mechanical energy plus exhaust heat (and high-entropy exhaust gas, mostly CO_2 and water)
- Around 25% of the high-quality chemical energy input in converted to high-quality mechanical energy output to the transmission
- The mechanical energy generated goes to accelerating the car and air in front of the car and to countering road friction. It quickly dissipates into low-quality heat

What is energy efficiency?

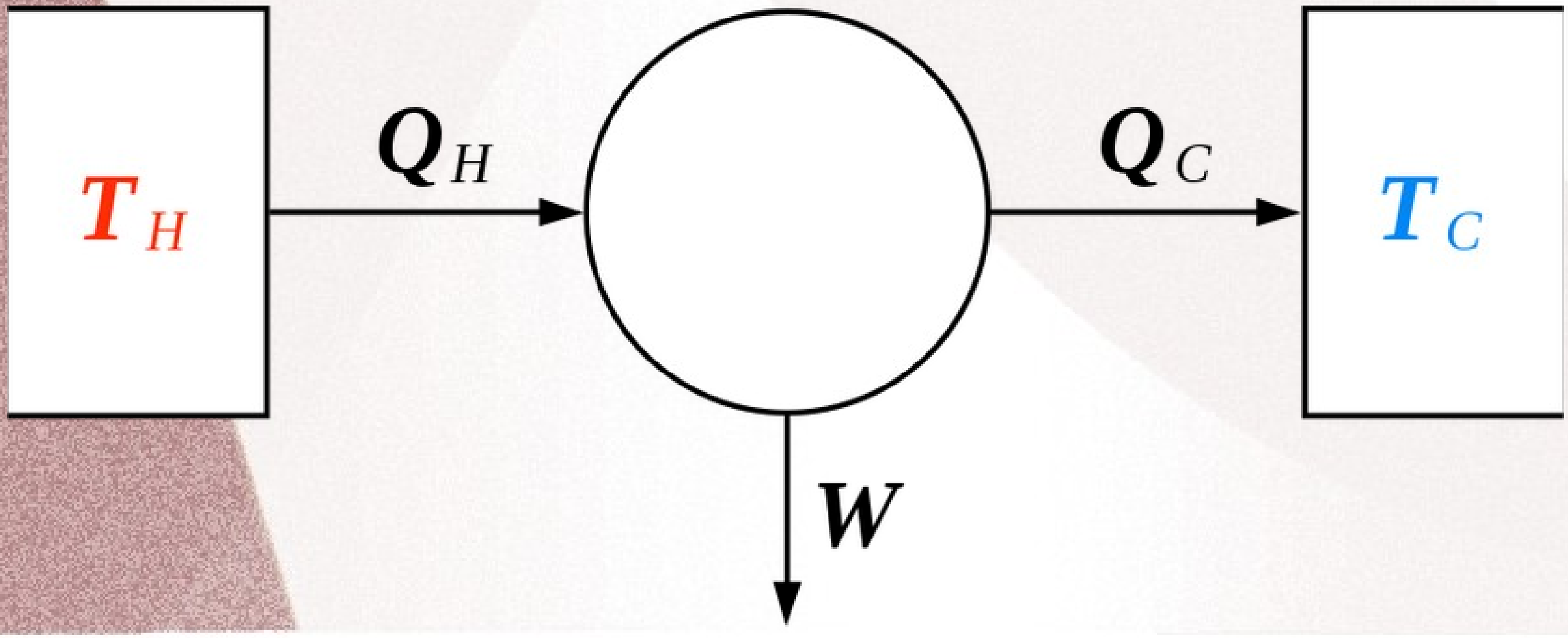
- First-law (energy) efficiency: energy obtained / energy put in
- Second-law (exergy) efficiency: exergy lost / minimum exergy loss theoretically needed to do the job (other definitions also possible)
- E.g. an insulated natural-gas fueled water heater might have an energy efficiency >0.9 but an exergy efficiency <0.2

Exergy analysis and environmental impacts

- Low exergy efficiency likely means that environmental damage is too high, esp. if obtaining the exergy is damaging (fossil fuel mining, burning)
  - Conserve exergy!
- High exergy of wastes means that they could have serious impacts on the environment
  - Encourage pests, damage life forms – as in nutrients and organic chemicals in wastewater
  - Hypothetical zero-exergy waste would be indistinguishable from environment, hence should blend in and have low impact
  - (However, toxicity/harm not always proportional to exergy)

