

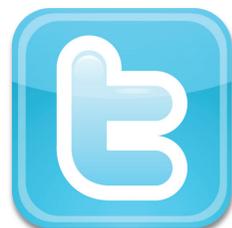
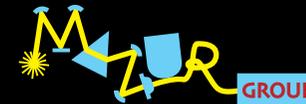
Teaching Physics, Conservation Laws First



Workshop for New Physics and Astronomy Faculty
College Park, MD, 19 November 2015



Teaching Physics, Conservation Laws First



@eric_mazur

Workshop for New Physics and Astronomy Faculty
College Park, MD, 19 November 2012



$F_d = -bv$ $x(t) = x_m e^{-\frac{b}{2m}t} \cos(\omega t + \theta)$ $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$ $E(t) \sim \frac{1}{2} k x_m^2 e^{-\frac{b}{m}t}$ $v(t) = \frac{1}{2} kx$ $E_{tot} = U$

$T = 2\pi \sqrt{\frac{L}{g}}$ simple pend $T = 2\pi \sqrt{\frac{I}{mgh}}$ physical pend $Y(x,t) = y_m \sin(kx - \omega t)$ wave in pos direction $w_d = \omega$ resonance

$x(t) = x_m \cos(\omega t + \theta)$ $v(t) = -\omega x_m \sin(\omega t + \theta)$ $a(t) = -\omega^2 x(t)$ $k = \frac{2\pi}{\lambda}$ $v = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f$ $v = \sqrt{\frac{T}{\mu}}$ $\mu = \frac{\text{mass}}{\text{length}}$ $P_{ave} = \frac{1}{2} \mu v \omega^2$

resonance $\lambda = \frac{2L}{n}$ $n=1,2,3$ $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n=1,2,3$ $V = \sqrt{\frac{B}{\rho}}$ bulk modulus $\Delta P_m = v \rho \omega S_m$ displacement $f_{beat} = |f_1 - f_2|$ $I = \frac{\text{Power}}{\text{Area}} = \frac{P_s}{4\pi r^2}$ $I = \frac{1}{2} \rho v \omega^2 S_m^2$ $\sin \theta = \frac{v}{v_s}$ $\frac{v_s}{v} = \text{mach \#}$

$\frac{\Delta L}{L} = 0, 2$ fully constructive $\theta = \frac{\Delta L}{\lambda} 2\pi$ $B = 3\alpha$ $Q = c \Delta T$ heat capacity $Q = c_m \Delta T$ specific heat $Q = L_m$ Heat of transformation $w = \int_{v_1}^{v_2} p dv$ $B = (10) \log \frac{I}{I_0}$ $\log \frac{x}{y} = \log x - \log y$ $\log_x x = y \Leftrightarrow x^y = x$

$\frac{\Delta L}{L} = 0.5, 1.5, 2.5$ fully destructive $\Delta L = L \alpha \Delta T$ $\Delta V = V \beta \Delta T$ $T_F = \frac{9}{5} T_C + 32$ $\Delta E_{int} = Q_{in} - W_{out}$ $P_{cond} = \frac{Q}{t} = k a \frac{T_h - T_c}{L}$ $R = \frac{L}{k}$ Multi Slab $P_{cond} = \frac{A (T_h - T_c)}{\sum L/k}$ $P_{radiation} = \sigma \epsilon A T^4$ $P_{net} = P_{abs} - P_{prod}$ $P_{abs} = \sigma \epsilon A T^4$

$n = \frac{\text{molecules}}{6.02 \times 10^{23}}$ $PV = nRT$ $Q=0$ $\Delta E = -W$ $P_{abs} = \sigma \epsilon A T^4$

Pipe 2 open ends displacement antinodes pressure nodes
 Pipe 1 open end displacement antinode at open, node at closed
 $I_0 = 1 \text{ x } 10^{-12} \text{ W/m}^2$

vectors

$F_d = -bv$ $x(t) = x_m e^{-\frac{bt}{2m}} \cos(\omega t + \theta)$ $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$ $E(t) \sim \frac{1}{2} k x_m^2 e^{-\frac{bt}{m}}$ $v(t) = \frac{1}{2} k x^2$ $E_{tot} = U$

$T = 2\pi \sqrt{\frac{L}{g}}$ simple pend $\omega_d = \omega$ resonance $\omega_d < \omega$ underdamped $b^2 < 4km$ $\omega_d > \omega$ overdamped $b^2 > 4km$

$T = 2\pi \sqrt{\frac{E}{mgh}}$ physical pend $Y(x,t) = y_m \sin(kx - \omega t)$ wave in pos direction $k = \frac{2\pi}{\lambda}$ $v = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f$ $v = \sqrt{\frac{T}{\mu}}$

$x(t) = x_m \cos(\omega t + \theta)$ $a(t) = -\omega^2 x(t)$ $v(t) = -\omega x_m \sin(\omega t + \theta)$ $v = \sqrt{\frac{E}{\rho}}$ Bulk modulus $\Delta P_m = v \rho \omega S_m$ displacement $f = \frac{v}{\lambda} = \frac{v}{2L}$ $n=1,2,3$ $f = \frac{v}{4L}$ ($n=1,2,3$) displacement antinode at open, node at closed

resonance $\lambda = \frac{2L}{n}$ $n=1,2,3$ $f = \frac{v}{\lambda} = \frac{v}{2L}$ $n=1,2,3$ $f = \frac{v}{4L}$ ($n=1,2,3$) $I = \frac{Power}{Area} = \frac{P_s}{4\pi r^2}$ $I = \frac{1}{2} \rho v \omega^2 S_m^2$ $\sin \theta = \frac{v}{v_s}$ $\frac{v_s}{v} = Mach \#$

interference $\frac{\Delta L}{\lambda} = 0, 1/2$ fully constructive $\theta = \frac{\Delta L}{\lambda} 2\pi$ $I = I_0 \cos^2 \theta$ $\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5$ fully destructive $B = 3\alpha$ $Q = C \Delta T$ Heat capacity $Q = C_m \Delta T$ specific heat $Q = L_m$ Heat of transformation $W = \int_{v_i}^{v_f} p dv$ $B = (10) \log \frac{I}{I_0}$ $\log \frac{x}{y} = \log x - \log y$ $\log_0 x = y \Leftrightarrow 0^y = x$

$T_F = \frac{9}{5} T_C + 32$ $\Delta L = L \alpha \Delta T$ $\Delta V = V \beta \Delta T$ $\Delta E_{int} = Q_{in} - W_{out}$ $P_{cond} = \frac{Q}{t} = k \alpha \frac{T_h - T_c}{L}$ $R = \frac{L}{k}$ Multi Slab $P_{cond} = \frac{A (T_h - T_c)}{\sum L/k}$ $P_{radiation} = \sigma \epsilon A T^4$ $P_{net} = P_{obs} - P_{rad}$ $P_{abs} = \sigma \epsilon A T^4$

$n = \frac{molecules}{6.02 \times 10^{23}}$ Adiabatic $Q=0$ $\Delta E = -W$ $PV = nRT$ $P_1 V_1^\gamma = P_2 V_2^\gamma$

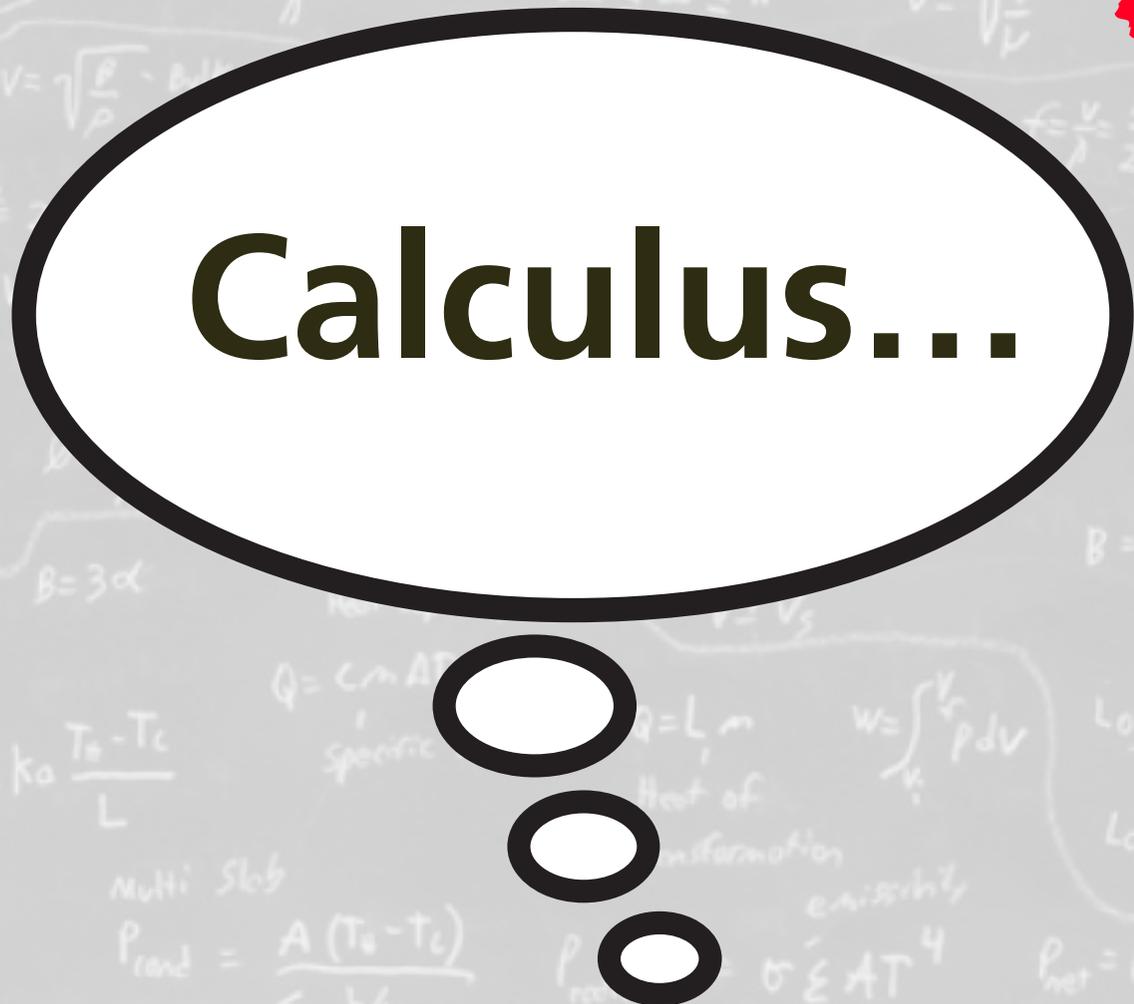
Kinematics

Vectors

$F_d = -bv$
 $x(t) = x_m e^{-\frac{bt}{2m}} \cos(\omega t + \theta)$
 $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$
 $E(t) \sim \frac{1}{2} k x_m^2 e^{-\frac{bt}{m}}$
 $T = 2\pi \sqrt{\frac{L}{g}}$ simple pend
 $T = 2\pi \sqrt{\frac{I}{\tau}}$ physical pend
 $x(t) = x_m \cos(kx - \omega t)$
 $k = \frac{2\pi}{\lambda}$
 $\omega = \frac{2\pi}{T}$
 $v = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f$
 $v = \sqrt{\frac{\tau}{\mu}}$
 $\lambda = \frac{2L}{n}$ $n=1,2,3$
 $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n=1,2,3$
 $v = \sqrt{\frac{E}{\rho}}$ Bulk modulus
 $\Delta P_m = v \rho \omega S_m$ displacement
 $I = \frac{\text{Power}}{\text{Area}} = \frac{P_s}{4\pi r^2}$
 $I = \frac{1}{2} \rho v \omega^2 S_m^2$
 $\sin \theta = \frac{v}{v_s}$ $\frac{v_s}{v} = \text{mach \#}$
 $\frac{\Delta L}{L} = 0, 1/2$ fully constructive
 $\frac{\Delta L}{L} = 0.5, 1.5, 2.5$ fully destructive
 $\Delta L = L \alpha \Delta T$
 $\Delta V = V \beta \Delta T$
 $T_F = \frac{9}{5} T_C + 32$
 $\Delta E_{int} = Q_{in} - W_{out}$
 $P_{cond} = \frac{Q}{t} = k \alpha \frac{T_h - T_c}{L}$
 $R = \frac{L}{k}$
 $n = \frac{\text{molecules}}{6.02 \times 10^{23}}$
 $PV = nRT$
 $Q = 0$ $\Delta E = -W$
 $Q = C \Delta T$ Heat capacity
 $Q = Cm \Delta T$ specific heat
 $Q = L_m$ Heat of transformation
 $W = \int_{V_i}^{V_f} P dV$
 $P_{radiation} = \sigma \epsilon AT^4$
 $S_b T_{10}^{-8} \frac{w}{m^2}$
 $P_{net} = P_{obs} - P_{prod}$
 $P_{abs} = \sigma \epsilon AT^4$
 $B = (10) \log \frac{I}{I_0}$
 $\log \frac{x}{y} = \log x - \log y$
 $\log_0 x = y \Leftrightarrow 0^y = x$
 $I_0 = 1 \text{ W/m}^2$
 $\text{critical damp } b^2 = 4km$
 $\text{over damped } b^2 < 4km$
 $\text{under damped } b^2 > 4km$
 $\omega_d = \omega$ resonance
 $y_m \sin(kx - \omega t)$ wave in pos direction
 $P_{ave} = \frac{1}{2} v \rho \omega^2 S_m^2$
 $f = \frac{v}{\lambda}$ $n=1,2,3$ displacement antinode
 $f = \frac{nv}{4L}$ $(n=1,2,3)$ displacement antinode at open, node at closed

kinematics

vectors



Calculus...

kinematics

vectors

$$\vec{F} = m\vec{a}$$

momentum

collisions

kinematics

vectors

work

$$\vec{F} = m\vec{a}$$

momentum

collisions

kinematics

energy

vectors

work

$$\vec{F} = m\vec{a}$$

momentum

collisions

kinematics

energy

vectors

work

$$\vec{F} = m\vec{a}$$

momentum

collisions

Background physics notes:

- $F_d = -bv$
- $x(t) = x_m e^{-\frac{bt}{2m}} \cos(\omega t + \theta)$
- $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$
- $E(t) \sim \frac{1}{2} k x_m^2 e^{-\frac{bt}{m}}$
- $T = 2\pi \sqrt{\frac{L}{g}}$ simple pend
- $T = 2\pi \sqrt{\frac{I}{\tau}}$ physical pend
- $x(t) = x_m \cos(\omega t + \phi)$
- $v = \frac{dx}{dt} = -\omega x_m \sin(\omega t + \phi)$
- $k = \frac{2\pi}{\lambda}$
- $\lambda = \frac{2L}{n}$ $n=1,2,3$
- $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n=1,2,3$
- $f = \frac{nv}{4L}$ ($n=1,2,3$)
- $\frac{\Delta L}{L} = 0.5, 1.5, 2.5$ fully destructive
- $\Delta L = L\alpha \Delta T$
- $\Delta V = V\beta \Delta T$
- $T_F = \frac{9}{5} T_C + 32$
- $\Delta E_{int} = Q_{in} - W_{out}$
- $n = \frac{\text{molecules}}{6.02 \times 10^{23}}$
- $R = \frac{L}{k}$
- $P_{cond} = \frac{A(T_h - T_c)}{\sum L/k}$
- $P_{rad} = \sigma \epsilon A T^4$
- $P_{net} = P_{obs} - P_{rad}$
- $P_{abs} = \sigma \epsilon A T^4$
- $Q = L_m$
- $Q = c \Delta T$
- $B = (10) \log \frac{I}{I_0}$
- $f = f \frac{v \pm v_d}{v \pm v_s}$
- $f = \frac{v}{\lambda}$
- $f = \frac{nv}{2L}$
- $f = \frac{nv}{4L}$ ($n=1,2,3$)
- $v_s = \text{mach } \#$
- $I_0 = 1 \text{ W/m}^2$
- $\log_0 x = y \Leftrightarrow 0^y = x$
- $P_{net} = P_{obs} - P_{rad}$
- $P_{abs} = \sigma \epsilon A T^4$
- $S_b T_{eq} = 8 \frac{w}{\dots}$
- $P_{obs} = \sigma \epsilon A T^4$

energy

$$\vec{F} = m\vec{a}$$

momentum

collisions

kinematics

$F_d = -bv$
 $x(t) = x_m e^{-\frac{bt}{2m}} \cos(\omega t + \theta)$
 $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$
 $E(t) \sim \frac{1}{2} k x_m^2 e^{-\frac{bt}{m}}$

$T = 2\pi \sqrt{\frac{L}{g}}$ simple pend

$F = 2\pi \sqrt{\frac{E}{mgh}}$ physical pend

$y(t) = y_m \sin(kx - \omega t)$ wave in pos direction

$x(t) = x_m \cos(\omega t + \theta)$
 $v(t) = -\omega x_m \sin(\omega t + \theta)$
 $a(t) = -\omega^2 x(t)$

$w_d = \omega$ resonance

critical damp $b^2 = 4km$
under damped $b^2 < 4km$
over damped $b^2 > 4km$

$v = \sqrt{\frac{T}{\mu}}$
 $f = \frac{v}{\lambda} = \frac{v}{2L}$
 $f = \frac{v}{4L}$ ($n = 1, 2, 3$)

resonance $\lambda = \frac{2L}{n}$ $n = 1, 2, 3$
 $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n = 1, 2, 3$

$v = \sqrt{\frac{E}{\rho}}$ bulk modulus

$\Delta P_m = v \rho \omega S_m$ displacement

$f_{beat} = |f_1 - f_2|$

$f = \frac{nv}{4L}$ ($n = 1, 2, 3$)

pipe 2 open ends
displacement antinodes
pressure node

pipe 1 open end
displacement antinode
at open, node at closed

$I = \frac{1}{2} \rho v \omega^2 S_m^2$

$\frac{\Delta L}{L} = 0.5, 2$ fully constructive

$\frac{\Delta L}{L} = 0.5, 1.5, 2.5$ fully destructive

$B = 3 \text{ dB}$

$Q = c \Delta T$

$f = f \frac{v_1 + v_2}{v_1}$

$B = (10) \log \frac{I}{I_0}$

$\Delta E_{int} = Q_{in} - W_{out}$
 $P_{cond} = \frac{Q}{t} = k a \frac{T_h - T_c}{L}$

specific heat

Heat of transformation

$\log_2 x = y \Leftrightarrow 2^y = x$

$\log_3 x = y \Leftrightarrow 3^y = x$

Multi Slab
 $P_{cond} = \frac{A (T_h - T_c)}{\sum L/k}$

$P_{radiation} = \sigma \epsilon A T^4$

$P_{net} = P_{obs} - P_{prod}$

$P_{abs} = \sigma \epsilon A T^4$

$n = \frac{\text{molecules}}{6.02 \times 10^{23}}$

$R = \frac{L}{k}$

Adiabatic $Q = 0$ $\Delta E = -W$ $PV = nRT$

conservation of energy

conservation of momentum

$$\vec{F} = m\vec{a}$$

conservation of energy

Just algebra!

conservation of momentum

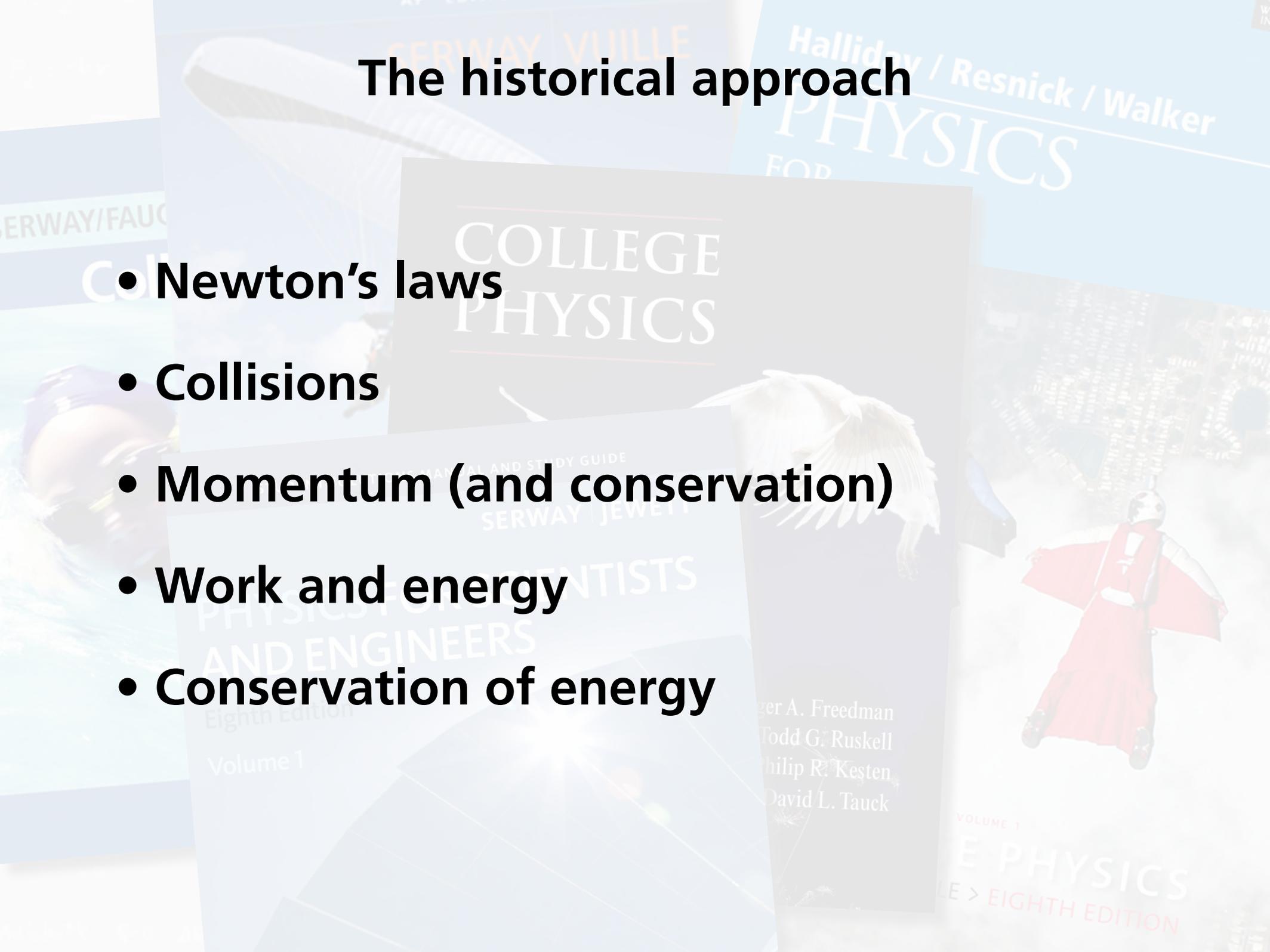
conservation of energy

Why not START
the easy way?

conservation of momentum

The historical approach

- Newton's laws
- Collisions
- Momentum (and conservation)
- Work and energy
- Conservation of energy



Ernst Mach (1838–1916)

- Collisions
- Conservation of momentum
- Newton's laws
- Work and energy
- Conservation of energy

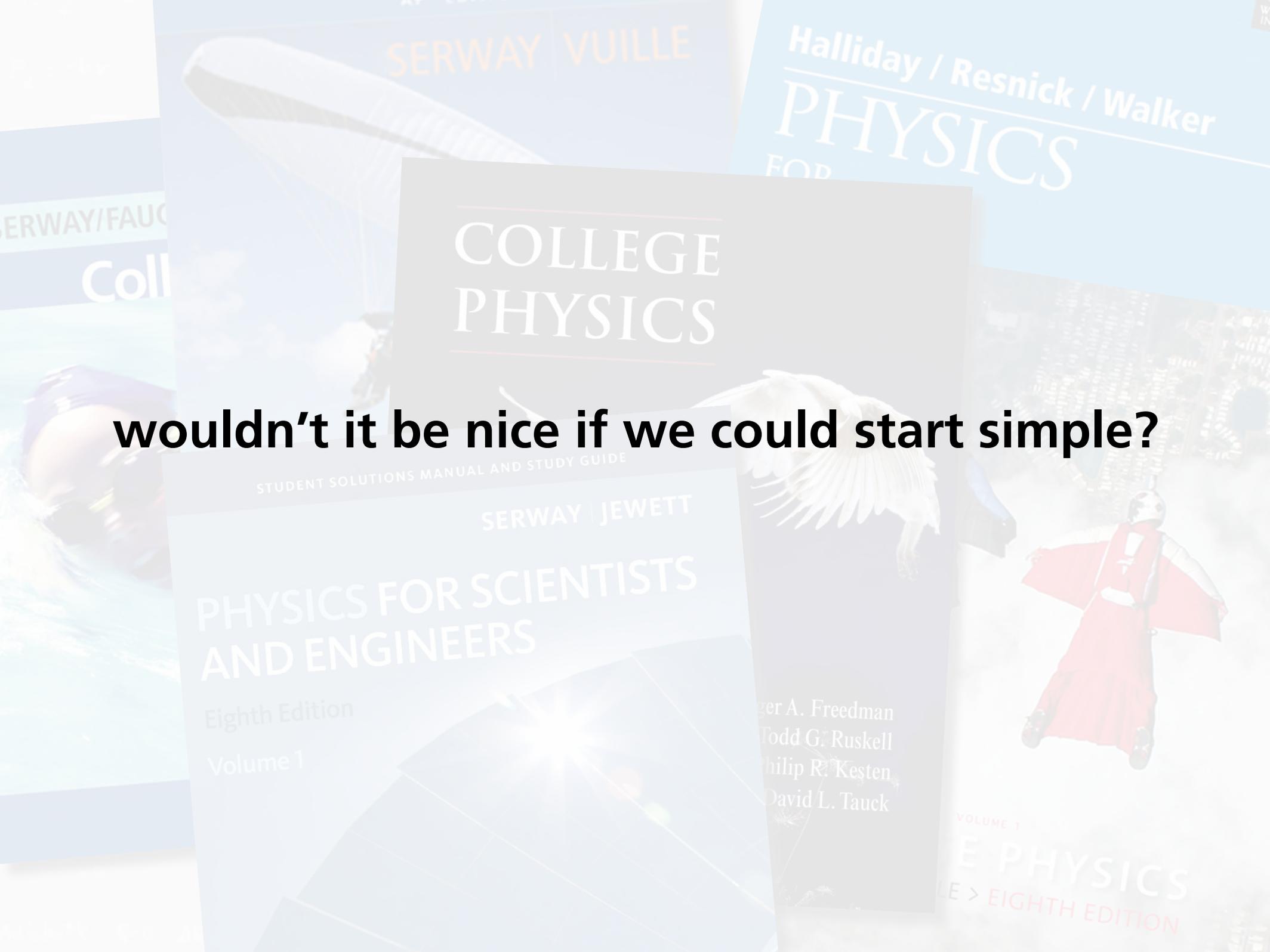
COLLEGE
PHYSICS

Frederick A. Freedman
Todd G. Ruskell
Philip R. Kesten
David L. Tauck

VOLUME 1
PHYSICS
EIGHTH EDITION

Ernst Mach (1838–1916)

