

Teaching Physics, Conservation Laws First



Singapore, 5 April 2016



Teaching Physics, Conservation Laws First



@eric_mazur

Singapore, 5 April 2016



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

$T = 2\pi \sqrt{\frac{L}{g}}$ simple pend $T = 2\pi \sqrt{\frac{I}{mgh}}$ physical pend $Y(x,t) = y_m \sin(kx - \omega t)$ wave in pos direction $\omega_d = \omega$ 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 $f_{beat} = |f_1 - f_2|$ $I = \frac{\text{Power}}{\text{Area}} = \frac{P_s}{4\pi r^2}$ $I = \frac{1}{2} \rho v \omega^2 S_m^2$ $\sin \theta = \frac{v}{v_s}$ $\frac{v_s}{v} = \text{mach \#}$

$\frac{\Delta L}{L} = 0, 0.5, 2$ 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 $\log \frac{x}{y} = \log x - \log y$ $\log_0 x = y \Leftrightarrow 0^y = x$

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

$n = \frac{\text{molecules}}{6.02 \times 10^{23}}$ $PV = nRT$ $Q=0$ $\Delta E = -W$ $\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$

Pipe 2 open ends displacement antinodes pressure nodes $f = \frac{nv}{4L}$ ($n=1,2,3$) displacement antinodes at open, node at closed $I_0 = I_{x0}$ $B = (10) \log \frac{I}{I_0}$ $w = \int_{v_1}^{v_2} p dv$

vectors

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

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

$F = 2\pi \sqrt{\frac{E}{mgh}}$ physical pend $Y(x,t) = y_m \sin(kx - \omega t)$ wave in pos direction $v(t) = -\omega x_m \sin(\omega t + \theta)$ $a(t) = -\omega^2 x(t)$ $k = \frac{2\pi}{\lambda}$ $v = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f$ $v = \sqrt{\frac{T}{\mu}}$ $P_{ave} = \frac{1}{2} \mu v \omega^2$

resonance $\lambda = \frac{2L}{n}$ $n=1,2,3$ $v = \sqrt{\frac{E}{\rho}}$ Bulk modulus $\Delta P_m = v \rho \omega S_m$ displacement $f = \frac{v}{\lambda} = \frac{v}{2L}$ $n=1,2,3$ $P_m^2 = 2PVI$ $P_m = v \rho \omega S_m$ $I = \frac{Power}{Area} = \frac{P_s}{4\pi r^2}$ $f_{beat} = |f_1 - f_2|$ $f = \frac{v}{4L}$ ($n=1,2,3$) $\sin \theta = \frac{v}{v_s}$ $\frac{v_s}{v} = Mach \#$ $I_0 = 10^{-12}$

interference $\frac{\Delta L}{\lambda} = 0, 1/2$ fully constructive $\theta = \frac{\Delta L}{\lambda} 2\pi$ $I = \frac{1}{2} \rho v \omega^2 S_m^2$ $B = (10) \log \frac{I}{I_0}$ $\log \frac{x}{y} = \log x - \log y$ $\log_0 x = y \Leftrightarrow 0^y = x$

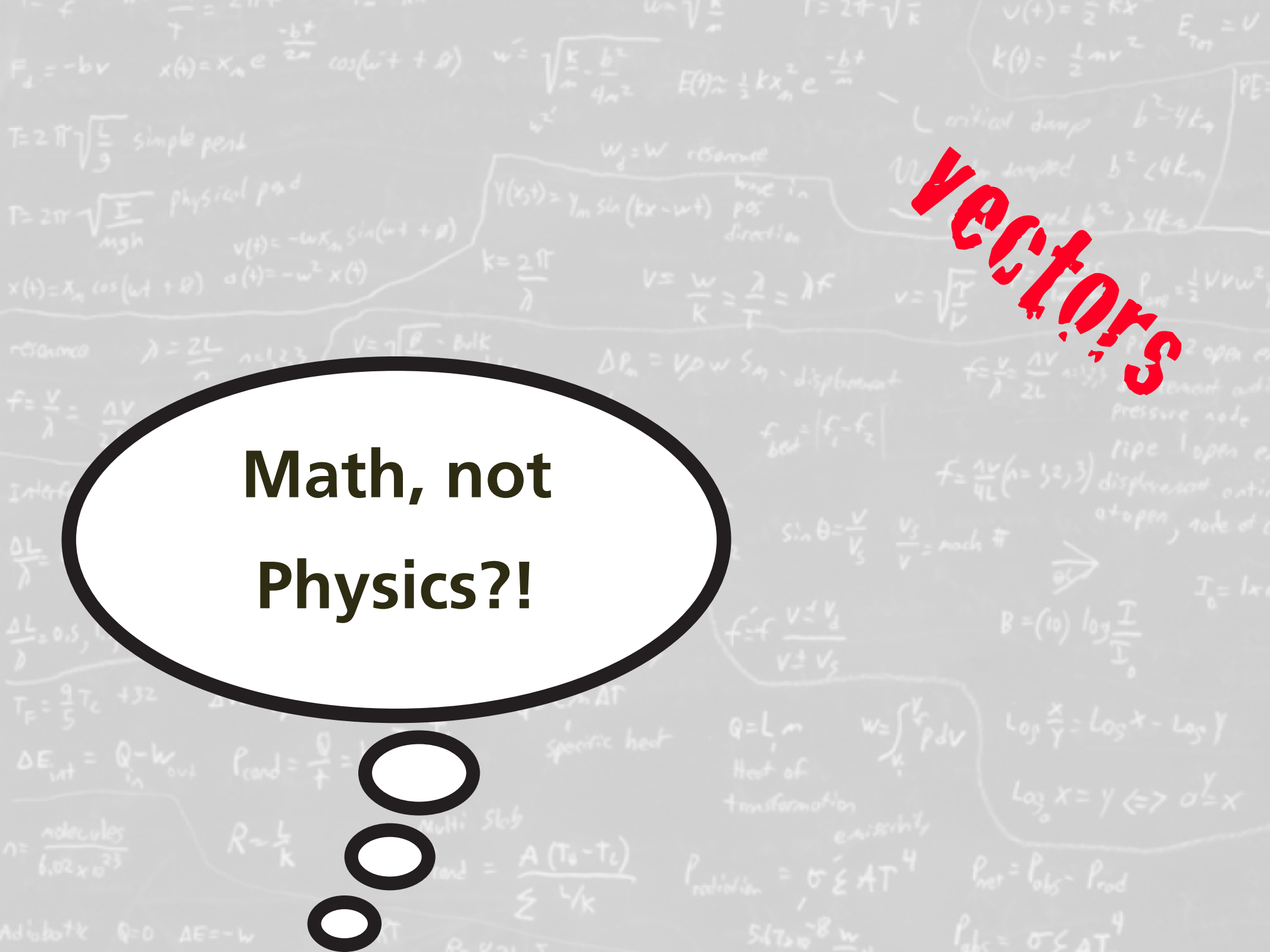
$\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5$ fully destructive $Q = c \Delta T$ Heat capacity $f = f \frac{v \pm v_d}{v \pm v_s}$ $Q = cm \Delta T$ specific heat $Q = L_m$ Heat of transformation $w = \int_{v_i}^{v_f} p dv$ $\log_0 x = y \Leftrightarrow 0^y = x$

$T_F = \frac{9}{5} T_C + 32$ $\Delta L = L \alpha \Delta T$ $\Delta V = V \beta \Delta T$ $\Delta E_{int} = Q_{in} - W_{out}$ $P_{cond} = \frac{Q}{t} = k \alpha \frac{T_h - T_c}{L}$ $P_{radiation} = \sigma \epsilon AT^4$ $P_{net} = P_{obs} - P_{prod}$ $P_{abs} = \sigma \epsilon AT^4$

$n = \frac{molecules}{6.02 \times 10^{23}}$ $R = \frac{L}{k}$ Multi Slab $P_{cond} = \frac{A(T_h - T_c)}{\sum L/k}$ $Adiabatic Q=0$ $\Delta E = -W$ $PV = nRT$ $P_{obs} = \sigma \epsilon AT^4$

**Math, not
Physics?!**

vectors



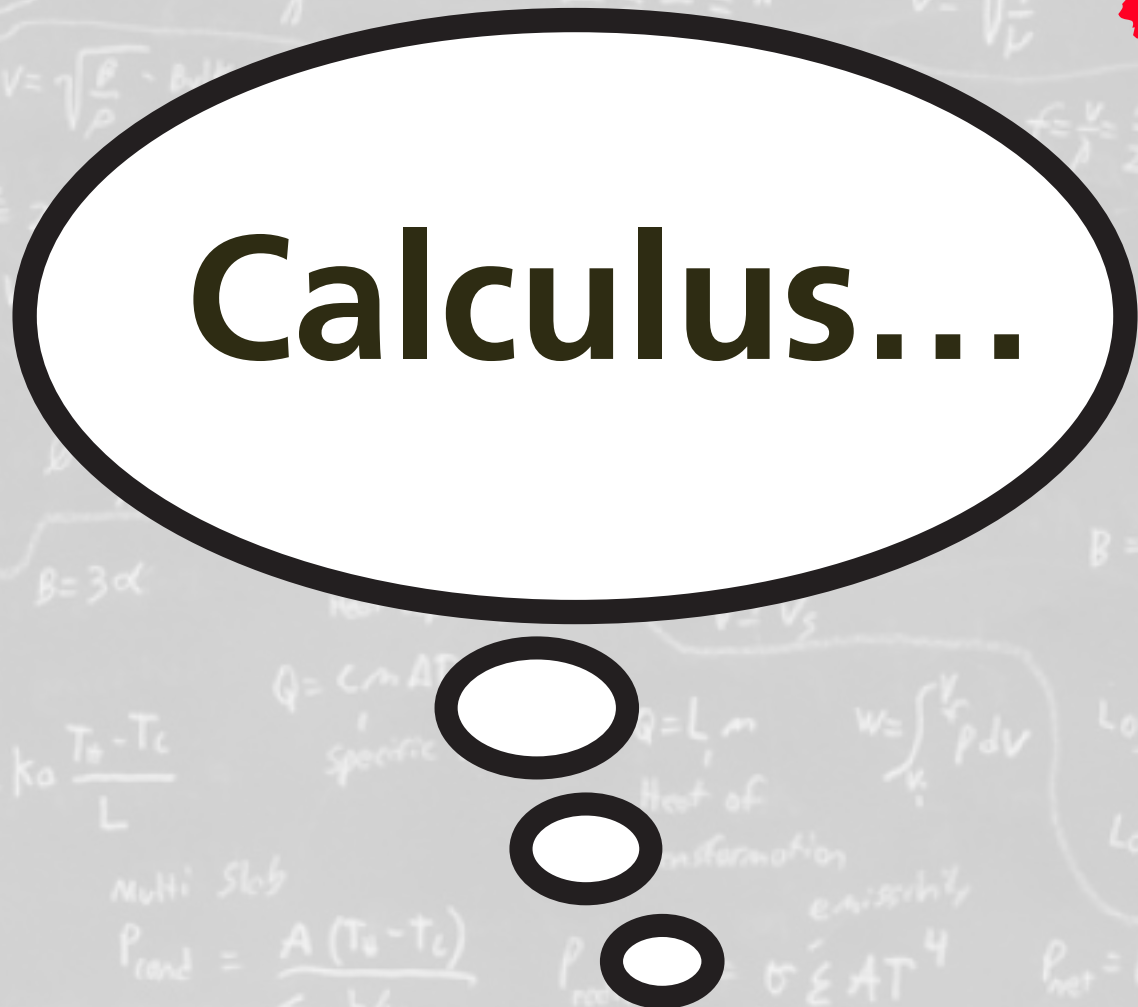
Kinematics

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
 $T = 2\pi \sqrt{\frac{I}{mg}}$ physical pend
 $x(t) = x_m \cos(\omega t - \phi)$
 $\omega_d = \omega$ resonance
 $y_m \sin(kx - \omega t)$ wave in pos direction
 $k = \frac{2\pi}{\lambda}$
 $v = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f$
 $v = \sqrt{\frac{T}{\mu}}$
 critical damp $b^2 = 4km$
 underdamped $b^2 < 4km$
 overdamped $b^2 > 4km$
 $\lambda = \frac{2L}{n}$ $n=1,2,3$
 $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n=1,2,3$
 $v = \sqrt{\frac{E}{\rho}}$ Bulk modulus
 $\Delta P_m = v \rho \omega S_m$ displacement
 $f_{beat} = |f_1 - f_2|$
 $I = \frac{\text{Power}}{\text{Area}} = \frac{P_s}{4\pi r^2}$
 $f = \frac{nv}{4L}$ ($n=1,2,3$)
 $\sin \theta = \frac{v}{v_s}$ $\frac{v_s}{v} = \text{mach \#}$
 $\frac{\Delta L}{L} = 0, 1/2$ fully constructive
 $\frac{\Delta L}{L} = 0.5, 1.5, 2.5$ fully destructive
 $\theta = \frac{\Delta L}{\lambda} 2\pi$
 $I = \frac{1}{2} \rho v \omega^2 S_m^2$
 $Q = c \Delta T$ Heat capacity
 $Q = C_m \Delta T$ specific heat
 $Q = L_m$ Heat of transformation
 $W = \int_{v_i}^{v_f} p dv$ enissity
 $B = (10) \log \frac{I}{I_0}$
 $\log \frac{x}{y} = \log x - \log y$
 $\log_0 x = y \Leftrightarrow 0^y = x$
 $\Delta E_{int} = Q_{in} - W_{out}$
 $P_{cond} = \frac{Q}{t} = k a \frac{T_h - T_c}{L}$
 $R = \frac{L}{k}$
 Multi Slab
 $P_{cond} = \frac{A (T_h - T_c)}{\sum L/k}$
 $P_{radiation} = \sigma \epsilon A T^4$
 $P_{net} = P_{obs} - P_{prod}$
 $P_{abs} = \sigma \epsilon A T^4$
 $n = \frac{\text{molecules}}{6.02 \times 10^{23}}$
 Adiabatic $Q=0$ $\Delta E = -W$ $PV = nRT$

kinematics

vectors



Calculus...

kinematics

vectors

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

Background content includes various physics formulas and notes:

- $F_d = -bv$
- $x(t) = x_m e^{-\frac{bt}{2m}} \cos(\omega t + \theta)$
- $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$
- $E(t) = \frac{1}{2} k x_m^2 e^{-\frac{bt}{m}}$
- $T = 2\pi \sqrt{\frac{L}{g}}$ simple pend
- $T = 2\pi \sqrt{\frac{m}{k}}$ physical pend
- $x(t) = x_m \cos(\omega t - \phi)$
- $k = \frac{2\pi}{\lambda}$
- $v = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f$
- $v = \sqrt{\frac{T}{\mu}}$
- critical damp $b^2 = 4km$
- over damped $b^2 < 4km$
- under damped $b^2 > 4km$
- $\omega_d = \omega$ resonance
- $y_m \sin(kx - \omega t)$ wave in pos direction
- $v = \sqrt{\frac{E}{\rho}}$ bulk modulus
- $\Delta p_m = v \rho \omega S_m$ displacement
- $f = \frac{v}{\lambda} = \frac{v}{2L}$
- $f = \frac{v}{\lambda} = \frac{v}{2L}$ $n=1,2,3$
- $f = \frac{v}{\lambda} = \frac{v}{2L}$ $n=1,2,3$
- interference $\frac{\Delta L}{\lambda} = 0, 1/2$ fully constructive
- $\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5$ fully destructive
- $B = 3\alpha$
- $Q = c \Delta T$ Heat capacity
- $Q = C m \Delta T$ specific heat
- $Q = L m$ Heat of transformation
- $W = \int_{v_1}^{v_2} p dv$
- $\log \frac{x}{y} = \log x - \log y$
- $\log_0 x = y \Leftrightarrow 0^y = x$
- $R = \frac{L}{k}$
- Multi Slab $P_{cond} = \frac{A(T_h - T_c)}{\sum L/k}$
- $P_{radiation} = \sigma \epsilon AT^4$
- $P_{net} = P_{obs} - P_{prod}$
- $P_{abs} = \sigma \epsilon AT^4$
- $n = \frac{\text{molecules}}{6.02 \times 10^{23}}$
- Adiabatic $Q=0$ $\Delta E = -W$ $PV = nRT$

kinematics

vectors

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

momentum

Background content includes:

- $F_d = -bv$
- $x(t) = x_m e^{-\frac{bt}{2m}} \cos(\omega t + \theta)$
- $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$
- $E(t) = \frac{1}{2} k x_m^2 e^{-\frac{bt}{m}}$
- $T = 2\pi \sqrt{\frac{L}{g}}$ simple pend
- $T = 2\pi \sqrt{\frac{m}{k}}$ physical pend
- $x(t) = x_m \cos(\omega t - \phi)$
- $\omega_d = \omega$ resonance
- $v = \frac{w}{k} = \frac{\lambda}{T} = \lambda f$
- $v = \sqrt{\frac{T}{\mu}}$
- critical damp $b^2 = 4km$
- over damped $b^2 < 4km$
- under damped $b^2 > 4km$
- $\lambda = \frac{2L}{n}$ $n=1,2,3$
- $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n=1,2,3$
- $v = \sqrt{\frac{E}{\rho}}$ bulk modulus
- $\Delta P_m = v \rho w S_m$ displacement
- $f_m^2 = 2PVI$
- $f_m = v \rho w S_m$
- $f = \frac{v}{\lambda}$ $n=1,2,3$
- $f = \frac{nv}{4L}$ ($n=1,2,3$)
- $\Delta L = L \alpha \Delta T$
- $\Delta V = V \beta \Delta T$
- $T_F = \frac{9}{5} T_C + 32$
- $\Delta E_{int} = Q - W_{out}$
- $n = \frac{\text{molecules}}{6.02 \times 10^{23}}$
- $R = \frac{L}{k}$
- Multi Slab $P_{cond} = \frac{A(T_h - T_c)}{\sum L/k}$
- $Q = L_m$ Heat of transformation
- $W = \int_{V_i}^{V_f} p dV$
- $Q = L_m$ Heat of transformation
- $P_{radiation} = \sigma \epsilon AT^4$
- $P_{net} = P_{obs} - P_{rad}$
- $P_{abs} = \sigma \epsilon AT^4$
- $B = (10) \log \frac{I}{I_0}$
- $\log \frac{x}{y} = \log x - \log y$
- $\log_a x = y \Leftrightarrow a^y = x$

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
- $x(t) = x_m \cos(\omega t + \phi)$
- $v = \frac{dx}{dt} = -\omega x_m \sin(\omega t + \phi)$
- $k = \frac{2\pi}{\lambda}$
- $\lambda = \frac{2L}{n}$ $n=1,2,3$
- $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n=1,2,3$
- $v = \sqrt{\frac{E}{\rho}}$ bulk modulus
- $\Delta P_m = \rho v^2 S_m$ pressure
- $P_m = 2PVI$
- $m = v\rho\omega S_m$
- $\theta = \frac{\Delta L}{\lambda} 2\pi$
- $I = \frac{1}{2} \rho v \omega^2 S_m^2$
- $Q = c\Delta T$ Heat
- $\Delta L = L\alpha\Delta T$
- $\Delta V = V\beta\Delta T$
- $T_F = \frac{9}{5}T_C + 32$
- $\Delta E_{int} = Q_{in} - W_{out}$
- $n = \frac{\text{molecules}}{6.02 \times 10^{23}}$
- $R = \frac{L}{k}$
- Multi Slab $P_{cond} = \frac{A(T_h - T_c)}{\sum L/k}$
- $P_{radiation} = \sigma \epsilon AT^4$
- $P_{net} = P_{obs} - P_{rad}$
- $P_{abs} = \sigma \epsilon AT^4$
- $\log_0 x = y \Leftrightarrow 0^y = x$
- $B = (10) \log \frac{I}{I_0}$
- $f = f \frac{v \pm v_d}{v \pm v_s}$
- $v_s = \text{mach } \#$
- $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n=1,2,3$
- $f = \frac{nv}{4L}$ $(n=1,2,3)$ displacement antinode at open, node at closed
- $P_{ave} = \frac{1}{2} \rho v \omega^2 A^2$
- $v = \sqrt{\frac{T}{\mu}}$
- critical damp $b^2 = 4km$
- over damped $b^2 < 4km$
- under damped $b^2 > 4km$
- $w_d = \omega$ resonance
- wave in pos direction
- $\lambda = \lambda f$
- $v = \sqrt{\frac{T}{\mu}}$
- $P_{ave} = \frac{1}{2} \rho v \omega^2 A^2$
- $f = \frac{v}{\lambda} = \frac{nv}{2L}$ $n=1,2,3$
- $f = \frac{nv}{4L}$ $(n=1,2,3)$
- $v_s = \text{mach } \#$
- $B = (10) \log \frac{I}{I_0}$
- $f = f \frac{v \pm v_d}{v \pm v_s}$
- $Q = L, m$
- Heat of fusion
- $\log_0 x = y \Leftrightarrow 0^y = x$
- $P_{net} = P_{obs} - P_{rad}$
- $P_{abs} = \sigma \epsilon AT^4$
- $S_b T_{obs} = \frac{8}{15} \frac{w}{c}$
- $P_{obs} = \sigma \epsilon AT^4$
- Adiabatic $Q=0$ $\Delta E = -W$ $PV = nRT$

energy

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

momentum

collisions

kinematics

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

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

$T = 2\pi \sqrt{\frac{I}{\tau}}$ physical pend

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

resonance $\lambda = \frac{2L}{n}$ $n=1,2,3$ $v = \sqrt{\frac{E}{\rho}}$ bulk modulus $\Delta P_m = v \rho \omega S_m$ displacement