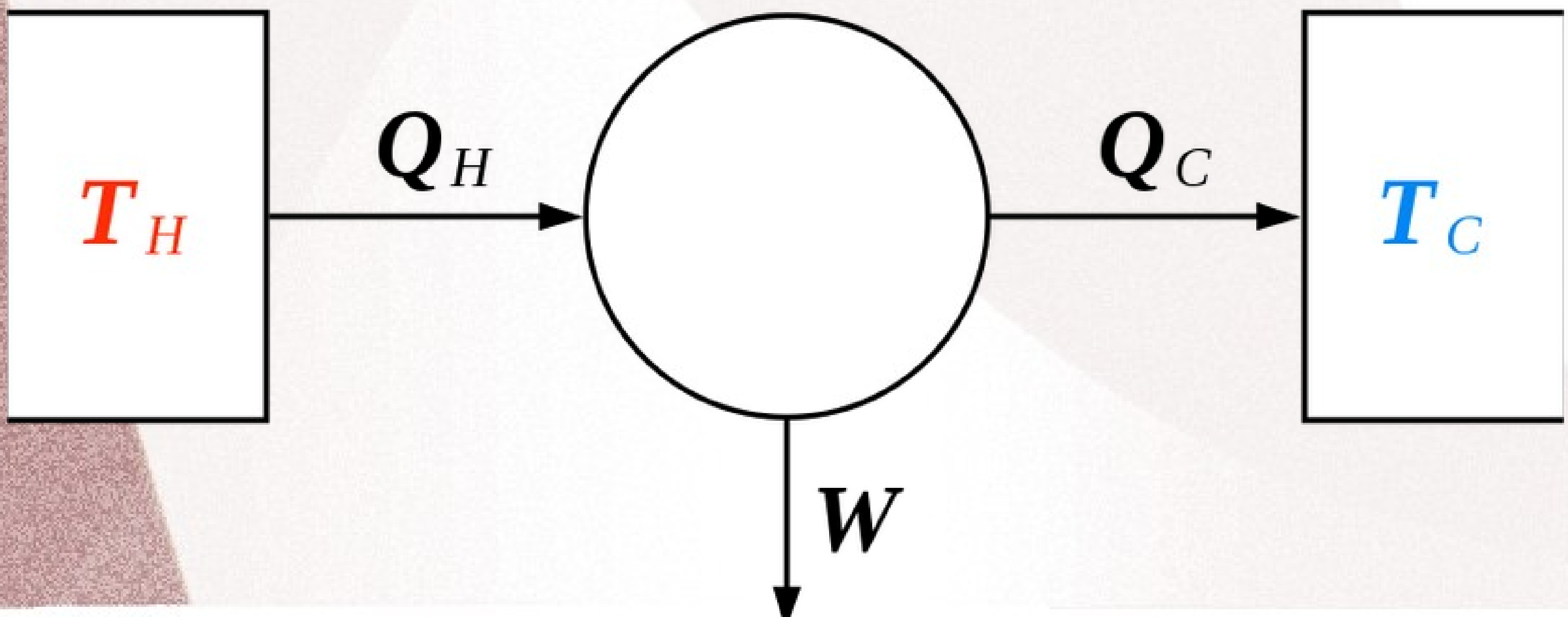
Heat engine

- Heat causes the expansion of a gas, which generates mechanical energy (pushes a piston or turns a turbine)
- Major source of motive power for last 200 y
- *Source of heat* can be burning fossil fuel or biomass; nuclear; direct (focused) sunlight; etc.



