Second Law of Thermodynamics

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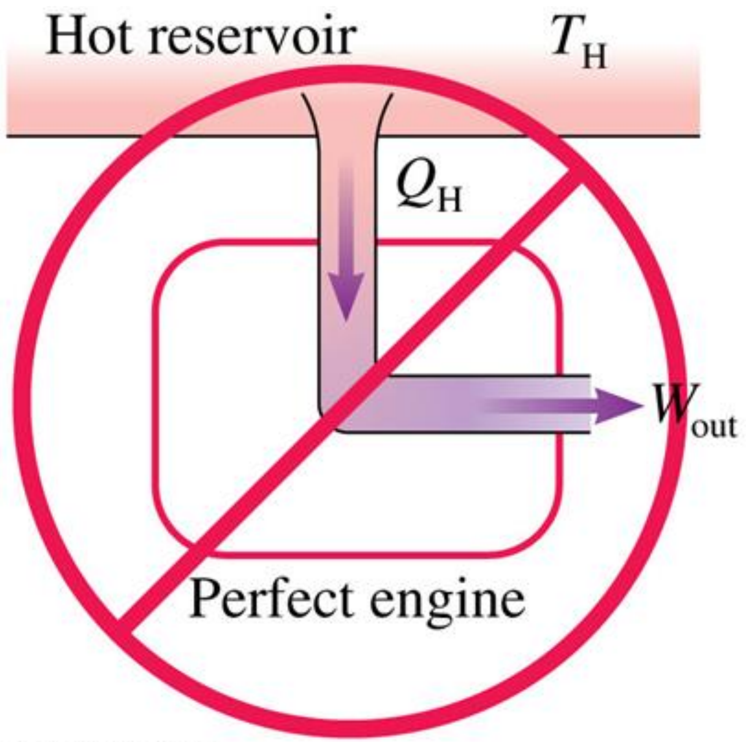
Outline

1. Second law of thermodynamics
2. Carnot cycle and maximum efficiency
3. Course review

1. Second law of thermodynamics

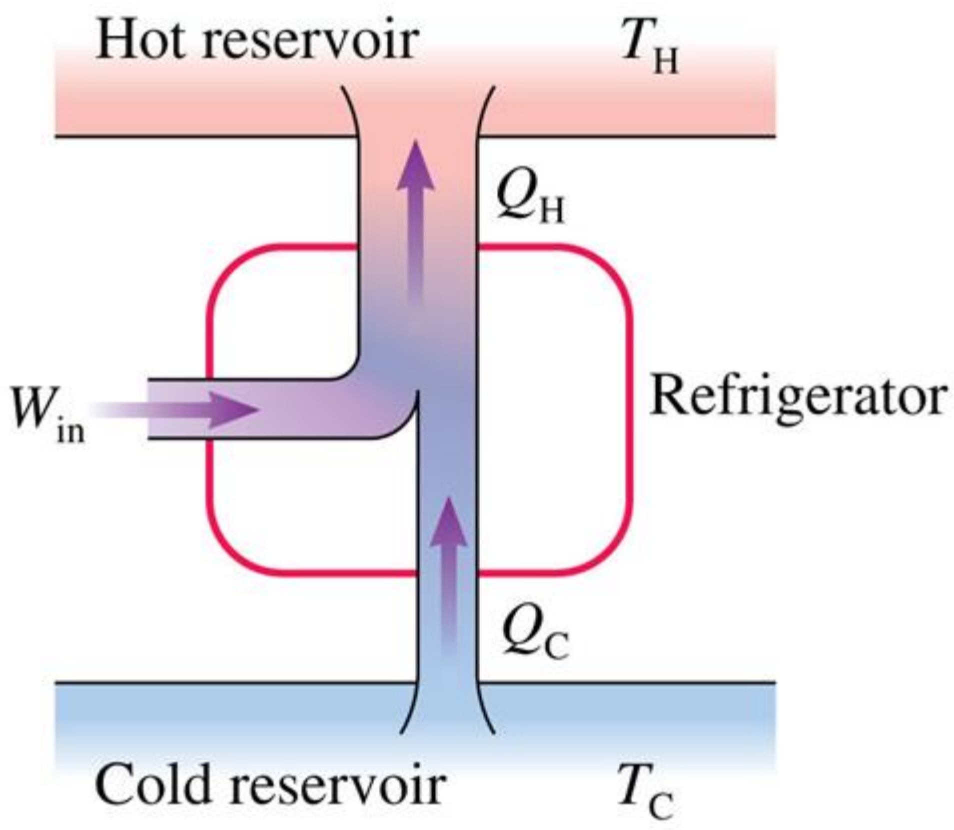
Maximum efficiency and inequivalence of heat and work

- We have *asserted* that a heat engine needs a **cold reservoir** to operate, which implies $Q_C > 0$ and thus $\eta < 1$. But why?



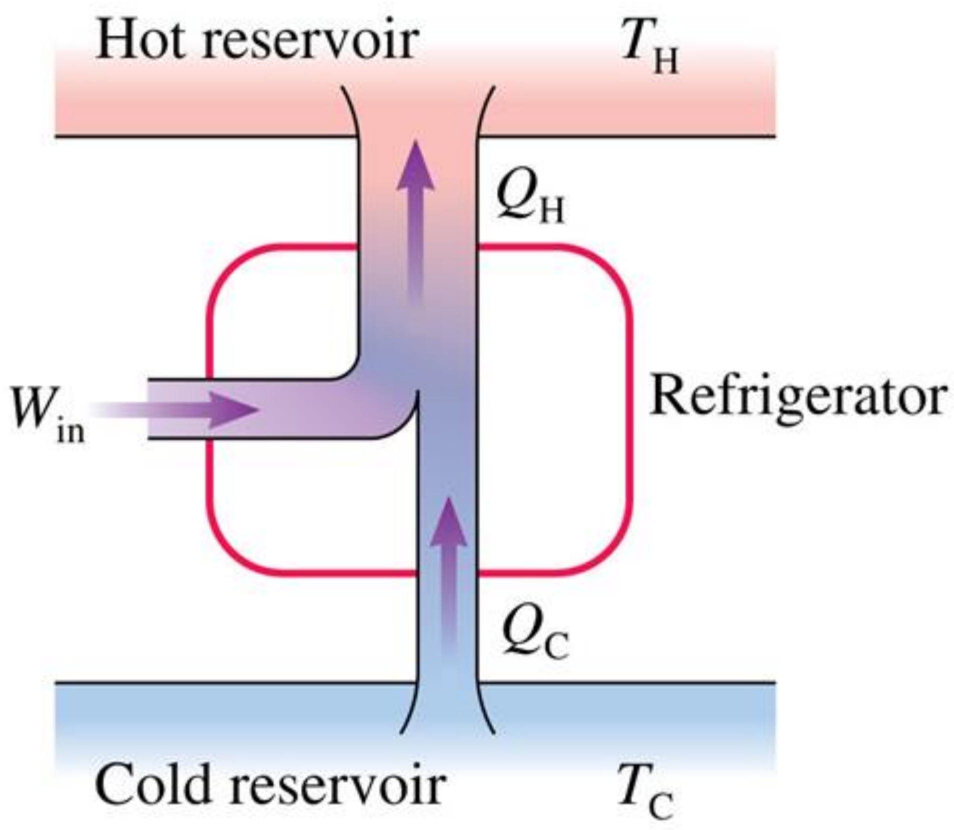
Interlude: refrigerator and heat pump

- **Refrigerators** and **heat pumps** transfer energy from a cold object to a warm object



