Second Law of Thermodynamics

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SWARTHMORE

End of semester surveys/practices (1/3)

- Final exam formula sheet
  - You will be given a copy during the final exam
  - Let me know if you spot any typos!
- Mock final exam
  - Follow the final exam format
  - Solutions is posted in a separate document
- **Also:** textbook alignment document updated

End of semester surveys/practices (2/3)

- End-of-semester course evaluation
  - **Open until:** Dec 15 (Sun) 8 PM
  - Participation is optional and responses are anonymous
  - I will not read your responses until I have finalized grades

End of semester surveys/practices (3/3)

- Practice problem for feedback
  - **Due date:** Dec 12 (Thu) 10:30 AM (for feedback + credit)
    Dec 15 (Sun) 8:00 PM (for credit)
  - Two homework-like questions (resp. on fluids and thermodynamics)
  - Opportunity to practice written solutions
  - Completion grant you extra 1% course credit
  - My faculty colleagues will provide individualized feedback
  - You are advised to study before attempting the problems

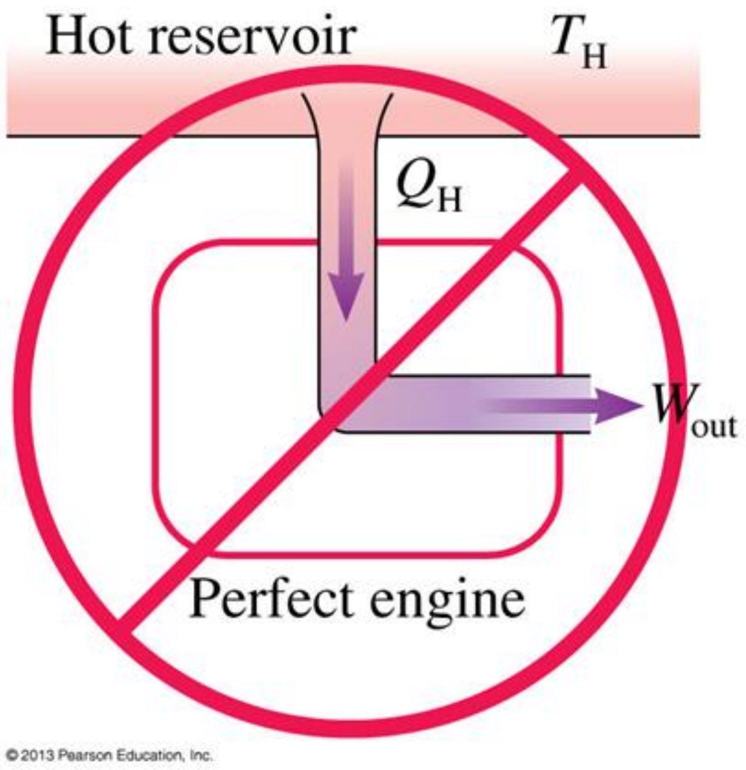
Outline

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

1. Second law of thermodynamics

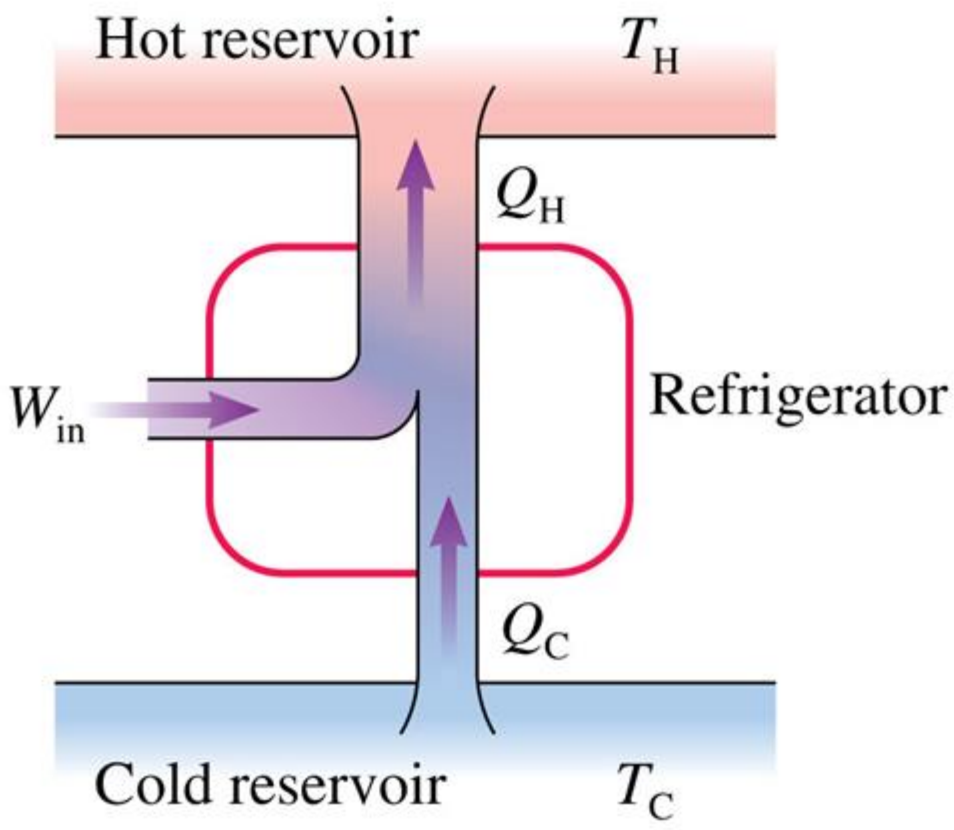
Maximum efficiency and inequivalence of heat and work