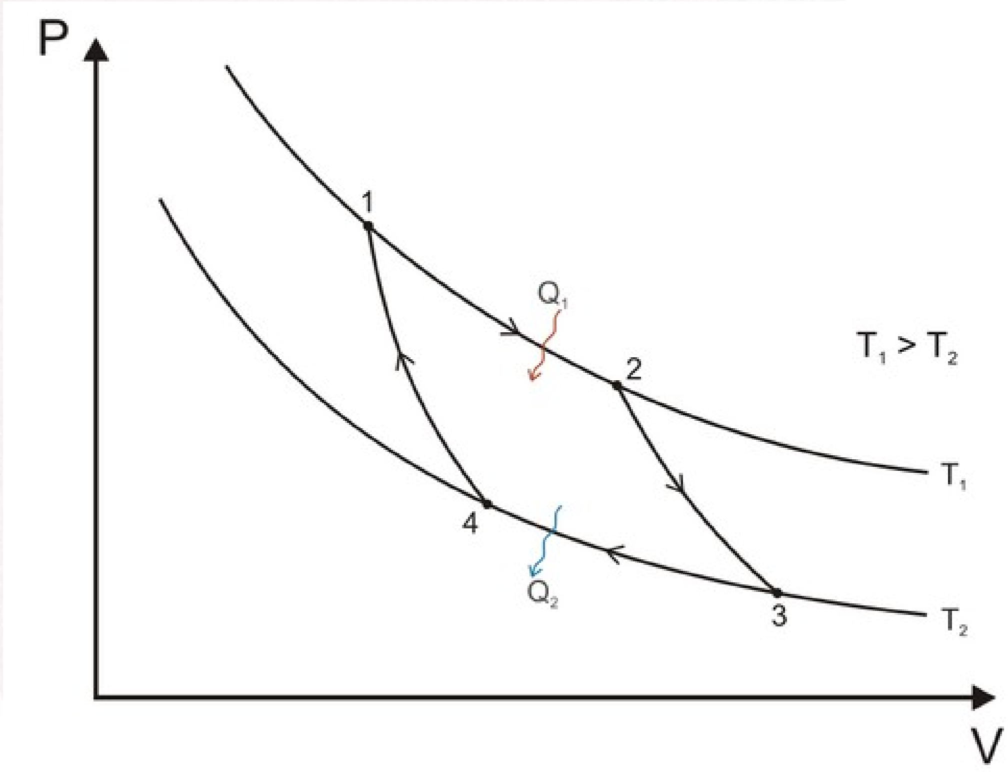
Processes and notation

- T_H: temperature of heat source; T_C: of heat sink
- Q: heat transfer
- W: work output, equal to $P\Delta V$
- At steady state, by energy balance, $W = Q_H - Q_C$; first-law efficiency: W / Q_H, or $1 - Q_C/Q_H$



