

# Introductory Physics III – Thermal and Modern Physics

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## Lecture 01: Introduction

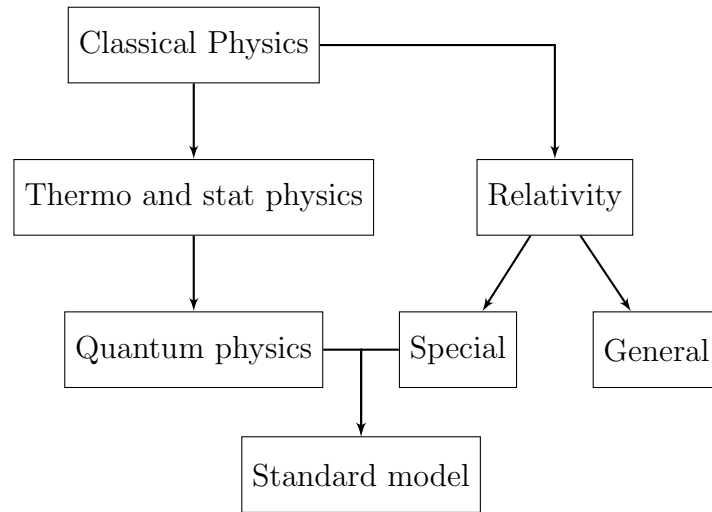
Fri 04  
Aug '23

## 1 The Course

### 1.1 Schedule

- MWF 12:00-13:00 lecture hours (no tutorial on Monday)
- Tutorials will still be held occasionally with homework discussions and quizzes.

## 1.2 Syllabus



## 1.3 Grading

- **Quizzes:** 20%.
- **Midterm:** 40%.
- **Final:** 40%.

# 2 Classical Physics

## 2.1 Newton's Laws

- (I) In an inertial frame,  $\mathbf{F}_{\text{net}} = 0 \implies \mathbf{v} = \text{const.}$
- (II)  $\ddot{\mathbf{r}} = \frac{\mathbf{F}_{\text{net}}}{m}$  where  $m$  is the inertial mass.
- (III) For any 2 particles,  $\mathbf{F}_{12} = -\mathbf{F}_{21}$ .

### 2.1.1 Math: Vector Equations

$$\ddot{\mathbf{r}} = \frac{\mathbf{F}}{m} \equiv \begin{cases} \ddot{x} = \frac{F_x}{m} \\ \ddot{y} = \frac{F_y}{m} \\ \ddot{z} = \frac{F_z}{m} \end{cases}$$

For a system of  $N$  particles, we have  $3N$  equations of motion. With  $6N$  initial conditions, the evolution of the system is uniquely determined.

## 2.2 Conservation Laws

### 2.2.1 Momentum

### 2.2.2 Energy

### 2.2.3 Angular Momentum

## Lecture 03

Wed 9  
Aug '23

Every path is a deviation from the classical path.

$$q(t) = q_{cl}(t) + \delta q(t) \\ \text{with } \delta q(t_1) = \delta q(t_2) = 0$$

Let  $q_0(t)$  be the optimal solution, *i.e.*,  $\frac{\partial S}{\partial q} \equiv 0$ .

$$q(t) = q_0(t) + \delta q(t) \\ \dot{q}(t) = \dot{q}_0(t) + \delta \dot{q}(t) \\ \delta S = \int_{t_1}^{t_2} L(t, q(t), \dot{q}(t)) - L(t, q_0(t), \dot{q}_0(t)) \, dx$$

For small  $\delta q$ , *i.e.*,  $\delta q(t) \ll q(t) \forall t \in [t_1, t_2]$ ,

$$\delta S = \int_{t_1}^{t_2} \frac{\partial L}{\partial q} \, dx$$

(i) **Free particle:**  $L = \frac{1}{2}m\dot{q}^2$ , so

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) = 0 \\ \frac{d}{dt} (m\dot{q}) = 0 \\ \ddot{q} = 0.$$

(ii)  $L = \frac{1}{2}m\dot{q}^2 - V(q)$ .

