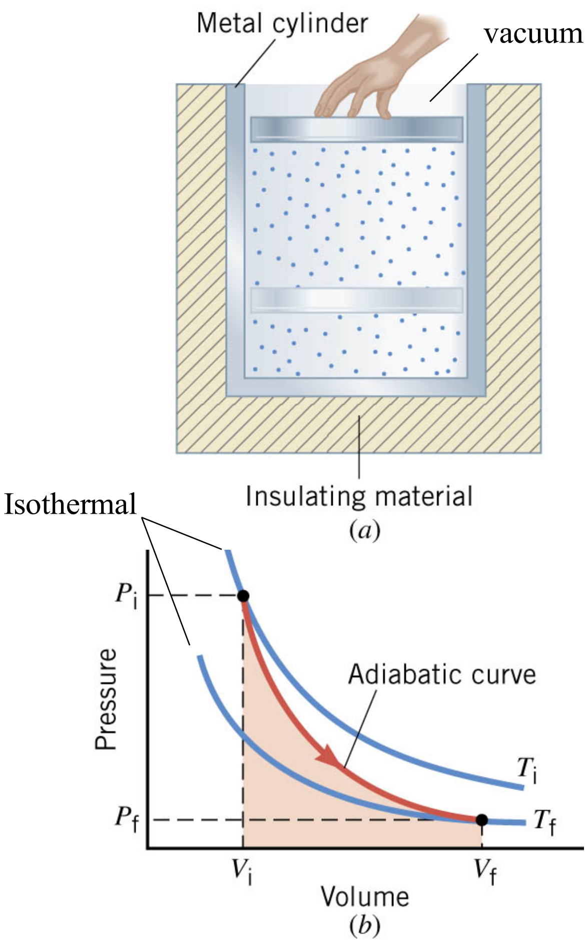
Chapter 14

Thermodynamics

Continued

14.2 Thermal Processes Using and Ideal Gas



ADIABATIC EXPANSION OR COMPRESSION

Adiabatic expansion or compression of a monatomic ideal gas

$$W_{\text{on gas}} = \tfrac{3}{2} nR\left(T_i - T_f\right)$$

Adiabatic expansion or compression of a monatomic ideal gas

$$P_i V_i^{\gamma} = P_f V_f^{\gamma}$$

$$\gamma = c_P / c_V$$

Ratio of heat capacity at constant P over heat capacity at constant V.

These are needed to understand basic operation of refrigerators and engines

ADIABATIC EXPANSION OR COMPRESSION

ISOTHERMAL EXPANSION OR COMPRESSION

14.2 Specific Heat Capacities

To relate heat and temperature change in solids and liquids (mass in kg), use:

$$\boxed{Q = mc\Delta T} \qquad \text{specific heat capacity, } c \; \left[\mathrm{J}/\left(\mathrm{kg}\cdot{}^\circ\mathrm{C}\right)\right]$$

For gases, the amount of gas is given in moles, use molar heat capacities:

$$\boxed{Q = nC\Delta T} \qquad \text{molar heat capacity, } C \; \left[\mathrm{J}/\left(\mathrm{mole}\cdot{}^\circ\mathrm{C}\right)\right]$$

$$\boxed{C = \left(m/n\right)c = m_u c; \quad m_u = \text{mass/mole (kg)}}$$

ALSO, for gases it is necessary to distinguish between the molar specific heat capacities at constant pressure and at constant volume:

$$C_P, C_V$$

14.2 Specific Heat Capacities

$$\boxed{\begin{array}{l}\text{Ideal Gas: } PV = nRT; \quad \Delta U = \tfrac{3}{2} nR\Delta T \\ \text{1st Law of Thermodynamics: } \Delta U = Q + W_{\text{on gas}}\end{array}}$$

Constant pressure for a monatomic ideal gas

$$\boxed{\begin{array}{l}\underline{\text{Constant Pressure } (\Delta P = 0)} \\ W_P = -P\Delta V = -nR\Delta T \\ Q_P = \Delta U - W = \tfrac{3}{2} nR\Delta T + nR\Delta T = \tfrac{5}{2} nR\Delta T\end{array}}$$

$$\boxed{\begin{array}{l}Q_P = nC_P\Delta T \\ C_P = \tfrac{5}{2} R\end{array}}$$

Constant volume for a monatomic ideal gas

$$\boxed{\begin{array}{l}\underline{\text{Constant Volume } (\Delta V = 0)} \\ W_V = -P\Delta V = 0 \\ Q_V = \Delta U - W = \tfrac{3}{2} nR\Delta T = \tfrac{3}{2} nR\Delta T\end{array}}$$

$$\boxed{\begin{array}{l}Q_V = nC_V\Delta T \\ C_V = \tfrac{3}{2} R\end{array}}$$

monatomic ideal gas

$$\boxed{\begin{array}{l}\gamma = C_P / C_V = \tfrac{5}{2} R / \tfrac{3}{2} R \\ \quad = 5/3\end{array}}$$

any ideal gas

$$\boxed{C_P - C_V = R}$$

14.3 The Second Law of Thermodynamics

The second law is a statement about the natural tendency of heat to flow from hot to cold, whereas the first law deals with energy conservation and focuses on both heat and work.

THE SECOND LAW OF THERMODYNAMICS: THE HEAT FLOW STATEMENT

Heat flows spontaneously from a substance at a higher temperature to a substance at a lower temperature and does not flow spontaneously in the reverse direction.

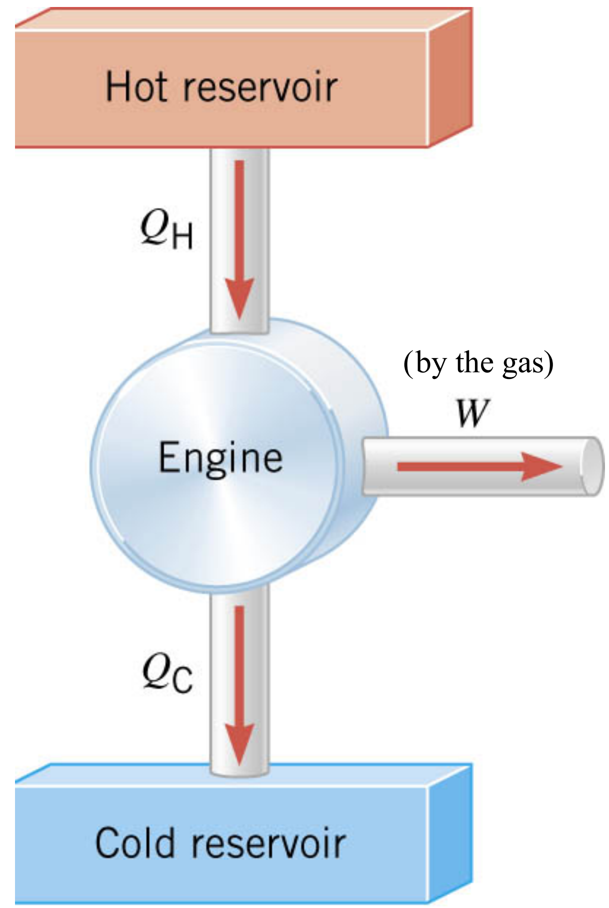
14.3 Heat Engines

A ***heat engine*** is any device that uses heat to perform work. It has three essential features.

1. Heat is supplied to the engine at a relatively high temperature from a place called the *hot reservoir.*

2. Part of the input heat is used to perform work by the *working substance* of the engine.

3. The remainder of the input heat is rejected to a place called the *cold reservoir.*



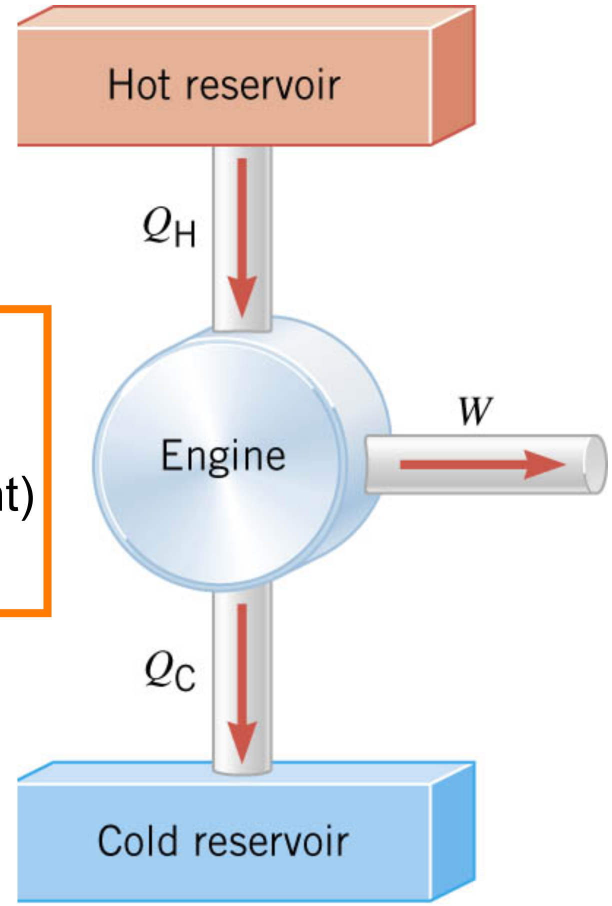
$$\left|Q_H\right| = \text{magnitude of input heat}$$