Carnot Cycle for a heat engine

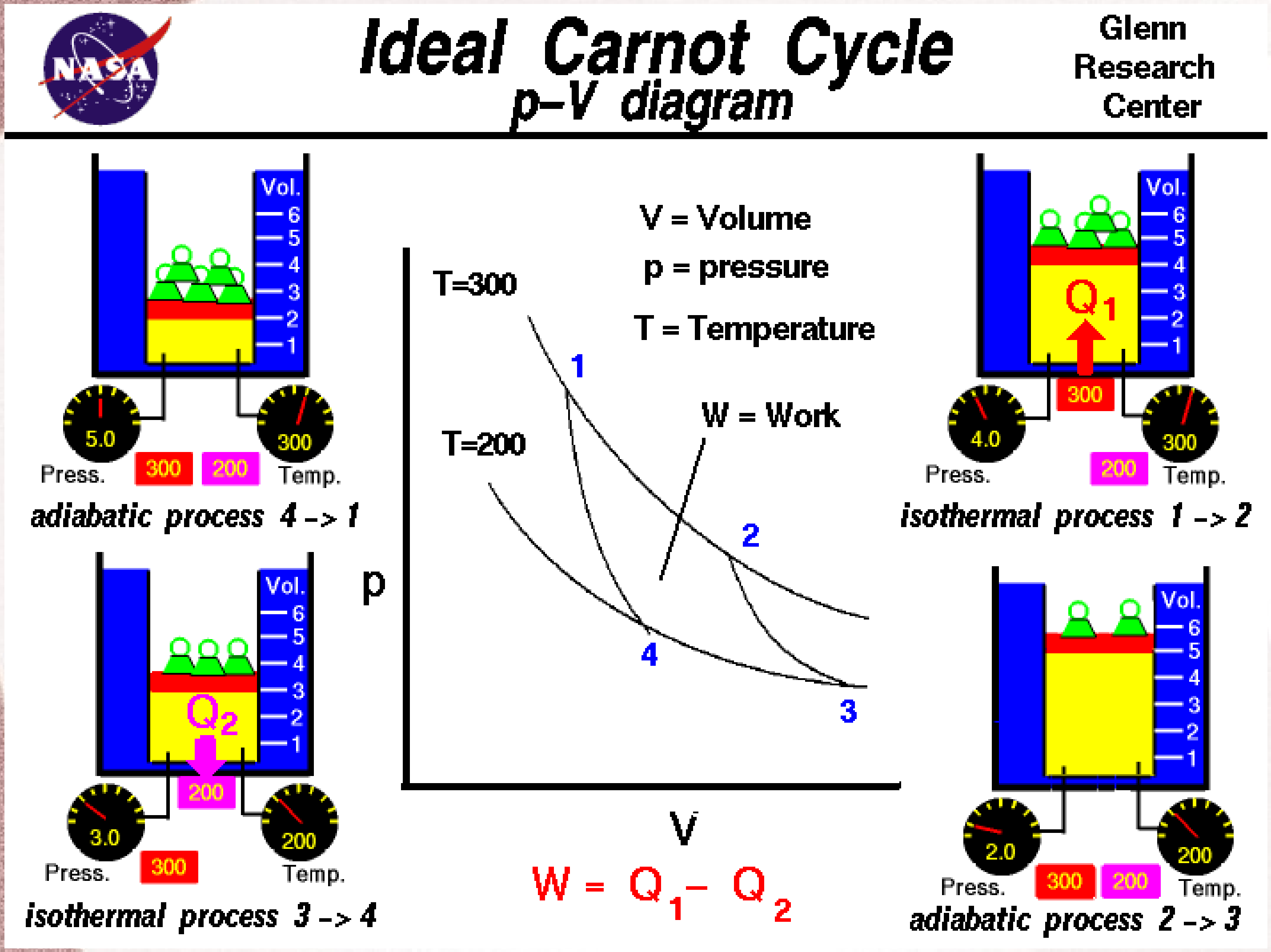
- 1-2: Add heat at T_H (isothermal expansion)
- 2-3: Allow gas to expand, cool to T_C (doing work; adiabatic)
- 3-4: Reject heat at T_C (isothermal compression)
- 4-1: Compress gas to T_H