Second law of thermodynamics

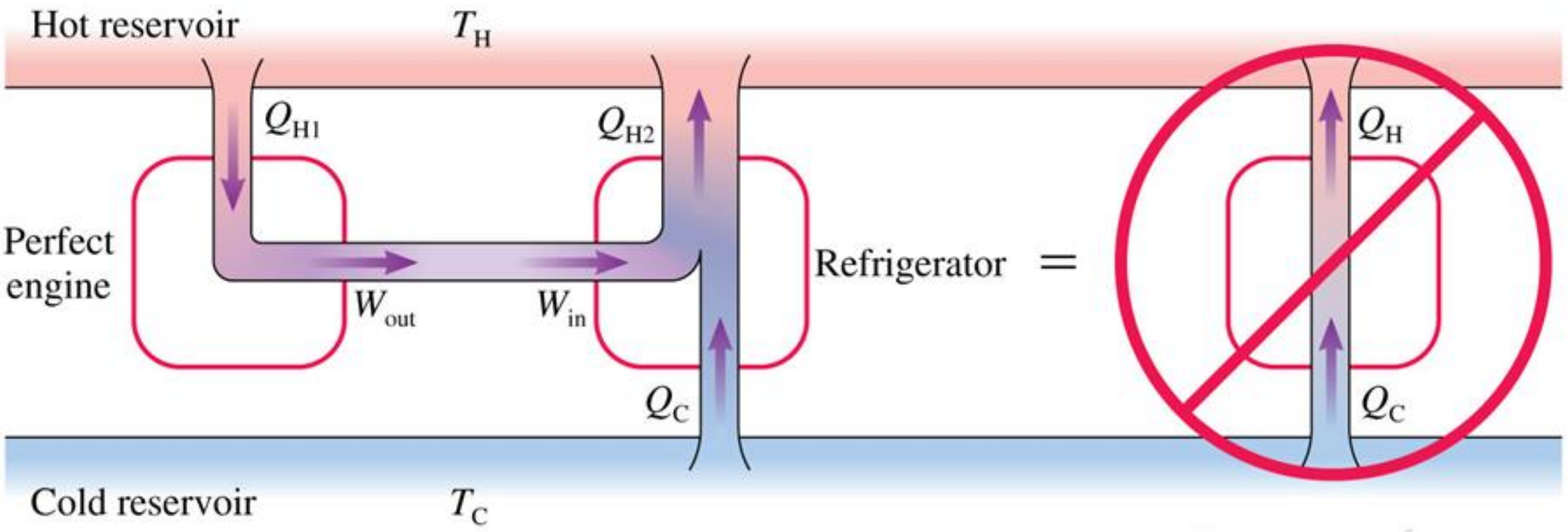
- One classic* formulation of the **second law of thermodynamics** is that heat cannot spontaneously flow from a cold object to a warm object
- This implies external work is needed for refrigerator and heat pumps to operate



* Read Knight §18.6 for more details and other formulations of the second law

Second law and maximum efficiency

- If heat engine with $\eta = 1$ exists, connecting it to a refrigerator will lead to spontaneous heat flow from cold to hot!
- Thus, the second law of thermodynamics implies $\eta_{\text{max}} < 1$ (!)

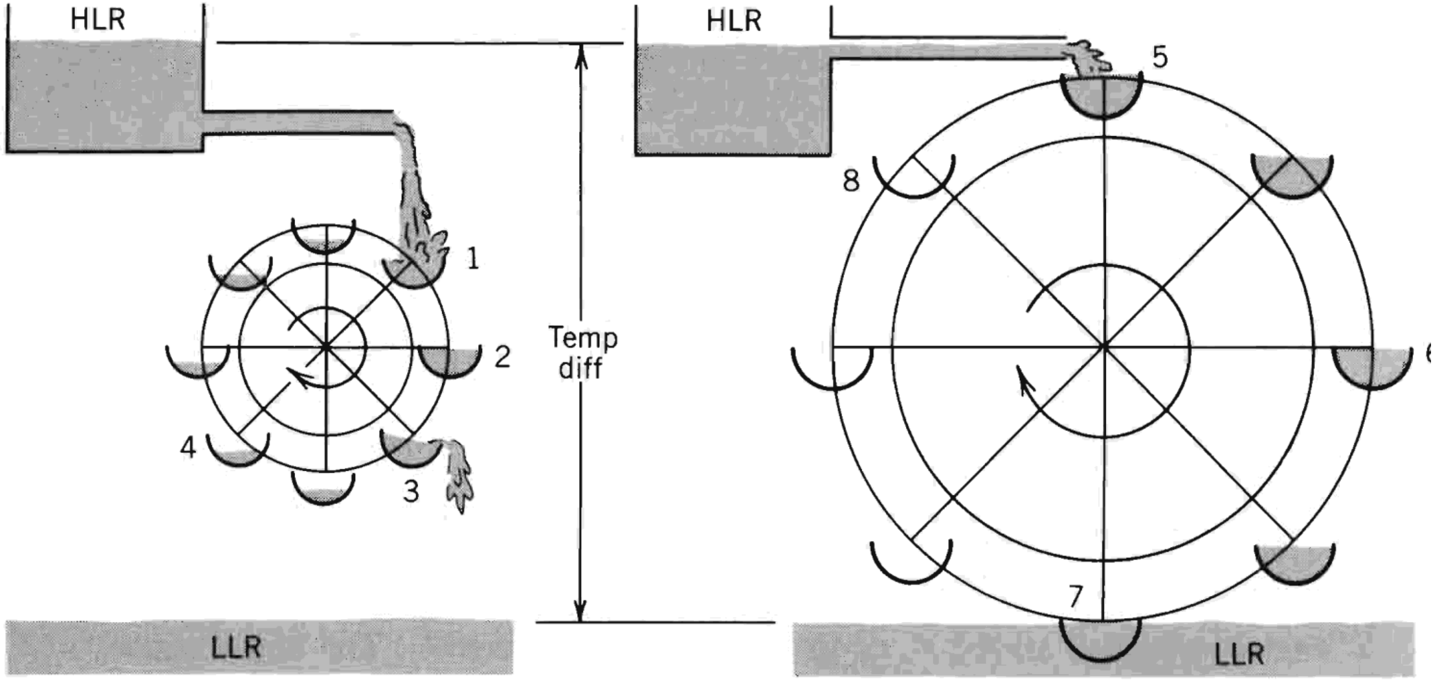


2. Carnot cycle and maximum efficiency

Optimal heat engine: the ideas

- Want: (1) minimal temperature difference while transferring heat

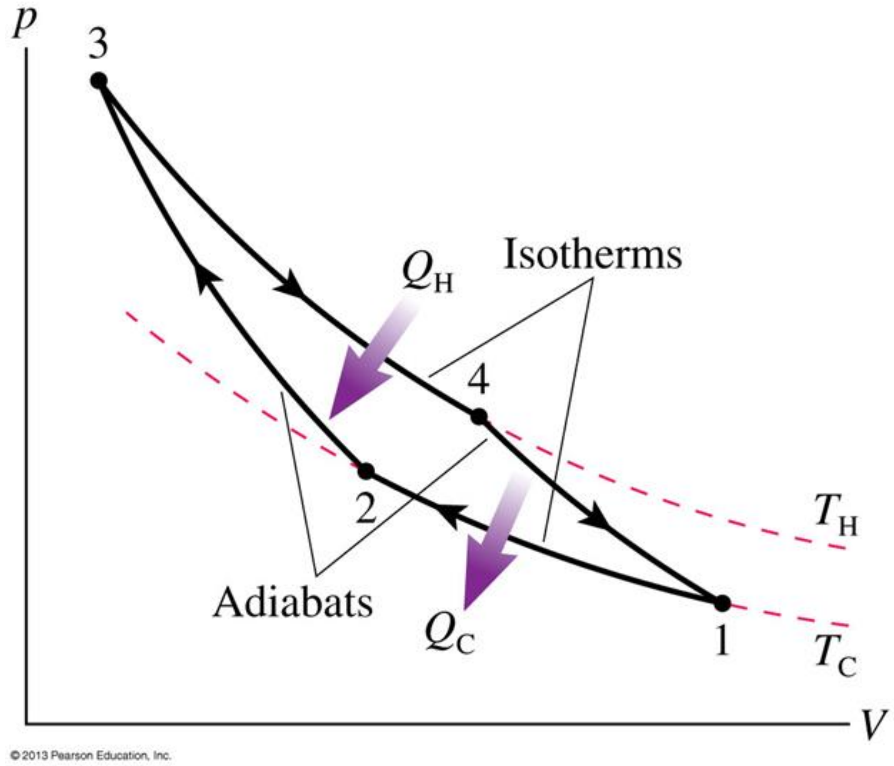
  (2) no "spilling" of heat in-between



* Figure and argument from Spielberg and Anderson, *Seven Ideas That Shook The Universe*

