

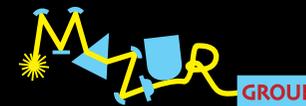
# Teaching Physics, Conservation Laws First



Webinar  
21 August 2015



# Teaching Physics, Conservation Laws First



**@eric\_mazur**

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

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

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

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

$\frac{\Delta L}{L} = 0, 1, 2$  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  $\log \frac{x}{y} = \log x - \log y$   $\log_x x = y \Leftrightarrow x^y = x$

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

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

Pipe 2 open ends displacement antinodes pressure nodes   
 Pipe 1 open end displacement antinode at open, node at closed   
 $f = \frac{v}{\lambda} = \frac{nv}{2L}$   $n=1,2,3$   $f = \frac{nv}{4L}$  ( $n=1,2,3$ )   
 $B = (10) \log \frac{I}{I_0}$   $I_0 = 10^{-12} W/m^2$

vectors

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

$T = 2\pi \sqrt{\frac{L}{g}}$  simple pend  $\omega_d = \omega$  resonance  $\omega_c = 2\omega$  critical damp  $b^2 = 4km$   $\omega < \omega_c$  underdamped  $b^2 < 4km$   $\omega > \omega_c$  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  $f = \frac{v}{\lambda} = \frac{v}{2L}$   $n=1,2,3$   $P_m^2 = 2PVI$   $P_m = v \rho \omega S_m$   $I = \frac{\text{Power}}{\text{Area}} = \frac{P_s}{4\pi r^2}$   $f_{beat} = |f_1 - f_2|$   $f = \frac{v}{4L}$  ( $n=1,2,3$ ) displacement antinodes at open, nodes at closed

interference  $\frac{\Delta L}{\lambda} = 0, 2$  fully constructive  $\theta = \frac{\Delta L}{\lambda} 2\pi$   $I = \frac{1}{2} \rho v \omega^2 S_m^2$   $\sin \theta = \frac{v}{v_s}$   $\frac{v_s}{v} = \text{mach } \#$   $B = (10) \log \frac{I}{I_0}$   $I_0 = 10^{-12}$

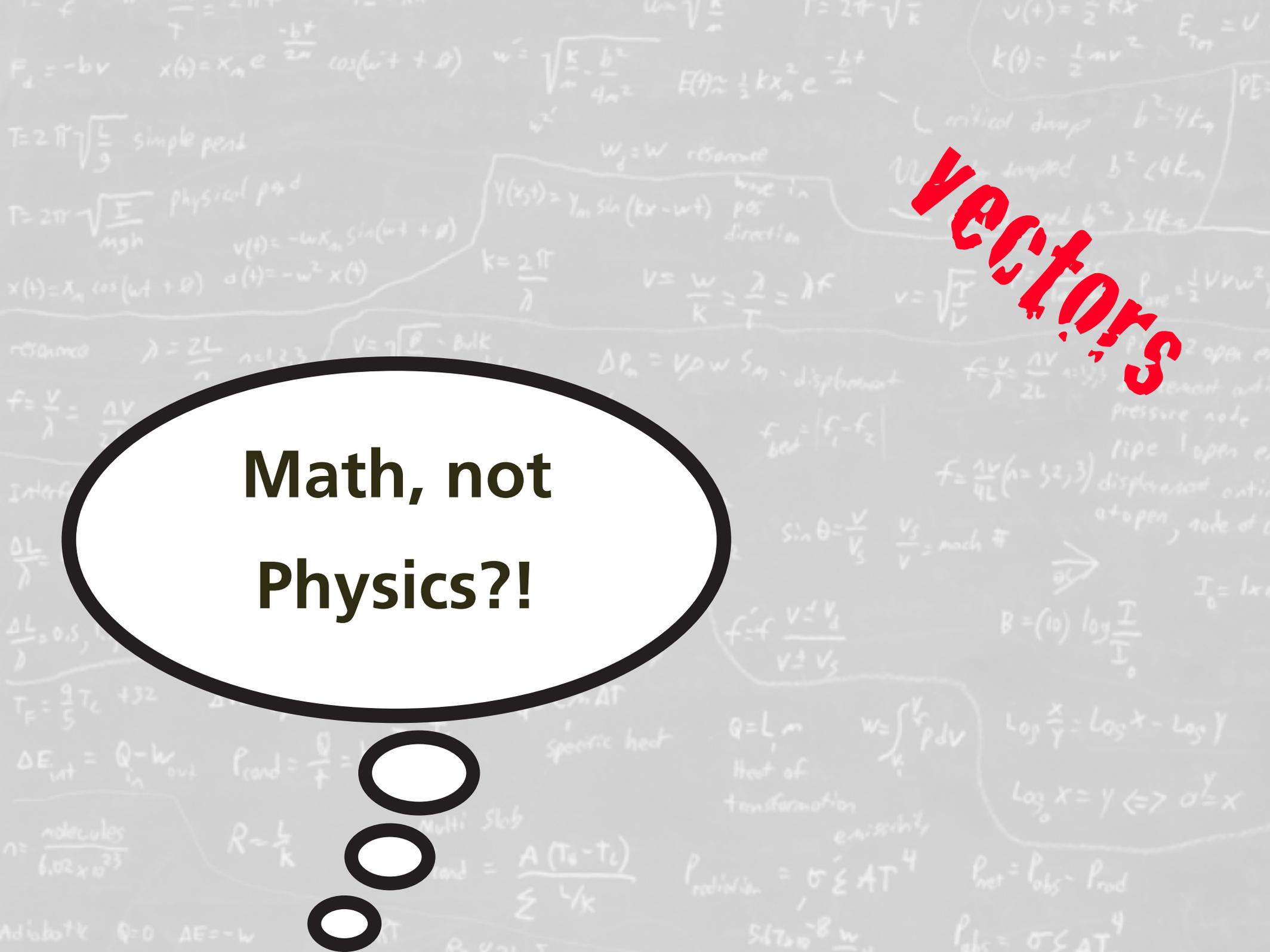
$\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5$  fully destructive  $B = 3\alpha$   $Q = c \Delta T$  Heat capacity  $f = f \frac{v \pm v_d}{v \pm v_s}$   $Q = cm \Delta T$  specific heat  $Q = L_m$  Heat of transformation  $\log \frac{x}{y} = \log x - \log y$   $\log_0 x = y \Leftrightarrow 0^y = x$

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

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

**Math, not  
Physics?!**

**vectors**



# Kinematics

# Vectors

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

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

$x(t) = x_m \cos(kx - \omega t)$   $y_m \sin(kx - \omega t)$  wave in pos direction  $k = \frac{2\pi}{\lambda}$   $v = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f$   $v = \sqrt{\frac{T}{\mu}}$

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  $f = \frac{v}{\lambda} = \frac{v}{2L}$   $n=1,2,3$   $f = \frac{v}{4L}$  ( $n=1,2,3$ )  $P_{ave} = \frac{1}{2} v \rho \omega^2 S_m^2$

$f = \frac{v}{\lambda} = \frac{v}{2L}$   $n=1,2,3$   $P_m^2 = 2PVI$   $P_m = v \rho \omega S_m$   $I = \frac{Power}{Area} = \frac{P_s}{4\pi r^2}$   $f_{beat} = |f_1 - f_2|$   $f = \frac{v}{4L}$  ( $n=1,2,3$ )  $v_s = \text{mach } \#$   $\frac{v_s}{v}$

Interference  $\frac{\Delta L}{\lambda} = 0, 1/2$  fully constructive  $\theta = \frac{\Delta L}{\lambda} 2\pi$   $I = \frac{1}{2} \rho v \omega^2 S_m^2$   $\sin \theta = \frac{v}{v_s}$   $\frac{v_s}{v} = \text{mach } \#$   $B = (10) \log \frac{I}{I_0}$   $I_0 = 10^{-12}$

$\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5$  fully destructive  $B = 3\alpha$   $Q = c \Delta T$  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  $W = \int_{v_i}^{v_f} p dv$   $\log \frac{x}{y} = \log x - \log y$   $\log_0 x = y \Leftrightarrow 0^y = x$

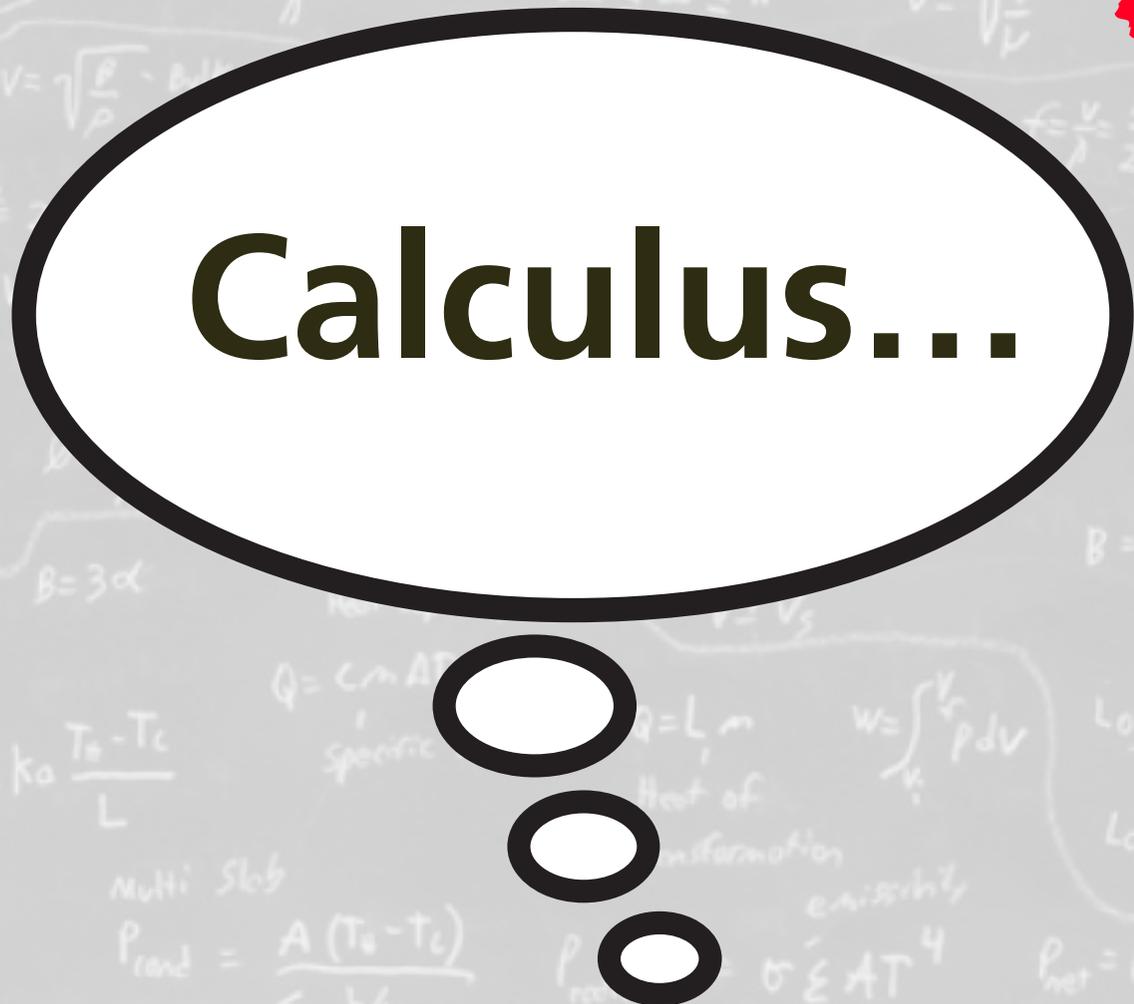
$T_F = \frac{9}{5} T_C + 32$   $\Delta L = L \alpha \Delta T$   $\Delta V = V \beta \Delta T$   $\Delta E_{int} = Q - W_{out}$   $P_{cond} = \frac{Q}{t} = k \alpha \frac{T_h - T_c}{L}$   $Q = L_m$  Heat of transformation  $W = \int_{v_i}^{v_f} p dv$   $\log \frac{x}{y} = \log x - \log y$   $\log_0 x = y \Leftrightarrow 0^y = x$

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

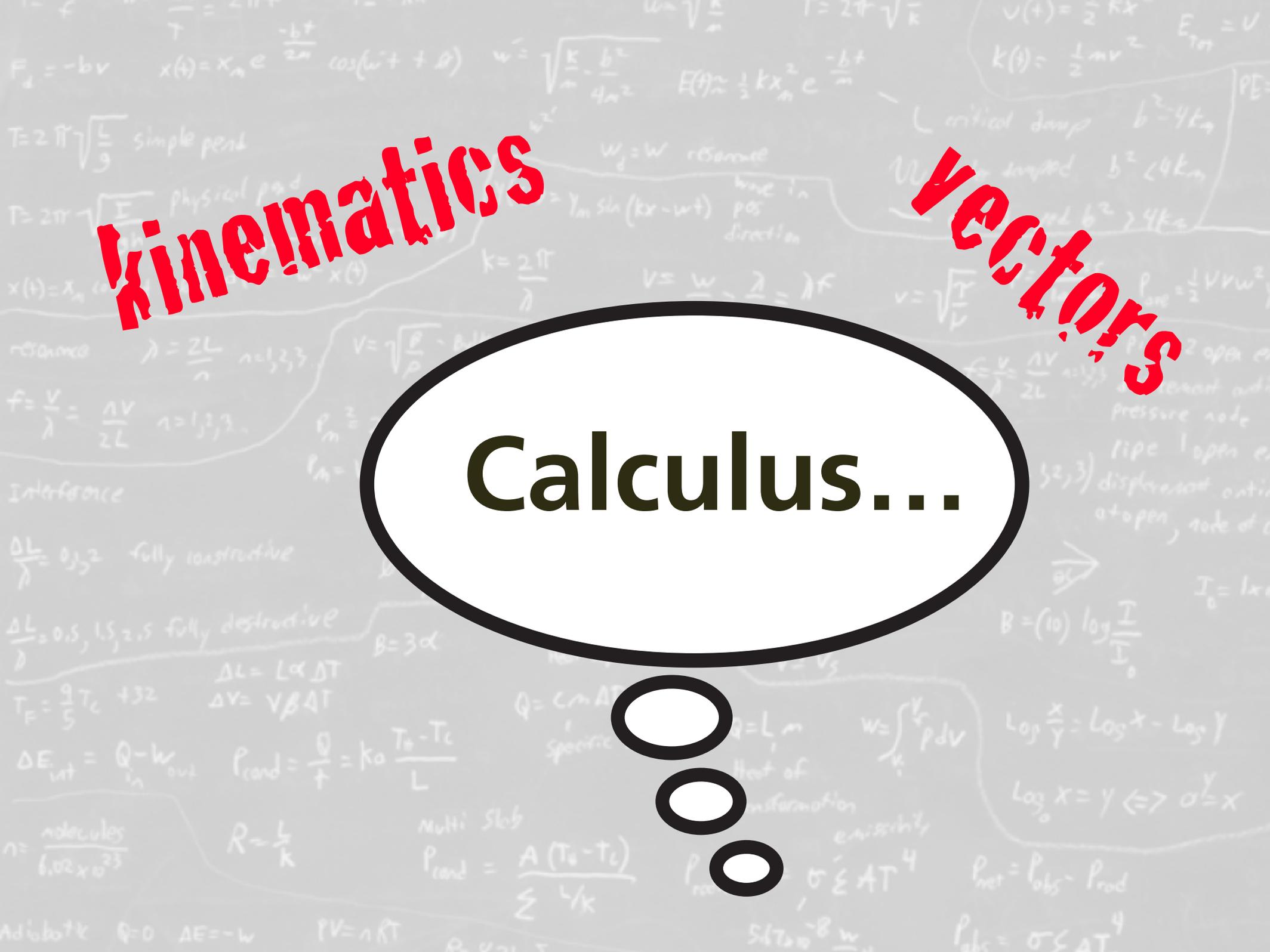
Adiabatic  $Q=0$   $\Delta E = -W$   $PV = nRT$   $P_1 V_1^\gamma = P_2 V_2^\gamma$   $T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$   $P_1^{1-\gamma} T_1^\gamma = P_2^{1-\gamma} T_2^\gamma$

kinematics

vectors



Calculus...





kinematics

vectors

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

momentum

Background content includes various physics formulas:

- $F_d = -bv$
- $x(t) = x_m e^{-\frac{bt}{2m}} \cos(\omega t + \theta)$
- $\omega = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$
- $E(t) = \frac{1}{2} k x_m^2 e^{-\frac{bt}{m}}$
- $T = 2\pi \sqrt{\frac{L}{g}}$  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
- $\lambda = \frac{2L}{n}$   $n=1,2,3$
- $v = \sqrt{\frac{E}{\rho}}$  bulk modulus
- $\Delta P_m = v \rho \omega S_m$  displacement
- $f = \frac{v}{\lambda} = \frac{v}{2L}$   $n=1,2,3$
- $f = \frac{v}{4L}$   $(n=1,2,3)$  pipe 1 open
- interference  $\frac{\Delta L}{\lambda} = 0, 1/2$  fully constructive
- $\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5$  fully destructive
- $\theta = \frac{\Delta L}{\lambda} 2\pi$
- $I = \frac{1}{2} \rho v \omega^2 S_m^2$
- $\frac{v_s}{v} = \text{mach } \#$
- $B = (10) \log \frac{I}{I_0}$
- $\log \frac{x}{y} = \log x - \log y$
- $\log_a x = y \Leftrightarrow a^y = x$
- $Q = L, m$  Heat of transformation
- $w = \int_{v_1}^{v_2} p dv$  enstrophy
- $P_{\text{radiation}} = \sigma \epsilon AT^4$
- $P_{\text{net}} = P_{\text{obs}} - P_{\text{prod}}$
- $P_{\text{abs}} = \sigma \epsilon AT^4$
- $R = \frac{L}{k}$  Multi Slab
- $P_{\text{cond}} = \frac{A(T_h - T_c)}{\sum L/k}$
- $PV = nRT$
- $Q = 0$  Adiabatic  $\Delta E = -W$
- $n = \frac{\text{molecules}}{6.02 \times 10^{23}}$

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
- physical pend
- $x(t) = x_m \cos(\omega t + \phi)$
- $k = \frac{2\pi}{\lambda}$
- $\omega_d = \omega$  resonance
- critical damp  $b^2 = 4km$
- over damped  $b^2 < 4km$
- under damped  $b^2 > 4km$
- $v = \sqrt{\frac{T}{\mu}}$
- $\lambda = \frac{2L}{n}$   $n=1,2,3$
- $v = \sqrt{\frac{E}{\rho}}$  bulk modulus
- $\Delta P_m = \rho v^2 S$
- $f = \frac{v}{\lambda} = \frac{v}{2L}$   $n=1,2,3$
- $f_m^2 = 2PVI$
- $m = v\rho\omega S_m$
- interference
- $\frac{\Delta L}{\lambda} = 0.5, 1.5, 2.5$  fully destructive
- $\theta = \frac{\Delta L}{\lambda} 2\pi$
- $I = \frac{1}{2} \rho v \omega^2 S_m^2$
- $\frac{v_s}{v} = \text{mach } \#$
- $B = (10) \log \frac{I}{I_0}$
- $Q = L, m$
- $Q = c \Delta T$
- $\Delta L = L \alpha \Delta T$
- $\Delta V = V \beta \Delta T$
- $T_F = \frac{9}{5} T_C + 32$
- $\Delta E_{int} = Q_{in} - W_{out}$
- $n = \frac{\text{molecules}}{6.02 \times 10^{23}}$
- $R = \frac{L}{k}$
- Multi Slab
- $P_{cond} = \frac{A(T_h - T_c)}{\sum L/k}$
- $P_{radiation} = \sigma \epsilon A T^4$
- $P_{net} = P_{obs} - P_{rad}$
- $P_{abs} = \sigma \epsilon A T^4$
- $PV = nRT$
- $Q = 0$   $\Delta E = -W$
- $\log_0 x = y \Leftrightarrow 0^y = x$

# energy

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

# momentum

# collisions

**kinematics**

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

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

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

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

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

$f = \frac{v}{\lambda} = \frac{v}{2L}$   $n=1,2,3$   $f_m = \frac{v}{2L}$   $n=1,2,3$   $f = \frac{v}{4L}$   $n=1,2,3$

**work**

$\Delta L = L \alpha \Delta T$   $\Delta V = V \beta \Delta T$   $\Delta E_{int} = Q - W_{out}$   $P_{cond} = \frac{Q}{t} = k \alpha \frac{T_h - T_c}{L}$   $R = \frac{L}{k}$

$Q = c \Delta T$   $Q = \int v \rho dv$   $\log_2 x = y \Leftrightarrow 2^y = x$

**resonance**  $\omega_d = \omega$  resonance

**critical damp**  $b^2 = 4km$

**under damped**  $b^2 < 4km$

**over damped**  $b^2 > 4km$

**interference**

$\frac{\Delta L}{\lambda} = 0, 1/2$  fully constructive

$\frac{\Delta L}{\lambda} = 0, 1.5, 2.5$  fully destructive

$\theta = \frac{\Delta L}{\lambda} 2\pi$   $I = \frac{1}{2} \rho v \omega^2 S_m^2$   $f_{beat} = |f_1 - f_2|$   $\frac{v_s}{v} = \text{mach } \#$   $B = (10) \log \frac{I}{I_0}$   $I_0 = 10^{-12}$

**collisions**

$P_{rad} = \sigma \epsilon AT^4$   $P_{net} = P_{obs} - P_{rad}$   $P_{abs} = \sigma \epsilon AT^4$

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



**conservation of energy**

**Just algebra!**

**conservation of momentum**

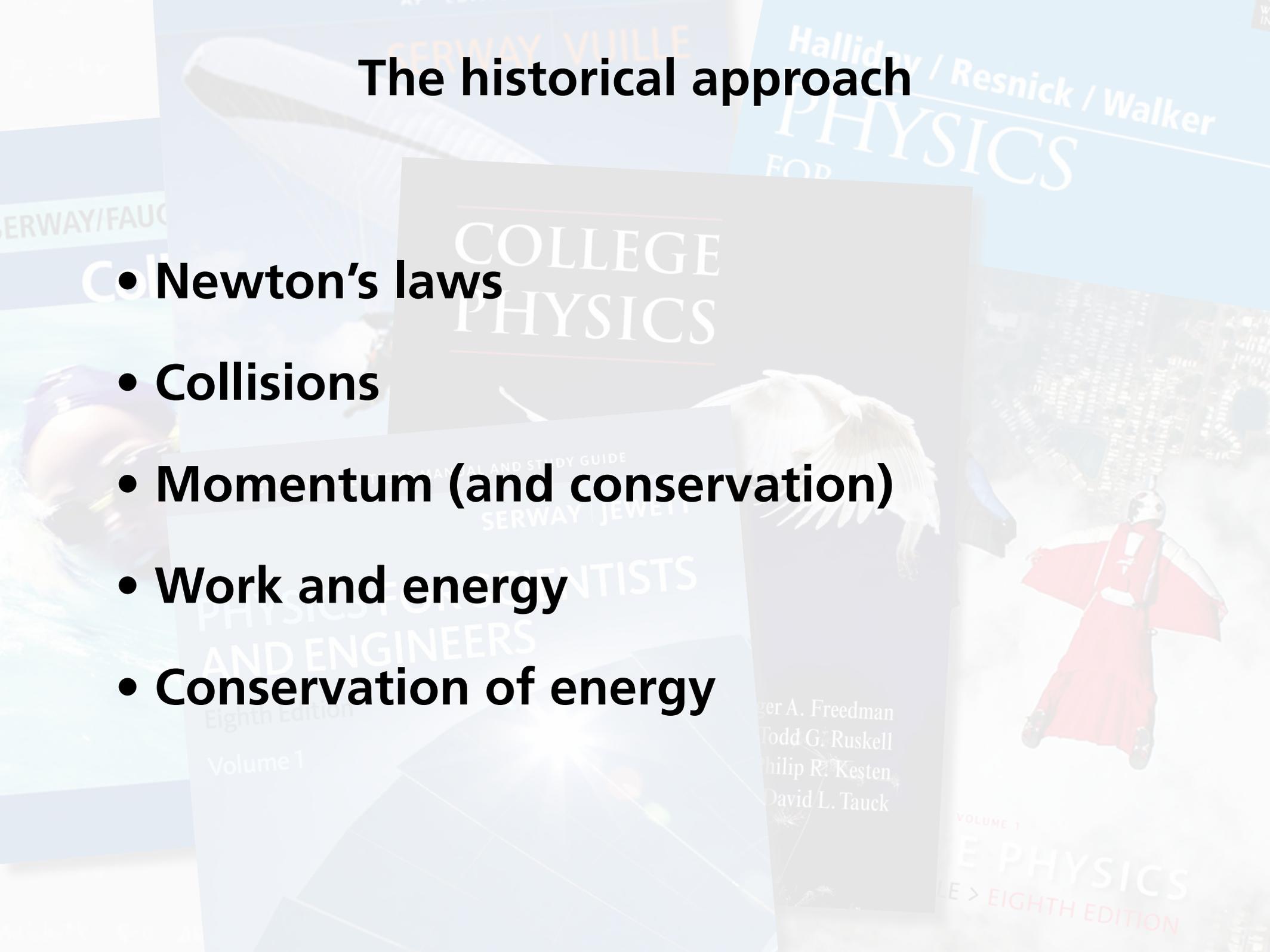
# conservation of energy

Why not START  
the easy way?