- Net work output is given by area enclosed by cycle in P-V diagram

  (clockwise = work out)

Carnot cycle (another rendering)



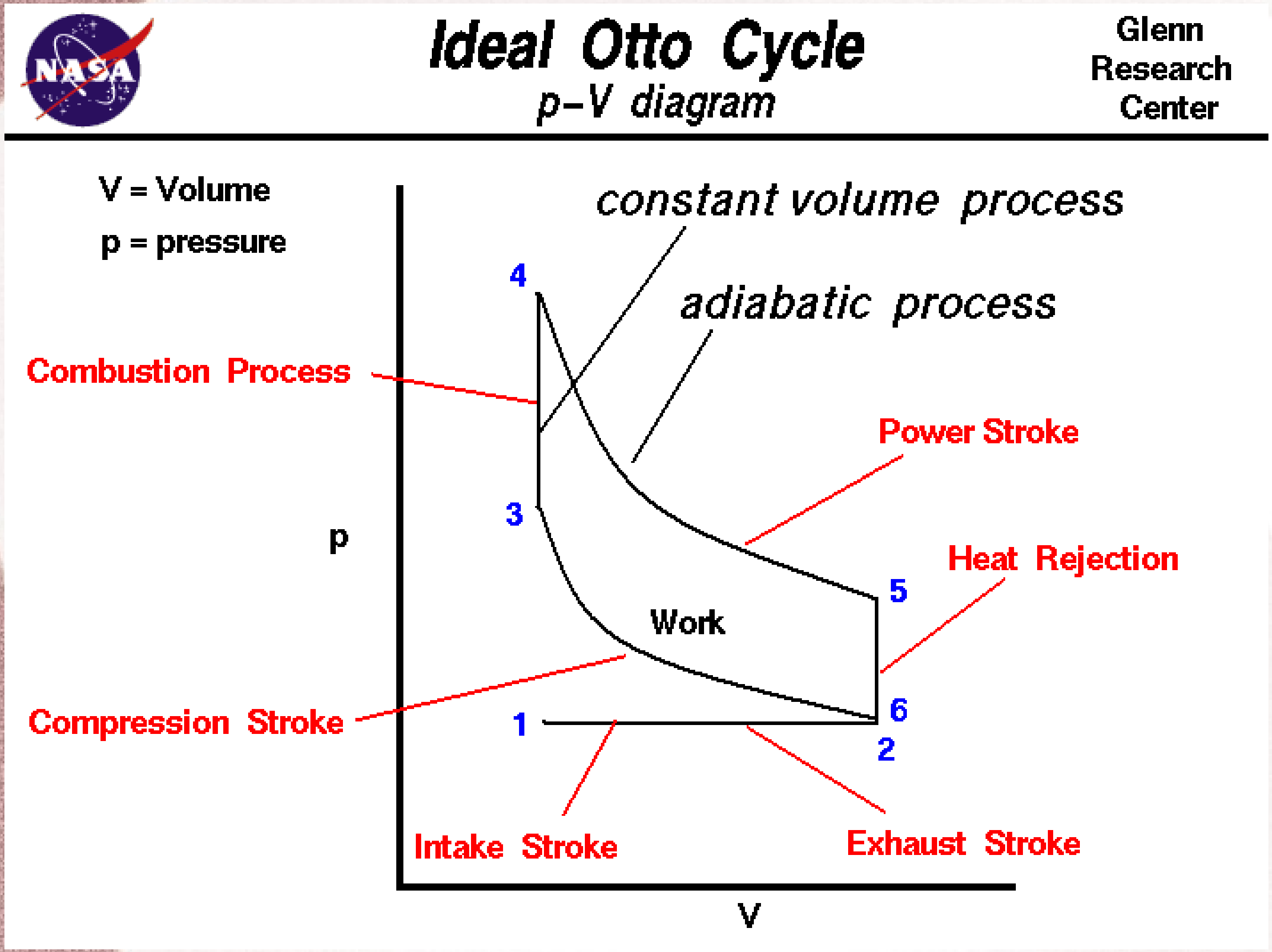
Ideal Carnot engine efficiency

- Net work output is $Q_H(T_H - T_C)/ T_H$
- First-law efficiency is $(T_H - T_C)/ T_H = 1 - T_C/ T_H$
- Second-law efficiency is 1 for the ideal engine