$$\left|Q_C\right| = \text{magnitude of rejected heat}$$

$$\left|W\right| = \text{magnitude of the work done}$$

Carnot Engine Working with an Ideal Gas

1. ISOTHERMAL EXPANSION ($Q_{in}=Q_H$, T_{Hot} constant)
2. ADIABATIC EXPANSION ($Q=0$, T drops to T_{Cold})
3. ISOTHERMAL COMPRESSION ($Q_{out}=Q_C$, T_{Cold} constant)
4. ADIABATIC COMPRESSION ($Q=0$, T rises to T_{Hot})



$$|Q_H| = \text{magnitude of input heat}$$

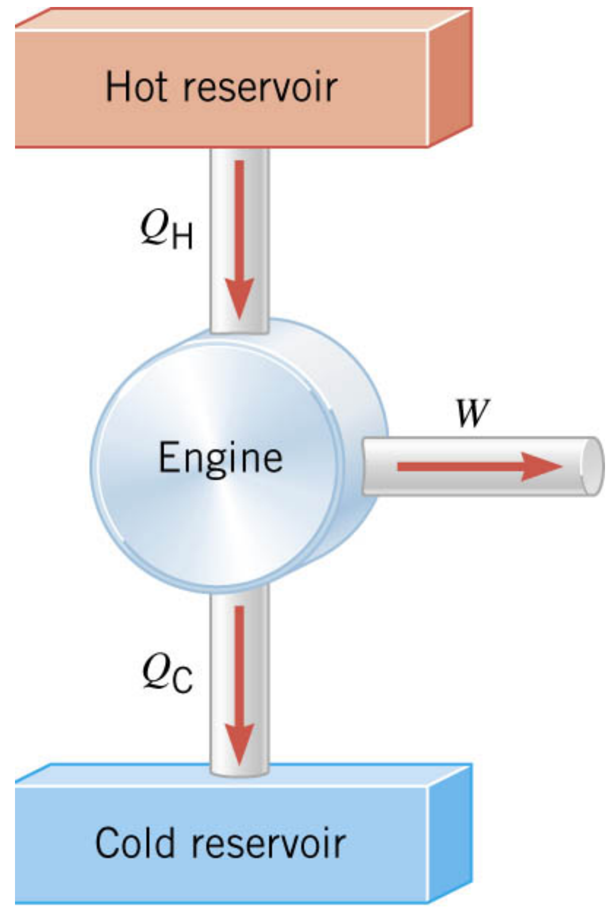
$$|Q_C| = \text{magnitude of rejected heat}$$

$$|W| = \text{magnitude of the work done}$$

14.3 Heat Engines

The ***efficiency*** of a heat engine is defined as the ratio of the work done to the input heat:

$$e = \frac{|W|}{|Q_H|}$$



If there are no other losses, then

$$|Q_H| = |W| + |Q_C|$$

$$\Downarrow$$

$$e = 1 - \frac{|Q_C|}{|Q_H|}$$

Example An Automobile Engine

An automobile engine has an efficiency of 22.0% and produces 2510 J of work. How much heat is rejected by the engine?

$$e = \frac{|W|}{|Q_H|}$$

$$= \frac{|W|}{|Q_C| + |W|} \quad \Rightarrow \quad e\left(|Q_C| + |W|\right) = |W|$$

$$|Q_C| = \frac{|W| - e|W|}{e} = |W|\left(\frac{1}{e} - 1\right) = 2510\,\mathrm{J}\left(\frac{1}{0.22} - 1\right)$$

$$= 8900\ \mathrm{J}$$

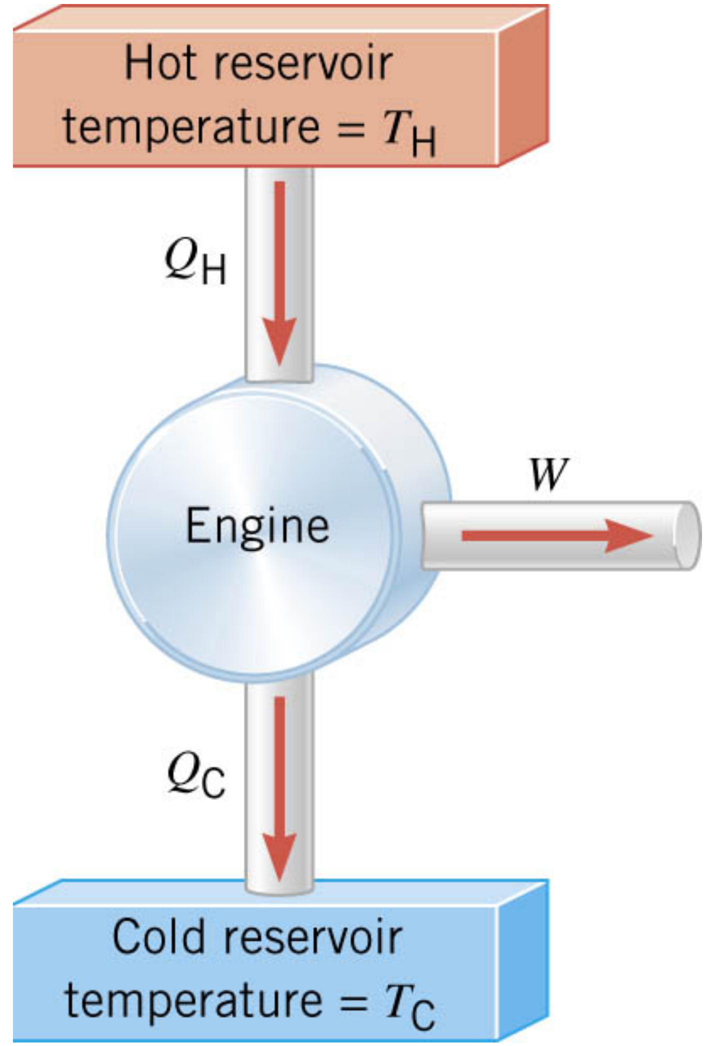
14.3 Carnot's Principle and the Carnot Engine

A reversible process is one in which both the system and the environment can be returned to exactly the states they were in before the process occurred.

CARNOT'S PRINCIPLE: AN ALTERNATIVE STATEMENT OF THE SECOND LAW OF THERMODYNAMICS

No irreversible engine operating between two reservoirs at constant temperatures can have a greater efficiency than a reversible engine operating between the same temperatures. Furthermore, all reversible engines operating between the same temperatures have the same efficiency.

14.3 Carnot's Principle and the Carnot Engine



The ***Carnot engine*** is useful as an idealized model.

All of the heat input originates from a single temperature, and all the rejected heat goes into a cold reservoir at a single temperature.

Since the efficiency can only depend on the reservoir temperatures, the ratio of heats can only depend on those temperatures.

$$e = 1 - \frac{|Q_C|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$

14.3 Carnot's Principle and the Carnot Engine

Example A Tropical Ocean as a Heat Engine

Surface temperature is 298.2 K, whereas 700 meters deep, the temperature is 280.2 K. Find the maximum efficiency for an engine operating between these two temperatures.

$$e_{\text{carnot}} = 1 - \frac{T_C}{T_H} = 1 - \frac{280.2\ \text{K}}{298.2\ \text{K}} = 0.060$$

Maximum of only 6% efficiency.
Real life will be worse.

Conceptual Example Natural Limits on the Efficiency of a Heat Engine

Consider a hypothetical engine that receives 1000 J of heat as input from a hot reservoir and delivers 1000J of work, rejecting no heat to a cold reservoir whose temperature is above 0 K. Decide whether this engine violates the first or second law of thermodynamics.