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



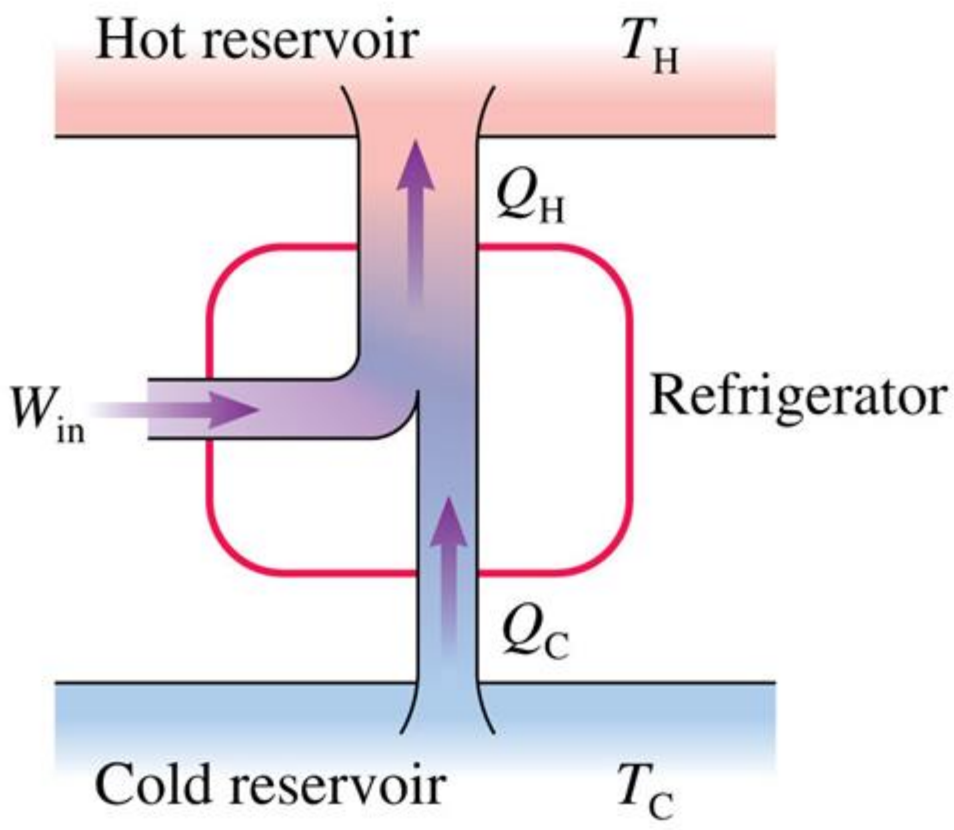
Interlude: refrigerator and heat pump

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



Second law of thermodynamics

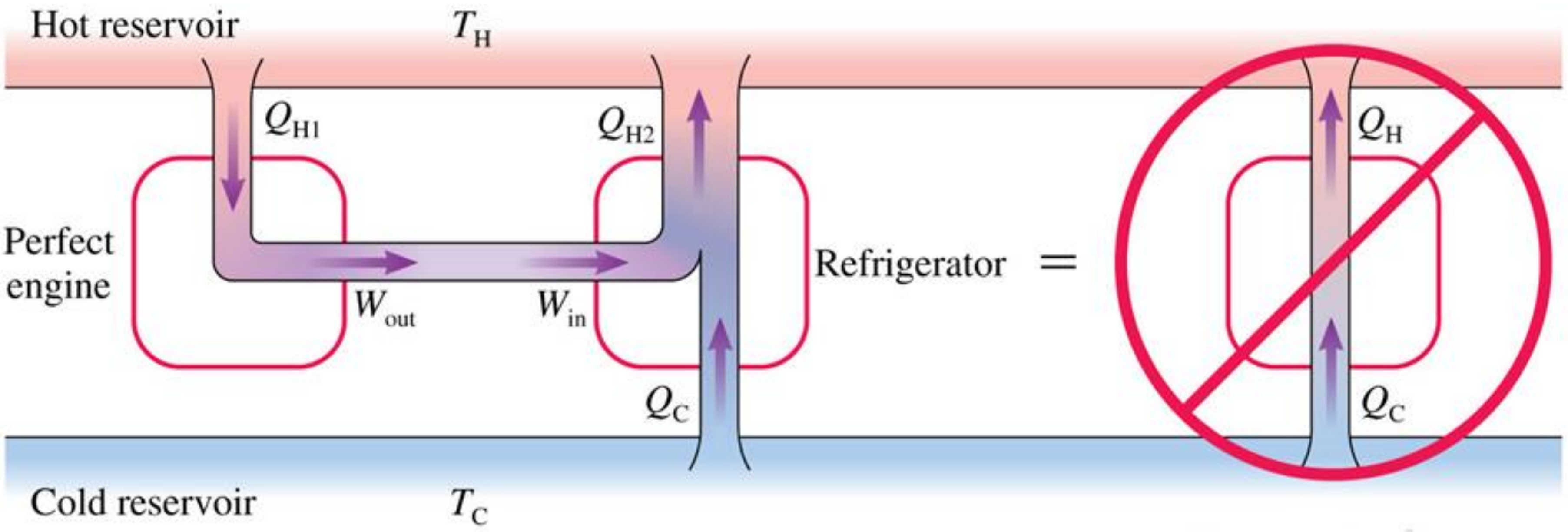
- One classic* formulation of the **second law of thermodynamics** is that heat cannot spontaneously flow from a cold object to a warm object
- This implies external work is needed for refrigerator and heat pumps to operate



* 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 $\eta_{\max} < 1$ (!)