  - All exergy available from the given temperature difference is converted to work
  - There is no net entropy generation (reversible)
  - Maximally efficient (ideal) heat engine
- Note: the greater the temperature difference, the more work can be extracted from a given heat flow

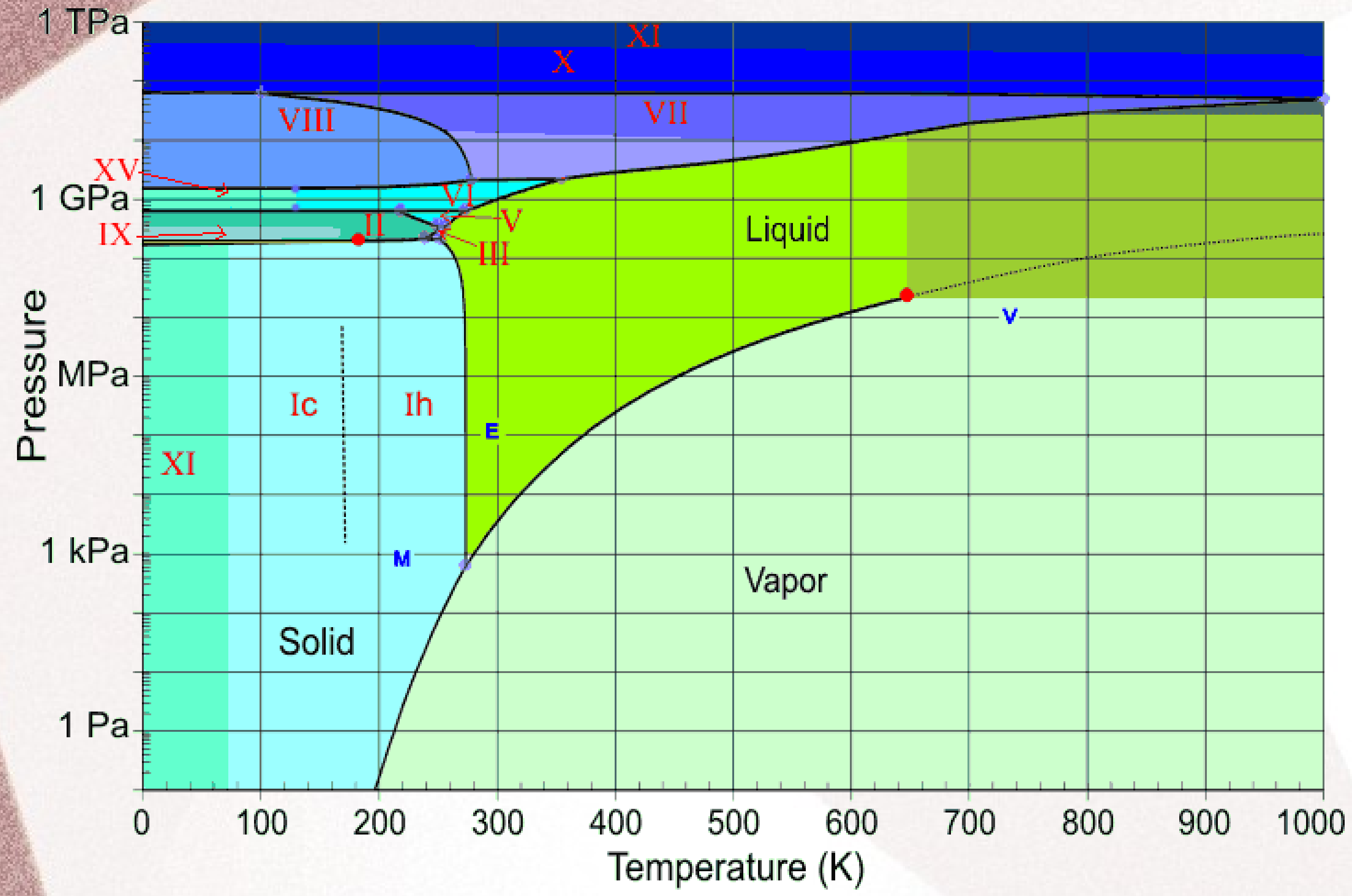
What makes real engines less efficient than ideal cycles?

