

# Notes for Lecture 3

## Conservation and SHM

### 3.1 Conservation theorems

It is not possible to overemphasize the importance of the principle of conservation. In classical mechanics, these principles can be thought as consequences of Newton's laws. So, we call them conservation theorems. We will revisit and enrich these principles later.

#### 3.1.1 Momentum conservation

$\dot{\vec{p}} = \vec{F}$  and so  $\vec{p}$  is conserved when the net force is zero. It can happen that only certain components of the net force is zero. Then, only the corresponding momentum components are conserved. An example is the previous example: the motion of a charge in a magnetic field. While the total momentum is certainly not conserved, the  $z$  component (parallel to  $\vec{B}$ ) of the momentum is conserved since the  $z$  component of the force is zero.

#### 3.1.2 Angular momentum conservation

$$\vec{L} \stackrel{def}{=} \vec{r} \times \vec{p}$$

Of the two terms that result on taking the time-derivative of  $\vec{L}$ , the term  $\dot{\vec{r}} \times \vec{p}$  vanishes since  $\dot{\vec{r}} = \vec{v}$  is parallel to  $\vec{p} = m\vec{v}$  (recall that  $\vec{A} \times \vec{A} = 0$ ). As a result,

$$\dot{\vec{L}} = \vec{r} \times \dot{\vec{F}} \stackrel{def}{=} \vec{N} \text{ (torque)}$$

So,  $\vec{L}$  is conserved when the net torque is zero. It can happen that only certain components of the net torque is zero. Then, only the corresponding angular momentum components are conserved.

### 3.1.3 Mechanical energy and its conservation

The total mechanical energy is conserved if all forces are conservative. Special attention will be paid to the case when the total mechanical energy can be written as

$$E = T + U$$

We now define what  $T$ ,  $U$ , and conservative force mean. In this course, we may drop “mechanical” in “mechanical energy.”

- **$T$  and work-energy theorem** Work ( $dW$ ) done on an object by an applied force  $\vec{F}$  is defined as

$$dW \stackrel{def}{=} \vec{F} \cdot d\vec{r}$$

This definition is valid for any force, not just the net force. Now, consider a motion of a particle moving from point 1 to point 2, and the total work done on it,  $W_{12}$ , during this movement. By total work, we mean work done by the net force, not by any individual force alone. For the net force, we can use Newton’s equation,  $\vec{F} = m\vec{a}$ , and so the total work done on the particle is  $W_{12} = \int_1^2 \vec{F} \cdot d\vec{r} = \int_1^2 m \frac{d\vec{v}}{dt} \cdot d\vec{r} = \int_1^2 m d\vec{v} \cdot \vec{v} = \int_1^2 \frac{m}{2} d(v^2) = \int_1^2 d(\frac{1}{2}mv^2) = T_2 - T_1$ , where

$$T \stackrel{def}{=} \frac{1}{2}mv^2$$

is the **kinetic energy**, and  $T_1 = \frac{1}{2}mv_1^2$  and  $T_2 = \frac{1}{2}mv_2^2$ . To summarize,

$$W_{12}(\text{work done by net force}) = T_2 - T_1$$

This is the **work energy theorem**, which is *always valid*, not just when the net force is conservative. So, it applies when air resistance or friction is involved as well. Actually, a better way to look at it is that **the work energy theorem is just the way the notion of “kinetic energy” is defined, and why it has to be defined as  $mv^2/2$ .**

- **$U$  and conservative force**  $\vec{F}$  is a conservative force if  $\oint_C \vec{F} \cdot d\vec{r} = 0$  for any closed path  $C$ . For instance, the Lorentz force is a conservative force, as is the gravitational force. For Lorentz force,  $\vec{F} \cdot d\vec{r} = 0$ . For the gravitational force, the positive work done by it and the negative work done by it cancel exactly in a closed path. So, a conservative force is in general a force that “gives back.”