$f = \frac{v}{\lambda} = \frac{v}{2L}$ $n=1,2,3$ $f_m = \frac{v}{2L}$ $n=1,2,3$ $f_{beat} = |f_1 - f_2|$ $f = \frac{v}{4L}$ ($n=1,2,3$)

interference $\frac{\Delta L}{\lambda} = 0, 1/2$ fully constructive $\theta = \frac{\Delta L}{\lambda} 2\pi$ $I = \frac{1}{2} \rho v \omega^2 S_m^2$ $\frac{v_s}{v} = \text{mach } \#$

$\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5$ fully destructive $B = 3 \text{ dB}$ $Q = c \Delta T$ $f = f \frac{v \pm v_d}{v}$

$T_F = \frac{9}{5} T_C + 32$ $\Delta L = L \alpha \Delta T$ $\Delta V = V \beta \Delta T$ $\Delta E_{int} = Q_{in} - W_{out}$ $P_{cond} = \frac{Q}{t} = k a \frac{T_h - T_c}{L}$ $Q = c \Delta T$ $Q = \int v \rho dv$ $\log \frac{x}{y} = \log x - \log y$ $\log_0 x = y \Leftrightarrow 0^y = x$

$n = \frac{\text{molecules}}{6.02 \times 10^{23}}$ $R = \frac{L}{k}$ Multi Slab $P_{cond} = \frac{A (T_h - T_c)}{\sum L/k}$ $P_{radiation} = \sigma \epsilon A T^4$ $P_{net} = P_{obs} - P_{rad}$ $P_{abs} = \sigma \epsilon A T^4$

Adiabatic $Q=0$ $\Delta E = -W$ $PV = nRT$ $P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$

$v = \sqrt{\frac{T}{\mu}}$ $\rho = \frac{\text{mass}}{\text{length}}$ $P_{ave} = \frac{1}{2} \rho v \omega^2$ $P_{ave} = \frac{1}{2} \rho v \omega^2$ $P_{net} = P_{obs} - P_{rad}$ $P_{abs} = \sigma \epsilon A T^4$

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

$E_{Tot} = U$ $k(s) = \frac{1}{2} m v^2$ $P_{net} = P_{obs} - P_{rad}$ $P_{abs} = \sigma \epsilon A T^4$

conservation of energy

conservation of momentum

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

Background content:

- $F_s = -bv$
- $x(t) = x_m e^{-\frac{bt}{2m}} \cos(\omega t + \phi)$
- $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$
- $E(t) \sim \frac{1}{2} k x_m^2 e^{-\frac{bt}{m}}$
- $T = 2\pi \sqrt{\frac{L}{g}}$ simple pend
- $T = 2\pi \sqrt{\frac{I}{mg}}$ physical pend
- $x(t) = x_m \cos(\omega t)$
- $y(x,t) = y_m \sin(kx - \omega t)$
- $v = \sqrt{\frac{E}{\rho}}$ bulk modulus
- $\Delta p_m = v \rho w S_m$ displacement
- $f = \frac{v}{\lambda} = \frac{v}{2L}$
- $f_m = \frac{v}{\lambda} = \frac{v}{2L}$
- $\frac{\Delta L}{L} = 0.5, 2$ fully constructive
- $\frac{\Delta L}{L} = 0.5, 1.5, 2.5$ fully destructive
- $T_F = \frac{Q}{T}$
- $\Delta E_{int} = Q_{in} - W_{out}$
- $P_{cond} = \frac{Q}{t} = k a \frac{T_h - T_c}{L}$
- $R = \frac{L}{k}$
- $P_{cond} = \frac{A(T_h - T_c)}{\sum L/k}$
- $P_{radiation} = \sigma \epsilon A T^4$
- $P_{net} = P_{obs} - P_{prod}$
- $P_{abs} = \sigma \epsilon A T^4$

conservation of energy

Just algebra!

conservation of momentum

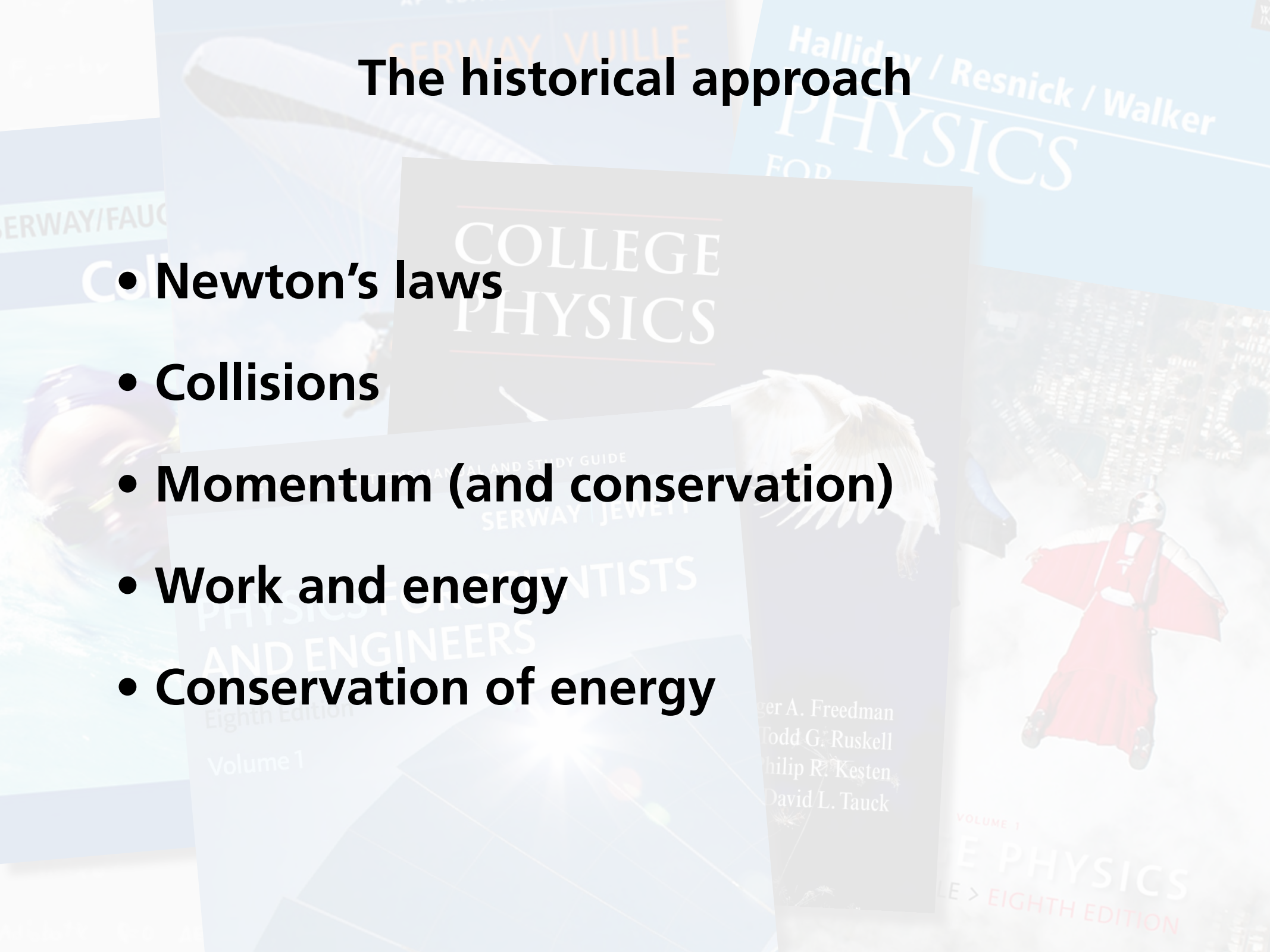
conservation of energy

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

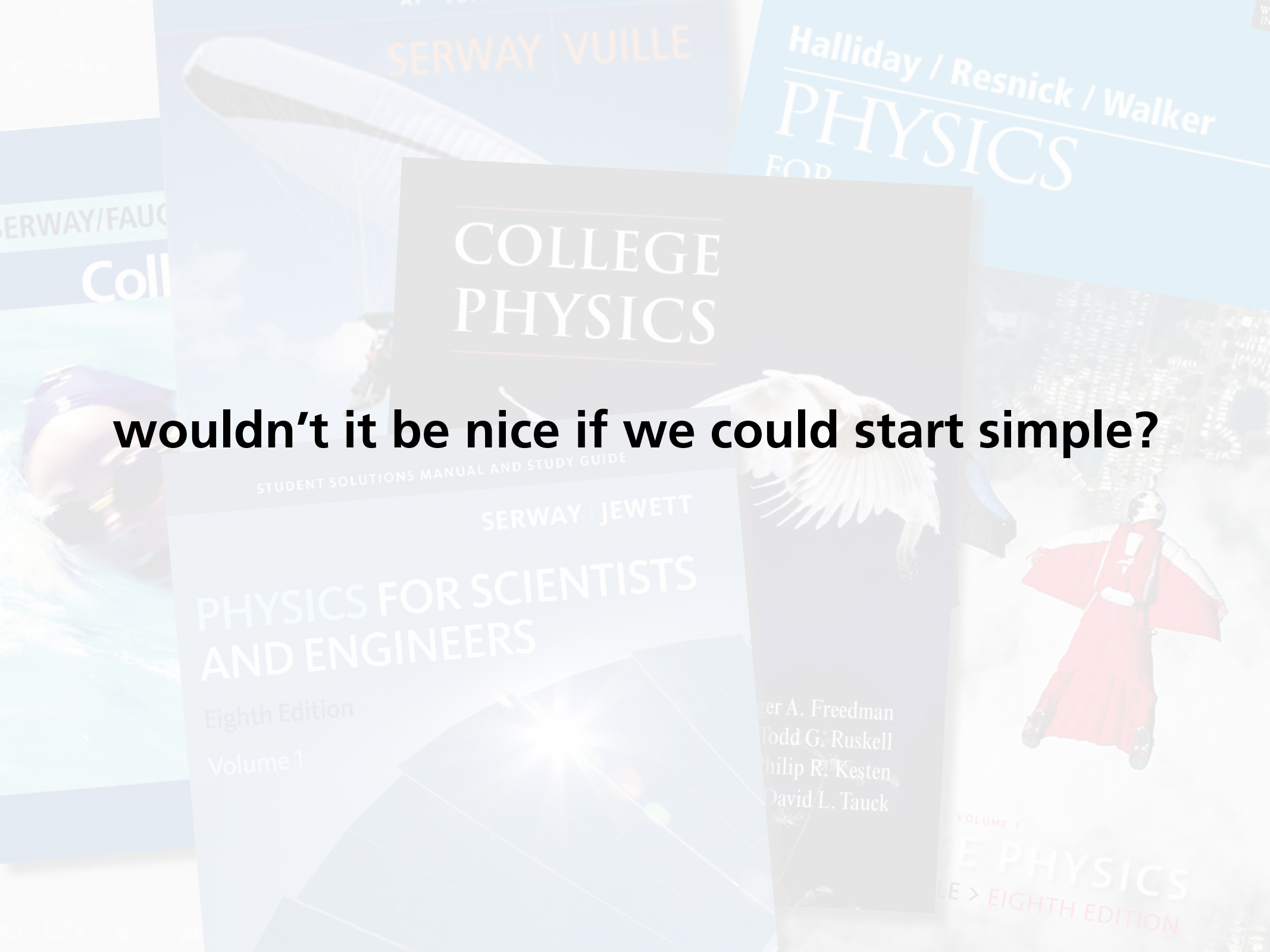
COLLEGE
PHYSICS

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?

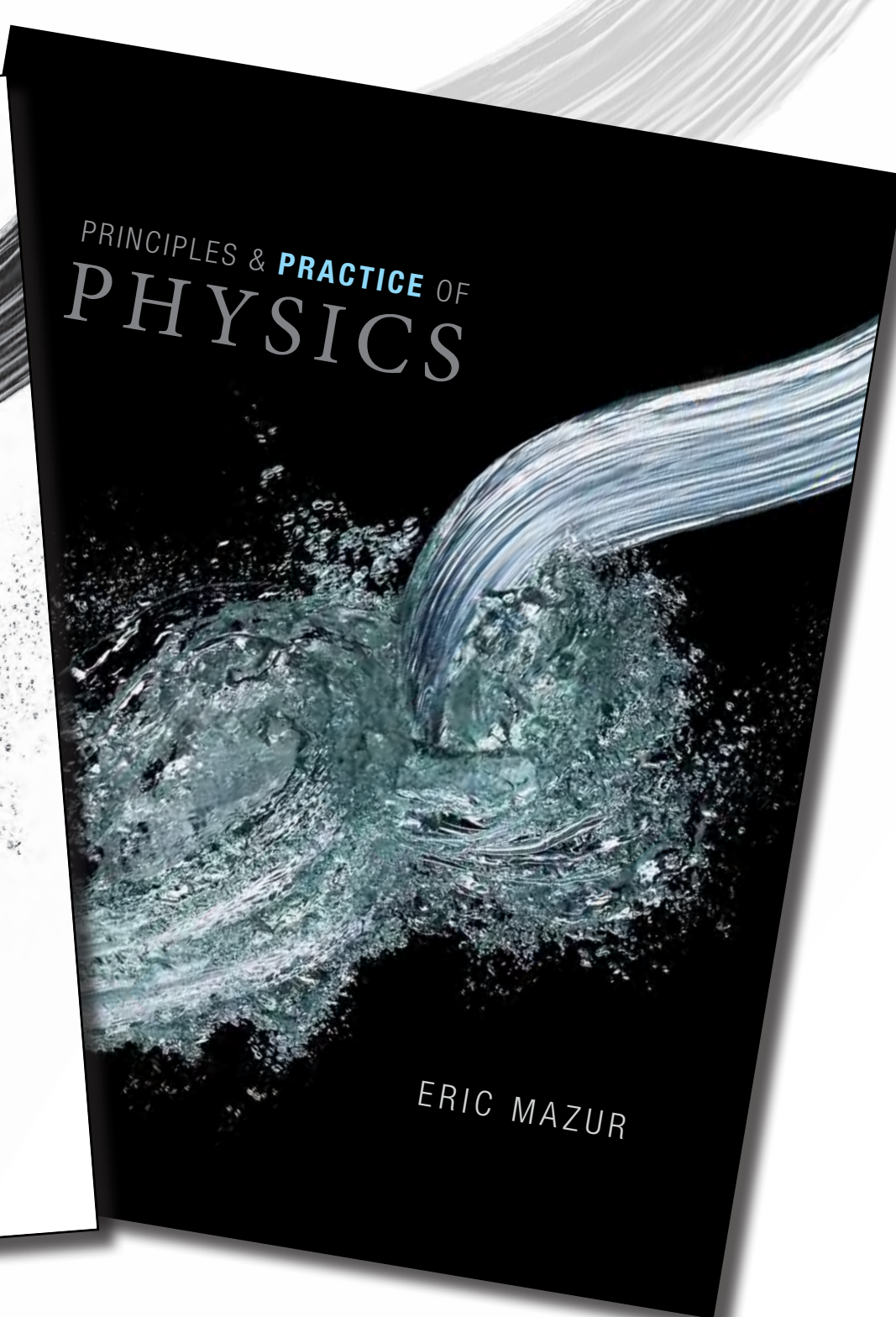
A dynamic, high-speed splash of water in shades of gray, creating a sense of movement and energy. The water is splashing upwards and outwards from the center, with many small droplets and bubbles visible. The background is a light, almost white color, making the gray water stand out.

we can!

A high-speed photograph of water splashing against a white background. The water is captured in mid-air, creating a complex, dynamic shape with many small droplets and larger, swirling masses. The lighting is bright, highlighting the texture and movement of the water.

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

A high-speed photograph of water splashing against a black background. The water is captured in mid-air, creating a complex, dynamic shape with many small droplets and larger, swirling masses. The lighting is dramatic, highlighting the texture and movement of the water against the dark background.

PRINCIPLES & **PRACTICE** OF
PHYSICS

ERIC MAZUR

Principles and Practice of Physics

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

ERIC MAZUR

ERIC MAZUR

Principles and Practice of Physics

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

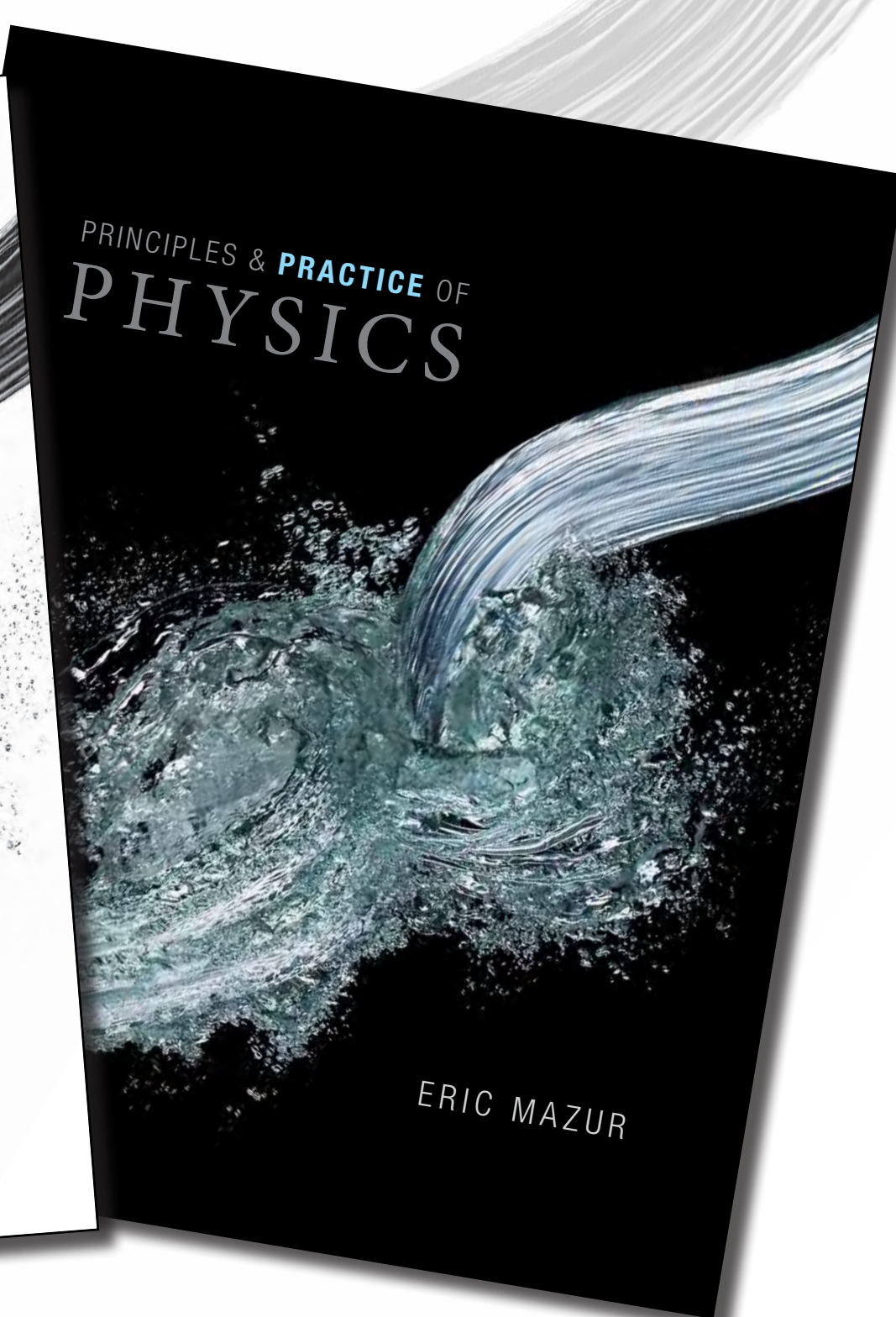
ERIC MAZUR

ERIC MAZUR

A high-speed photograph of water splashing on a white background. The water is captured in mid-air, creating a complex, turbulent pattern of droplets and streams. The splash is centered and extends towards the bottom left corner of the frame.