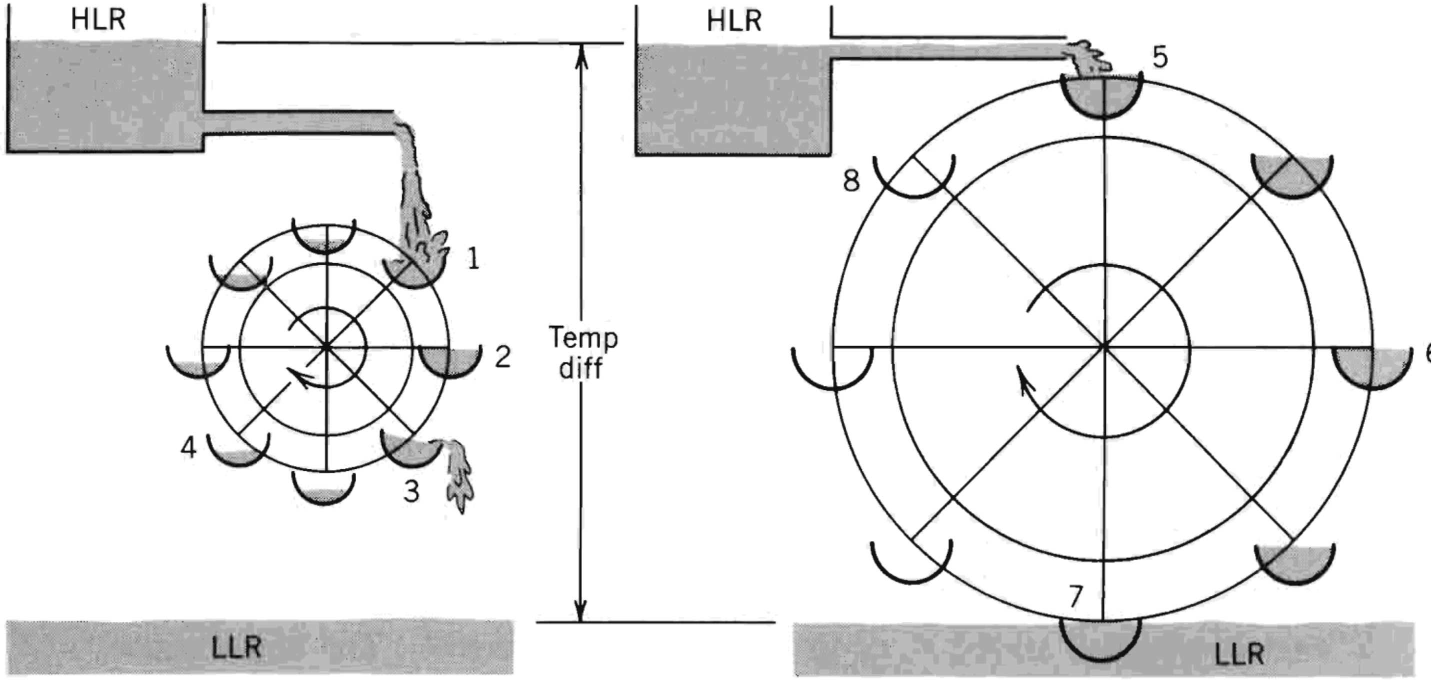


2. Carnot cycle and maximum efficiency

Optimal heat engine: the ideas

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

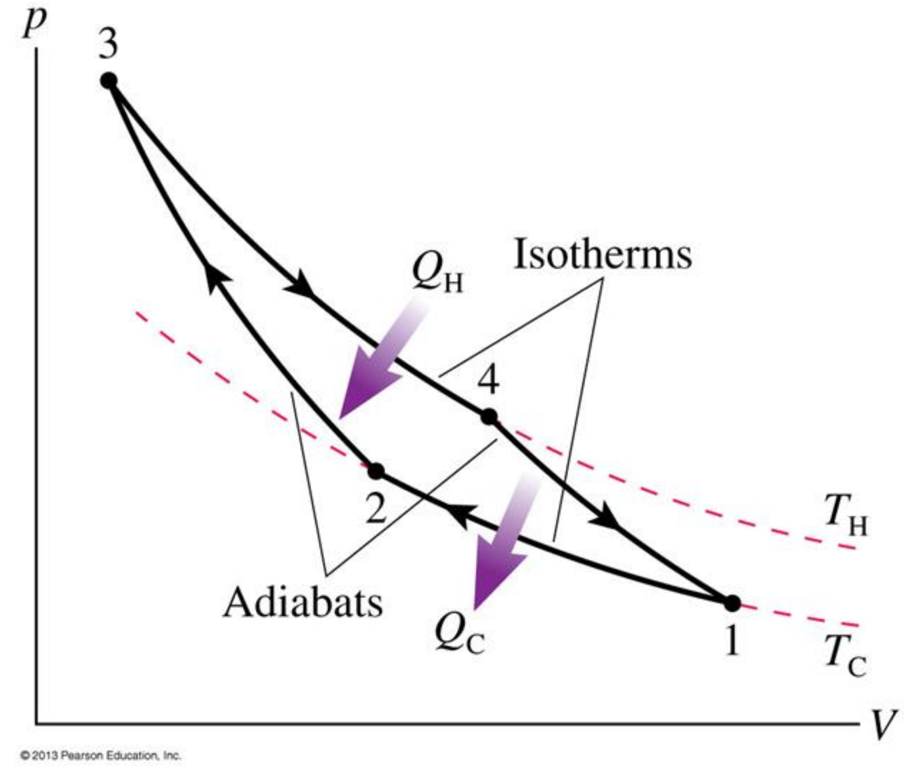
  (2) no “spilling” of heat in-between



* 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

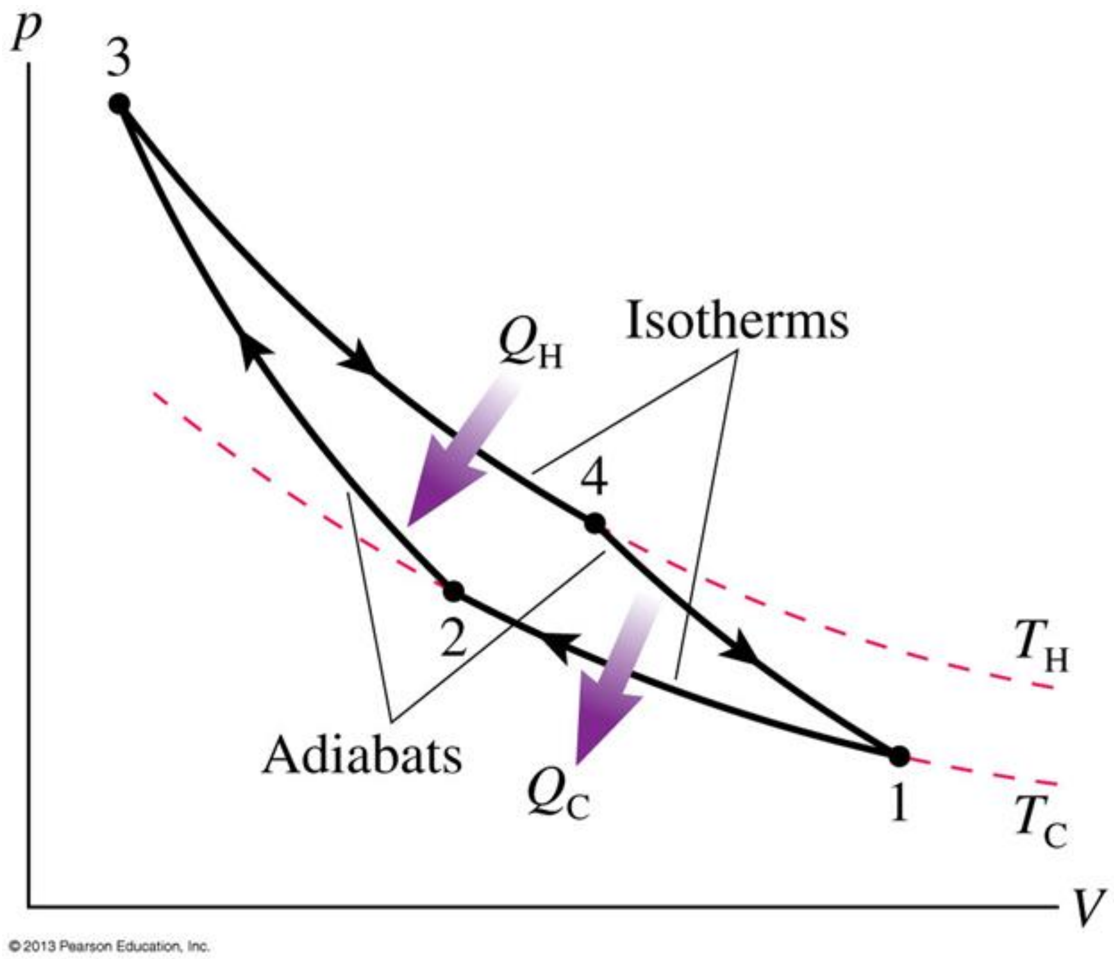
Analyzing the Carnot cycle (1/2)

- 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,

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



Analyzing the Carnot cycle (2/2)

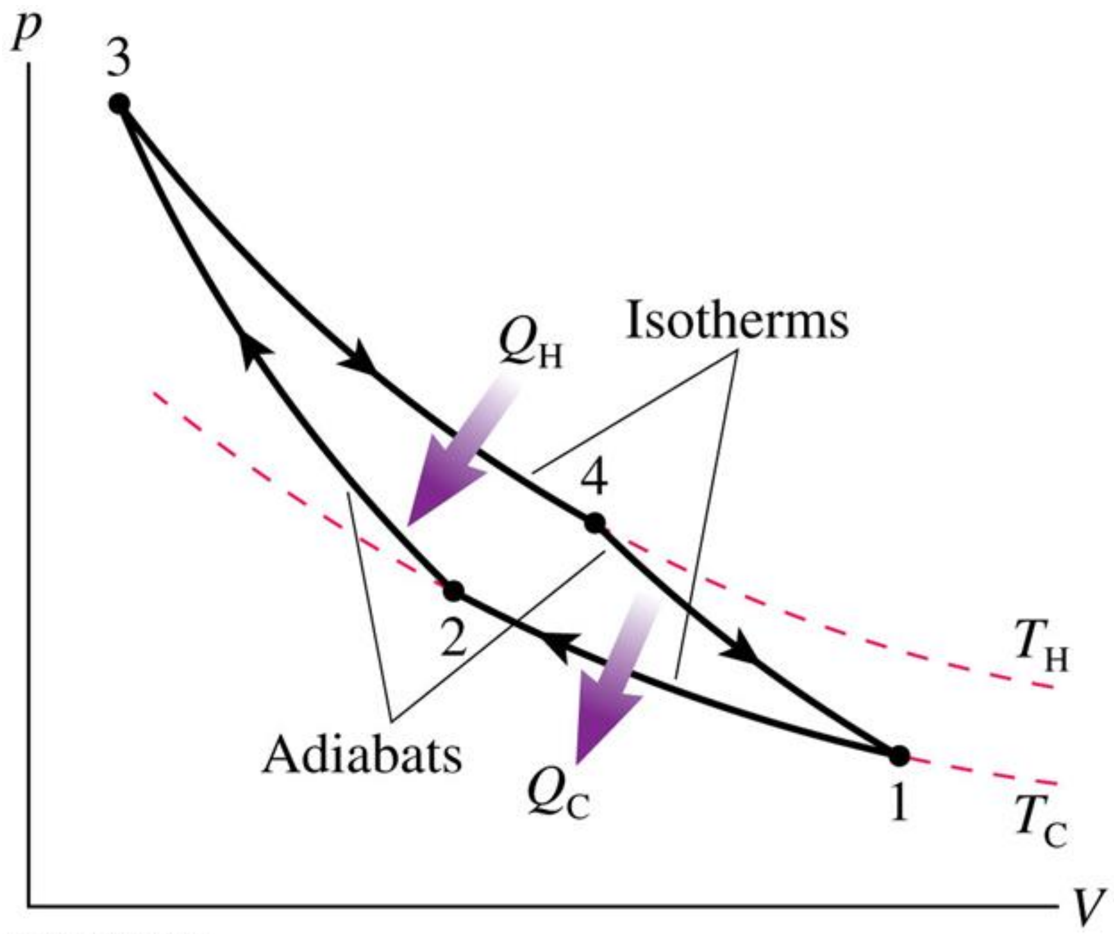
- Meanwhile, from what we know about adiabats:

$$T_H\, {V_4}^{\gamma-1} = T_C\, {V_1}^{\gamma-1}$$

$$T_H\, {V_3}^{\gamma-1} = T_C\, {V_2}^{\gamma-1}$$

Taking ratio,

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



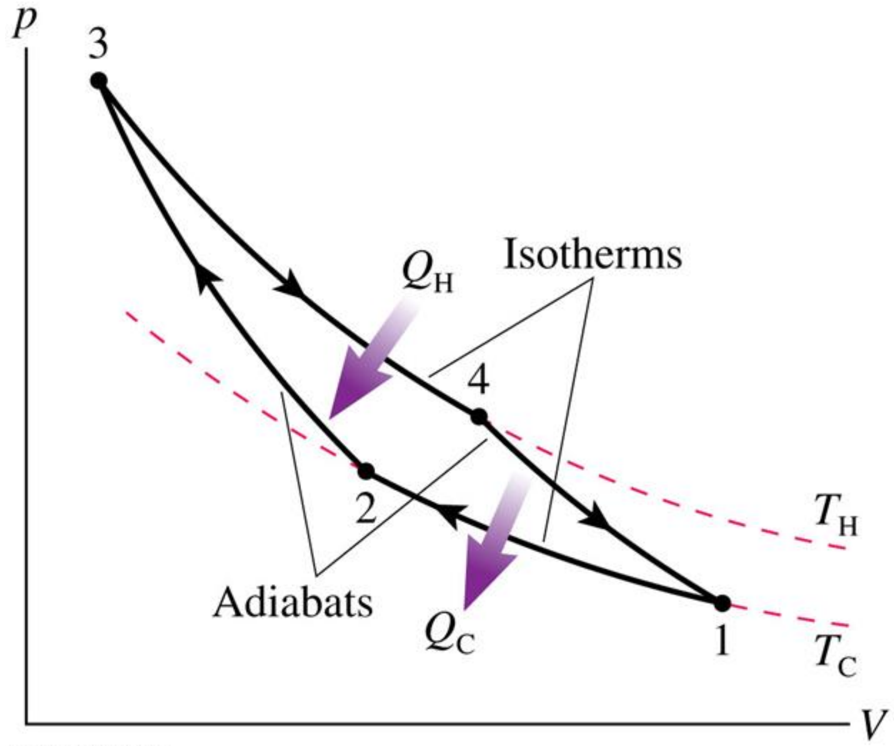
Optimal (Carnot) thermal efficiency

- 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

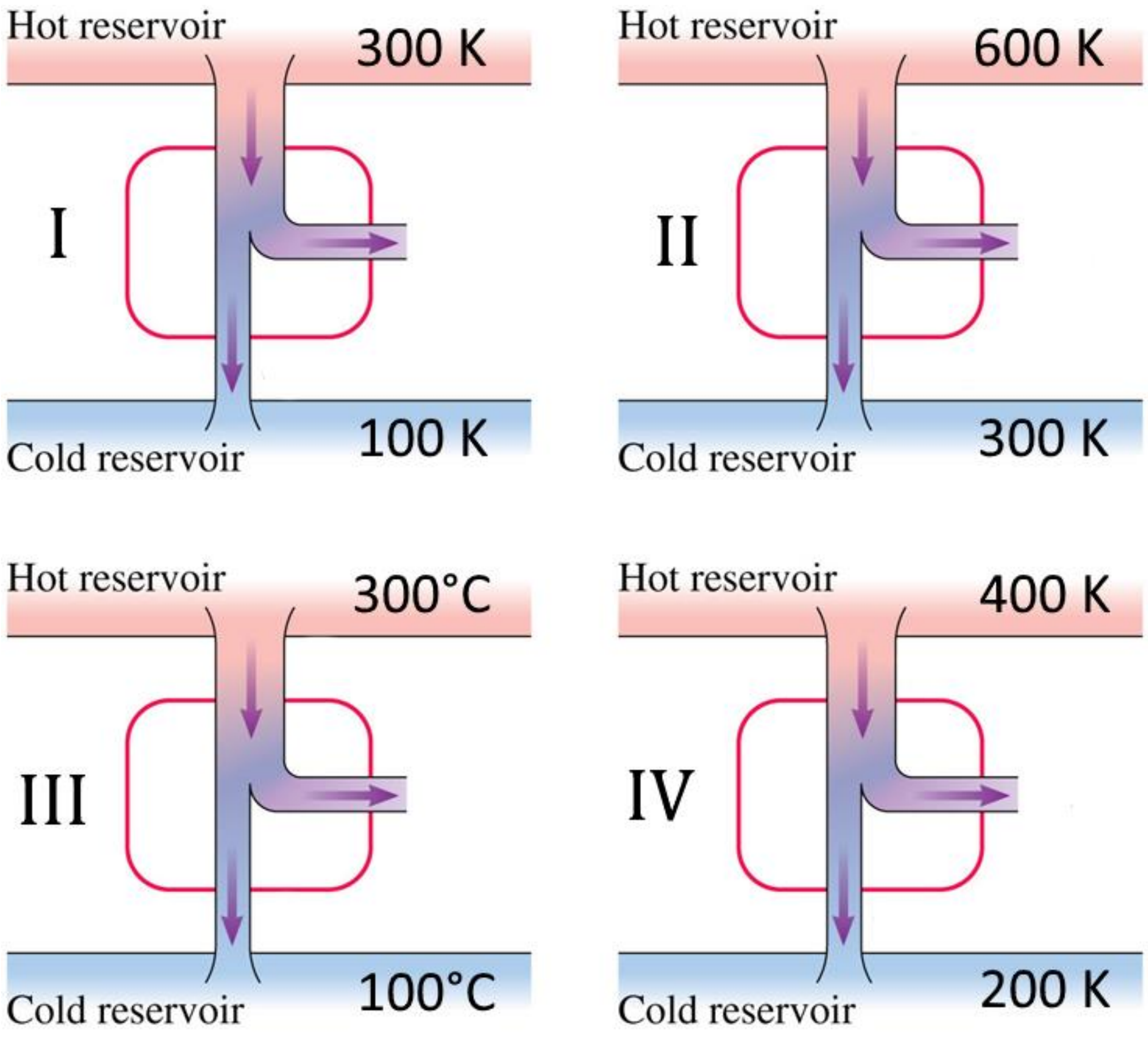
Rank the following 4 situations by the corresponding Carnot efficiency:

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

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

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

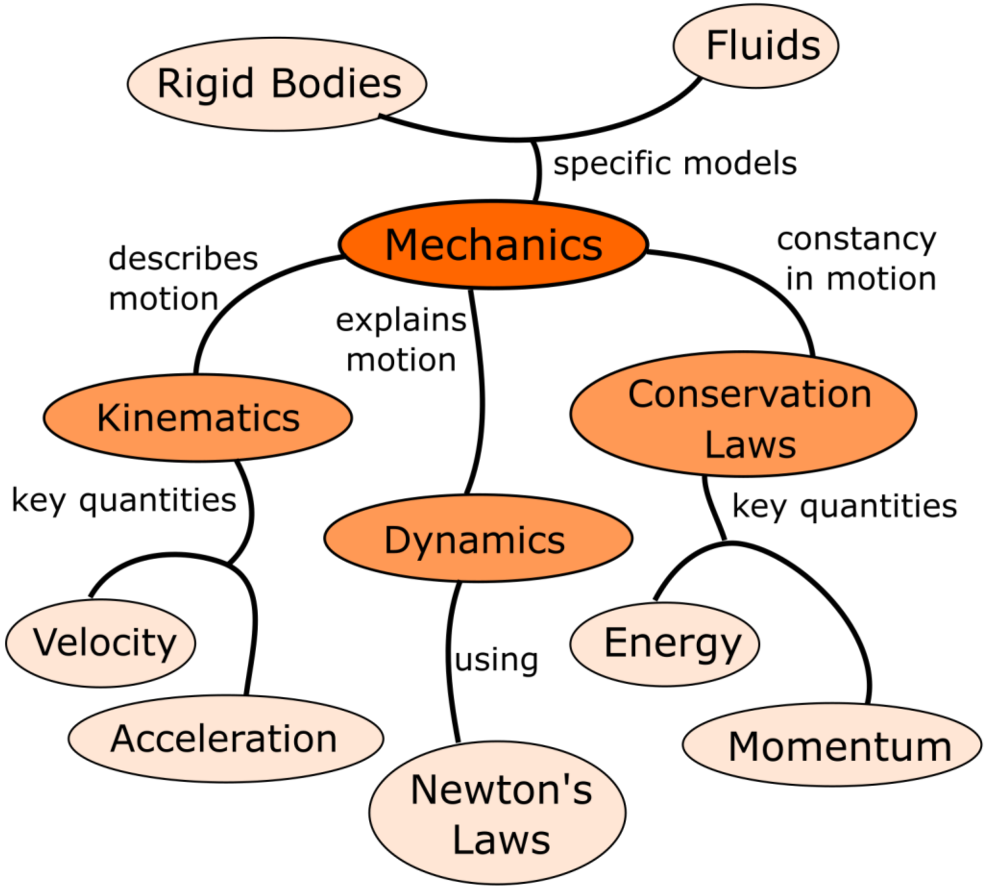
D. (II) > (I) = (III) = (IV)