However, air resistance or friction force is not a conservative force, as such a force does a negative work for any finite path, including a closed path. Such a force “only takes away” without giving back. An important type of force is a conservative force that depends on position only. In this case, the following three conditions are equivalent to one another.

$$\begin{aligned} \oint_C \vec{F} \cdot d\vec{r} &= 0 && \text{for any closed path } C \\ \vec{\nabla} \times \vec{F} &= 0 \\ \vec{F} &= -\vec{\nabla}U(\vec{r}) && \text{where } U(\vec{r}) = -\int^{\vec{r}} \vec{F}(\vec{r}') \cdot d\vec{r}' \end{aligned}$$

where  $U$  is the so-called **potential energy** function.<sup>1</sup> The integral notation  $\int^{\vec{r}}$  used to define  $U$  means an indefinite line integral,<sup>2</sup> for which *any* path can be chosen as long as it ends at point  $\vec{r}$ . Note that if  $U = U(\vec{r}, t)$ , i.e. an explicit function of time, then the force will not be conservative. This will happen, e.g., if the source of the gravitational force is in motion.<sup>3</sup>

- **Energy is only relative.** The definition of the potential energy is ambiguous up to a constant, because the line integral,  $U(\vec{r}) = -\int^{\vec{r}} \vec{F} \cdot d\vec{r}'$ , has an arbitrary starting point. The kinetic energy is also not an absolute concept, since, due to the Galilean invariance, the speed can be measured differently depending on which inertial frame is used. It follows then that the absolute value of energy is not meaningful. What matters is the *change of energy*. The energy conservation means that once the energy is defined in an inertial frame with a fixed zero reference, then the energy is constant as a function of time.

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<sup>1</sup> To prove the equivalence of the first two, use Stoke’s theorem  $\oint_C \vec{F} \cdot d\vec{r} = \int d\vec{S} \cdot \vec{\nabla} \times \vec{F}$ . (To go from the first to the second, consider an arbitrarily small, but finite, closed loop integral.) To prove the equivalence of the first and the third, note that the vanishing loop integral means that  $-\int_{\vec{r}_1, P_1}^{\vec{r}} \vec{F} \cdot d\vec{r} = -\int_{\vec{r}_1, P}^{\vec{r}} \vec{F} \cdot d\vec{r}$ . Here,  $P_1$  is taken as a *particular* path from  $\vec{r}_1$  to  $\vec{r}$ , randomly chosen, while  $P$  is any path with the same end points. Since the RHS is independent of what the path  $P$  is as long as its end points are  $\vec{r}_1$  and  $\vec{r}$ , we see that both sides are only dependent on the end points. Either side can be taken as  $U(\vec{r})$ .

<sup>2</sup> Recall from calculus that the definition of a line integral is an integral on a path (including a line, a curve, joined line segments, joined curve segments, etc.), *not* necessarily on a line.

<sup>3</sup>In this case, the force might still satisfy, at a *fixed* time,  $\vec{\nabla} \times \vec{F} = 0$ ! For example, consider  $F(\vec{r}) = -\hat{r}ae^{-\gamma t}/r^2$ , a gravitational force due to a hypothetical “dying star.” This is not a conservative force, even if  $\vec{\nabla} \times \vec{F} = 0$  at any *fixed* time  $t$ , since in physical motions  $t$  and  $\vec{r}$  are dependent on each other, and so  $\vec{\nabla} \times \vec{F} \neq 0$  if that dependence is taken into account.

### 3.1.4 Constant or integral of motion

The importance of conservation principles cannot be overemphasized. When a certain physical quantity is conserved, it means that there is a function  $f$ , or a set of such functions, of  $\vec{x}$  and  $\dot{\vec{x}}$ , which satisfies

$$f(\vec{x}, \dot{\vec{x}}) = \text{constant}$$

Here,  $f$  can be the energy function  $T + U$ , each/a component of the momentum function  $m\vec{v}$ , or each/a component of the angular momentum function  $m\vec{r} \times \vec{v}$ . Or, in general, it can be some other function (do a web search on Laplace-Runge-Lenz vector, for example). Each function  $f$  represents a conserved quantity, which is called a **constant of motion**, if the RHS of the above equation is emphasized, or an **integral of motion**, if the LHS of the above equation is emphasized.