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

A high-speed photograph of water splashing on a black background. The water is captured in mid-air, creating a complex, turbulent pattern of droplets and streams. The splash is centered and extends towards the bottom right corner of the frame.

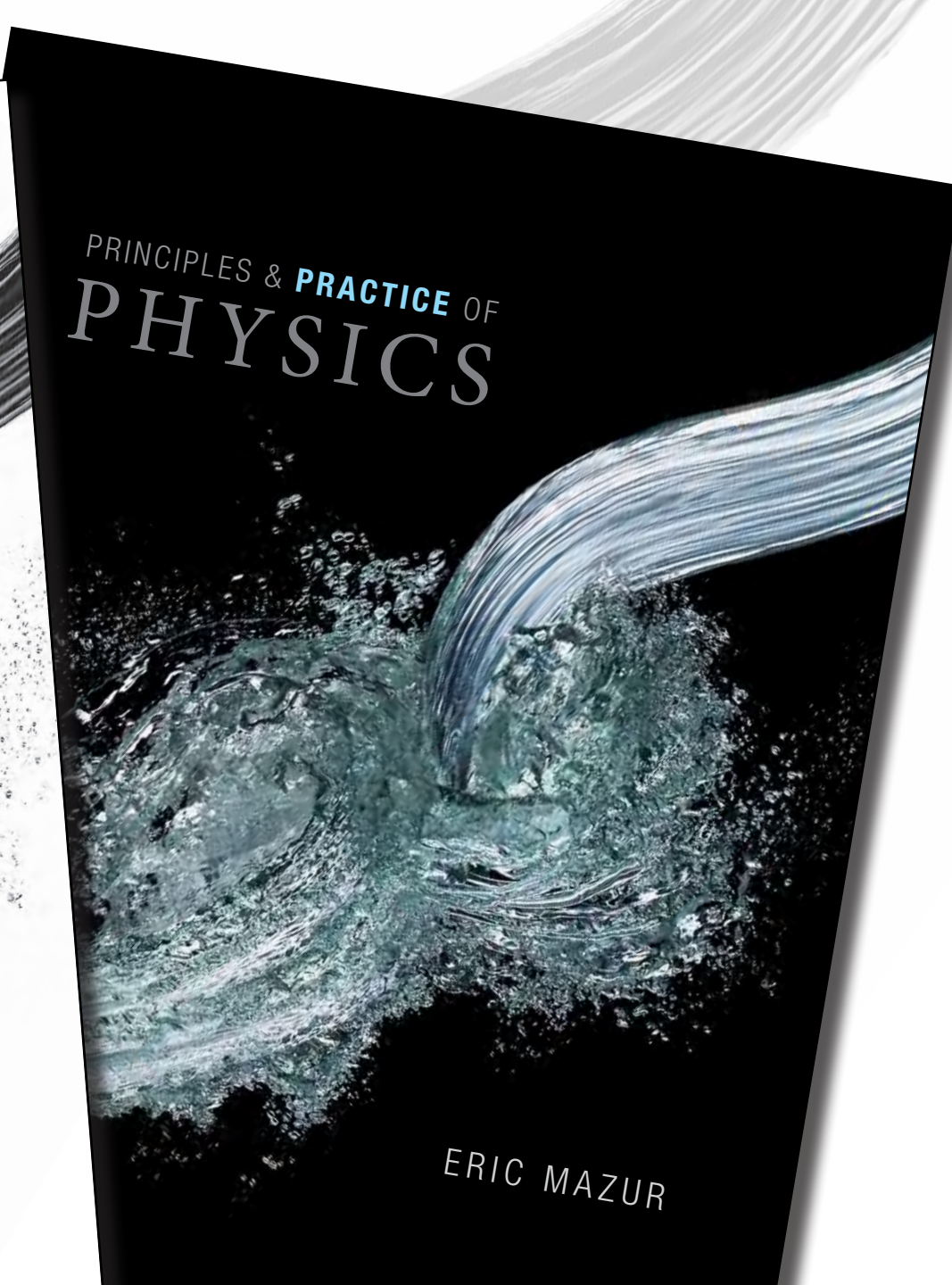
PRINCIPLES & **PRACTICE** OF
PHYSICS

ERIC MAZUR



PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR



PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

1 architecture

2 content

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

1 architecture

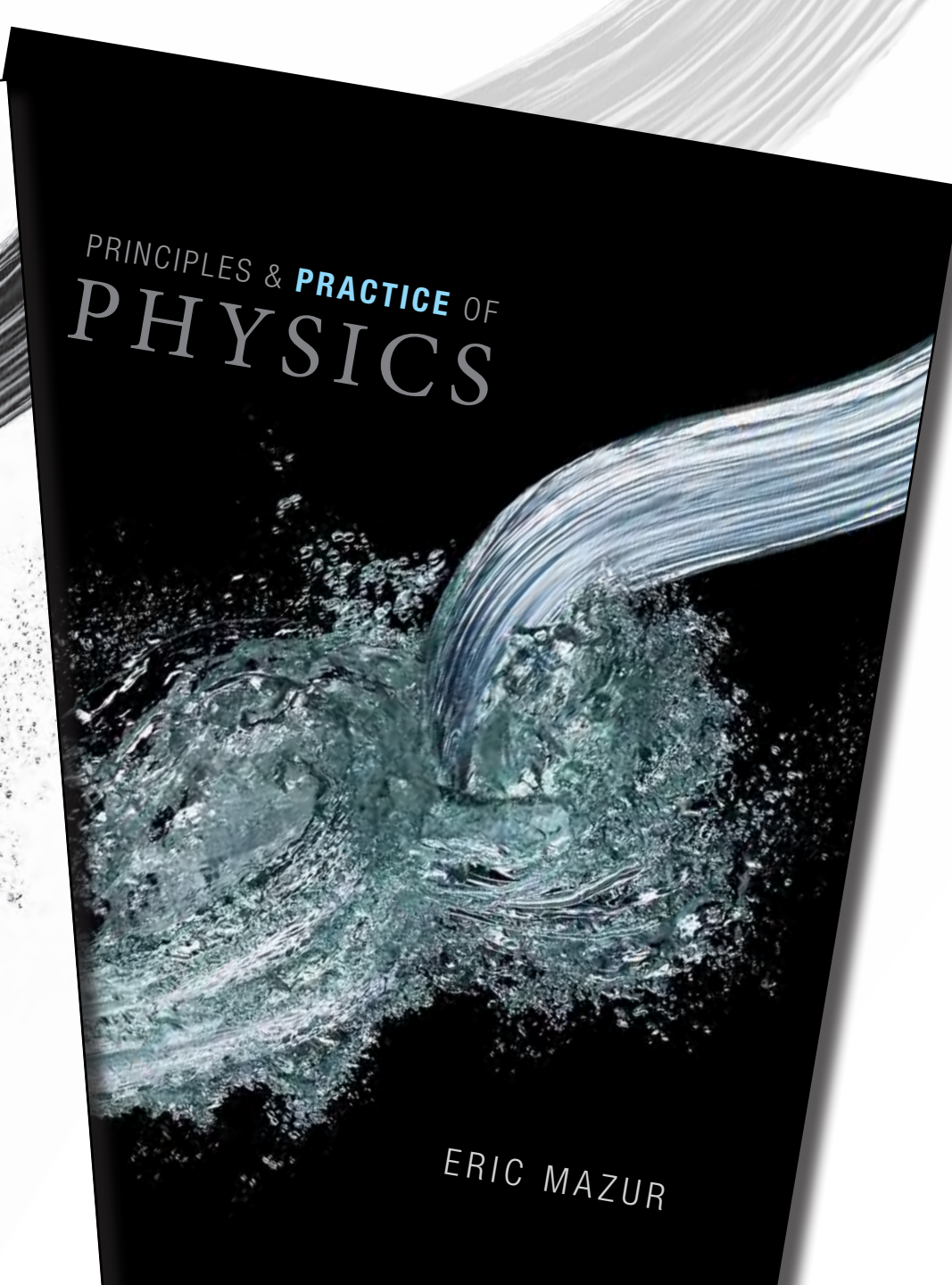
2 content

3 results



PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR



PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

PRINCIPLES & PRACTICE OF
PHYSICS

why 2 books?

ERIC MAZUR

ERIC MAZUR



PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

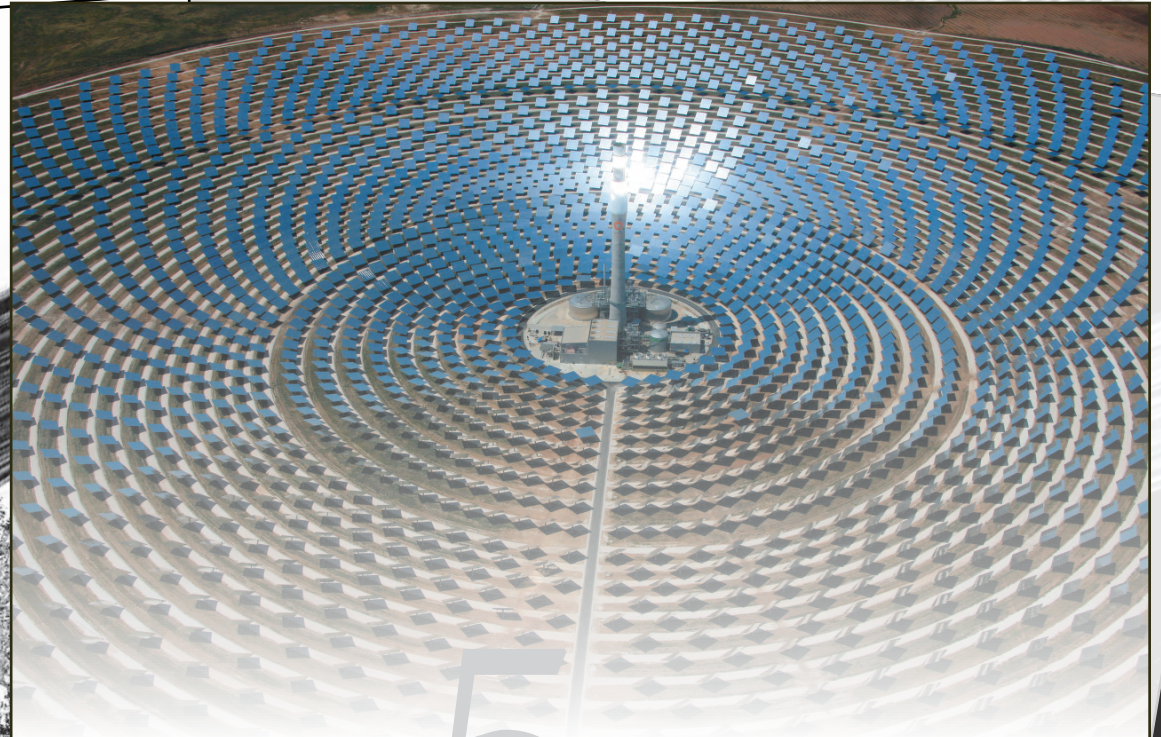


PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

PRINCIPLES & PRACTICE OF PHYSICS

ERIC



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.

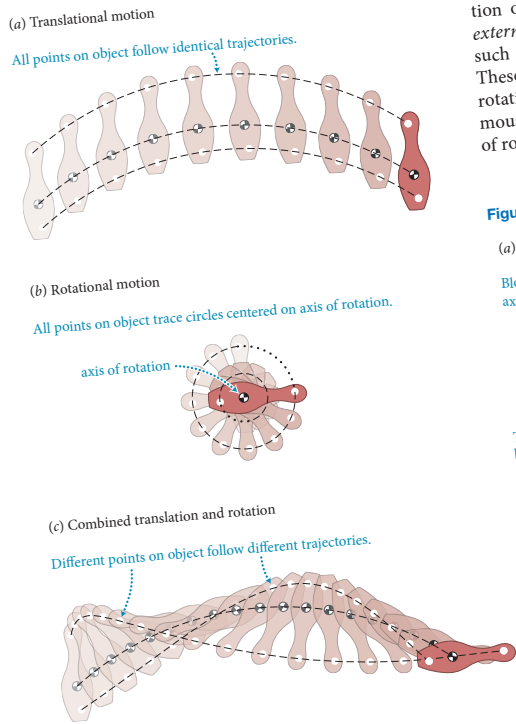
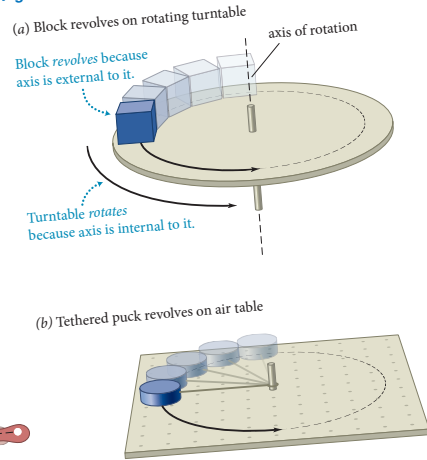


Figure 11.2 Examples of circular motion.



CONCEPTS

ation of collisions
energy
energy
systems

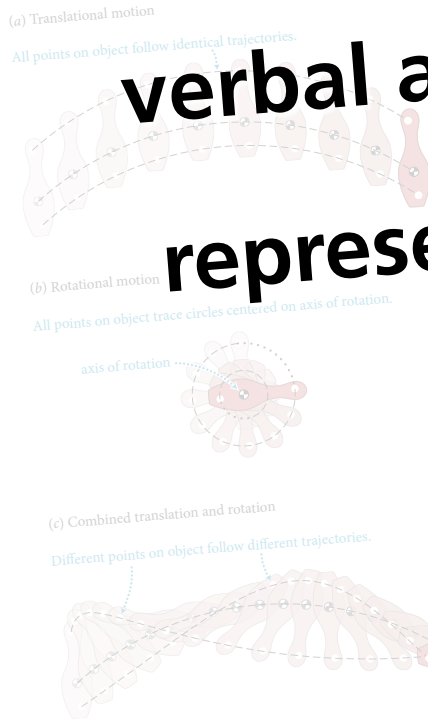
isions
ollisions
on of energy
eparations

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.

Figure 11.1 Translational and rotational motion of a rigid object.

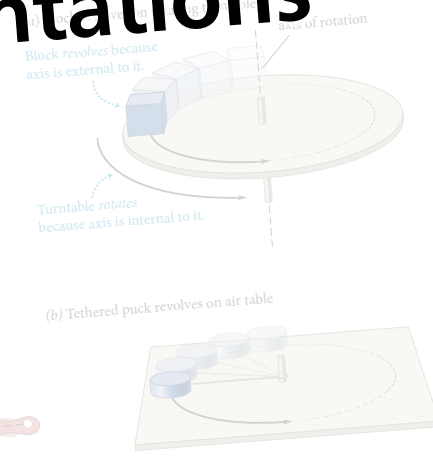


motion. We therefore begin our analysis of rotational motion by describing circular motion. Circular motion occurs all around us. A speck of dust stuck to a spinning CD, a stone being whirled around on a string, a person on a Ferris wheel—all travel along the perimeter of a circle, repeating their motion 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 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, such as the turntable, 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 11.2 Examples of circular motion.



teach concepts using verbal and visual representations

gy

ation of collisions
energy
energy
systems

CONCEPTS

isions
ollisions
on of energy
eparations

CONCEPTS

QUANTITATIVE TOOLS



PRINCIPLES & PRACTICE OF
PHYSICS

ERIC

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

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:

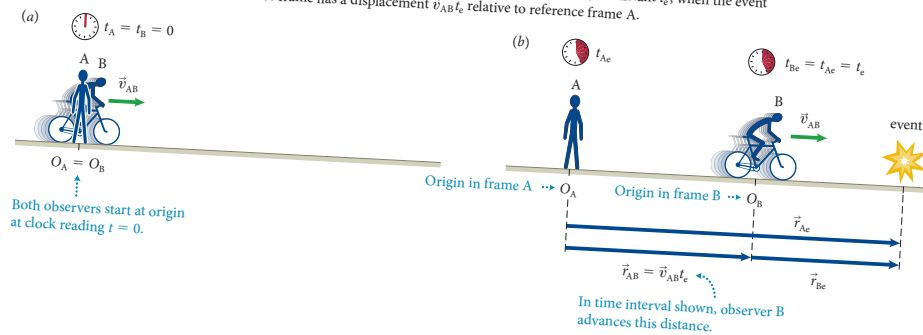
$$t_A = t_B = t. \quad (6.2)$$

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.