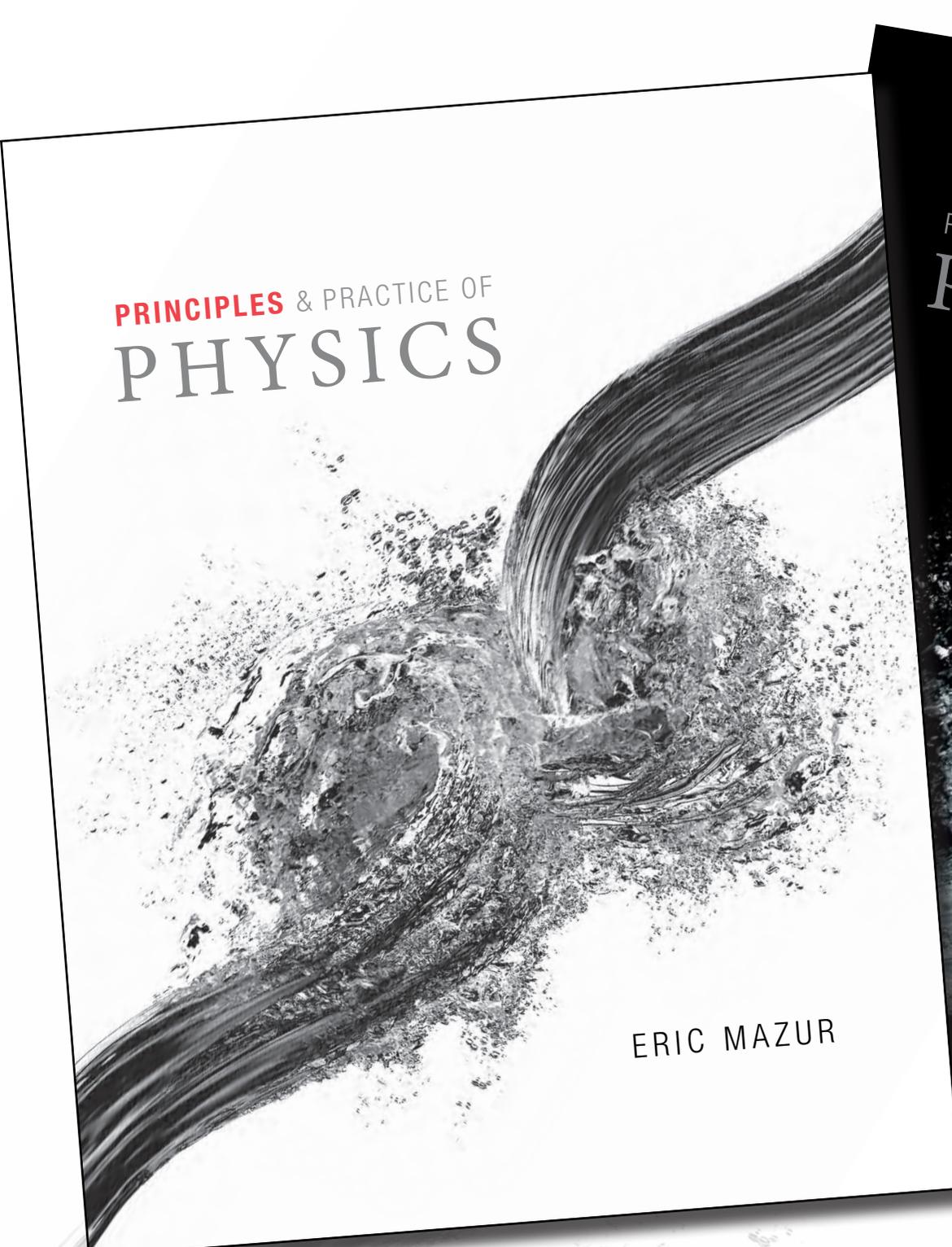
- Collisions (experimental)
- Conservation of momentum (experimental)
- Newton's laws
- Work and energy
- Conservation of energy



wouldn't it be nice if we could start simple?

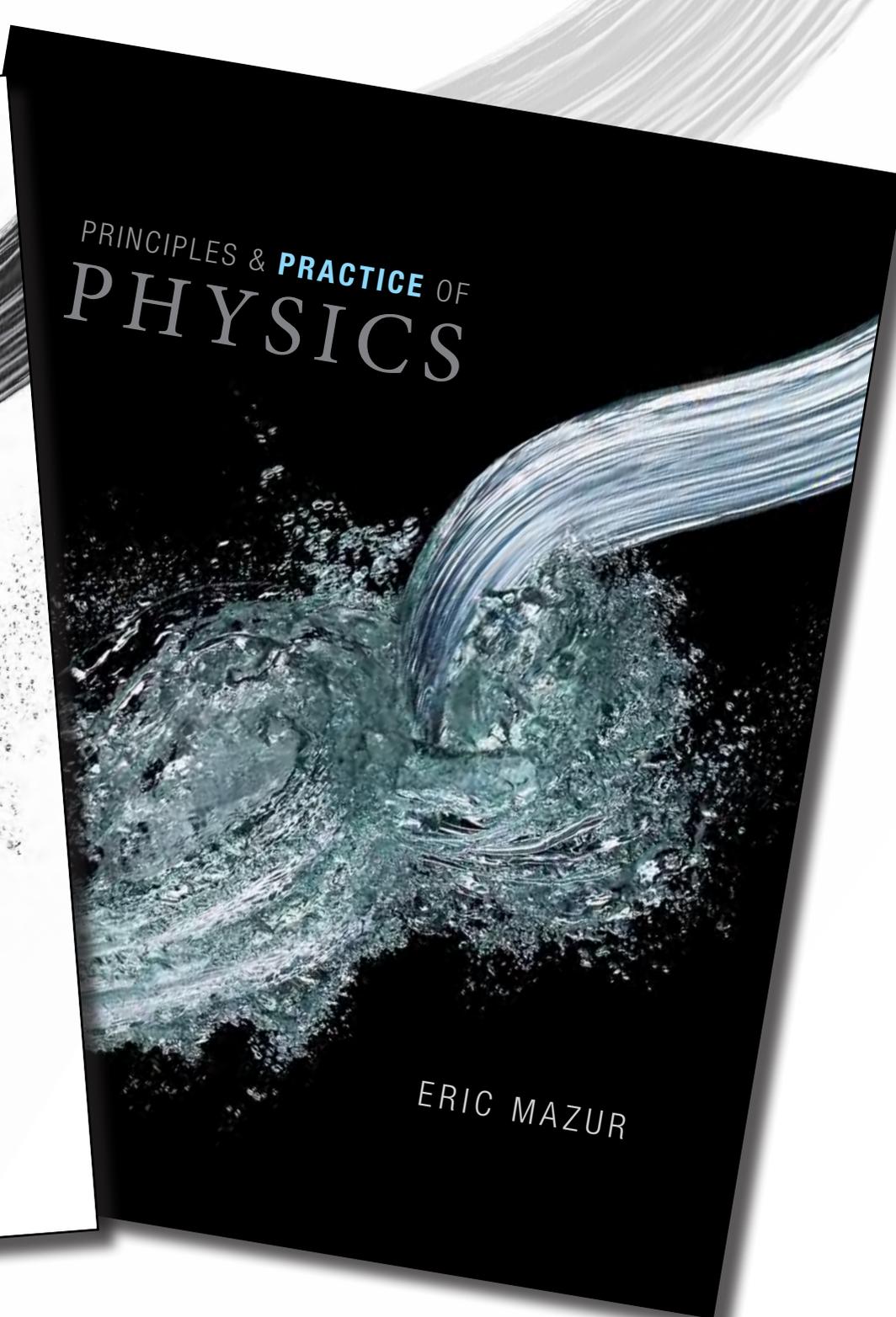
A dynamic, grayscale image of water splashing and flowing. The water is captured in motion, with numerous droplets and bubbles visible, creating a sense of energy and movement. The background is a light, almost white color, which makes the darker tones of the water stand out.

we can!

A high-speed photograph of water splashing against a white background. The water is captured in mid-air, creating a complex, textured shape with many small droplets and larger, more defined sections. The lighting is bright, highlighting the individual water molecules and the overall form of the splash.

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A high-speed photograph of water splashing against a black background. The water is captured in mid-air, creating a complex, textured shape with many small droplets and larger, more defined sections. The lighting is dramatic, highlighting the individual water molecules and the overall form of the splash against the dark background.

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Principles and Practice of Physics

- Conservation of momentum
- Conservation of energy
- Interactions
- Force
- Work

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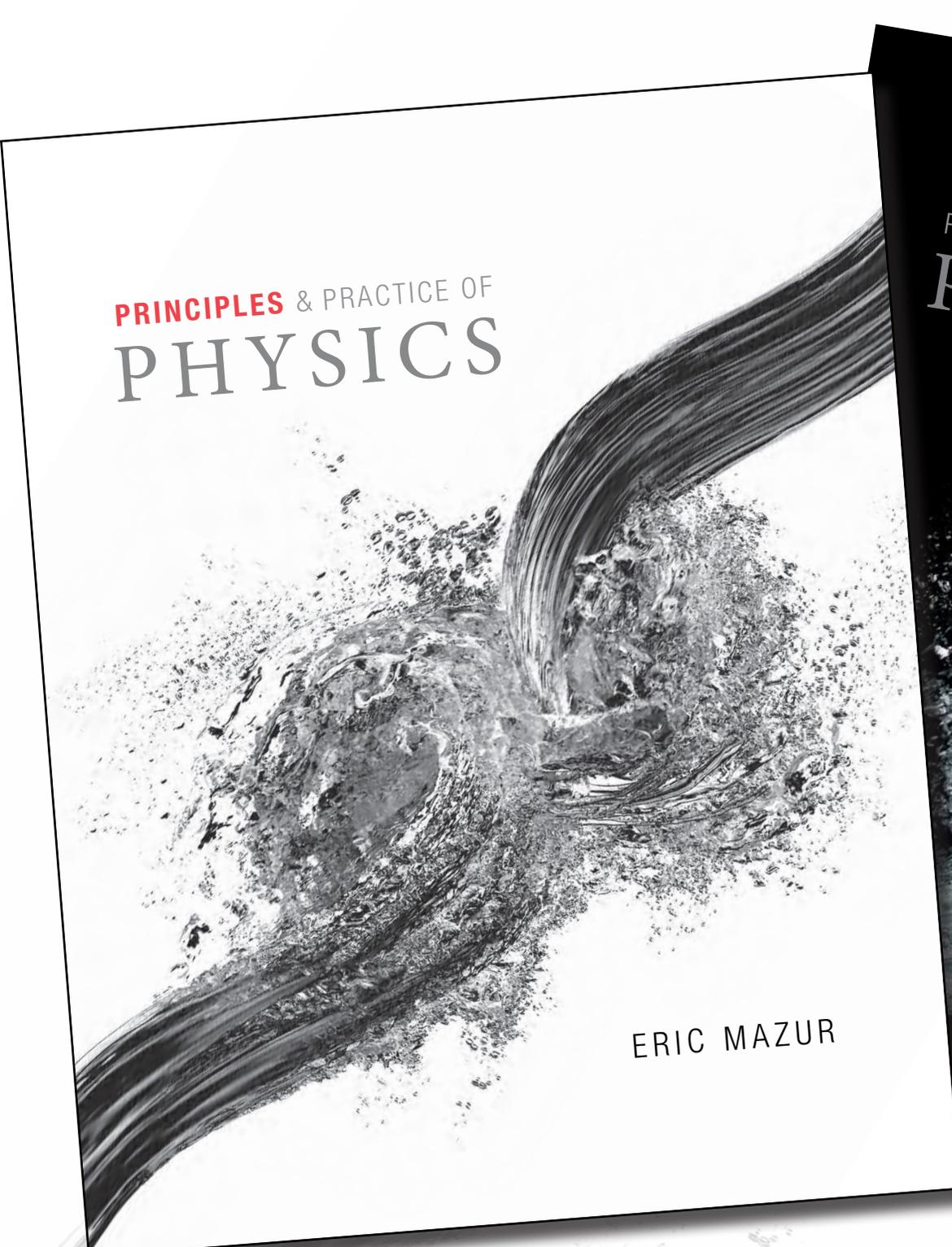
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Principles and Practice of Physics

- Conservation of momentum (experimental)
- Conservation of energy (experimental)
- Interactions
- Force
- Work

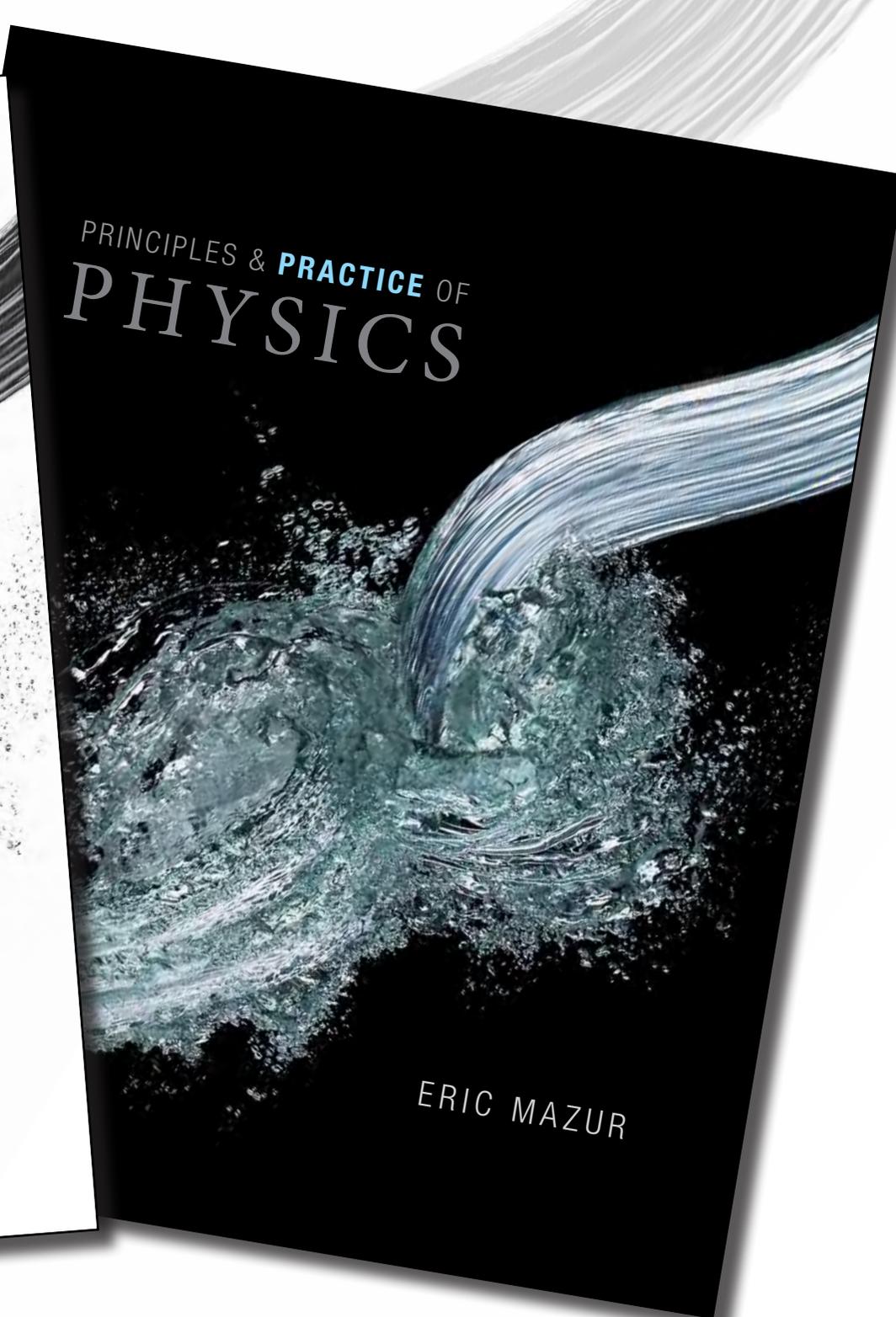
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A high-speed photograph of water splashing against a white background. The water is captured in mid-air, creating a complex, textured shape with many small droplets and larger, more defined sections. The lighting is bright, highlighting the individual water molecules and the overall form of the splash.

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A high-speed photograph of water splashing against a black background. The water is captured in mid-air, creating a complex, textured shape with many small droplets and larger, more defined sections. The lighting is dramatic, highlighting the individual water molecules and the overall form of the splash against the dark background.

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1 architecture

2 content

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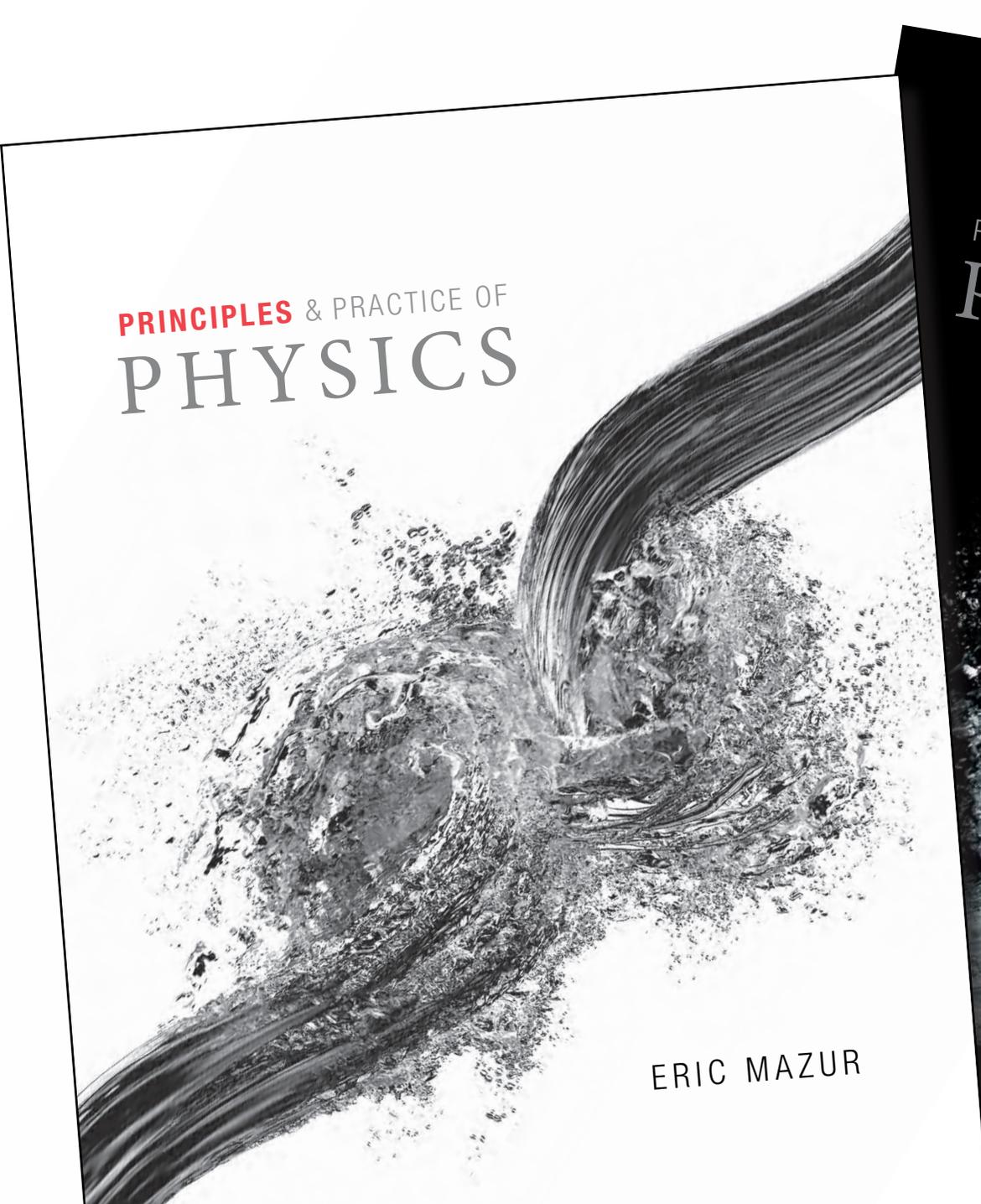
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1 architecture

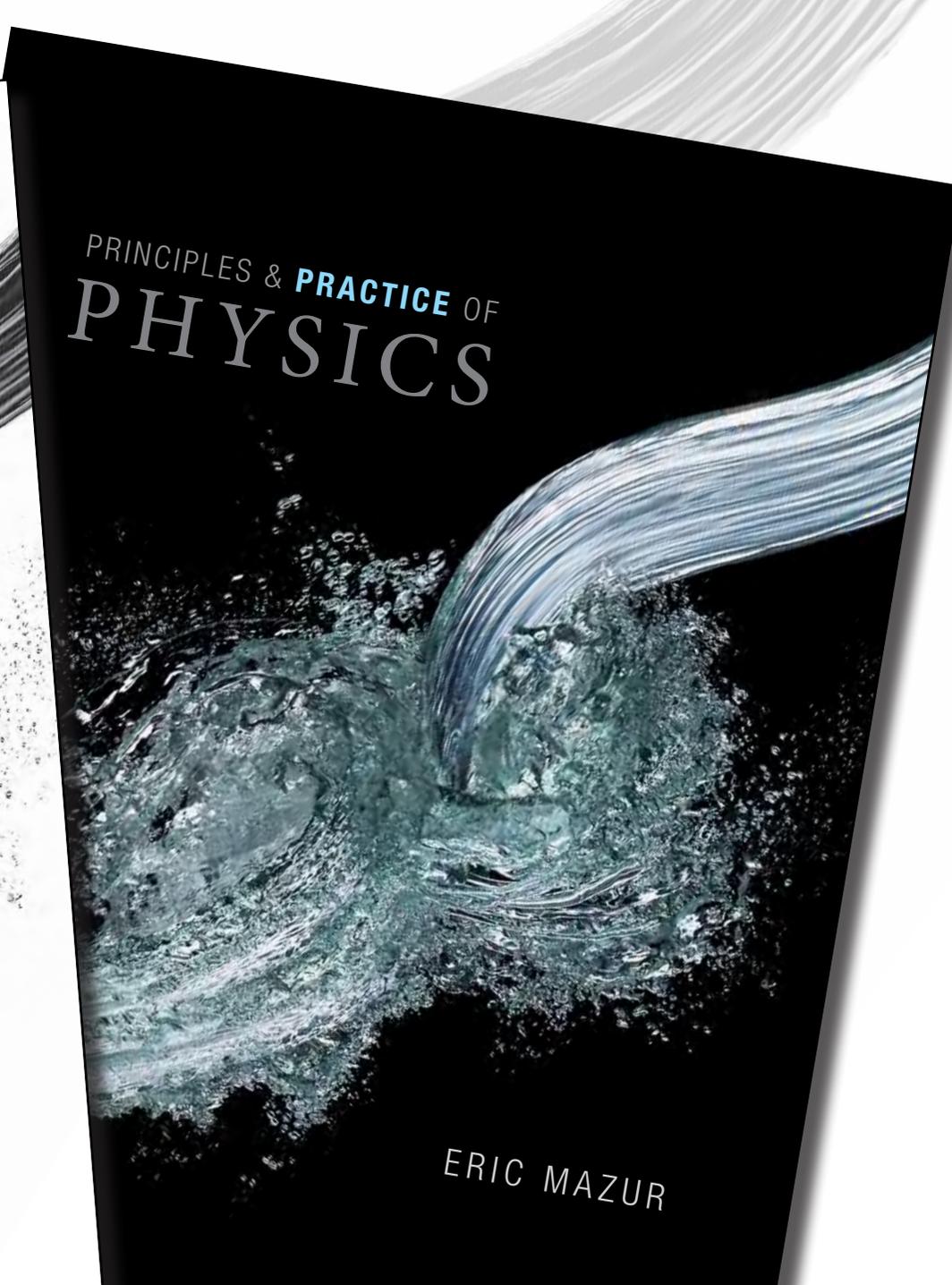
2 content

3 results



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why 2 books?