# conservation of momentum

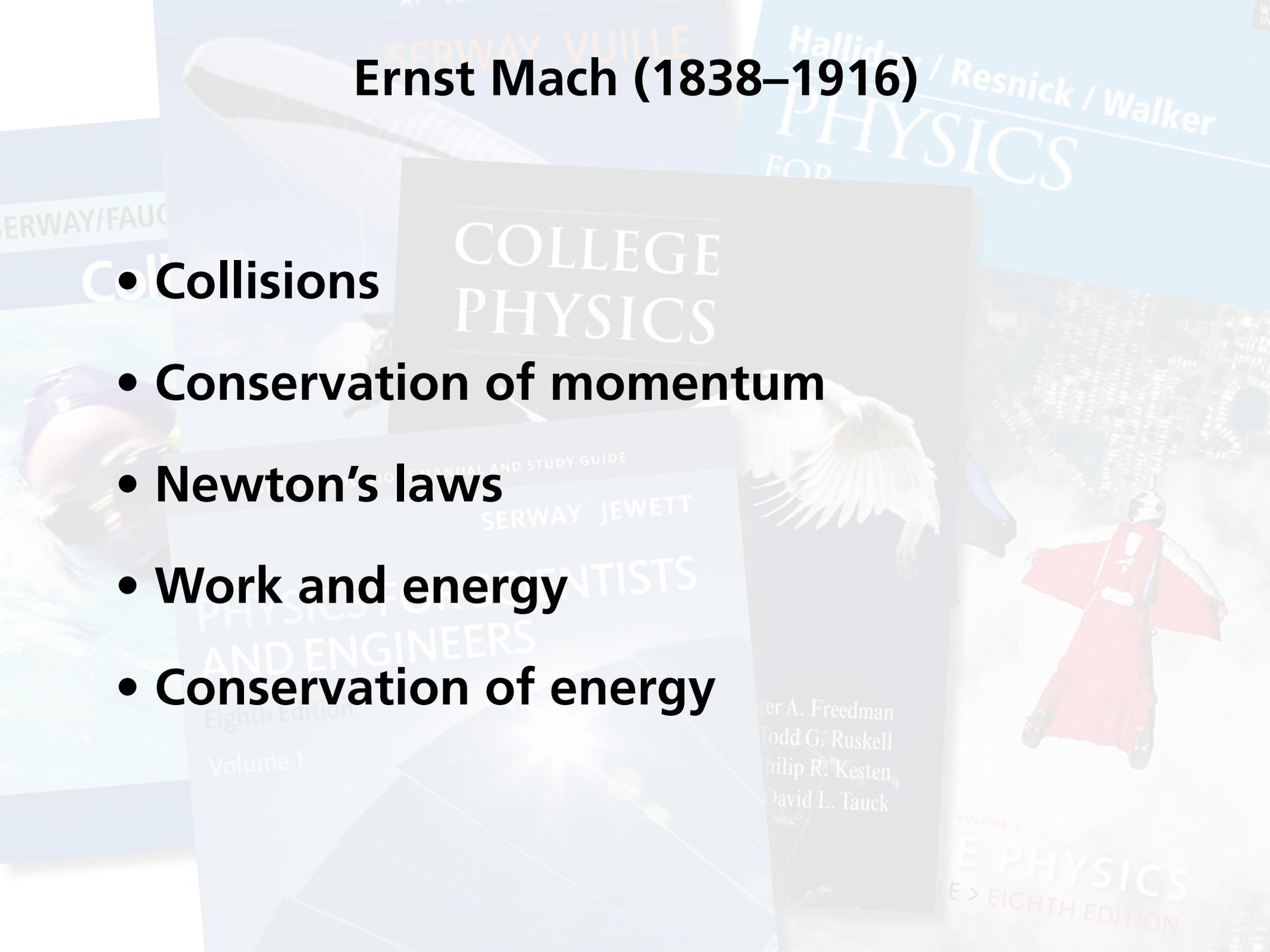
# The historical approach

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



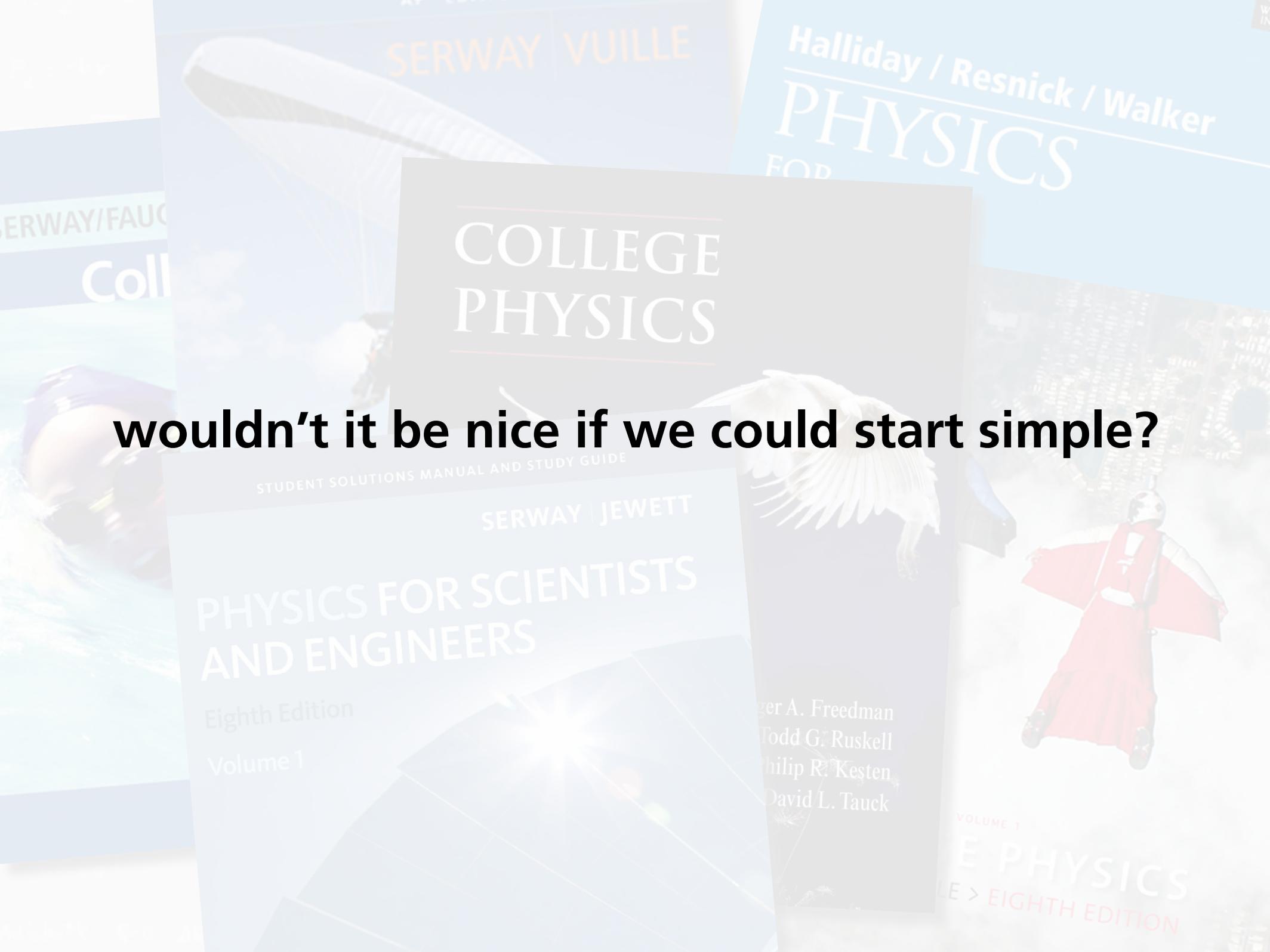
# Ernst Mach (1838–1916)

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



# Ernst Mach (1838–1916)

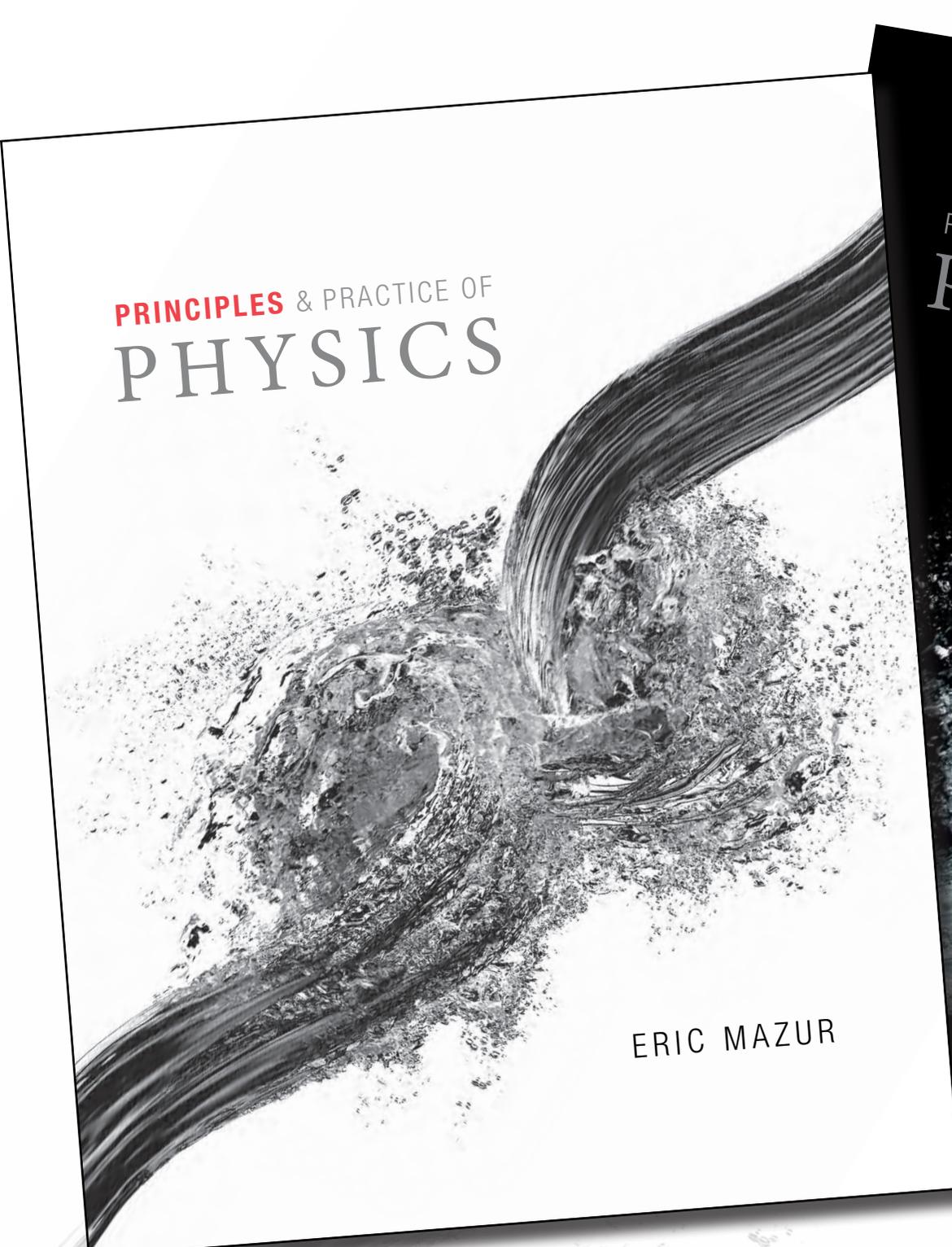
- Collisions (experimental)
- Conservation of momentum (experimental)
- Newton's laws
- Work and energy
- Conservation of energy



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

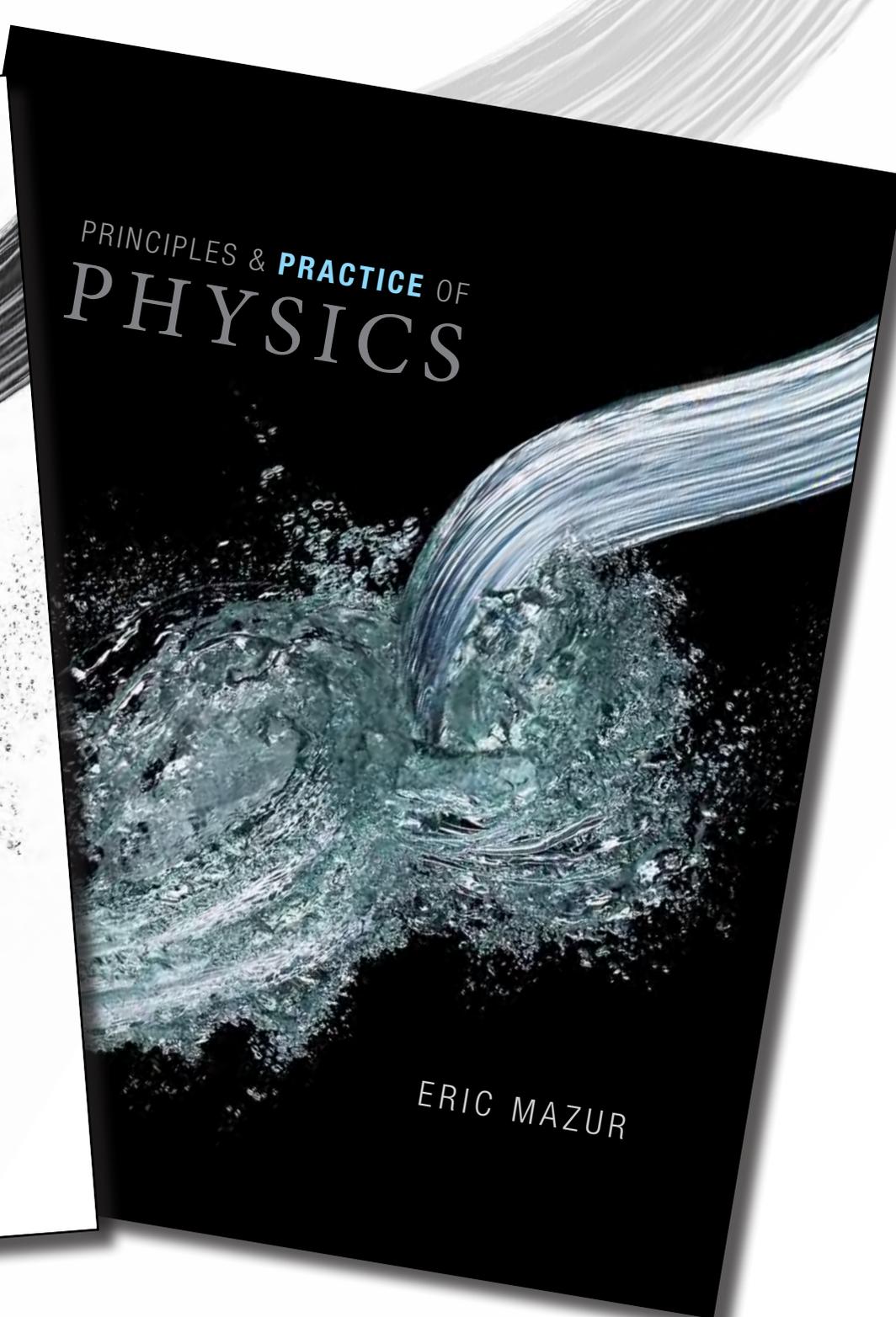
A dynamic, grayscale image of water splashing and flowing. The water is captured in motion, creating a sense of energy and movement. The splash is centered, with water spraying outwards and downwards. The background is a light, hazy gray, making the darker tones of the water stand out.

**we can!**

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

**PRINCIPLES** & PRACTICE OF  
**PHYSICS**

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

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# Principles and Practice of Physics

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

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# Principles and Practice of Physics

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

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# Principles and Practice of Physics

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

*“Shouldn't engineers know about force?”*

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# Principles and Practice of Physics

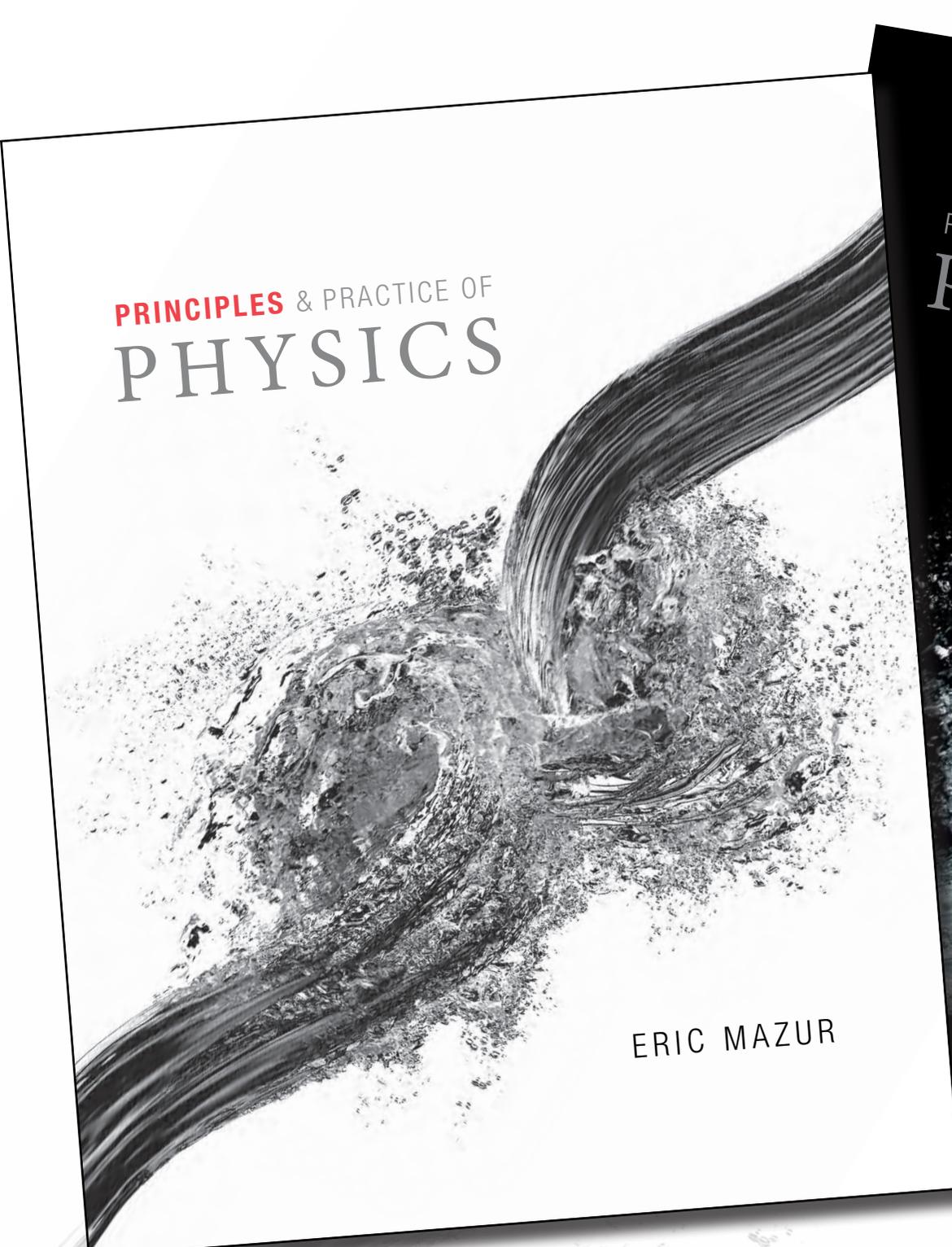
- Conservation of momentum (experimental)
- Conservation of energy (experimental)
- Interactions
- Force
- Work

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PHYSICS

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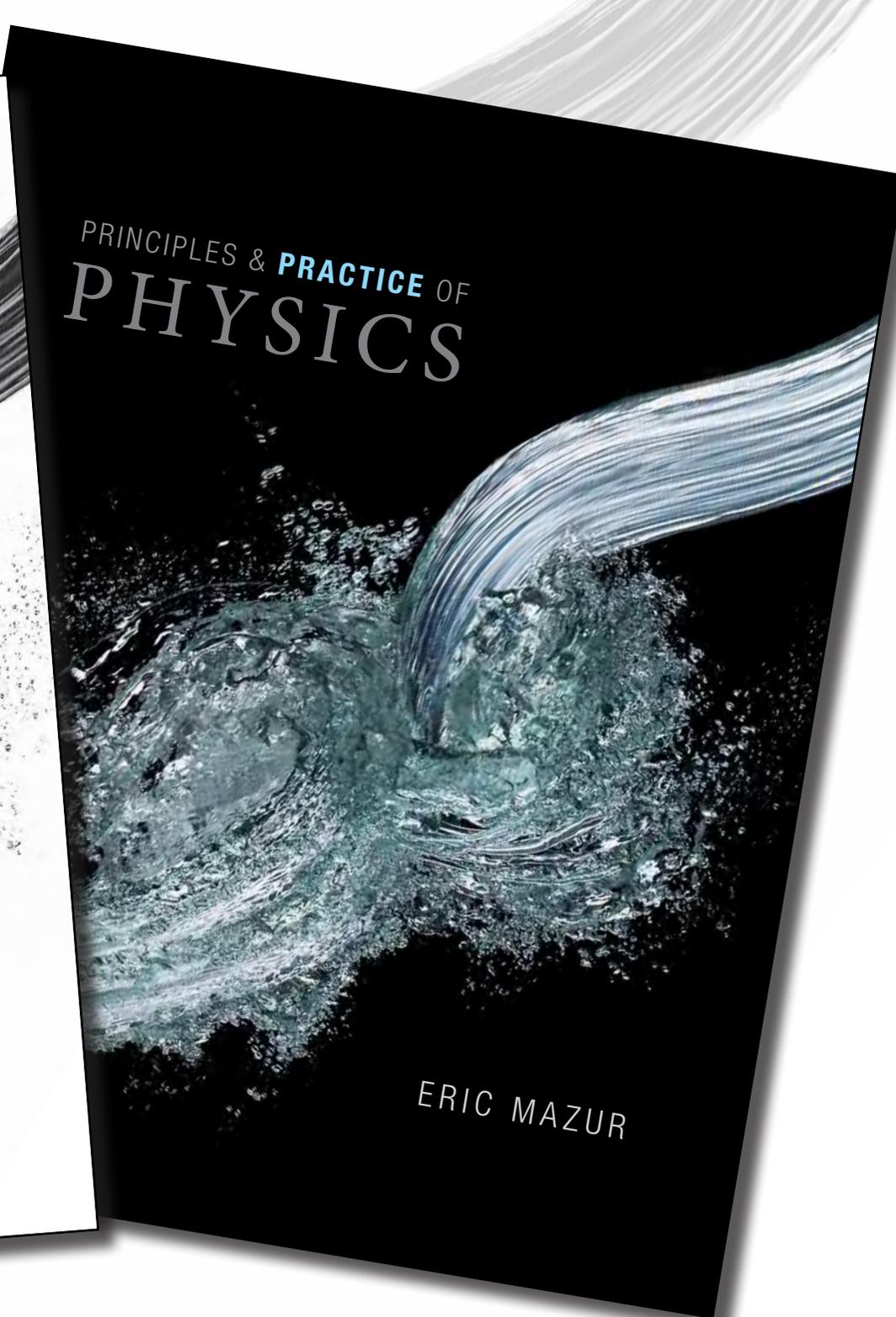
PRINCIPLES & PRACTICE OF  
PHYSICS

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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**

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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.

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PHYSICS

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1 architecture

2 content

PRINCIPLES & PRACTICE OF  
PHYSICS

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PHYSICS

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1 architecture

2 content

3 results

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PHYSICS

**why 2 books?**

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PHYSICS

**More logical!**

- **Unity**
- **Focus on physics**

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PHYSICS

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PHYSICS

**More practical!**

- **Contexts different**
- **Lighter**

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PRINCIPLES & PRACTICE OF  
PHYSICS

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PRINCIPLES & PRACTICE OF  
PHYSICS

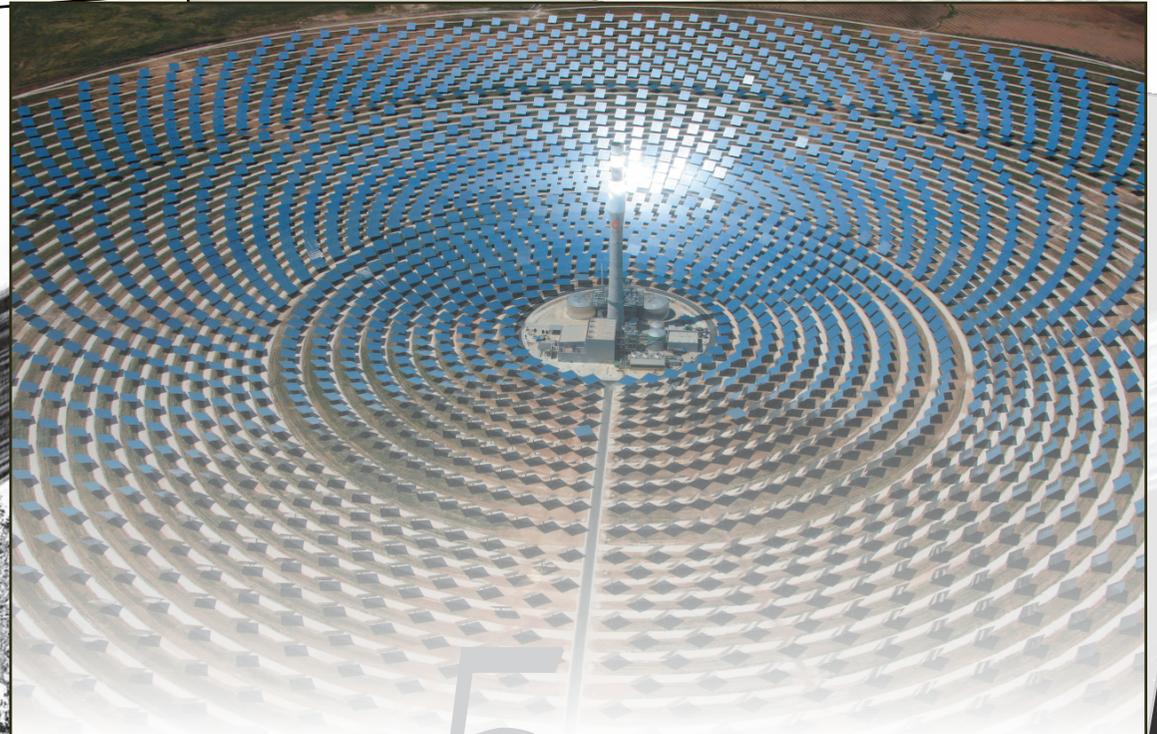
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PHYSICS

ERIC MAZUR

# PRINCIPLES & PRACTICE OF PHYSICS

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## 5 Energy

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

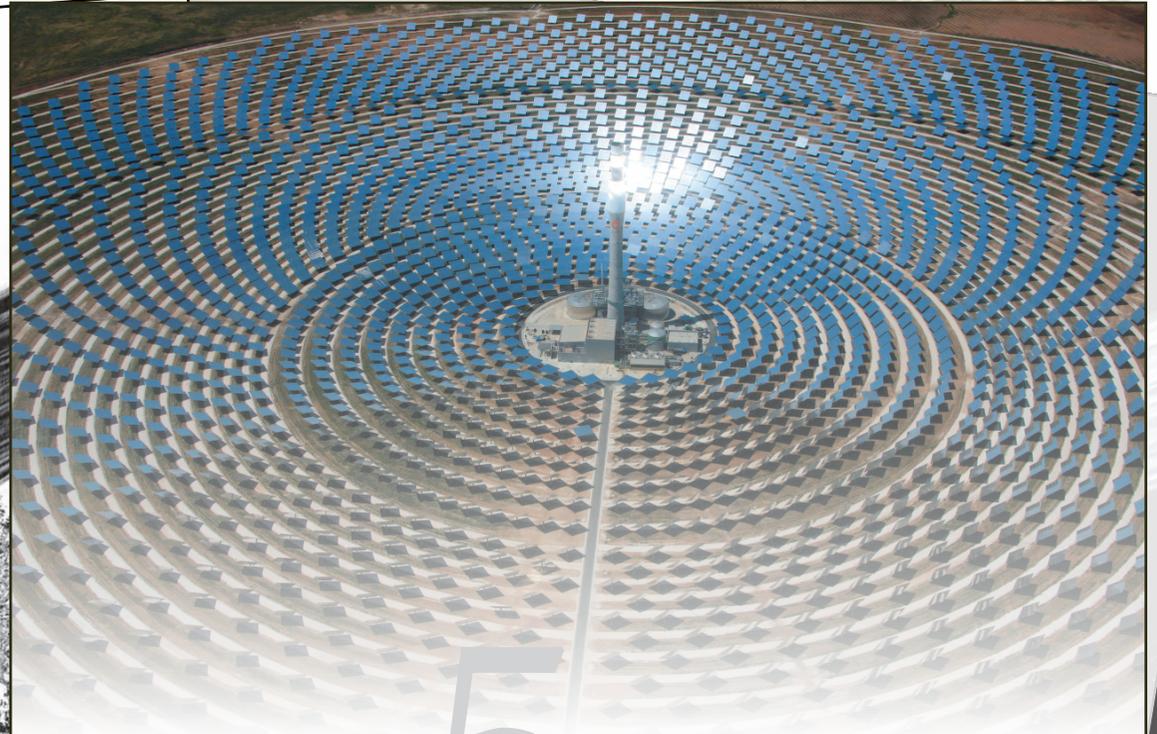
- 5.5 Elastic collisions
- 5.6 Inelastic collisions
- 5.7 Conservation of energy
- 5.8 Explosive separations