Optimal heat engine: the Carnot cycle

- Want: (1) minimal temperature difference while transferring heat
  (2) no "spilling" of heat in-between
- (1) ⇒ transfer heat via isothermal processes
- (2) ⇒ connect between the two temperatures via adiabatic processes



* See Knight §19.5 for a slightly different argument

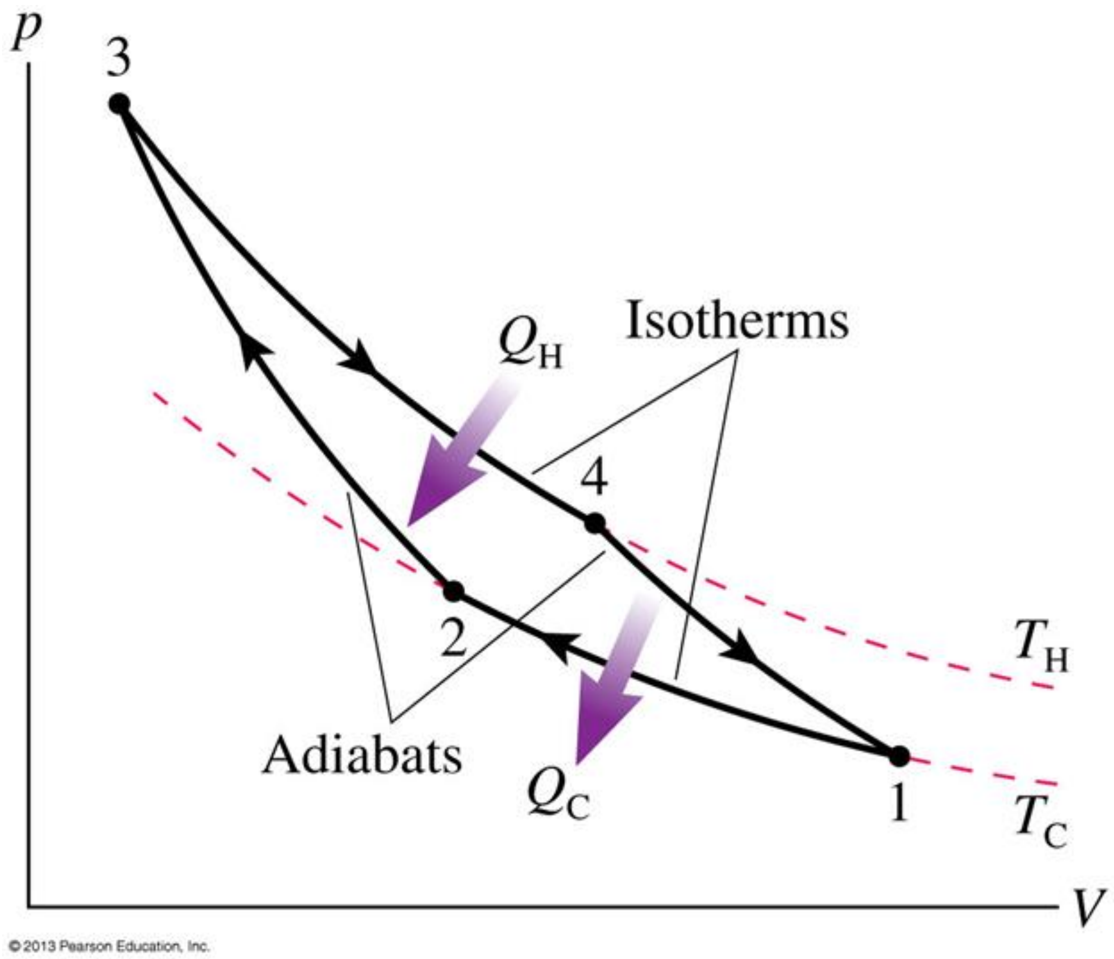
Analyzing the Carnot cycle (1/2)

- From our knowledge of isothermal processes:

$$Q_H = nRT_H \ln(V_4/V_3)$$
$$Q_C = nRT_C \ln(V_1/V_2)$$

Hence,

$$\eta_{\mathrm{Carnot}} = 1 - \frac{T_C \ln(V_1/V_2)}{T_H \ln(V_4/V_3)}$$



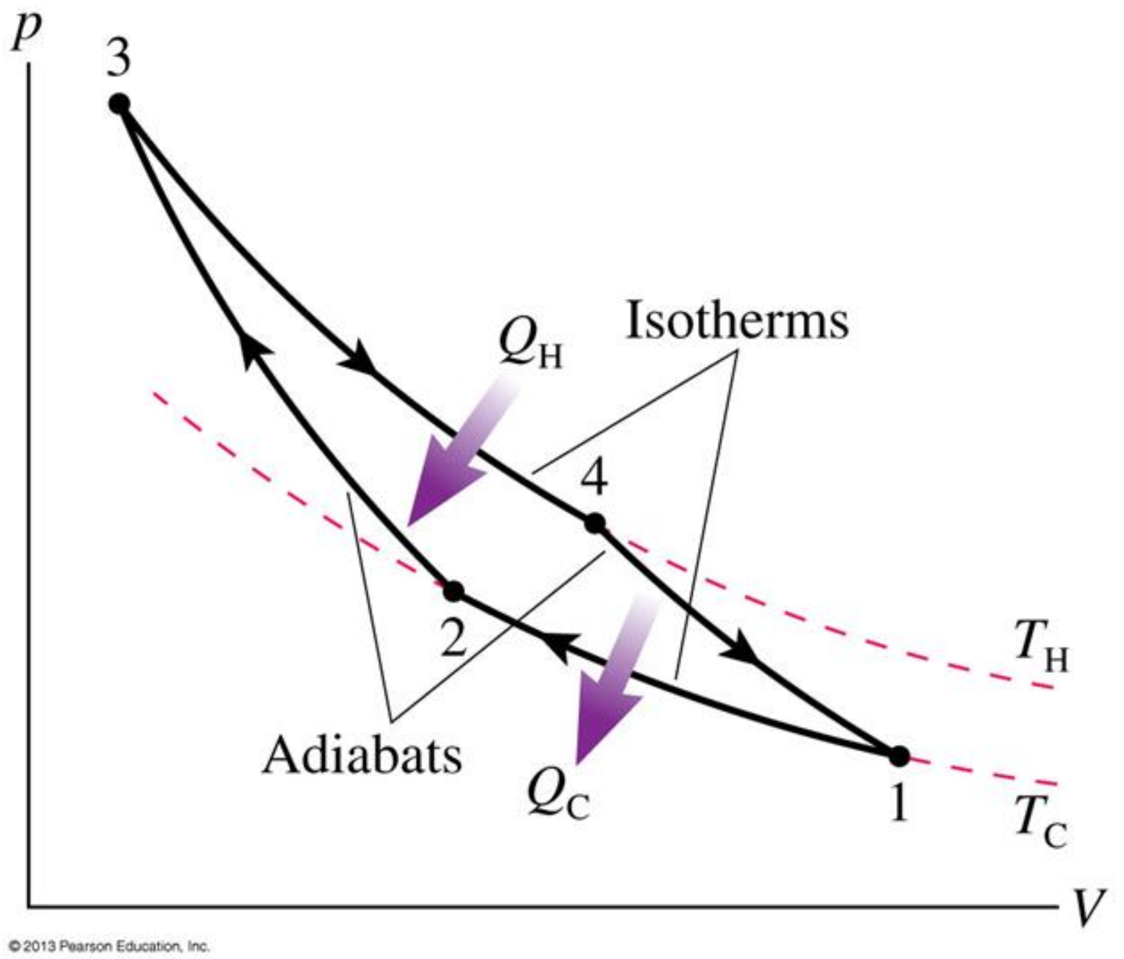
Analyzing the Carnot cycle (2/2)