1. **Constant of motion** We know that the general solution for Newton's equation should involve  $2M$  integration constants ( $M = \text{degrees of freedom}$ ). They correspond to the initial condition of position and velocity. A constant of motion due to a conservation principle is not any additional constant, but simply a function of those initial condition constants. Namely, one can re-express some of the initial condition constants in terms of constants of motion associated with conservation principles.

For instance, a uniform circular motion (centered at the origin) can be specified by giving the radius and the initial phase (the last lecture). Equivalently, it can be specified by giving the energy and the initial phase. Or, the angular momentum and the initial phase.

2. **Integral of motion** Each integral of motion  $f(\vec{x}, \dot{\vec{x}})$ , if found, means "one less integration to do" for solving Newton's equation. This is why it is called an integral of motion. To illustrate this point, consider the general form of Newton's equation in 2D.

$$\begin{aligned} m\ddot{x} &= F_x(x, y, \dot{x}, \dot{y}, t) \\ m\ddot{y} &= F_y(x, y, \dot{x}, \dot{y}, t) \end{aligned}$$

If there is a constant of motion,  $f(x, y, \dot{x}, \dot{y}) = \text{const}$ , we can solve for, say,  $\dot{x} = g(x, y, \dot{y})$ , where  $g$  is the result of inverting  $f(\dots) = \text{const}$ . Therefore, the above Newton's equation can be rewritten as

$$\begin{aligned} m \frac{d}{dt} g(x, y, \dot{y}) &= F_x(x, y, \dot{x}, \dot{y}, t) \\ m\ddot{y} &= F_y(x, y, \dot{x}, \dot{y}, t) \end{aligned}$$

Notice that the second derivative of  $x$  has completely disappeared, making it much easier to find an analytical solution, since we now have a first order differential equation for  $x$ , rather than a second order one. This is the meaning of “one less integration to do.”

If a sufficient number of integration constants are recognized first, a seemingly complicated problem can become easy to solve and understand. **In fact, the first question one should ask when given any physics problem is “what are the integrals of motion?”** because of this reason.

### 3.1.5 Example 2.11

A mouse jumps on a ceiling fan. Angular momentum conservation.  $L_0 = I\omega_0 = L = I\omega + mvR = \frac{v}{R}(I + mR^2)$ .  $\therefore \omega/\omega_0 = I/(I + mR^2)$ . Questions. Why is the angular momentum conserved in this problem? Why is the energy not conserved in this problem? What will happen if the (horizontal) ceiling fan was (vertical) windmill blades instead? Will the angular momentum conserved? Is the energy conserved during the collision? After the collision?

## 3.2 Stable or unstable equilibrium

If the potential satisfies  $\vec{\nabla}U(\vec{r}) = 0$  at a certain point in space, then it means that the force is zero. If a particle can be placed at such a point with zero velocity, then the particle will stay there forever. Such particle is said to be in **equilibrium**. An important physical question is whether such an equilibrium will be stable or not. If a small perturbation from the environment pushes the particle away from the equilibrium by an ever so tiny displacement, will the state be robust enough to come back to the equilibrium point (stable) or not (unstable)?

- If the potential is minimum, then it is a stable equilibrium. This is because, in the immediate vicinity of a minimum potential, the force points towards the minimum point.<sup>4</sup>
- If the potential is maximum, then it is an unstable equilibrium. This is because in the immediate vicinity of a maximum potential, the force points away from the maximum point.

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<sup>4</sup>  $\vec{\nabla}U(\vec{r})$  is the direction in which  $U$  increases the most, when a small displacement  $\vec{r} \rightarrow \vec{r} + d\vec{r}$  is considered with fixed  $|d\vec{r}|$ . So, near the minimum point  $\vec{\nabla}U$  points away from the minimum, and thus the force  $\vec{F} = -\vec{\nabla}U$  points towards the minimum point.