CONCEPTS

QUANTITATIVE TOOLS

# PRINCIPLES & PRACTICE OF PHYSICS

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# 5

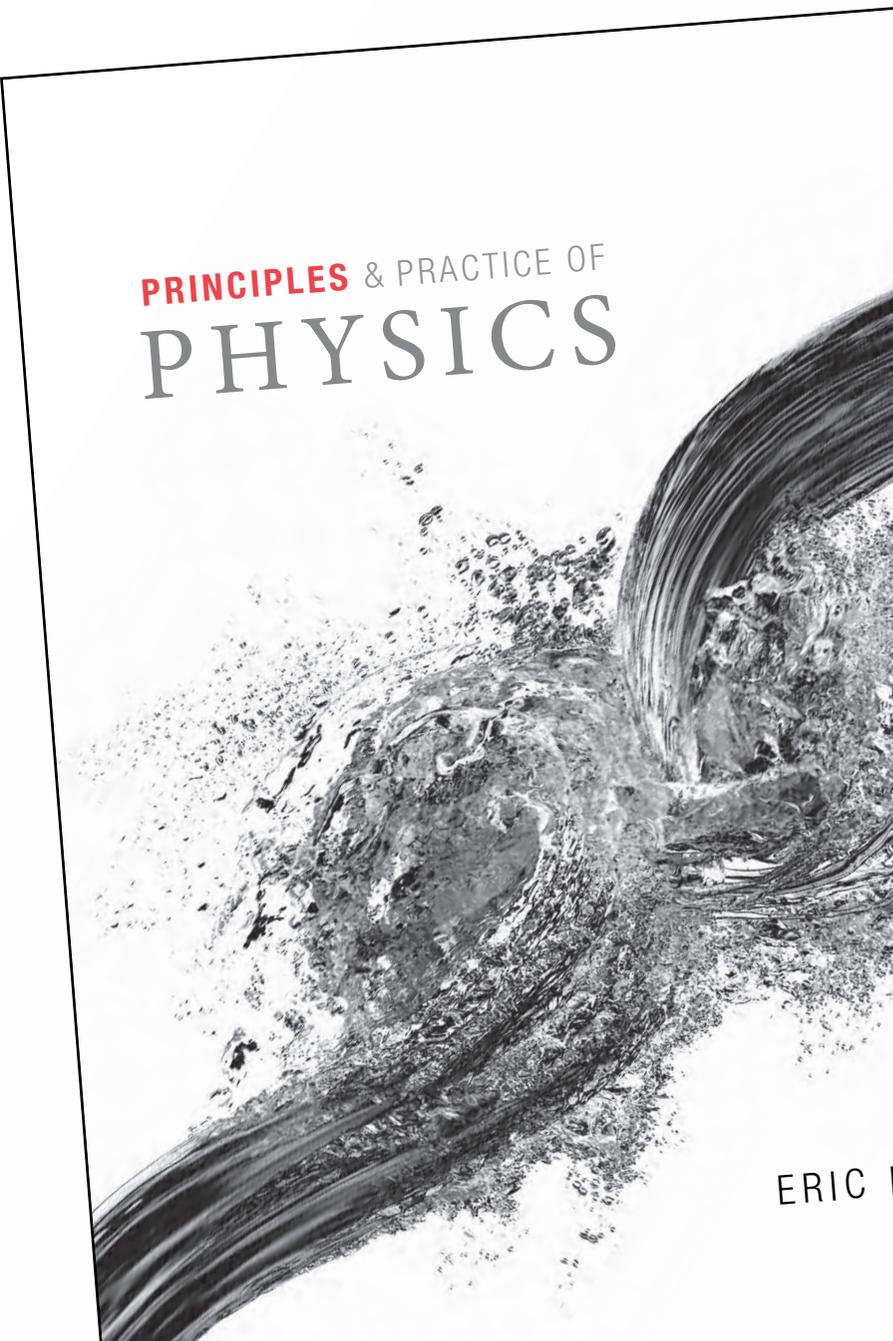
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# Energy

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**5.5 Elastic collisions**

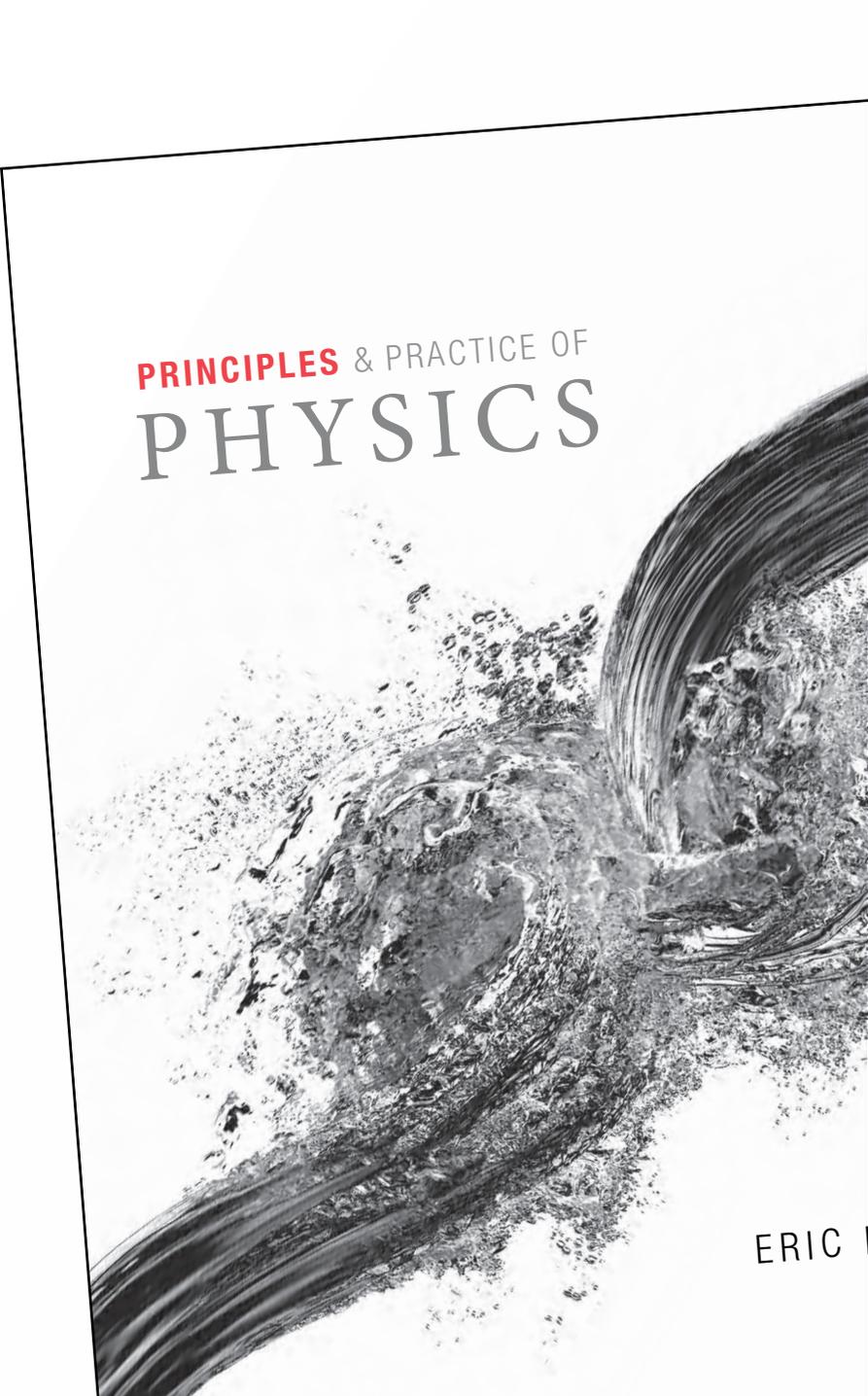
**5.6 Inelastic collisions**

**5.7 Conservation of energy**

**5.8 Explosive separations**

CONCEPTS

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The image shows the cover of a physics textbook. The title 'PRINCIPLES & PRACTICE OF PHYSICS' is written in a serif font, with 'PRINCIPLES' in red and '& PRACTICE OF' in grey. Below the title is a black and white photograph of water splashing and forming a large, curved splash. The author's name 'ERIC' is visible at the bottom right of the cover.

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# Energy

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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.

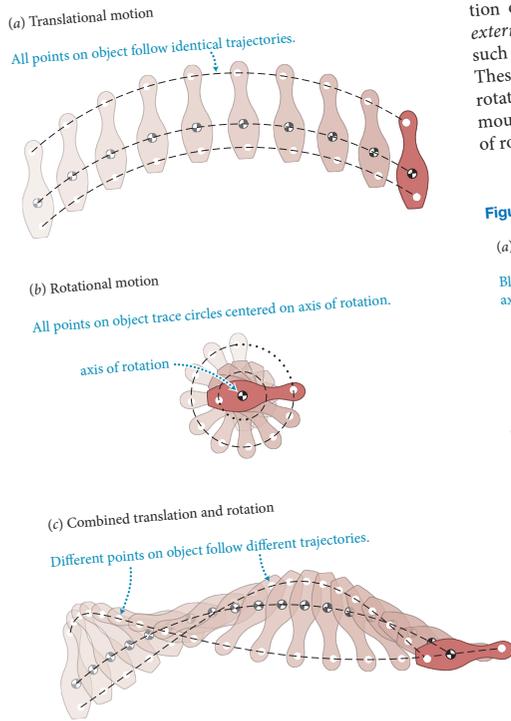
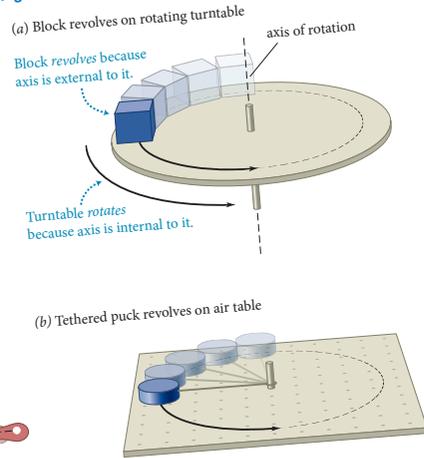


Figure 11.2 Examples of circular motion.



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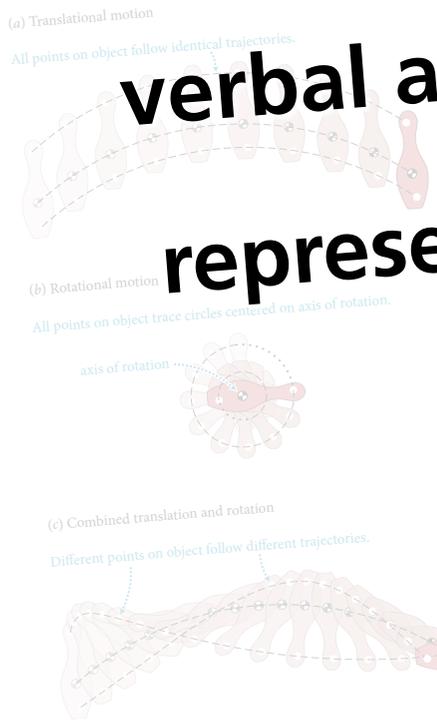
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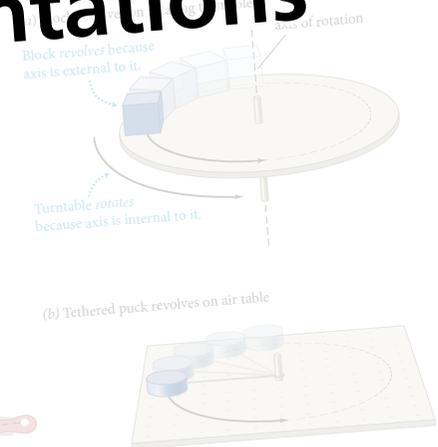


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### 11.1 Circular motion at constant speed

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

Figure 11.2 Examples of circular motion.



# teach concepts using verbal and visual representations

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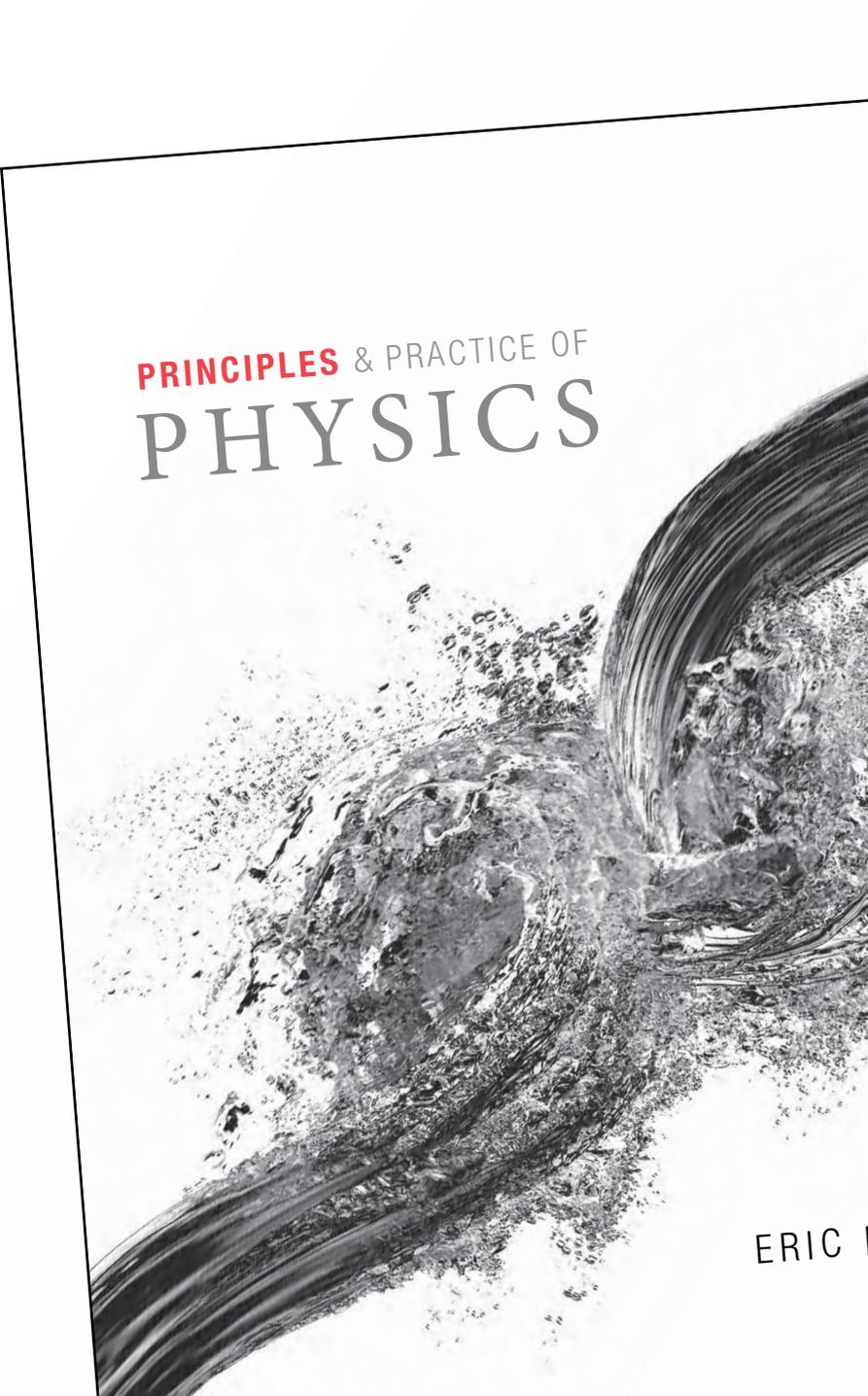
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The book cover features a black and white photograph of a large, turbulent wave crashing, with water splashing and creating a dense spray of droplets. The text is overlaid on the top left of the image.

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### 6.5 Galilean relativity

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

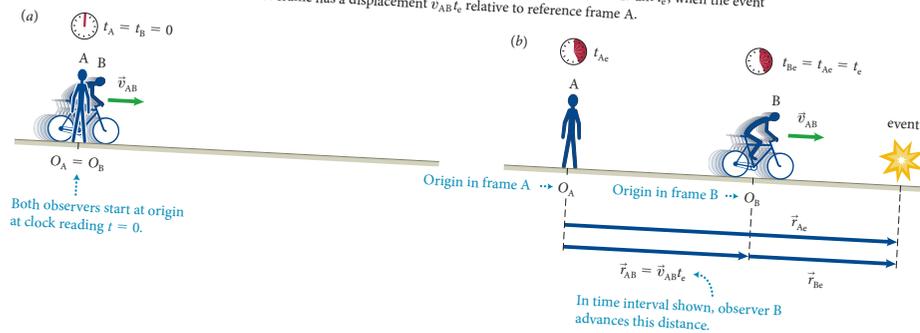
$$t_A = t_B = t. \quad (6.2)$$

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.



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

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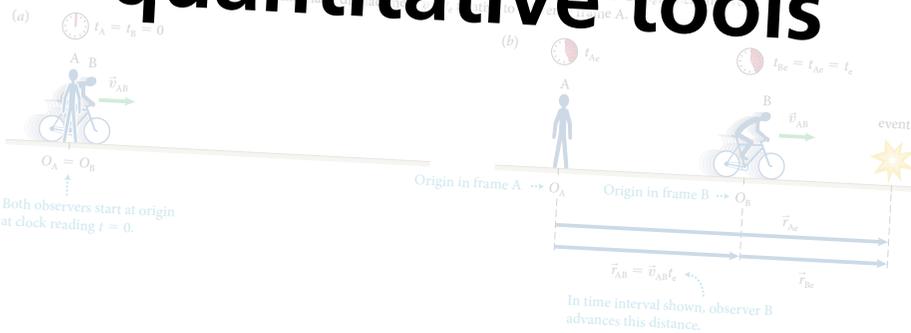
$$t_A = t_B = t. \quad (6.2)$$

From Figure 6.13b, the distance between the origin of reference frame A and the event is  $\Delta \vec{r}_e = \vec{r}_{Ae} - \vec{r}_{A0} = \vec{r}_{Ae}$ , and so  $\vec{r}_{Ae} = \vec{v}_{AB} t_e + \vec{r}_{Be}$ . Therefore

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

Equations 6.2 and 6.3 relate the data of the event in reference frame A to 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  $\vec{r}_{Ae}$  in frame A and  $\vec{r}_{Be}$  in frame B. In time interval shown, observer B advances this distance.



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

# build on conceptual underpinnings to effectively teach quantitative tools

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(b) From Figure 10.18 I see that  $\tan \theta = |F_{\text{sp}x}^c|/|F_{\text{sp}y}^c|$ . For  $\theta < 45^\circ$ ,  $\tan \theta < 1$ , and so  $|F_{\text{sp}x}^c| < |F_{\text{sp}y}^c|$ . Because  $|F_{\text{sp}y}^c| = F_{\text{Ep}}^G$  and  $|F_{\text{sp}x}^c| = F_{\text{rp}}^c$ , I find that for  $\theta < 45^\circ$ ,  $F_{\text{rp}}^c < F_{\text{Ep}}^G$ . When  $\theta > 45^\circ$ ,  $\tan \theta > 1$ , and so  $|F_{\text{sp}x}^c| > |F_{\text{sp}y}^c|$  and  $F_{\text{rp}}^c > F_{\text{Ep}}^G$ . ✓

(c)  $|F_{\text{sp}y}^c| = F_{\text{Ep}}^G$  and  $F_{\text{sp}}^c = \sqrt{(F_{\text{sp}x}^c)^2 + (F_{\text{sp}y}^c)^2}$ . Therefore,  $F_{\text{sp}}^c$  must always be larger than  $F_{\text{Ep}}^G$  when  $\theta \neq 0$ . ✓

**4 EVALUATE RESULT** I know from experience that you have to pull harder to move a swing farther from its equilibrium position, and so my answer to part *a* makes sense. With regard to part *b*, when the swing is at rest at  $45^\circ$ , the forces  $F_{\text{rp}}^c$  and  $F_{\text{Ep}}^G$  on your friend make the same angle with the force  $F_{\text{sp}}^c$ , and so  $F_{\text{rp}}^c$  and  $F_{\text{Ep}}^G$  should be equal in magnitude. The force of gravity is independent of the angle, but the force exerted by the rope increases with increasing angle, and so it makes sense that for angles larger than  $45^\circ$ ,  $F_{\text{rp}}^c$  is larger than  $F_{\text{Ep}}^G$ . In part *c*, because the vertical component of the force  $F_{\text{sp}}^c$  exerted by the seat on your friend always has to be equal to the force of gravity, adding a horizontal component makes  $F_{\text{sp}}^c$  larger than  $F_{\text{Ep}}^G$ , as I found.

**10.4** You decide to move a heavy file cabinet by sliding it across the floor. You push against the cabinet, but it doesn't budge. Draw a free-body diagram for it.

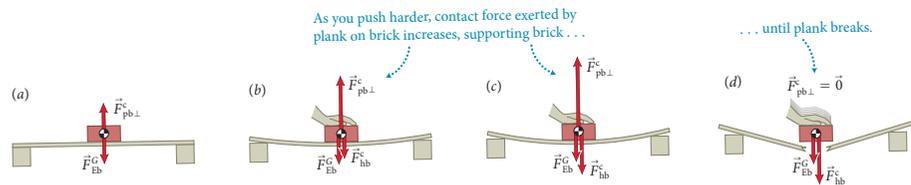
### 10.4 Friction

The force that opposes your push on the file cabinet in Checkpoint 10.4—the tangential component of the contact force exerted by the floor on the cabinet—has to do with friction. If the floor were very slick or if the cabinet had casters, there would be little friction and your push would easily move the cabinet. Instead, you have to lean against it with all your strength until, with a jerk, it suddenly begins to slide. Once you get the cabinet moving, you must keep pushing to keep it in motion. If you stop pushing, friction stops the motion.

**10.5** (a) Suppose you push the file cabinet just enough to keep it moving at constant speed. Draw a free-body diagram for the cabinet while it slides at constant speed. (b) Suddenly you stop pushing. Draw a free-body diagram for the file cabinet at this instant.

Don't skip Checkpoint 10.5! It will be harder to understand the rest of this section if you haven't thought about these situations.

Figure 10.19 A demonstration of the normal force.



Even though the normal and tangential components of the contact force exerted by the floor on the cabinet belong to the same interaction, they behave differently and are usually treated as two separate forces: the normal component being called the **normal force** and the tangential component being called the **force of friction**.

To understand the difference between normal and frictional forces, consider a brick on a horizontal wooden plank supported at both ends (Figure 10.19a). Because the brick is at rest, the normal force  $F_{\text{pb}\perp}^c$  exerted by the plank on it is equal in magnitude to the gravitational force exerted on it. Now imagine using your hand to push down on the brick with a force  $F_{\text{hb}}^c$ . Your downward push increases the total downward force exerted on the brick, and, like a spring under compression, the plank bends until the normal force it exerts on the brick balances the combined downward forces exerted by your hand and by Earth on the brick (Figure 10.19b). As you push down harder, the plank bends more, and the normal force continues to increase (Figure 10.19c) until you exceed the plank's capacity to provide support and it snaps, at which point the normal force suddenly disappears (Figure 10.19d). So, normal forces take on whatever value is required to prevent whatever is pushing down on a surface from moving through that surface—up to the breaking point of the supporting material.

Next imagine that instead of pushing down on the brick of Figure 10.19a, you gently push it to the right, as in Figure 10.20. As long as you don't push hard, the brick remains at rest. This tells you that the horizontal forces exerted on the brick add to zero, and so the plank must be exerting on the brick a horizontal frictional force that is equal in magnitude to your push but in the opposite direction. This horizontal force is caused by microscopic bonds between the surfaces in contact. Whenever two objects are placed in contact, such bonds form at the extremities of microscopic bumps on the surfaces of the objects. When you try to slide the surfaces past each other, these tiny bonds prevent sideways motion. As you push the brick to the right, the bumps resist bending and, like microscopic springs, each bump exerts a force to the left. The net effect of all these microscopic forces is to hold the brick in place. As you increase the force of your push, the bumps resist bending more and the tangential component of the contact force grows. This friction exerted by surfaces that are not moving relative to each other is called **static friction**.

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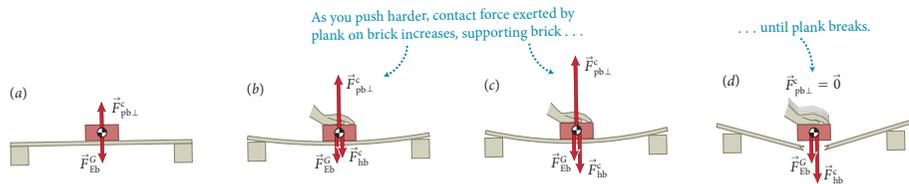
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**Figure 10.19** A demonstration of the normal force.

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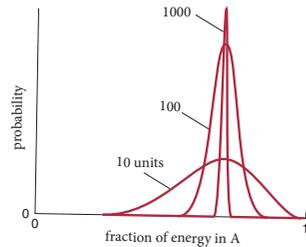
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**Figure 19.14** Probability of finding a given fraction of the system's energy in compartment A of the box in Figure 19.13. As the number of energy units increases from 10 to 1000, the probability distribution becomes narrower but remains centered about the mean energy.



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In Figure 19.13, after a very large number of particle-partition collisions have occurred, what is the probability of finding the system in (a) the macrostate  $E_A = 1$  and (b) the macrostate  $E_A = 7$ ?

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(b) For the macrostate  $E_A = 7$ ,  $\Omega = 4.34 \times 10^6$ . So the probability of this macrostate occurring is  $(4.34 \times 10^6)/(2.00 \times 10^7) = 2.17 \times 10^{-1}$ . ✓

**4 EVALUATE RESULT** My result shows that the macrostate  $E_A = 7$  is more than 150 times more probable than the macrostate  $E_A = 1$ . This makes sense because, as we saw earlier, the macrostate  $E_A = 7$  is the equilibrium state for which there is an equipartitioning of energy.

If we increase the number of energy units in the box of Figure 19.13 to 100 or 1000, the number of basic states grows exponentially, and if we plot the probability of each macrostate as a function of the fraction of energy in A, we obtain the two curves labeled 100 and 1000 in Figure 19.14. Just as we saw in Figure 19.7, the most probable macrostate doesn't change, but the probability peaks much more narrowly around this state. In other words, the most probable macrostate—the equilibrium state—is now even more likely than any other macrostate.

Note that the number of basic states is very large, even with just ten energy units and 20 particles. In a box of volume  $1 \text{ m}^3$  containing air at atmospheric pressure and room temperature, there are on the order of  $10^{25}$  particles and  $10^{20}$  energy units per particle, and so the number of basic states becomes unimaginably large—on the order of ten raised to the power  $10^{21}$ ! Because the number of basic states is so large, it is more convenient to work with the natural logarithm of that number. As you can see from the right-most column in Table 19.2, the natural logarithm of the number of basic states is indeed much more manageable.

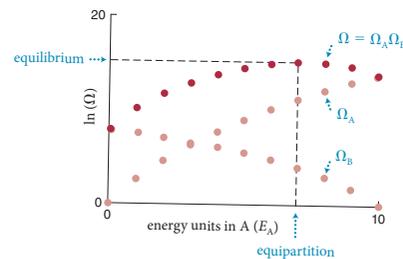
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**19.15** What is the average energy per particle in compartments A and B in Figure 19.13 (a) when there is one energy unit in A and (b) when the system is at equilibrium?

As you can see from Table 19.2, with  $E_A = 1$  the number of basic states for the system ( $2.80 \times 10^4$ ) is more than 100 times smaller than it is at equilibrium ( $E_A = 7$ ,  $\Omega = 4.34 \times 10^6$ ). Collisions between the particles and the partition redistribute

**Figure 19.15** Natural logarithm of the number of basic states for compartment A, for compartment B, and for the two compartments in Figure 19.13 combined. The number of basic states is maximal when the energy is equipartitioned (seven energy units in A).