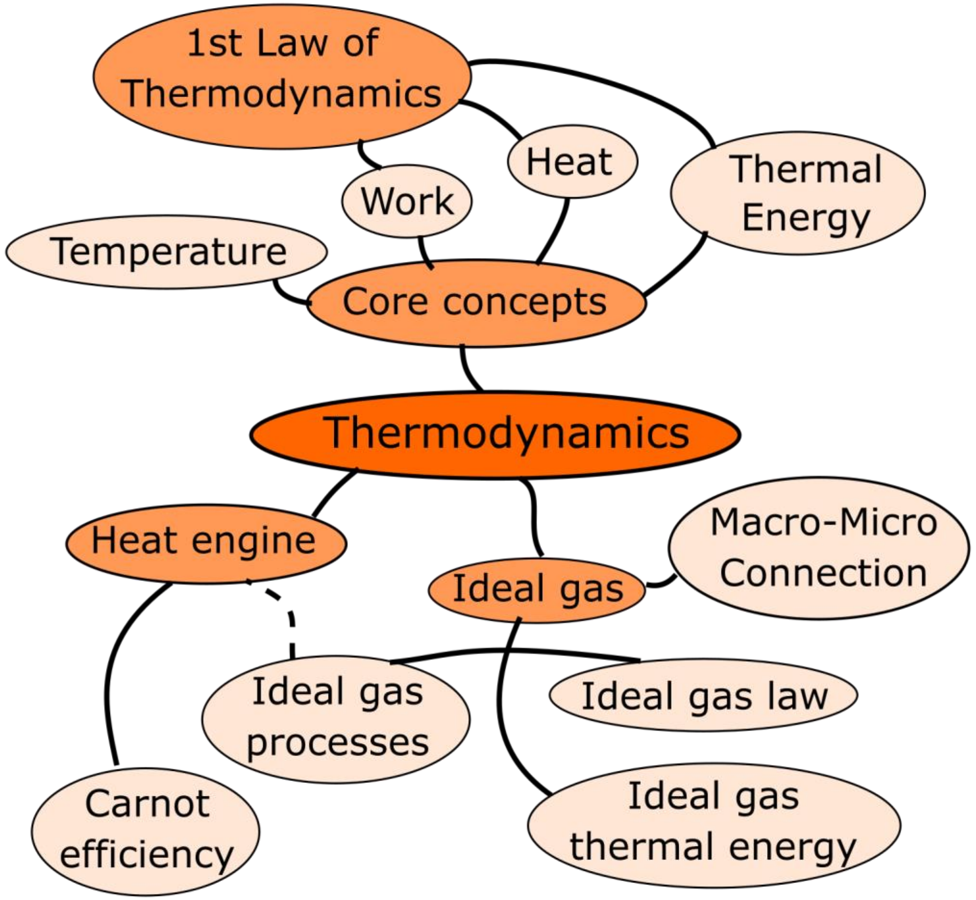
3. Course review

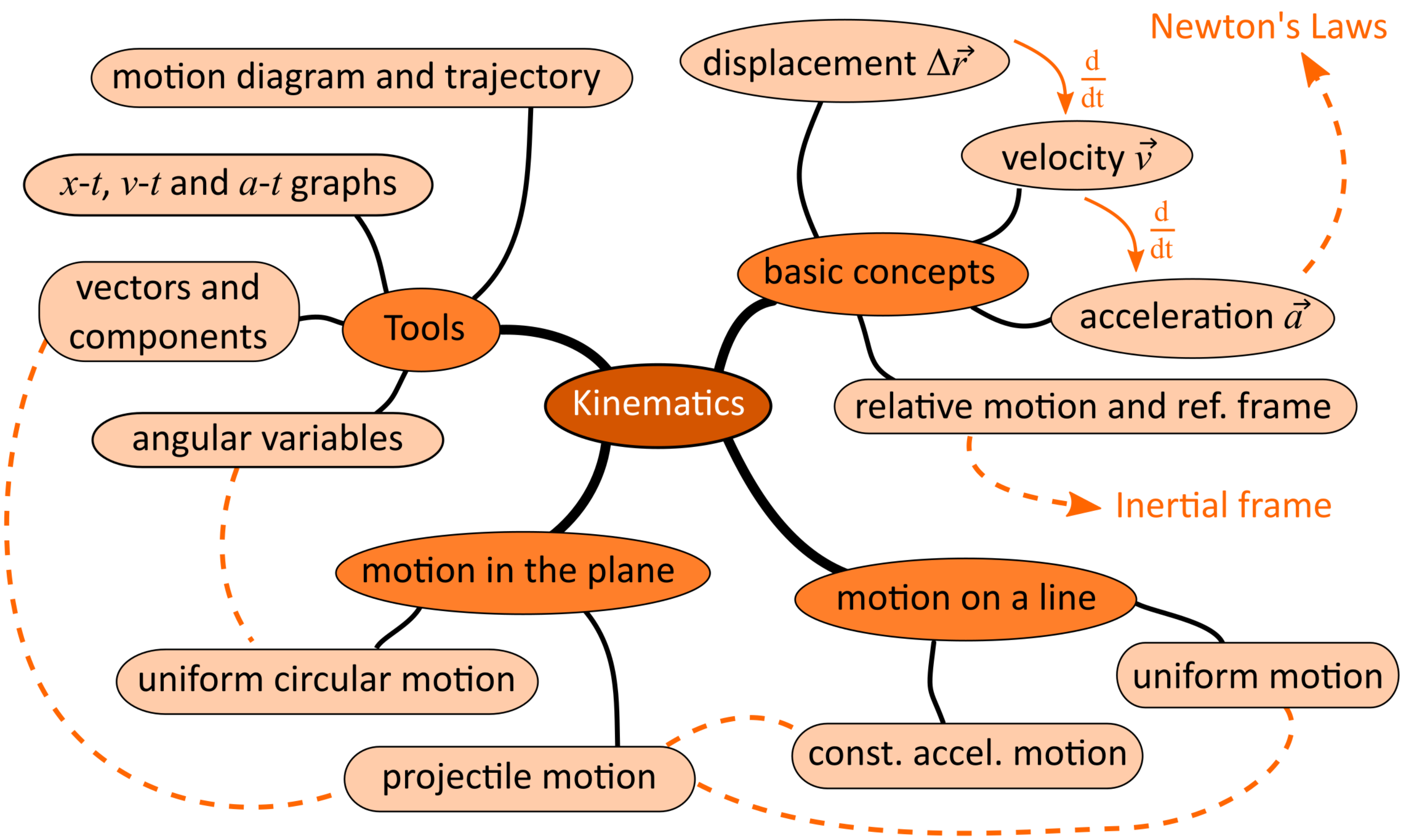
Reminder: bird eye’s view of the course

- Mechanics (~3/4)

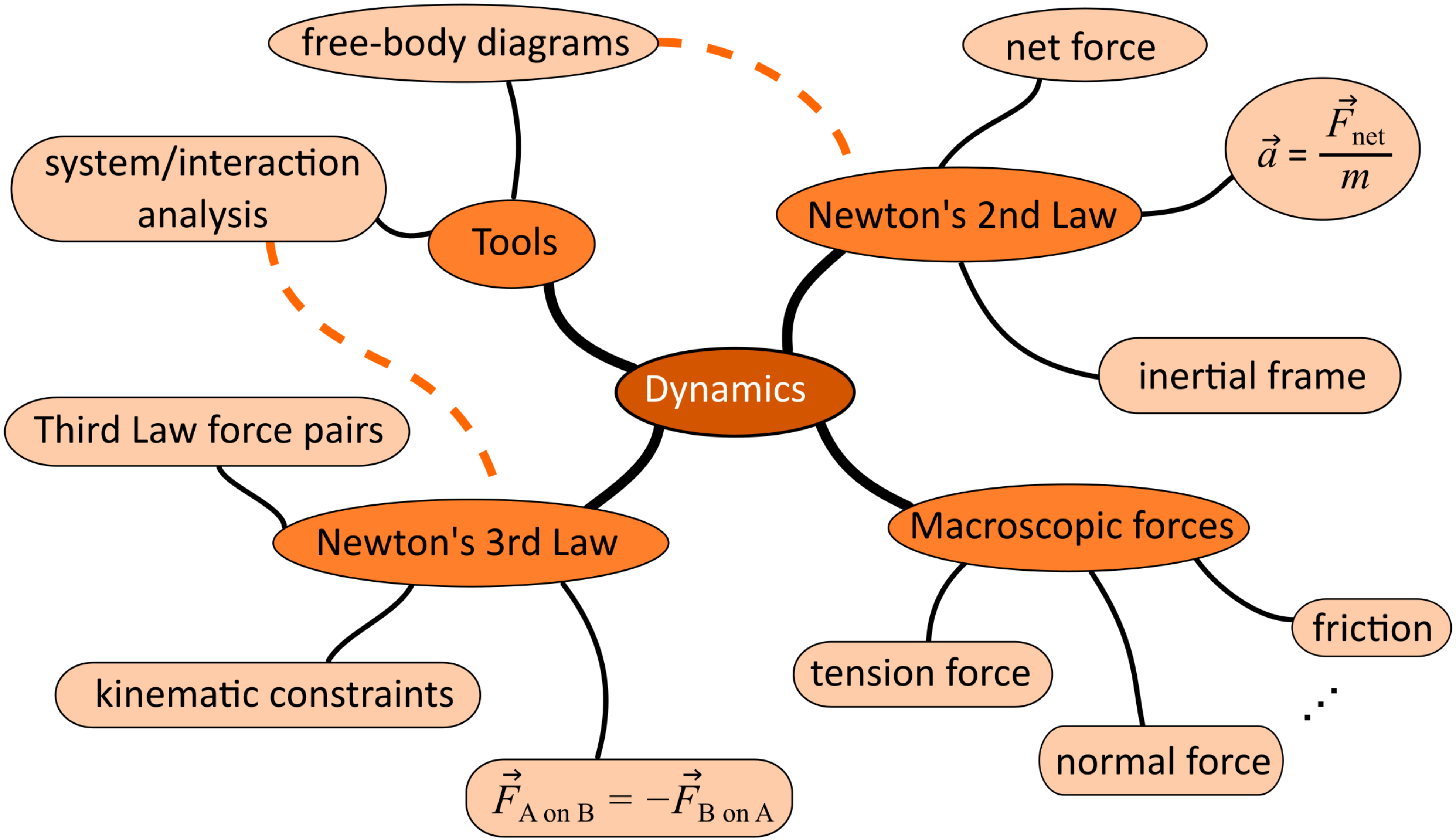


- Thermodynamics (~1/4)