QUANTITATIVE TOOLS

CONCEPTS

QUANTITATIVE TOOLS

gy
ation of collisions
energy
energy
systems

ic collisions
tic collisions
ervation of energy
sive separations

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

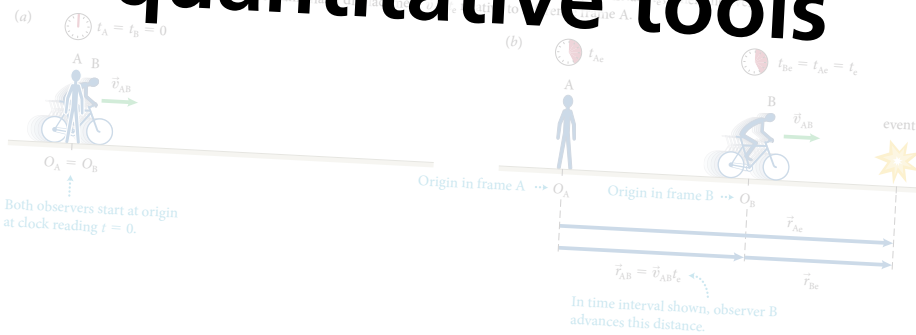
$$t_A = t_B = t. \quad (6.2)$$

From Figure 6.13b, the distance between the event and the origin in frame A is $\Delta \vec{r}_e = \vec{r}_{Ae} - 0 = \vec{r}_{Ae}$, 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 relate the data of the event in reference frame A to the 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

gy

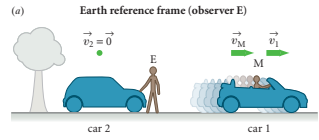
ation of collisions
energy
l energy
systems

c collisions
tic collisions
ervation of energy
sive separations

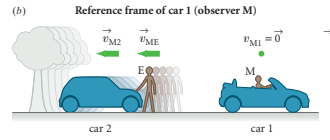
CONCEPTS

QUANTITATIVE TOOLS

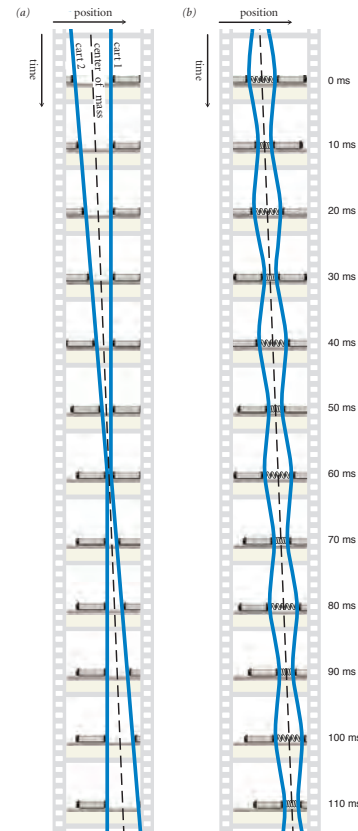
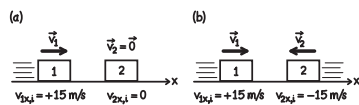
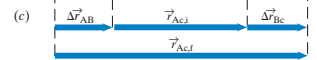
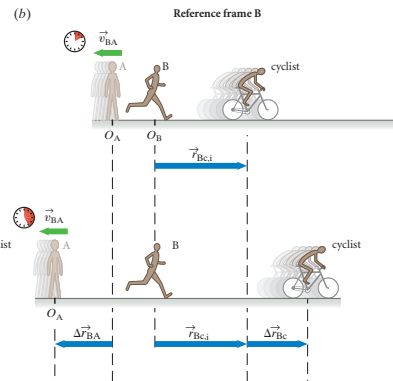
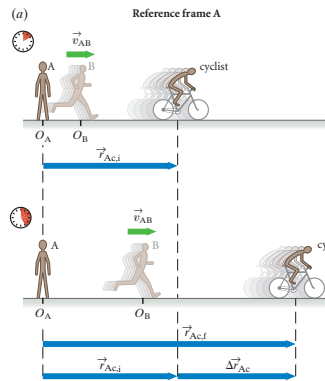
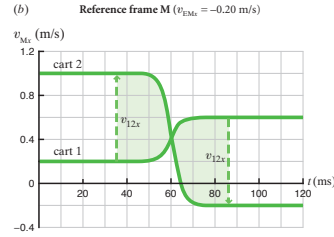
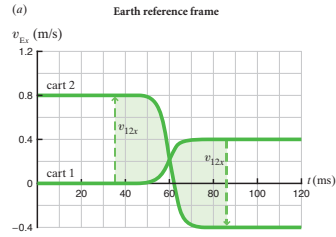
QUANTITATIVE TOOLS



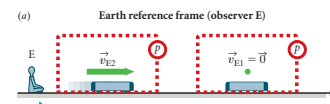
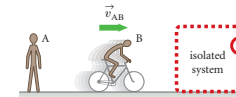
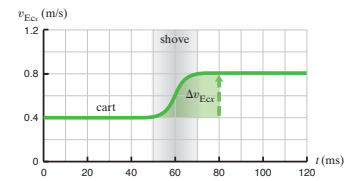
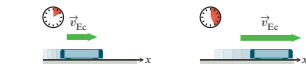
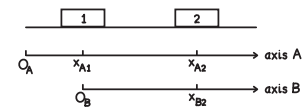
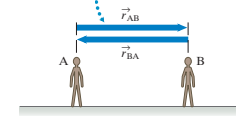
Relative to observer E, car 2 is at rest and car 1 moves to the right.



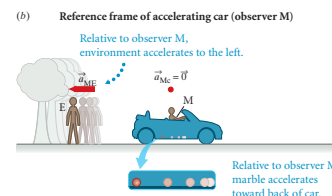
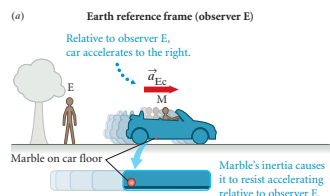
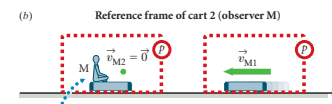
But relative to observer M, car 1 is at rest while car 2, observer E, and the earth move to the left.



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
PHYSICS

- 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?

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 will observe the same time for the event. In other words, $t_{Ae} = t_{Be} = t_e$. (6.1)

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

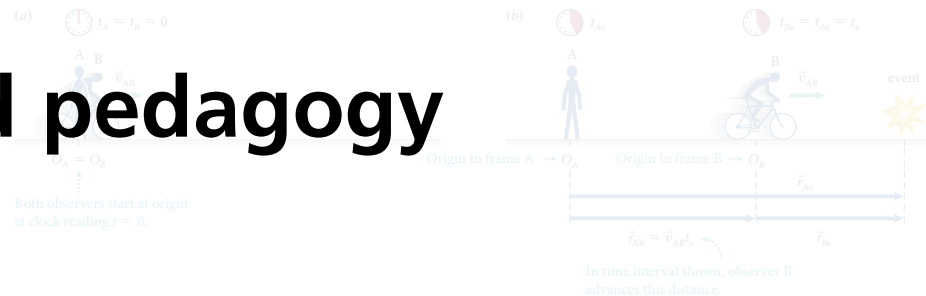
$$\vec{r}_{AB} = \vec{v}_{AB} t_e \quad (6.2)$$

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

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

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{r}_{AB} relative to reference frame A.



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

PRINCIPLES & PRACTICE OF
PHYSICS

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC

ERIC MAZUR



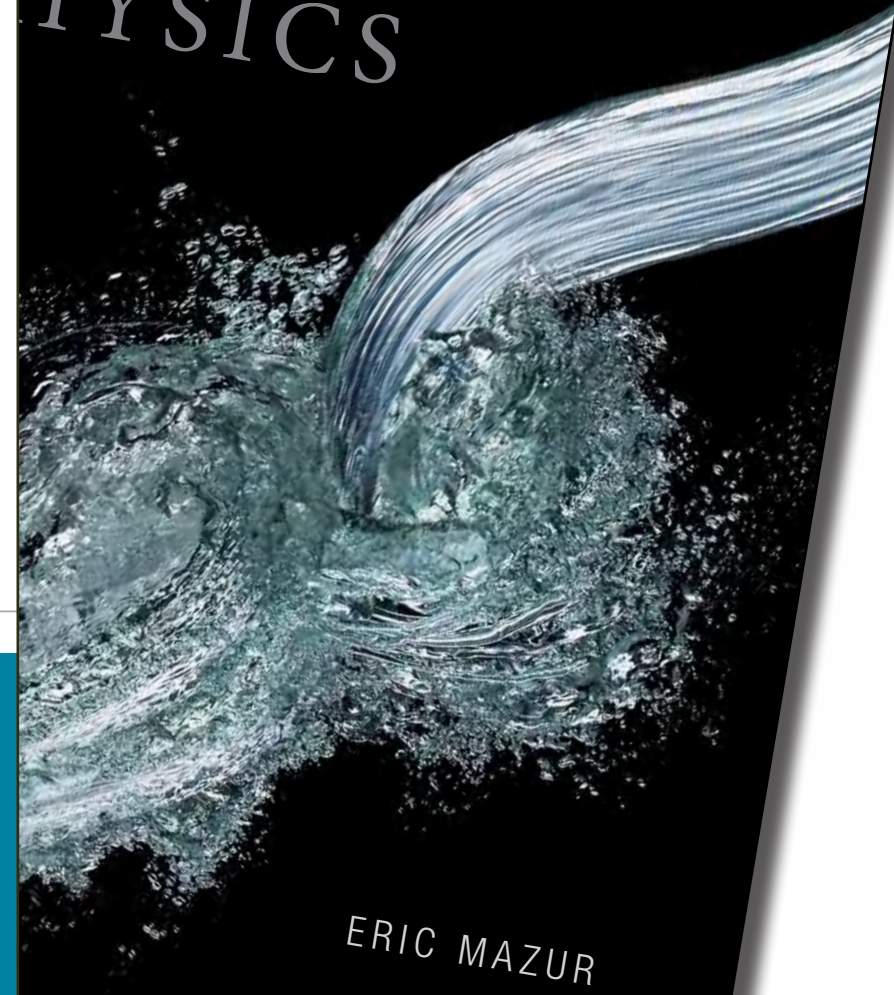
17

PRACTICE
**Waves in Two and
Three Dimensions**

Chapter Summary	304
Review Questions	305
Developing a Feel	306
Worked and Guided Problems	307
Questions and Problems	311
Answers to Review Questions	316
Answers to Guided Problems	316

PRACTICE

PRINCIPLES & PRACTICE OF
PHYSICS



ERIC MAZUR

PRACTICE

Waves in Two Three Dimens

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

Answers to Guided Problems 316

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

PRACTICE

Waves in Two Three Dimens

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

Answers to Guided Problems 316

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

PRACTICE

Waves in Two Three Dimens

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

Answers to Guided Problems 316

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. $4 \text{ kg} \cdot \text{m}^2$; 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

PRACTICE

Waves in Two Three Dimens

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

Answers to Guided Problems 316

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. $1 \text{ yr} = 3 \times 10^7 \text{ s}$; 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, $\Sigma F = ma$, so $mg = mv^2/r$; G. a solid cylinder with two thin-rod arms of inertia 4 kg held out perpendicularly; H. $2 \times 10^3 \text{ kg}$; 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. $2 \times 10^{11} \text{ m}$; M. $2 \times 10^4 \text{ m}$; 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. $6 \times 10^6 \text{ m}$; 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. $7 \times 10^4 \text{ kg}$; W. 0.5 s; X. the parallel-axis theorem; Y. $3 \times 10^4 \text{ mi/h}$; Z. $6 \times 10^{24} \text{ kg}$; AA. $3 \times 10^4 \text{ m/s}$

PRACTICE

Waves in Two Three Dimens

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

Answers to Guided Problems 316

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 (I, 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 (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. 10^4 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. $2 \times 10^{11} \text{ m}$; M. $2 \times 10^4 \text{ m}$; 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. $6 \times 10^6 \text{ m}$; 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. $7 \times 10^4 \text{ kg}$; W. 0.5 s; X. the parallel-axis theorem; Y. $3 \times 10^4 \text{ mi/h}$; Z. $6 \times 10^{24} \text{ kg}$; AA. $3 \times 10^4 \text{ m/s}$

PRACTICE

Waves in Two Three Dimens

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

Answers to Guided Problems 316

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 (I, 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 (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, $\Sigma \vec{F} = m\vec{a}$, 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. 3×10^8 m/s

PRACTICE

Waves in Two Three Dimens

Chapter Summary	304
Review Questions	305
Developing a Feel	
Worked and Guided Problems	307
Questions and Problems	311
Answers to Review Questions	316
Answers to Guided Problems	316

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 (Y, C)
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, C)

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 do you model the water's surface during her spin?
- G. How do you model the surface of a rotating cylinder?
- H. What is the radius of Earth's orbit?
- I. How many turns are needed to rewind the yo-yo?
- J. What is the yo-yo's rotational inertia?
- K. What is the perpendicular distance from the house to the car's line of motion?
- L. What is the skater's rotational inertia with arms held out?
- M. How can you model the combined rotational inertia of the wheel and tire?
- N. What is Earth's radius?
- O. What is the final rotational speed?
- P. What is the radius of a bowling ball?
- Q. What is the rotational speed of the tire?
- R. What is the required centripetal acceleration?
- S. What is the rotational speed of the tire?
- T. What is the required centripetal acceleration?
- U. What is the rotational speed of the tire?
- V. What is the rotational speed of the tire?
- W. How long a time interval does the yo-yo take to complete 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. $1 \text{ y} = 3 \times 10^7 \text{ s}$; C. solid cylinder of radius 0.2 m; D. period = 24 h, so $\omega = 7 \times 10^{-5} \text{ s}^{-1}$; E. 10^4 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. $2 \times 10^3 \text{ kg}$; 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. $2 \times 10^{11} \text{ m}$; M. $2 \times 10^4 \text{ m}$; 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. $6 \times 10^6 \text{ m}$; 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. $7 \times 10^4 \text{ kg}$; W. 0.5 s; X. the parallel-axis theorem; Y. $3 \times 10^4 \text{ mi/h}$; Z. $6 \times 10^{24} \text{ kg}$; AA. $3 \times 10^8 \text{ m/s}$

PRACTICE

Waves in Two and Three Dimensions

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

Answers to Guided Problems 316

PRACTICE

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

PRACTICE

Waves in Two and Three Dimensions

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

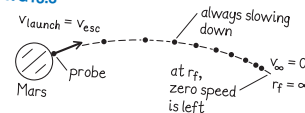
Answers to Guided Problems 316

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:

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

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

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

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

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

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.

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?

PRACTICE

PRACTICE

Waves in Two and Three Dimensions

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

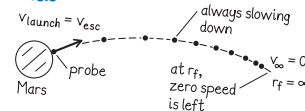
Answers to Guided Problems 316

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 $v_i = v_{\text{esc}}$ 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 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:

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

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

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

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

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

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.

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.

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?

PRACTICE

PRACTICE

Waves in Two and Three Dimensions

Chapter Summary 294
Review Questions 300
Developing Your Skills 306

Worked and Guided Problems 307

Questions and Problems 311

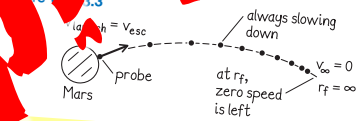
Answers to Review Questions 316

Answers to Guided Problems 316

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. As the separation distance increases, we assume a reference frame in which the probe is fixed and only the probe moves. As the probe moves far enough away (infinity, really, but practically, as far as we can take it), the kinetic energy has a minimum value, which can take to be zero because the probe presumably does not supply any more energy than needed to get it out there. The gravitational potential energy of the probe at infinity 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 probe is fixed and only the probe moves. We assume that the probe is fixed and only the probe moves. We assume that the probe is fixed and only the probe moves.

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

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.

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?

4-Step Procedure

PRACTICE

PRACTICE

Waves in Two and Three Dimensions

Chapter Summary 304

Review Questions 305

Developing a Feel 306

Worked and Guided Problems 307

Questions and Problems 311

Answers to Review Questions 316

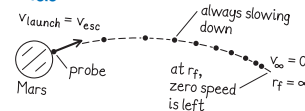
Answers to Guided Problems 316

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:

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

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

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

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

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

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.

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?

PRACTICE

PRACTICE

Waves in Two and Three Dimensions

Chapter Summary 300

Review Questions 305

Developing a Model 306

Worked and Guided Problems 307

Questions and Problems 311

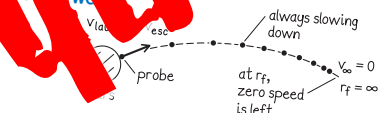
Answers to Review Questions 316

Answers to Guided Problems 316

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 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 must travel far enough away (infinity, really, but practically, it doesn't need to go quite that far), the kinetic energy of the probe must be zero. The probe must have any more energy than that, and it would get the probe off where the gravitational potential energy is maximum, which is also zero. (Remember, the initial potential energy is also zero.) The probe must also have any more energy than that, 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.

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 set up the initial Mars-probe system with center-to-center separation distance $r_i = R_M$ and initial radial distance, R_M for Mars' radius, and m_M for the Mars mass. We will use Eq. 13.23, which is $G \frac{m_M m_P}{r} + \frac{1}{2} m_P v^2 = \text{constant}$.

$$G \frac{m_M m_P}{R_M} + \frac{1}{2} m_P v_{esc}^2 = G \frac{m_M m_P}{r_f} + \frac{1}{2} m_P v_f^2$$
$$G \frac{m_M}{R_M} + \frac{1}{2} v_{esc}^2 = G \frac{m_M}{r_f} + \frac{1}{2} v_f^2$$

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

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

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

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.

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?

PRACTICE

PRACTICE Waves in Two and Three Dimensions

PRACTICE VOLUME

- not just end-of-chapter material
- many innovative features
- teaches authentic problem solving

Chapter 13 Practice Volume
Review Questions 305
Developing a Feel 306
Worked and Guided Problems 307
Questions and Problems 311
Answers to Review Questions 316
Answers to Guided Problems 316

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 from a cannon. 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 is 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



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 $v_i = v_{\text{esc}}$ 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?

- 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?

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:

$$E_{\text{mech}} = \frac{1}{2} m_p v_{\text{esc}}^2 - G \frac{m_M m_p}{R_M} = 0$$
$$\frac{1}{2} v_{\text{esc}}^2 - G \frac{m_M}{R_M} = 0$$
$$\frac{1}{2} v_{\text{esc}}^2 = G \frac{m_M}{R_M}$$
$$v_{\text{esc}} = \sqrt{2G \frac{m_M}{R_M}} = \sqrt{2 \left(\frac{6.42 \times 10^{23} \text{ kg}}{3.40 \times 10^6 \text{ m}} \right)}$$
$$= 5.02 \times 10^3 \text{ m/s} = 5 \text{ km/s} \checkmark$$

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 the escape speed is reasonable. 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.

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?

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.

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?

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

1 architecture

2 content

PRINCIPLES & PRACTICE OF
PHYSICS

conservation principles *before* force laws?

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

1 architecture

2 content



Foundations

- 1.1 The scientific method
- 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**

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



2 Motion in Two Dimensions

CONCEPTS

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

QUANTITATIVE TOOLS

- 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



3 Acceleration

CONCEPTS

- 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

1 architecture

2 content



4.1 Friction

4.2 Inertia

4.3 What determines inertia?

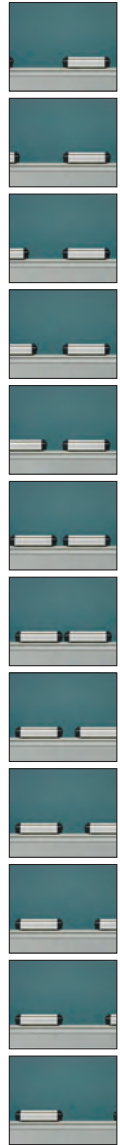
4.4 Systems

4.5 Inertial standard

4.6 Momentum

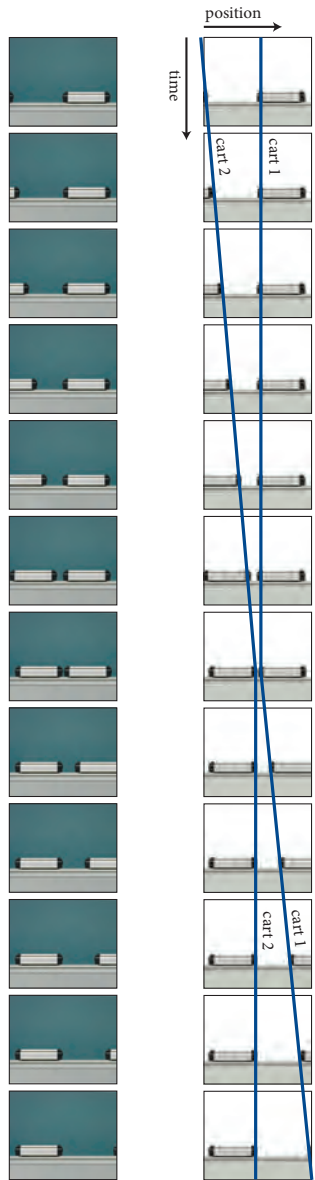
4.7 Isolated systems

4.8 Conservation of momentum



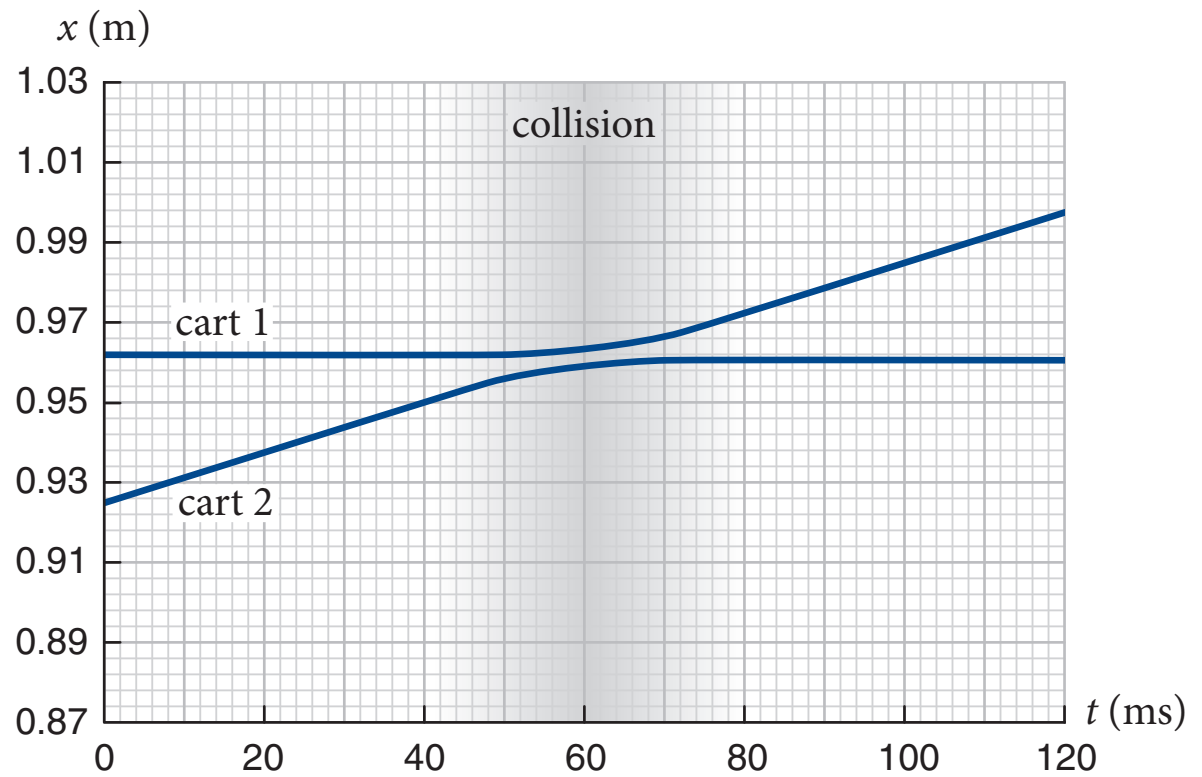
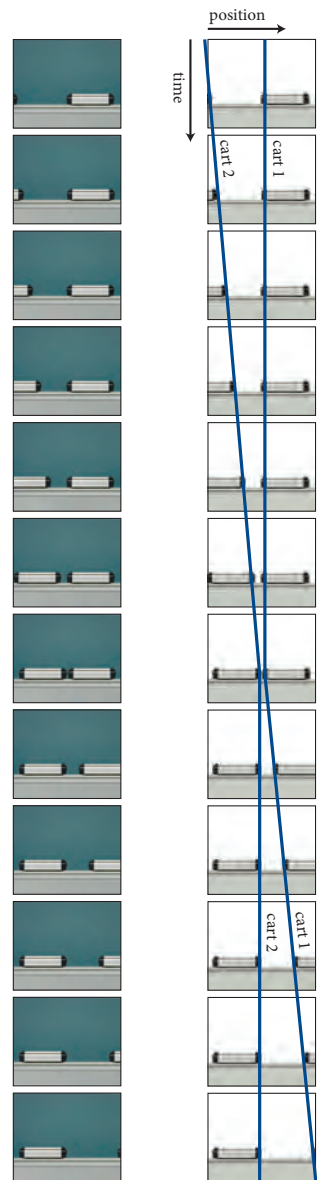
1 architecture