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## Classification of collisions

Energy

Energy

Systems

CONCEPTS

Collisions

Collisions

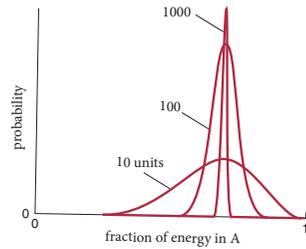
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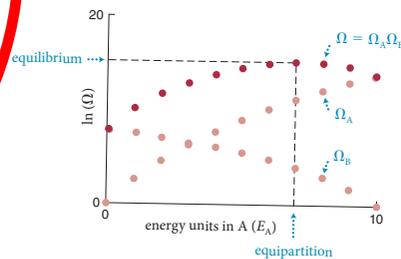
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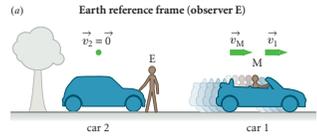
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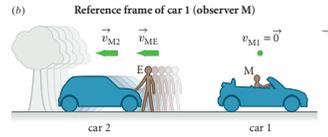
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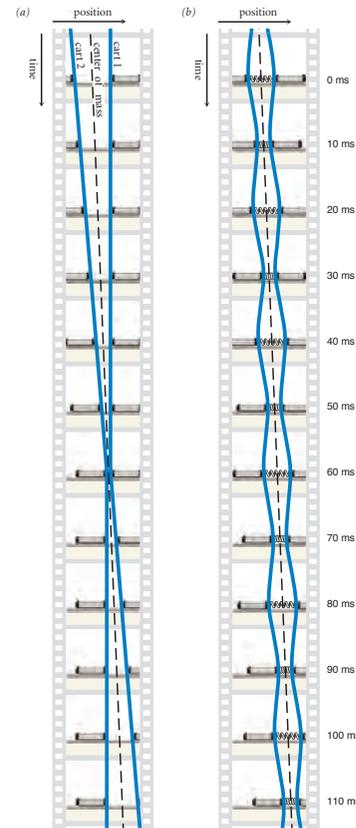
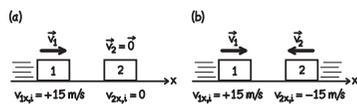
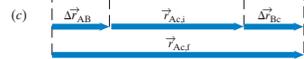
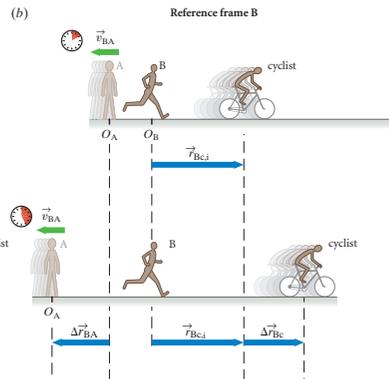
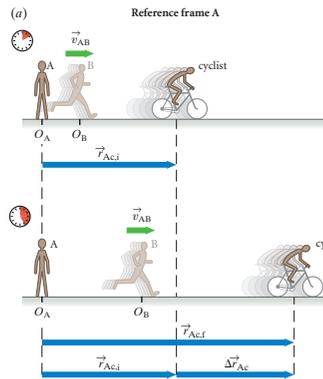
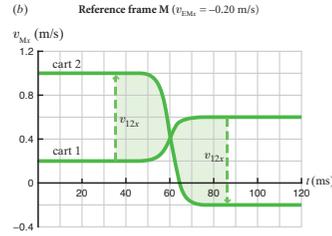
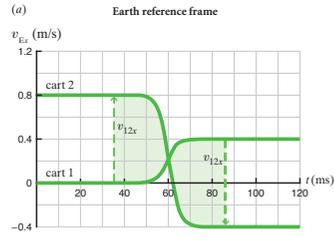
QUANTITATIVE TOOLS



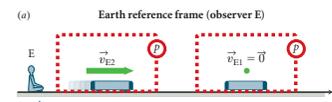
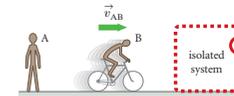
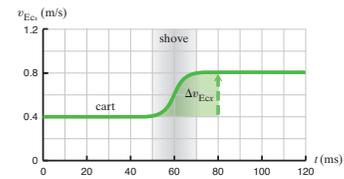
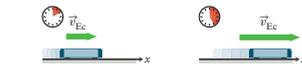
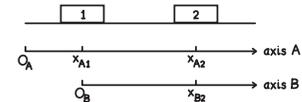
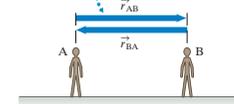
Relative to observer E, car 2 is at rest and car 1 moves to the right.



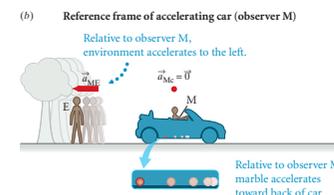
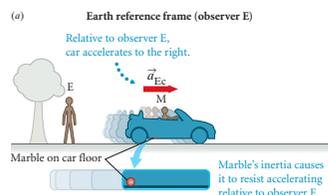
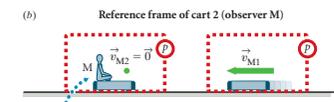
But relative to observer M, car 1 is at rest while car 2, observer E, and the earth move to the left.

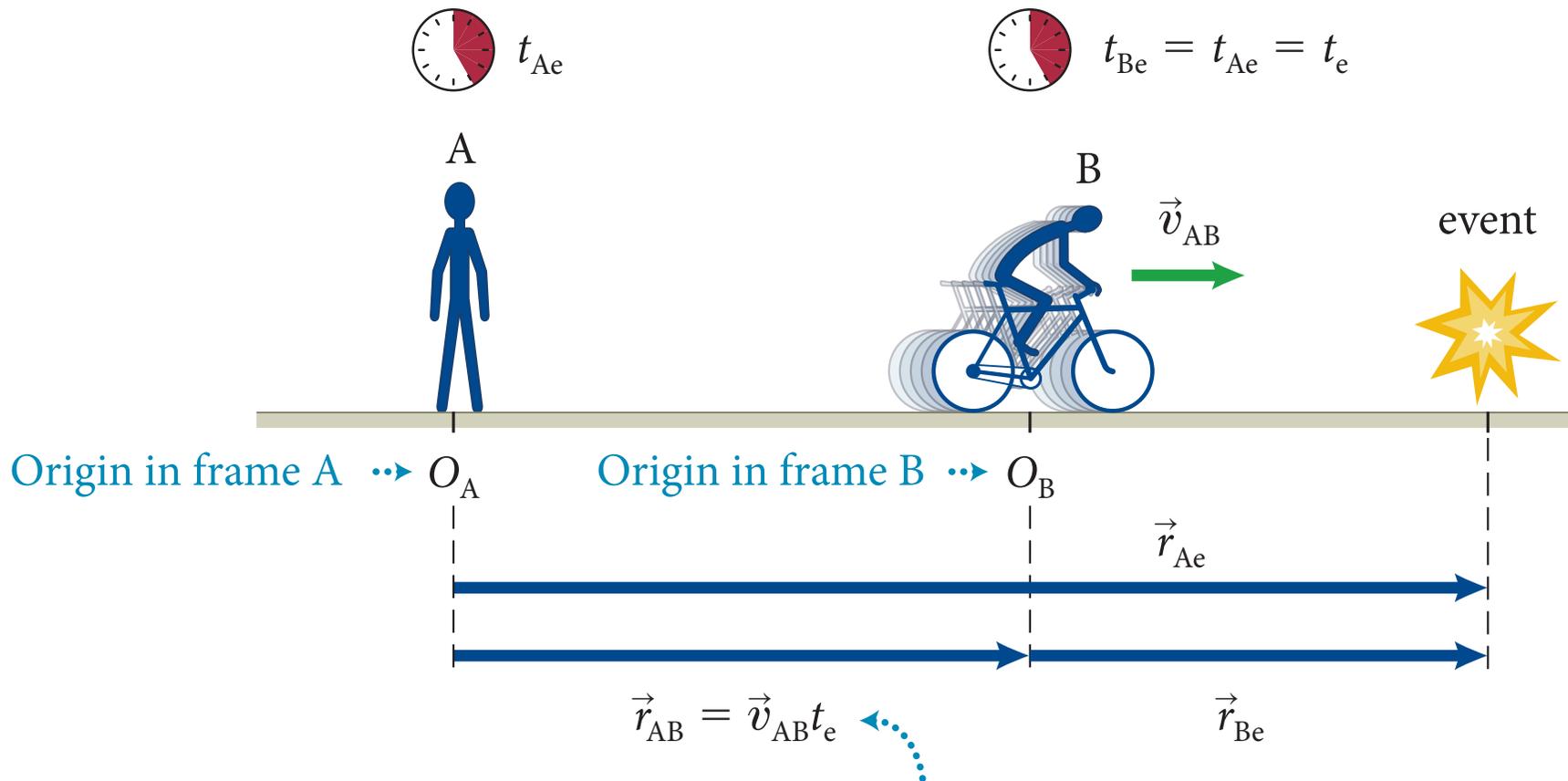


Position vectors are each other's opposites.



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





In time interval shown, observer B advances this distance.

**Visual representations: simple, effective, correct!**



In time interval shown, observer B advances this distance.

# PRINCIPLES VOLUME

- 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).<sup>\*</sup> 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:

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

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

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

Figure 6.13 illustrates the relationship between the two reference frames. 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

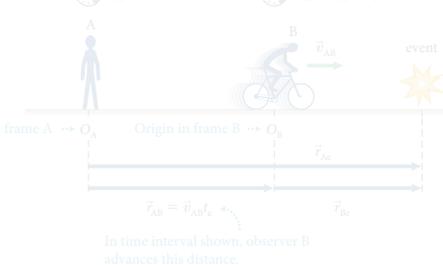
Figure 6.13 illustrates the relationship between the two reference frames. Observer B moves at constant velocity  $\vec{v}_{AB}$  relative to reference frame A. (a) At instant  $t = 0$ , when the event occurs, the origin of observer B's reference frame has a displacement  $\vec{v}_{AB} t_e$  relative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

(a)  $t_A = t_B = 0$



Both observers start at origin at clock reading  $t = 0$ .

(b)  $t_{Ae} = t_{Be} = t_e$



In time interval shown, observer B advances this distance.

<sup>\*</sup>Remember our subscript form: The capital letter refers to the reference frame; the lowercase e is for

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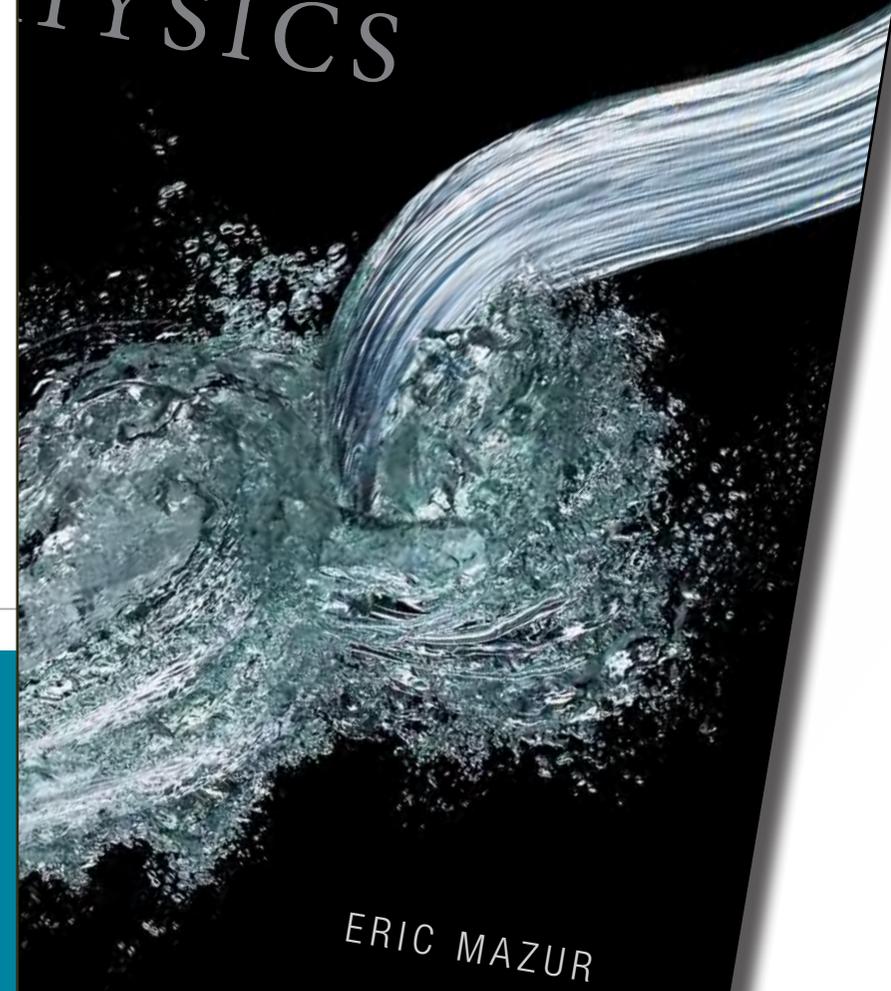
# 17

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**Waves in Two and  
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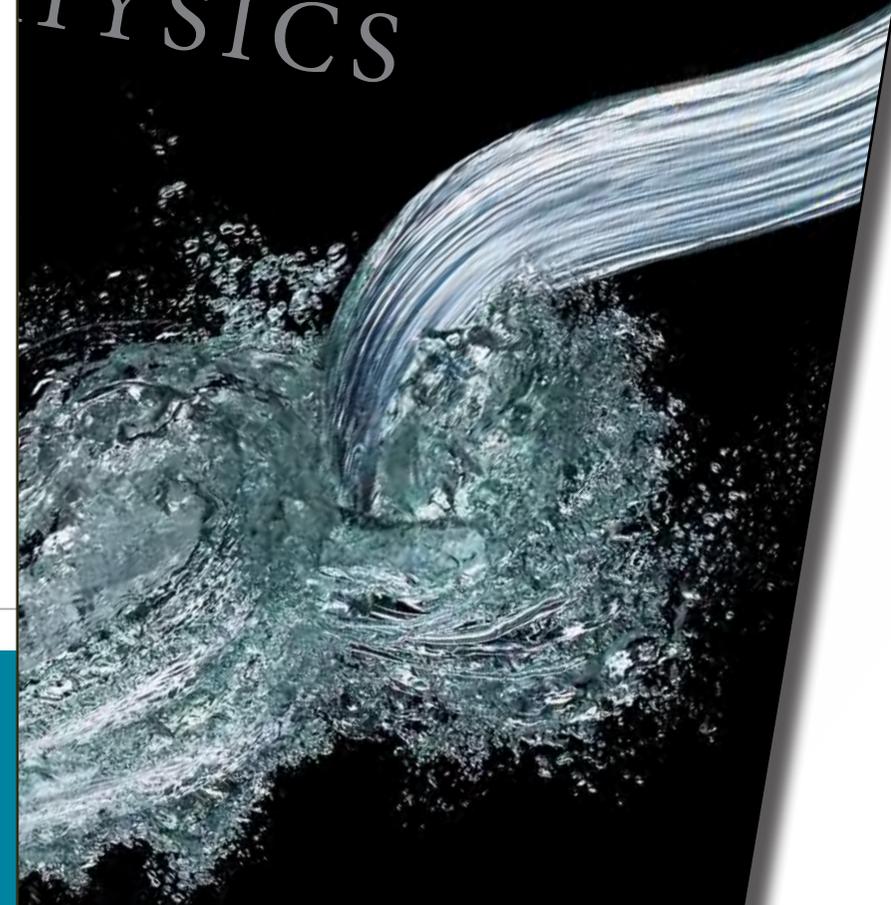
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## Developing a Feel

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

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

### Hints

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

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

### Key (all values approximate)

A. 7 kg; B. 1 y =  $3 \times 10^7$  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.  $2 \times 10^3$  kg; I. 0.3 m; J.  $2 \times 10^4$  turns; K.  $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$  (with yo-yo modeled as solid cylinder); L.  $2 \times 10^{11}$  m; M.  $2 \times 10^4$  m; N. 4 kg  $\cdot$  m<sup>2</sup>; O. between  $MR^2$  (cylindrical shell representing tire) and  $MR^2/2$  (solid cylinder representing wheel)—say,  $3MR^2/4$ ; P.  $6 \times 10^6$  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.  $7 \times 10^4$  kg; W. 0.5 s; X. the parallel-axis theorem; Y.  $3 \times 10^4$  mi/h; Z.  $6 \times 10^{24}$  kg; AA.  $3 \times 10^4$  m/s

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## Developing a Feel

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

1. The speed  $v$  of a point on the equator as Earth rotates (D, P)
2. The rotational inertia of a bowling ball about an axis tangent to its surface (A, R, X)
3. Your rotational inertia as you turn over in your sleep (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 =  $3 \times 10^7$  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.  $2 \times 10^3$  kg; I. 0.3 m; J.  $2 \times 10^4$  turns; K.  $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$  (with yo-yo modeled as solid cylinder); L.  $2 \times 10^{11}$  m; M.  $2 \times 10^4$  m; N. 4 kg  $\cdot$  m<sup>2</sup>; O. between  $MR^2$  (cylindrical shell representing tire) and  $MR^2/2$  (solid cylinder representing wheel)—say,  $3MR^2/4$ ; P.  $6 \times 10^6$  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.  $7 \times 10^4$  kg; W. 0.5 s; X. the parallel-axis theorem; Y.  $3 \times 10^4$  mi/h; Z.  $6 \times 10^{24}$  kg; AA.  $3 \times 10^4$  m/s

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## Developing a Feel

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

1. The speed  $v$  of a point on the equator as Earth rotates (D, P)
2. The rotational inertia of a bowling ball about an axis tangent to its surface (A, R, X)
3. Your rotational inertia as you turn over in your sleep (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 =  $3 \times 10^7$  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.  $2 \times 10^3$  kg; I. 0.3 m; J.  $2 \times 10^4$  turns; K.  $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$  (with yo-yo modeled as solid cylinder); L.  $2 \times 10^{11}$  m; M.  $2 \times 10^4$  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.  $6 \times 10^6$  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.  $7 \times 10^4$  kg; W. 0.5 s; X. the parallel-axis theorem; Y.  $3 \times 10^4$  mi/h; Z.  $6 \times 10^{24}$  kg; AA.  $3 \times 10^3$  m/s

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## Developing a Feel

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

1. The speed  $v$  of a point on the equator as Earth rotates (D, P)
2. The rotational inertia of a bowling ball about an axis tangent to its surface (A, R, X)
3. Your rotational inertia as you turn over in your sleep (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.  $10^3 \text{ kg}$ ; F. from Eqs. 8.6, 8.17, and 11.16,  $\Sigma F = m\bar{a}$ , 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.  $2 \times 10^4$  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.  $3 \times 10^7 \text{ m/s}$

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## Developing a Feel

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

1. The speed  $v$  of a point on the equator as Earth rotates (D, P)
2. The rotational inertia of a bowling ball about an axis tangent to its surface (A, R, X)
3. Your rotational inertia as you turn over in your sleep (I, C)
4. The angular momentum around the axle of a wheel/tire combination on your car as you cruise on the freeway (E, 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.  $1 \text{ y} = 3 \times 10^7 \text{ s}$ ; C. solid cylinder of radius 0.2 m; D. period = 24 h, so  $\omega = 7 \times 10^{-5} \text{ s}^{-1}$ ; E.  $10^3 \text{ kg}$ ; 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.  $2 \times 10^4$  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.  $3 \times 10^4 \text{ m/s}$

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## Developing a Feel

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

1. The speed  $v$  of a point on the equator as Earth rotates (D, P)
2. The rotational inertia of a bowling ball about an axis tangent to its surface (A, R, X)
3. Your rotational inertia as you turn over in your sleep (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 =  $3 \times 10^7$  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.  $2 \times 10^3$  kg; I. 0.3 m; J.  $2 \times 10^4$  turns; K.  $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$  (with yo-yo modeled as solid cylinder); L.  $2 \times 10^{11}$  m; M.  $2 \times 10^4$  m; N. 4 kg  $\cdot$  m<sup>2</sup>; O. between  $MR^2$  (cylindrical shell representing tire) and  $MR^2/2$  (solid cylinder representing wheel)—say,  $3/4$ ; P.  $6 \times 10^6$  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.  $7 \times 10^4$  kg; W. 0.5 s; X. the parallel-axis theorem; Y.  $3 \times 10^4$  mi/h; Z.  $6 \times 10^{24}$  kg; AA.  $3 \times 10^3$  m/s

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### Developing a Feel

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

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

### Hints

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

- A. What is the inertia of a bowling ball?
- B. How long a time interval is needed for Earth to make one rotation around the Sun?
- C. What simple geometric shape is a good approximation of a sleeping person?
- D. What is Earth's radius?
- E. What is the relationship between the wheel/tire combination on your car and the relationship between the wheel/tire combination on a yo-yo?
- F. How long a time interval is needed to rewind the yo-yo?
- G. What is the radius of Earth's orbit?
- H. What is the perpendicular distance from the house to the car's line of motion?
- I. What is the yo-yo's rotational inertia?
- J. What is the radius of Earth's orbit?
- K. What is the skater's rotational inertia with arms held out?
- L. How can you model the combined rotational inertia of the wheel and tire?
- M. What is Earth's radius?
- N. What is the final rotational speed?
- O. What is the radius of a bowling ball?
- P. What is the rotational speed of the tire?
- Q. What is the required centripetal acceleration?
- 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 inertia?
- V. What is the yo-yo's inertia?
- 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 y =  $3 \times 10^7$  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.  $2 \times 10^3$  kg; I. 0.3 m; J.  $2 \times 10^4$  turns; K.  $6 \times 10^{-5} \text{ kg} \cdot \text{m}^2$  (with yo-yo modeled as solid cylinder); L.  $2 \times 10^{11}$  m; M.  $2 \times 10^4$  m; N. 4 kg  $\cdot$  m<sup>2</sup>; O. between  $MR^2$  (cylindrical shell representing tire) and  $MR^2/2$  (solid cylinder representing wheel)—say,  $3/4$ ; P.  $6 \times 10^6$  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.  $7 \times 10^4$  kg; W. 0.5 s; X. the parallel-axis theorem; Y.  $3 \times 10^4$  mi/h; Z.  $6 \times 10^{24}$  kg; AA.  $3 \times 10^8$  m/s

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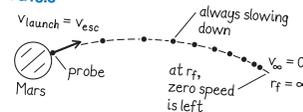
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### Worked Problem 13.3 Escape at last

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**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.

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- 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?

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- What law of physics should you invoke?

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

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  $v_{\text{esc}}$  to increase with  $m_M$  because the gravitational pull increases with increasing mass. We also expect  $v_{\text{esc}}$  to decrease as the distance between the launch position and Mars’s center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is just what our result predicts.

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- As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you ignore this effect?
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**3 EXECUTE PLAN**

- What is your target unknown quantity? Algebraically isolate it on one side of your equation.
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# Waves in Two and Three Dimensions

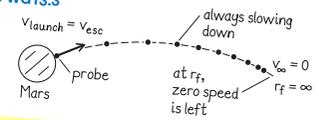
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# Waves in Two and Three Dimensions

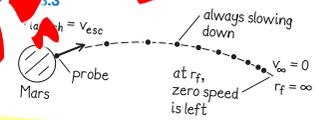
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4-Step Problem Solving

**Worked Problem 13.3 Escape at last**

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- 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 a reference frame in which the probe is fixed and only the probe moves. The initial kinetic energy is  $\frac{1}{2}m_p v_{esc}^2$  and the initial potential energy is  $-G \frac{m_M m_p}{R_M}$ . The final kinetic energy is zero and the final potential energy is zero. We solve for  $v_{esc}$ .

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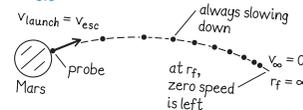
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## PRACTICE VOLUME

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

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

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

**EVALUATE RESULT** Our algebraic expression for the escape speed is plausible because it involves the mass of Mars, the initial center-to-center radial separation distance of our two objects (which is Mars's radius), and  $G$ . We expect  $v_{\text{esc}}$  to increase with  $m_M$  because the gravitational pull increases with increasing mass. We also expect  $v_{\text{esc}}$  to decrease as the distance between the launch position and Mars's center increases because the gravitational force exerted by the planet on the probe decreases with increasing separation distance. All this is in line with what our intuition tells us. The order of magnitude of the escape speed is reasonable. The distance from the surface of Mars to the center of Mars is only a few thousand 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.

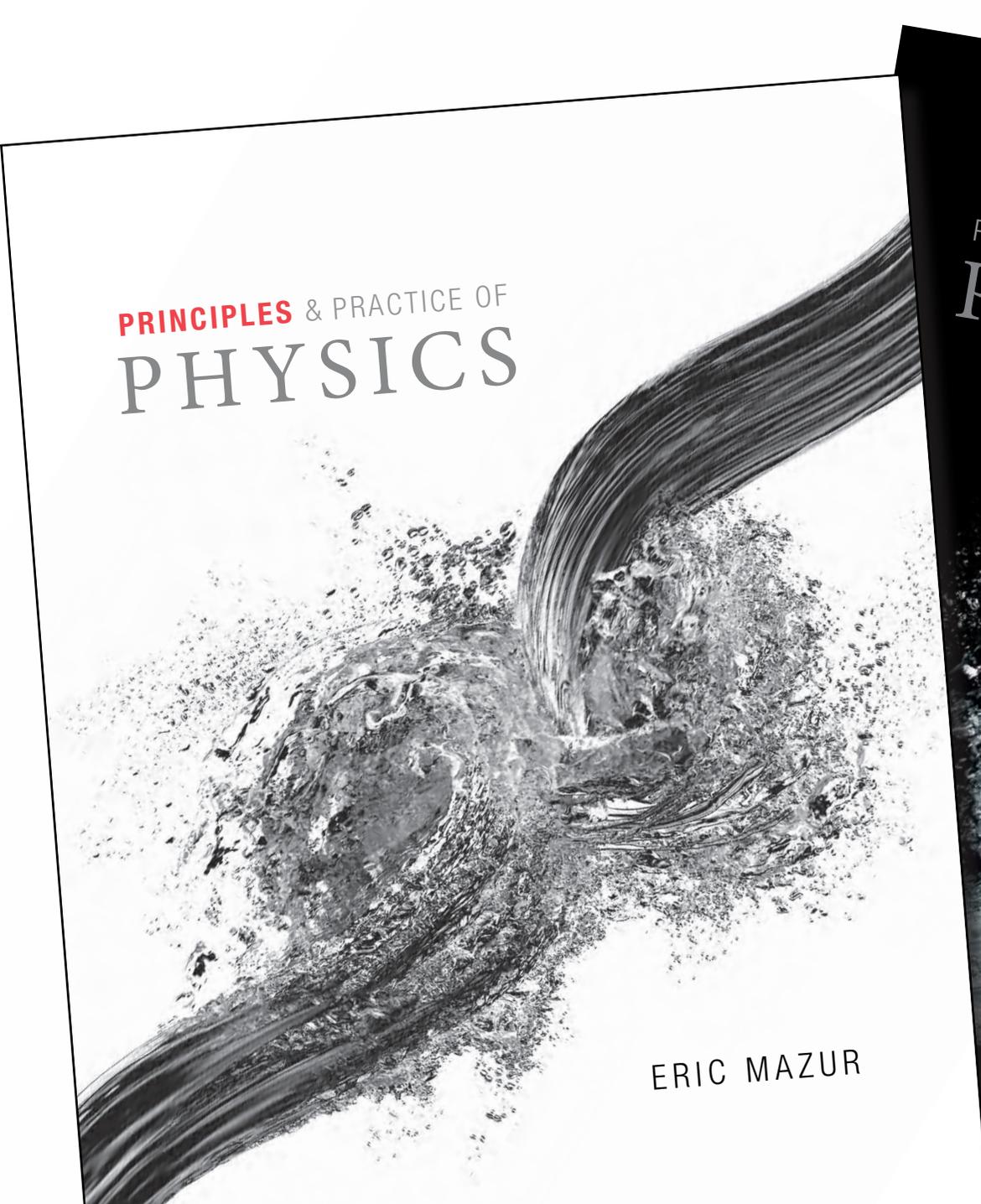
5. As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you ignore this effect?
6. What equation allows you to relate the initial and final states?