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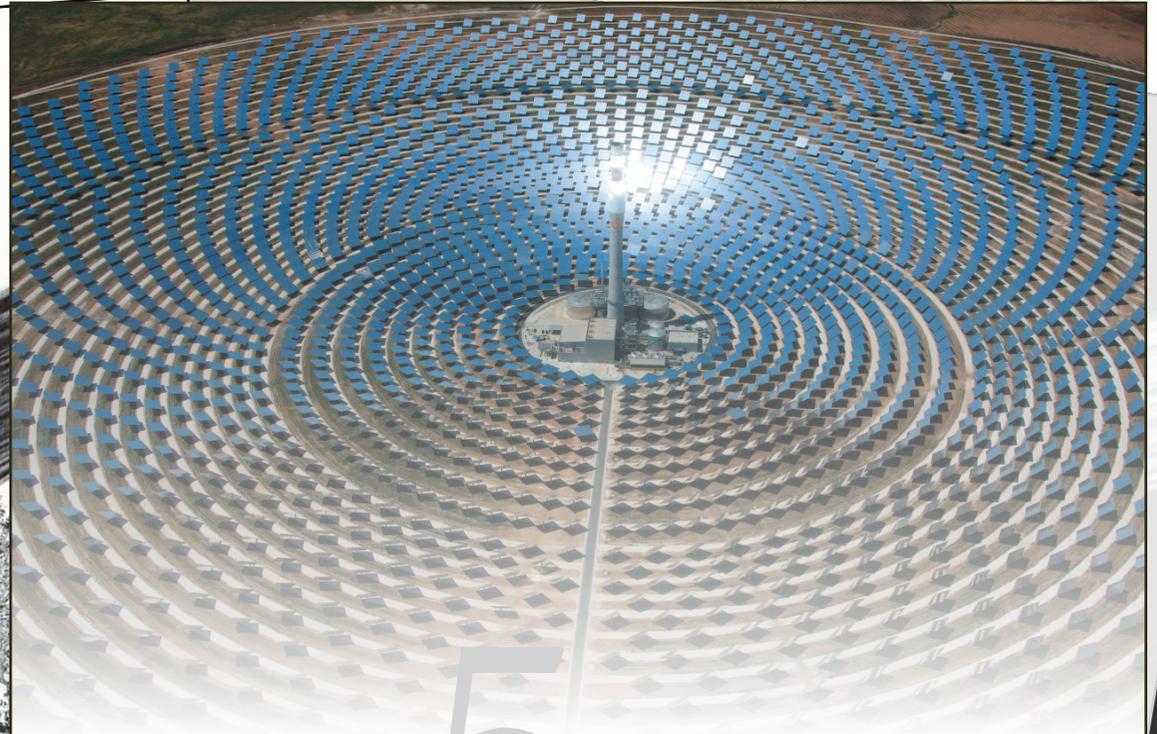
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5 Energy

- 5.1 Classification of collisions
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems

- 5.5 Elastic collisions
- 5.6 Inelastic collisions
- 5.7 Conservation of energy
- 5.8 Explosive separations

CONCEPTS

QUANTITATIVE TOOLS

The motion we have been dealing with so far in this text is called **translational motion** (Figure 11.1a). This type of motion involves no change in an object's orientation; in other words, all the particles in the object move along identical parallel trajectories. During **rotational motion**, which we begin to study in this chapter, the orientation of the object changes, and the particles in an object follow different circular paths centered on a straight line called the *axis of rotation* (Figure 11.1b). Generally, the motion of rigid objects is a combination of these two types of motion (Figure 11.1c), but as we shall see in Chapter 12 this combined motion can be broken down into translational and rotational parts that can be analyzed separately. Because we already know how to describe translational motion, knowing how to describe rotational motion will complete our description of the motion of rigid objects.

As Figure 11.1b shows, each particle in a rotating object traces out a circular path, moving in what we call *circular motion*. We therefore begin our analysis of rotational motion by describing circular motion. Circular motion occurs all around us. A speck of dust stuck to a spinning CD, a stone being whirled around on a string, a person on a Ferris wheel—all travel along the perimeter of a circle, repeating their motion over and over. Circular motion takes place in a plane, and so in principle we have already developed all the tools required to describe it. To describe circular and rotational motion we shall follow an approach that is analogous to the one we followed for the description of translational motion. Exploiting this analogy, we can then use the same results and insights gained in earlier chapters to introduce a third conservation law.

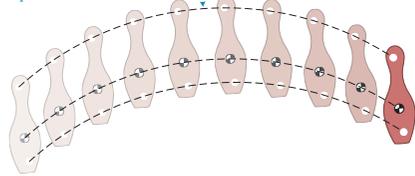
11.1 Circular motion at constant speed

Figure 11.2 shows two examples of circular motion: a block dragged along a circle by a rotating turntable and a puck constrained by a string to move in a circle. The block and puck are said to *revolve* around the vertical axis through the center of each circular path. Note that the axis about which they revolve is external to the block and perpendicular to the plane of rotation. This is the definition of *revolve*—to move in circular motion around an *external* center. Objects that turn about an *internal* axis, such as the turntable in Figure 11.2a, are said to *rotate*. These two types of motion are closely related because a rotating object can be considered as a system of an enormous number of particles, each revolving around the axis of rotation.

Figure 11.1 Translational and rotational motion of a rigid object.

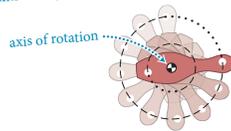
(a) Translational motion

All points on object follow identical trajectories.



(b) Rotational motion

All points on object trace circles centered on axis of rotation.



(c) Combined translation and rotation

Different points on object follow different trajectories.

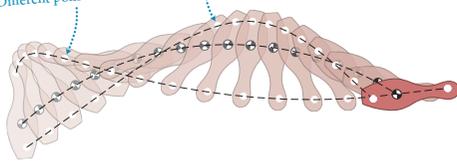
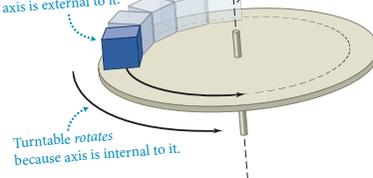


Figure 11.2 Examples of circular motion.

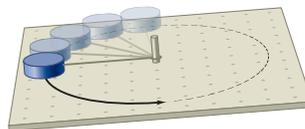
(a) Block revolves on rotating turntable

Block revolves because axis is external to it.



Turntable rotates because axis is internal to it.

(b) Tethered puck revolves on air table



ation of collisions
energy
energy
systems

CONCEPTS

isions
ollisions
on of energy
eparations

CONCEPTS

QUANTITATIVE TOOLS

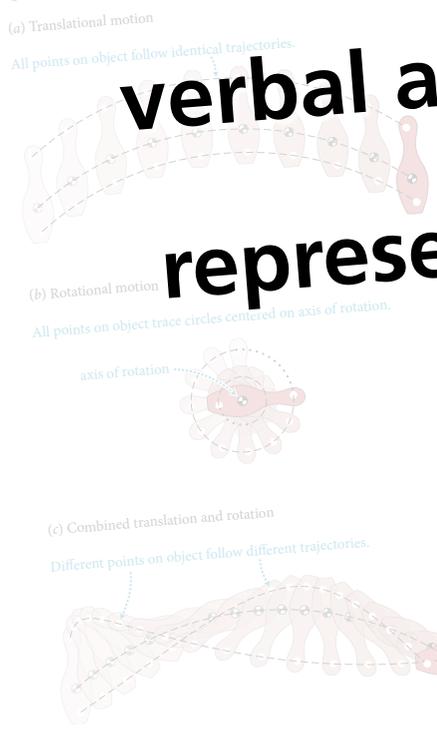
The motion we have been dealing with so far in this text is called **translational motion** (Figure 11.1a). This type of motion involves no change in an object's orientation; in other words, all the particles in the object move along identical parallel trajectories. During **rotational motion**, which we begin to study in this chapter, the orientation of the object changes, and the particles in an object follow different circular paths centered on a straight line called the *axis of rotation* (Figure 11.1b). Generally, the motion of rigid objects is a combination of these two types of motion (Figure 11.1c), but as we shall see in Chapter 12 this combined motion can be broken down into translational and rotational parts that can be analyzed separately. Because we already know how to describe translational motion, knowing how to describe rotational motion will complete our description of the motion of rigid objects.

We therefore begin our analysis of rotational motion by describing circular motion. Circular motion occurs all around us. A speck of dust stuck to a spinning CD, a stone being whirled around on a string, a person on a Ferris wheel—all travel along the perimeter of a circle, repeating their motion over and over. Circular motion takes place in a plane, and so in principle we have already developed all the tools required to describe it. To describe circular and rotational motion we shall follow an approach that is analogous to the one we followed for the description of translational motion. Exploiting this analogy, we can then use the same results and insights gained in earlier chapters to introduce a third conservation law.

11.1 Circular motion at constant speed

Figure 11.2 shows two examples of circular motion: a block dragged along a circle by a rotating turntable and a puck dragged along a circle by a rotating turntable and a puck. Note that the center of each circular path, which they revolve is external to the block and puck and perpendicular to the plane of rotation. This is the definition of *revolve*—to move in circular motion around an external center. Objects that turn about an internal axis, which is the axis of rotation, are said to *rotate*. A rotating object can be considered as a system of an enormous number of particles, each revolving around the axis of rotation.

Figure 11.1 Translational and rotational motion of a rigid object.



(a) Translational motion

All points on object follow identical trajectories.

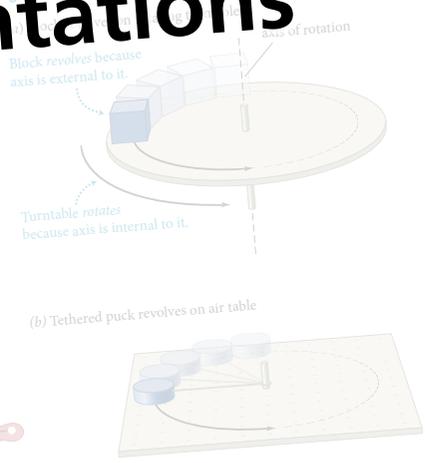
(b) Rotational motion

All points on object trace circles centered on axis of rotation.

(c) Combined translation and rotation

Different points on object follow different trajectories.

Figure 11.2 Examples of circular motion.



Block revolves because axis is external to it.

Turntable rotates because axis is internal to it.

(b) Tethered puck revolves on air table

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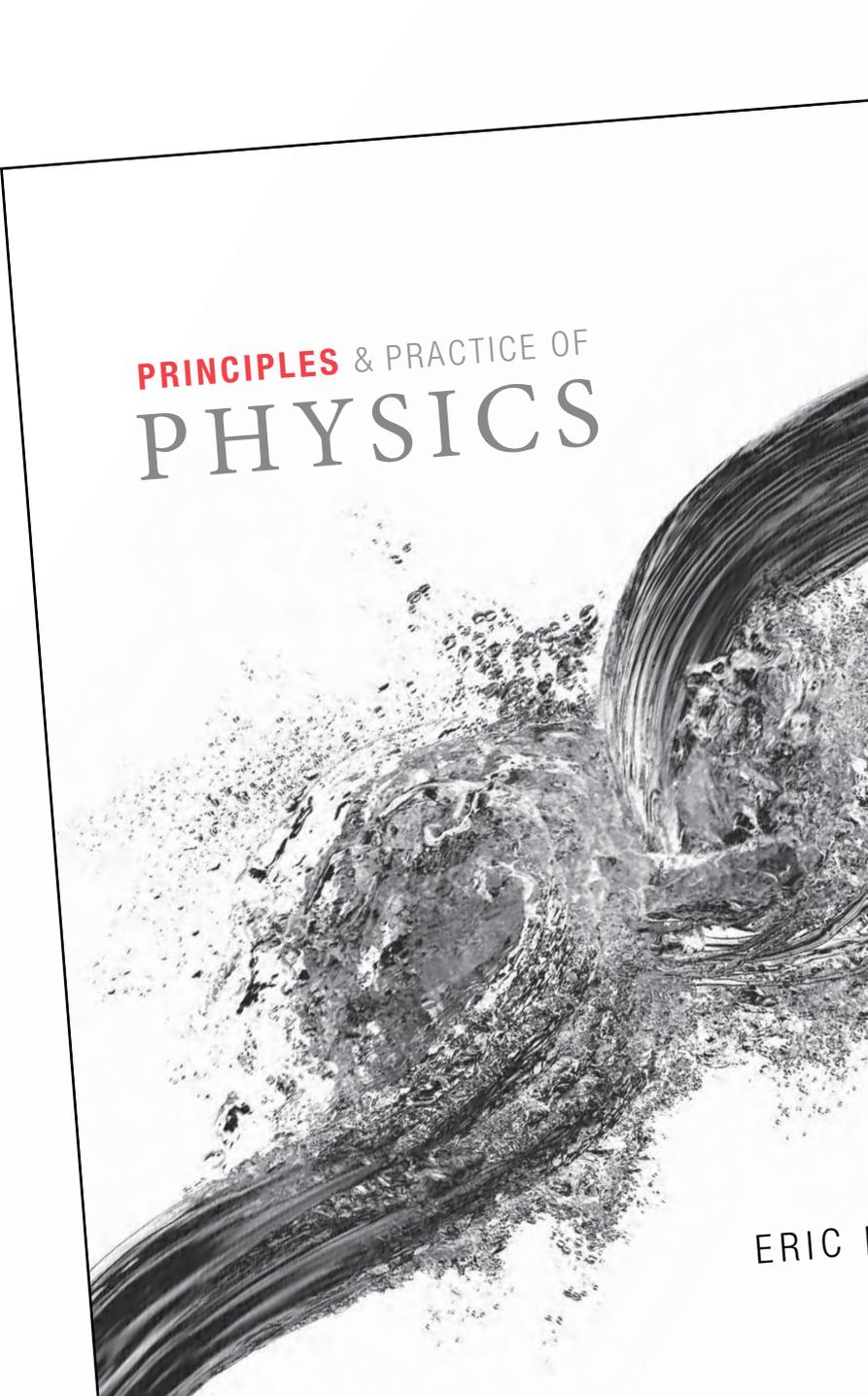
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CONCEPTS

QUANTITATIVE TOOLS

The book cover features a high-speed, black and white photograph of water splashing and forming a large, curved splash. The text is overlaid on the top left of the image.

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Energy

- 5.1 Classification of collisions
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems

- 5.5 Elastic collisions**
- 5.6 Inelastic collisions**
- 5.7 Conservation of energy**
- 5.8 Explosive separations**

CONCEPTS

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6.5 Galilean relativity

Consider two observers, A and B, moving at constant velocity relative to each other. Suppose they observe the same event and describe it relative to their respective reference frames and clocks (Figure 6.13). Let the origins of the two observers' reference frames coincide at $t = 0$ (Figure 6.13a). Observer A sees the event as happening at position \vec{r}_{Ae} at clock reading t_{Ae} (Figure 6.13b).^{*} Observer B sees the event at position \vec{r}_{Be} at clock reading t_{Be} . What is the relationship between these clock readings and positions?

If, as we discussed in Chapter 1, we assume time is absolute—the same everywhere—and if the two observers have synchronized their (identical) clocks, they both observe the event at the same clock readings, which means

$$t_{Ae} = t_{Be}. \quad (6.1)$$

Because the clock readings of the two observers always agree, we can omit the subscripts referring to the reference frames:

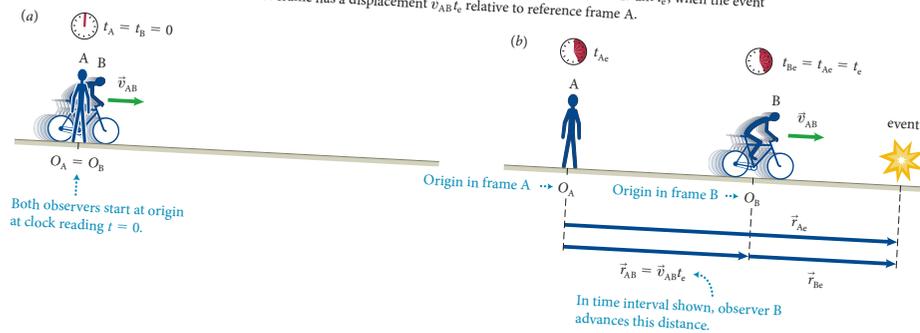
$$t_A = t_B = t. \quad (6.2)$$

From Figure 6.13 we see that the position \vec{r}_{AB} of observer B in reference frame A at instant t_e is equal to B's displacement over the time interval $\Delta t = t_e - 0 = t_e$, and so $\vec{r}_{AB} = \vec{v}_{AB} t_e$ because B moves at constant velocity \vec{v}_{AB} . Therefore

$$\vec{r}_{Ae} = \vec{r}_{AB} + \vec{r}_{Be} = \vec{v}_{AB} t_e + \vec{r}_{Be}. \quad (6.3)$$

Equations 6.2 and 6.3 allow us to relate event data collected in one reference frame to data on the same event e collected in a reference frame that moves at constant velocity relative to the first one (neither of these has to be at rest relative to Earth, but their origins must coincide at $t = 0$). To this end we rewrite these equations so that they give the values of time and position in reference frame B

Figure 6.13 Two observers moving relative to each other observe the same event. Observer B moves at constant velocity \vec{v}_{AB} relative to observer A. (a) The origins O of the two reference frames overlap at instant $t = 0$. (b) At instant t_e , when the event occurs, the origin of observer B's reference frame has a displacement $\vec{v}_{AB} t_e$ relative to reference frame A.



^{*}Remember our subscript form: The capital letter refers to the reference frame; the lowercase e is for "event." Thus the vector \vec{r}_{Ae} represents observer A's measurement of the position at which the event occurs.

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6.5 Galilean relativity

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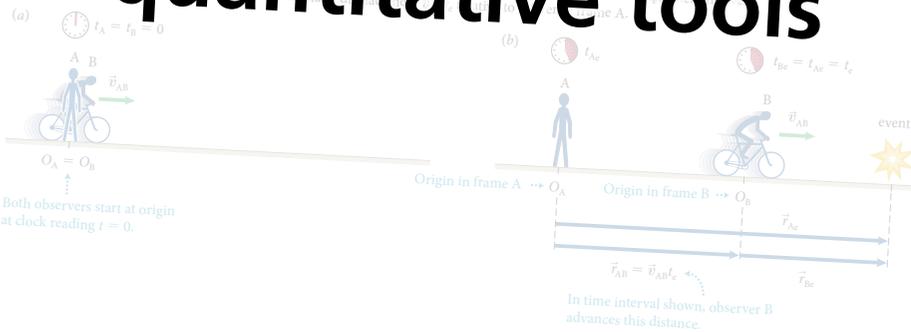
$$t_A = t_B = t. \tag{6.2}$$

From Figure 6.13b, the distance between the origin of reference frame A and the event is $\Delta \vec{r}_e = \vec{r}_{Ae} - \vec{r}_{A0} = \vec{r}_{Ae}$. The time interval between the event and the origin of frame A is $\Delta t = t_e - 0 = t_e$, and so $\vec{r}_{Ae} = \vec{v}_{AB} t_e$ because B moves at constant velocity \vec{v}_{AB} . Therefore

$$\vec{r}_{Ae} = \vec{v}_{AB} t_e + \vec{r}_{Be}. \tag{6.3}$$

Equations 6.2 and 6.3 relate the data of the event in reference frame A to data of the event in reference frame B. The two frames move with constant velocity relative to the first one (neither of these has to be at rest relative to Earth, but their origins must coincide at $t = 0$). To this end we rewrite these equations so that they give the values of time and position in reference frame B

Figure 6.13 Two observers moving relative to each other observe the same event. Observer B moves at constant velocity \vec{v}_{AB} relative to observer A. (a) At $t_A = t_B = 0$, the origins of the two reference frames coincide. (b) An event occurs, the origin of which is at position \vec{r}_{Ae} in frame A and \vec{r}_{Be} in frame B. In time interval shown, observer B advances this distance.



^{*}Remember our subscript form: The capital letter refers to the reference frame; the lowercase e is for "event." Thus the vector \vec{r}_{Ae} represents observer A's measurement of the position at which the event occurs.

build on conceptual underpinnings to effectively teach quantitative tools

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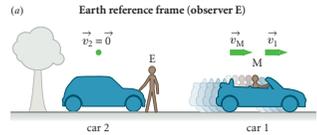
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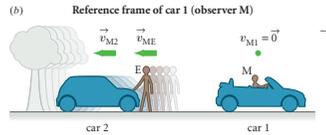
CONCEPTS

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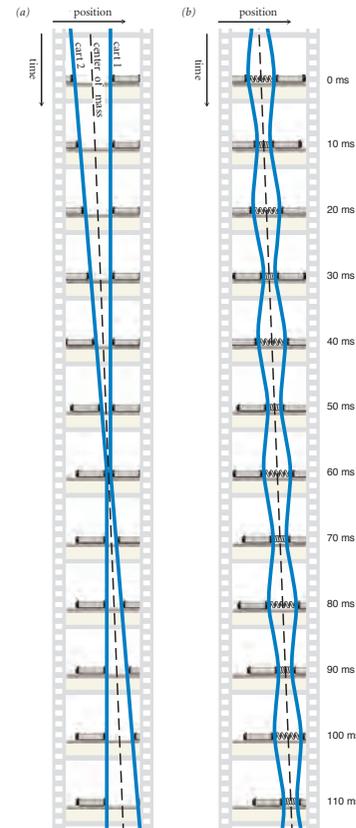
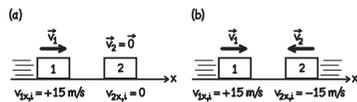
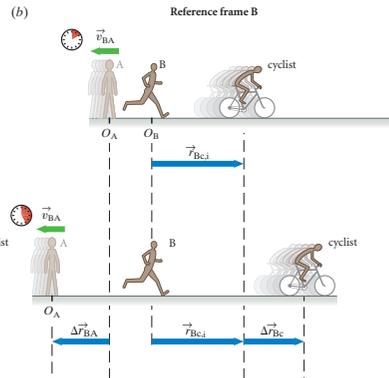
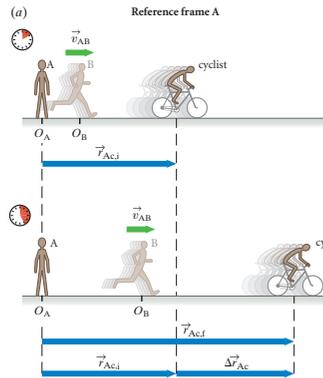
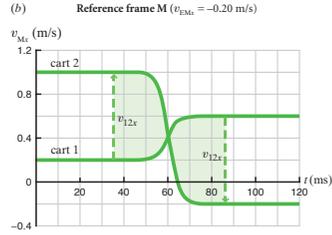
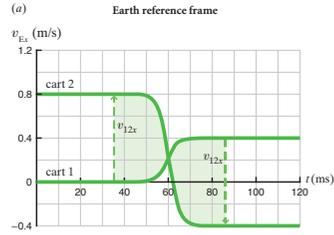
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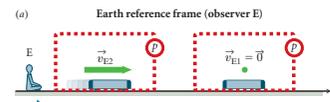
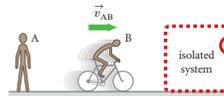
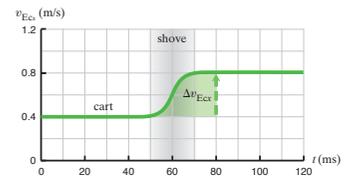
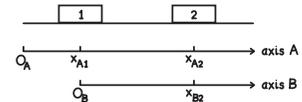
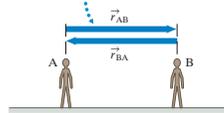
Relative to observer E, car 2 is at rest and car 1 moves to the right.



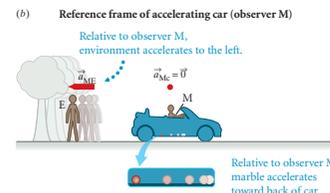
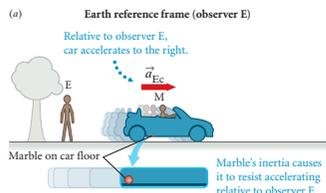
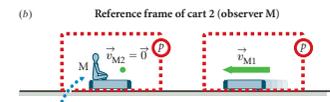
But relative to observer M, car 1 is at rest while car 2, observer E, and the earth move to the left.



Position vectors are each other's opposites.



Observers E and M both see both carts as isolated and as having constant momentum.



PRINCIPLES VOLUME

PRINCIPLES & PRACTICE OF
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- concepts before quantitative tools
- checkpoints to thinking
- 4-step worked examples
- research-based illustrations
- research-based pedagogy

Consider two observers, A and B, moving at constant velocity relative to each other. Suppose they observe the same event and describe it relative to their respective reference frames and clocks (Figure 6.13). Let the origins of the two observers' reference frames coincide at $t = 0$ (Figure 6.13a). Observer A sees the event as happening at position \vec{r}_{Ae} at clock reading t_{Ae} (Figure 6.13b).^{*} Observer B sees the event at position \vec{r}_{Be} at clock reading t_{Be} . What is the relationship between these clock readings and positions?

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$$\vec{r}_{Ae} = \vec{r}_{AB} + \vec{r}_{Be} \quad (6.2)$$

The displacement \vec{r}_{AB} of observer B in reference frame A at instant t_e is equal to the displacement over the time interval $\Delta t = t_e - 0 = t_e$, and so $\vec{r}_{AB} = \vec{v}_{AB} t_e$ because B moves at constant velocity \vec{v}_{AB} . Therefore

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Equation 6.3 relates the data collected in one reference frame to data on the same event collected in a reference frame that moves at constant velocity relative to the first one (neither of these has to be at rest relative to Earth, but their origins must coincide at $t = 0$). To this end we rewrite these equations so that they give the values of time and position in reference frame B

Figure 6.13 illustrates the relationship between the two reference frames. Observer B moves at constant velocity \vec{v}_{AB} relative to reference frame A. (a) At $t = 0$, the origins of the two reference frames coincide. (b) At instant t_e , when the event occurs, the origin of observer B's reference frame has a displacement $\vec{v}_{AB} t_e$ relative to reference frame A.