### 3.3. EXAMPLE 2.12

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- If the potential is neither maximum nor minimum (“saddle point”), then its stability is direction dependent. ~~A saddle point can occur only in dimensions higher than 1.~~

It follows that, in 1D, if the second derivative is positive, then it means a stable equilibrium. If negative, then an unstable equilibrium. If zero, then examine higher derivatives, or perhaps plot the potential, to figure out whether it is minimum or maximum.  
**or saddle point.**

### 3.3 Example 2.12

$$\begin{aligned}U &= -m_1 g x_1 - m_2 g (x_2 + c) \\x_2 &= \sqrt{(b - x_1)^2 / 4 - d^2} \\U &= -m_1 g x_1 - m_2 g \sqrt{(b - x_1)^2 / 4 - d^2} - m_2 g c \\dU/dx_1 &= -m_1 g - \frac{m_2 g (x_1 - b)}{4 \sqrt{\dots}}\end{aligned}$$

So, the equilibrium position is given by

$$\begin{aligned}4m_1 \sqrt{\dots} &= -m_2 (x_1 - b) \\16m_1^2 ((b - x_1)^2 / 4 - d^2) &= m_2^2 (x_1 - b)^2 && \text{square both sides.} \\(4m_1^2 - m_2^2)(x_1 - b)^2 &= 16m_1^2 d^2 \\x_1 &= b \pm \frac{4m_1 d}{\sqrt{(2m_1)^2 - m_2^2}}\end{aligned}$$

So, if  $2m_1 > m_2$ , then there will be an equilibrium. (You should verify this by solving the free body diagram also.) The physical solution is the one with the minus sign, since  $x_1$  can't be greater than  $b$ .

$$x_0 \stackrel{def}{=} (x_1)_{equilibrium} = b - \frac{4m_1 d}{\sqrt{(2m_1)^2 - m_2^2}}$$

Notice that  $-m_1 g x_1$  is a decreasing function of  $x_1$  while  $-m_2 g \sqrt{(b - x_1)^2 / 4 - d^2}$  is an increasing function of  $x_1$  in the physical range ( $0 < x_1 < b$ ). So,  $U(x_0)$  must be a

minimum, i.e.  $d^2U(x_0)/dx_0^2$  must be positive. Indeed,

$$\begin{aligned} d^2U/dx_1^2 &= -\frac{m_2g}{4\sqrt{\dots}} + \frac{m_2g}{16} \frac{(b-x_1)^2}{\sqrt[3]{\dots}} \\ &= \frac{m_2g}{16\sqrt[3]{\dots}} (-4[(b-x_1)^2/4 - d^2] + (b-x_1)^2) \\ &= \frac{m_2gd^2}{4\sqrt[3]{\dots}} \end{aligned}$$

Obviously, this is positive, but, for completeness: at  $x_1 = x_0$ , we get

$$\begin{aligned} d^2U/dx_1^2|_{x_0} &= \frac{m_2gd^2}{4\sqrt[3]{\frac{4m_1^2d^2}{(2m_1)^2 - m_2^2} - d^2}} \\ &= \frac{g\sqrt[3]{(2m_1)^2 - m_2^2}}{4m_2^2d} > 0 \end{aligned}$$

### 3.4 Example 2.13

$$\begin{aligned} U(x) &= -W \frac{d^2(x^2 + d^2)}{x^4 + 8d^4} \\ Z(y) \stackrel{\text{def}}{=} U(x)/W &= -\frac{y^2 + 1}{y^4 + 8} && y \stackrel{\text{def}}{=} x/d \\ dZ/dy &= -\frac{2y}{y^4 + 8} + \frac{(y^2 + 1)(4y^3)}{(y^4 + 8)^2} \\ &= \frac{4y^5 + 4y^3 - 2y(y^4 + 8)}{(y^4 + 8)^2} \\ &= \frac{2y^5 + 4y^3 - 16y}{(y^4 + 8)^2} \\ &= 2y \frac{y^4 + 2y^2 - 8}{(y^4 + 8)^2} \end{aligned}$$

The zeroes of this function are  $y = 0, \pm\sqrt{2}$ .  $Z(y)$  is an even function. Various limits are very useful to examine.

$$\begin{aligned} Z(y) &\approx -(1 + y^2)/8 && y \approx 0 \\ &\approx -1/y^2 && |y| \rightarrow \infty \end{aligned}$$

So, this is a “double well” potential, as shown in Figure 2-16 of the text. The  $y = 0$  is an unstable equilibrium ( $E = -W/8$ ). The two stable equilibrium points at

$x = \pm\sqrt{2}d$ . The turning points at energy  $-W/8$  is obtained by  $Z(y) = -1/8$ , which means

$$y^4 + 8 - 8y^2 - 8 = 0$$

So, we get  $x = \pm 2\sqrt{2}d, 0$ .