**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.

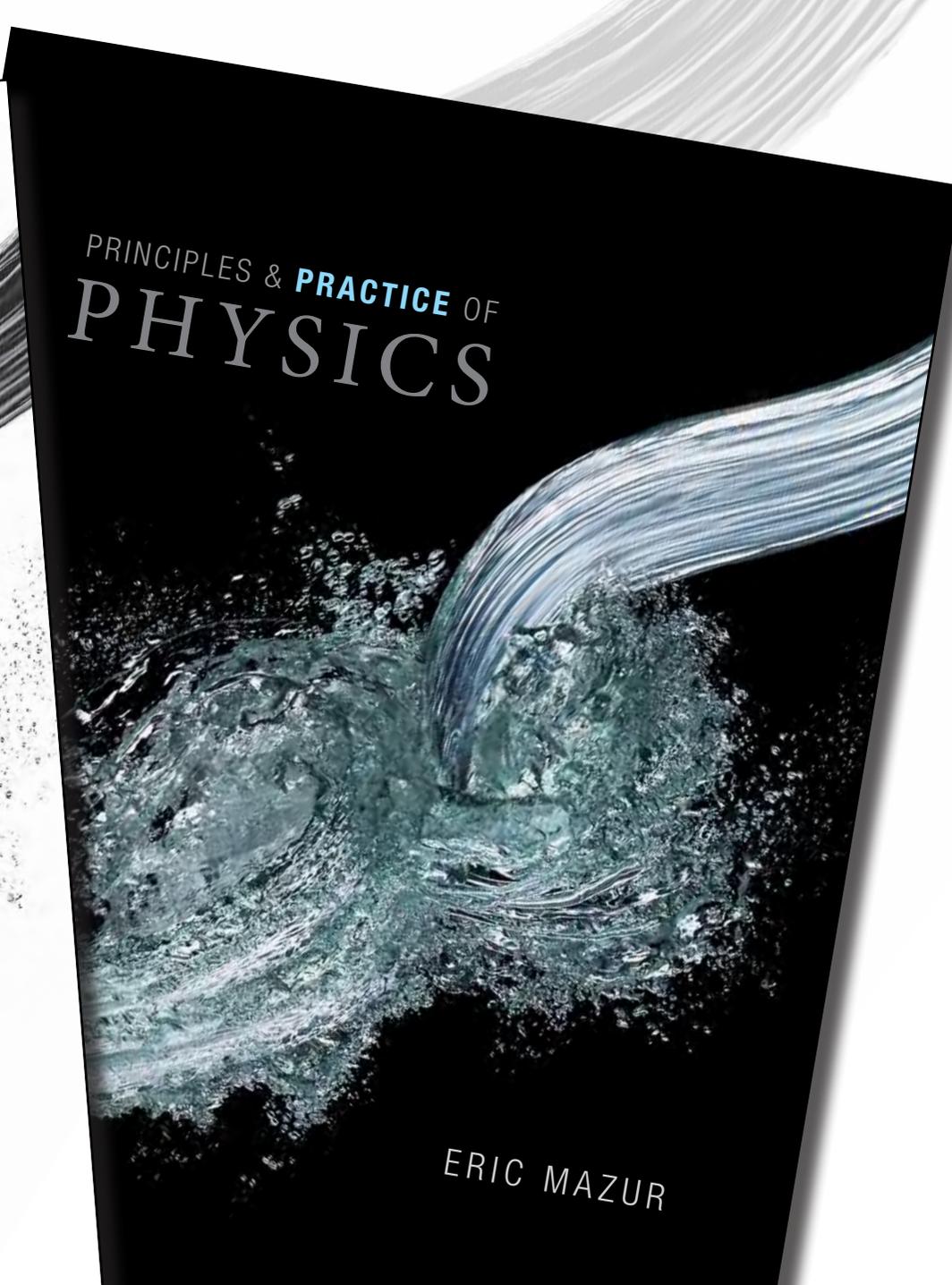
**EVALUATE RESULT**

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

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1 architecture

2 content

PRINCIPLES & PRACTICE OF  
PHYSICS

# conservation principles *before* force laws?

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PRINCIPLES & PRACTICE OF  
PHYSICS

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1 architecture

2 content



# Foundations

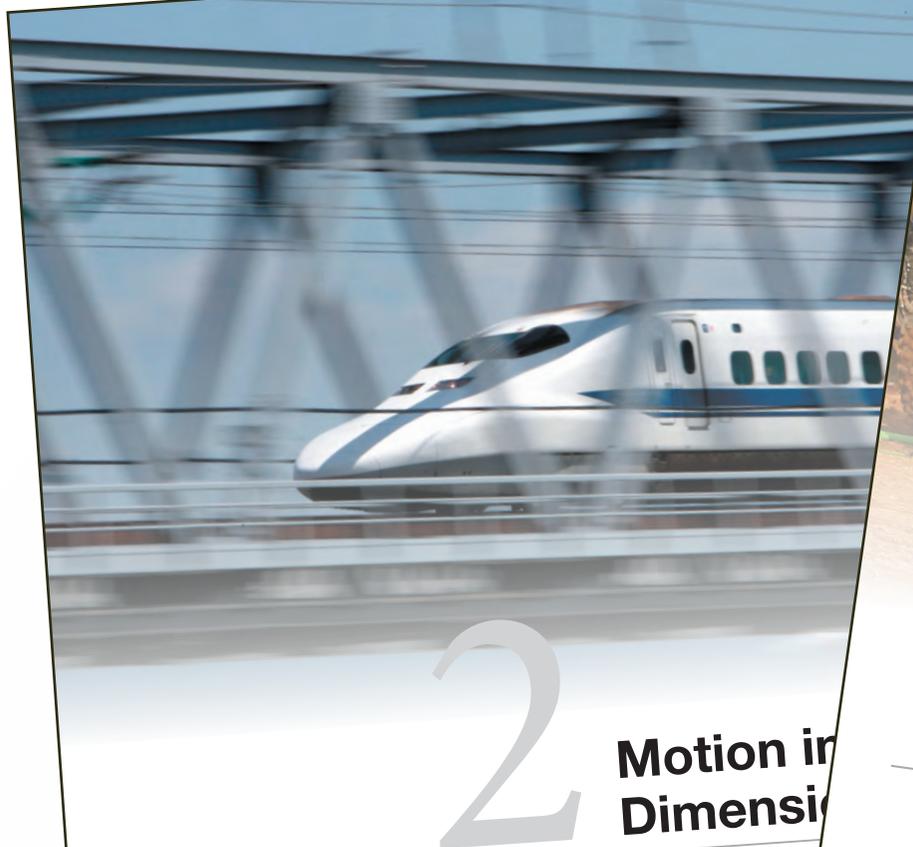
- 1.1 The scientific method
- 1.2 Symmetry
- 1.3 Matter and the universe
- 1.4 Time and change
- 1.5 Representations
  
- 1.6 Physical quantities and units
- 1.7 Significant digits
- 1.8 Solving problems
- 1.9 Developing a feel

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



**4.1 Friction**

**4.2 Inertia**

**4.3 What determines inertia?**

**4.4 Systems**

**4.5 Inertial standard**

**4.6 Momentum**

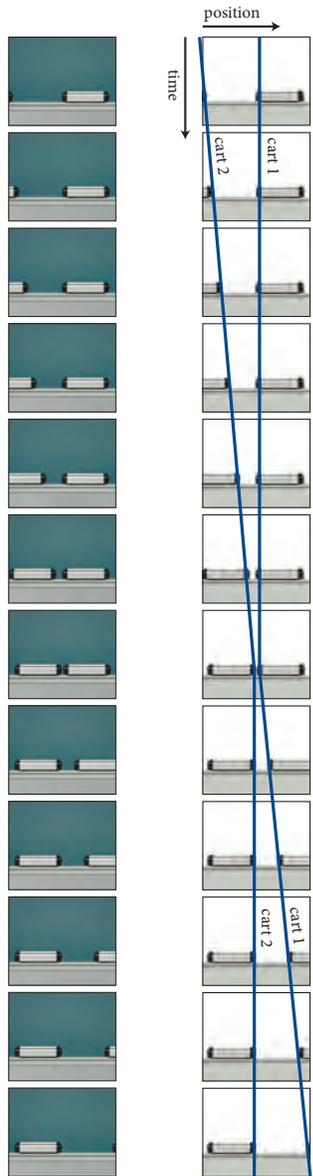
**4.7 Isolated systems**

**4.8 Conservation of momentum**



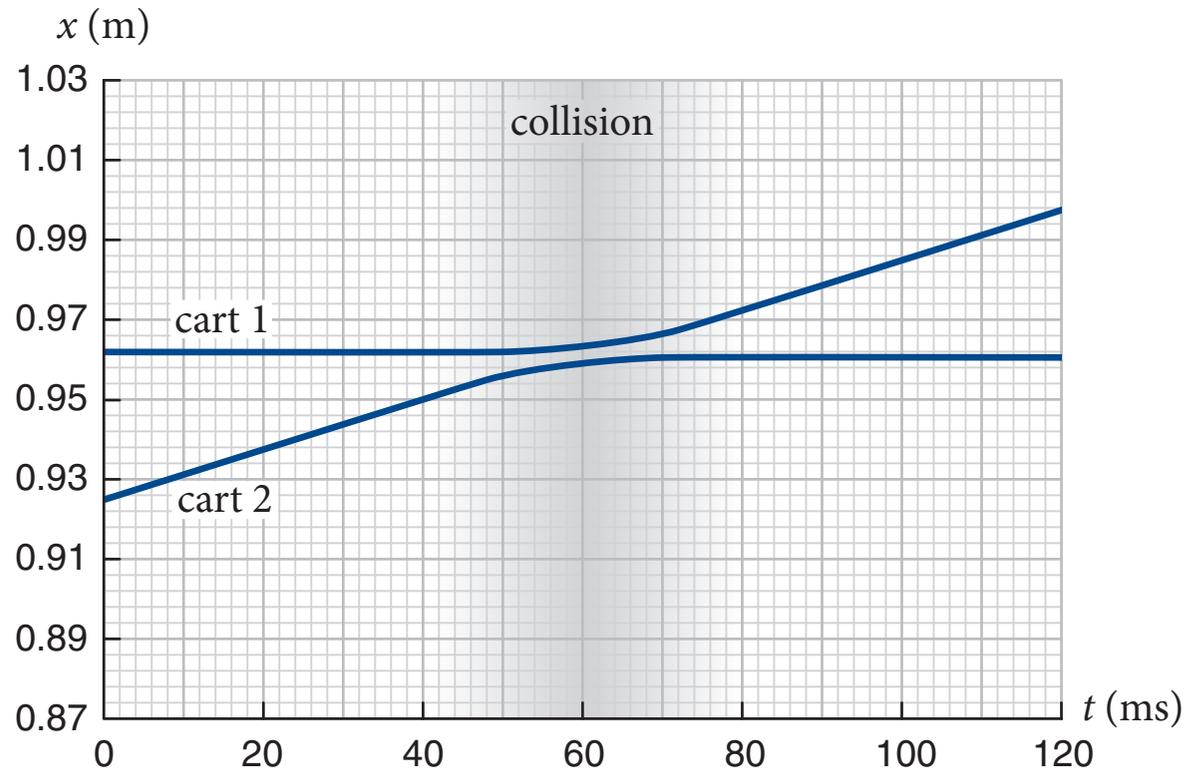
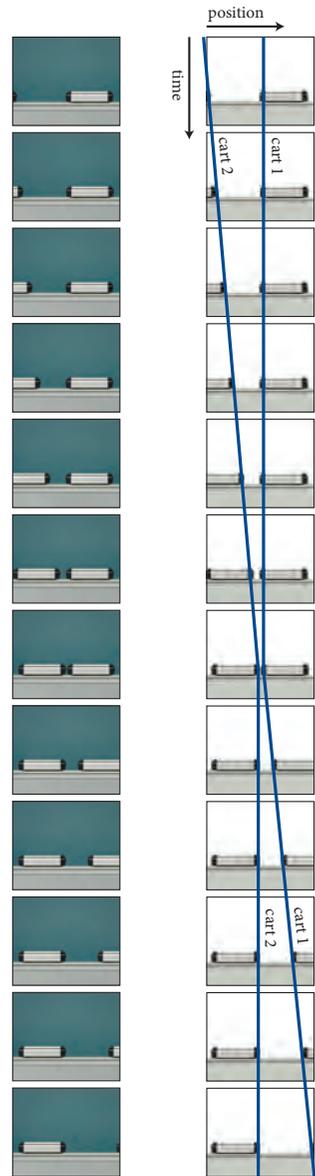
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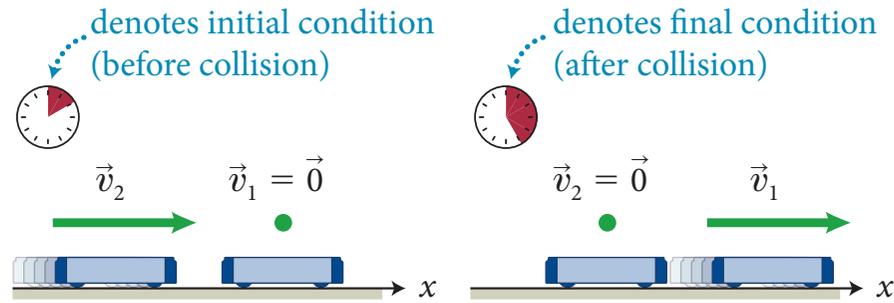
**2** content

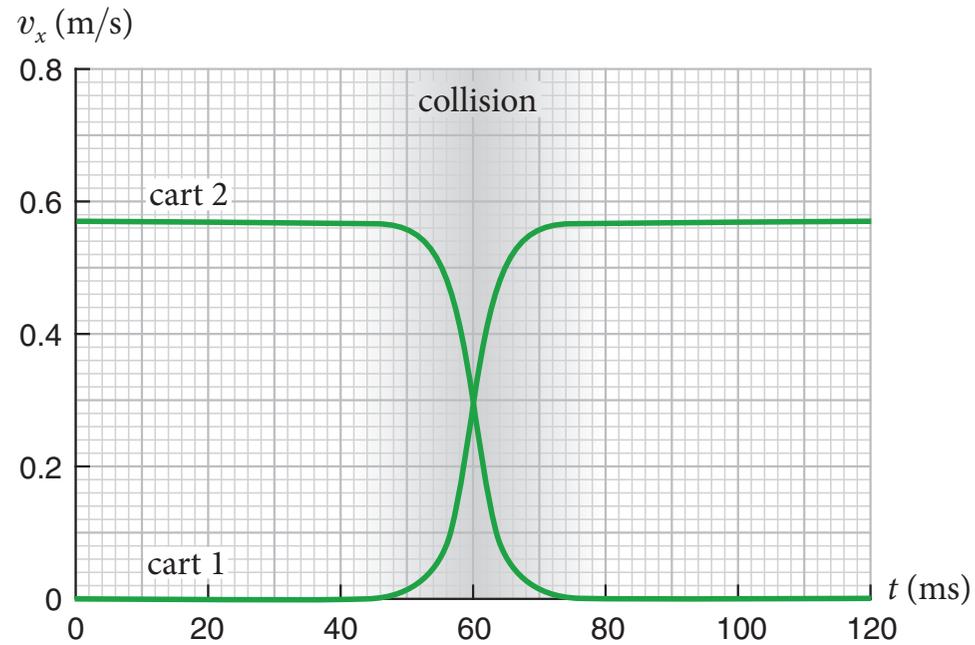
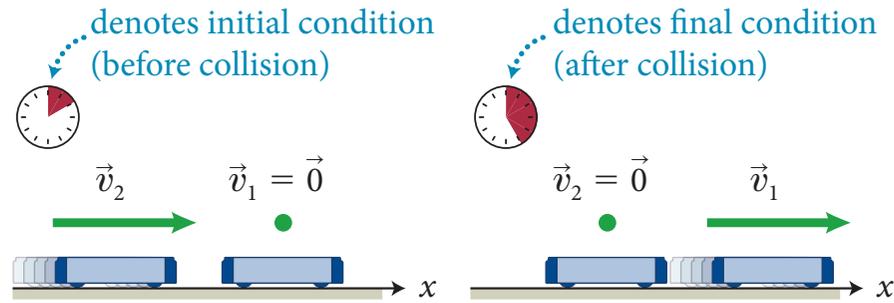


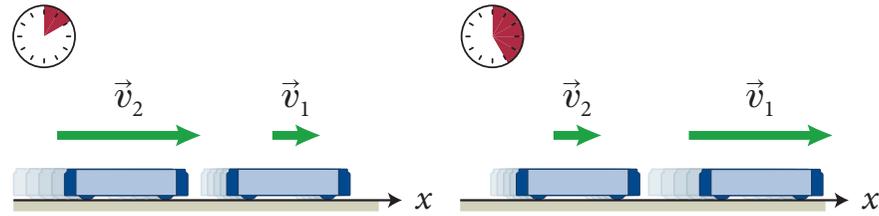
1 architecture

2 content



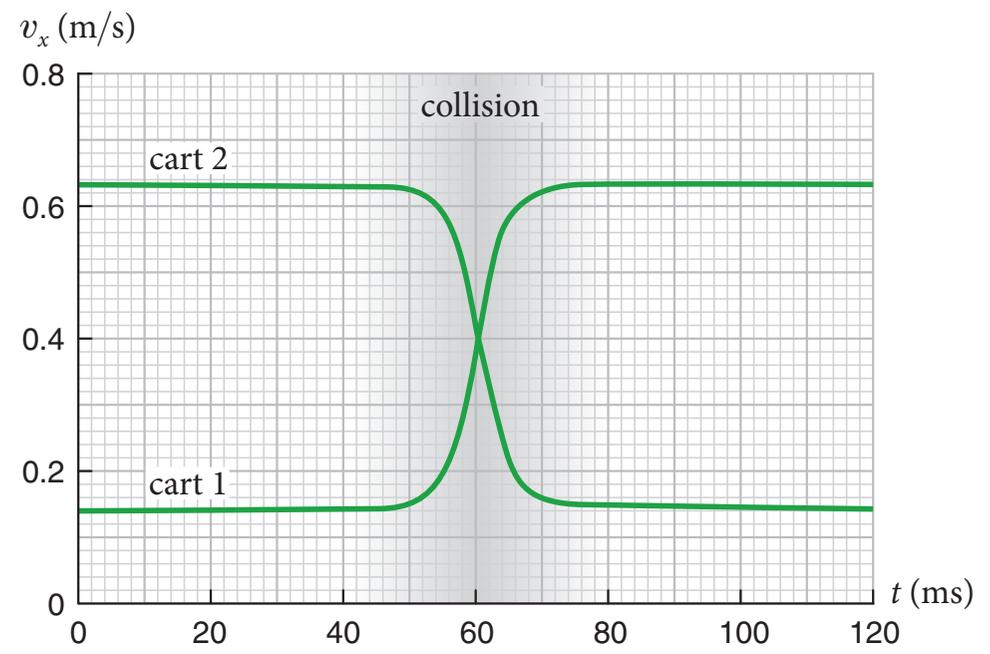
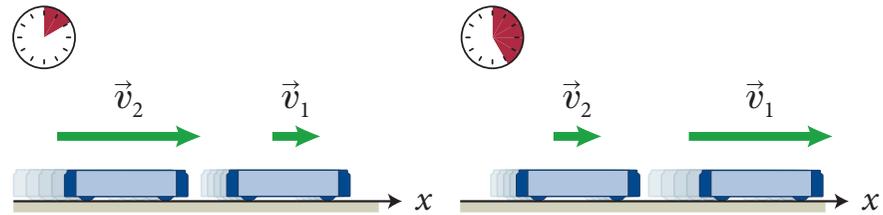


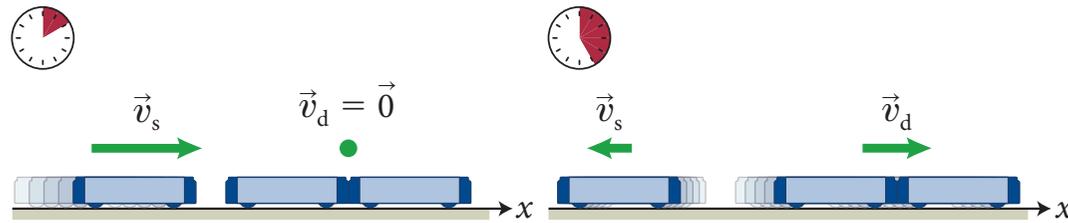


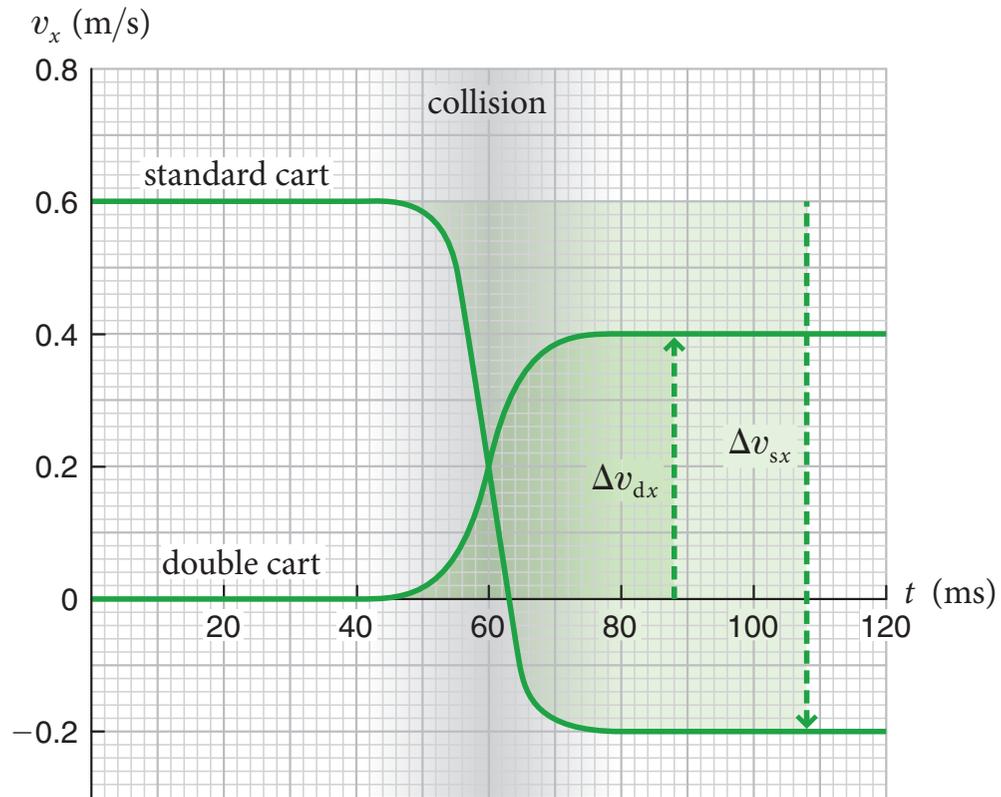
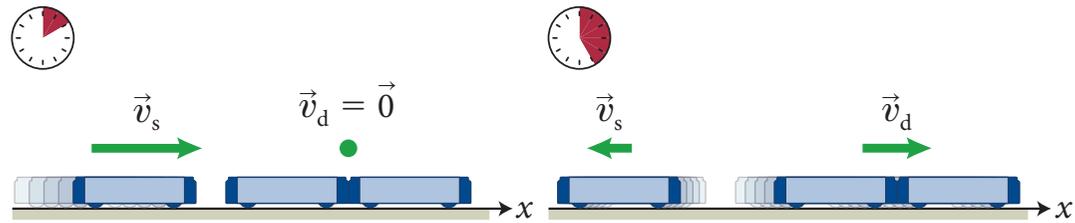


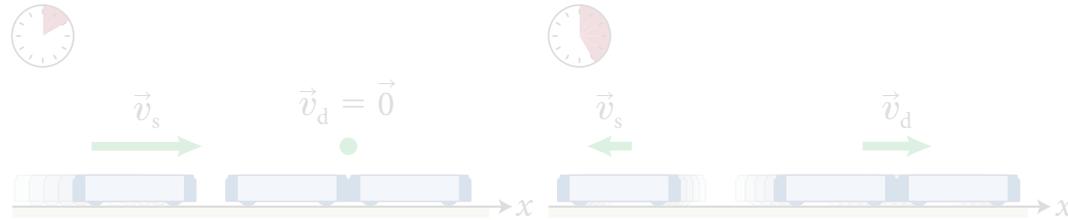
1 architecture

2 content

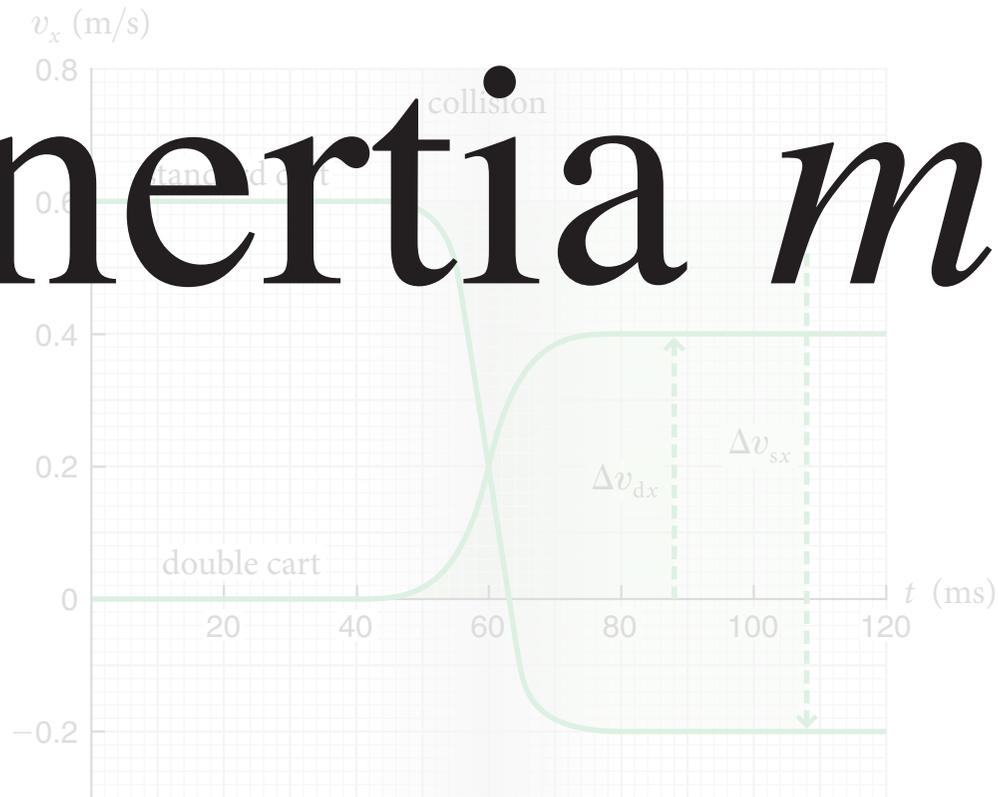








# inertia $m$

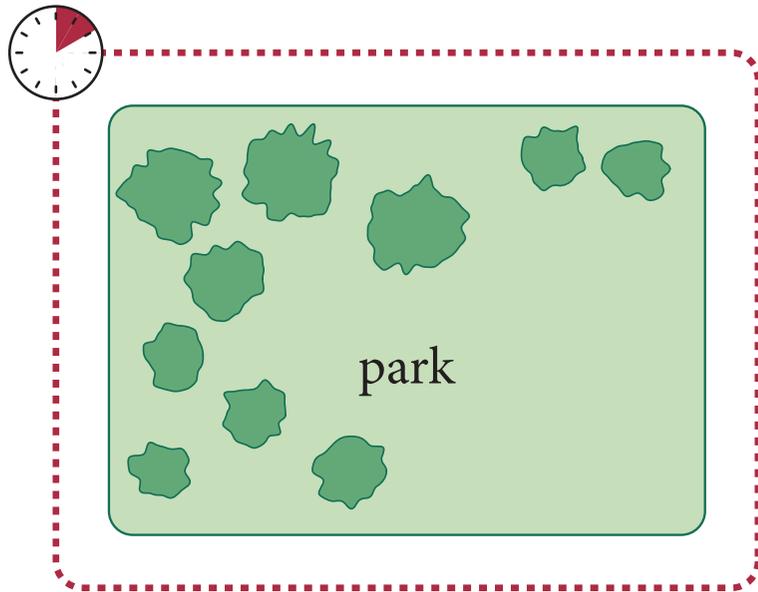


# systems & extensive quantities

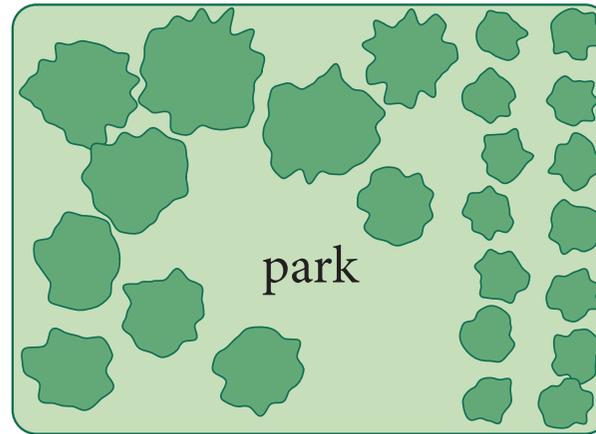
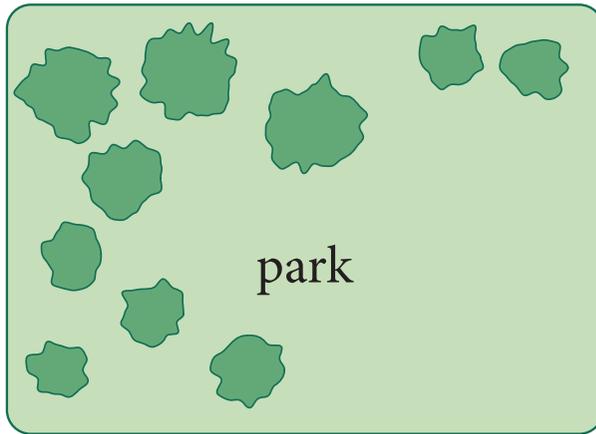
1 architecture