- Meanwhile, from what we know about adiabats:

$$T_\mathrm{H}\, {V_4}^{\gamma-1} = T_\mathrm{C}\, {V_1}^{\gamma-1}$$
$$T_\mathrm{H}\, {V_3}^{\gamma-1} = T_\mathrm{C}\, {V_2}^{\gamma-1}$$

Taking ratio,

$$\left(\frac{V_4}{V_3}\right)^{\gamma-1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$



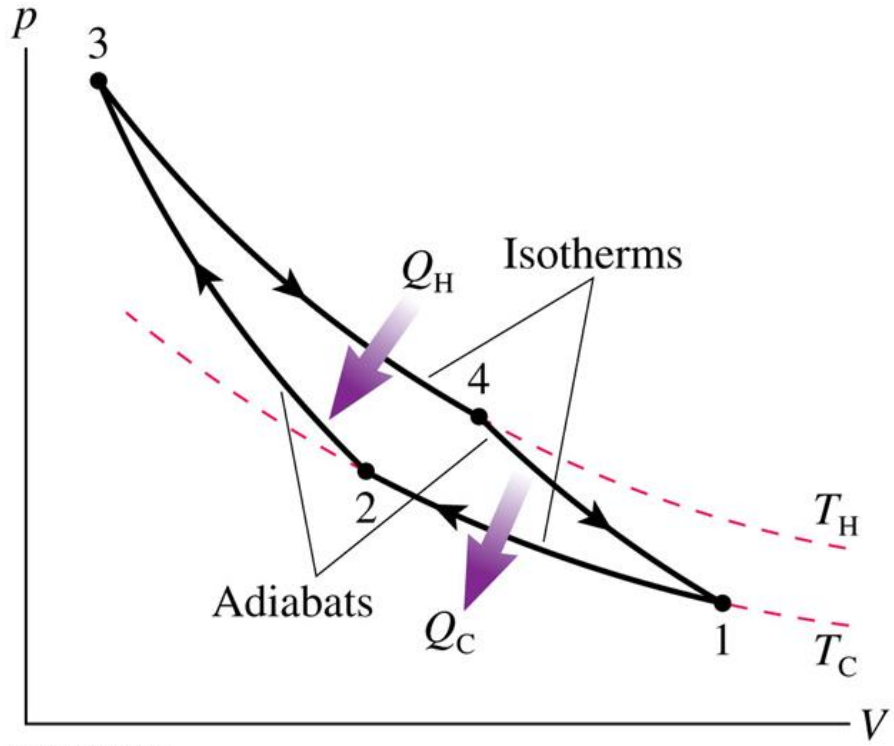
Optimal (Carnot) thermal efficiency

- Putting all together….

$$\boxed{\eta_{\text{Carnot}} = 1 - \frac{T_C}{T_H}}$$

- Put differently, for an optimal engine,

$$\frac{Q_C}{Q_H} = \frac{T_C}{T_H}$$



Your turn: Carnot efficiency

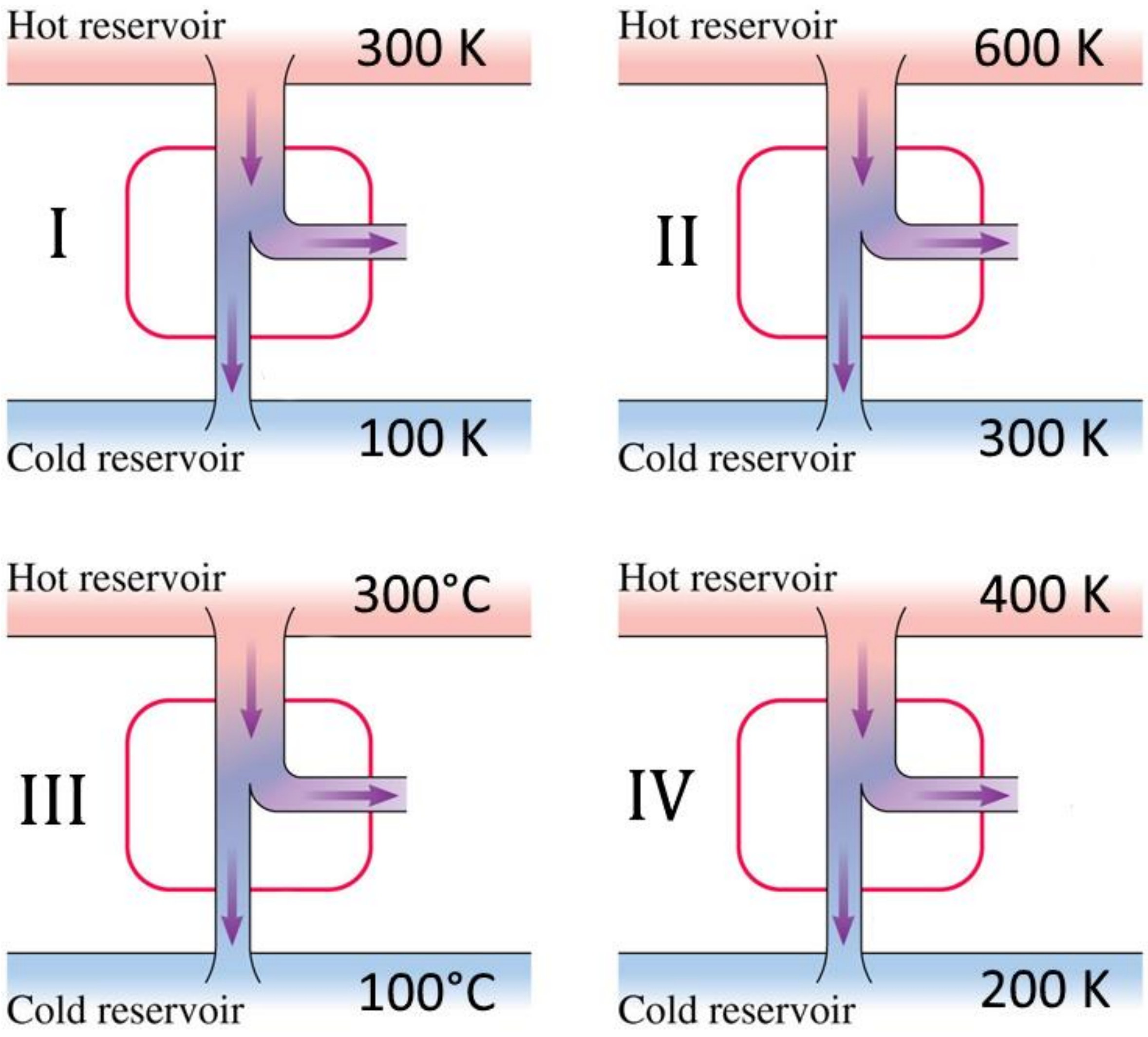
Rank the following 4 situations by the corresponding Carnot efficiency:

A. (I) > (II) = (IV) > (III)

B. (I) = (III) > (II) = (IV)

C. (II) > (III) = (IV) > (I)

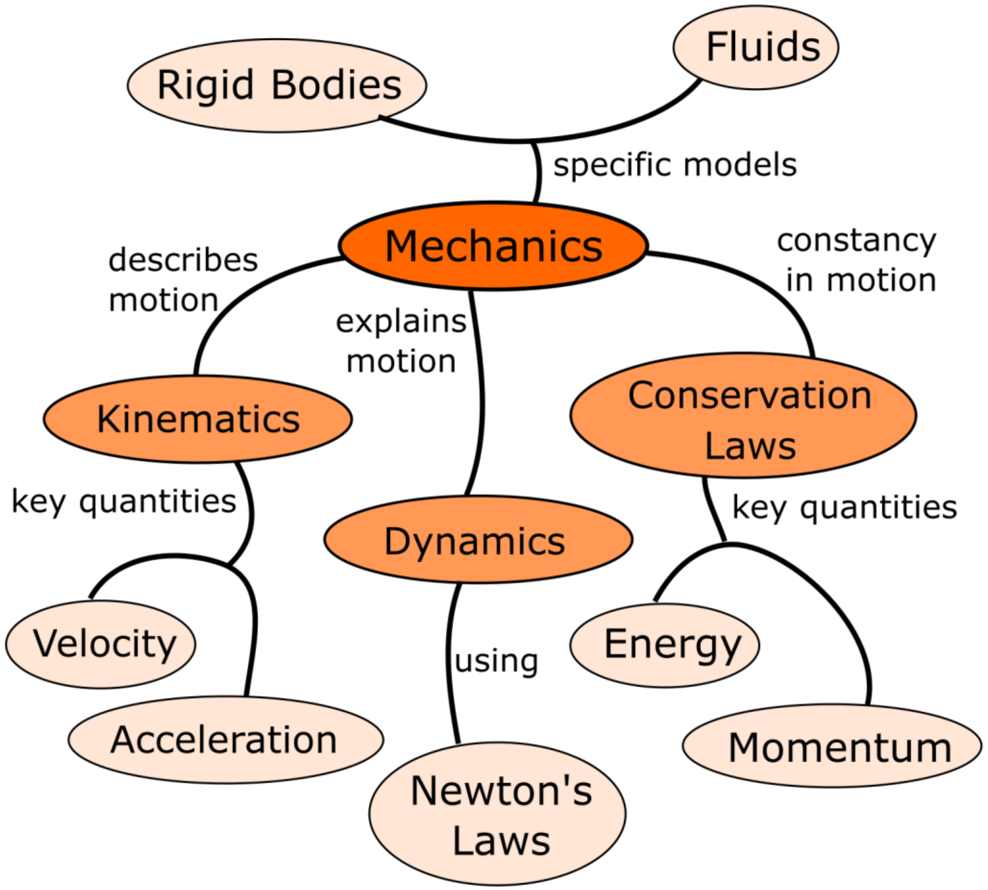
D. (II) > (I) = (III) = (IV)