$$\text{If } T_H > T_C > 0$$

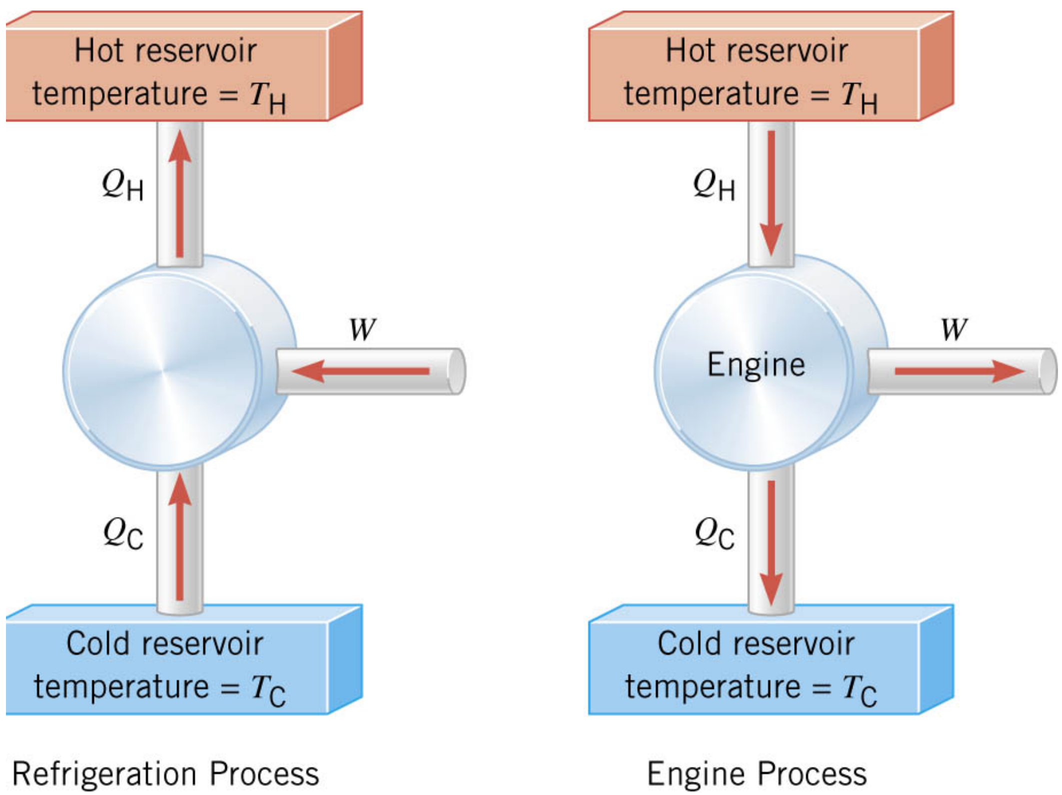
$$e_{\text{carnot}} = 1 - \frac{T_C}{T_H} \text{ must be less than 1}$$

$$e_{hypothetical} = \frac{|W|}{|Q_H|} = \frac{1000\,\text{J}}{1000\,\text{J}} = 1$$

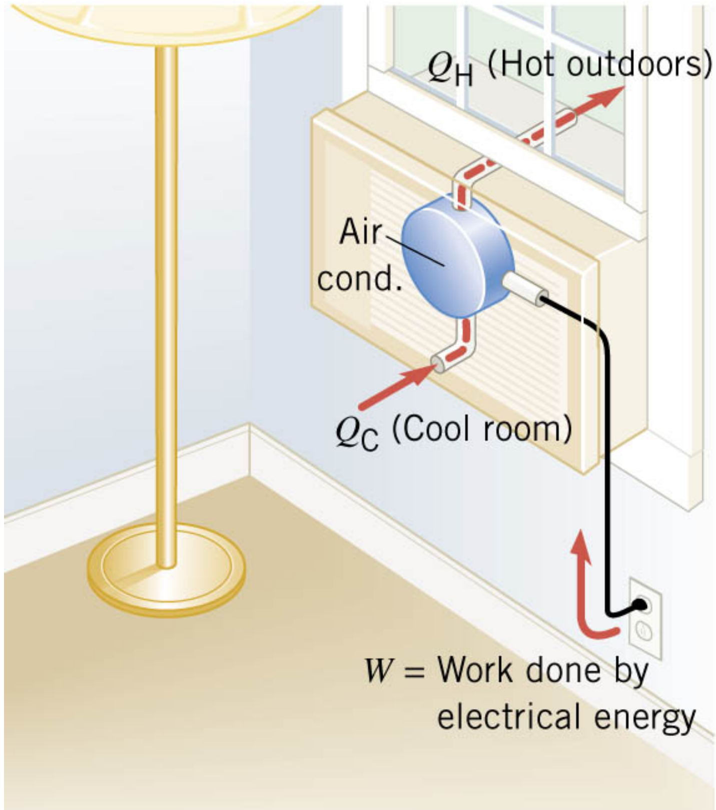
Violates 2nd law of thermodynamics

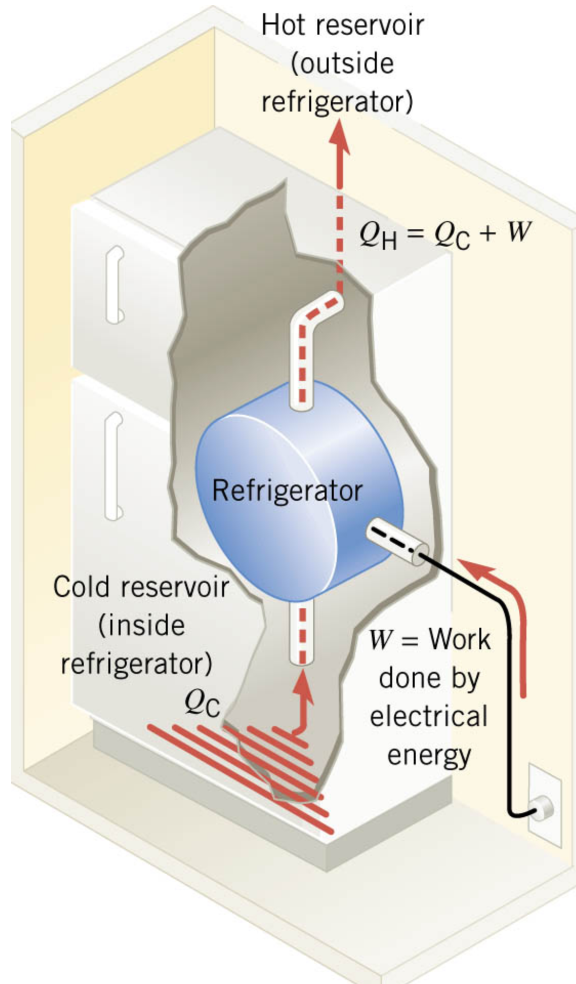
14.4 Refrigerators, Air Conditioners, and Heat Pumps

Refrigerators, air conditioners, and heat pumps are devices that make heat flow from cold to hot. This is called the ***refrigeration process***.



14.4 Refrigerators, Air Conditioners, and Heat Pumps





14.5 Entropy

In general, irreversible processes cause us to lose some, but not necessarily all, of the ability to do work. This partial loss can be expressed in terms of a concept called ***entropy***.

Carnot engine

$$\frac{|Q_C|}{|Q_H|} = \frac{T_C}{T_H} \quad \Longrightarrow \quad \frac{|Q_C|}{T_C} = \frac{|Q_H|}{T_H}$$

entropy change

$$\Delta S = \left(\frac{Q}{T}\right)_{\mathrm{R}}$$

reversible

14.3 Entropy

Entropy, like internal energy, is a function of the state of the system.

$$\Delta S = \left(\frac{Q}{T}\right)_{\mathrm{R}}$$

Consider the entropy change of a Carnot engine. The entropy of the hot reservoir decreases and the entropy of the cold reservoir increases.

$$\Delta S = +\frac{|Q_C|}{T_C} - \frac{|Q_H|}{T_H} = 0$$

Reversible processes do not alter the entropy of the universe.