2 content

# systems & extensive quantities



# systems & extensive quantities



# systems & extensive quantities



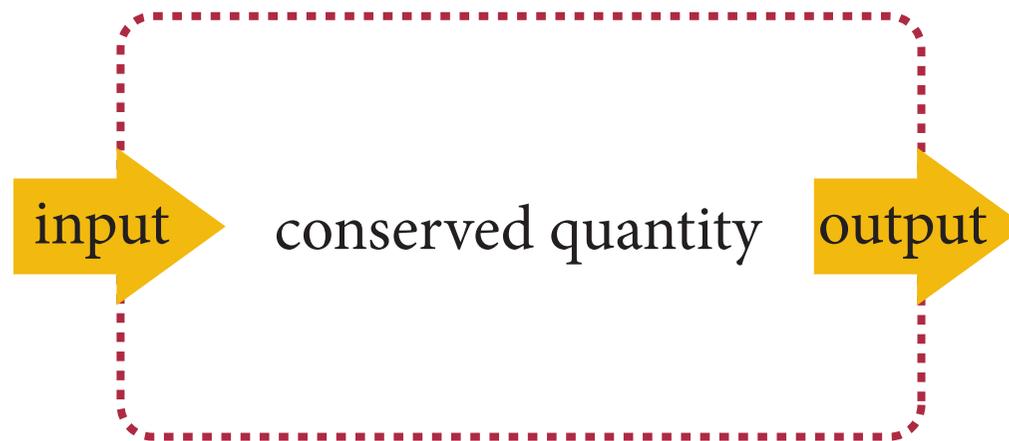
# systems & extensive quantities



# systems & extensive quantities



# systems & extensive quantities



# systems & extensive quantities

conserved quantity

# systems & extensive quantities

**conserved quantity in isolated system**

conserved quantity  
**can't change (constant)**

# systems & extensive quantities

conserved quantities

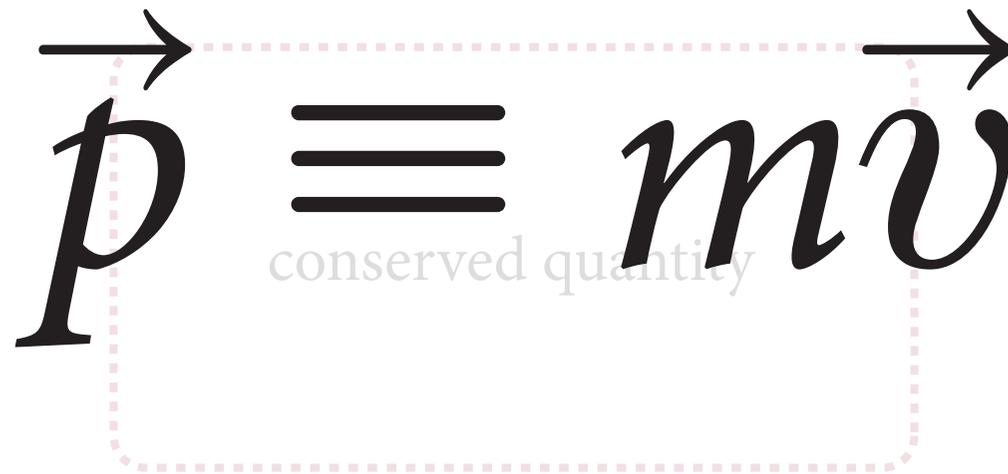
can't change

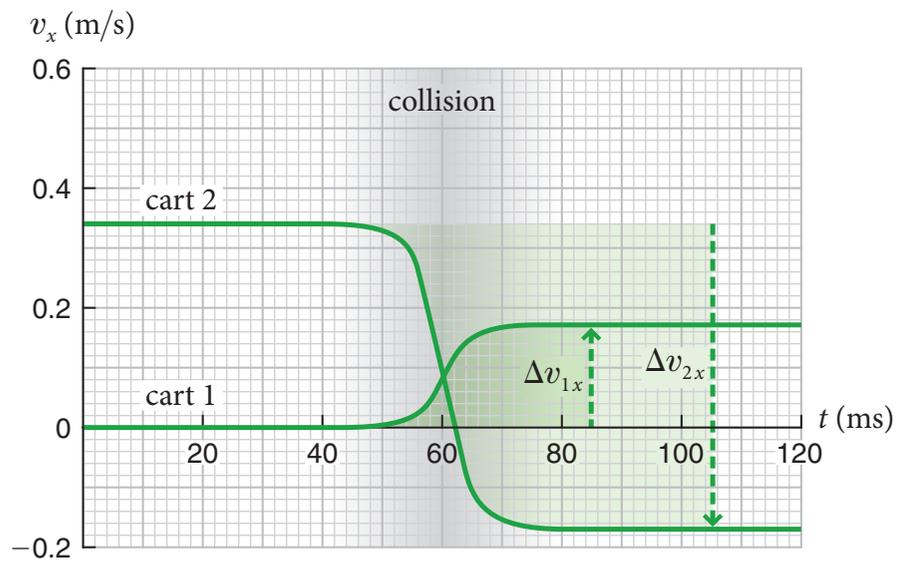
*"When do you address systems that are not closed/isolated?"*

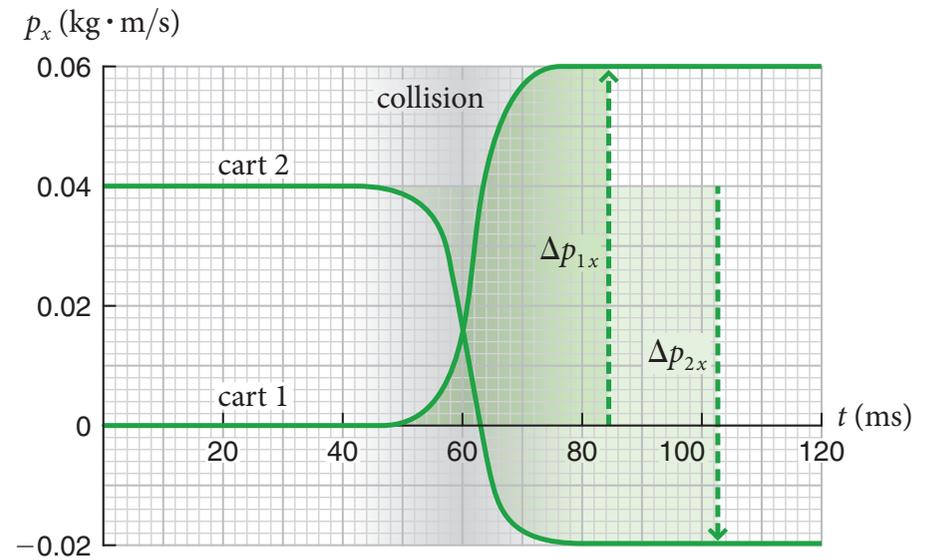
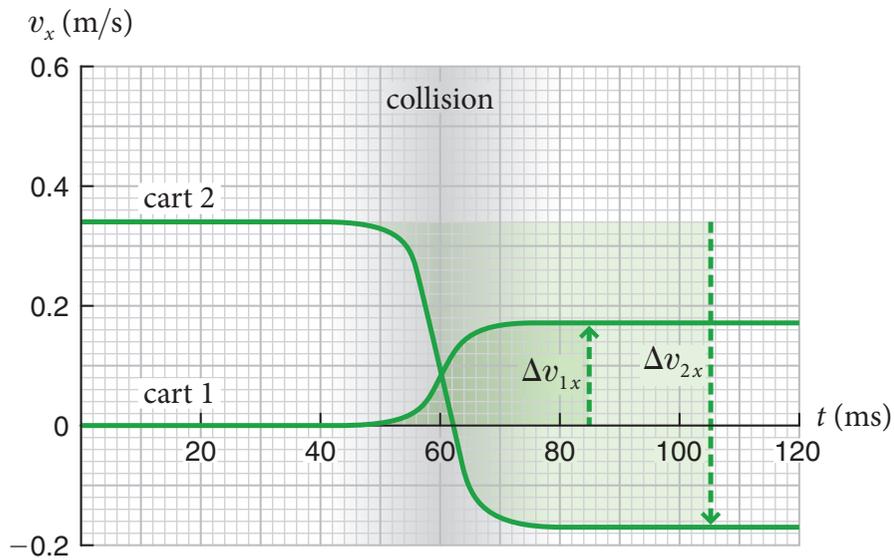
# systems & extensive quantities

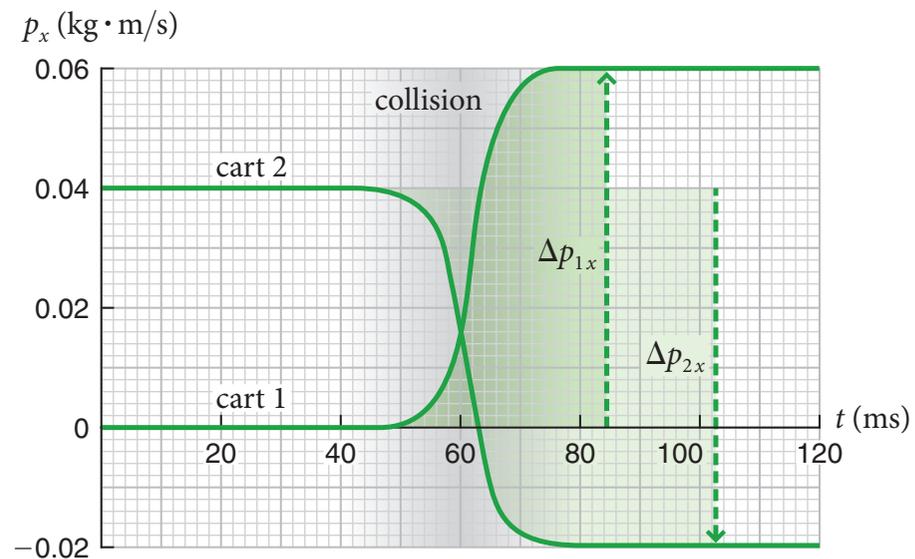
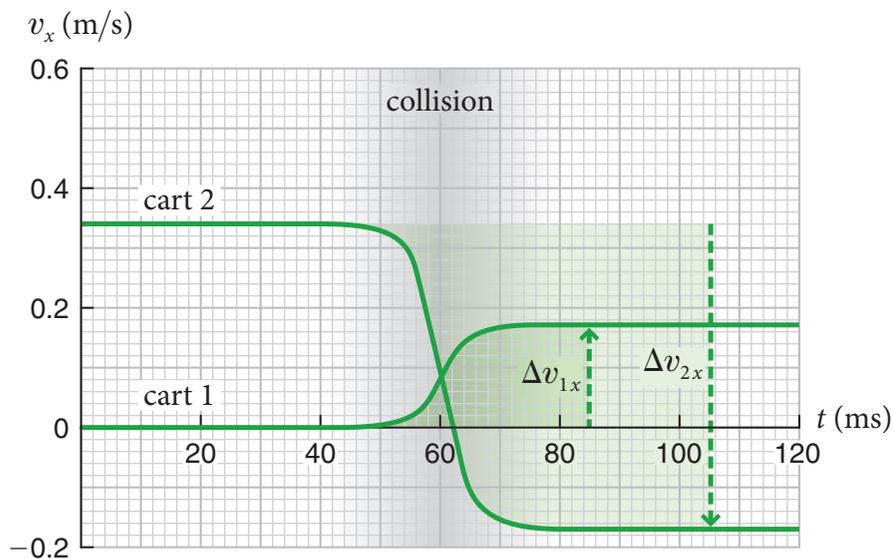
$$\vec{p} \equiv m\vec{v}$$

conserved quantity

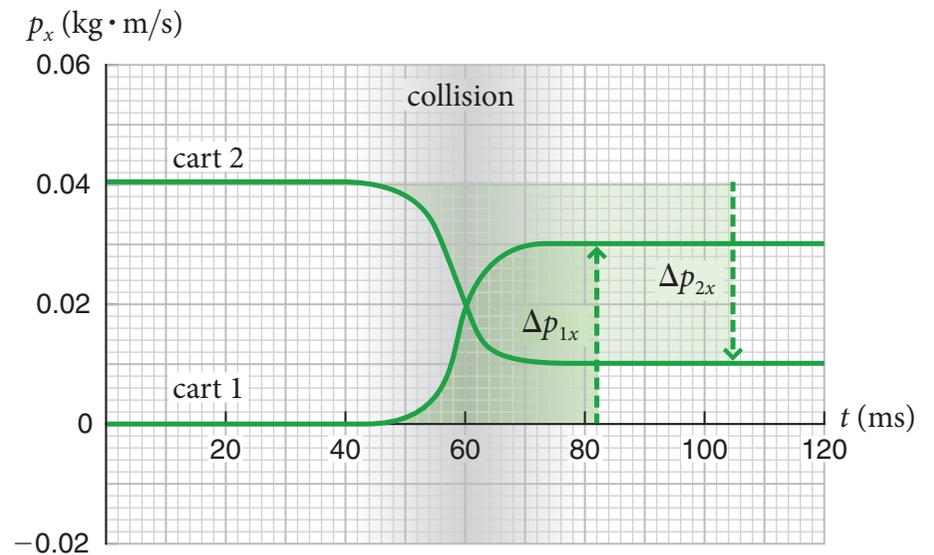
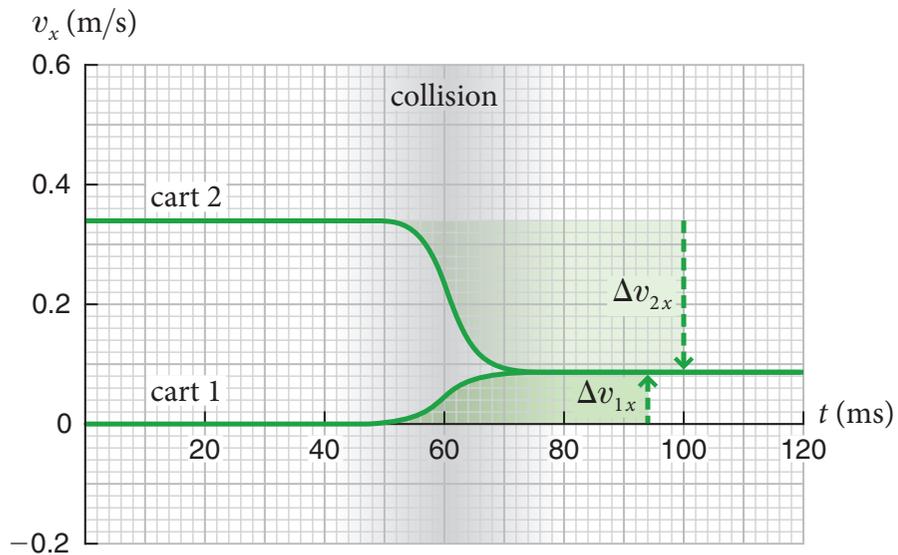




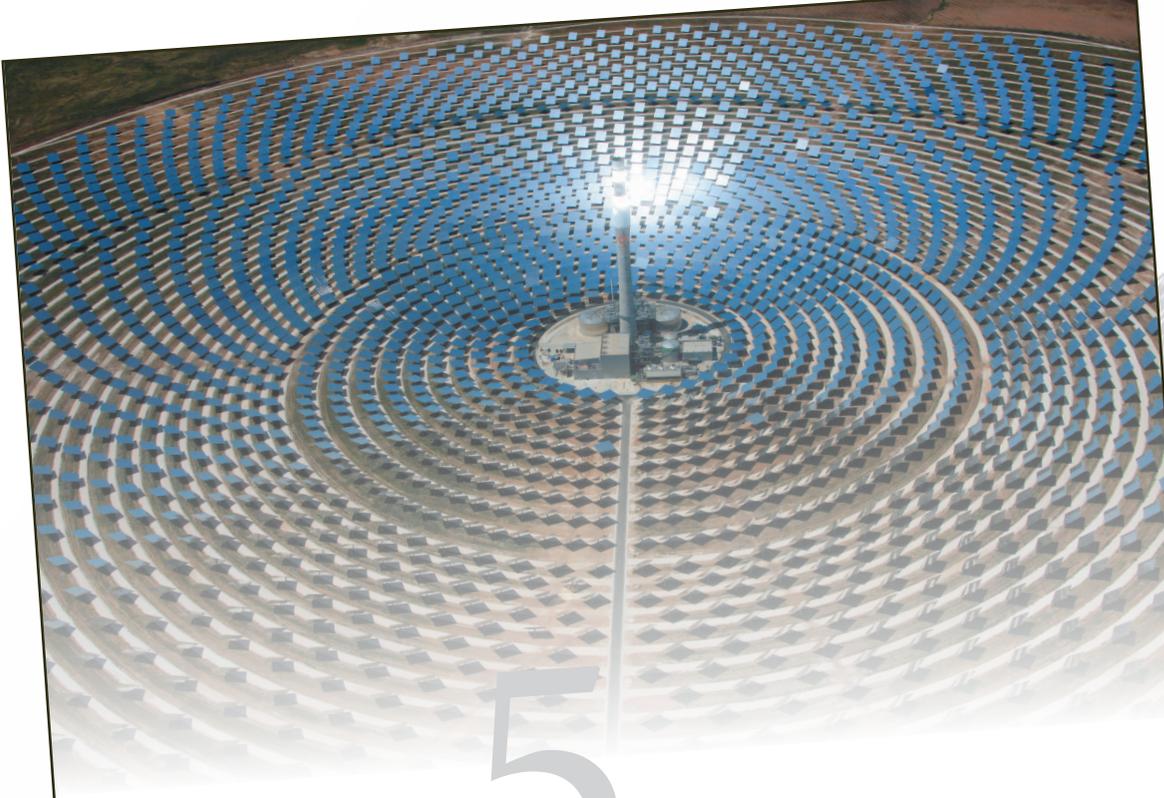




$$\Delta \vec{p} \equiv \Delta \vec{p}_1 + \Delta \vec{p}_2 = \vec{0}.$$



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



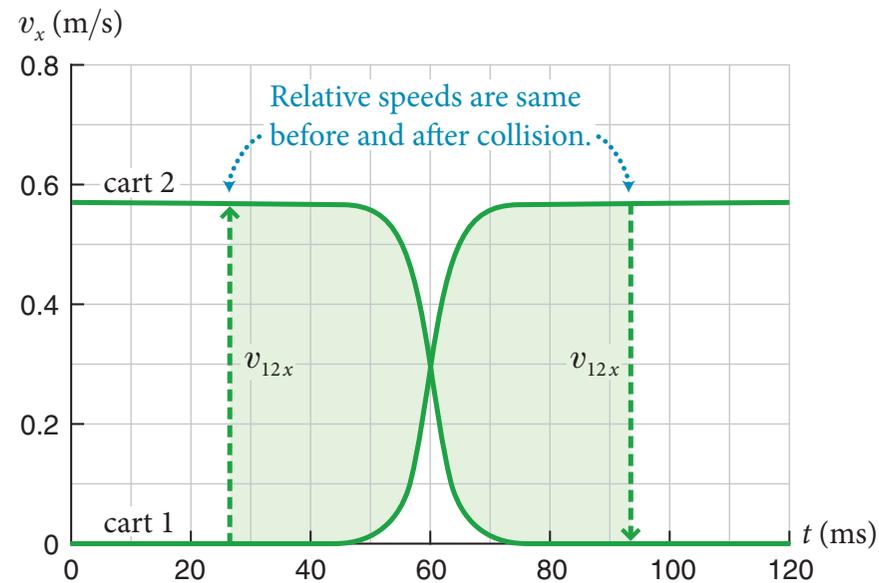
# 5

## Energy

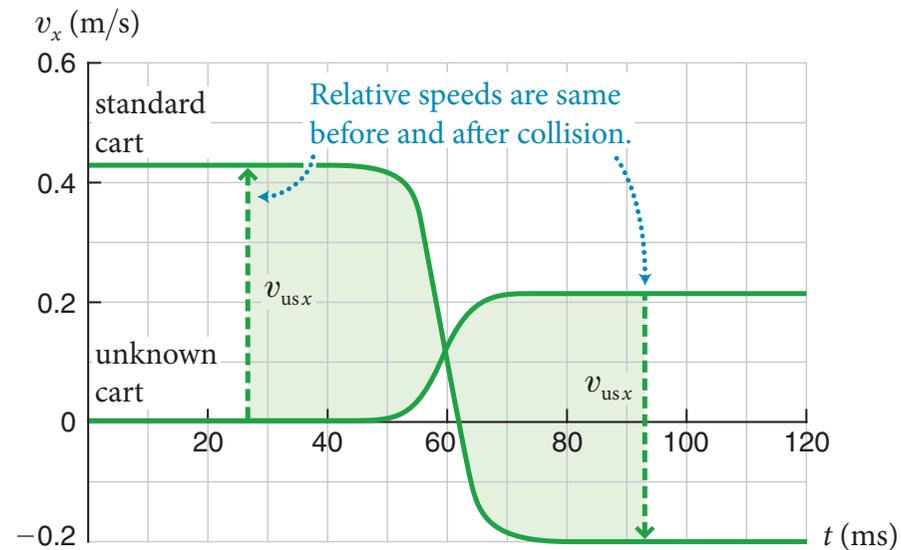
- 5.1 Classification of collisions
- 5.2 Kinetic energy
- 5.3 Internal energy
- 5.4 Closed systems
  
- 5.5 Elastic collisions
- 5.6 Inelastic collisions
- 5.7 Conservation of energy
- 5.8 Explosive separations

CONCEPTS  
QUANTITATIVE TOOLS

# elastic: relative speed unchanged

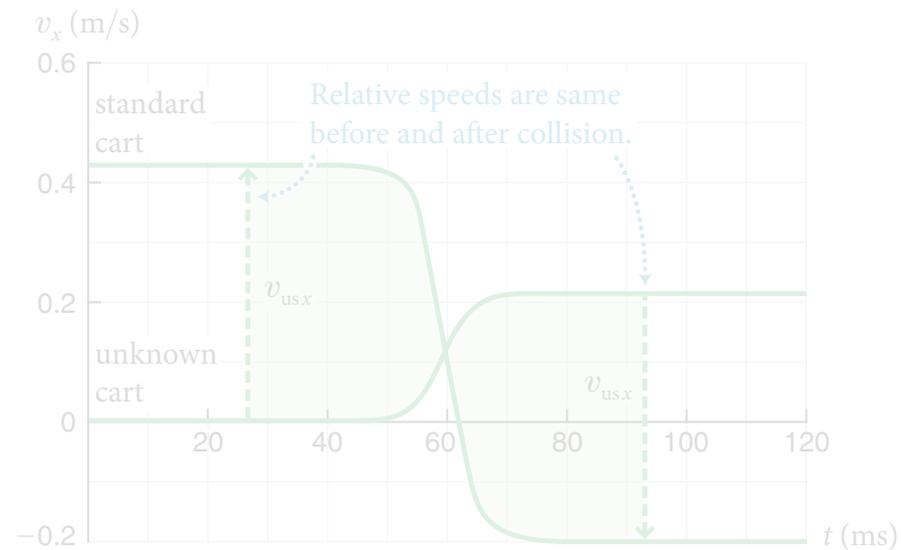


# elastic: relative speed unchanged



# elastic: relative speed unchanged

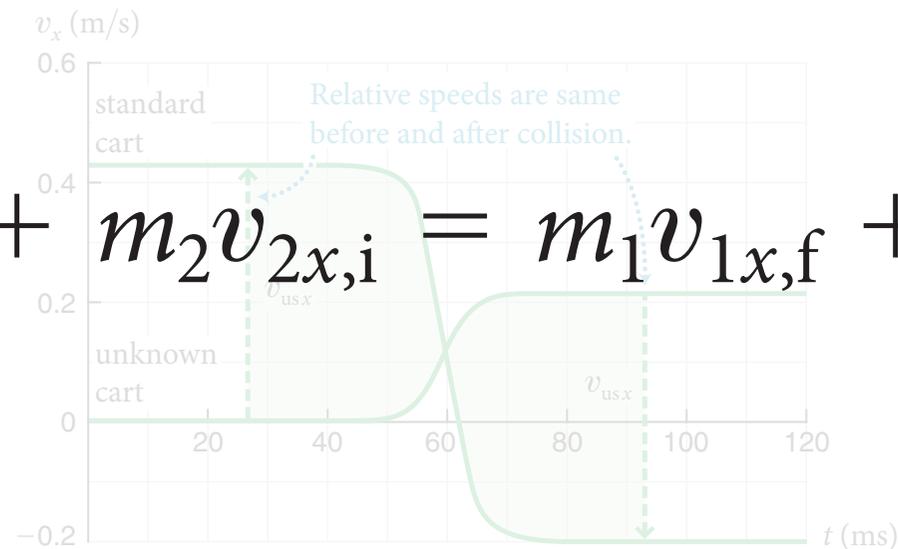
$$v_{12i} = v_{12f}$$



# elastic: relative speed unchanged

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

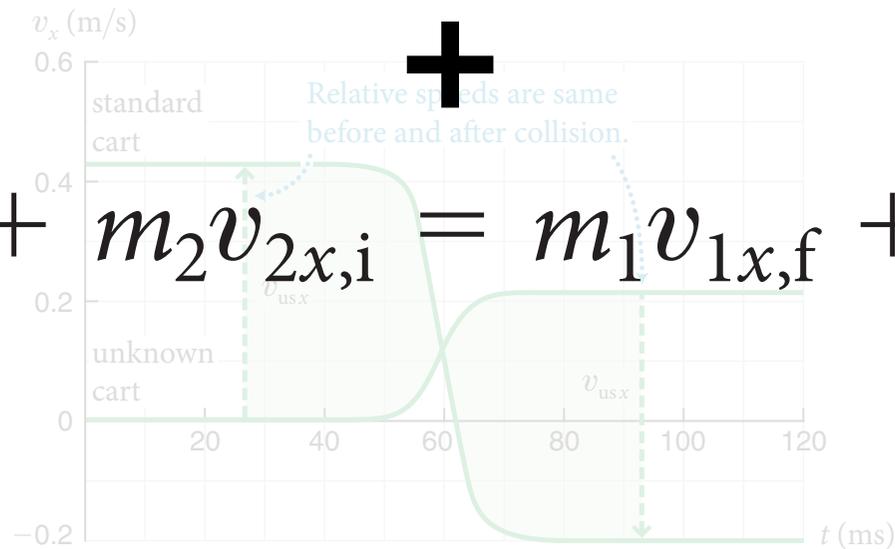
$$m_1 v_{1x,i} + m_2 v_{2x,i} = m_1 v_{1x,f} + m_2 v_{2x,f}$$



# elastic: relative speed unchanged

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

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

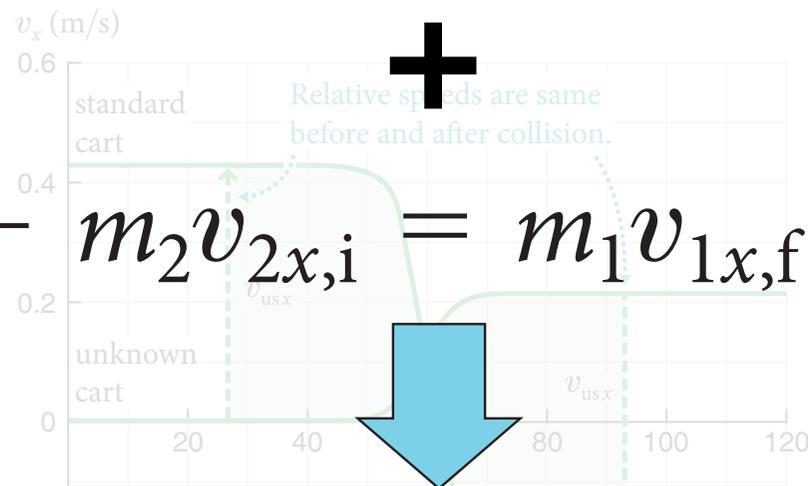


# elastic: relative speed unchanged

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

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

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



# elastic vs. inelastic



# elastic vs. inelastic



before or after?