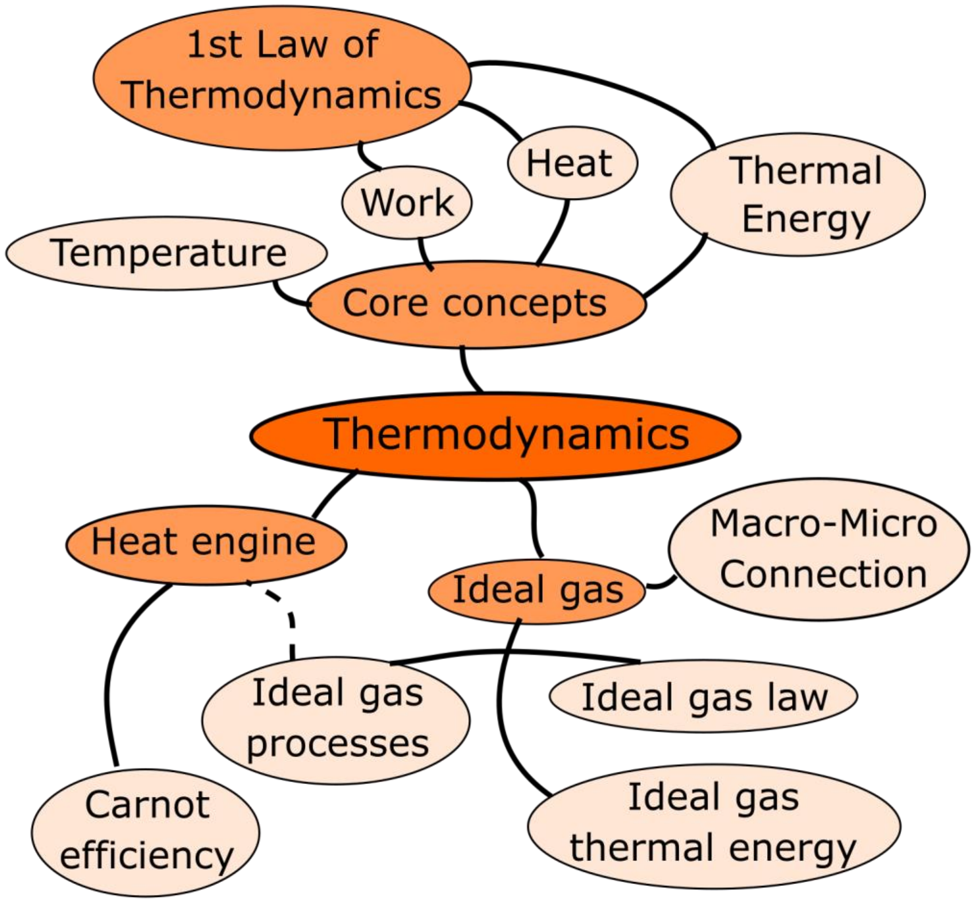
3. Course review

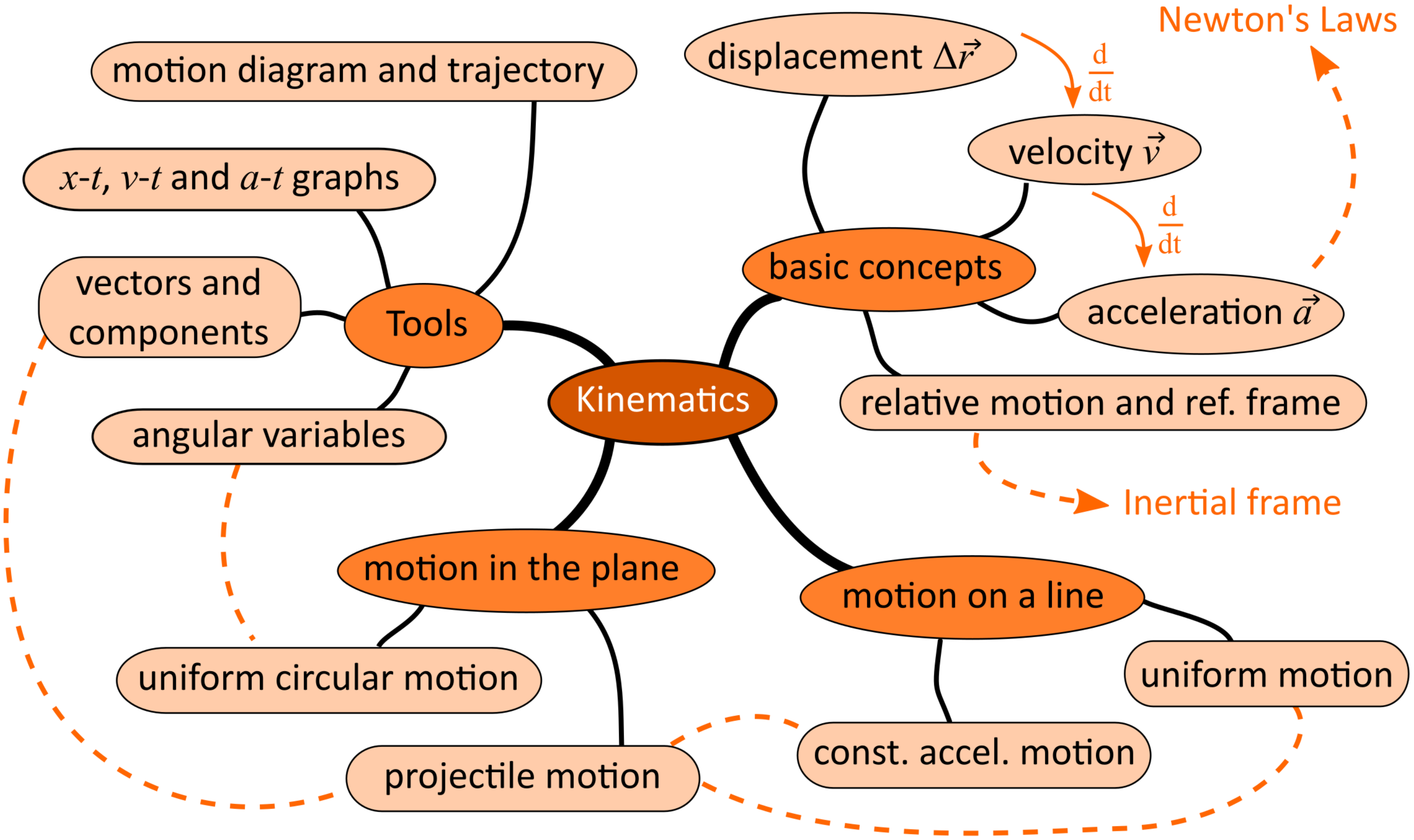
Reminder: bird eye's view of the course

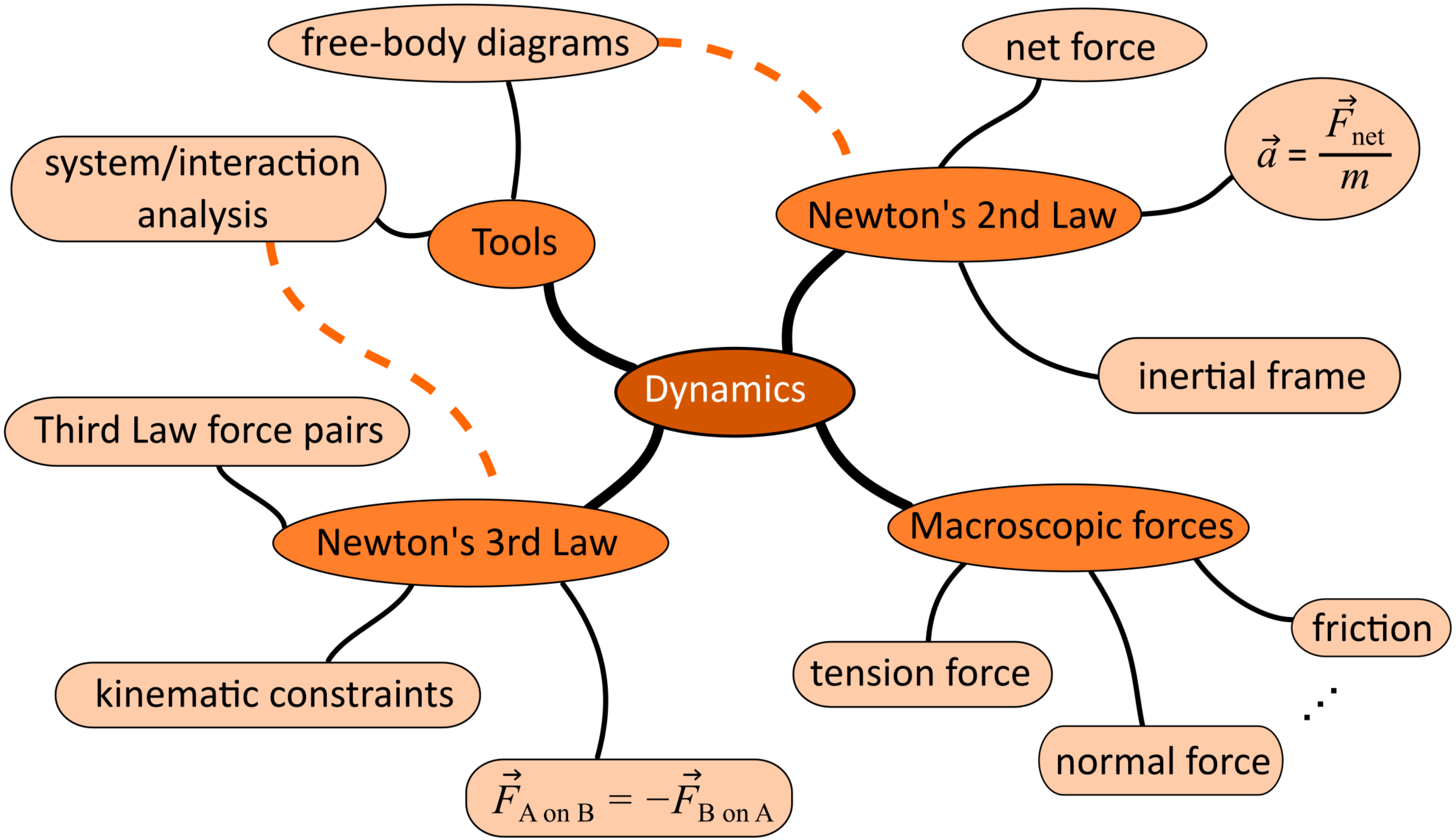
- Mechanics (~3/4)