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q} = 0 \\ \frac{d}{dt} + \frac{\partial V}{\partial q} = 0 \\ m\ddot{q} = -\frac{\partial V}{\partial q}.$$

In general, for a Lagrangian specified by  $L(q_1, \dots, q_f, \dot{q}_1, \dots, \dot{q}_f, t)$ ,

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = 0 \text{ for } i = 1, \dots, f.$$

If  $L$  does not depend on  $q_j$  *explicitly* for some  $j$ , then

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_j} \equiv 0$$

Such a coordinate is called a **cyclical** or **ignorable coordinate**.

This is a generalised way of understanding conservation laws.

- $\theta$ -independent Lagrangians have rotational symmetry, so angular momentum is conserved.
- $x$ -independent Lagrangians have translational symmetry, so linear momentum is conserved.
- $t$ -independent Lagrangians have time symmetry, so energy is conserved.

## Lecture 05

Wed 16  
Aug '23

### 2.3 First Law of Thermodynamics

Defines *internal energy*.

When  $\delta q$  is the heat supplied to the system, and  $\delta w$  is the work done by the system, then the first law of thermodynamics states that the change in internal energy  $U$  is given by

$$dU = \delta q + \delta w.$$

This is a restatement of the conservation of energy, more generalised than in mechanics.

How do we measure  $\delta q$  and  $\delta w$ ?

#### 2.3.1 Heat

*Specific heat* ( $C$ ) is the energy required to change the temperature of a unit mass of a substance by one kelvin.

*Molar specific heat* ( $C_{\text{mol}}$ ) is the energy required to change the temperature of a mole of a substance by one kelvin.

$$\delta q = mC\Delta T.$$

Since heat (and work) is path dependent, we need to specify more than just the initial and final states of the system. We must also specify the path taken by the system.

Two common paths are *isobaric* and *isochoric*. The corresponding specific

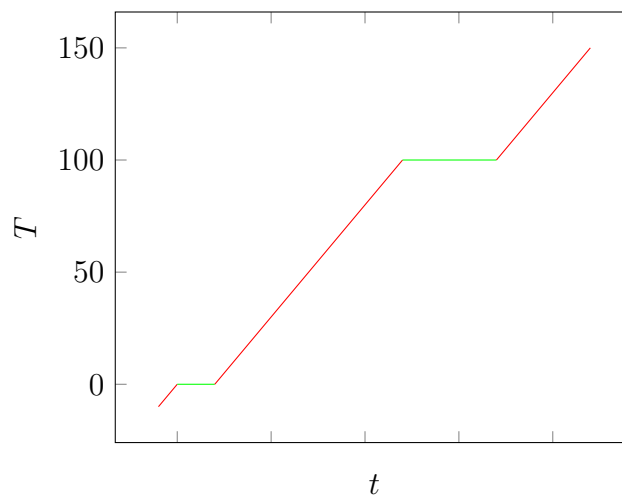
heats are *specific heat at constant pressure* ( $C_p$ ) and *specific heat at constant volume* ( $C_v$ ).

In case of solids and liquids,  $C_p \approx C_v$ .

We can however generalise the specific heat at constant volume to *anergetic specific heat* ( $C_{an}$ ). This is along a path where no work is done by the system. In the particular case of an ideal gas, this path is the same as the isochoric one.

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Not all heating processes lead to an increase in temperature. For example, heating a block of ice at  $-10^\circ\text{C}$  will look like:




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### 2.3.2 Work

Work done by an ideal gas is defined as

$$\delta w = p \, dV.$$

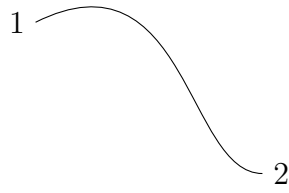
Is this  $p$  the internal pressure or the external pressure?

For *any* process from state 1 to 2,

$$U_2 - U_1 = Q - W,$$

irrespective of the path taken.

But what does the “path” mean here?



Every point along a curve describing a thermodynamic process is an equilibrium state. This is called a *quasi-static* process. Such a process must take infinite time to complete.

In such a process, the internal and external pressures are always equal.