# elastic vs. inelastic



**elastic: reversible**

**inelastic: irreversible**



# elastic vs. inelastic

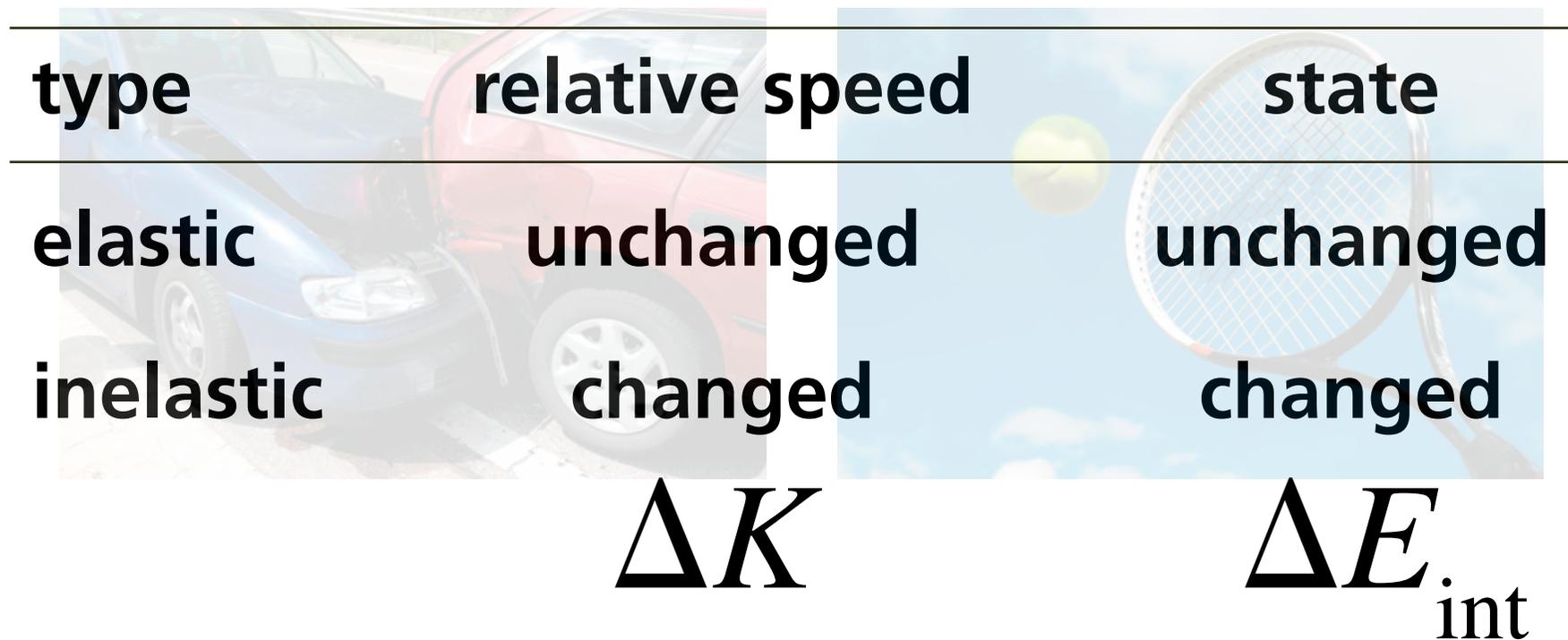
type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

# 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

$\Delta K$                        $\Delta E_{\text{int}}$

## conservation of energy

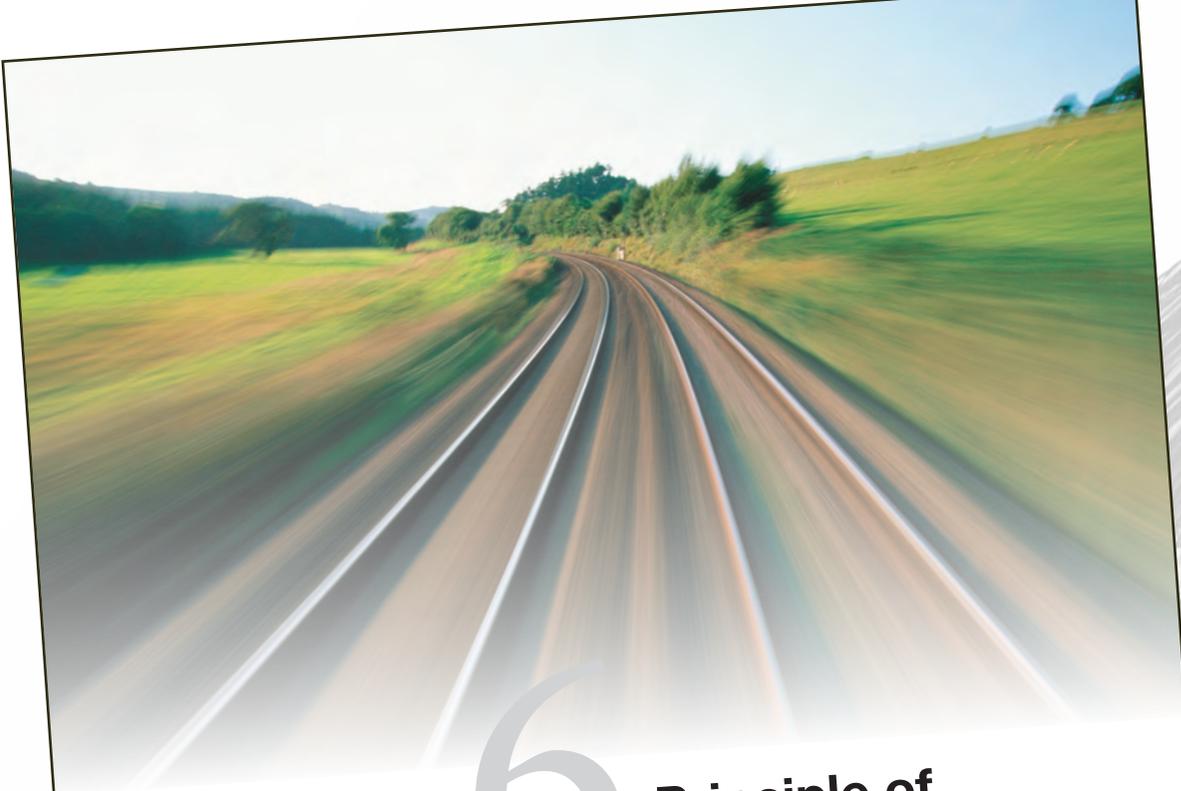
$$E = K + E_{\text{int}}$$

**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

# inertial reference frames

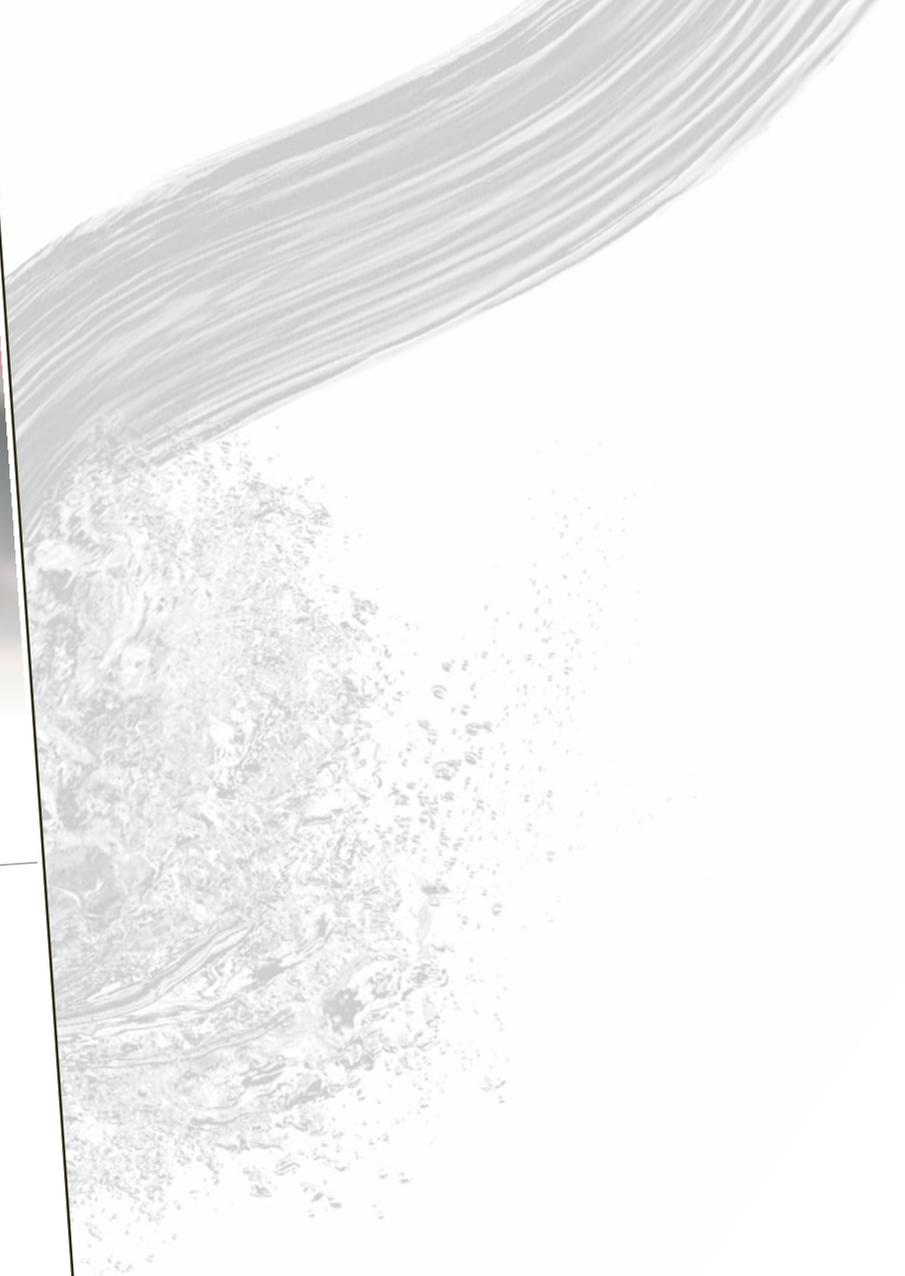
## 6 Principle of Galilean relativity

- 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

- 
- 7.1 The effects of interactions**
  - 7.2 Potential energy**
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- 7.7 Interactions and accelerations**
- 7.8 Nondissipative interactions**
- 7.9 Potential energy near Earth's surface**
- 7.10 Dissipative interactions**

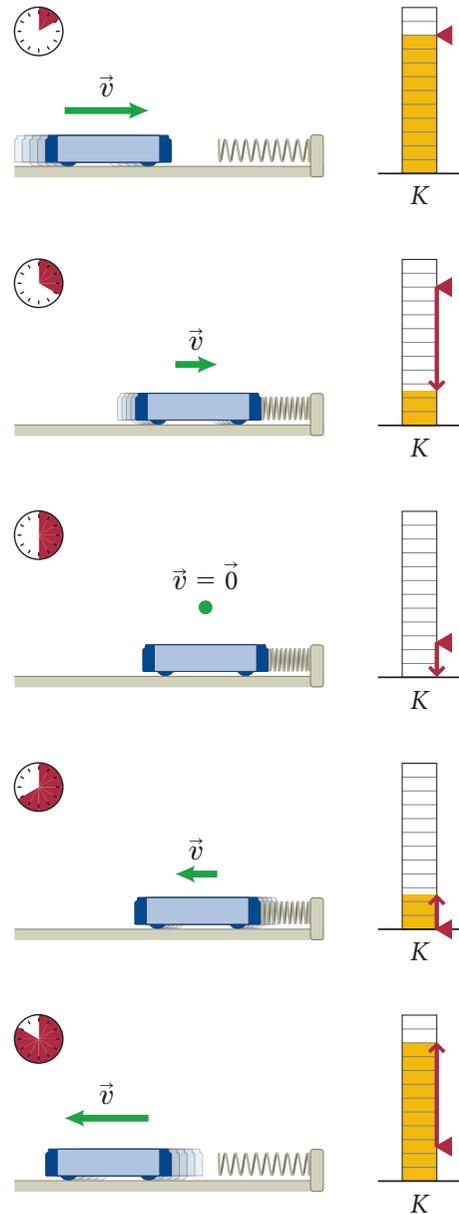
CONCEPTS

- 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

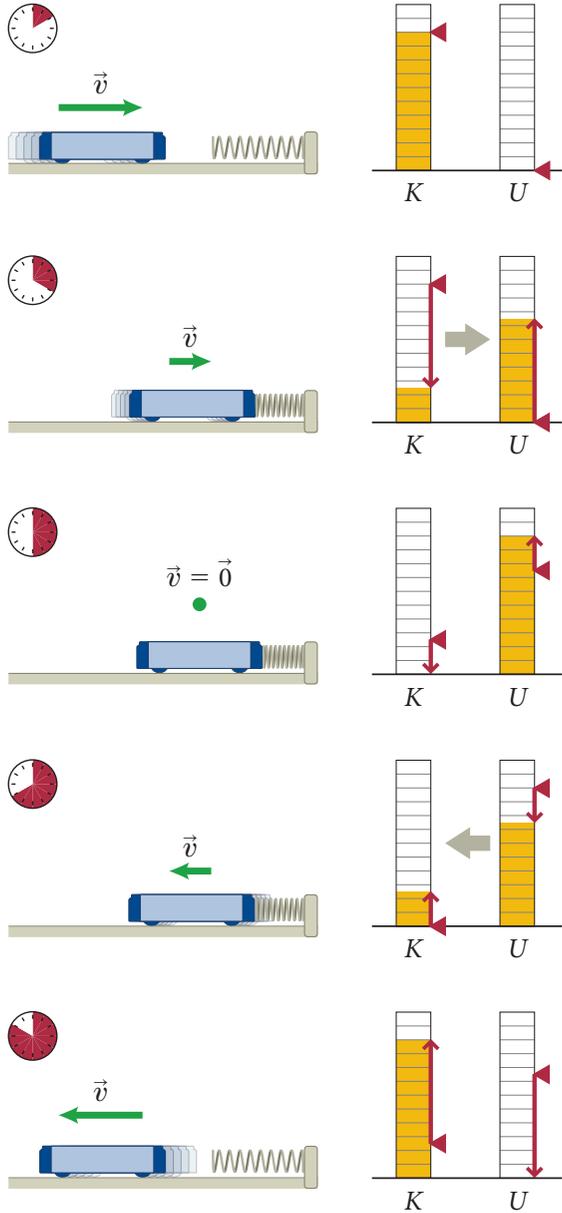
QUANTITATIVE TOOLS

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

# potential energy

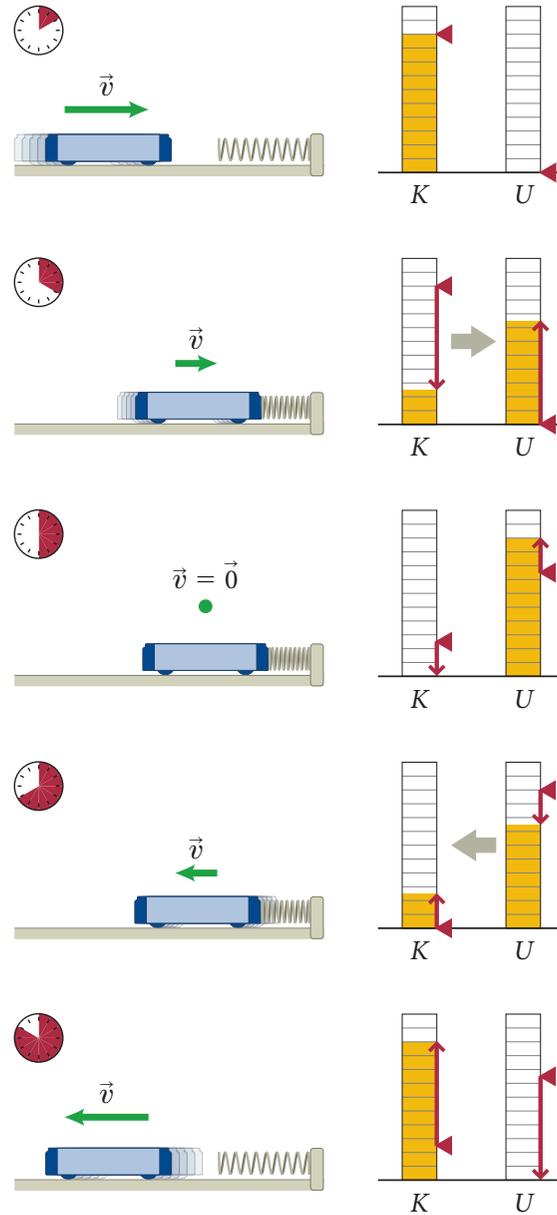


# potential energy

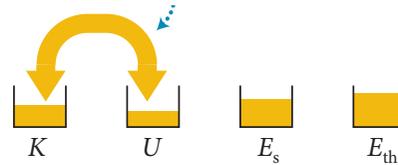


# potential energy

## reversible state change

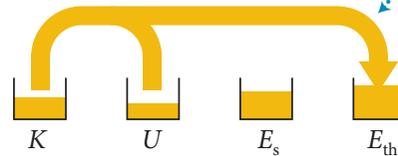


# energy conversions

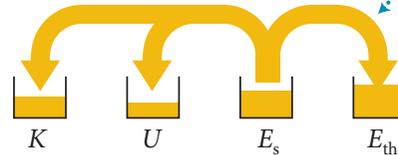


**NONDISSIPATIVE**  
(reversible)

Friction dissipates mechanical energy irreversibly to thermal energy.

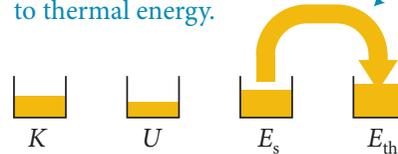


When source energy is converted to mechanical energy, some dissipates irreversibly to thermal energy.

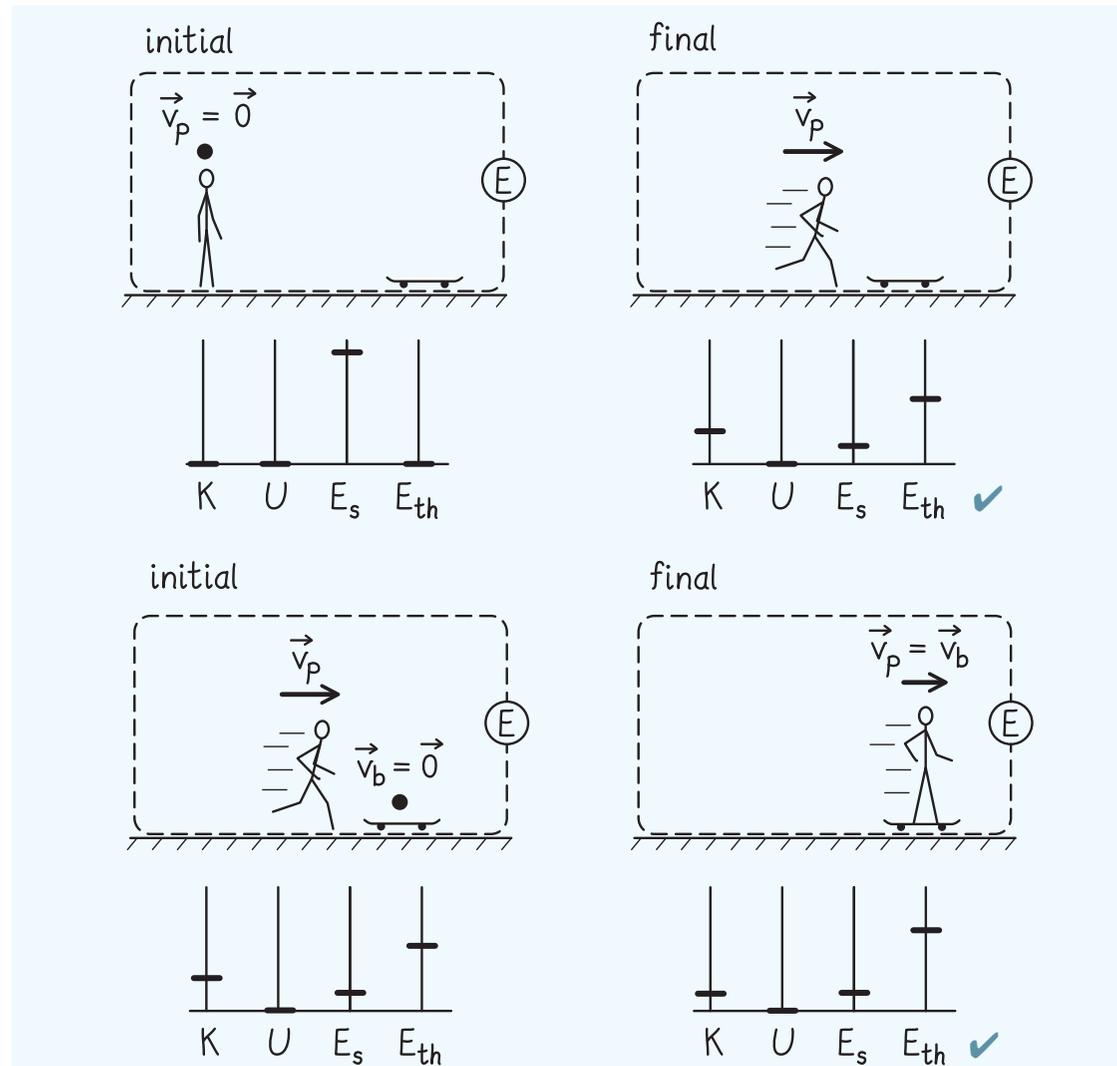


**DISSIPATIVE**  
(irreversible)

Source energy can be converted completely and irreversibly to thermal energy.