Chapter 7

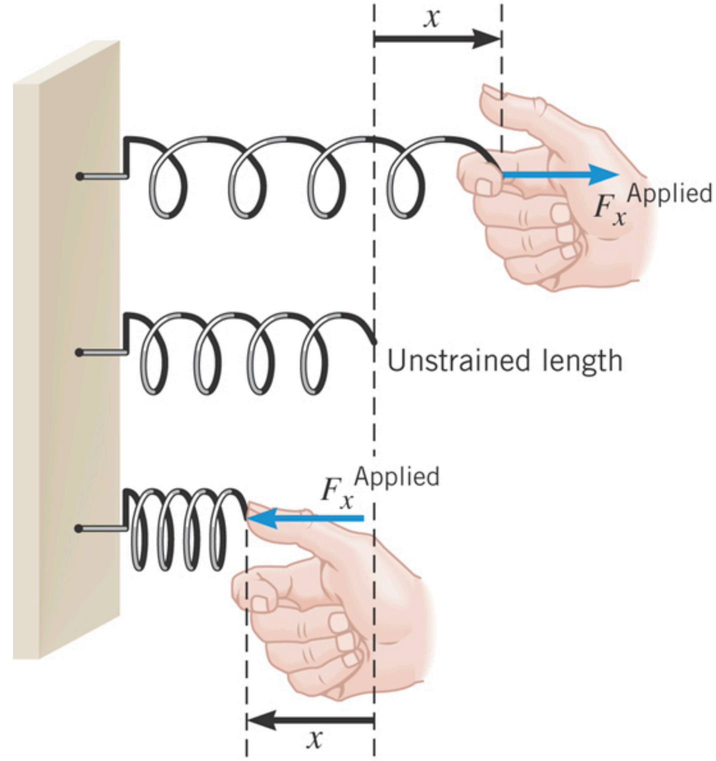
Simple Harmonic Motion

5.2 The Ideal Spring and Simple Harmonic Motion

$$F_x^{Applied} = kx$$

spring constant

Units: N/m

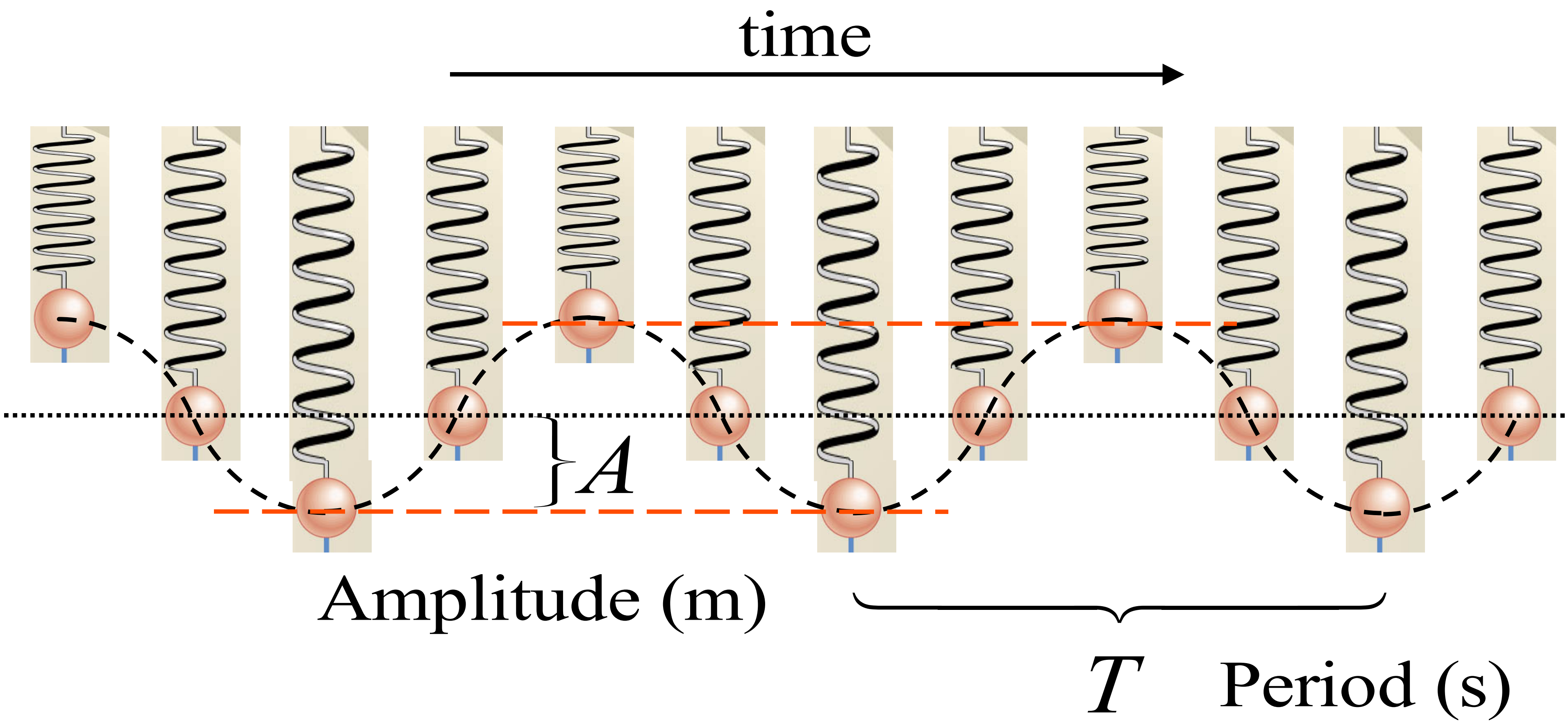


$F_x^{Applied}$ is the applied force in the x direction
x is the spring displacement
k is the spring constant (strength of the spring)

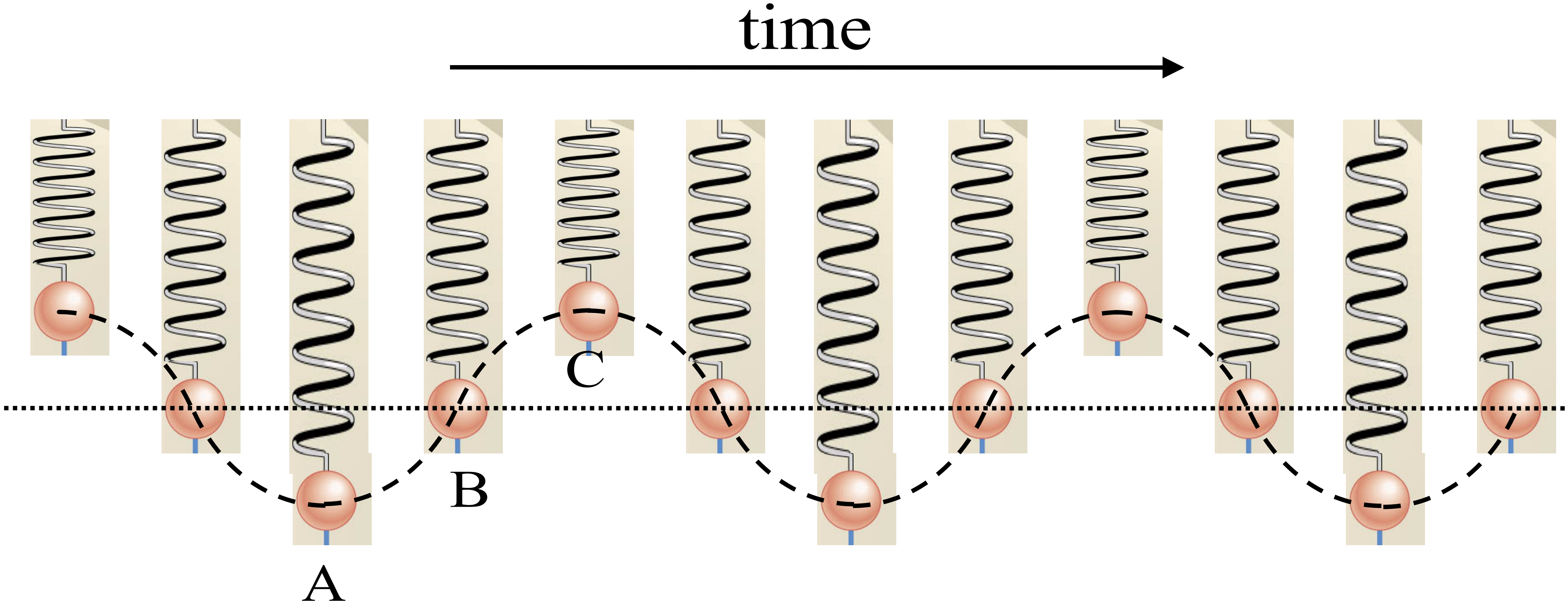
$$F_x^{Spring} = -kx$$

F_x^{Spring} is the spring's force in the x direction

Simple Harmonic Motion



Clicker Question 7.1



Where is the mass moving vertically at the highest speed?