^{*}Remember our subscript form: The capital letter refers to the reference frame; the lowercase e is for

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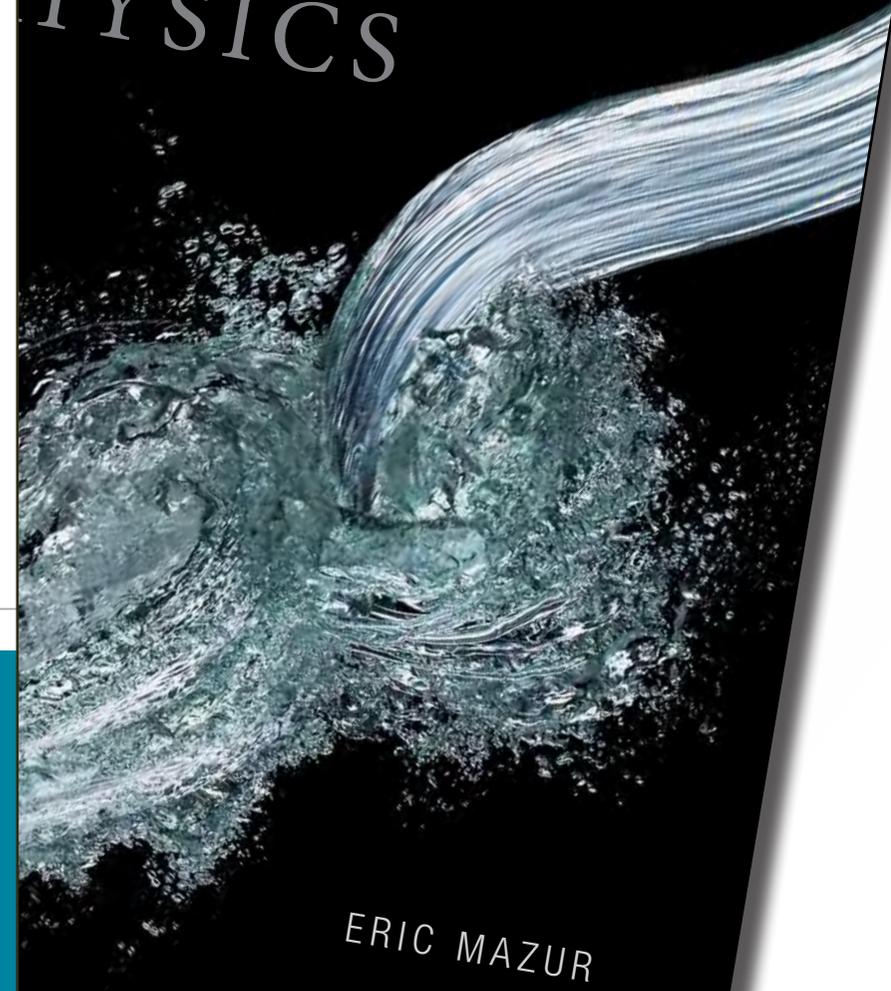
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**Waves in Two and
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Developing a Feel

Make an order-of-magnitude estimate of each of the following quantities. Letters in parentheses refer to hints below. Use them as needed to guide your thinking.

1. The speed v of a point on the equator as Earth rotates (D, P)
2. The rotational inertia of a bowling ball about an axis tangent to its surface (A, R, X)
3. Your rotational inertia as you turn over in your sleep (V, C)
4. The angular momentum around the axle of a wheel/tire combination on your car as you cruise on the freeway (E, I, O, AA, S)
5. The angular momentum of a spinning ice skater with each arm held out to the side and parallel to the ice (G, X, N, U)
6. The speed you would need to orbit Earth in a low orbit (F, P)
7. The magnitude of the force exerted by the Sun on Earth to hold Earth in orbit (B, L, T, Z)
8. The kinetic energy associated with Earth's rotation (Z, P, D)
9. The angular momentum, about a vertical axis through your house, of a large car driving down your street (H, Y, M)
10. The kinetic energy of a spinning yo-yo (K, W, J, Q)

Hints

If needed, see Key for answers to these guiding questions.

- A. What is the inertia of a bowling ball?
- B. How long a time interval is needed for Earth to make one revolution around the Sun?
- C. What simple geometric shape is an appropriate model for a sleeping person?
- D. What is Earth's rotational speed?
- E. What is the combined inertia of the wheel and tire?
- F. What is the relationship between force and acceleration for this orbit?
- G. How can you model the skater's shape during her spin?
- H. What is the inertia of a midsize car?
- I. What is the radius of the tire?
- J. How many turns are needed to rewind the yo-yo?
- K. What is the yo-yo's rotational inertia?
- L. What is the radius of Earth's orbit?
- M. What is the perpendicular distance from the house to the car's line of motion?
- N. What is the skater's rotational inertia with arms held out?
- O. How can you model the combined rotational inertia of the wheel and tire?
- P. What is Earth's radius?
- Q. What is the final rotational speed?
- R. What is the radius of a bowling ball?
- S. What is the rotational speed of the tire?
- T. What is the required centripetal acceleration?
- U. What is the skater's initial rotational speed?
- V. What is your inertia?
- W. When thrown, how long a time interval does the yo-yo take to reach the end of the string?
- X. What is needed in addition to the formulas in *Principles* Table 11.3 in order to determine this quantity?
- Y. What is a typical speed for a car moving on a city street?
- Z. What is Earth's inertia?
- AA. What is a typical freeway cruising speed?

Key (all values approximate)

A. 7 kg; B. 1 y = 3×10^7 s; C. solid cylinder of radius 0.2 m; D. period = 24 h, so $\omega = 7 \times 10^{-5} \text{ s}^{-1}$; E. 10^3 kg; F. from Eqs. 8.6, 8.17, and 11.16, $\sum \vec{F} = m\vec{a}$, so $mg = mv^2/r$; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H. 2×10^3 kg; I. 0.3 m; J. 2×10^4 turns; K. $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$ (with yo-yo modeled as solid cylinder); L. 2×10^{11} m; M. 2×10^4 m; N. 4 kg \cdot m²; O. between MR^2 (cylindrical shell representing tire) and $MR^2/2$ (solid cylinder representing wheel)—say, $3MR^2/4$; P. 6×10^6 m; Q. about twice the average rotational speed, or $\omega = 5 \times 10^2 \text{ s}^{-1}$; R. 0.1 m; S. no slipping, so $\omega = v/r \approx 10^2 \text{ s}^{-1}$; T. $8 \times 10^{-3} \text{ m/s}^2$; U. $\omega \approx 10 \text{ s}^{-1}$; V. 7×10^4 kg; W. 0.5 s; X. the parallel-axis theorem; Y. 3×10^4 mi/h; Z. 6×10^{24} kg; AA. 3×10^4 m/s

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5. The angular momentum of a spinning ice skater with each arm held out to the side and parallel to the ice (G, X, N, U)
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- D. What is Earth's rotational speed?
- E. What is the combined inertia of the wheel and tire?
- F. What is the relationship between force and acceleration for this orbit?
- G. How can you model the skater's shape during her spin?
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- K. What is the yo-yo's rotational inertia?
- L. What is the radius of Earth's orbit?
- M. What is the perpendicular distance from the house to the car's line of motion?
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- O. How can you model the combined rotational inertia of the wheel and tire?
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- X. What is needed in addition to the formulas in Principles Table 11.3 in order to determine this quantity?
- Y. What is a typical speed for a car moving on a city street?
- Z. What is Earth's inertia?
- AA. What is a typical freeway cruising speed?

Key (all values approximate)

A. 7 kg; B. 1 y = 3×10^7 s; C. solid cylinder of radius 0.2 m; D. period = 24 h, so $\omega = 7 \times 10^{-5} \text{ s}^{-1}$; E. 10^3 kg; F. from Eqs. 8.6, 8.17, and 11.16, $\sum \vec{F} = m\vec{a}$, so $mg = mv^2/r$; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H. 2×10^3 kg; I. 0.3 m; J. 2×10^4 turns; K. $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$ (with yo-yo modeled as solid cylinder); L. 2×10^{11} m; M. 2×10^4 m; N. $4 \text{ kg} \cdot \text{m}^2$; O. between MR^2 (cylindrical shell representing tire) and $MR^2/2$ (solid cylinder representing wheel)—say, $3MR^2/4$; P. 6×10^6 m; Q. about twice the average rotational speed, or $\omega = 5 \times 10^2 \text{ s}^{-1}$; R. 0.1 m; S. no slipping, so $\omega = v/r \approx 10^2 \text{ s}^{-1}$; T. $8 \times 10^{-3} \text{ m/s}^2$; U. $\omega \approx 10 \text{ s}^{-1}$; V. 7×10^4 kg; W. 0.5 s; X. the parallel-axis theorem; Y. 3×10^4 mi/h; Z. 6×10^{24} kg; AA. 3×10^3 m/s

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Make an order-of-magnitude estimate of each of the following quantities. Letters in parentheses refer to hints below. Use them as needed to guide your thinking:

1. The speed v of a point on the equator as Earth rotates (D, P)
2. The rotational inertia of a bowling ball about an axis tangent to its surface (A, R, X)
3. Your rotational inertia as you turn over in your sleep (V, C)
4. The angular momentum around the axle of a wheel/tire combination on your car as you cruise on the freeway (E, I, O, AA, S)
5. The angular momentum of a spinning ice skater with each arm held out to the side and parallel to the ice (G, X, N, U)
6. The speed you would need to orbit Earth in a low orbit (F, P)
7. The magnitude of the force exerted by the Sun on Earth to hold Earth in orbit (B, L, T, Z)
8. The kinetic energy associated with Earth's rotation (Z, P, D)
9. The angular momentum, about a vertical axis through your house, of a large car driving down your street (H, Y, M)
10. The kinetic energy of a spinning yo-yo (K, W, J, Q)

Hints

If needed, see Key for answers to these guiding questions.

- A. What is the inertia of a bowling ball?
- B. How long a time interval is needed for Earth to make one revolution around the Sun?
- C. What simple geometric shape is an appropriate model for a sleeping person?
- D. What is Earth's rotational speed?
- E. What is the combined inertia of the wheel and tire?
- F. What is the relationship between force and acceleration for this orbit?
- G. How can you model the skater's shape during her spin?
- H. What is the inertia of a midsize car?
- I. What is the radius of the tire?
- J. How many turns are needed to rewind the yo-yo?
- K. What is the yo-yo's rotational inertia?
- L. What is the radius of Earth's orbit?
- M. What is the perpendicular distance from the house to the car's line of motion?
- N. What is the skater's rotational inertia with arms held out?
- O. How can you model the combined rotational inertia of the wheel and tire?
- P. What is Earth's radius?
- Q. What is the final rotational speed?
- R. What is the radius of a bowling ball?
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- P. What is Earth's radius?
- Q. What is the final rotational speed?
- R. What is the radius of a bowling ball?
- S. What is the rotational speed of the tire?
- T. What is the required centripetal acceleration?

- U. What is the skater's initial rotational speed?
- V. What is your inertia?
- W. When thrown, how long a time interval does the yo-yo take to reach the end of the string?
- X. What is needed in addition to the formulas in Principles Table 11.3 in order to determine this quantity?
- Y. What is a typical speed for a car moving on a city street?
- Z. What is Earth's inertia?
- AA. What is a typical freeway cruising speed?

Key (all values approximate)

A. 7 kg; B. 1 y = 3×10^7 s; C. solid cylinder of radius 0.2 m; D. period = 24 h, so $\omega = 7 \times 10^{-5} \text{ s}^{-1}$; E. 10^3 kg; F. from Eqs. 8.6, 8.17, and 11.16, $\Sigma \vec{F} = m\vec{a}$, so $mg = mv^2/r$; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H. 2×10^3 kg; I. 0.3 m; J. 2×10^4 turns; K. $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$ (with yo-yo modeled as solid cylinder); L. 2×10^{11} m; M. 2×10^4 m; N. $4 \text{ kg} \cdot \text{m}^2$; O. between MR^2 (cylindrical shell representing tire) and $MR^2/2$ (solid cylinder representing wheel)—say, $3/4$; P. 6×10^6 m; Q. about twice the average rotational speed, or $\omega = 5 \times 10^2 \text{ s}^{-1}$; R. 0.1 m; S. no slipping, so $\omega = v/r \approx 10^2 \text{ s}^{-1}$; T. $8 \times 10^{-3} \text{ m/s}^2$; U. $\omega \approx 10 \text{ s}^{-1}$; V. 7×10^4 kg; W. 0.5 s; X. the parallel-axis theorem; Y. 3×10^4 mi/h; Z. 6×10^{24} kg; AA. 3×10^4 m/s

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Developing a Feel

Make an order-of-magnitude estimate of each of the following quantities. Letters in parentheses refer to hints below. Use them as needed to guide your thinking.

1. The speed v of a point on the equator as Earth rotates (D, P)
2. The rotational inertia of a bowling ball about an axis tangent to its surface (A, R, X)
3. Your rotational inertia as you turn over in your sleep (Y, C)
4. The angular momentum around the axle of a wheel/tire combination on your car as you cruise on the freeway (E, S, O, AA, S)
5. The angular momentum of a spinning ice skater with each arm held out to the side and parallel to the ice (G, Y, N, U)
6. The speed you would need to orbit Earth in a low orbit (F, P)
7. The magnitude of the force exerted by the Sun on Earth to hold Earth in orbit (B, L, T, Z)
8. The kinetic energy associated with Earth's rotation (C, Y)
9. The angular momentum, about a vertical axis through the center of a house, of a large car driving down your street (Y, S, W)
10. The kinetic energy of a yo-yo (Y, W)

Hints

If needed, see Key for answers to these guiding questions.

- A. What is the inertia of a bowling ball?
- B. How long a time interval is needed for Earth to make one rotation around the Sun?
- C. What simple geometric shape is a good approximation of a sleeping person?
- D. What is Earth's radius?
- E. What is the relationship between the wheel/tire combination on your car and the relationship between the wheel/tire combination on a yo-yo?
- F. How long a time interval is needed to rewind the yo-yo?
- G. What is the radius of Earth's orbit?
- H. What is the perpendicular distance from the house to the car's line of motion?
- I. What is the radius of the yo-yo's orbit?
- J. What is the yo-yo's rotational inertia?
- K. What is the radius of the yo-yo's orbit?
- L. What is the yo-yo's rotational inertia?
- M. What is the yo-yo's rotational inertia?
- N. What is the skater's rotational inertia with arms held out?
- O. How can you model the combined rotational inertia of the wheel and tire?
- P. What is Earth's radius?
- Q. What is the final rotational speed?
- R. What is the radius of a bowling ball?
- S. What is the rotational speed of the tire?
- T. What is the required centripetal acceleration?
- U. What is the yo-yo's rotational inertia?
- V. What is the yo-yo's rotational inertia?
- W. How long a time interval does the yo-yo take to make one rotation?
- X. What is needed in addition to the formulas in *Principles of Physics*, 7e, to determine this quantity?
- Y. What is a typical speed for a car moving on a city street?
- Z. What is Earth's inertia?
- AA. What is a typical freeway cruising speed?

Key (all values approximate)

A. 7 kg; B. 1 y = 3×10^7 s; C. solid cylinder of radius 0.2 m; D. period = 24 h, so $\omega = 7 \times 10^{-5} \text{ s}^{-1}$; E. 10^3 kg; F. from Eqs. 8.6, 8.17, and 11.16, $\Sigma \vec{F} = m\vec{a}$, so $mg = mv^2/r$; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H. 2×10^3 kg; I. 0.3 m; J. 2×10^4 turns; K. $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$ (with yo-yo modeled as solid cylinder); L. 2×10^{11} m; M. 2×10^4 m; N. $4 \text{ kg} \cdot \text{m}^2$; O. between MR^2 (cylindrical shell representing tire) and $MR^2/2$ (solid cylinder representing wheel)—say, $3/4$; P. 6×10^6 m; Q. about twice the average rotational speed, or $\omega = 5 \times 10^2 \text{ s}^{-1}$; R. 0.1 m; S. no slipping, so $\omega = v/r \approx 10^2 \text{ s}^{-1}$; T. $8 \times 10^{-3} \text{ m/s}^2$; U. $\omega = 10 \text{ s}^{-1}$; V. 7×10^4 kg; W. 0.5 s; X. the parallel-axis theorem; Y. 3×10^4 mi/h; Z. 6×10^{24} kg; AA. $3 \times 10^8 \text{ m/s}$

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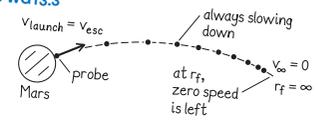
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Worked Problem 13.3 Escape at last

The Mars Colony wants to launch a deep-space probe, but they have no rocket engines. They decide to launch a probe with an electromagnetic cannon, which means they must launch at escape speed. Determine this speed.

1 GETTING STARTED Let us do a quick sketch to help our thinking (Figure WG13.3). We select the Mars-probe system for analysis. In order to reach “deep space,” the probe must attain a very great distance from Mars. This will require a significant amount of initial kinetic energy, which the probe must acquire during launch. After launch, the kinetic energy immediately begins to decrease, and the potential energy of the Mars-probe system increases as the separation distance increases. We assume a reference frame where Mars is fixed and only the probe moves. When the probe is far enough away (infinity, really, but practically it doesn’t need to go quite this far), the kinetic energy has its minimum value, which we can take to be zero because the colonists presumably do not want to supply any more energy than needed to get the probe out there. The gravitational potential energy has its maximum value, which is also zero. (Remember that universal gravitational potential energy is *negative*.) We also assume that the Sun and other planets have a negligible influence on our system, and we ignore the rotation of Mars.

Figure WG13.3



2 DEVISE PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted to gravitational potential energy of the Mars-probe system. We want to know the initial speed of the probe acquired at launch. The initial potential energy is the value when the probe is still near the Martian surface. The final state of the probe is zero speed at an infinite distance from Mars. The *Principles* volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this version of an energy conservation equation for $v_i = v_{esc}$ in terms of the known quantities.

Guided Problem 13.4 Spring to the stars

Suppose that, instead of using chemical rockets, NASA decided to use a compressed spring to launch a spacecraft. If the spring constant is 100,000 N/m and the mass of the spacecraft is 10,000 kg, how far must the spring be compressed in order to launch the craft to a position outside Earth’s gravitational influence?

- 1 GETTING STARTED**
- Describe the problem in your own words. Are there similarities to Worked Problem 13.3?
 - Draw a diagram showing the initial and final states. What is the spacecraft’s situation in the final state?
 - How does the spacecraft gain the necessary escape speed?

2 DEVISE PLAN

- What law of physics should you invoke?

3 EXECUTE PLAN Let us use r_i for the initial Mars-probe radial center-to-center separation distance, $r_f = \infty$ for the final separation distance, R_M for the radius of Mars, and m_M and m_p for the two masses. We begin with Eq. 13.23:

$$E_{mech} = \frac{1}{2} m_p v_{esc}^2 - G \frac{m_M m_p}{R_M} = 0$$

$$\frac{1}{2} v_{esc}^2 - G \frac{m_M}{R_M} = 0$$

$$\frac{1}{2} v_{esc}^2 = G \frac{m_M}{R_M}$$

$$v_{esc} = \sqrt{2G \frac{m_M}{R_M}}$$

$$v_{esc} = \sqrt{2(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2) \frac{6.42 \times 10^{23} \text{ kg}}{3.40 \times 10^6 \text{ m}}}$$

$$= 5.02 \times 10^3 \text{ m/s} = 5 \text{ km/s} \checkmark$$

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars’s gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars’s radius), and G . We expect v_{esc} to increase with m_M because the gravitational pull increases with increasing mass. We also expect v_{esc} to decrease as the distance between the launch position and Mars’s center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

An escape speed of 18,000 km/h is smaller than (but on the order of) the escape speed from Earth, and so the answer is not unreasonable. We assumed that the initial Mars-probe separation distance is equal to the planet’s radius. Of course, the length of the cannon may be tens of meters, but this tiny difference would have no impact on the numerical answer. We ignored the rotation of Mars, which could supply a small amount of the needed kinetic energy. We also ignored the effect of the Sun, which is fine for getting away from the surface of Mars, but we would need to account for it if the destination was another star.

- As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you ignore this effect?
- What equation allows you to relate the initial and final states?

3 EXECUTE PLAN

- What is your target unknown quantity? Algebraically isolate it on one side of your equation.
- Substitute the numerical values you know to get a numerical answer.

4 EVALUATE RESULT

- Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth’s mass and radius change?
- If you were the head of a design team, would you recommend pursuing this launch method?

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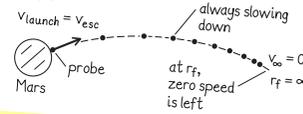
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$$\frac{1}{2} v_{esc}^2 - G \frac{m_M}{R_M} = 0$$

$$\frac{1}{2} v_{esc}^2 = G \frac{m_M}{R_M}$$

$$v_{esc} = \sqrt{2G \frac{m_M}{R_M}}$$

$$v_{esc} = \sqrt{2(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2) \frac{6.42 \times 10^{23} \text{ kg}}{3.40 \times 10^6 \text{ m}}}$$

$$= 5.02 \times 10^3 \text{ m/s} = 5 \text{ km/s} \checkmark$$

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars’s gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars’s radius), and G . We expect v_{esc} to increase with m_M because the gravitational pull increases with increasing mass. We also expect v_{esc} to decrease as the distance between the launch position and Mars’s center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

An escape speed of 18,000 km/h is smaller than (but on the order of) the escape speed from Earth, and so the answer is not unreasonable.

We assumed that the initial Mars-probe separation distance is equal to the planet’s radius. Of course, the length of the cannon may be tens of meters, but this tiny difference would have no impact on the numerical answer. We ignored the rotation of Mars, which could supply a small amount of the needed kinetic energy. We also ignored the effect of the Sun, which is fine for getting away from the surface of Mars, but we would need to account for it if the destination was another star.

- As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you ignore this effect?
- What equation allows you to relate the initial and final states?

3 EXECUTE PLAN

- What is your target unknown quantity? Algebraically isolate it on one side of your equation.
- Substitute the numerical values you know to get a numerical answer.

4 EVALUATE RESULT

- Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth’s mass and radius change?
- If you were the head of a design team, would you recommend pursuing this launch method?

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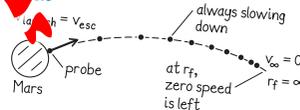
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Worked Problem 13.3 Escape at last

The Mars Colony wants to launch a deep-space probe, but they have no rocket engines. They decide to launch a probe with an electromagnetic cannon, which means they must launch at escape speed. Determine this speed.

1 GETTING STARTED Let us do a quick sketch to help thinking (Figure WG13.3). We select the Mars-probe system for analysis. In order to reach “deep space,” the probe must attain a very large distance from Mars. This will require a significant amount of kinetic energy, which the probe must acquire during launch. At launch, the kinetic energy immediately begins to decrease. As the potential energy of the Mars-probe system increases, the kinetic energy decreases. We assume a reference point where the separation distance is fixed and only the probe moves. As the probe moves far away (infinity, really, but practically, as far as we can get), the kinetic energy has a minimum value. It can take to be zero because the probe presumably does not supply any more energy than needed to get out there. The gravitational potential energy of the probe out there, which is also zero. (We also assume that the Sun and other planets have a negligible influence on our system, and we ignore the rotation of Mars.)



2 DEVISE PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted to gravitational potential energy of the Mars-probe system. We want to know the initial speed of the probe acquired at launch. The initial potential energy is the value when the probe is still near the Martian surface. The final state of the probe is zero speed at an infinite distance from Mars. The *Principles* volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this version of an energy conservation equation for $v_i = v_{esc}$ in terms of the known quantities.

Guided Problem 13.4 Spring to the stars

Suppose that, instead of using chemical rockets, NASA decided to use a compressed spring to launch a spacecraft. If the spring constant is 100,000 N/m and the mass of the spacecraft is 10,000 kg, how far must the spring be compressed in order to launch the craft to a position outside Earth's gravitational influence?

1 GETTING STARTED

1. Describe the problem in your own words. Are there similarities to Worked Problem 13.3?
2. Draw a diagram showing the initial and final states. What is the spacecraft's situation in the final state?
3. How does the spacecraft gain the necessary escape speed?

2 DEVISE PLAN

4. What law of physics should you invoke?

3 EXECUTE PLAN Let us use conservation of energy. The initial center-to-center separation distance is $r_i = R_M$ for the final separation distance, $r_f = \infty$. We assume that the masses are m_M and m_p for the two

$$E_{\text{initial}} = \frac{1}{2} m_p v_{\text{esc}}^2 - G \frac{m_M m_p}{R_M} = 0$$

$$\frac{1}{2} v_{\text{esc}}^2 - G \frac{m_M}{R_M} = 0$$

$$\frac{1}{2} v_{\text{esc}}^2 = G \frac{m_M}{R_M}$$

$$v_{\text{esc}} = \sqrt{2G \frac{m_M}{R_M}}$$

$$v_{\text{esc}} = \sqrt{2(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2) \frac{6.42 \times 10^{23} \text{ kg}}{3.40 \times 10^6 \text{ m}}} = 5.02 \times 10^3 \text{ m/s} = 5 \text{ km/s} \checkmark$$

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars's gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars's radius), and G . We expect v_{esc} to increase with m_M because the gravitational pull increases with increasing mass. We also expect v_{esc} to decrease as the distance between the launch position and Mars's center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

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5. As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you ignore this effect?
6. What equation allows you to relate the initial and final states?

3 EXECUTE PLAN

7. What is your target unknown quantity? Algebraically isolate it on one side of your equation.
8. Substitute the numerical values you know to get a numerical answer.

4 EVALUATE RESULT

9. Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth's mass and radius change?
10. If you were the head of a design team, would you recommend pursuing this launch method?

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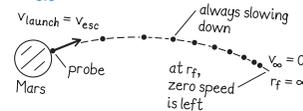
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Worked Problem 13.3 Escape at last

The Mars Colony wants to launch a deep-space probe, but they have no rocket engines. They decide to launch a probe with an electromagnetic cannon, which means they must launch at escape speed. Determine this speed.

1 GETTING STARTED Let us do a quick sketch to help our thinking (Figure WG13.3). We select the Mars-probe system for analysis. In order to reach “deep space,” the probe must attain a very great distance from Mars. This will require a significant amount of initial kinetic energy, which the probe must acquire during launch. After launch, the kinetic energy immediately begins to decrease, and the potential energy of the Mars-probe system increases as the separation distance increases. We assume a reference frame where Mars is fixed and only the probe moves. When the probe is far enough away (infinity, really, but practically it doesn’t need to go quite this far), the kinetic energy has its minimum value, which we can take to be zero because the colonists presumably do not want to supply any more energy than needed to get the probe out there. The gravitational potential energy has its maximum value, which is also zero. (Remember that universal gravitational potential energy is *negative*.) We also assume that the Sun and other planets have a negligible influence on our system, and we ignore the rotation of Mars.

Figure WG13.3



2 DEVISE PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted to gravitational potential energy of the Mars-probe system. We want to know the initial speed of the probe acquired at launch. The initial potential energy is the value when the probe is still near the Martian surface. The final state of the probe is zero speed at an infinite distance from Mars. The *Principles* volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this version of an energy conservation equation for $v_i = v_{esc}$ in terms of the known quantities.

Guided Problem 13.4 Spring to the stars

Suppose that, instead of using chemical rockets, NASA decided to use a compressed spring to launch a spacecraft. If the spring constant is 100,000 N/m and the mass of the spacecraft is 10,000 kg, how far must the spring be compressed in order to launch the craft to a position outside Earth’s gravitational influence?