What is the period of the motion when  $E = -W/8$ ?

## 3.5 One dimensional motion

As we will see in this course, many problems become effectively one dimensional in certain ways, so it is worthwhile to summarize this simple case. We consider a 1D motion in the presence of a potential energy  $U(x)$ . Because the energy is then an integral of motion, the 2nd order equation becomes the 1st order equation, for which the formal solution can be written down with ease.



### Solution for 1D problems with $U(x)$

When a problem in 1D is described by a potential energy  $U(x)$ , its general solution can be written down as an integral.

$$\begin{aligned} E &= \frac{1}{2}mv^2 + U(x) = \text{constant} \\ v &= \pm\sqrt{\frac{2}{m}(E - U(x))} = \frac{dx}{dt} \\ \therefore t &= \pm\int_{x_0}^x dx' \sqrt{\frac{m}{2(E - U(x'))}} \end{aligned}$$

The last equation is the general solution of a 1D problem with the potential energy  $U(x)$ . The two integration constant symbols are  $E$  and  $x_0$ . The fact that the solution occurs in pair with a different overall sign of  $t$  ( $\pm$ ) means that, if  $x(t)$  is a solution, then its “time-reversed” solution  $x(-t)$  is also a solution.<sup>a</sup> For a periodic motion, it is redundant to keep the time-reversed solution, because reversing time is equivalent to shifting time (please convince yourself of this).

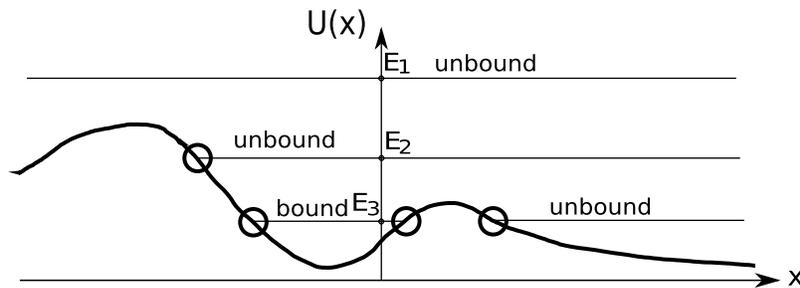
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<sup>a</sup> Therefore, this problem has the “time-reversal symmetry.” It comes from the fact that the EOM,  $md^2x/dt^2 = -dU(x)/dx$ , is invariant, when the sign of  $t$  is inverted.

For a given potential energy, the physical motion is possible only when

$$E \geq U(x)$$

(this is true in any dimensions, actually; it is because  $T = E - U \geq 0$ ). For a given energy value  $E$  and the initial position  $x_0$ , the motion can be **bound** or **unbound** depending on how many **turning points** are encountered as the  $x$  value is changed continuously from  $x_0$ . A bound motion has two turning points. An unbound motion has one or no turning point. However, a turning point occurring at an unstable equilibrium point (see next section) should be treated as an exception. The diagram below illustrates the turning points (centers of large circles). Note that a bound motion or an unbound motion can occur at the same energy (e.g.,  $E_3$ ).



**Any bound motion in 1D is a periodic motion.** The period is given by

$$T = 2 \int_{x_{t,1}}^{x_{t,2}} dx' \sqrt{\frac{m}{2(E - U(x'))}}$$

where  $x_{t,1}$  and  $x_{t,2}$  are the two turning points.

## 3.6 Simple harmonic oscillator

### 3.6.1 Free SHO

(This sub-section is repeated between Lecture Notes 3 and 4. In the old version (before Oct. 5), there were some missing  $A$ 's in the second page ( $x$  instead of  $x/A$ , and  $x = \cos(\omega t + \theta_0)$  instead of  $x = A \cos(\omega t + \theta_0)$  and so on). They are now corrected. Also, there are couple of comments added at the end.)