A) only at A

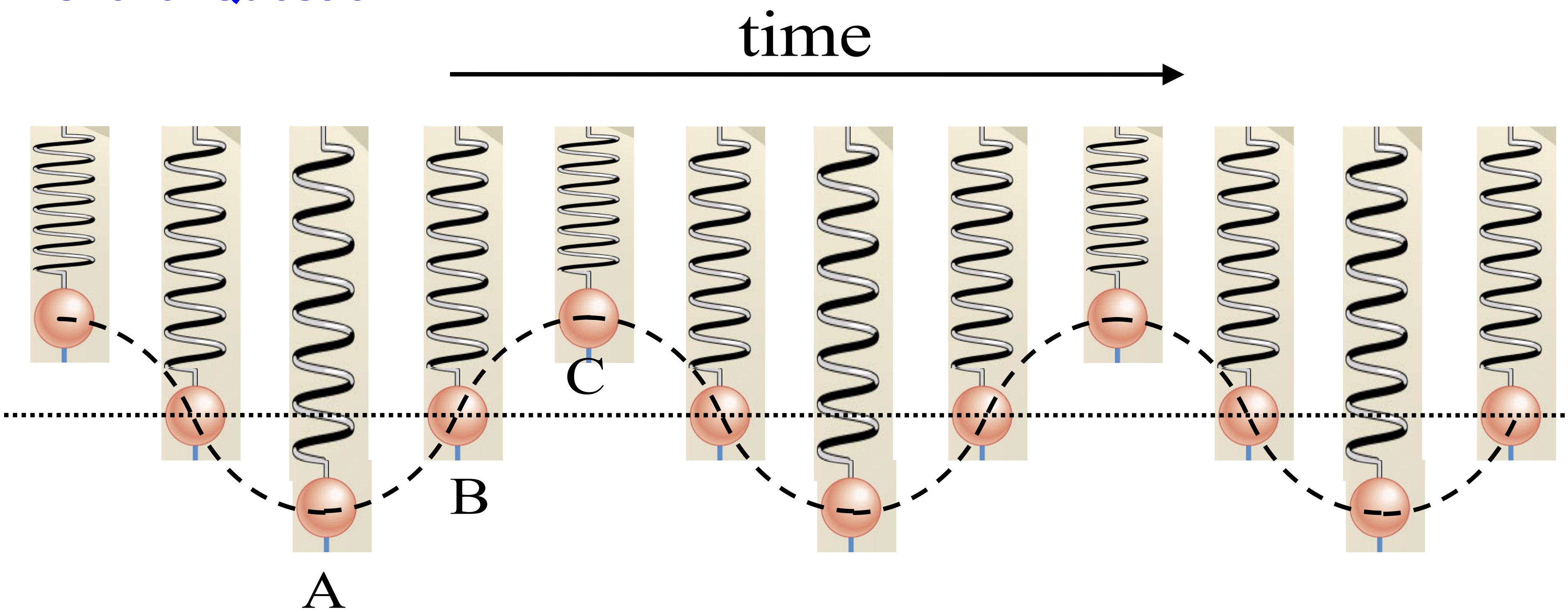
B) only at B

C) only at C

D) at both A and C

E) none of the above

Clicker Question 7.1



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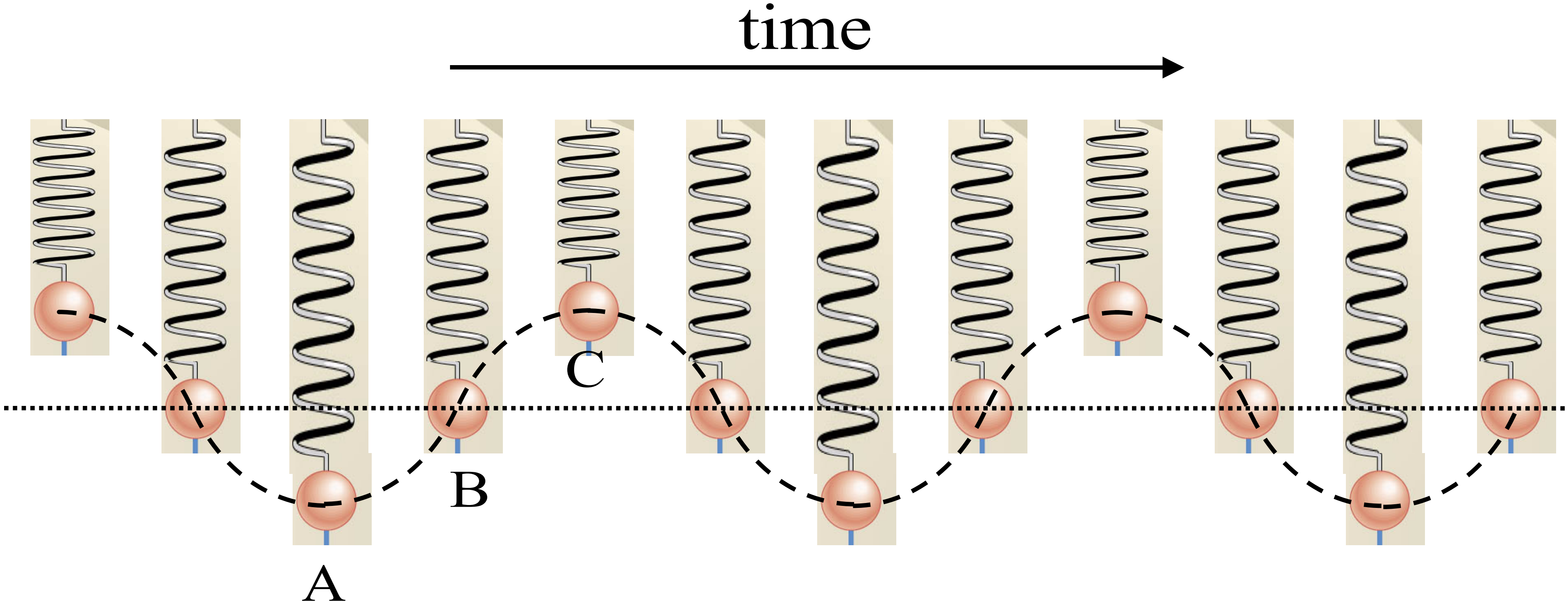
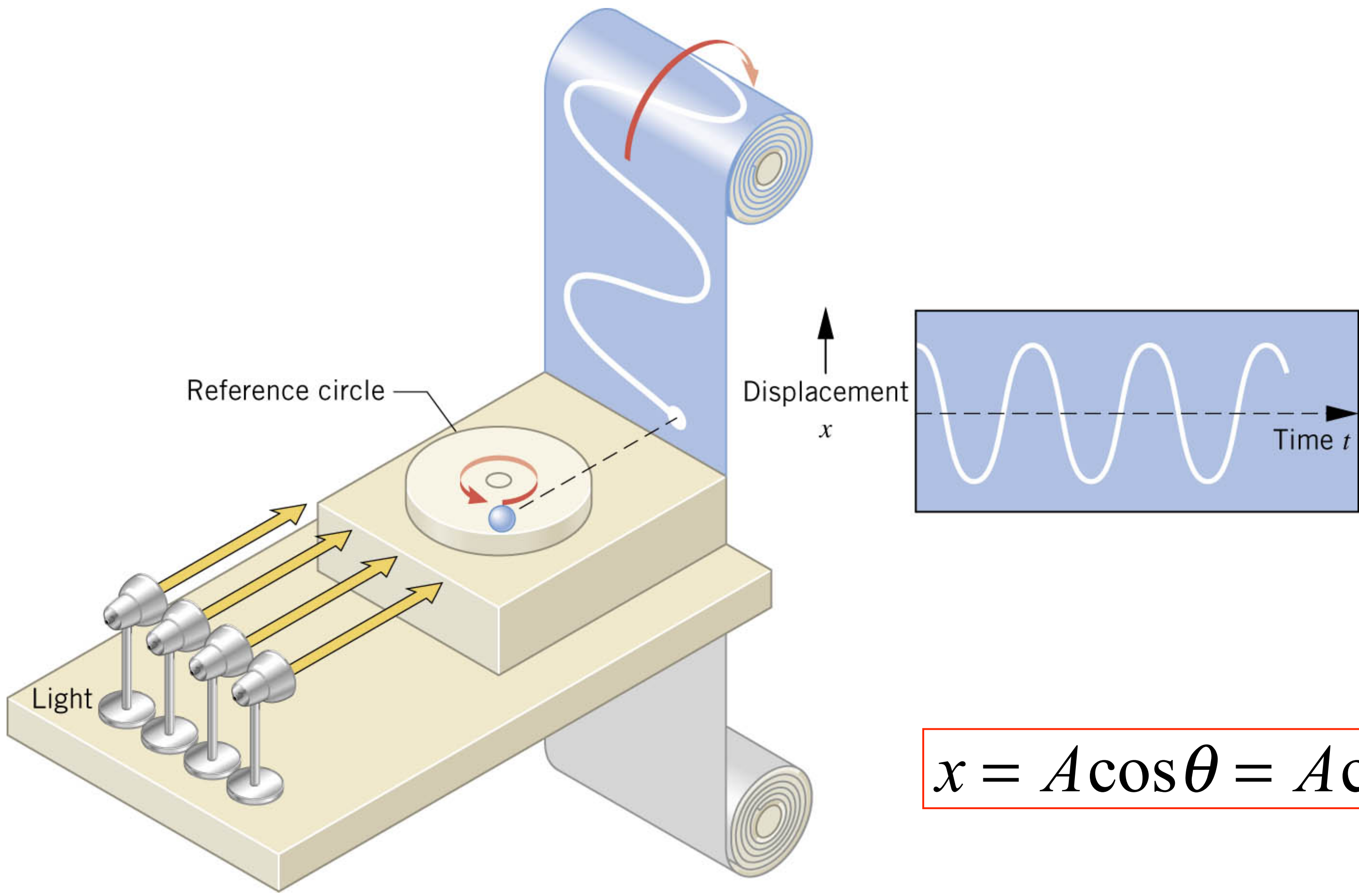


mass has the greatest magnitude of acceleration when
at points A and C - when it is turning around (speed is slowest)

acceleration vector is positive at point A and negative at C

mass has zero acceleration at point B - when speed is the greatest.