1 GETTING STARTED

- Describe the problem in your own words. Are there similarities to Worked Problem 13.3?
- Draw a diagram showing the initial and final states. What is the spacecraft’s situation in the final state?
- How does the spacecraft gain the necessary escape speed?

2 DEVISE PLAN

- What law of physics should you invoke?

3 EXECUTE PLAN Let us use r_i for the initial Mars-probe radial center-to-center separation distance, $r_f = \infty$ for the final separation distance, R_M for the radius of Mars, and m_M and m_p for the two masses. We begin with Eq. 13.23:

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Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars’s gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars’s radius), and G . We expect v_{esc} to increase with m_M because the gravitational pull increases with increasing mass. We also expect v_{esc} to decrease as the distance between the launch position and Mars’s center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

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- Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth’s mass and radius change?
- If you were the head of a design team, would you recommend pursuing this launch method?

PRACTICE

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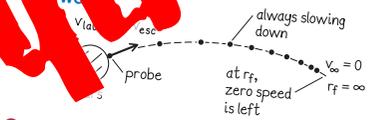
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Worked Problem 13.3 Escape at last

The Mars Colony wants to launch a deep-space probe, but they have no rocket engines. They decide to launch a probe with an electromagnetic cannon, which means they must launch at escape speed. Determine this speed.

1 GETTING STARTED Let us do a quick sketch to help our thinking (Figure WG13.3). We select the Mars-probe system for analysis. In order to reach “deep space,” the probe must attain a very great distance from Mars. This will require a significant amount of initial kinetic energy, which the probe must acquire at launch. At the moment of launch, the kinetic energy immediately begins to decrease as the potential energy of the Mars-probe system increases. As the separation distance increases, we assume a reference frame in which the probe is fixed and only the probe moves. The probe moves far enough away (infinity, really, but practically, quite far) that the kinetic energy of the probe is zero because the probe has stopped. Presumably, it was not possible to apply any more energy than that needed to get the probe off the surface. The gravitational potential energy of the probe is also zero. The gravitational potential energy of the Mars-probe system is also zero. The initial potential energy is negative, and other planets have a negligible influence on the system, and we ignore the rotation of Mars.



2 DEVISE PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted to gravitational potential energy of the Mars-probe system. We want to know the initial speed of the probe acquired at launch. The initial potential energy is the value when the probe is still near the Martian surface. The final state of the probe is zero speed at an infinite distance from Mars. The *Principles* volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this form of an energy conservation equation for $v_i = v_{esc}$ in terms of the known quantities.

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Suppose that, instead of using chemical rockets, NASA decided to use a compressed spring to launch a spacecraft. If the spring constant is 100,000 N/m and the mass of the spacecraft is 10,000 kg, how far must the spring be compressed in order to launch the craft to a position outside Earth's gravitational influence?

- 1 GETTING STARTED**
1. Describe the problem in your own words. Are there similarities to Worked Problem 13.3?
 2. Draw a diagram showing the initial and final states. What is the spacecraft's situation in the final state?
 3. How does the spacecraft gain the necessary escape speed?

2 DEVISE PLAN

4. What law of physics should you invoke?

3 EXECUTE PLAN Let us use the initial Mars-probe system for analysis. The initial center-to-center separation distance of the Mars-probe system is the Mars radius, R_M . The initial potential energy of the Mars-probe system is $U_i = -G \frac{m_M m_P}{R_M}$. The initial kinetic energy of the Mars-probe system is $K_i = \frac{1}{2} m_P v_{esc}^2$. The final potential energy of the Mars-probe system is $U_f = 0$. The final kinetic energy of the Mars-probe system is $K_f = 0$.

$$U_i + K_i = U_f + K_f$$
$$-G \frac{m_M m_P}{R_M} + \frac{1}{2} m_P v_{esc}^2 = 0 + 0$$
$$\frac{1}{2} v_{esc}^2 = G \frac{m_M}{R_M}$$
$$v_{esc} = \sqrt{2G \frac{m_M}{R_M}}$$
$$v_{esc} = \sqrt{2(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2) \frac{6.42 \times 10^{23} \text{ kg}}{3.40 \times 10^6 \text{ m}}}$$
$$= 5.02 \times 10^3 \text{ m/s} = 5 \text{ km/s} \checkmark$$

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars's gravitational pull.

4 EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars's radius), and G . We expect v_{esc} to increase with m_M because the gravitational pull increases with increasing mass. We also expect v_{esc} to decrease as the distance between the launch position and Mars's center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

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7. What is your target unknown quantity? Algebraically isolate it on one side of your equation.
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9. Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth's mass and radius change?
10. If you were the head of a design team, would you recommend pursuing this launch method?

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Worked Problem 13.3 Escape at last

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Figure WG13.3



DEVELOP PLAN We can use conservation of energy because the probe has all of the needed kinetic energy at the beginning, as it is shot from a cannon. As the probe travels, this kinetic energy is converted into gravitational potential energy. The kinetic energy is zero at infinite distance from Mars. The *Principles* volume analyzes a similar situation in Section 13.7, leading to Eq. 13.23, so there is no need to derive this result again here. We begin with Eq. 13.23, solving this version of an energy conservation equation for $v_i = v_{esc}$ in terms of the known quantities.

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- GETTING STARTED**
1. Describe the problem in your own words. Are there similarities to Worked Problem 13.3?
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DEVELOP PLAN

4. What law of physics should you invoke?

EXECUTE PLAN Let us use r_i for the initial Mars-probe radial center-to-center separation distance, $r_f = \infty$ for the final separation distance, R_M for the radius of Mars, and m_M and m_p for the two masses. We begin with Eq. 13.23:

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$$= 5.02 \times 10^3 \text{ m/s} = 5 \text{ km/s} \checkmark$$

Notice that this speed does not depend on the mass of the probe. A probe of any other size shot from the cannon would need the same minimum speed to break free of Mars's gravitational pull.

EVALUATE RESULT Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars's radius), and G . We expect v_{esc} to increase with m_M because the gravitational pull increases with increasing mass. We also expect v_{esc} to decrease as the distance between the launch position and Mars's center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is in line with what our intuition tells us. The order of magnitude of the escape speed is reasonable. The distance is equal to the planet's radius. Of course, the length of the cannon may be tens of meters, but this tiny difference would have no impact on the numerical answer. We ignored the rotation of Mars, which could supply a small amount of the needed kinetic energy. We also ignored the effect of the Sun, which is fine for getting away from the surface of Mars, but we would need to account for it if the destination was another star.

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conservation principles *before* force laws?

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- 1.2 Symmetry
- 1.3 Matter and the universe
- 1.4 Time and change
- 1.5 Representations

- 1.6 Physical quantities and units
- 1.7 Significant digits
- 1.8 Solving problems
- 1.9 Developing a feel

CONCEPTS

QUANTITATIVE TOOLS



1.1 The scientific method

1.2 Symmetry

1.3 Matter and the universe

1.4 Time and change

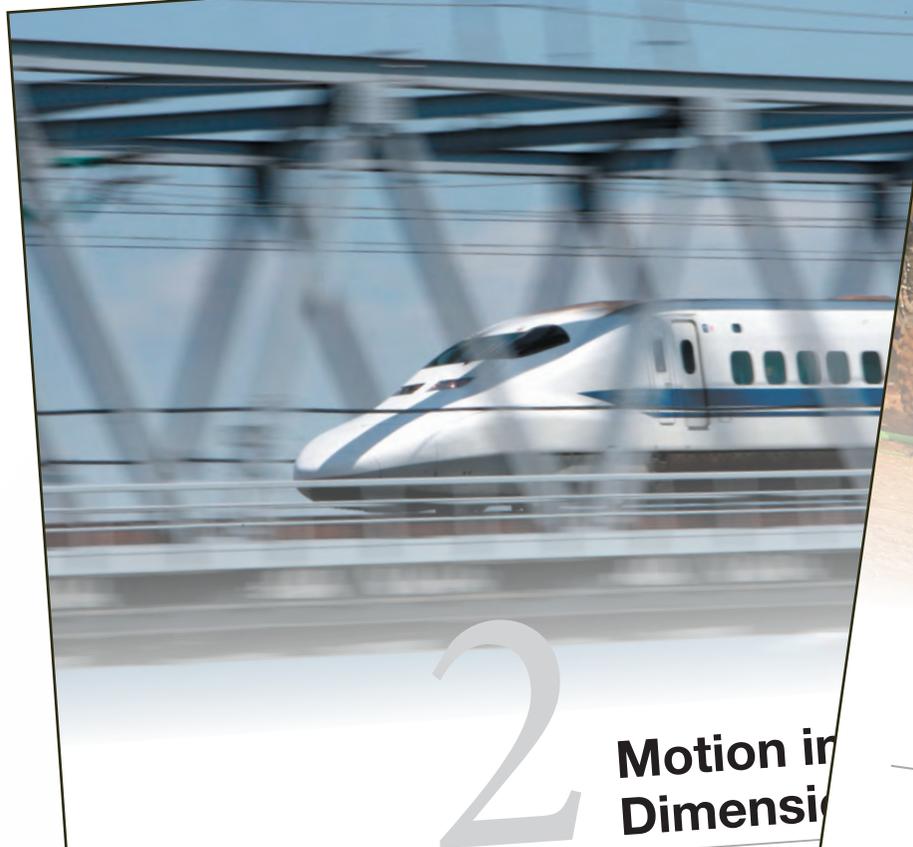
1.5 Representations

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- 2.1 From reality to model
- 2.2 Position and displacement
- 2.3 Representing motion
- 2.4 Average speed and average velocity

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- 2.5 Scalars and vectors
- 2.6 Position and displacement vectors
- 2.7 Velocity as a vector
- 2.8 Motion at constant velocity
- 2.9 Instantaneous velocity



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Acceleration

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- 3.1 Changes in velocity
- 3.2 Acceleration due to gravity
- 3.3 Projectile motion
- 3.4 Motion diagrams

QUANTITATIVE TOOLS

- 3.5 Motion with constant acceleration
- 3.6 Free-fall equations
- 3.7 Inclined planes
- 3.8 Instantaneous acceleration



4 Momentum

- 4.1 Friction
- 4.2 Inertia
- 4.3 What determines inertia?
- 4.4 Systems

- 4.5 Inertial standard
- 4.6 Momentum
- 4.7 Isolated systems
- 4.8 Conservation of momentum

CONCEPTS

QUANTITATIVE TOOLS

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4.1 Friction

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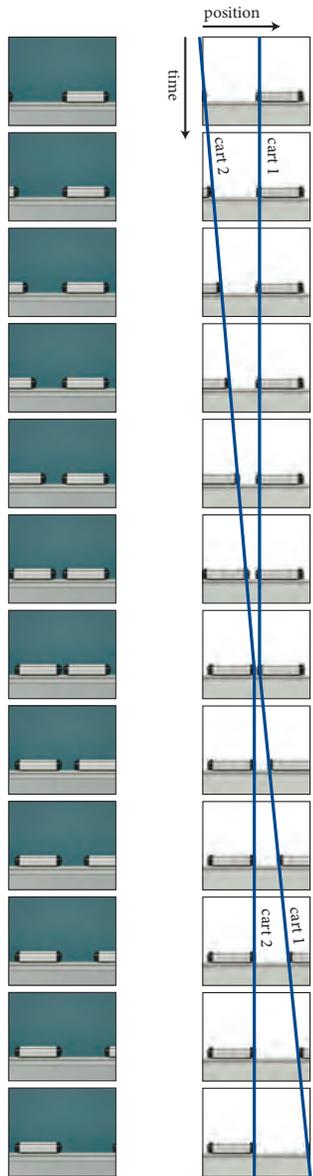
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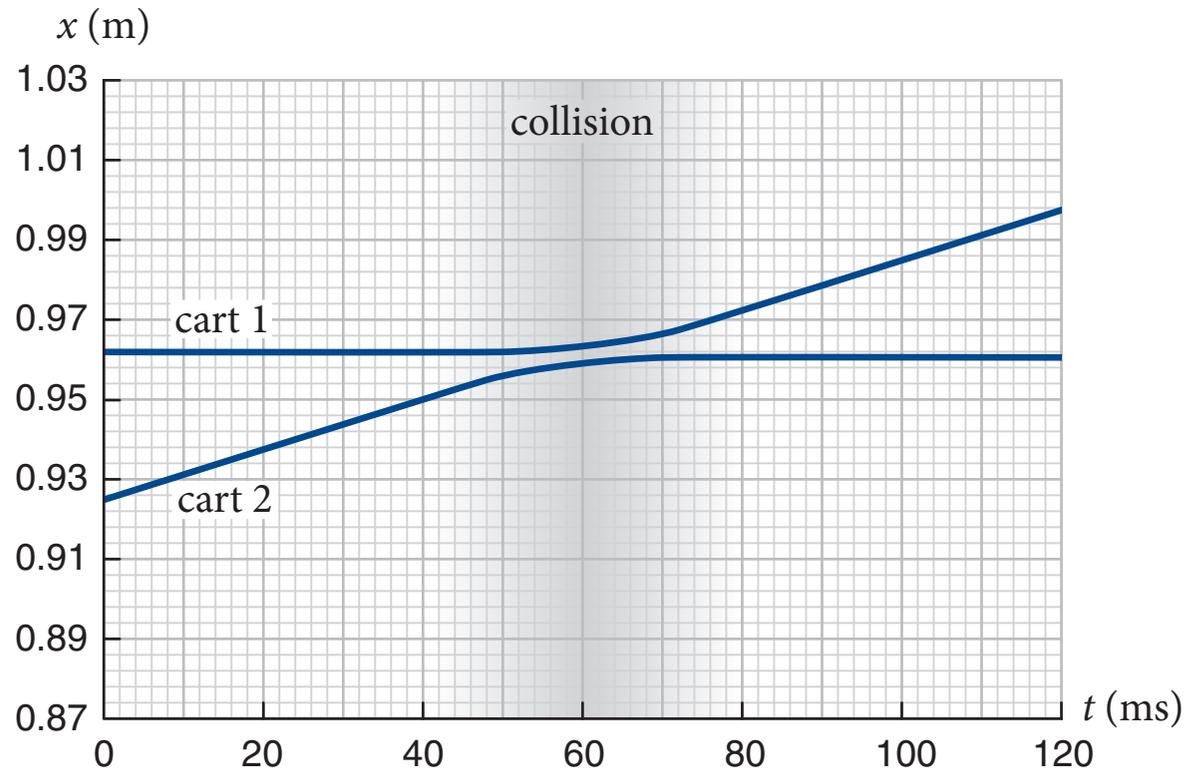
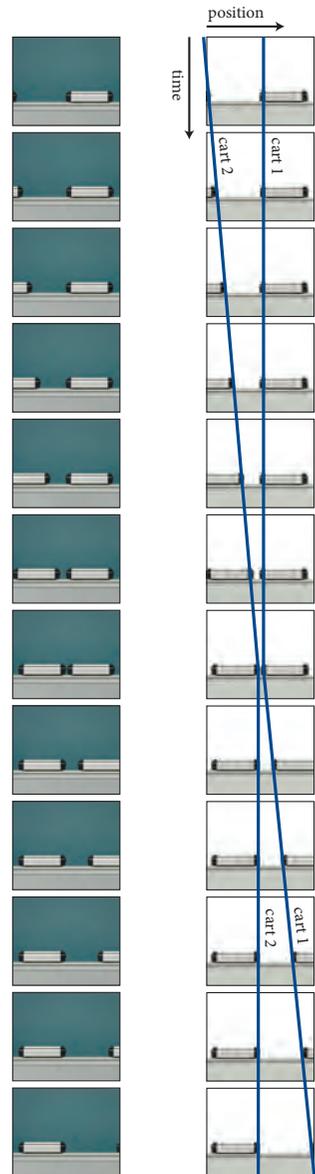
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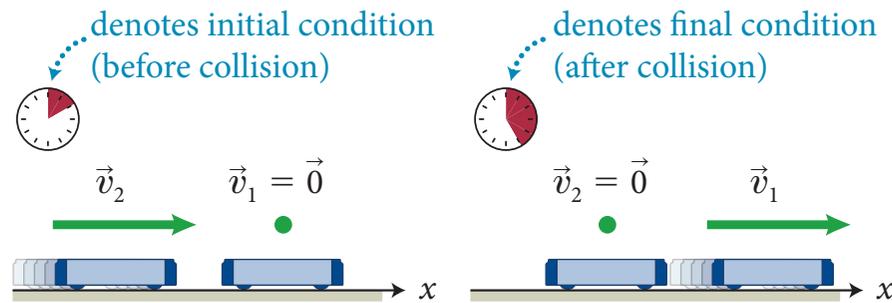
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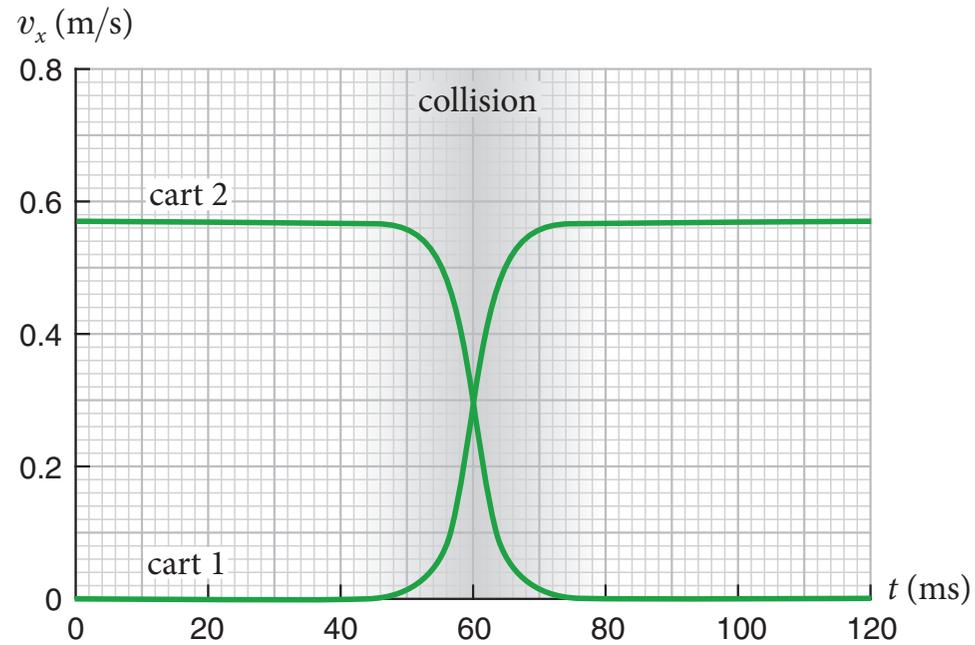
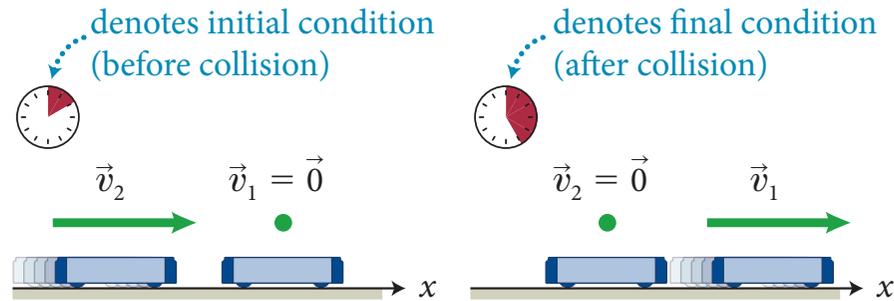


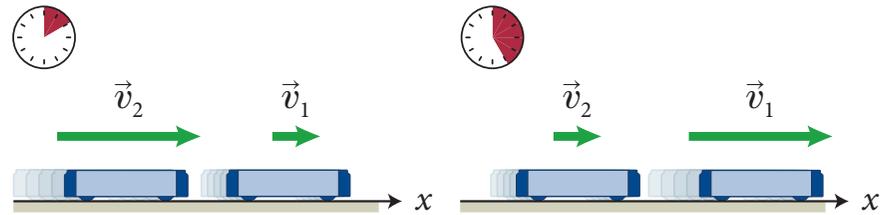
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2 content



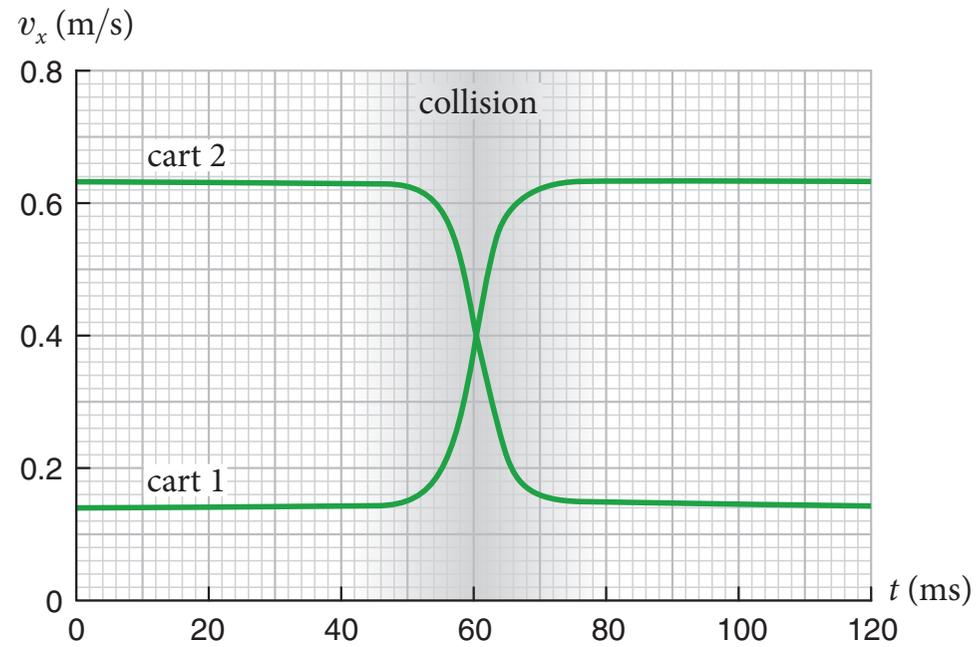
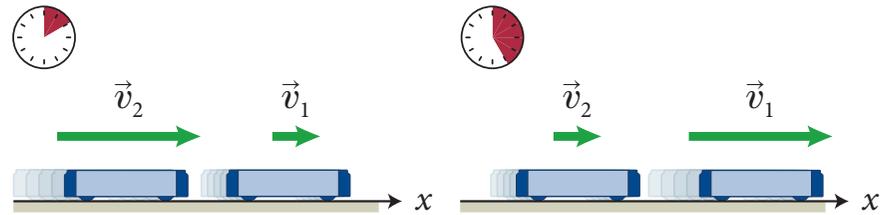


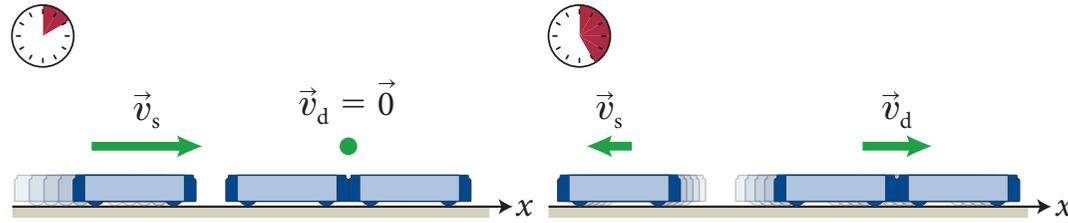


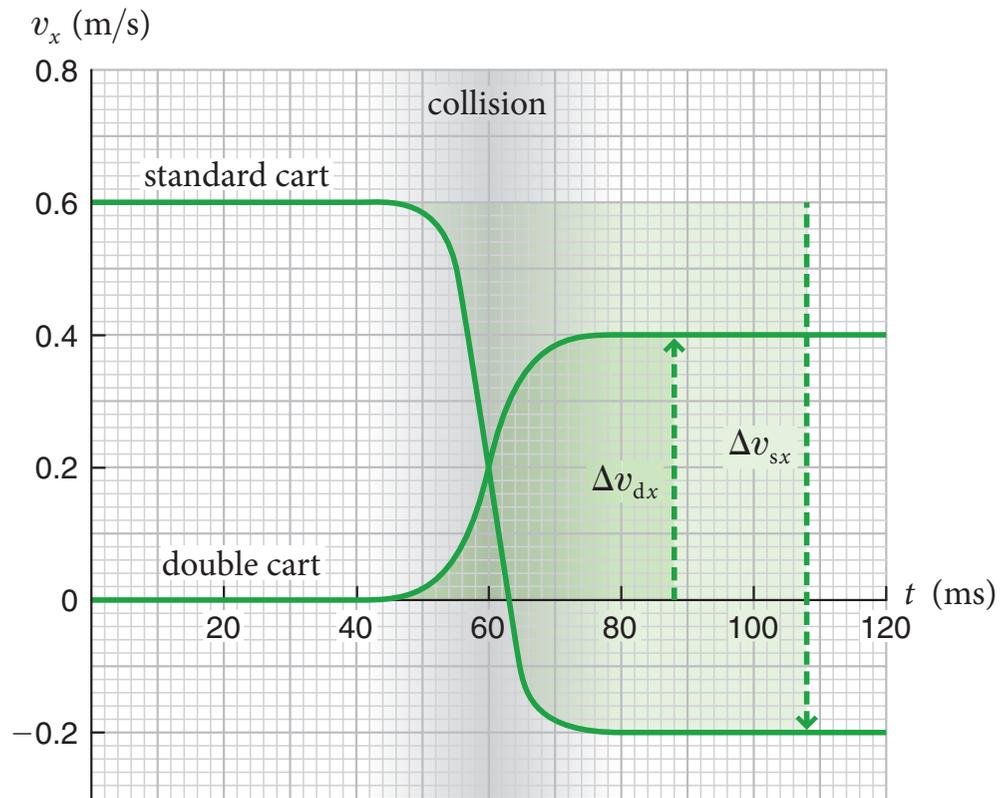
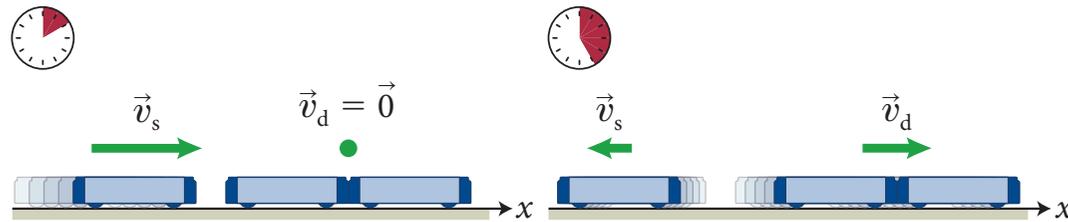