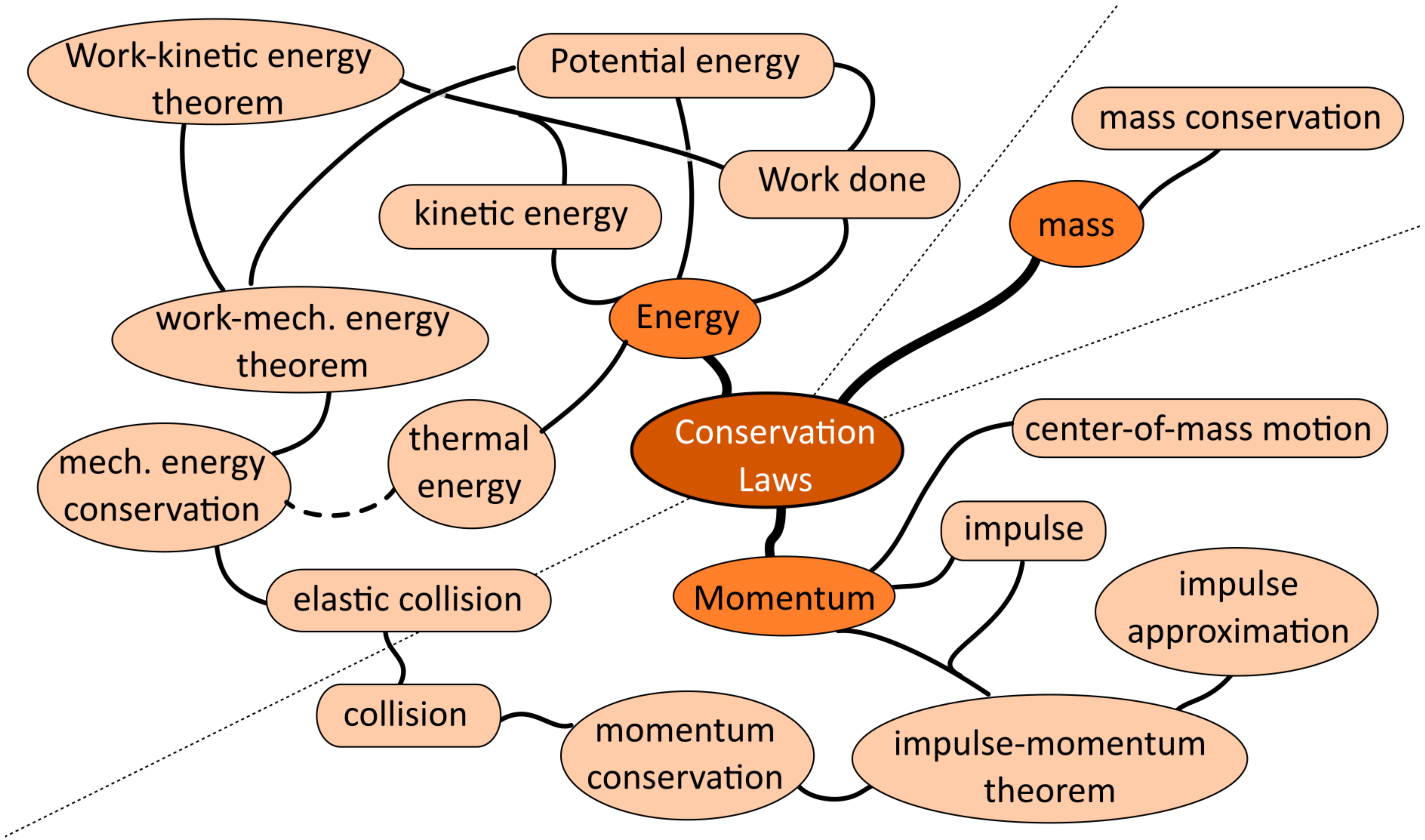


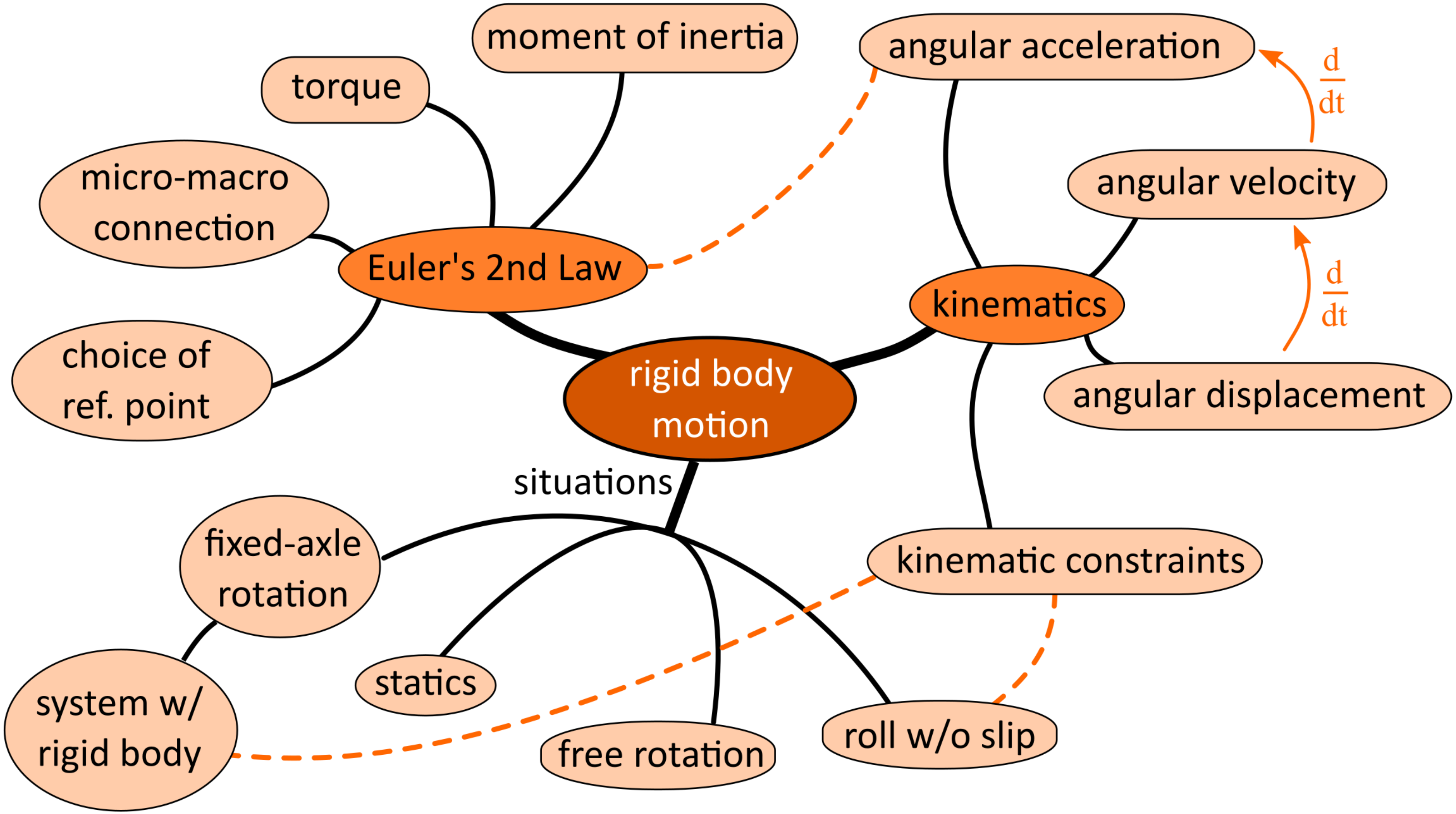
- Thermodynamics (~1/4)