DISPLACEMENT

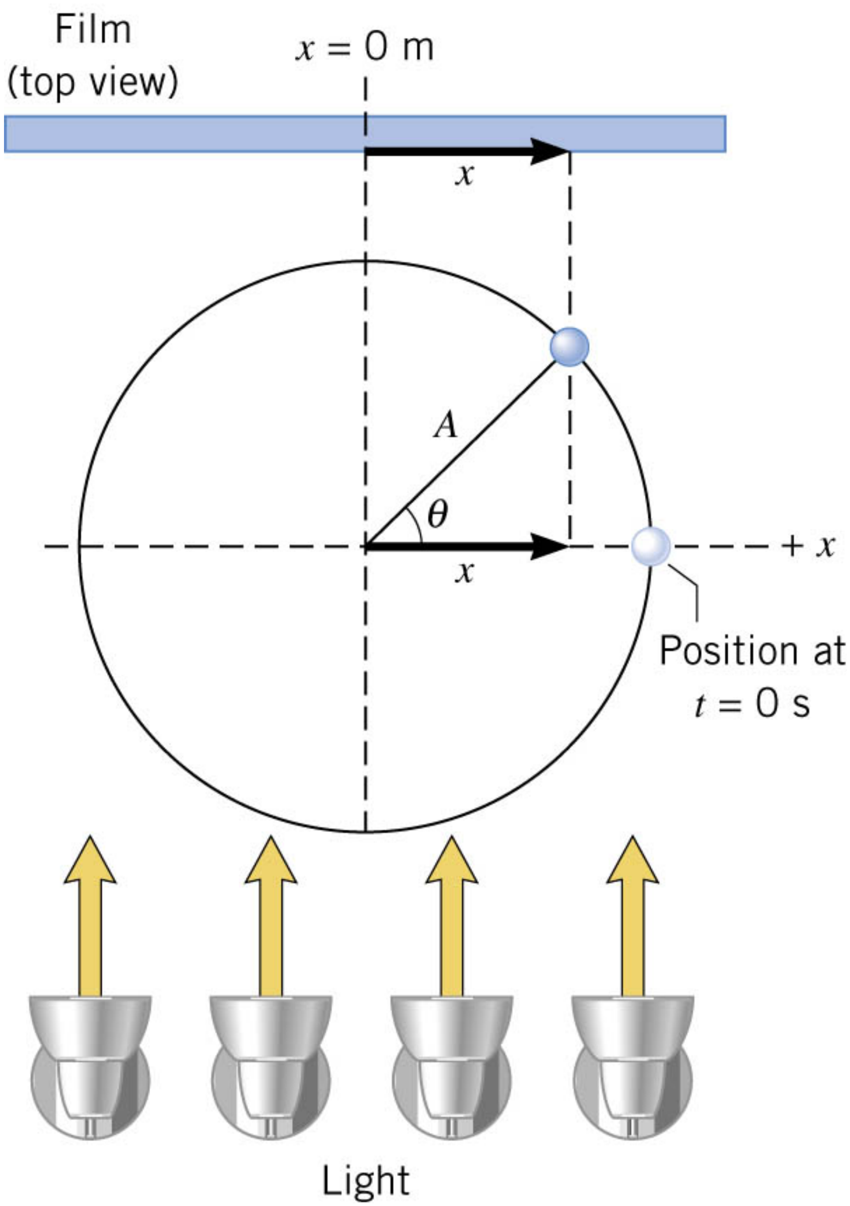


$$\boxed{x = A\cos\theta = A\cos\omega t}$$

Angular velocity, ω (unit: rad/s)

Angular displacement, $\theta = \omega t$ (unit: radians)

7.2 Simple Harmonic Motion and the Reference Circle



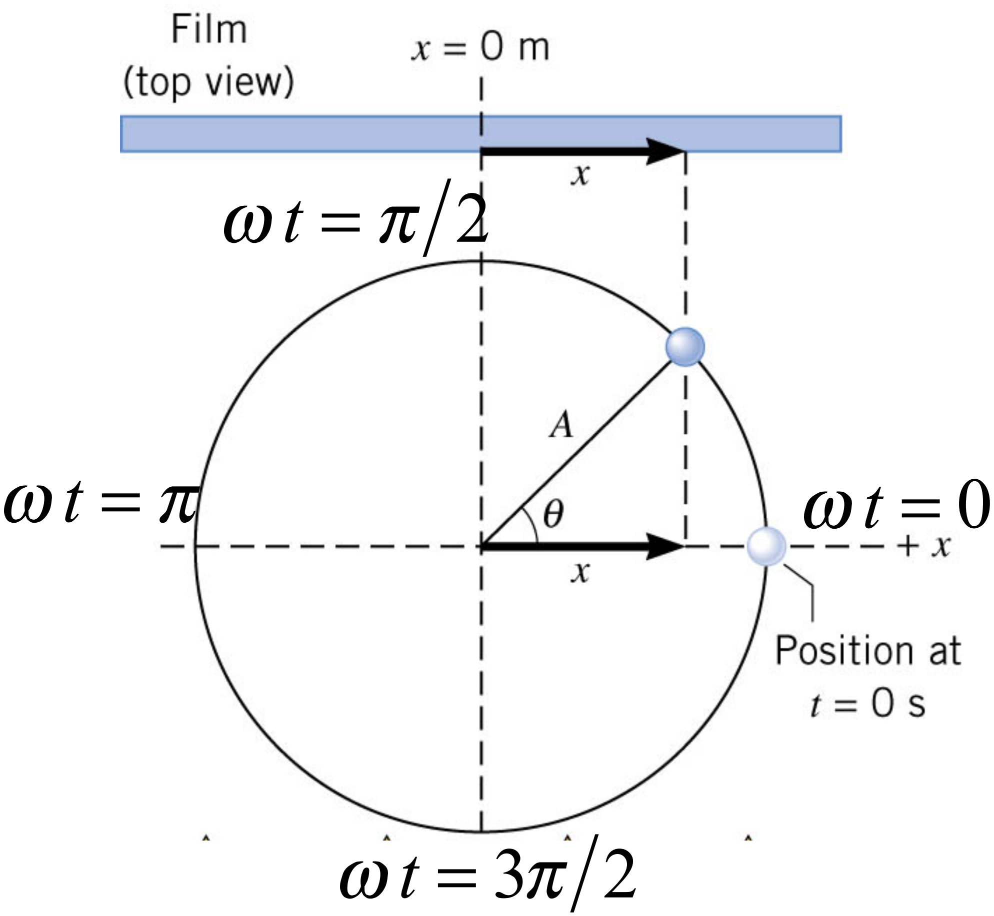
<u>uniform circular motion</u>

$$\theta = \omega t + \tfrac{1}{2}\alpha t^2 \text{ with } \alpha = 0$$

$$\theta = \omega t$$

$$\boxed{\begin{aligned} x &= A\cos\theta \\ &= A\cos(\omega t) \end{aligned}}$$

7.2 Simple Harmonic Motion and the Reference Circle



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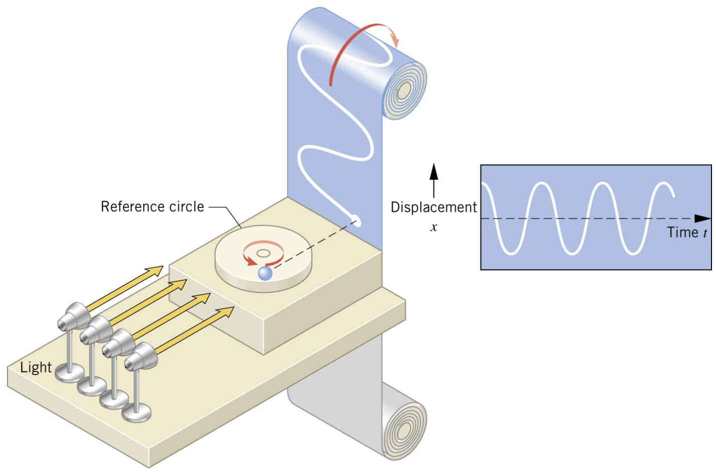
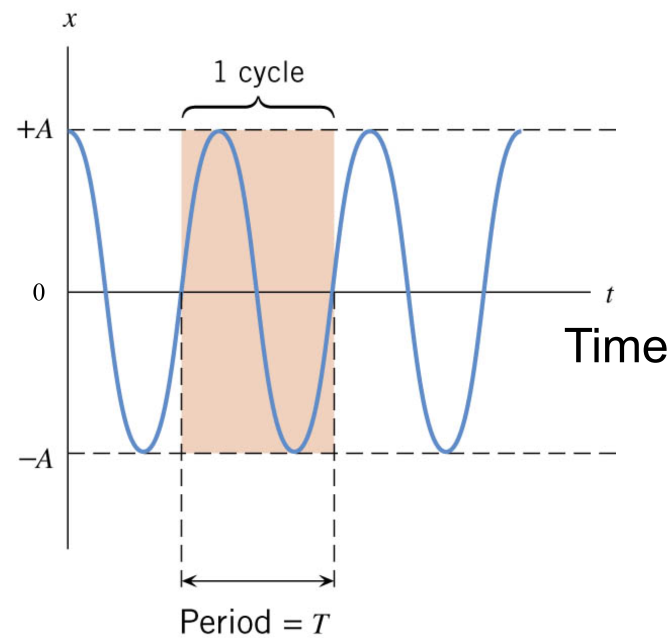
7.2 Simple Harmonic Motion and the Reference Circle



amplitude A:



amplitude A: the maximum displacement

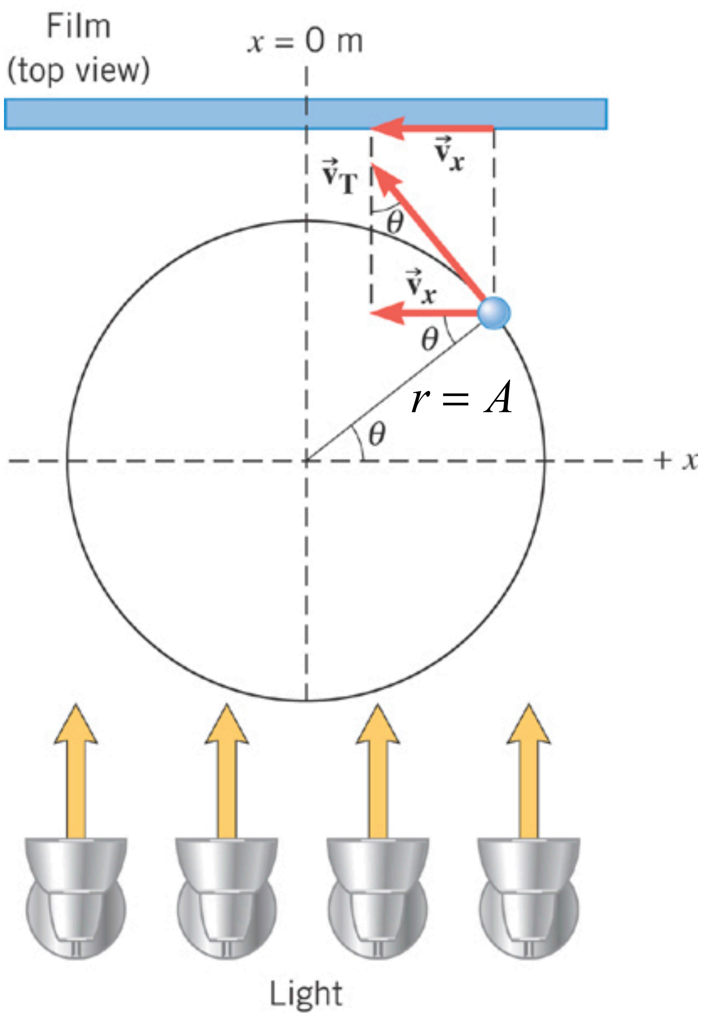
period T: the time required to complete one “cycle”

frequency f: the number of “cycles” per second (measured in Hz = 1/s)

frequency f: $\boxed{f = \dfrac{1}{T}}$

angular frequency: $\boxed{\omega = 2\pi f = \dfrac{2\pi}{T}}$ (Radians per second)

VELOCITY



Note: $\sin(\omega t)$

$$v_x = -v_T \sin\theta = -\underbrace{A\omega}_{v_{max}} \sin(\omega t)$$

Maximum velocity: $\mp A\omega$ (units, m/s)

$$\boxed{\begin{array}{l} v_x = -A\omega \sin(\omega t) = \mp A\omega \\ \text{when } \omega t = \pi/2,\ 3\pi/2 \text{ radians} \end{array}}$$

Maximum velocity occurs at

$$\boxed{\begin{aligned} x &= A\cos(\omega t) \\ &= A\cos(\pi/2) = 0 \end{aligned}}$$

Example The Maximum Speed of a Loudspeaker Diaphragm

The frequency of motion is 1.0 KHz and the amplitude is 0.20 mm.
(a) What is the maximum speed of the diaphragm?
(b) Where in the motion does this maximum speed occur?

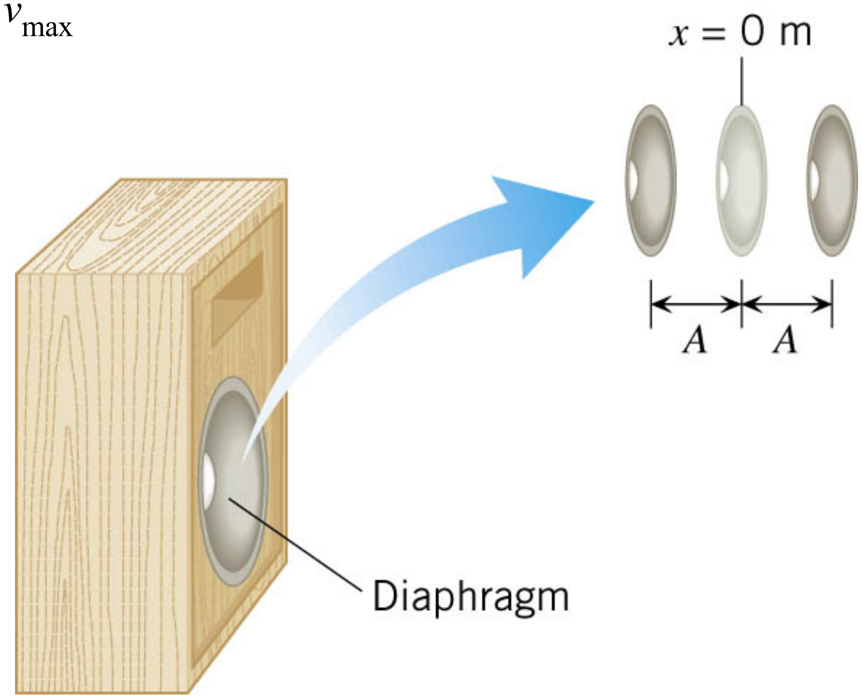
$$v_x = -v_T \sin\theta = -\underbrace{A\omega}_{v_{\max}} \sin\omega t$$

a) $v_{\max} = A\omega = A(2\pi f)$

$= (0.20\times10^{-3}\,\text{m})(2\pi)(1.0\times10^{3}\,\text{Hz})$

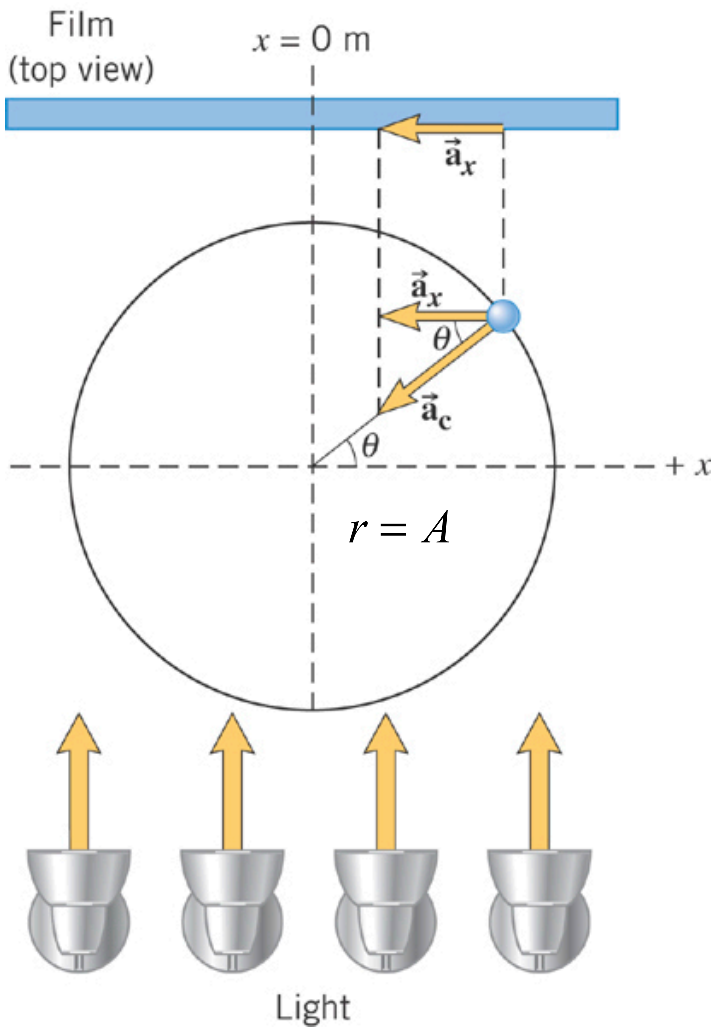
$= 1.3\,\text{m/s}$

b) The maximum speed occurs midway between the ends of its motion.