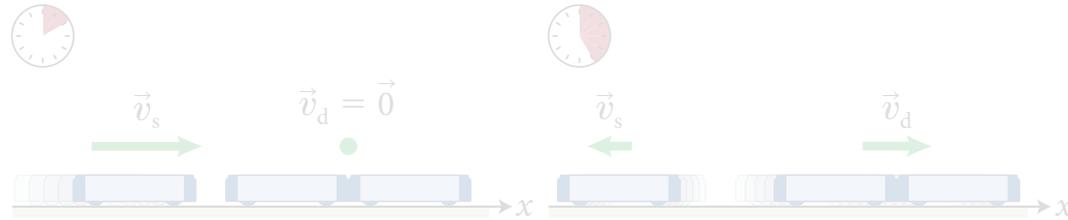
1 architecture

2 content

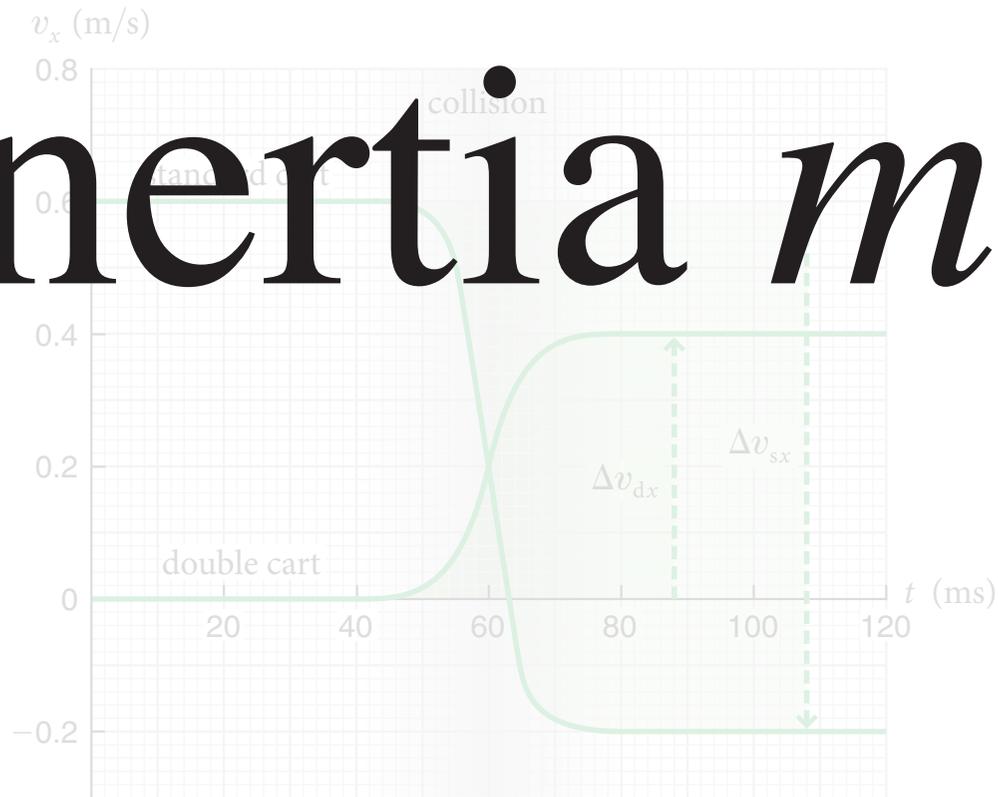




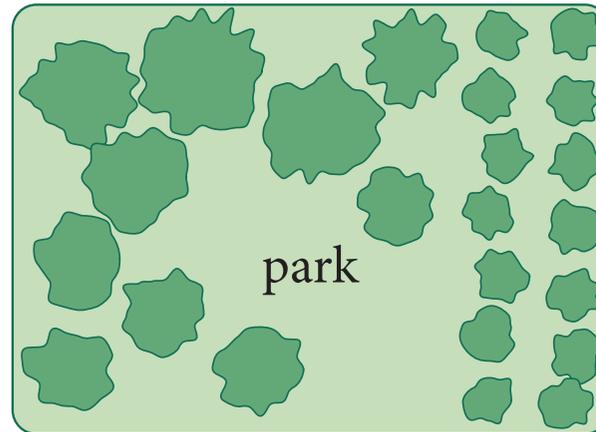
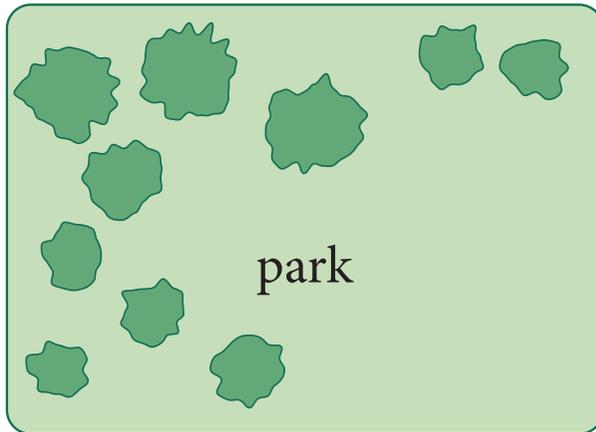




inertia m



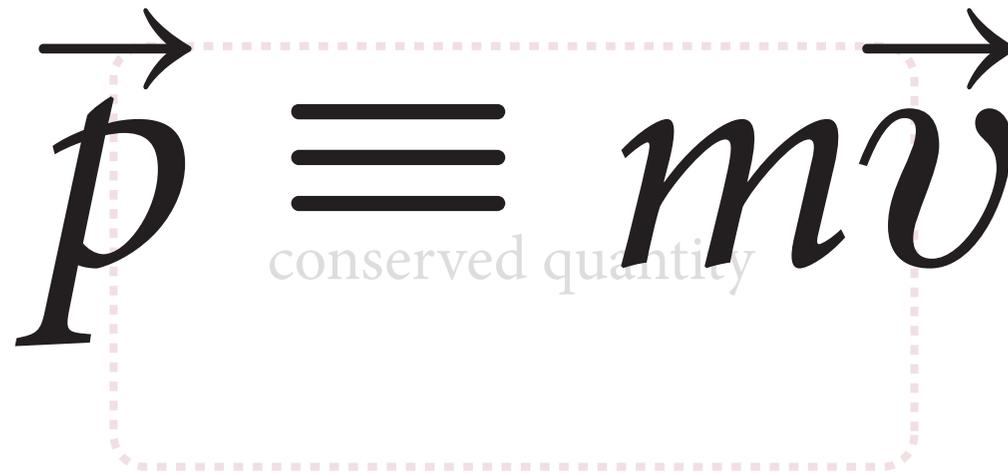
systems & extensive quantities

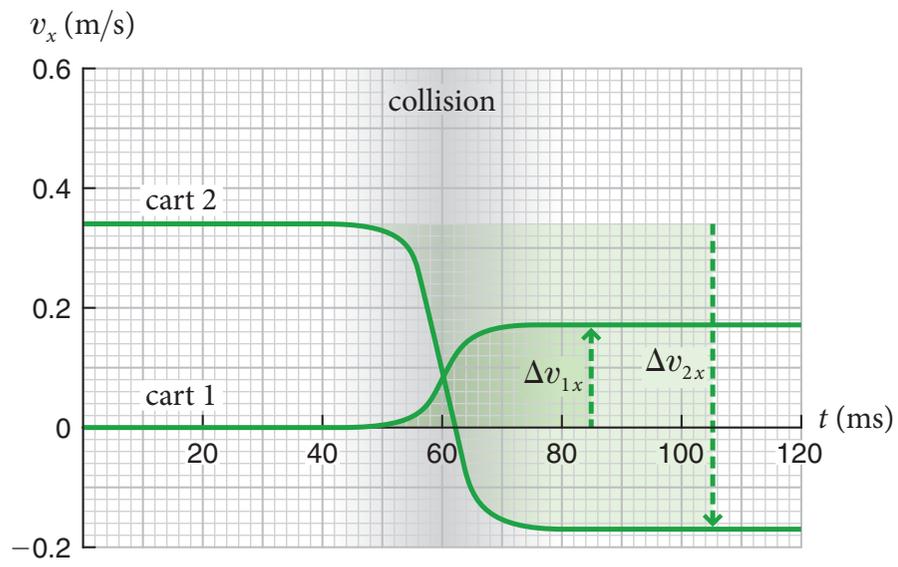


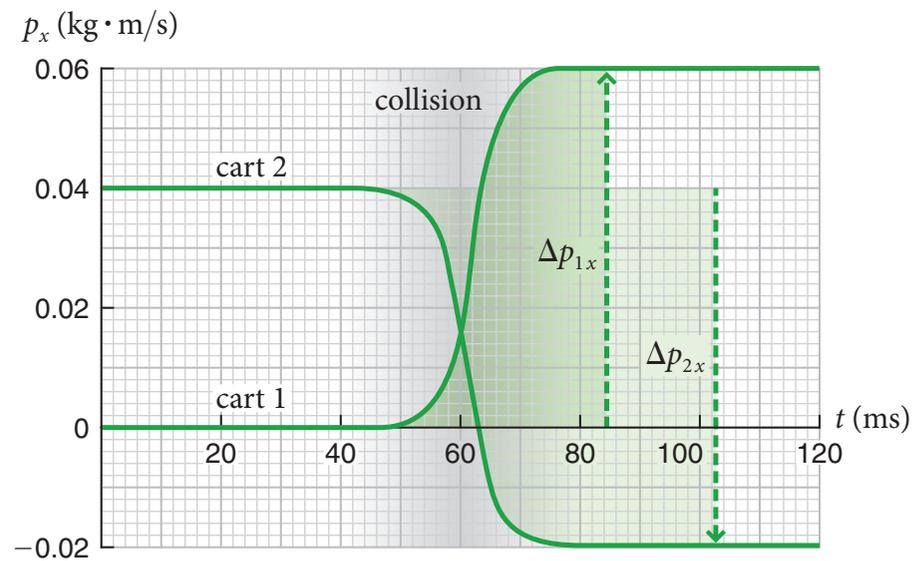
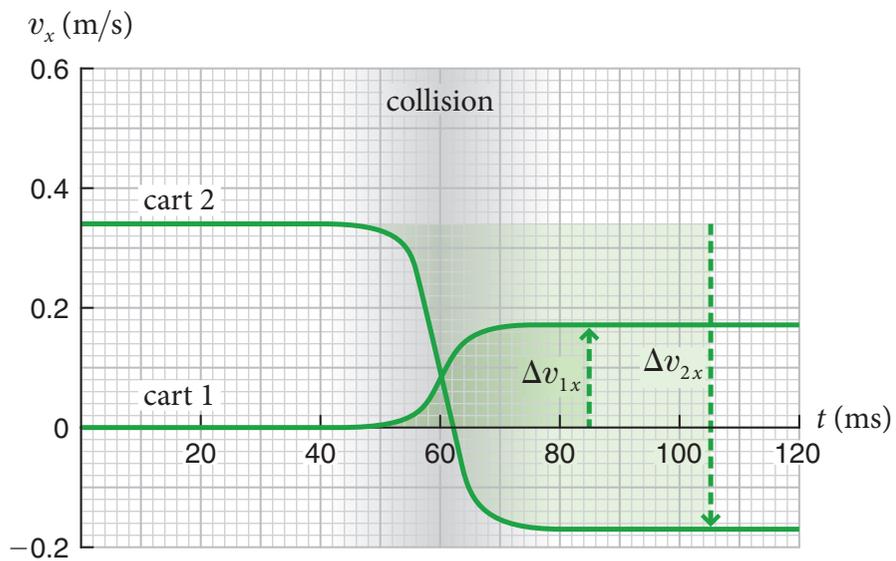
systems & extensive quantities

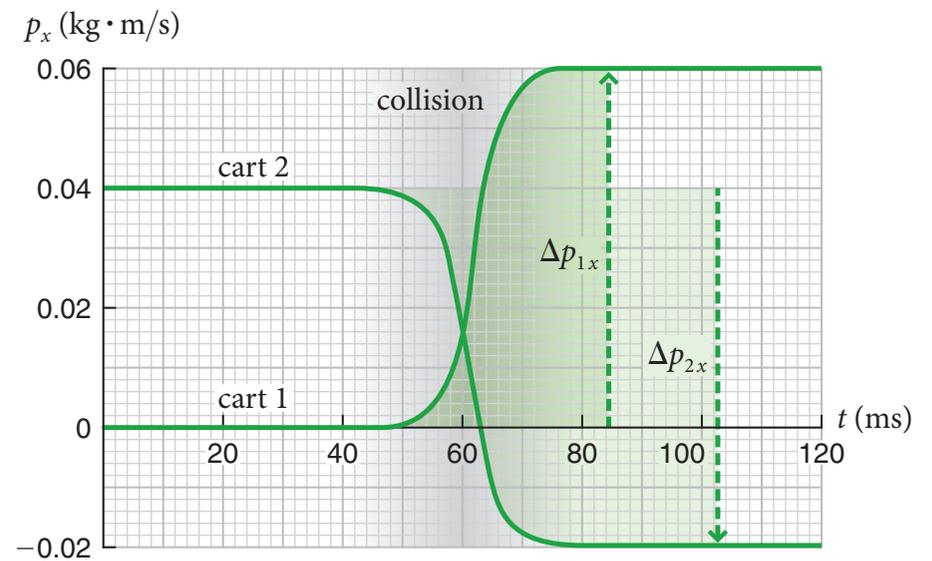
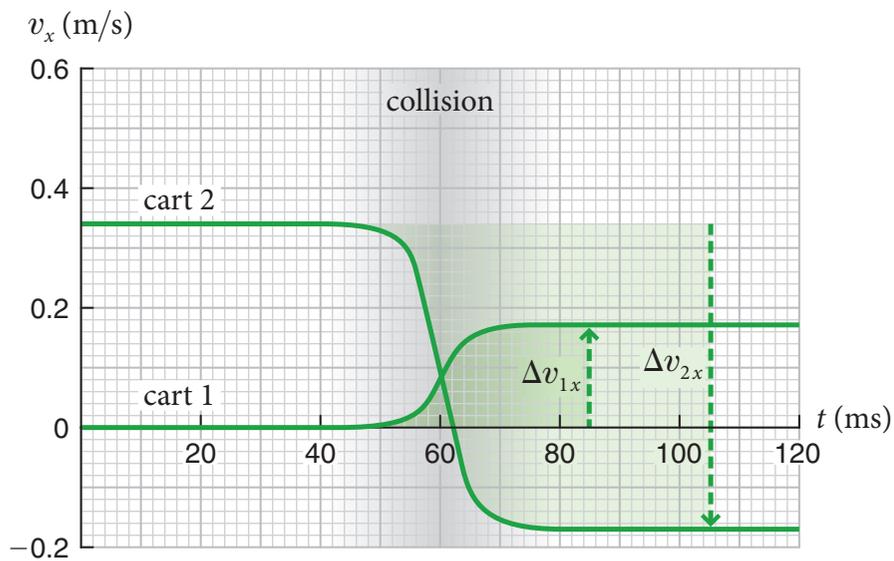
$$\vec{p} \equiv m\vec{v}$$

conserved quantity

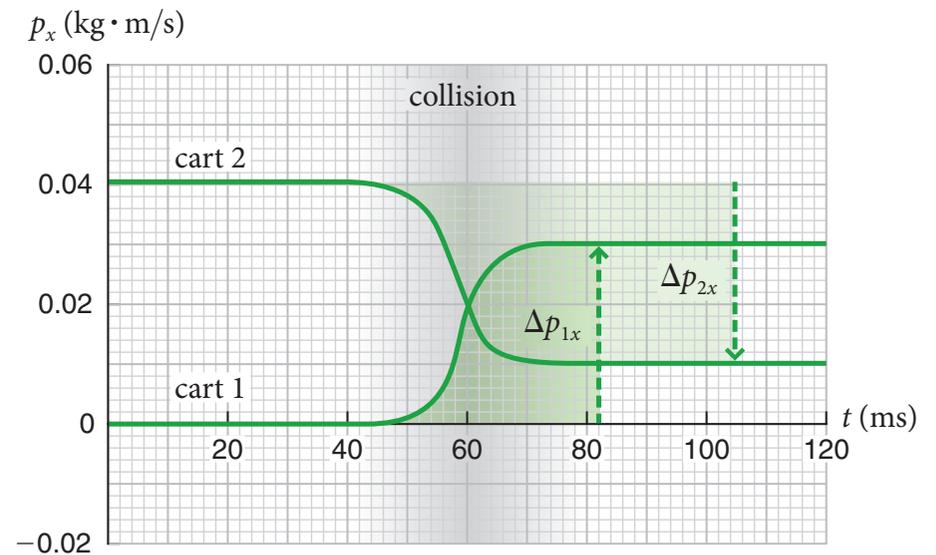
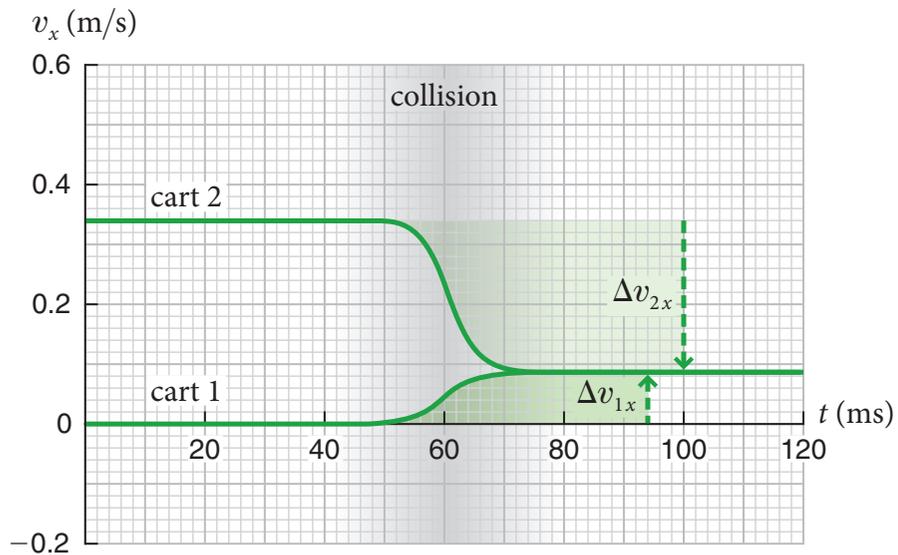




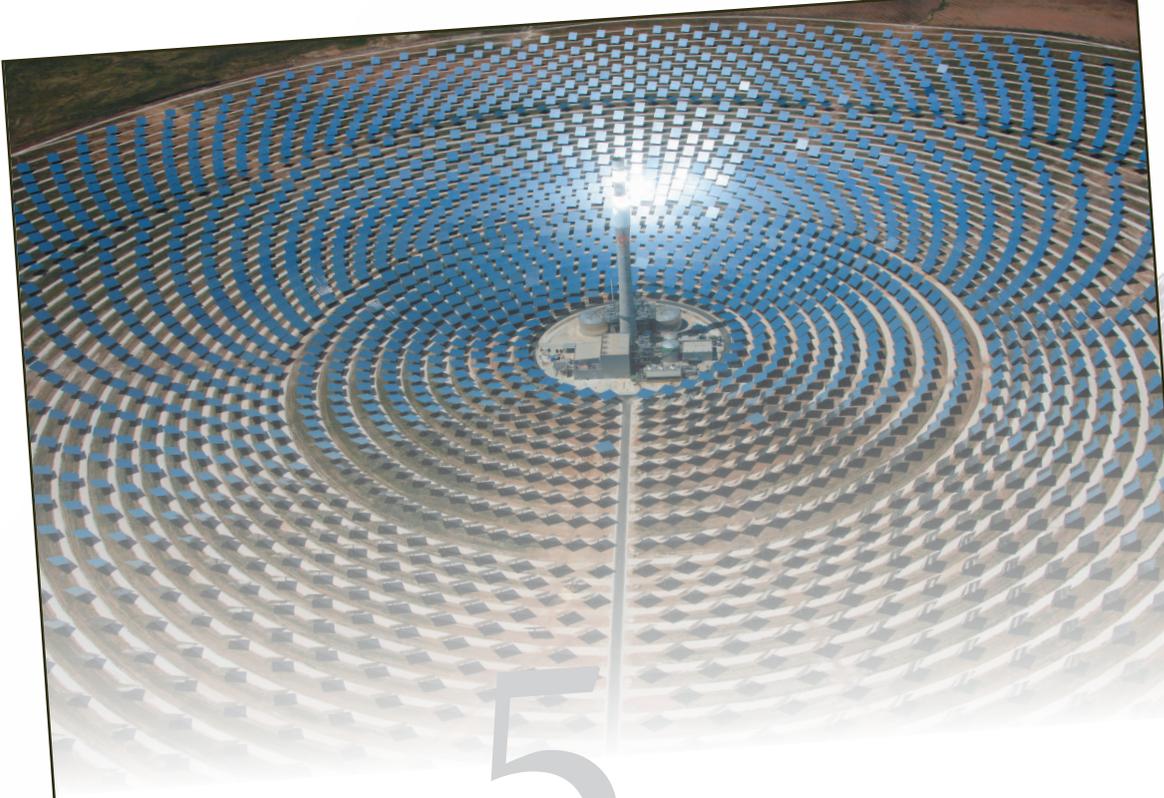




$$\Delta \vec{p} \equiv \Delta \vec{p}_1 + \Delta \vec{p}_2 = \vec{0}.$$



$$\Delta \vec{p} \equiv \Delta \vec{p}_1 + \Delta \vec{p}_2 = \vec{0}.$$



5

Energy

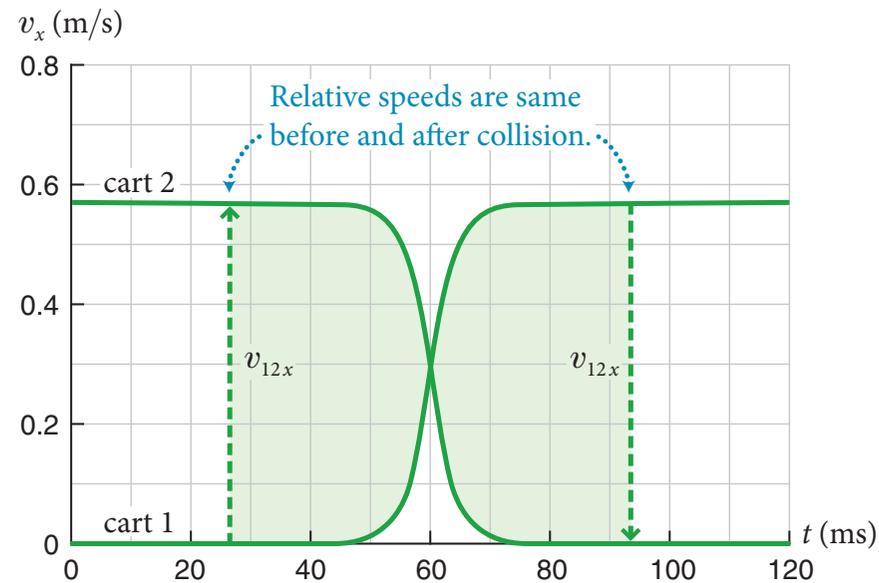
- 5.1 Classification of collisions
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems

- 5.5 Elastic collisions
- 5.6 Inelastic collisions
- 5.7 Conservation of energy
- 5.8 Explosive separations