- Taking in and rejecting heat at an infinitesimal temperature difference would be infinitely slow!
- Engine materials (e.g. steel) limit the maximum operating temperature and pressure, usually well below that attainable from the fuel
- Friction and viscosity: compressor and turbine losses plus turbulence in the working gas

Another heat-engine cycle example: the Otto Cycle



The thermodynamics of water

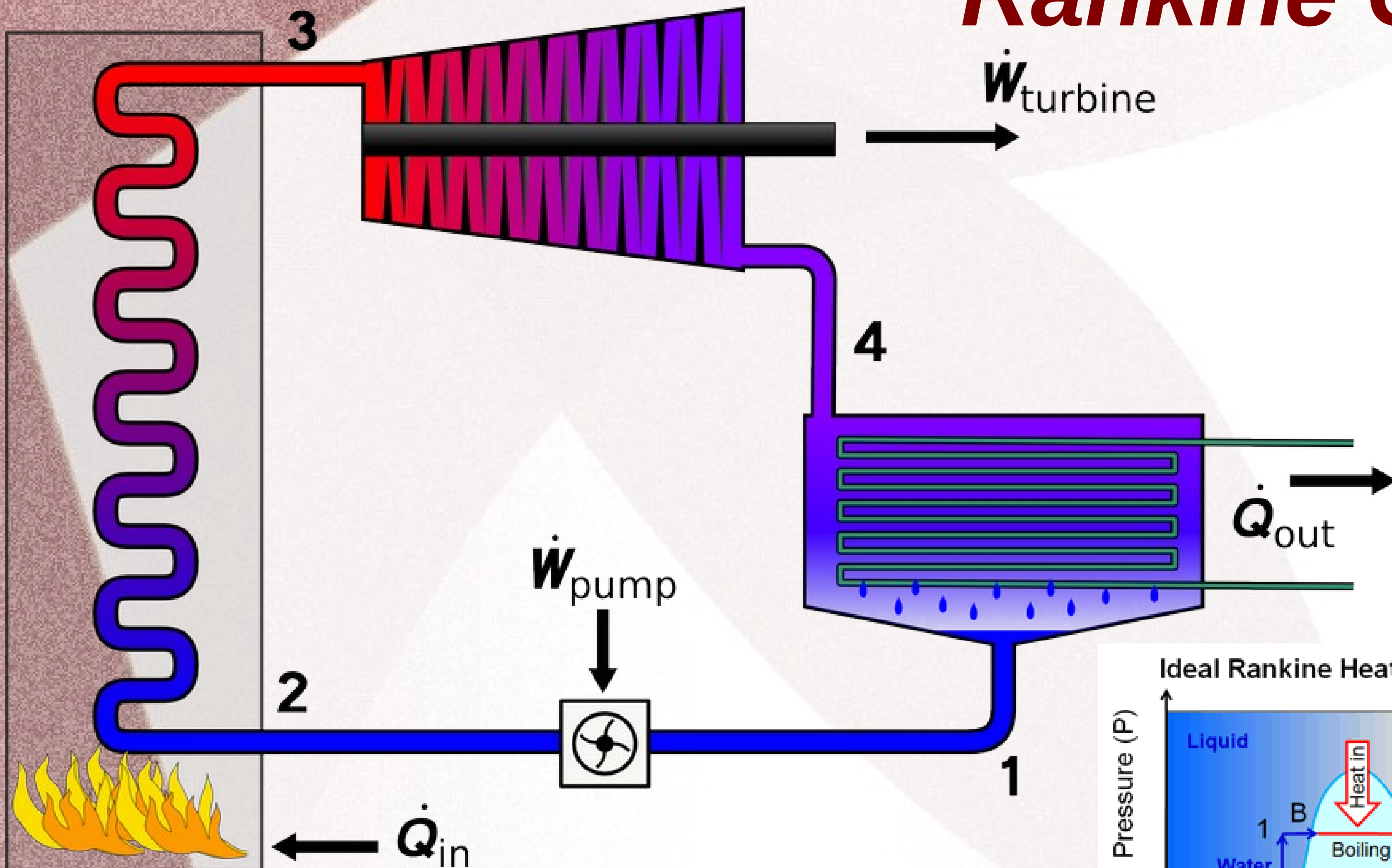


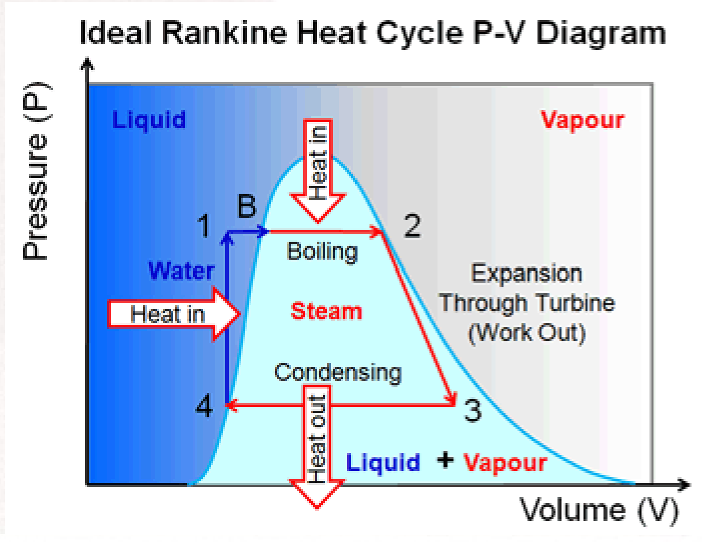
Phase diagram

Vapor pressure and evaporation

- Vapor pressure doubles per 10 K warming (around room temperature)
- Liquid water heat capacity is 4.2 J g^{-1} K^{-1}
- Heat of melting is 330 J g^{-1}; heat of evaporation is 2500 J g^{-1}
- For a substance changing phase, adding or removing heat goes into the phase change, and doesn't change the temperature (infinite heat capacity)

Steam engines – the Rankine Cycle





This is how electricity is generated from coal or nuclear power

Heat pumps: heat engines reversed

- Heat a warm area, or cool a cold area
- If electricity, etc. (high-quality energy) is available, can put in work to transfer heat from low to high temperatures
- Ideal first-law efficiency: $Q/W = T_H / (T_H - T_C)$ (the "coefficient of performance" – can exceed 1!)
- Applications: heat pumps, refrigerators, air conditioners (reverse Rankine cycle with an organic working fluid)
- Even so, refrigerators and air conditioners heat up the surroundings

Combined heat and power

- Hot water from power plant exhaust can be piped for heating buildings or industrial processes
  - Needs relatively high density to be economical (e.g. the NYC Steam System; college campuses)
- Can be integrated into renewables, e.g. roof water heating under photovoltaics

Heat transfer

- Heat flows from hot to cool – but speed can vary
- Heat transfer modes:
  - Conduction: slow!
  - Convection: natural or forced (fans/blowers)
  - Radiation