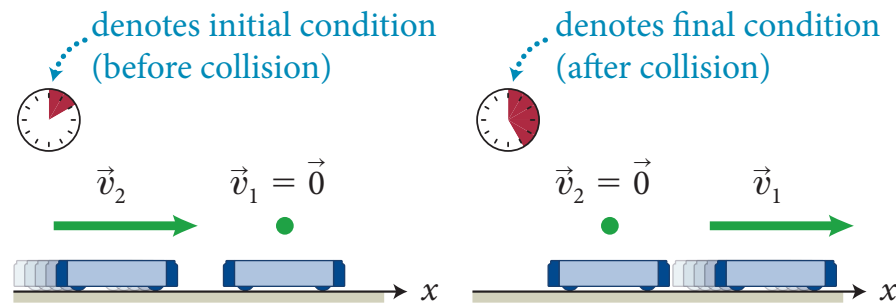
2 content

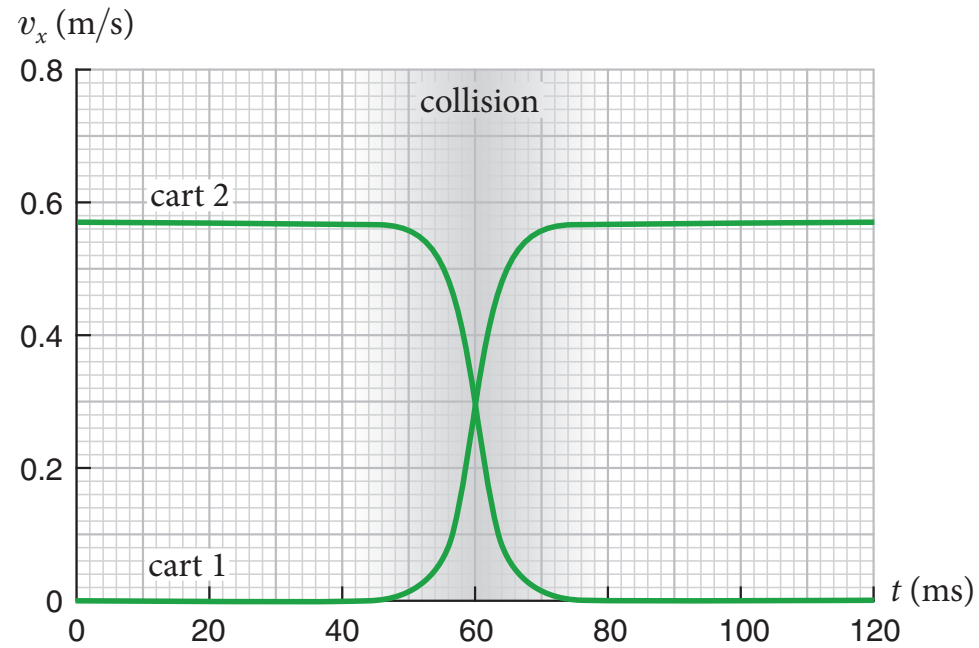
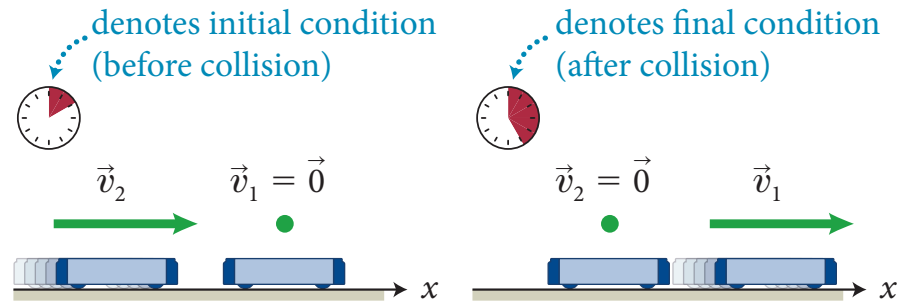


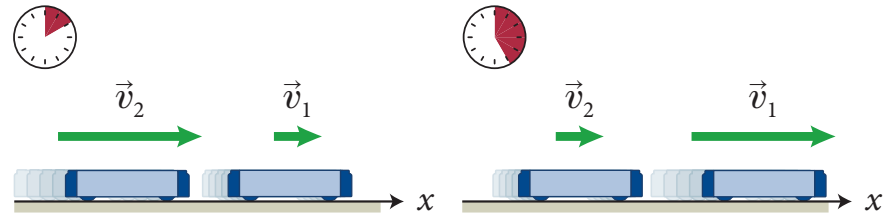
1 architecture

2 content



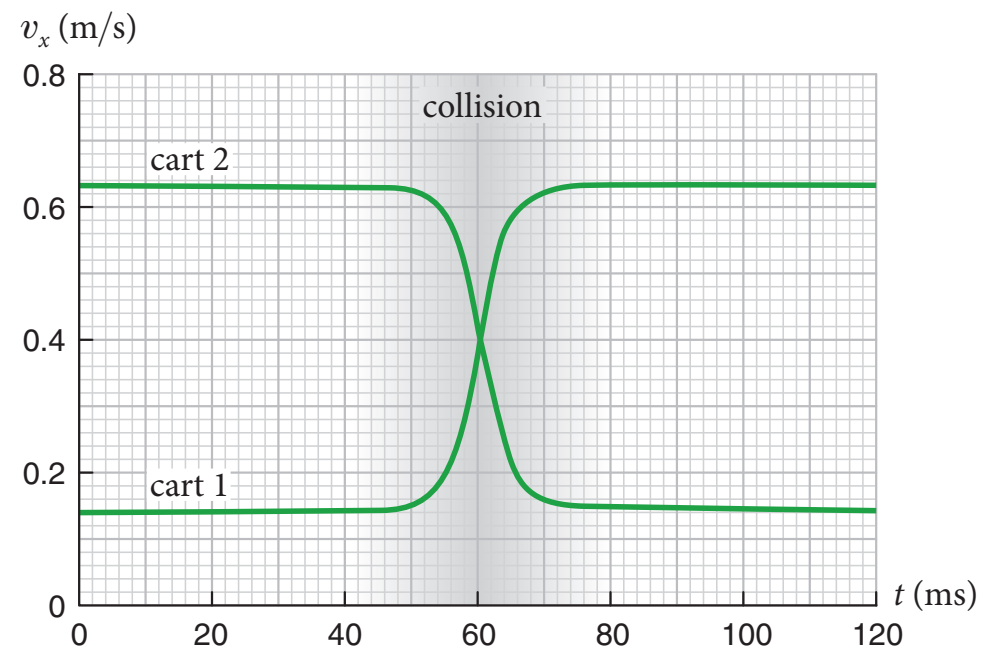
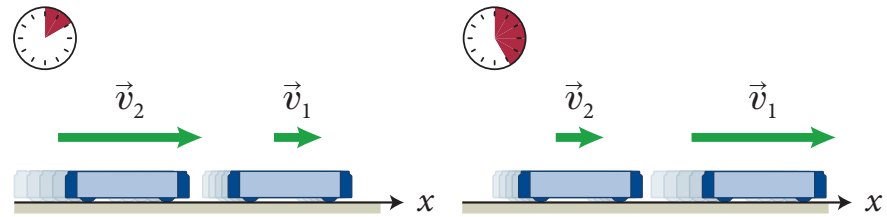


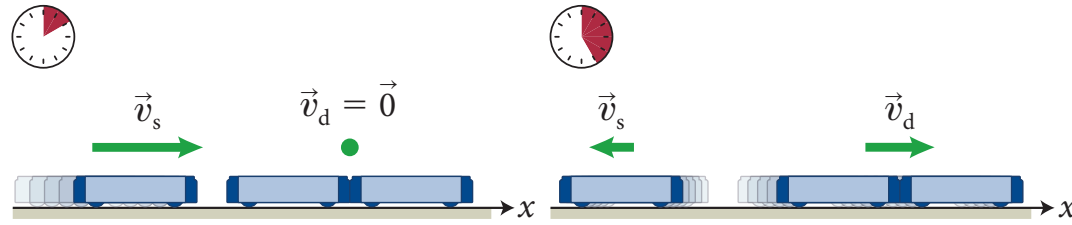


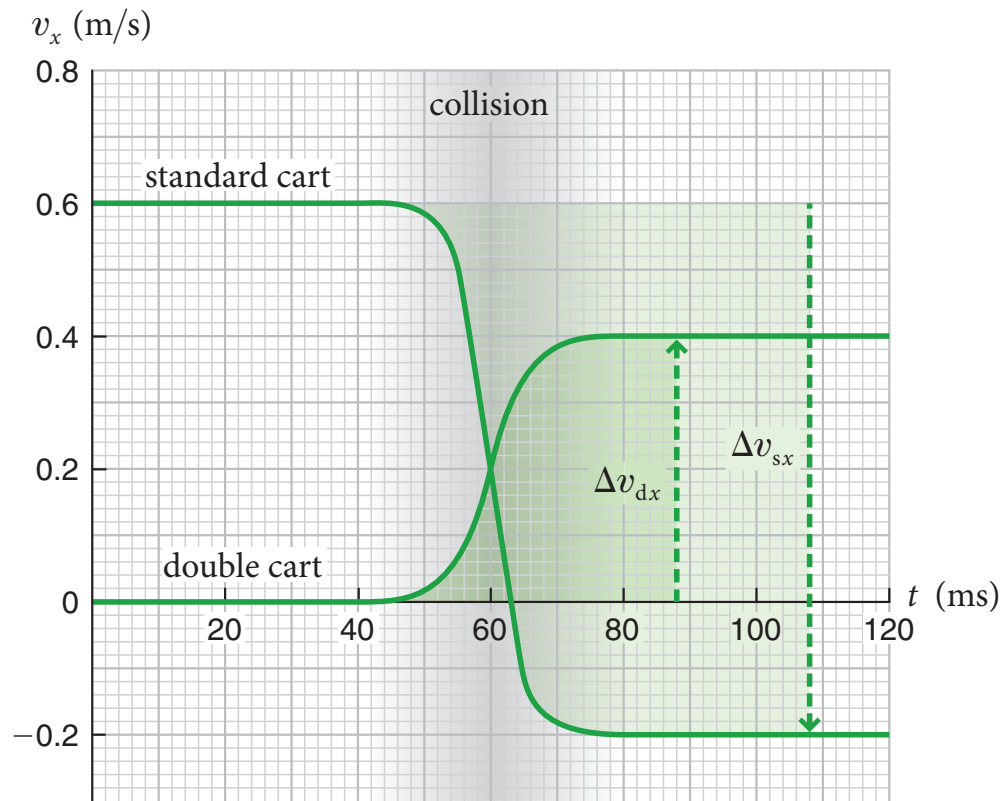
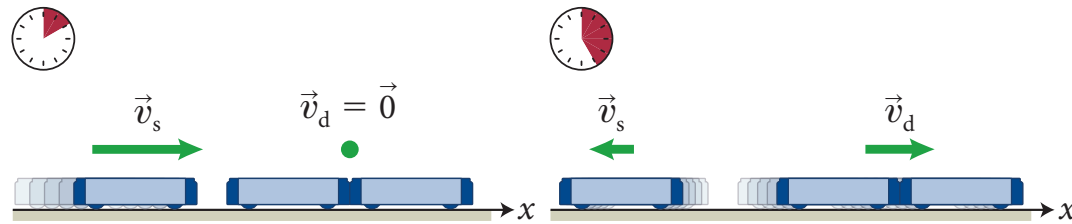


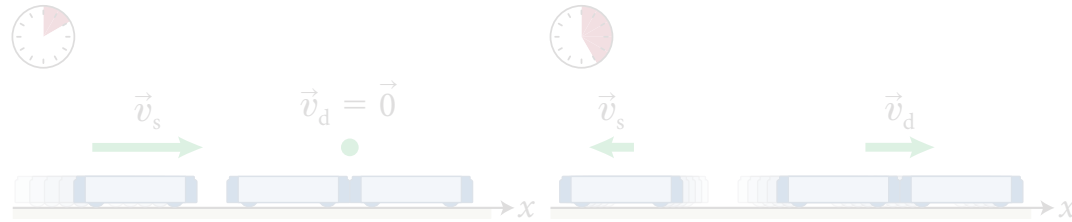
1 architecture

2 content

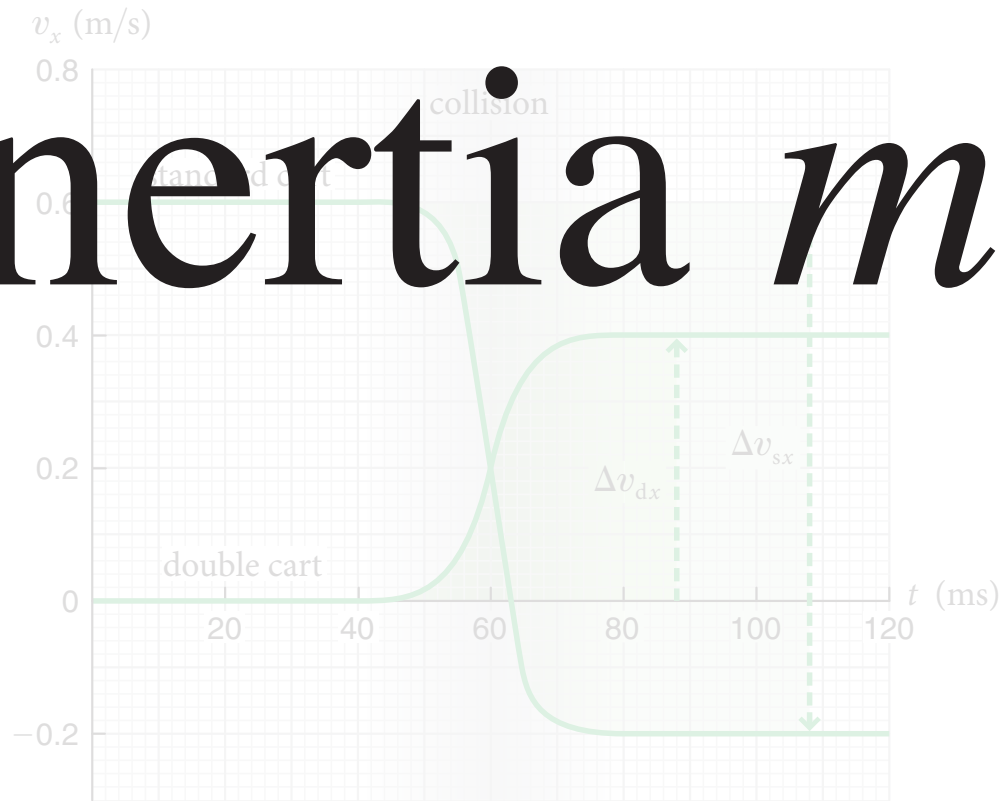




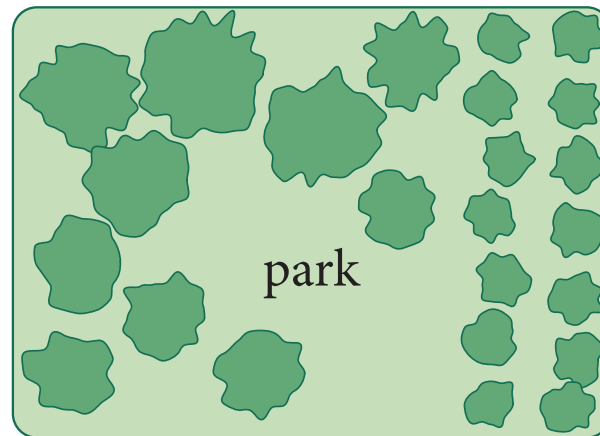
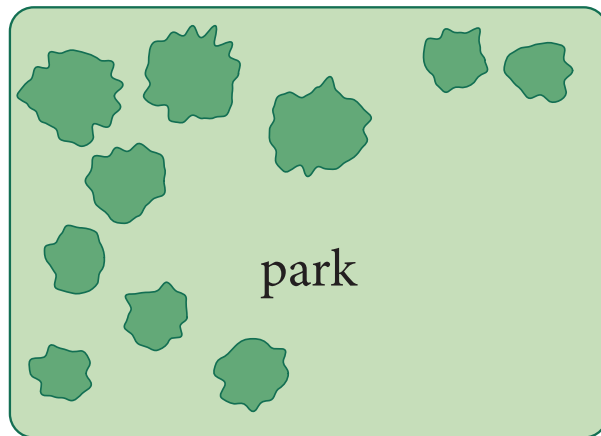