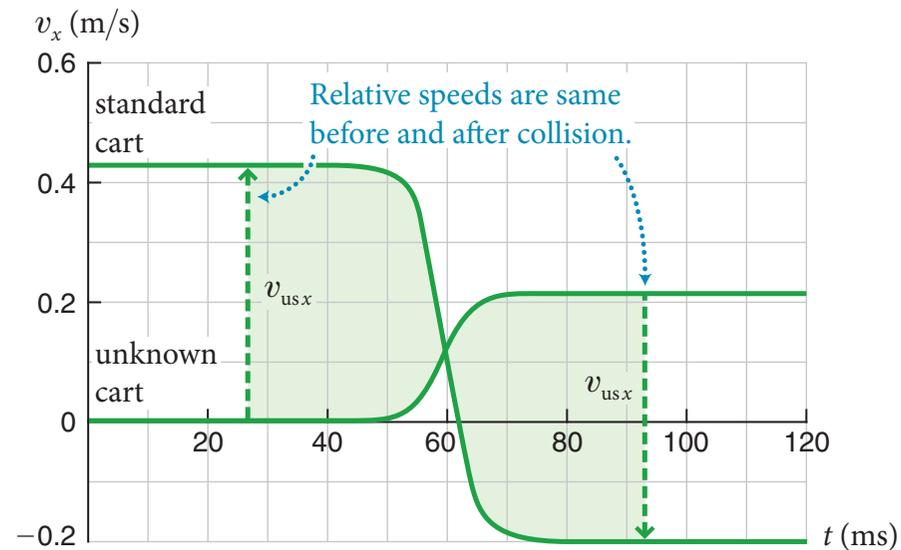
CONCEPTS

QUANTITATIVE TOOLS

elastic: relative speed unchanged

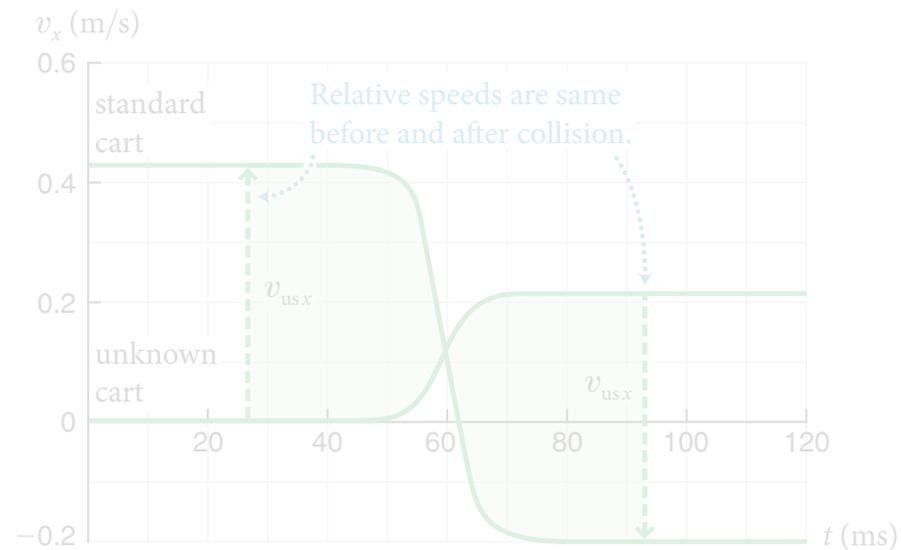


elastic: relative speed unchanged



elastic: relative speed unchanged

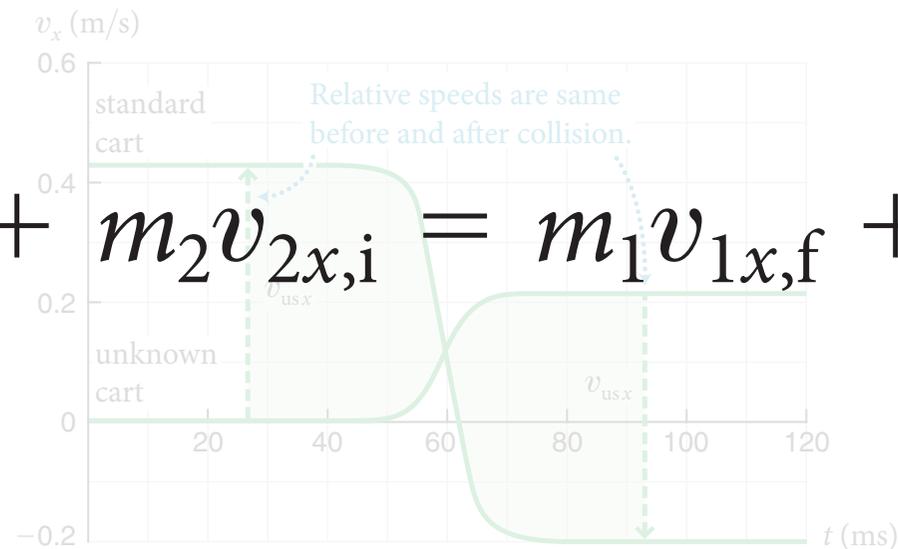
$$v_{12i} = v_{12f}$$



elastic: relative speed unchanged

$$v_{12i} = v_{12f}$$

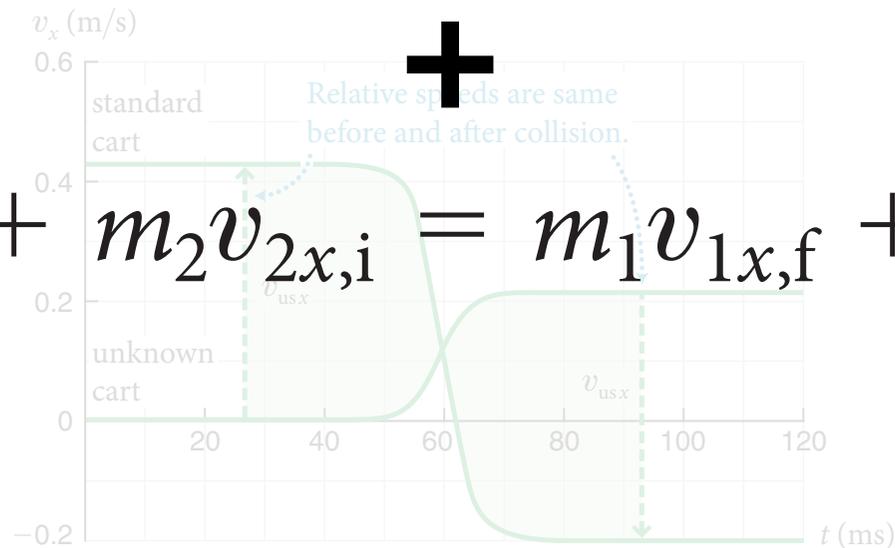
$$m_1 v_{1x,i} + m_2 v_{2x,i} = m_1 v_{1x,f} + m_2 v_{2x,f}$$



elastic: relative speed unchanged

$$v_{12i} = v_{12f}$$

$$m_1 v_{1x,i} + m_2 v_{2x,i} = m_1 v_{1x,f} + m_2 v_{2x,f}$$

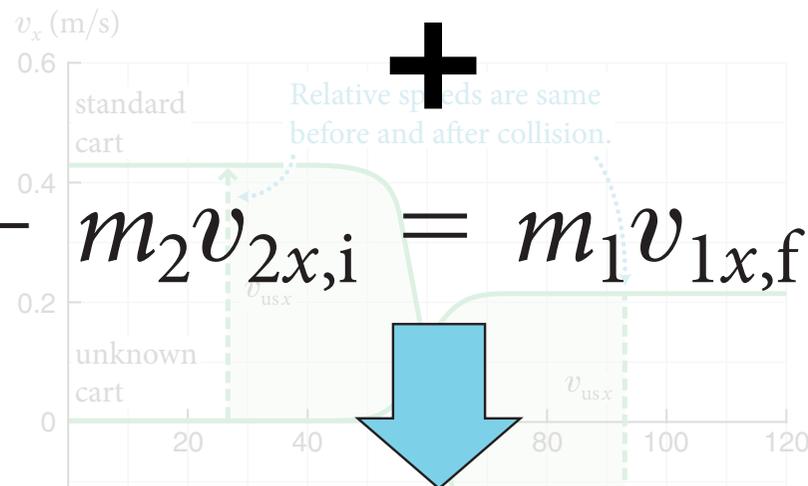


elastic: relative speed unchanged

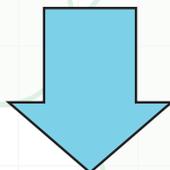
$$v_{12i} = v_{12f}$$

$$m_1 v_{1x,i} + m_2 v_{2x,i} = m_1 v_{1x,f} + m_2 v_{2x,f}$$

$$\frac{1}{2} m_1 v_{1i}^2 + \frac{1}{2} m_2 v_{2i}^2 = \frac{1}{2} m_1 v_{1f}^2 + \frac{1}{2} m_2 v_{2f}^2$$



+



elastic vs. inelastic



elastic vs. inelastic



before or after?



elastic vs. inelastic



elastic: reversible

inelastic: irreversible



elastic vs. inelastic

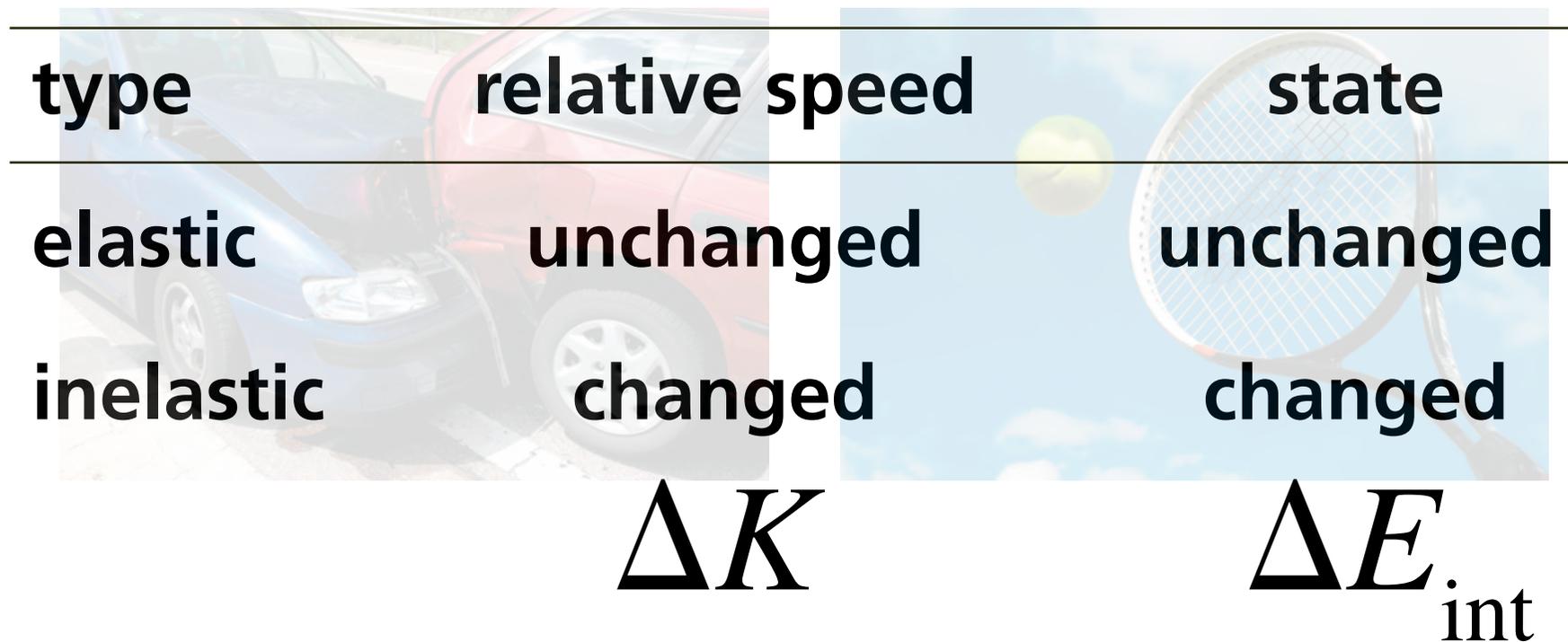
type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

elastic vs. inelastic

type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

$$\Delta K$$

elastic vs. inelastic



type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

ΔK ΔE_{int}

conservation of energy

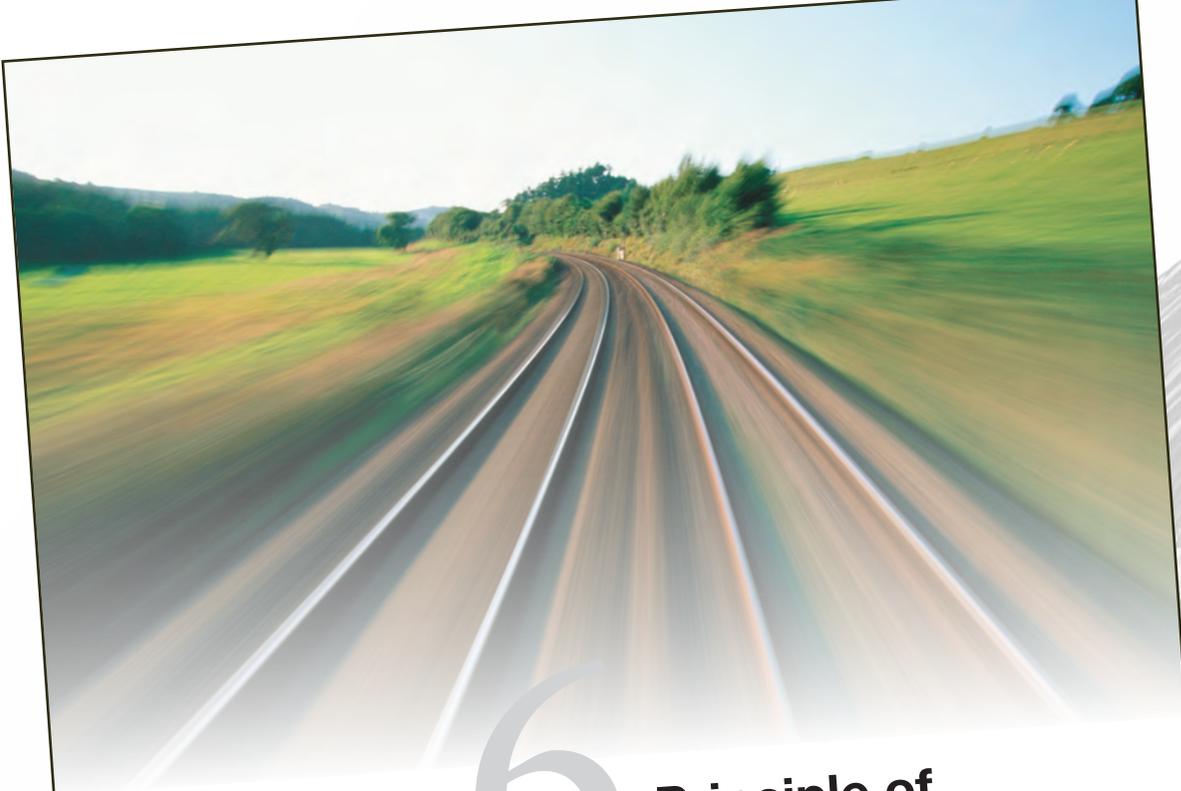
$$E = K + E_{\text{int}}$$

conservation of energy

$$E = K + E_{\text{int}}$$

closed system:

$$\Delta E = 0$$



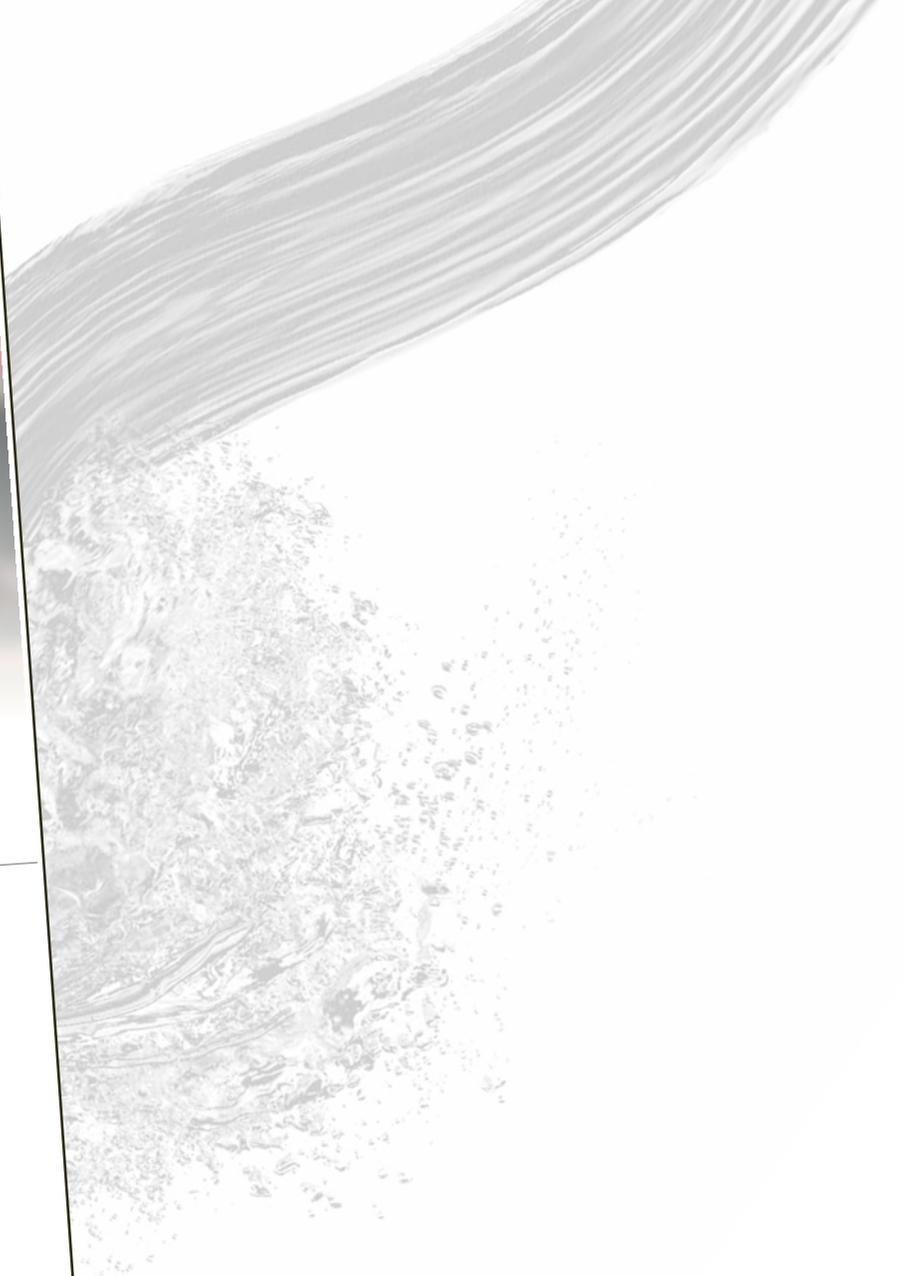
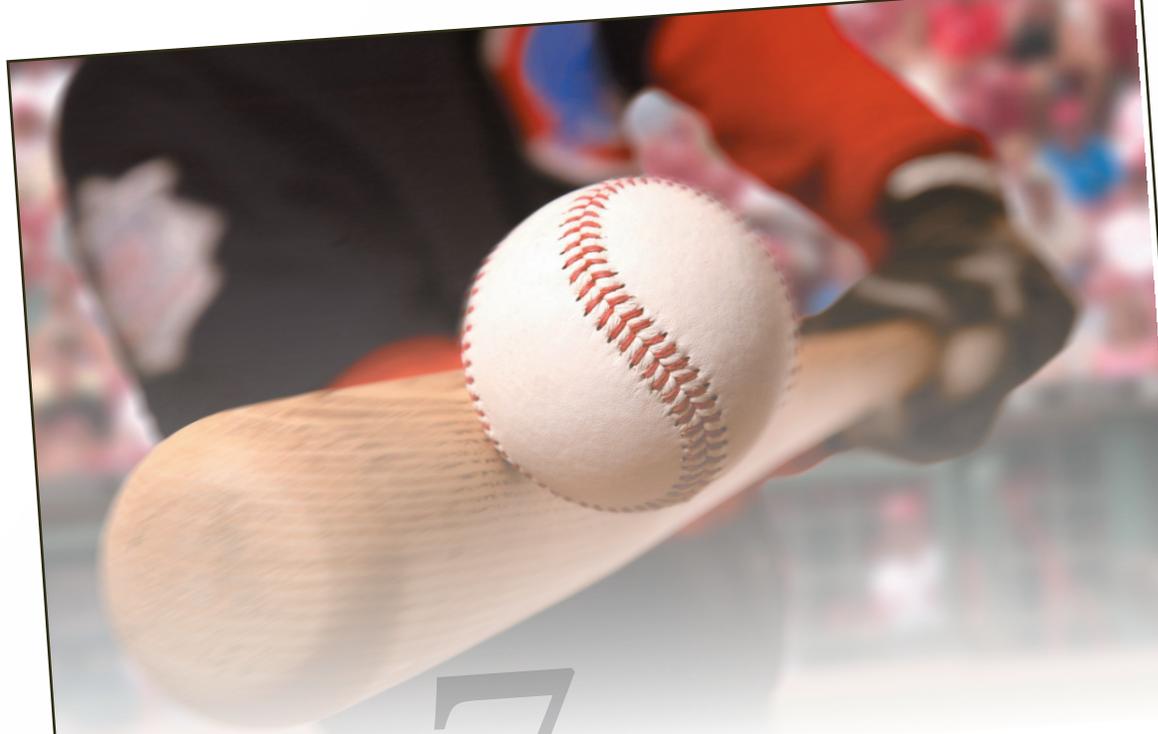
6 Principle of Relativity

- 6.1 Relativity of motion
- 6.2 Inertial reference frames
- 6.3 Principle of relativity
- 6.4 Zero-momentum reference frame

- 6.5 Galilean relativity
- 6.6 Center of mass
- 6.7 Convertible kinetic energy
- 6.8 Conservation laws and relativity

CONCEPTS

QUANTITATIVE TOOLS



7

Interactions

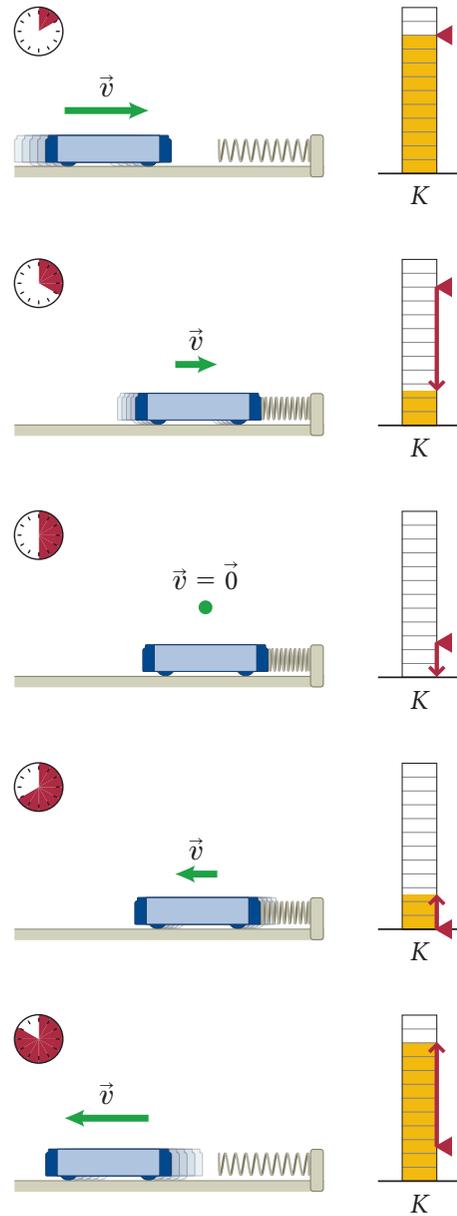
CONCEPTS

- 7.1 The effects of interactions
- 7.2 Potential energy
- 7.3 Energy dissipation
- 7.4 Source energy
- 7.5 Interaction range
- 7.6 Fundamental interactions

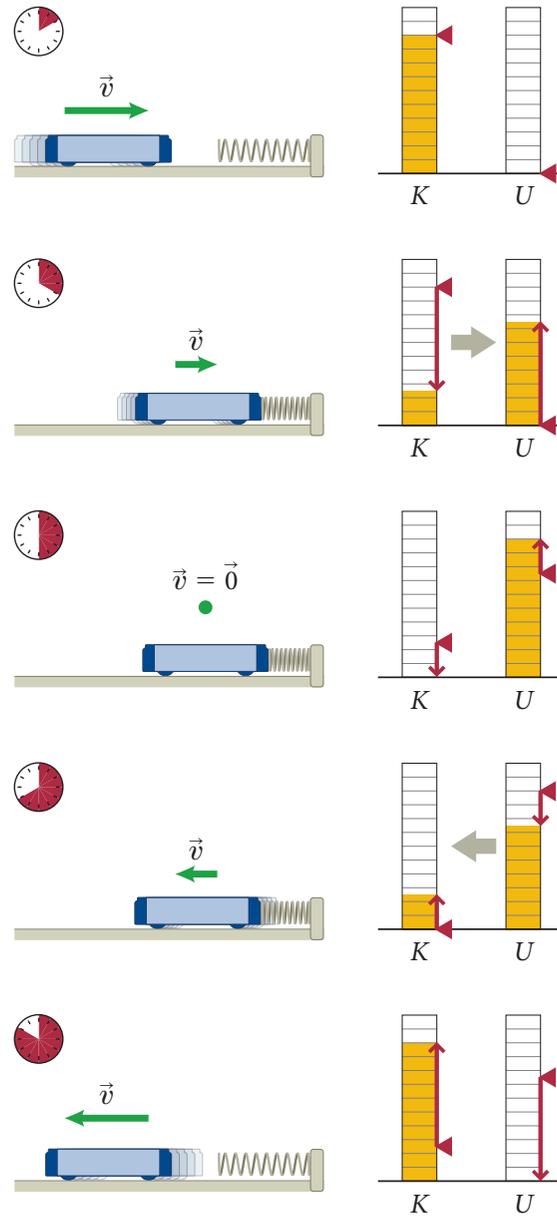
QUANTITATIVE TOOLS

- 7.7 Interactions and accelerations
- 7.8 Nondissipative interactions
- 7.9 Potential energy near Earth's surface
- 7.10 Dissipative interactions