### 3.6. SIMPLE HARMONIC OSCILLATOR

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Near a stable equilibrium point, the potential usually shows a quadratic behavior, and a simple harmonic motion results.

This is the problem of a **small oscillation**. This is a ubiquitous phenomenon for all stable physical systems.

We will do a 1D case, here. Multi-dimensional cases and coupled oscillators will be picked up later.

We consider Hooke's law potential and force.

$$U(x) = \frac{1}{2}kx^2$$

$$F(x) = -kx$$

Any motion is a bound motion, and thus a periodic motion.  $E$  is conserved, and  $E \geq 0$  is required, since  $U \geq 0$  and  $E \geq U$ .

The solution is (choosing the negative sign for slight convenience),

$$\begin{aligned} t &= - \int dx \sqrt{\frac{m}{2(E - \frac{1}{2}kx^2)}} \\ &= -\frac{1}{\omega_0} \int dx \frac{1}{\sqrt{A^2 - x^2}} && \omega_0 \stackrel{def}{=} \sqrt{k/m}, \quad A \stackrel{def}{=} \sqrt{2E/k} \\ &= \frac{1}{\omega_0} (\cos^{-1}(x/A) - \cos^{-1}(x_0/A)) \\ &= \frac{1}{\omega_0} (\cos^{-1}(x/A) - \theta_0) \end{aligned}$$

Therefore, the solution is

$$\begin{aligned} x &= A \cos(\omega_0 t + \theta_0) \\ v &= -A\omega_0 \sin(\omega_0 t + \theta_0) \end{aligned}$$

You will notice that this solution is exactly the same form as the solution for the circular motion (last lecture, the last topic), if we make the substitution  $\omega_0 \rightarrow \omega_c$ ,  $A \rightarrow r$ , and  $-v/\omega_0 \rightarrow y$ . How so? First of all, note that the energy conservation equation is  $\frac{1}{2}mv^2 + \frac{1}{2}kx^2 = E$  or

$$x^2 + (v/\omega_0)^2 = A^2$$

This is a circle equation in the  $(X, Y)$  space, if we take  $X = x$  and  $Y = -v/\omega_0$ .

Also, the EOM is of identical nature. The equation of motion for the current problem is  $\ddot{x} = -\frac{k}{m}x$  or

$$\ddot{x} = -\omega_0^2 x$$

The equation of motion in the  $(X, Y)$  space is

$$\begin{aligned}\dot{X} &= \dot{x} = v = -\omega_0 Y \\ \dot{Y} &= -\dot{v}/\omega_0 = \omega_0 X\end{aligned}$$

If we differentiate one more time, we get

$$\begin{aligned}\ddot{X} &= -\omega_0 \dot{Y} \\ \ddot{Y} &= \omega_0 \dot{X}\end{aligned}$$

which has exactly the same form as before ( $a_x = -\omega_c v_y$  and  $a_y = \omega_c v_x$ ; see the last lecture).

**The motion of a simple harmonic oscillator with the coordinate  $x$  corresponds to a circular motion in the  $(x, -v/\omega_0)$  space.**

**Angular frequency**  $\omega_0 = \sqrt{k/m}$ . (**Natural frequency**)

**Amplitude**  $A$

**Phase**  $\theta = \omega_0 t + \theta_0$

**Period**  $T = 2\pi/\omega_0$

**Frequency**  $\nu = 1/T = \omega_0/2\pi$

The 2D SHO (section 3.3) is left for reading (Lissajous curve).

Couple of comments. First, the “amplitude” is defined as  $A$ , but occasionally, the whole thing  $x = A \cos(\omega t + \theta_0)$  is also called the amplitude.  $A$  as the amplitude distinguishes it from the phase ( $\theta$ ).  $x$  as the amplitude distinguishes it from the intensity ( $|x|^2$ ). Second, when it may cause confusion,  $T$  as the symbol for the period may be replaced by  $\tau$ .