ACCELERATION

$$\boxed{a_c = \frac{v^2}{r} = r\omega^2}$$



$$a_x = -a_c \cos\theta = -\underbrace{A\omega^2}_{a_{\max}} \cos\omega t$$

Maximum a_x: $\mp A\omega^2$ (units, m/s^2)

$$\boxed{\begin{aligned} &a_x = -A\omega^2\cos(\omega t) = \mp A\omega^2 \\ &\text{when } \omega t = 0, \pi \text{ radians} \end{aligned}}$$

Maximum a_x occurs at

$$\boxed{\begin{aligned} x &= A\cos(\omega t) \\ &= A\cos(0) = A \\ &= A\cos(\pi) = -A \end{aligned}}$$

FREQUENCY OF VIBRATION

$$\sum F_x = ma_x$$

$$-kx = ma_x$$

$$x = A\cos\omega t$$

$$a_x = -A\omega^2\cos\omega t$$

$$-Ak\cos\omega t = -Am\omega^2\cos\omega t$$

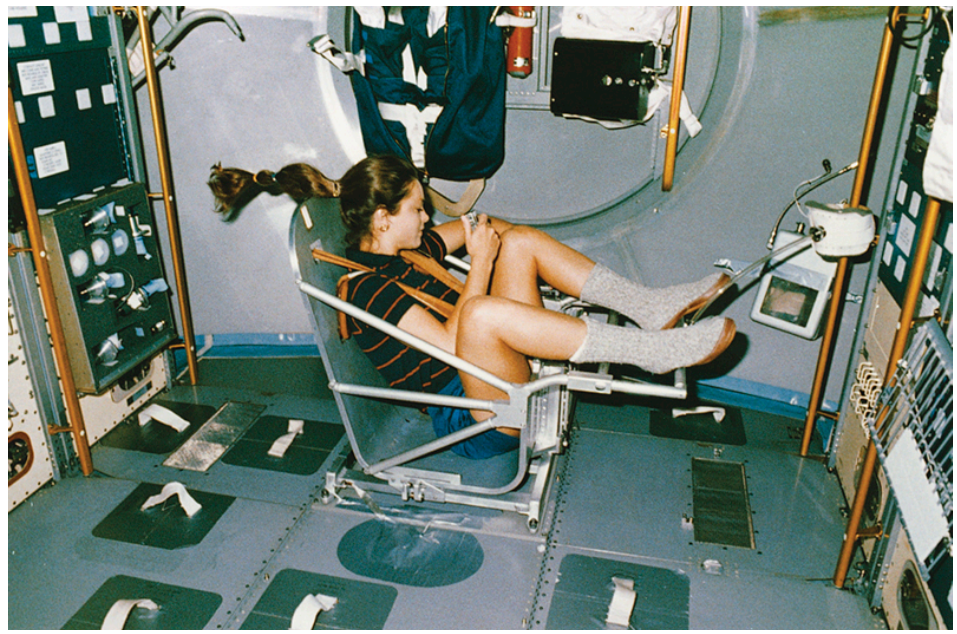
$$k = m\omega^2$$

$$\boxed{\omega = \sqrt{\frac{k}{m}}}$$

angular frequency for oscillations of a mass (m) on a spring (k)

Example A Body Mass Measurement Device

The device consists of a spring-mounted chair in which the astronaut sits. The spring has a spring constant of 606 N/m, and the mass of the chair is 12.0 kg. The measured period is 2.41 s. Find the mass of the astronaut.



spring constant: $k = 606\,\text{N/m}$

chair mass: $m_{\text{chair}} = 12.0\,\text{kg}$

oscillation period: $T = 2.41\,\text{s}$

$$\boxed{\omega = \sqrt{\frac{k}{m_{\text{total}}}}} \qquad \boxed{\omega = 2\pi f = \frac{2\pi}{T}}$$

$$m_{\text{total}} = \frac{k}{\omega^2} = \frac{kT^2}{4\pi^2} = 89.2\ \text{kg}$$

$$\boxed{m_{\text{astro}} = m_{\text{total}} - m_{\text{chair}} = 77.2\,\text{kg}}$$

Summary: spring constants & oscillations

Hooke's Law $\boxed{F_A = kx}$ Displacement proportional to applied force

Oscillations $\boxed{\omega = \sqrt{\dfrac{k}{m}}}$ Angular frequency $(\omega = 2\pi f = 2\pi/T)$

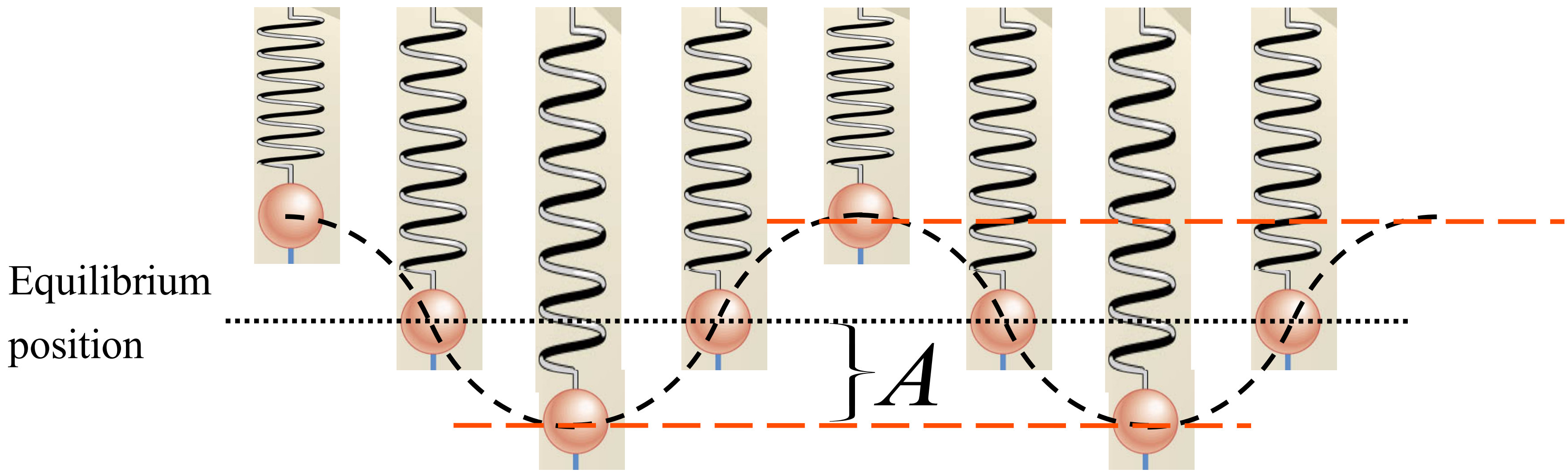
position: $\boxed{x = A\cos(\omega t)}$

velocity: $\boxed{v_x = -\underbrace{A\omega}_{v_{\max}}\sin(\omega t)}$

acceleration: $\boxed{a_x = -\underbrace{A\omega^2}_{a_{\max}}\cos\omega t}$

7.3 Energy in Simple Harmonic Motion

Consider this motion taking place far from the Earth



Speed maximum at equilibrium position

Energy all in kinetic energy: $E = \frac{1}{2}mv_{\max}^2 = \frac{1}{2}mA^2\omega^2$

At highest and lowest point energy is

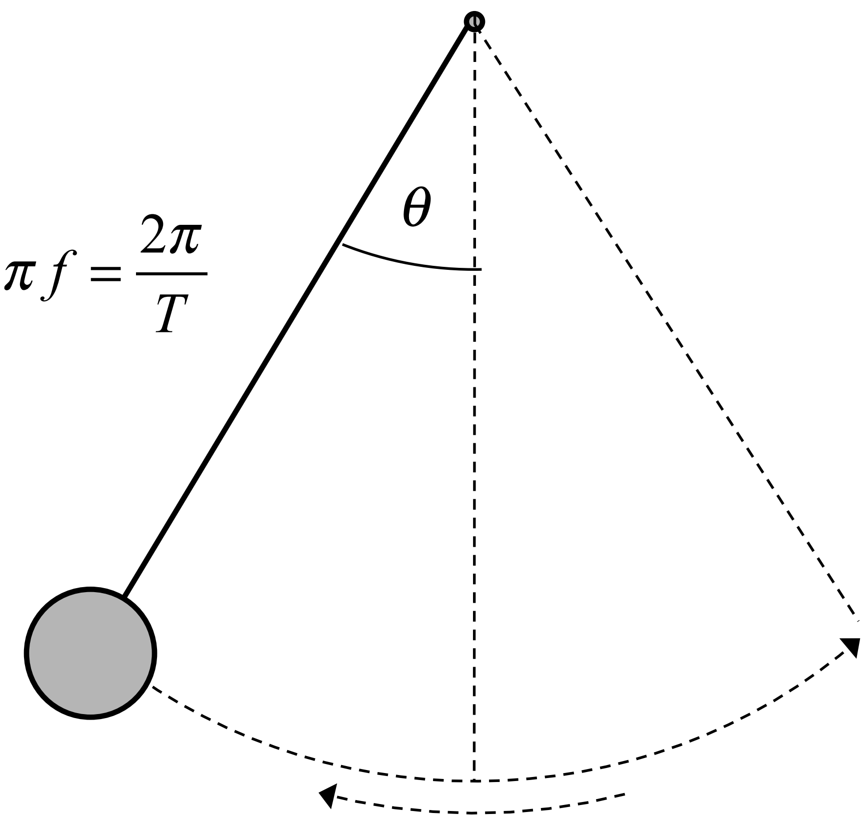
all in spring potential energy: $U_S = \frac{1}{2}kA^2 = E_{Total}$

At intermediate points total energy

$E_{Total} = \frac{1}{2}kA^2 = K + U_S = \frac{1}{2}mv^2 + \frac{1}{2}kx^2$

7.5 The Pendulum

A ***simple pendulum*** consists of a particle attached to a frictionless pivot by a cable of negligible mass.



<u>Angular frequency</u>

$$\omega = 2\pi f = \frac{2\pi}{T}$$

$$\omega = \sqrt{\frac{g}{L}} \quad \text{(small angles only)}$$

$$I = mL^2$$

$$\frac{1}{L} = \frac{mL}{I}$$

$$\omega = \sqrt{\frac{mgL}{I}} \quad \text{(small angles only)}$$

Works for objects with moment of inertia, I

and distance to center of mass, L_{CM}