potential energy

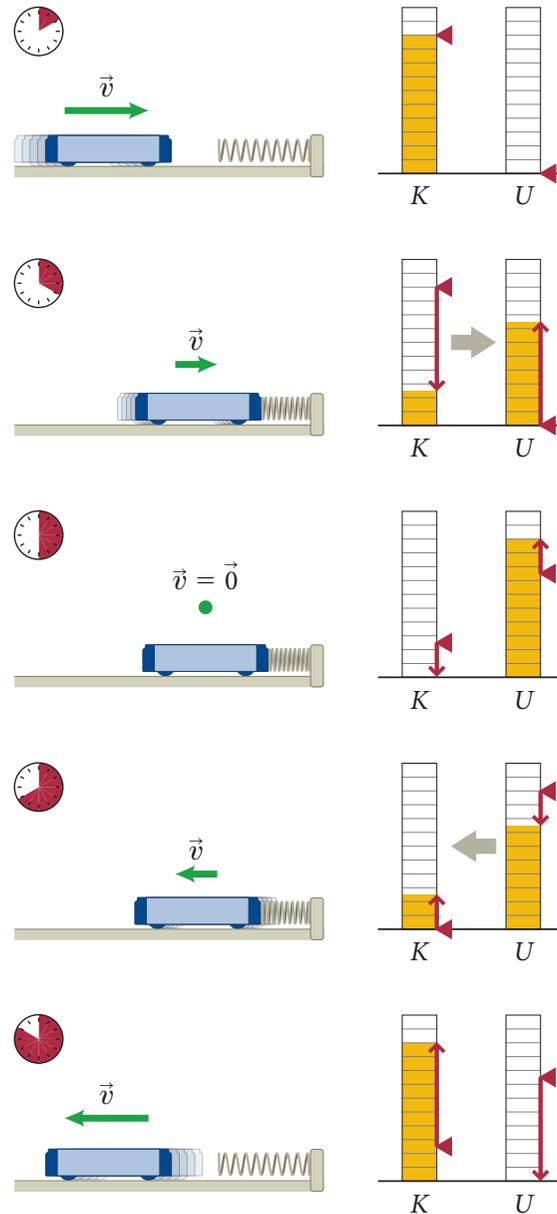


potential energy



potential energy

reversible state change





8

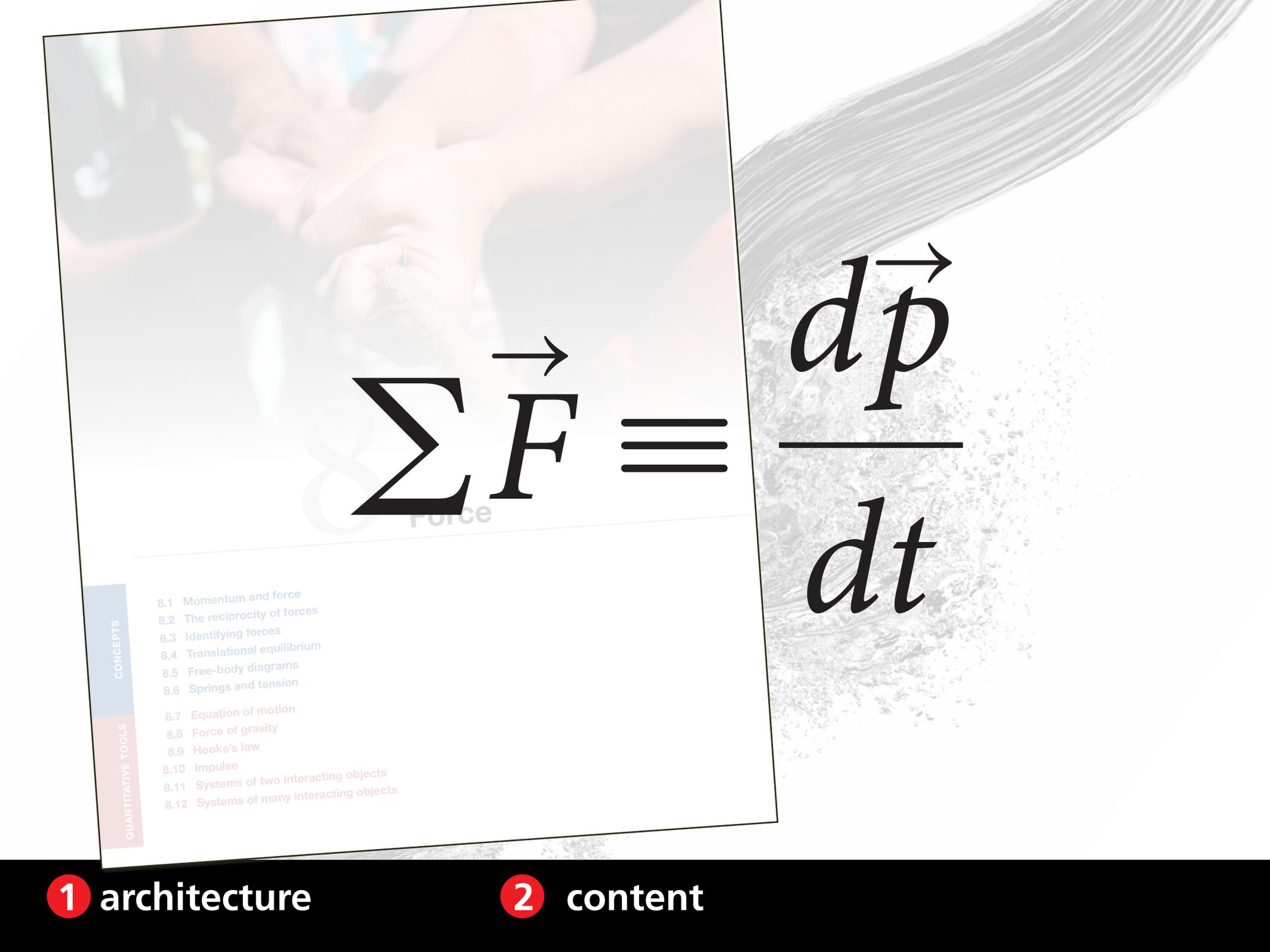
Force

CONCEPTS

- 8.1 Momentum and force
- 8.2 The reciprocity of forces
- 8.3 Identifying forces
- 8.4 Translational equilibrium
- 8.5 Free-body diagrams
- 8.6 Springs and tension

QUANTITATIVE TOOLS

- 8.7 Equation of motion
- 8.8 Force of gravity
- 8.9 Hooke's law
- 8.10 Impulse
- 8.11 Systems of two interacting objects
- 8.12 Systems of many interacting objects


$$\sum \vec{F} \equiv$$

$$\frac{d\vec{p}}{dt}$$

CONCEPTS

- 8.1 Momentum and force
- 8.2 The reciprocity of forces
- 8.3 Identifying forces
- 8.4 Translational equilibrium
- 8.5 Free-body diagrams
- 8.6 Springs and tension

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- 8.9 Hooke's law
- 8.10 Impulse
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- 8.12 Systems of many interacting objects



9

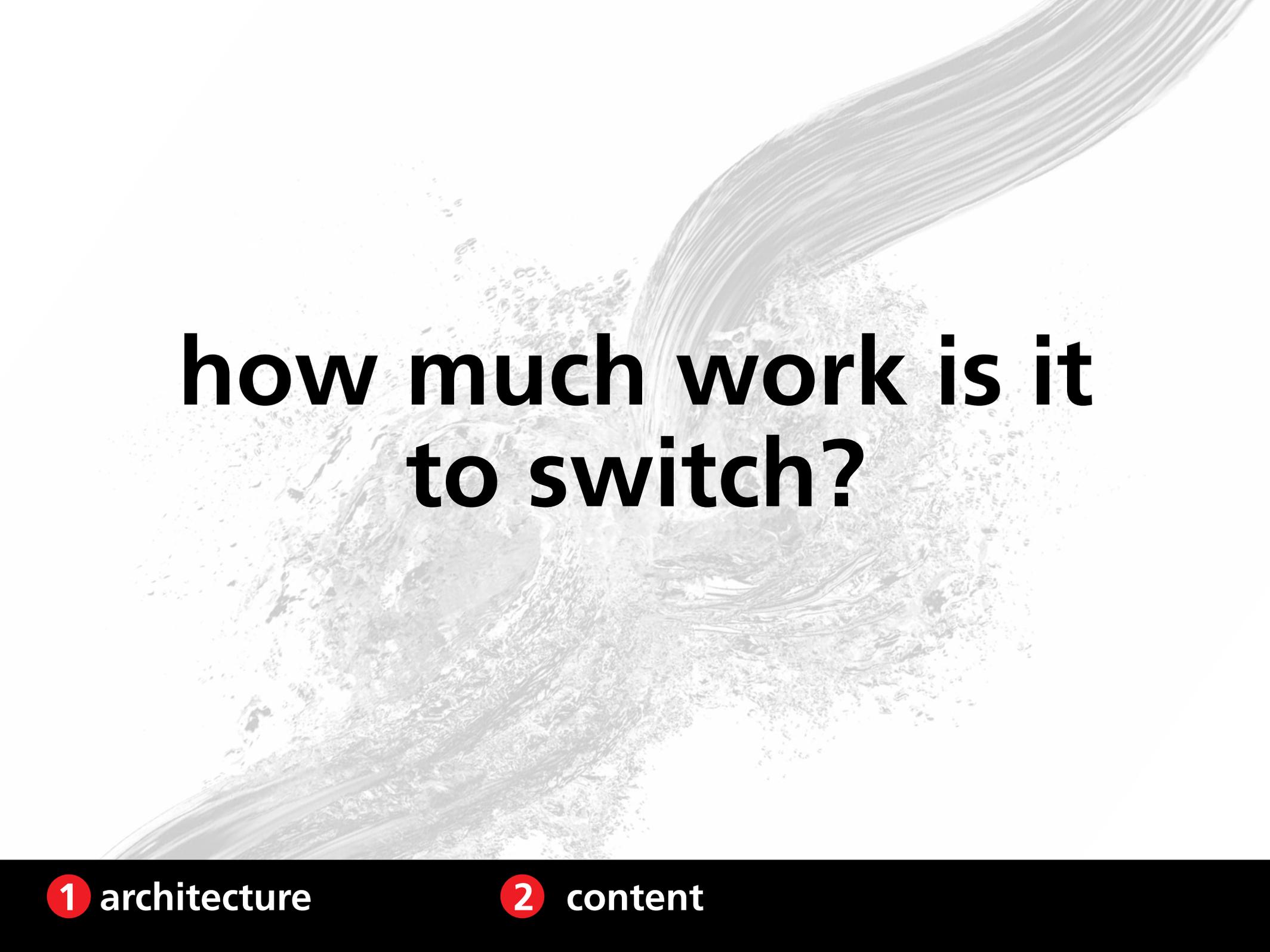
Work

CONCEPTS

- 9.1 Force displacement
- 9.2 Positive and negative work
- 9.3 Energy diagrams
- 9.4 Choice of system

QUANTITATIVE TOOLS

- 9.5 Work done on a single particle
- 9.6 Work done on a many-particle system
- 9.7 Variable and distributed forces
- 9.8 Power

A high-speed photograph of water splashing, creating a large, dynamic splash that fills the background. The water is captured in mid-air, with many droplets and a turbulent, swirling motion. The color is a light, translucent grey, giving it a soft, ethereal appearance. The splash originates from the top right and moves towards the bottom left, creating a sense of movement and energy.

**how much work is it
to switch?**

1 architecture

2 content

Traditional

1. Physics and measurement
2. Motion in one dimension
3. Vectors
4. Motion in two dimensions
5. The laws of motion
6. Circular motion
7. Work and kinetic energy
8. Potential energy and CoE
9. Momentum and collisions
10. Rotation about a fixed axis
11. Rolling motion and angular momentum
12. Static equilibrium and elasticity
13. Oscillatory motion
14. The law of gravity
15. Fluid mechanics
16. Wave motion
17. Sound waves
18. Superposition and standing waves

Principles and Practice

1. Foundations
2. Motion in one dimension
3. Acceleration
4. Momentum
5. Energy
6. Principle of relativity
7. Interactions
8. Force
9. Work
10. Motion in a plane
11. Motion in a circle
12. Torque
13. Gravity
14. Special Relativity
15. Periodic Motion
16. Waves in one dimension
17. Waves in 2 and 3 dimensions
18. Fluids

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1D

3D

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3D

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3D

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1D

3D

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Principles and Practice

1. Foundations
2. Motion in one dimension
3. Acceleration
4. Momentum
5. Energy **conservation**
6. Principle of relativity
7. Interactions
8. Force **dynamics**
9. Work
10. Motion in a plane
11. Motion in a circle
12. Torque
13. Gravity
14. Special Relativity
15. Periodic Motion
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rotation

Traditional

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18. Fluids

periodic

A dynamic splash of water in shades of grey and white, with a thick, curved stream of water falling from the top right towards the center. The water is splashing and creating many small droplets and bubbles.

**mostly minor
rearrangements!**

1 architecture

2 content

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

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PHYSICS

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1 architecture

2 content

3 results

PRINCIPLES & PRACTICE OF
PHYSICS

for students

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

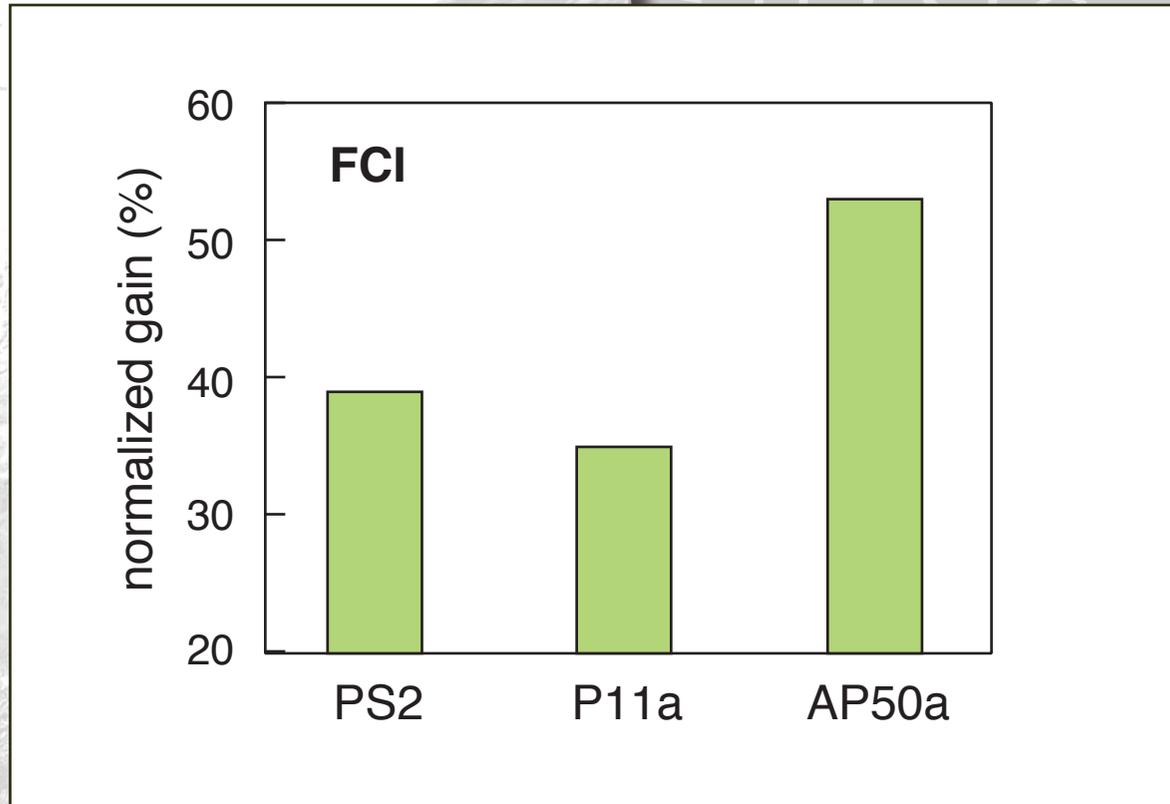
ERIC MAZUR

1 architecture

2 content

3 results

AP50: no lectures, students read book only



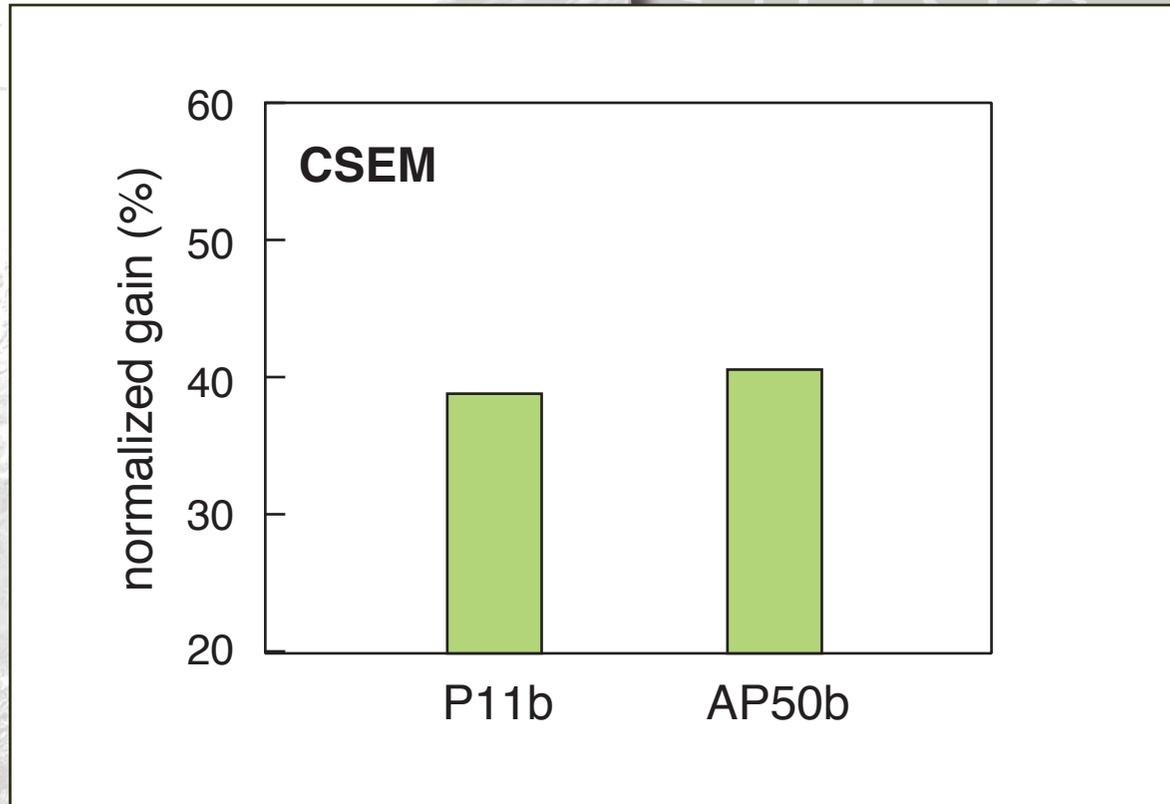
largest conceptual gain in *any* course past 6 yrs!

1 architecture

2 content

3 results

AP50: no lectures, students read book only



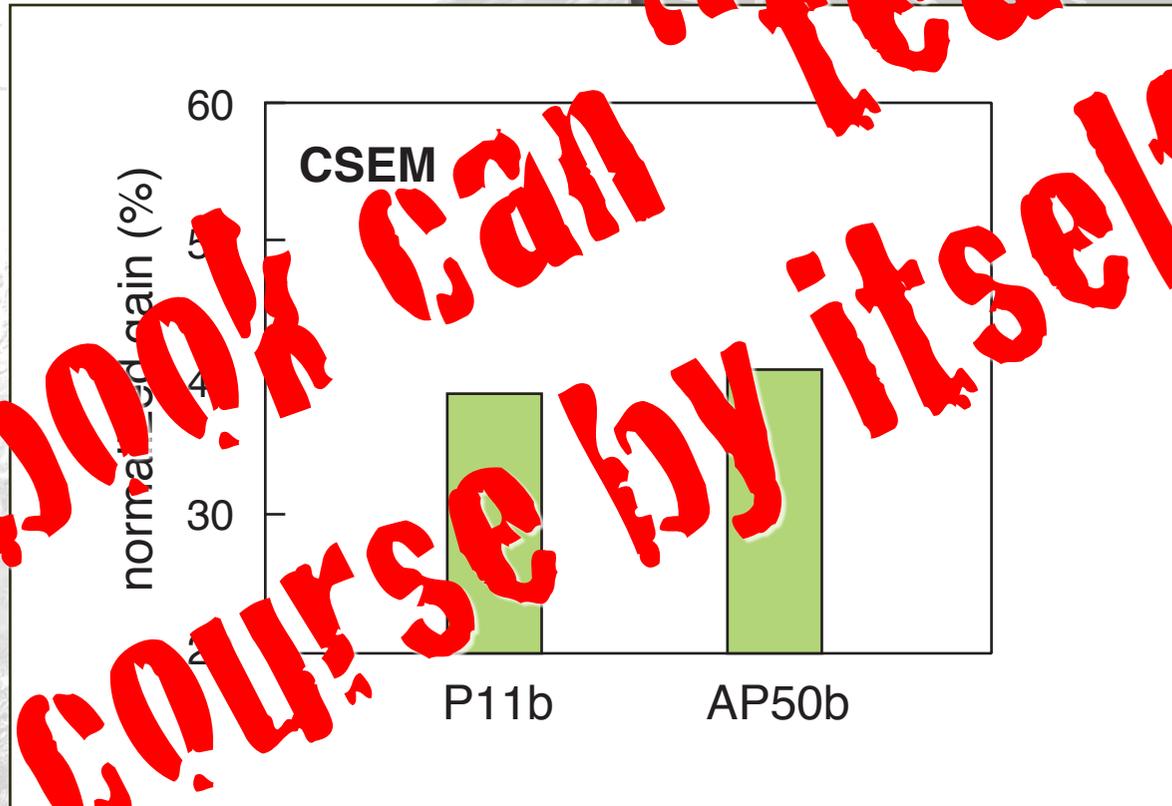
as good as when I do my best teaching!

1 architecture

2 content

3 results

AP50: no lectures, students read book only



this book can "teach" the course by itself...

as good as when I do my best teaching!

1 architecture

2 content

3 results

University of Arkansas

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PHYSICS

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

**course revision based on
preliminary version of manuscript:**

1 architecture

2 content

3 results

University of Arkansas

PRINCIPLES & PRACTICE OF
PHYSICS

PRINCIPLES & PRACTICE OF
PHYSICS

**course revision based on
preliminary version of manuscript:
normalized FCI gain DOUBLED**

ERIC MAZUR

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1 architecture

2 content

3 results

Current Adoptions

Abilene Christian University
Bellingham Technical College
Bethany Lutheran College
Chaffey College
Eastfield College
Embry-Riddle Aera Universit–Prescott
Evergreen State College
Florida State University
Gallaudet University
Gogebic Community College
Harvard University
Highline Community College
Hope College
Ithaca College
James Madison University
Laramie County Community College
Louisiana State University
Monmouth Univiversity
Normandale Community College
Northeastern University
Otterbein University
Penn State University
Siena College
Southwestern Illinois College

Spokane Falls Community College
St Olaf College
Suffolk University
University of Arkansas
University of Central Florida
University of Florida
University of Connecticut–Storrs
University of Maine at Orono
University of Minnesota
University of Pennsylvania
University of Washington
Victoria College
Virginia Tech University
Washington University
Williams College

John Abbott College (Canada)
Helsinki University (Finland)
McMaster University (Canada)
Monash University (Australia)
Mount Saint Vincent University (Canada)
University of British Columbia (Canada)
University of Toronto (Canada)
University of Waterloo (Canada, 2016)

1 architecture

2 content

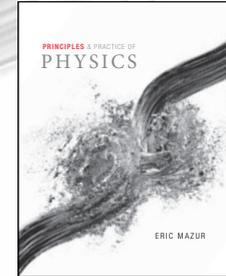
3 results

approach

before class

in class

traditional



1 architecture

2 content

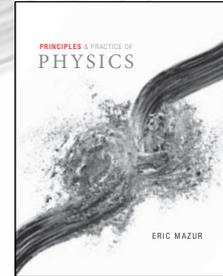
3 results

approach

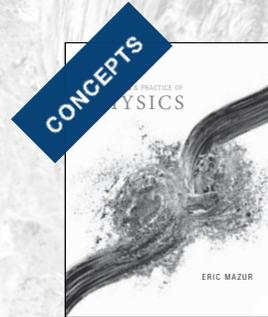
before class

in class

traditional



partially flipped



1 architecture

2 content

3 results

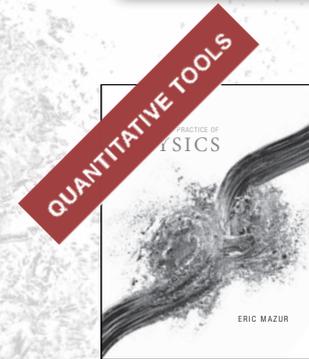
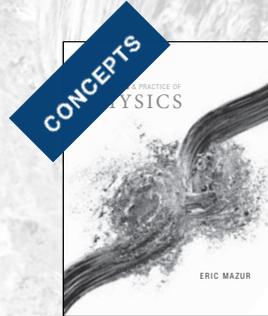
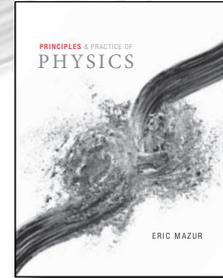
approach

before class

in class

traditional

partially flipped



1 architecture

2 content

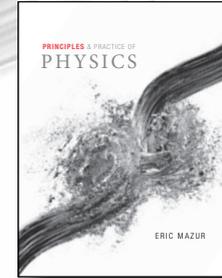
3 results

approach

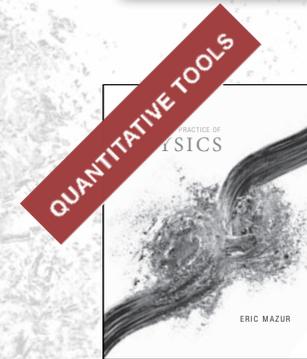
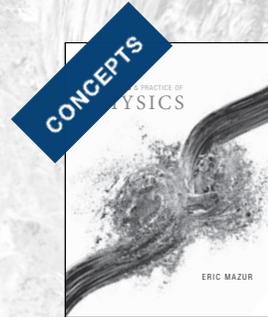
before class

in class

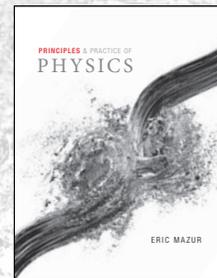
traditional



partially flipped



fully flipped



1 architecture

2 content

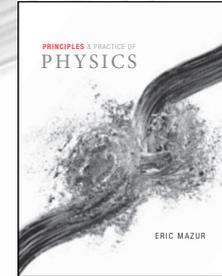
3 results

approach

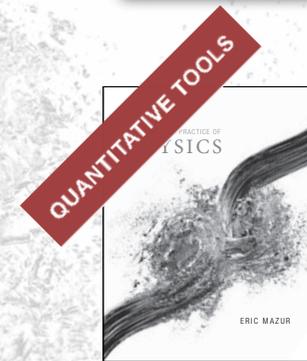
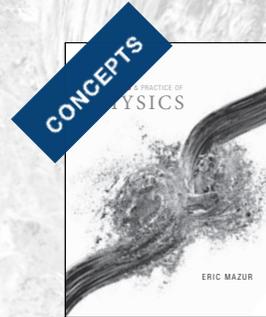
before class

in class

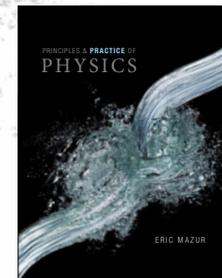
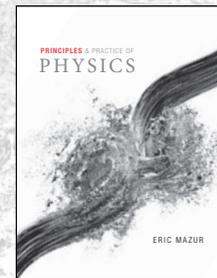
traditional



partially flipped



fully flipped



1 architecture

2 content

3 results

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