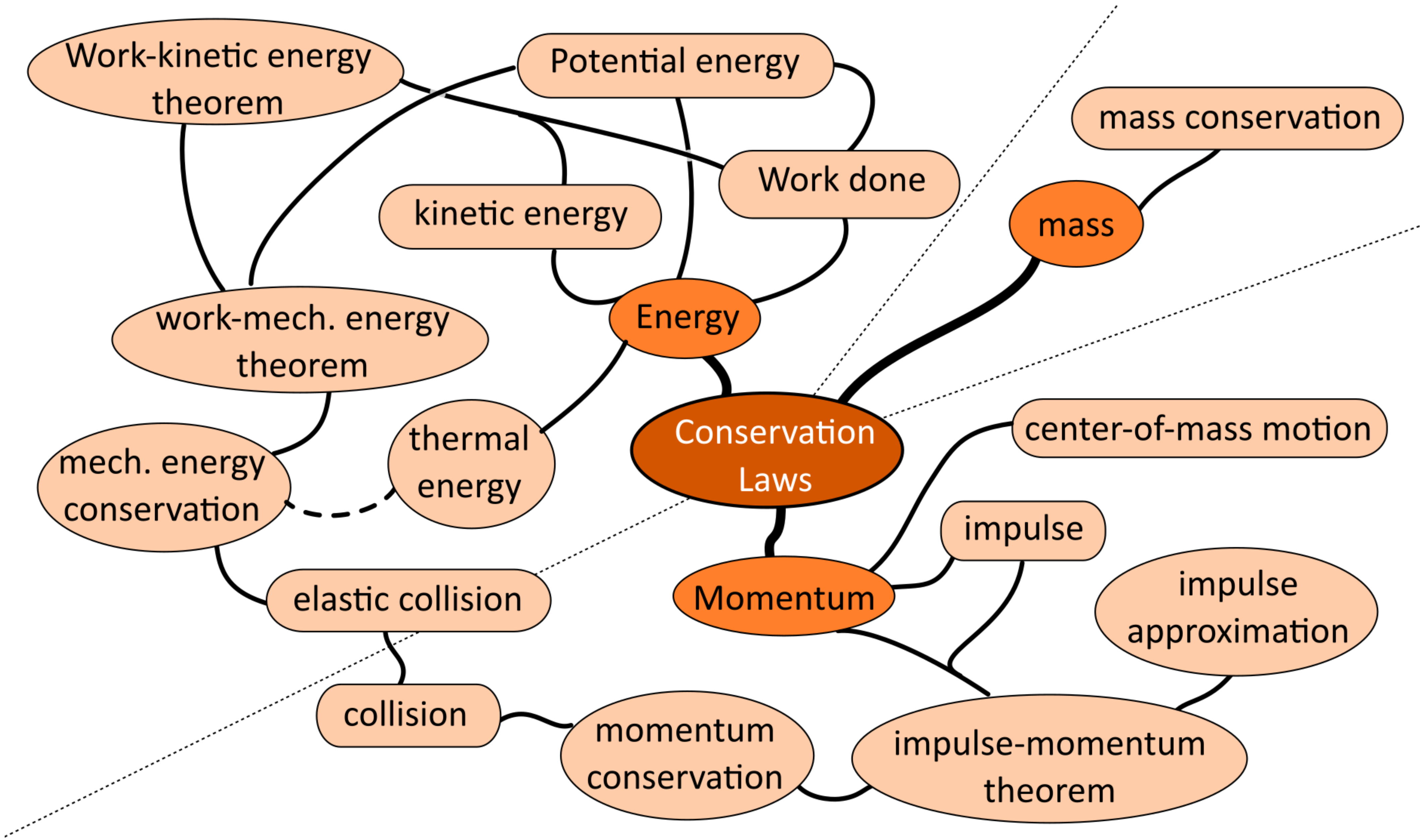


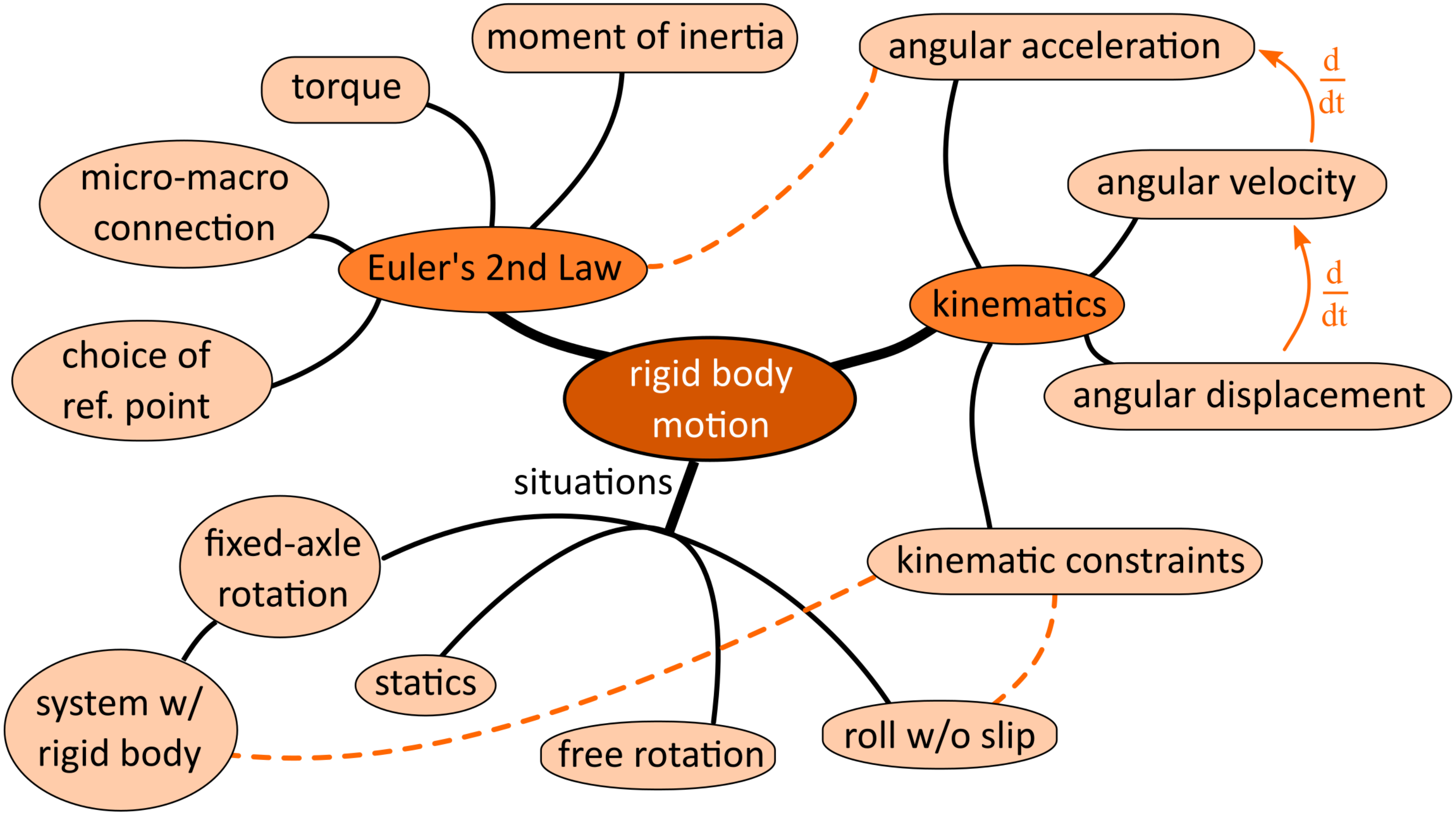


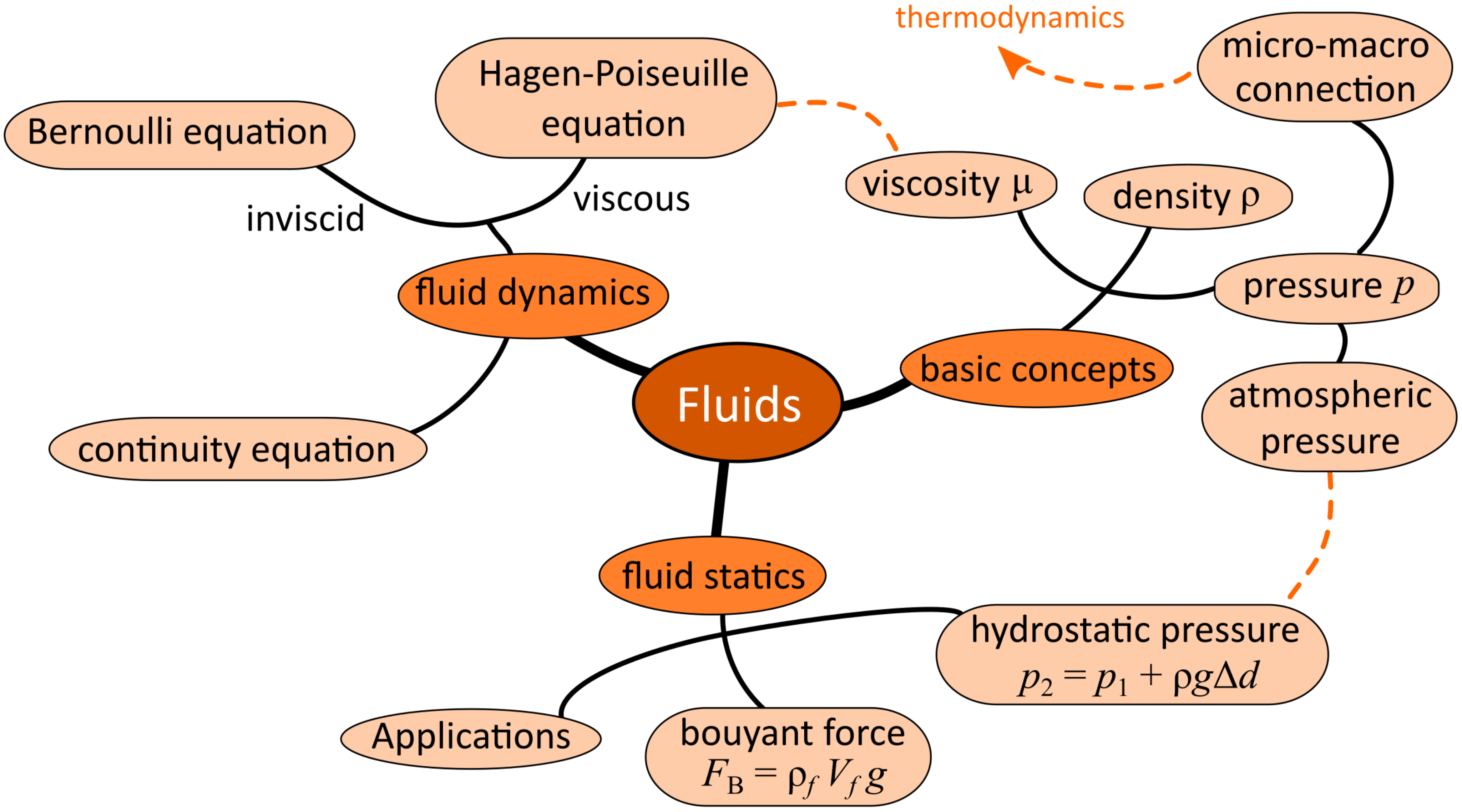
Newton's Laws
motion diagram and trajectory
displacement $\Delta\vec{r}$
$\frac{d}{dt}$
velocity $\vec{v}$
x-t, v-t and a-t graphs
$\frac{d}{dt}$
vectors and components
basic concepts
Tools
acceleration $\vec{a}$
Kinematics
relative motion and ref. frame
angular variables
Inertial frame
motion in the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

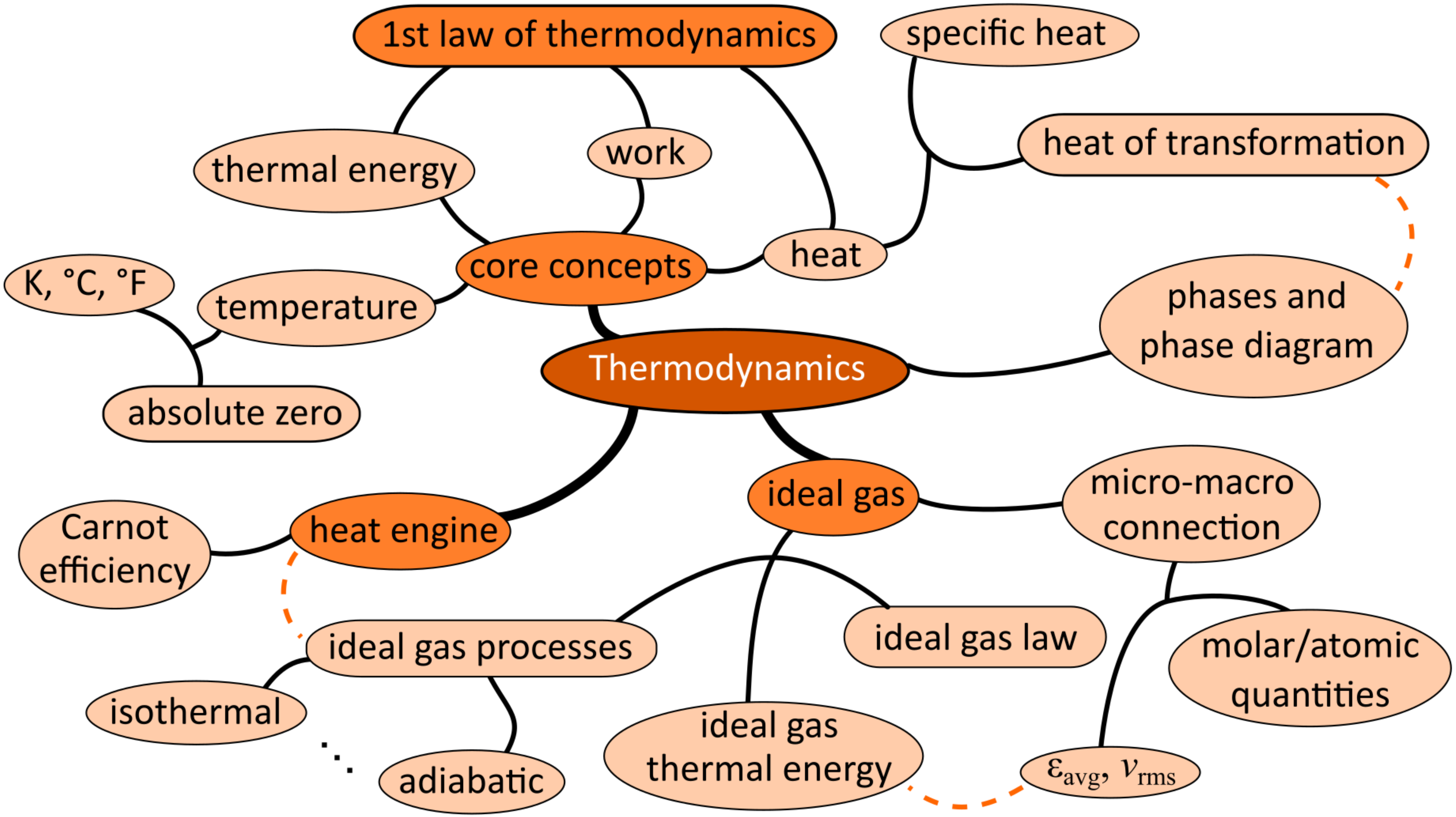


Dynamics
Tools
free-body diagrams
system/interaction analysis
Newton's 2nd Law
net force
$\vec{a} = \dfrac{\vec{F}_{\text{net}}}{m}$
inertial frame
Newton's 3rd Law
Third Law force pairs
kinematic constraints
$\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$
Macroscopic forces
tension force
normal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


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


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


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
micro-macro connection
ideal gas
Carnot efficiency
heat engine
ideal gas law
molar/atomic quantities
ideal gas processes
isothermal
...
adiabatic
ideal gas thermal energy
ε_{avg}, v_{rms}