inertia m



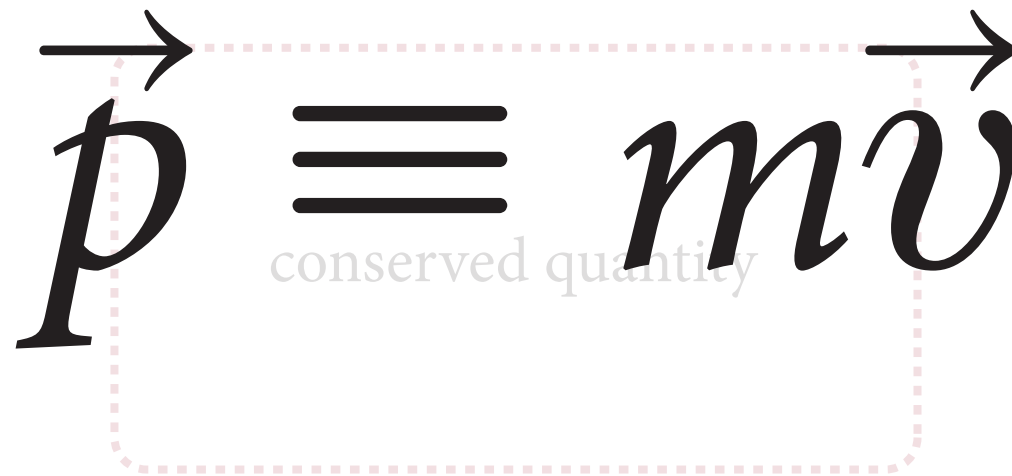
systems & extensive quantities

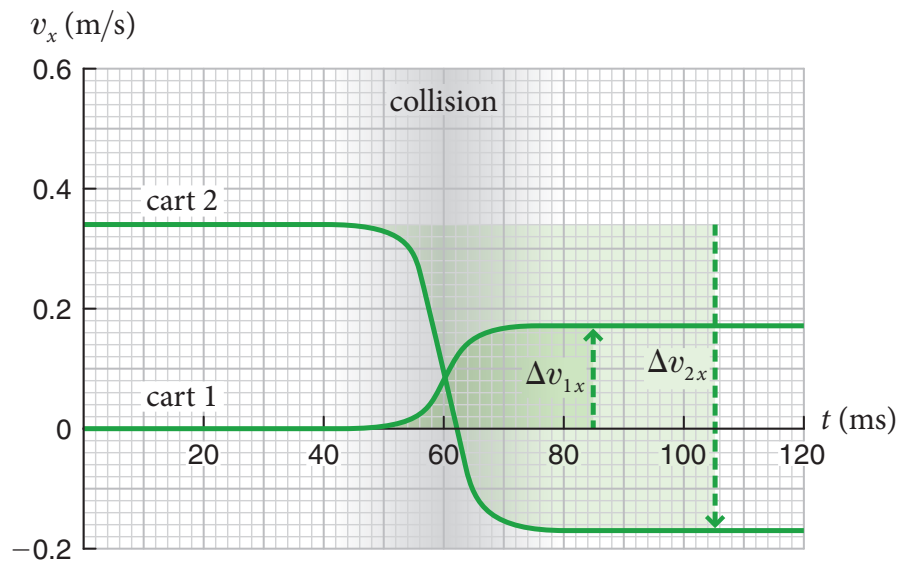


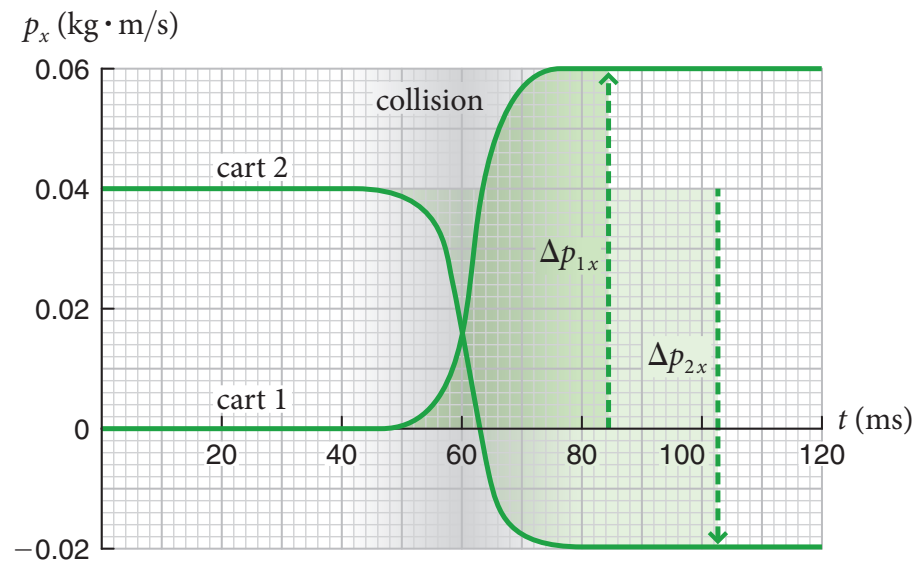
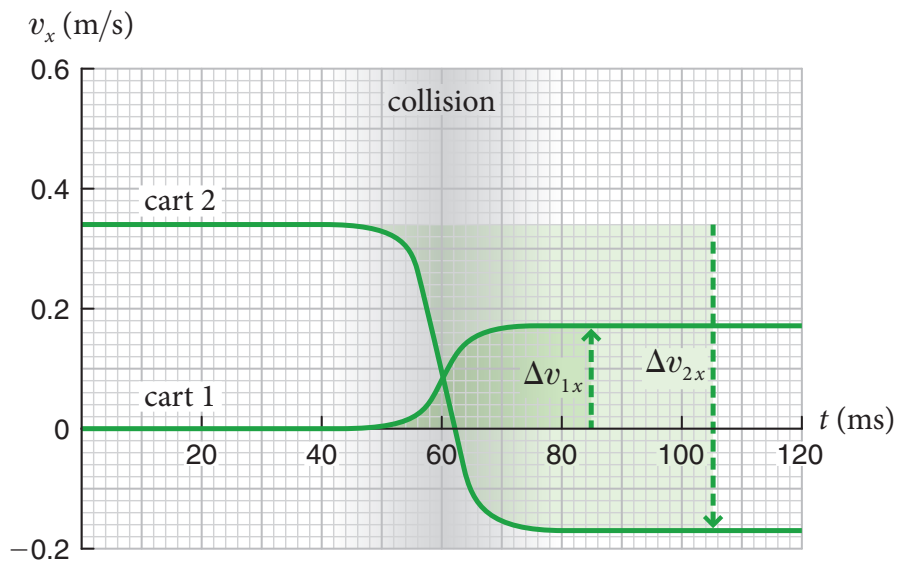
systems & extensive quantities

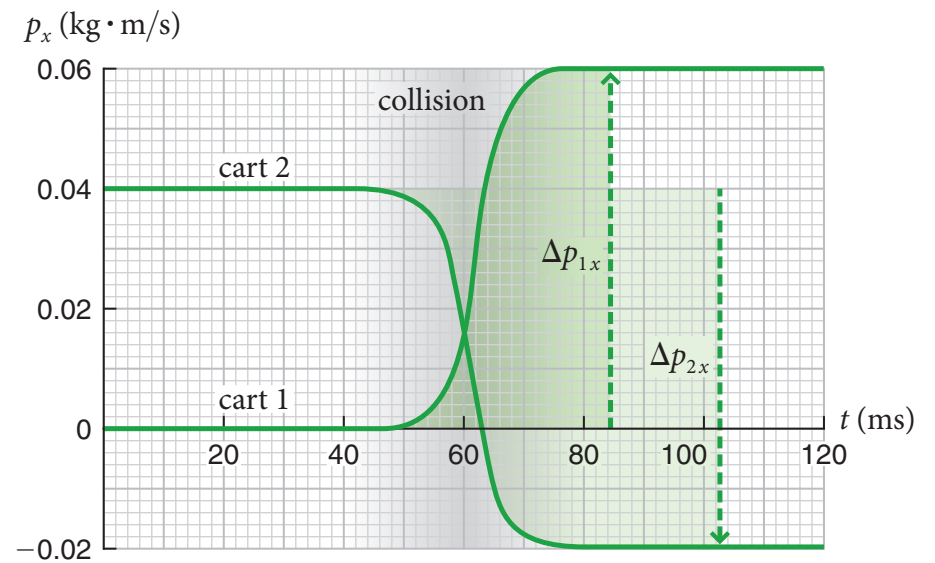
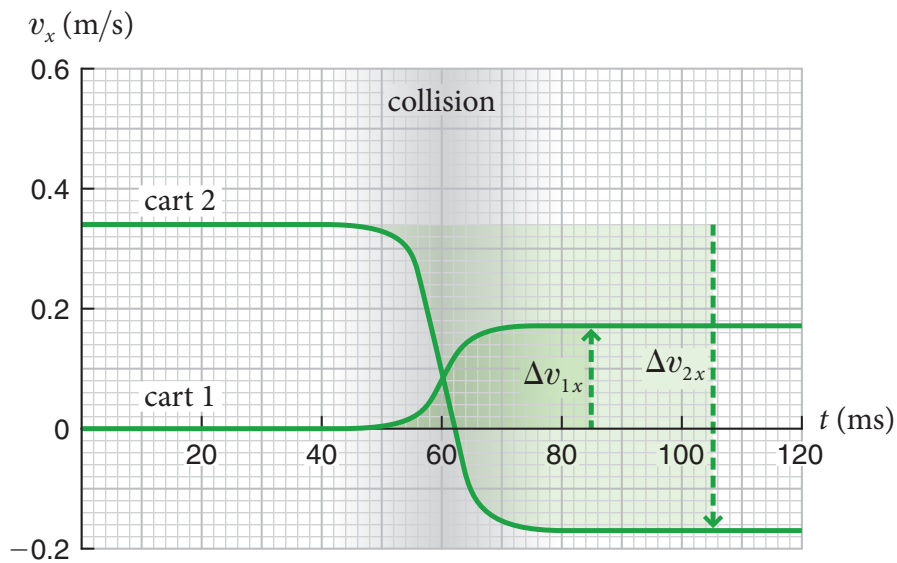
$$\vec{p} \equiv m\vec{v}$$

conserved quantity

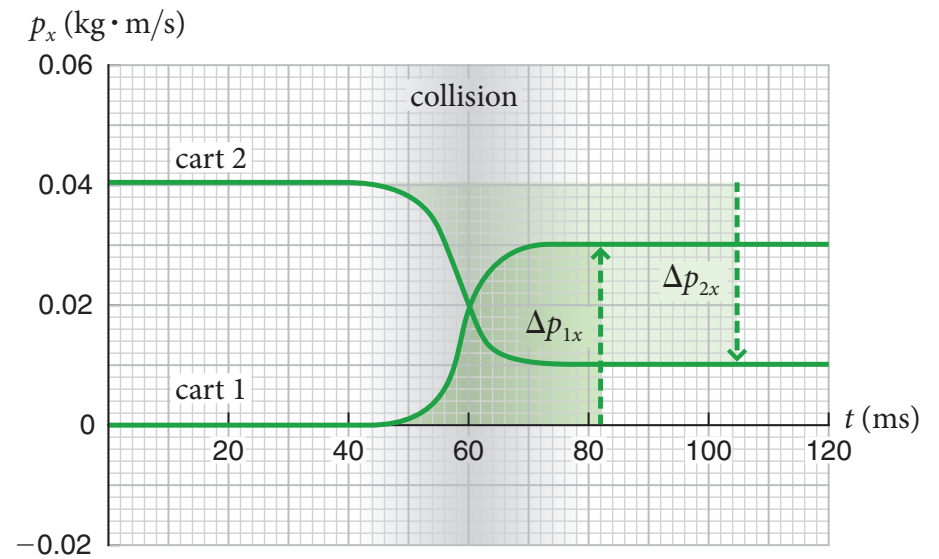
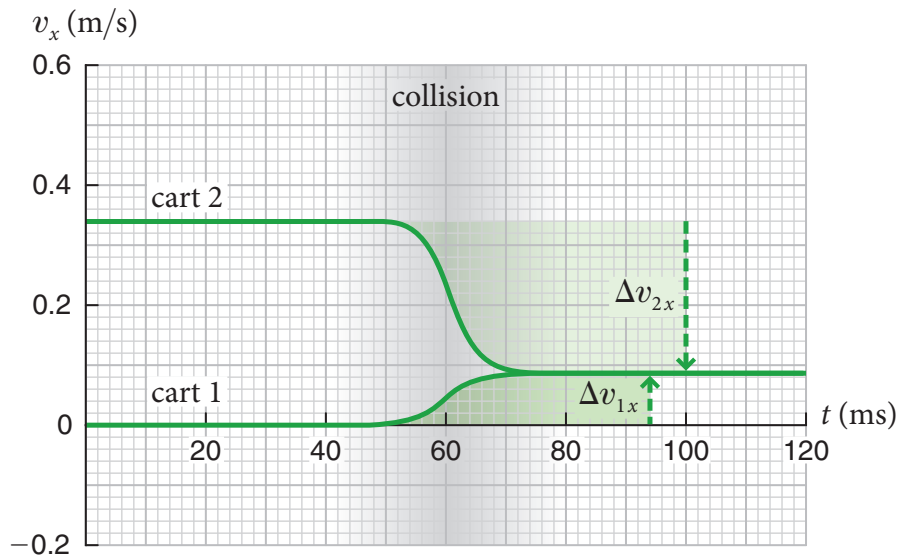




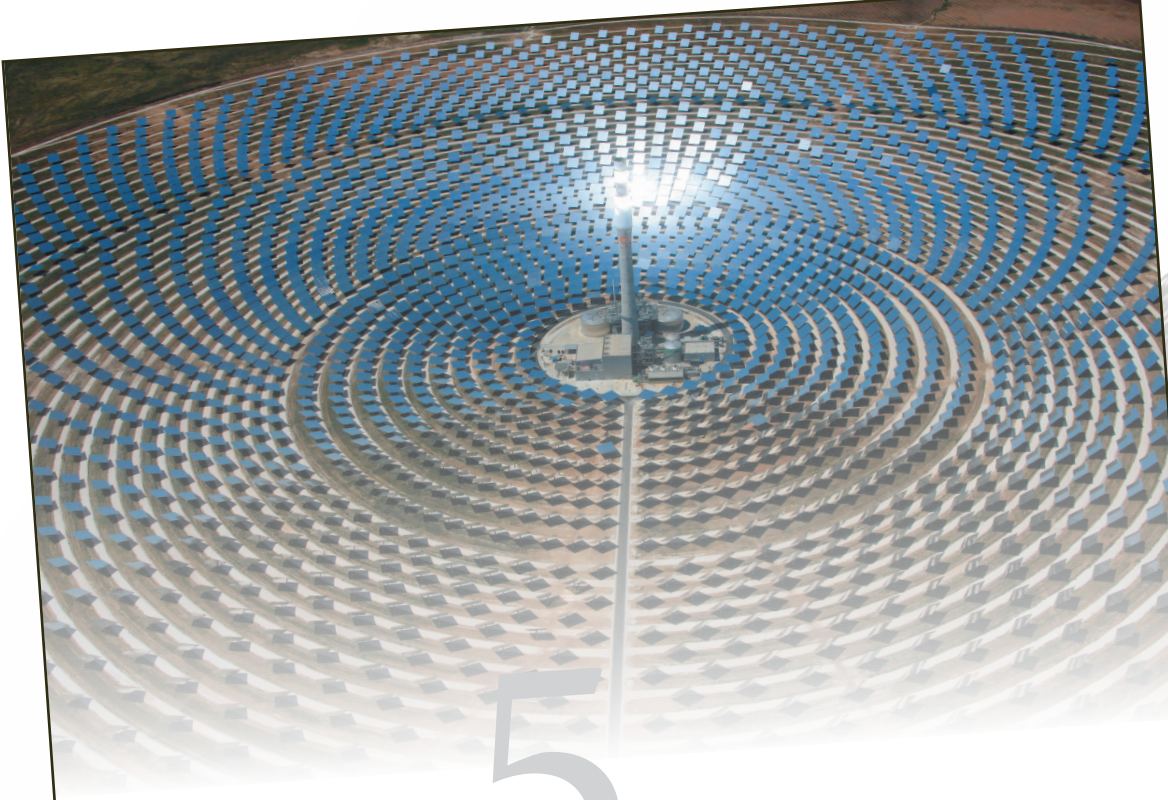




$$\Delta \vec{p} \equiv \Delta \vec{p}_1 + \Delta \vec{p}_2 = \vec{0}.$$



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



5

Energy

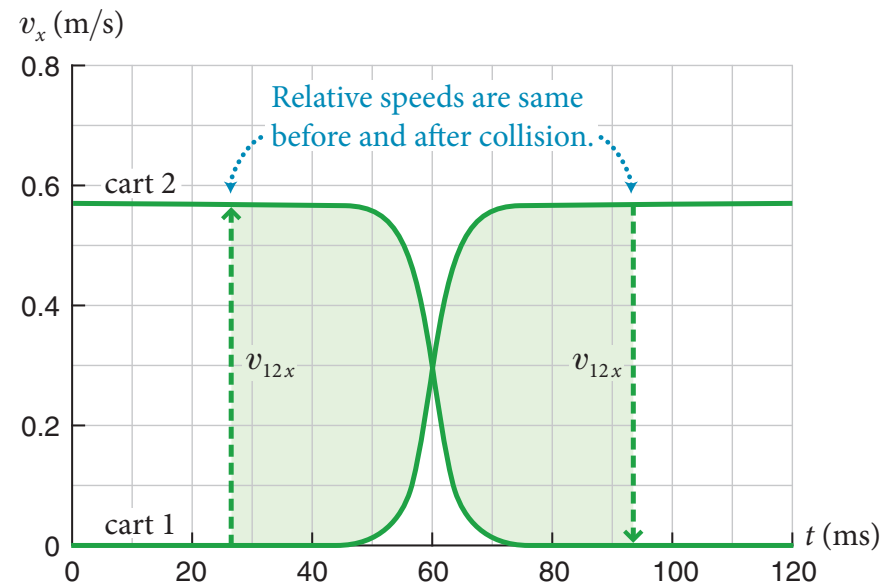
- 5.1 Classification of collisions
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems

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

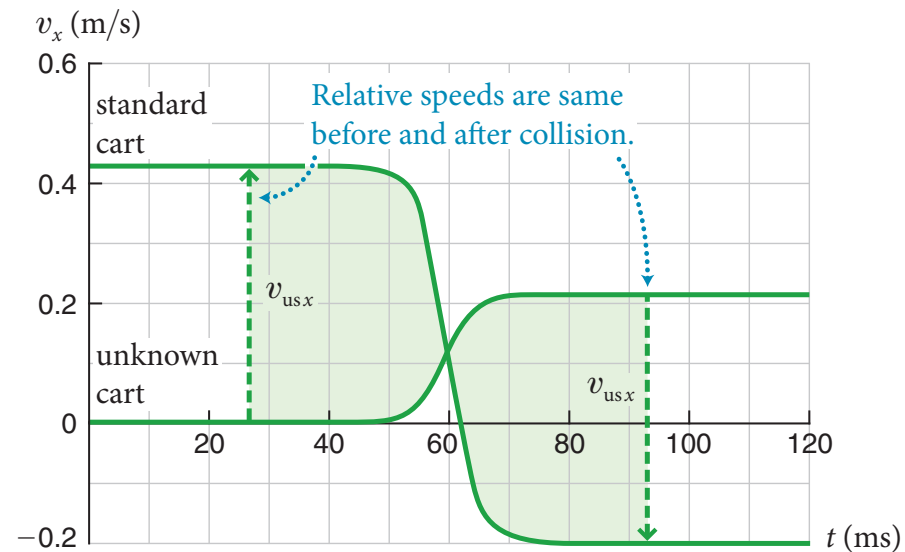
CONCEPTS

QUANTITATIVE TOOLS

elastic: relative speed unchanged

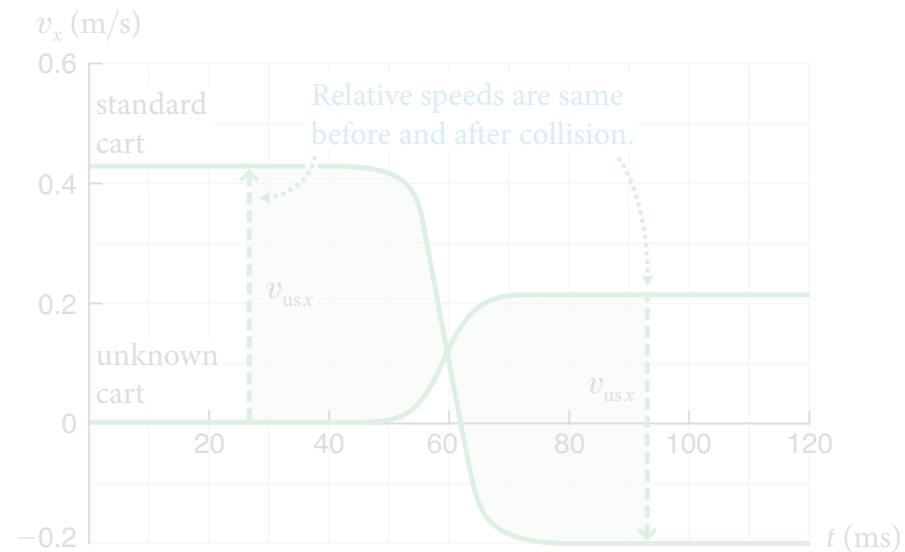


elastic: relative speed unchanged



elastic: relative speed unchanged

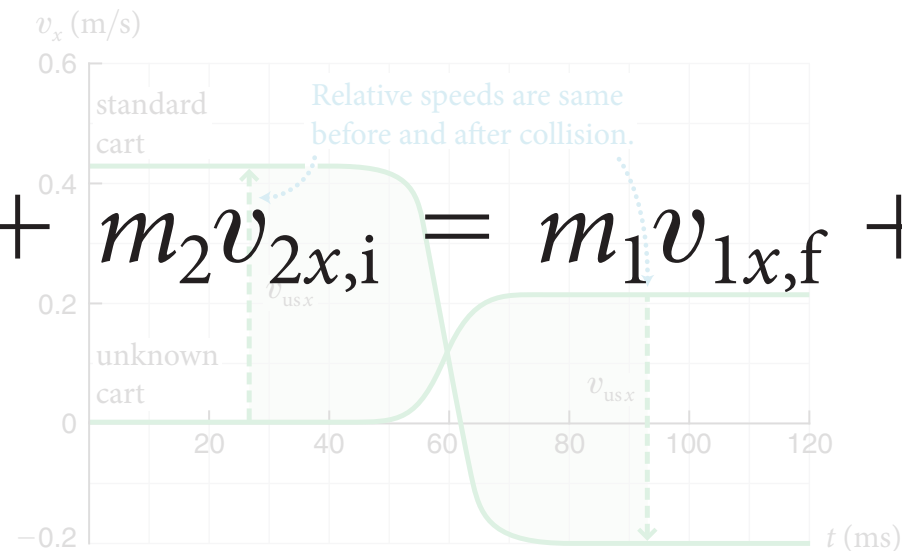
$$v_{12i} = v_{12f}$$



elastic: relative speed unchanged

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

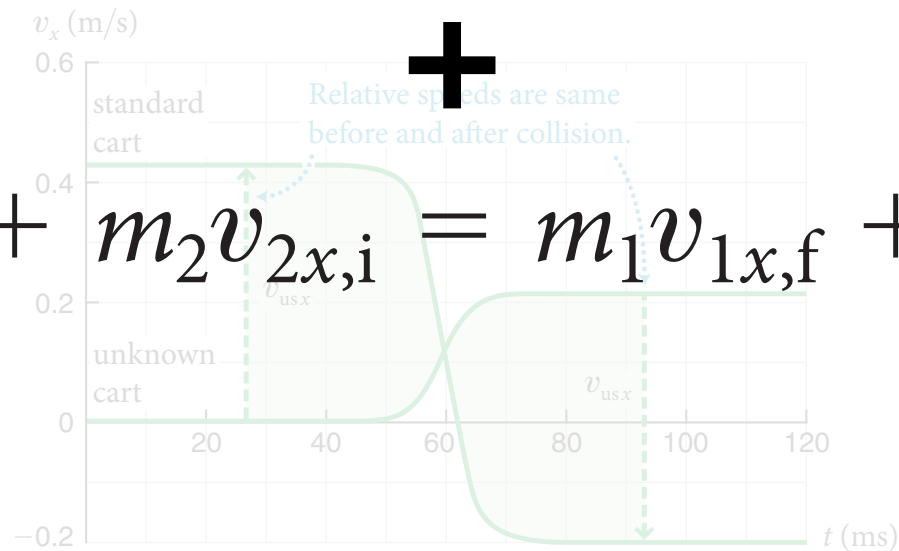
$$m_1 v_{1x,i} + m_2 v_{2x,i} = m_1 v_{1x,f} + m_2 v_{2x,f}$$



elastic: relative speed unchanged

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

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

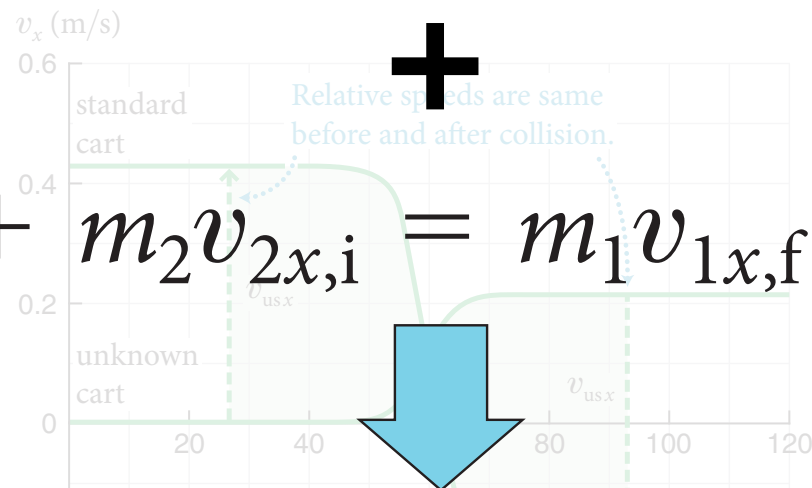


elastic: relative speed unchanged

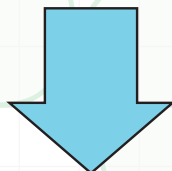
$$v_{12i} = v_{12f}$$

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

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



+



elastic vs. inelastic



elastic vs. inelastic



before or after?



elastic vs. inelastic



elastic: reversible

inelastic: irreversible



elastic vs. inelastic

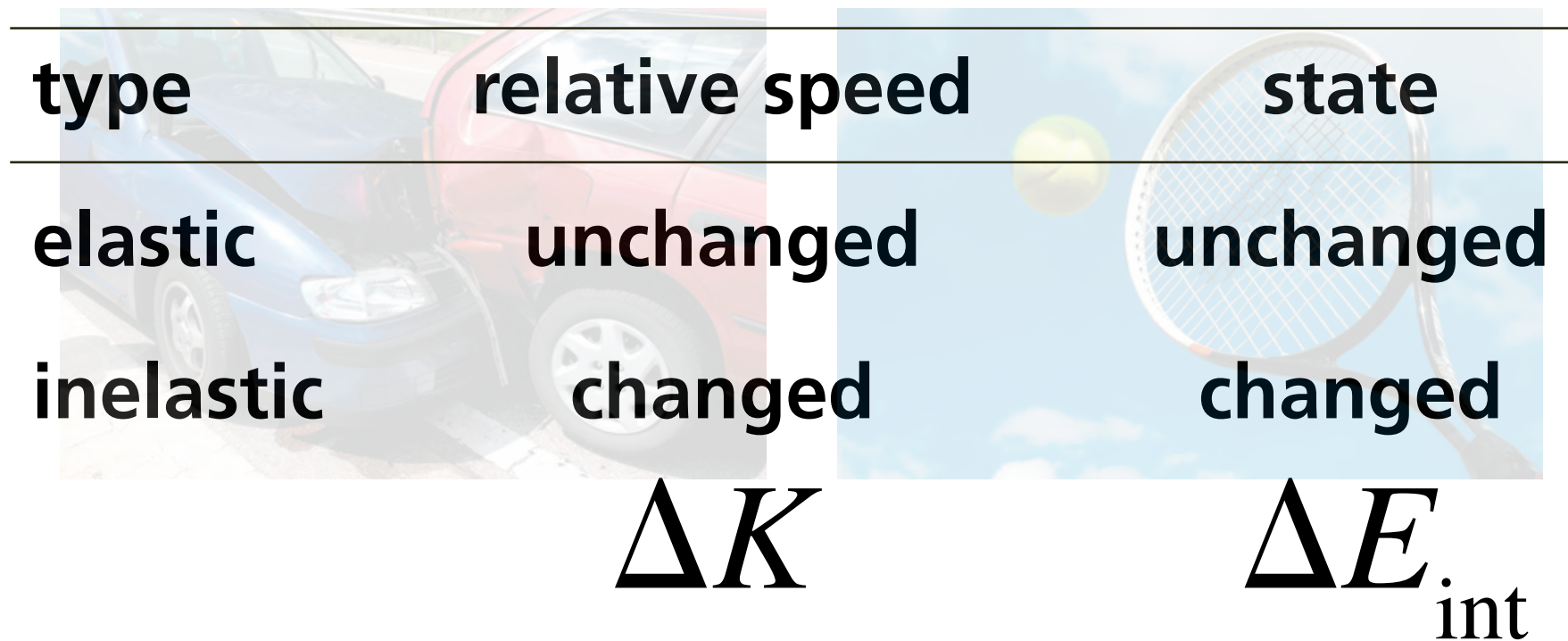
type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

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

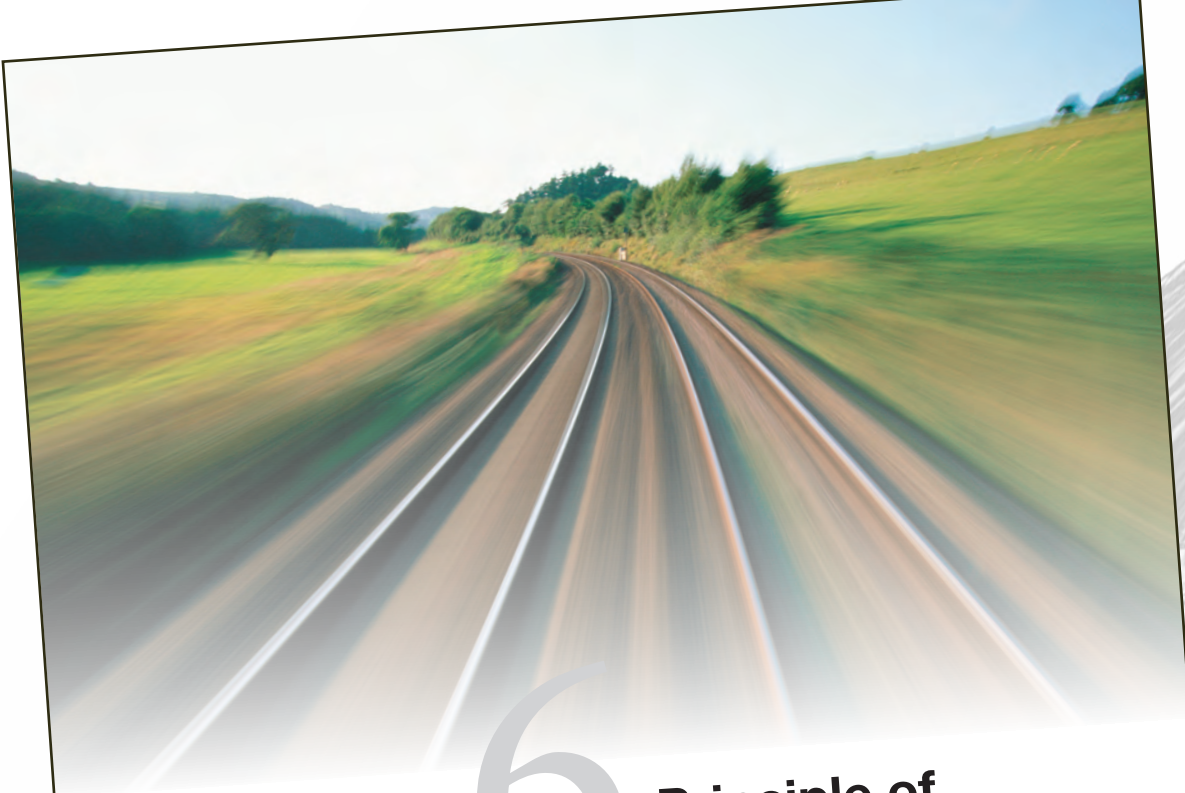
$$E = K + E_{\text{int}}$$

conservation of energy

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

closed system:

$$\Delta E = 0$$



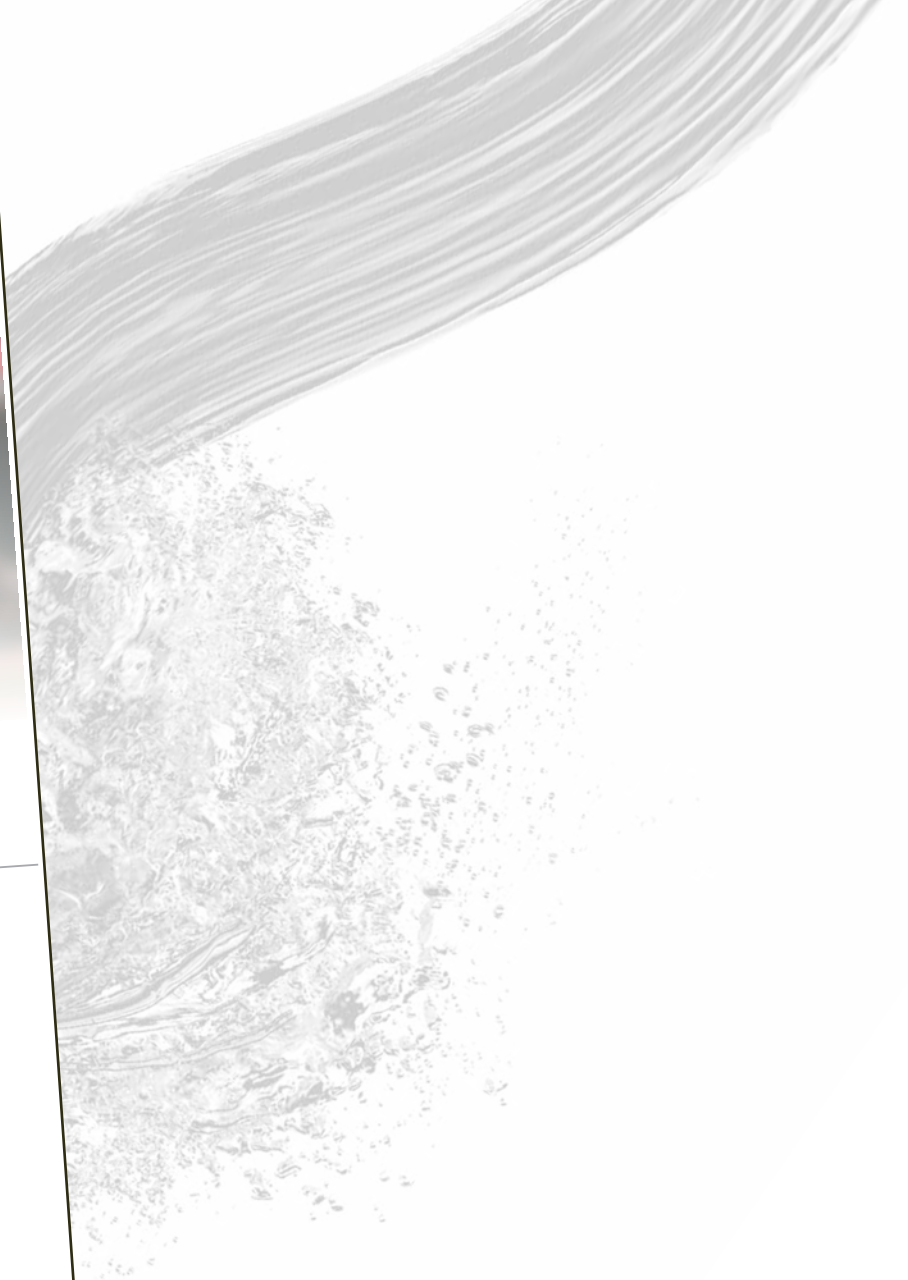
6 Principle of Relativity

- 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

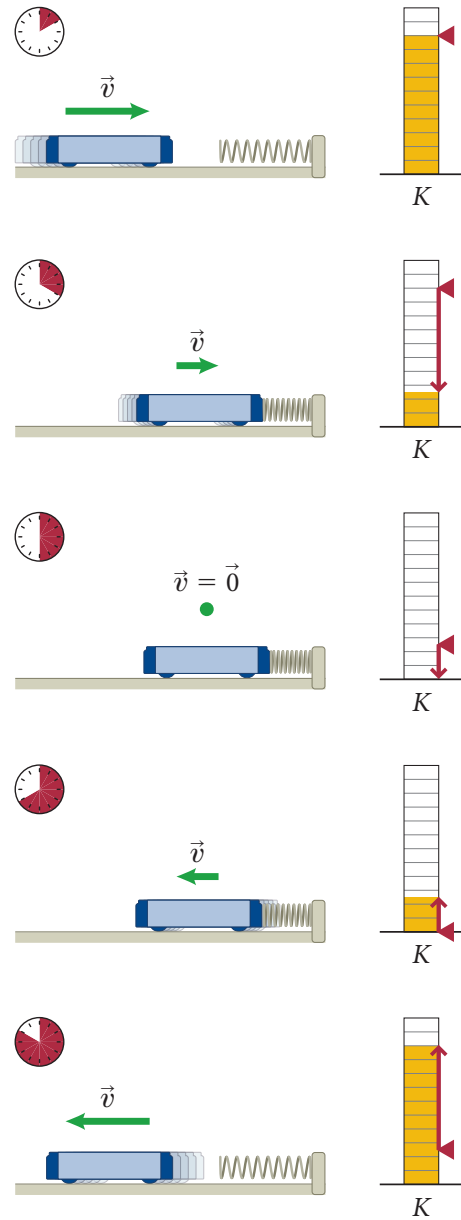
CONCEPTS

- 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

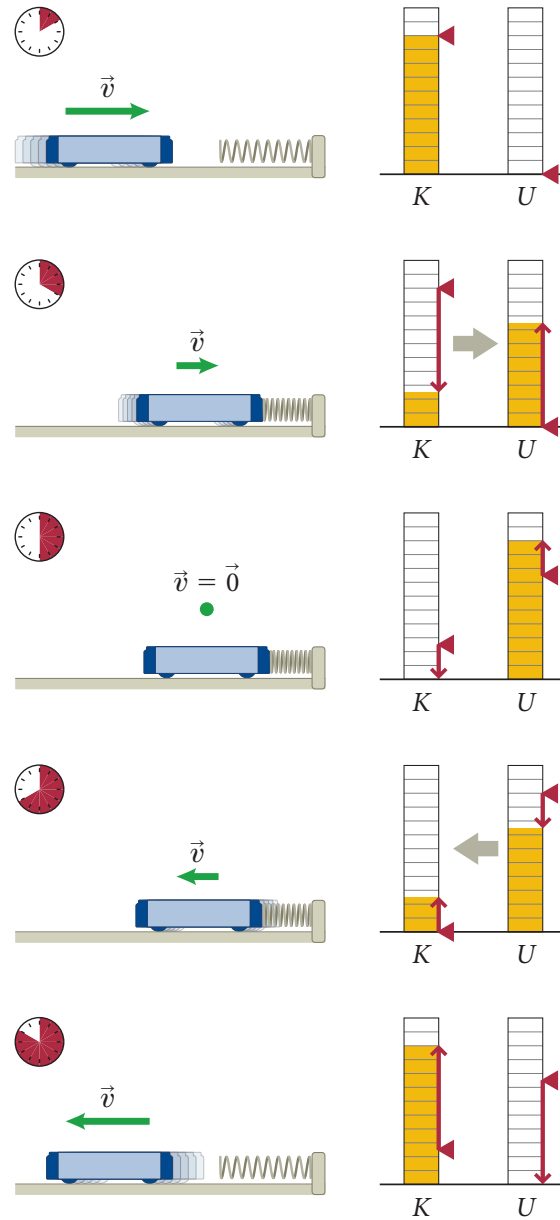
QUANTITATIVE TOOLS

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

potential energy

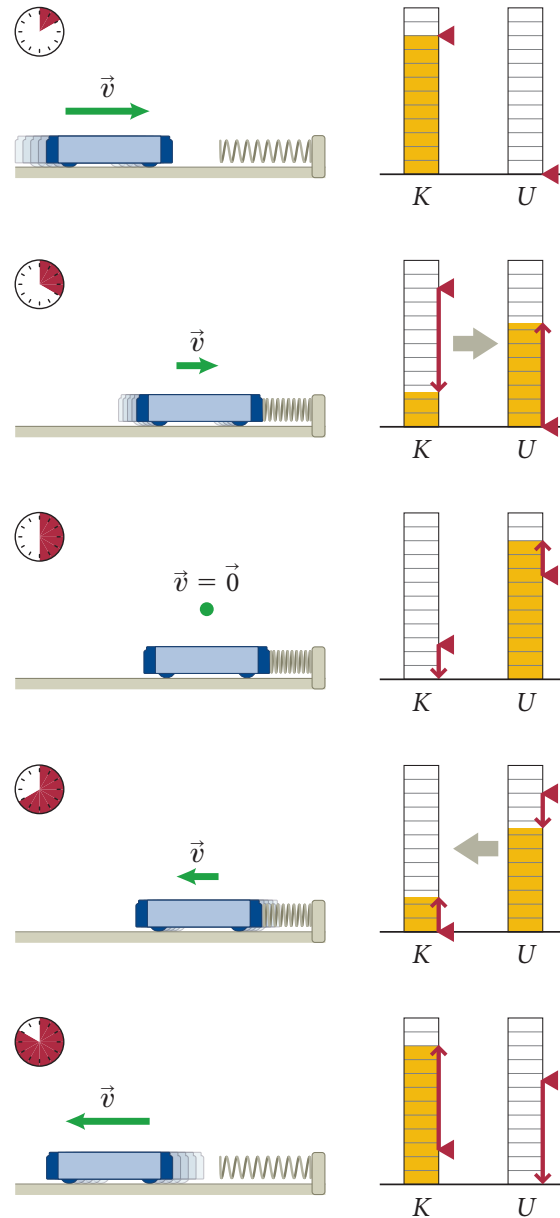


potential energy



potential energy

reversible state change





8

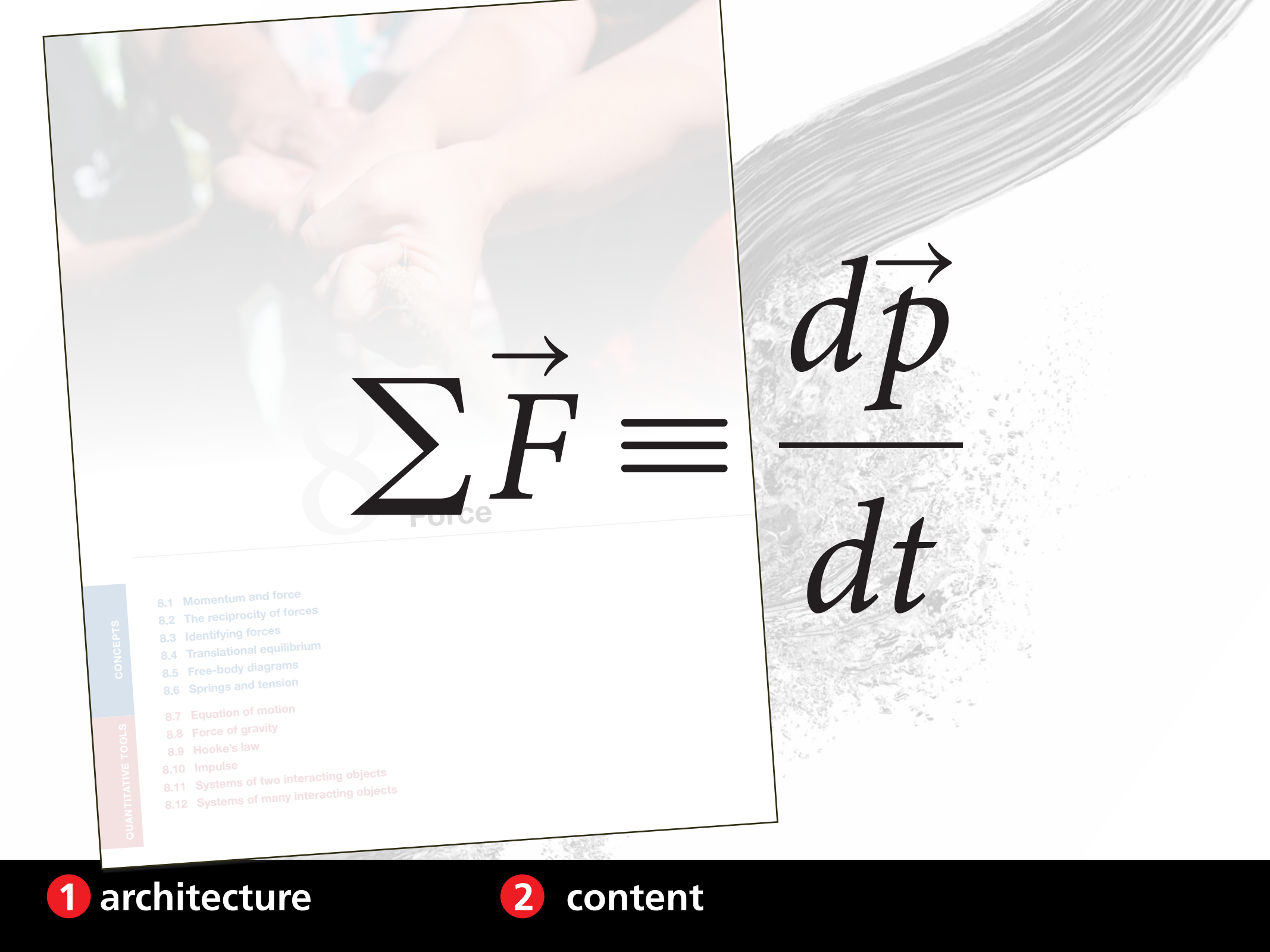
Force

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

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

1 architecture

2 content



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 thick, curved wall of water. The lighting is bright, highlighting the texture and movement of the water.

**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

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

1D

3D

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

1D

3D

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

1D

3D

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

1D

3D

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 **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
16. Waves in one dimension
17. Waves in 2 and 3 dimensions
18. Fluids

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

rotation

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

periodic

A dynamic, high-speed photograph of water splashing, creating a large, turbulent splash that fills most of the frame. The water is captured in mid-air, with many droplets and bubbles visible, giving it a sense of motion and energy. The background is a plain, light color, making the water splash stand out prominently.

**mostly minor
rearrangements!**

1 architecture

2 content

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

ERIC MAZUR

1 architecture

2 content

3 results

PRINCIPLES & PRACTICE OF
PHYSICS

for students

ERIC MAZUR

PRINCIPLES & PRACTICE OF
PHYSICS

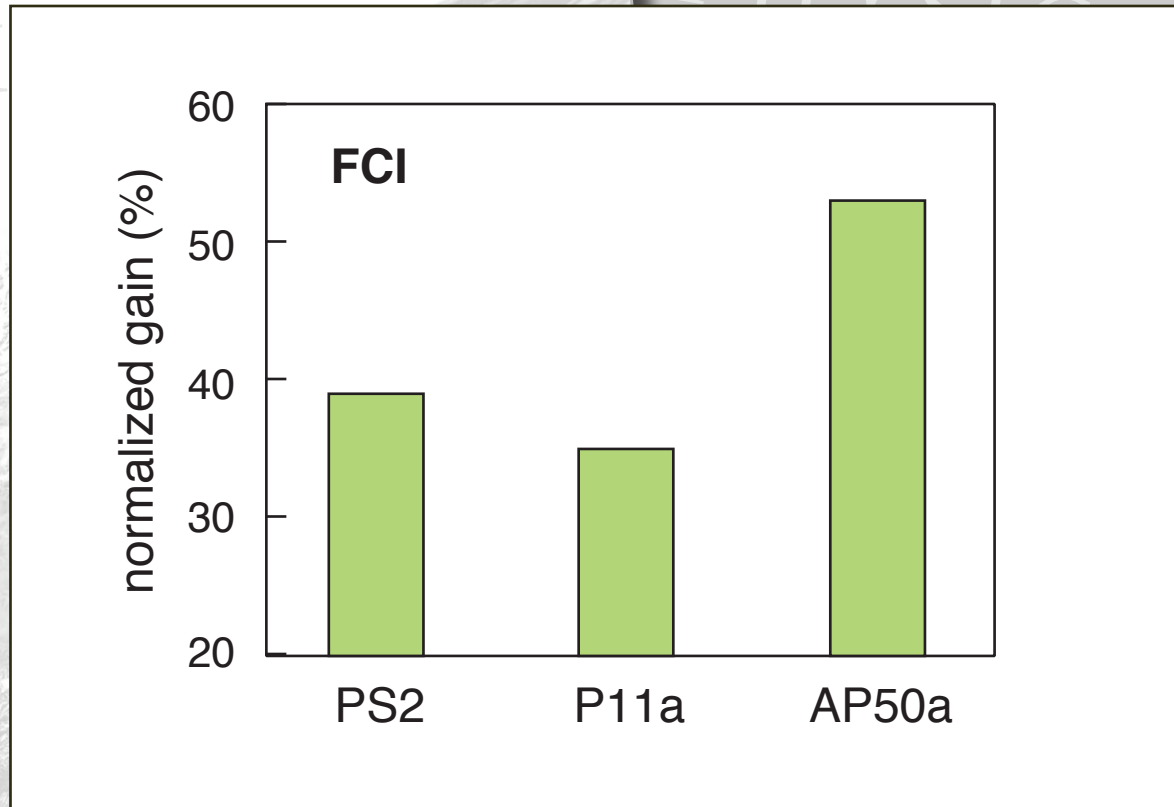
ERIC MAZUR

1 architecture

2 content

3 results

AP50: no lectures, students read book only



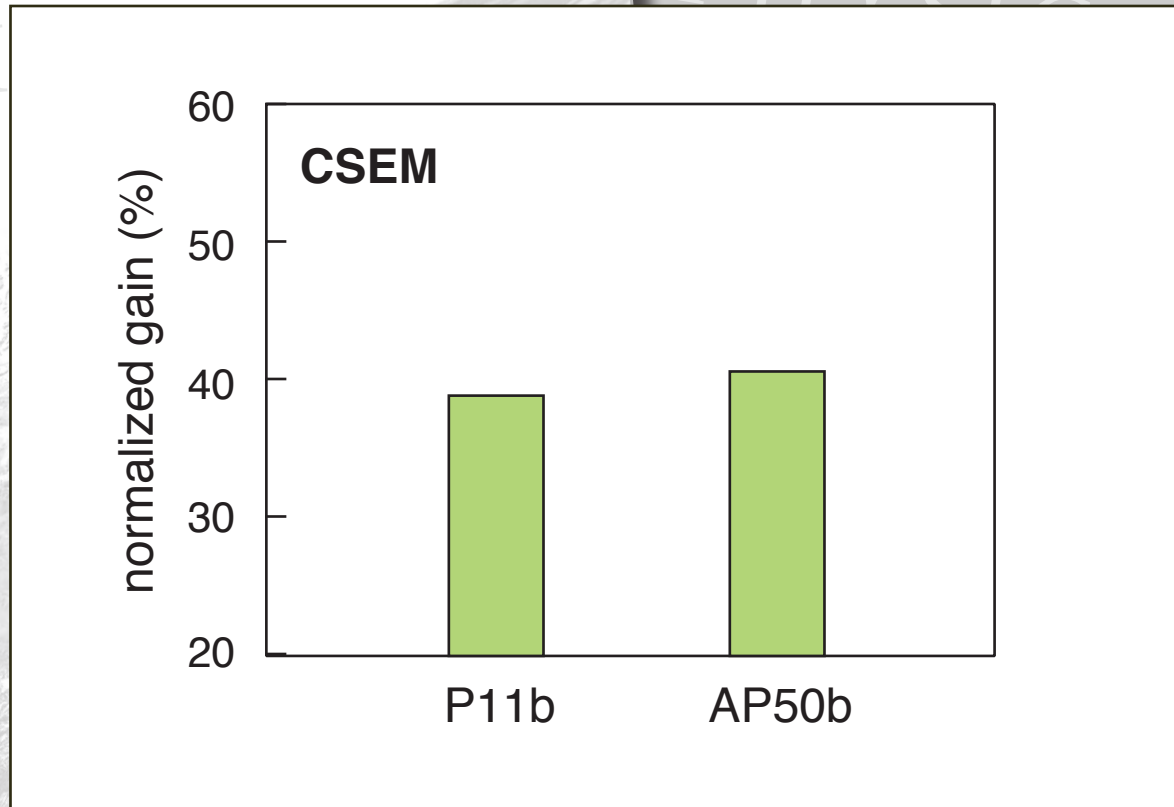
largest conceptual gain in *any* course past 6 yrs!

1 architecture

2 content

3 results

AP50: no lectures, students read book only



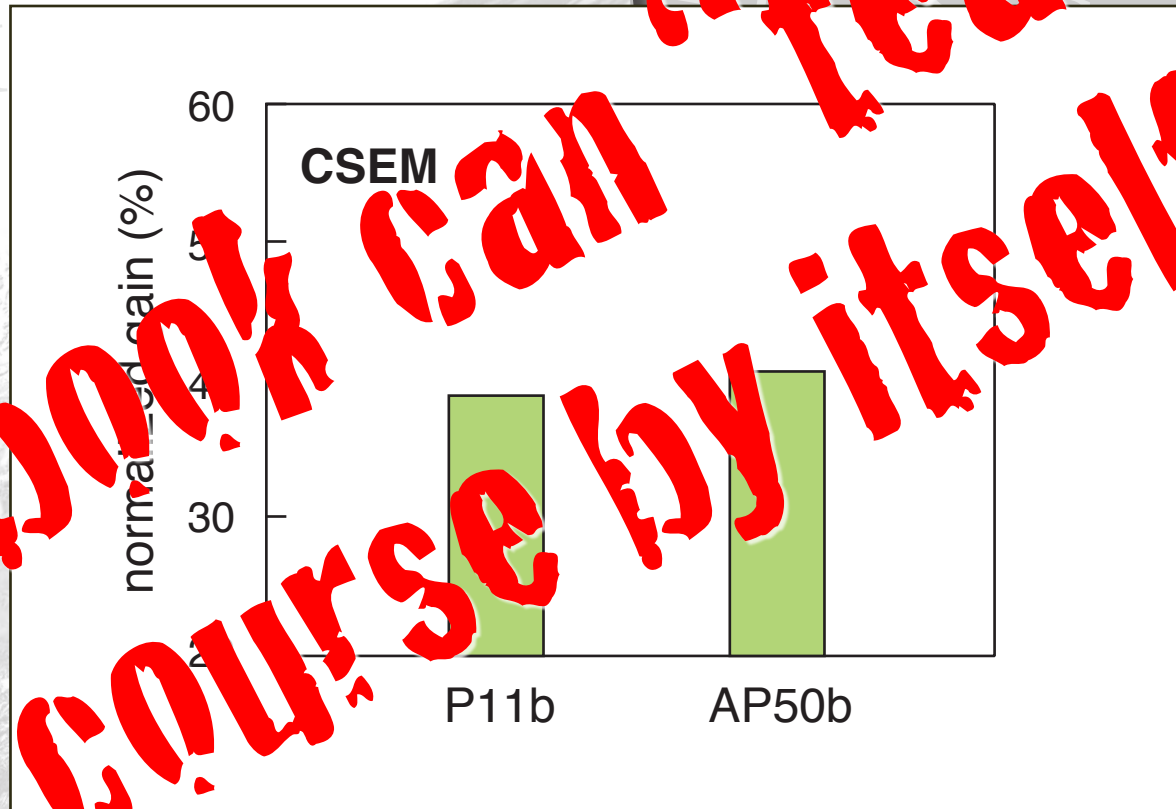
as good as when I do my best teaching!

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

PRINCIPLES & PRACTICE OF
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

ERIC MAZUR

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)

ERIC MAZUR

ERIC MAZUR

1 architecture

2 content

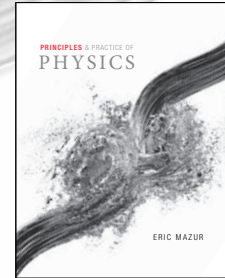
3 results

approach

before class

in class

traditional



1 architecture

2 content

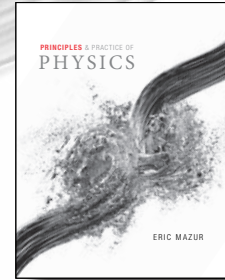
3 results

approach

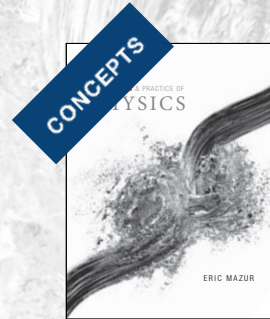
before class

in class

traditional



partially flipped



1 architecture

2 content

3 results

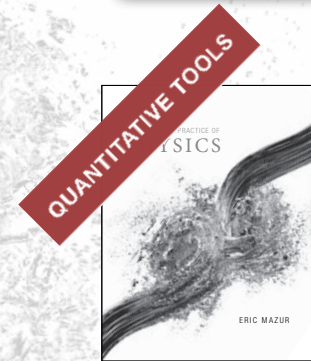
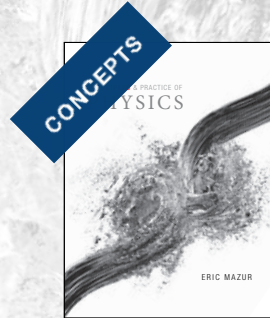
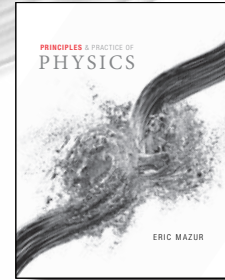
approach

before class

in class

traditional

partially flipped



1 architecture

2 content

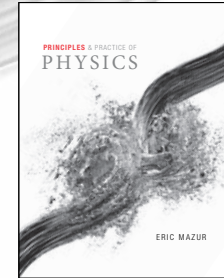
3 results

approach

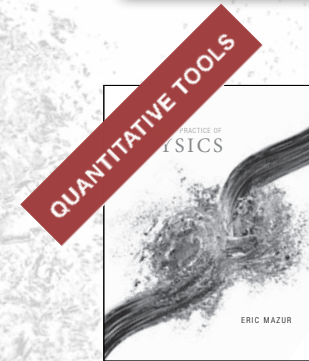
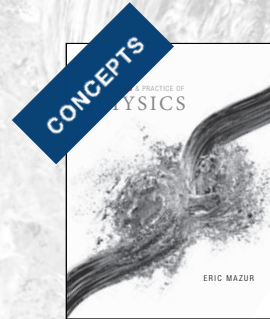
before class

in class

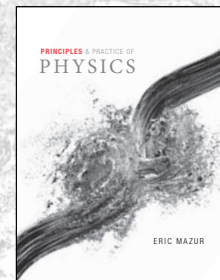
traditional



partially flipped



fully flipped



1 architecture

2 content

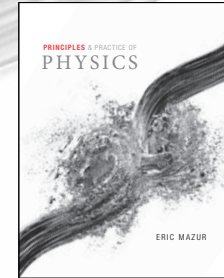
3 results

approach

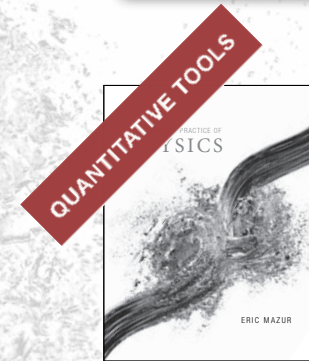
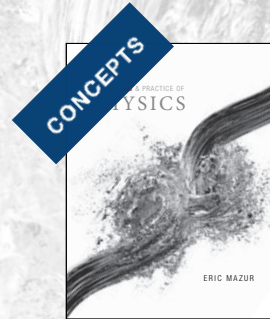
before class

in class

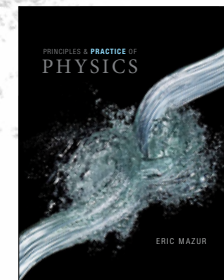
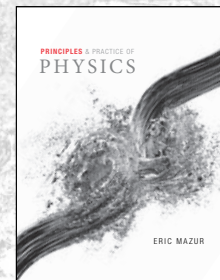
traditional



partially flipped



fully flipped



1 architecture

2 content

3 results

For a copy of these slides:

ericmazur.com

Textbook info/copies:

pearsonhighered.com/mazur1einfo

Follow me!



[eric_mazur](https://twitter.com/eric_mazur)