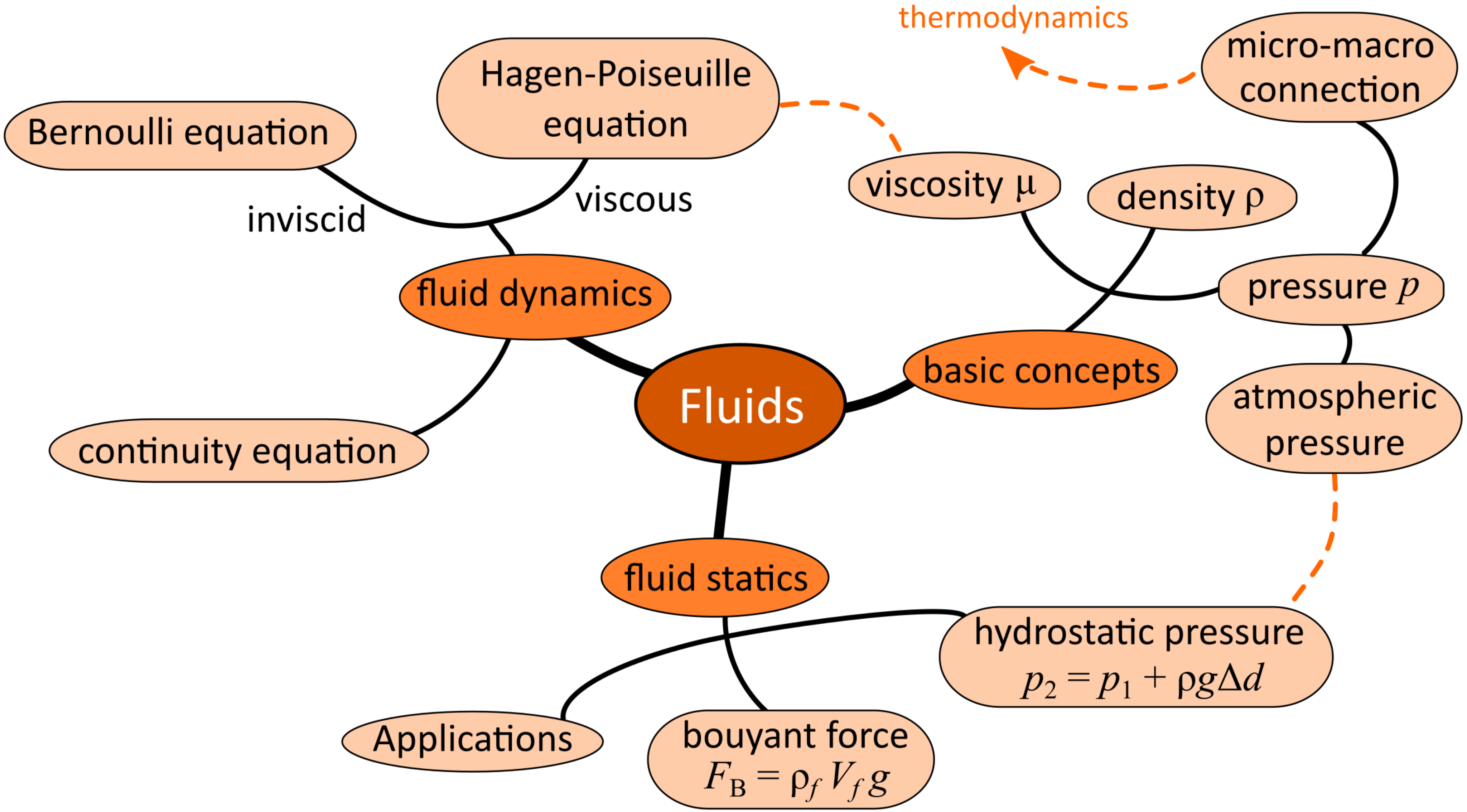


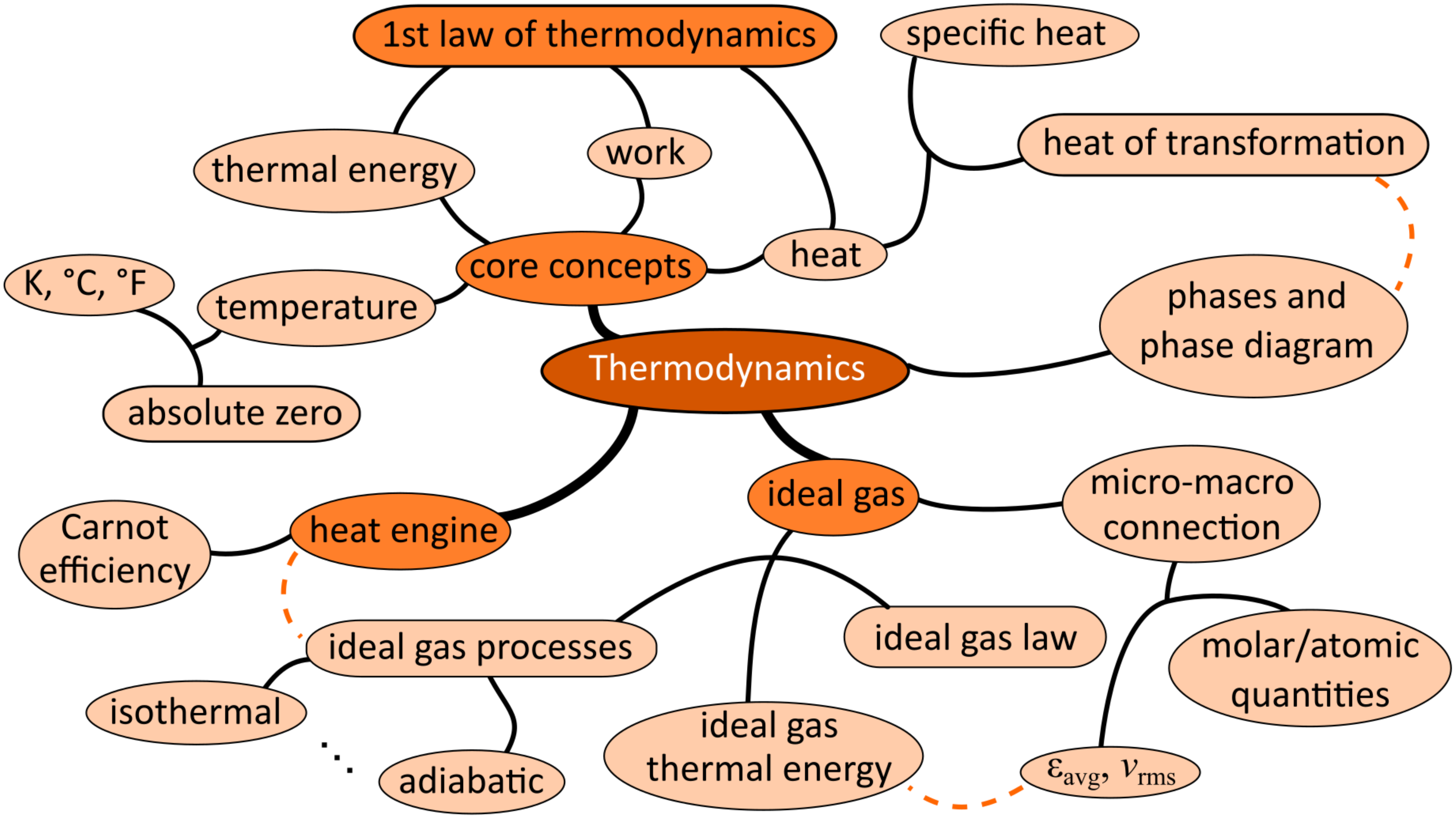

Newton's Laws
displacement $\Delta\vec{r}$
$\frac{d}{dt}$
motion diagram and trajectory
velocity $\vec{v}$
x-t, v-t and a-t graphs
$\frac{d}{dt}$
basic concepts
vectors and components
Tools
acceleration $\vec{a}$
Kinematics
relative motion and ref. frame
angular variables
Inertial frame
motion in the plane
motion on a line
uniform circular motion
uniform motion
const. accel. motion
projectile motion


free-body diagrams
net force
system/interaction analysis
Tools
Newton's 2nd Law
$\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$
Dynamics
inertial frame
Third Law force pairs
Newton's 3rd Law
Macroscopic forces
friction
tension force
kinematic constraints
normal force
$\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$


Work-kinetic energy theorem
Potential energy
mass conservation
Work done
kinetic energy
mass
Energy
work-mech. energy theorem
Conservation Laws
center-of-mass motion
thermal energy
mech. energy conservation
impulse
impulse approximation
elastic collision
Momentum
collision
momentum conservation
impulse-momentum theorem


moment of inertia
torque
micro-macro connection
Euler's 2nd Law
choice of ref. point
angular acceleration
$\frac{d}{dt}$
angular velocity
$\frac{d}{dt}$
kinematics
angular displacement
rigid body motion
situations
fixed-axle rotation
system w/ rigid body
statics
free rotation
roll w/o slip
kinematic constraints


thermodynamics
micro-macro connection
Hagen-Poiseuille equation
Bernoulli equation
viscosity μ
density ρ
inviscid
viscous
pressure p
fluid dynamics
basic concepts
Fluids
atmospheric pressure
continuity equation
fluid statics
hydrostatic pressure
$p_2 = p_1 + \rho g \Delta d$
Applications
bouyant force
$F_B = \rho_f V_f g$


1st law of thermodynamics
specific heat
thermal energy
work
heat of transformation
core concepts
heat
K, °C, °F
temperature
phases and phase diagram
Thermodynamics
absolute zero
ideal gas
micro-macro connection
Carnot efficiency
heat engine
ideal gas law
molar/atomic quantities
ideal gas processes
isothermal
...
adiabatic
ideal gas thermal energy
ε_{avg}, v_{rms}