Slowing down heat transfer

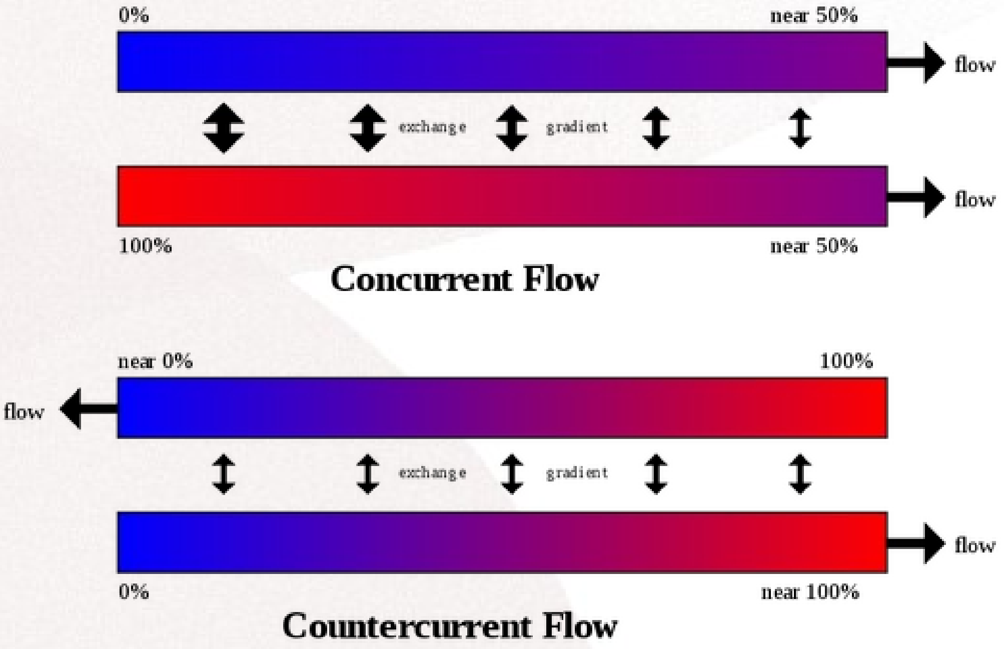
- When is this good?
- General solutions:
  - Air transfers heat poorly as long as it stays still
    - Insulation: material with many small air pockets that can't readily exchange heat
    - Multi-paned windows
  - Low-emissivity coatings

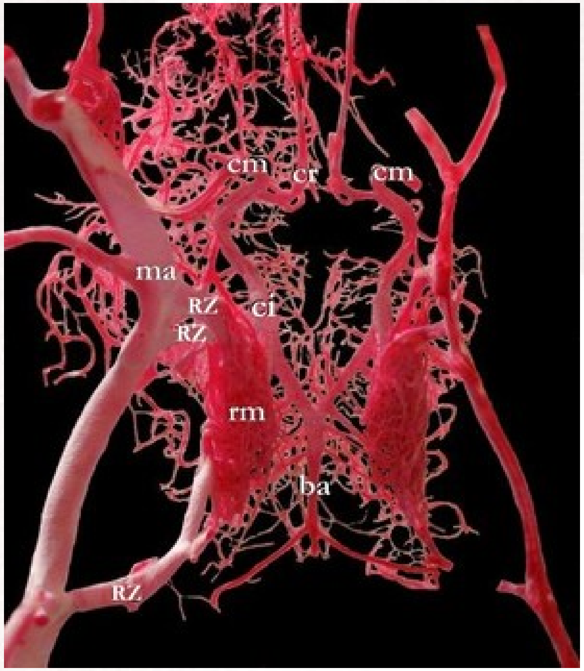
    to reduce radiation

Straw-bale building

Speeding up heat transfer

- More surface area: Heat exchangers, distribution systems, radiators
- Fans, blowers, mixers





Biological example:
rete mirabile for transfer
of heat, ions, oxygen

Reducing temperature fluctuations

- Increase effective heat capacity:
  - Thermal mass
  - Natural or induced circulation from e.g. outside or underground
  - Phase-change materials (sweating, icepacks, molten salt)

Eastgate Centre in Zimbabwe -- stays cool with ventilation system that emulates a termite mound

Basis for “geothermal” heating/cooling