# energy conversions





# 8

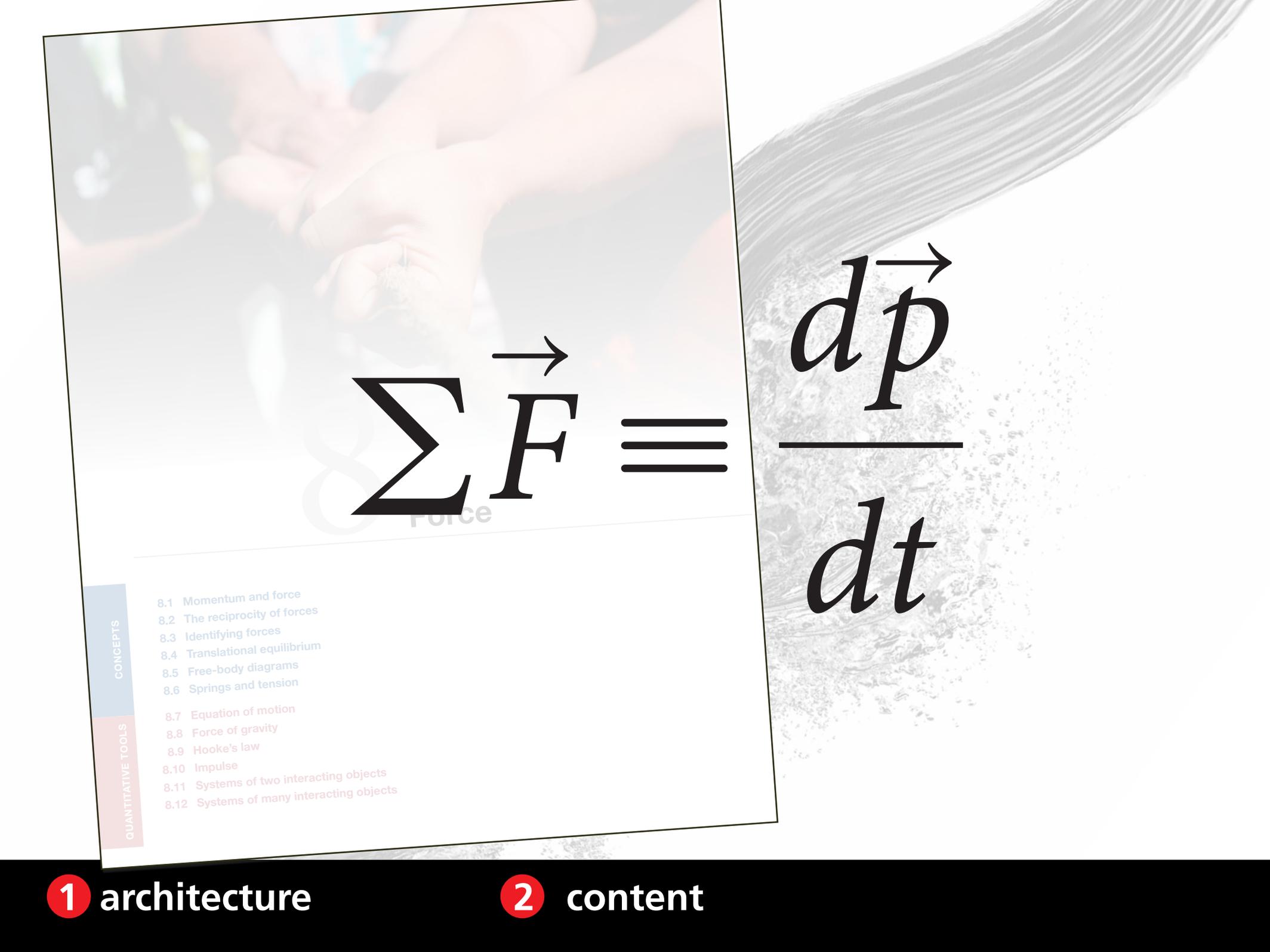
## Force

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


$$\Sigma \vec{F} \equiv \frac{d\vec{p}}{dt}$$

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

CONCEPTS

- 8.1 Momentum and force
- 8.2 The reciprocity of forces
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**8.2 The reciprocity of forces**

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**8.4 Translational equilibrium**

**8.5 Free-body diagrams**

**8.6 Springs and tension**

**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**

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



# 9

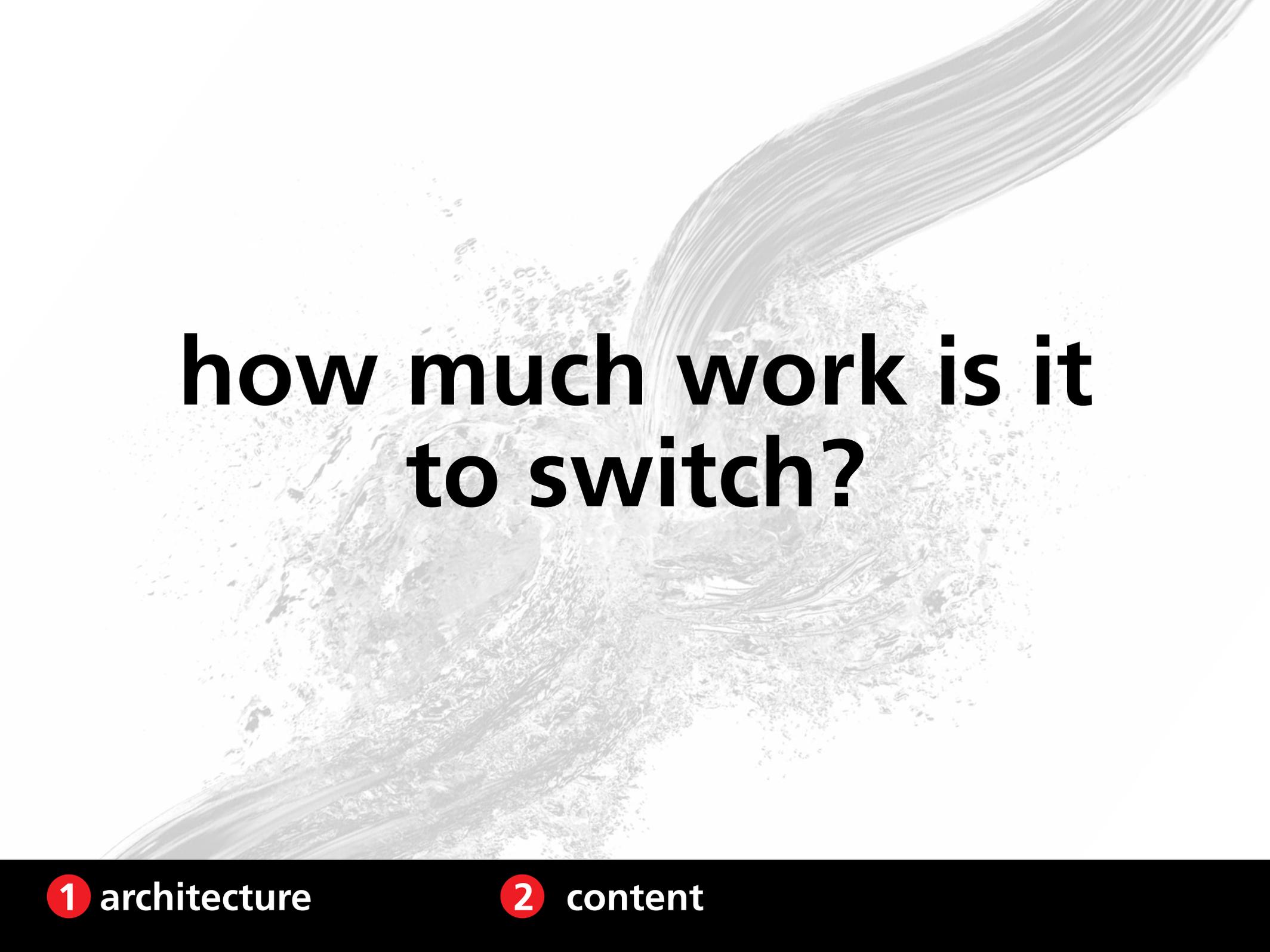
## Work

### CONCEPTS

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

### QUANTITATIVE TOOLS

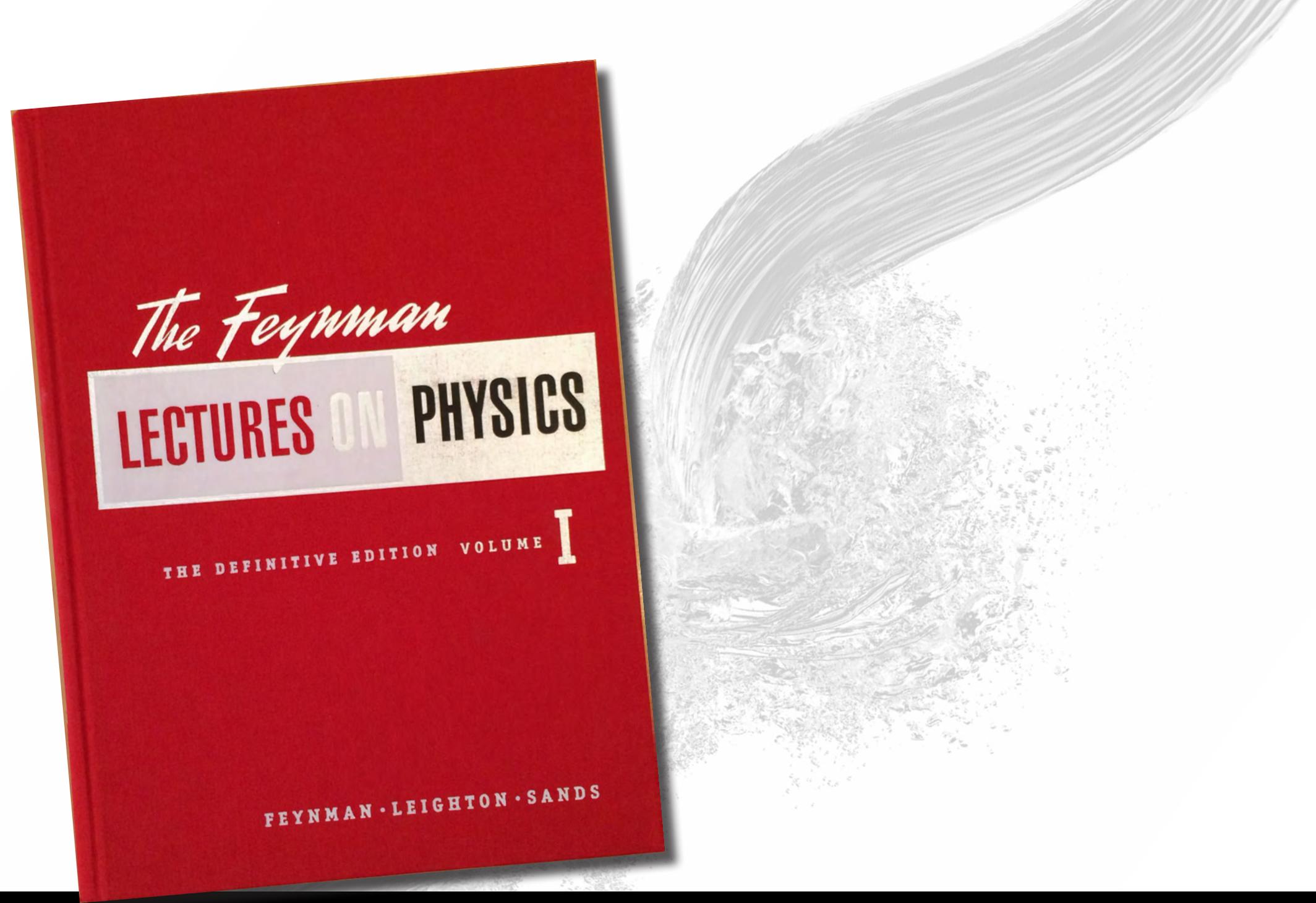
- 9.5 Work done on a single particle
- 9.6 Work done on a many-particle system
- 9.7 Variable and distributed forces
- 9.8 Power

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?**

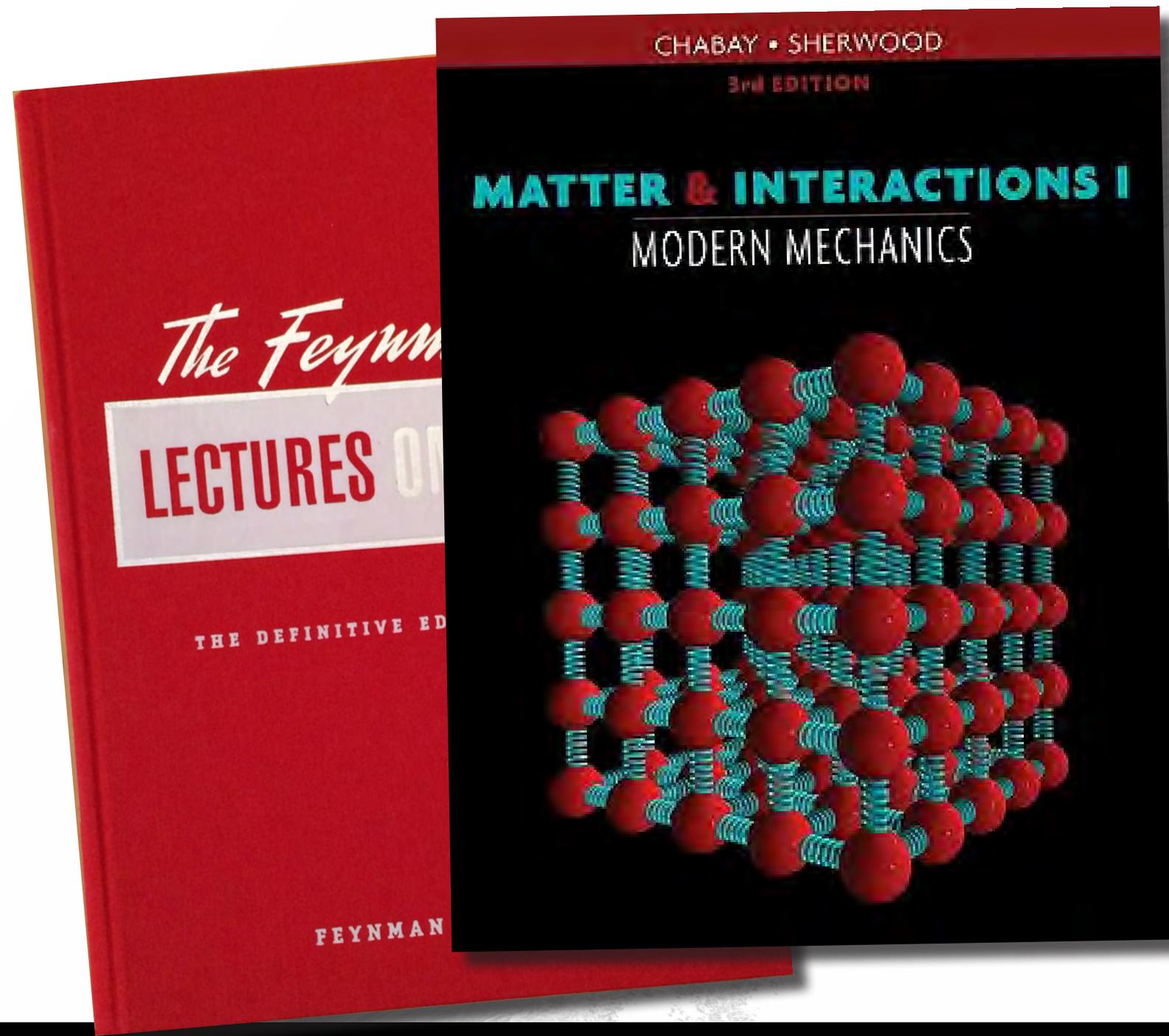
**1** architecture

**2** content



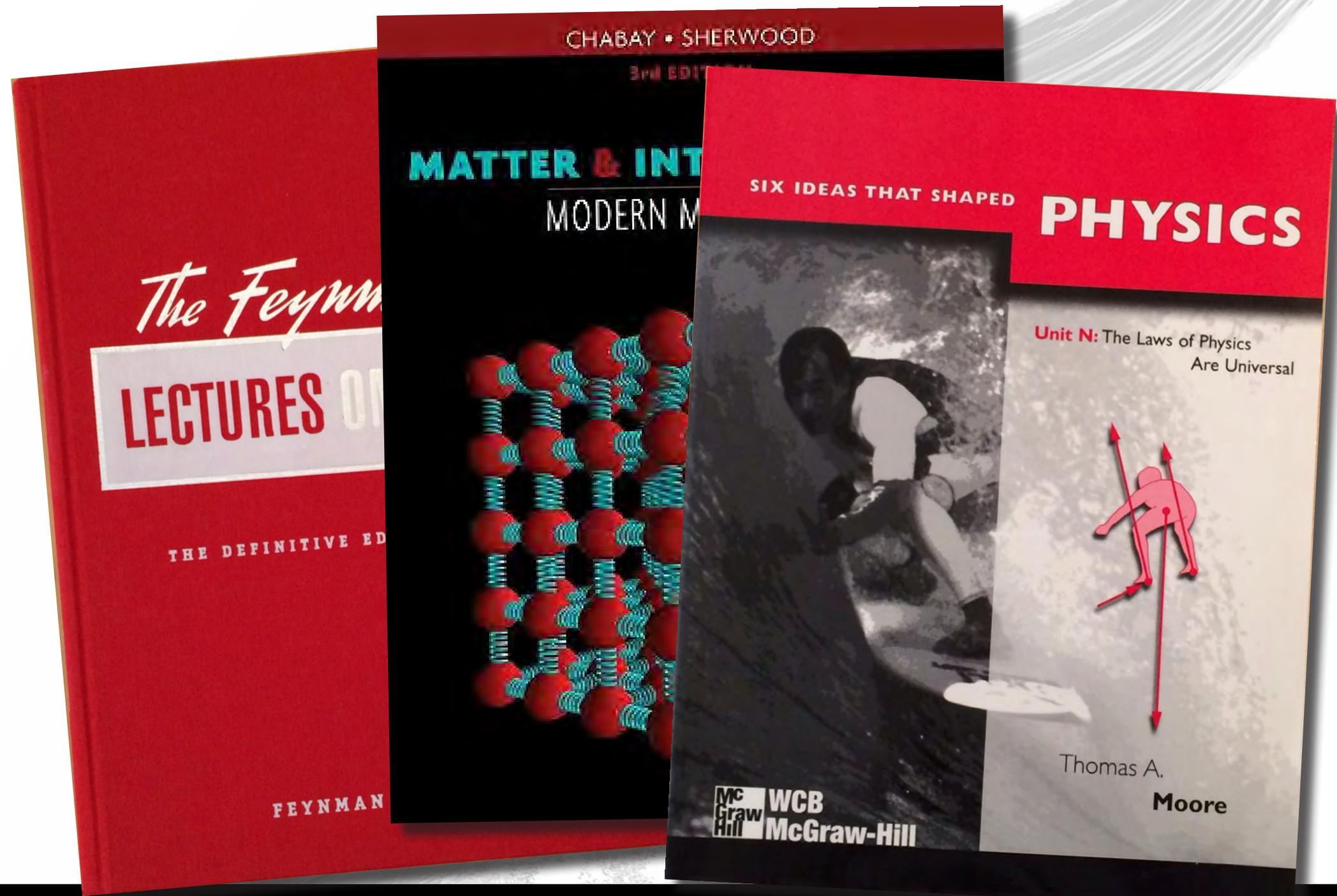
1 architecture

2 content



1 architecture

2 content



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

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**3D**

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**3D**

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**3D**

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## Principles and Practice

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4. Momentum
5. Energy **conservation**
6. Principle of relativity
7. Interactions
8. Force **dynamics**
9. Work
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14. Special Relativity
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**rotation**

## Traditional

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## Principles and Practice

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18. Fluids

**periodic**

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

**mostly minor  
rearrangements!**

**1** architecture

**2** content

# easily custom tailored

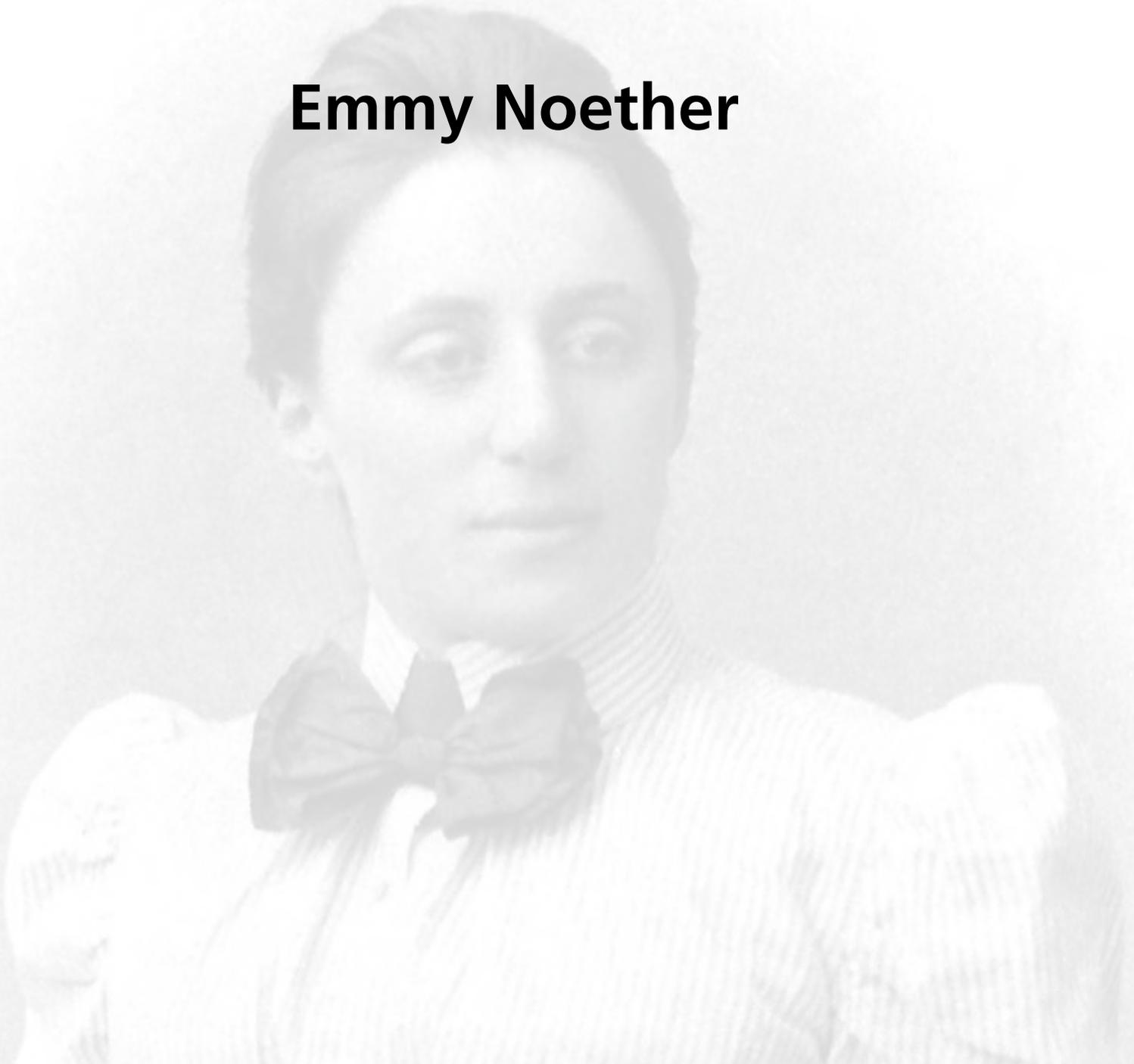
TO THE INSTRUCTOR

VII

**Table 1** Scheduling matrix

Topic	Chapters	Can be inserted after chapter...	Chapters that can be omitted without affecting continuity
Mechanics	1–14		6, 13–14
Waves	15–17	12	16–17
Fluids	18	9	
Thermal Physics	19–21	10	21
Electricity & Magnetism	22–30	12 (but 17 is needed for 29–30)	29–30
Circuits	31–32	26 (but 30 is needed for 32)	32
Optics	33–34	17	34

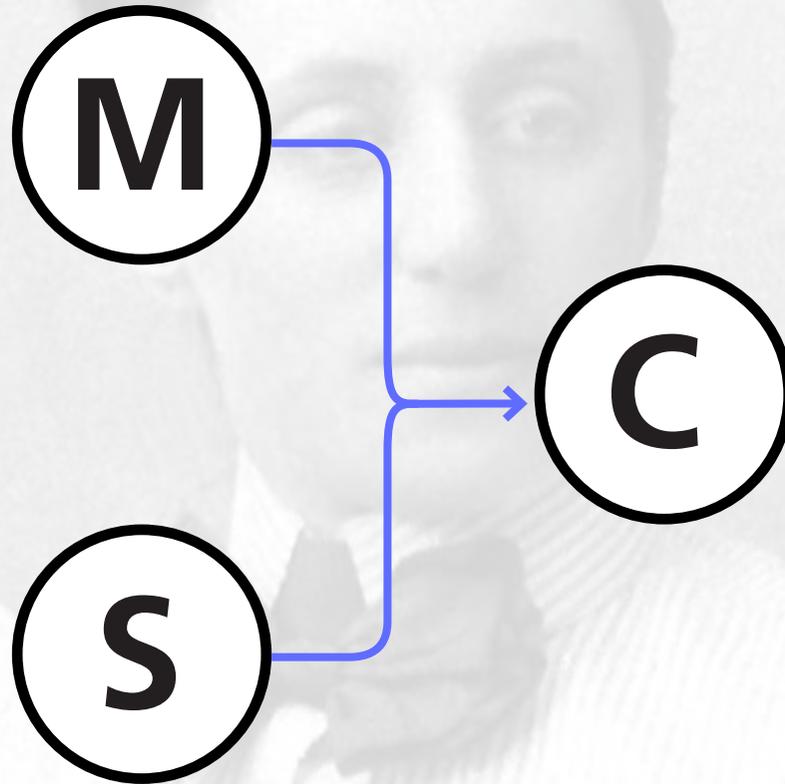
# Emmy Noether



1 architecture

2 content

# Emmy Noether



1 architecture

2 content

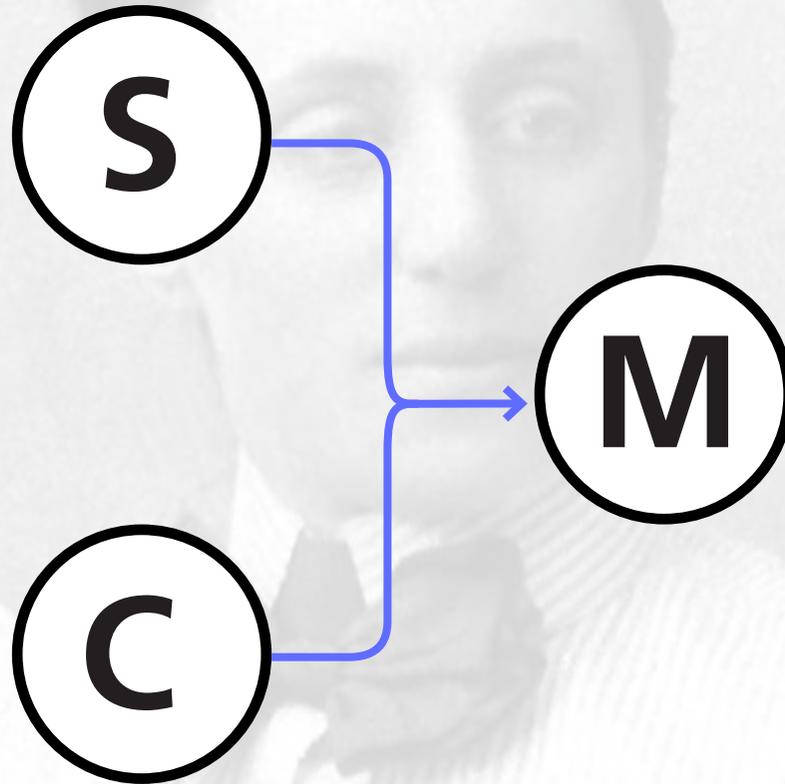
# Emmy Noether

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**C**

**S**

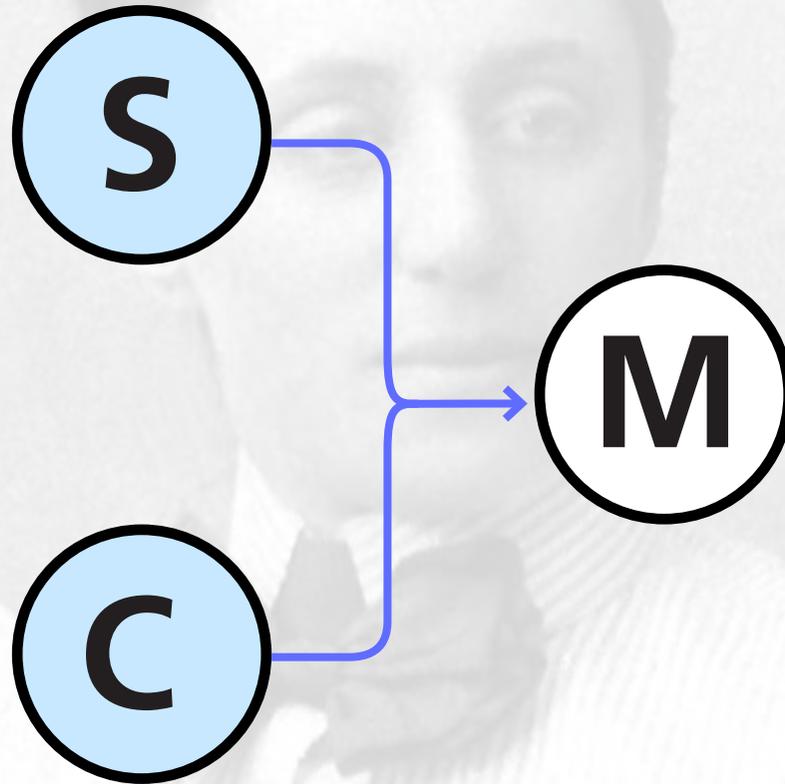
# Noether inverted



1 architecture

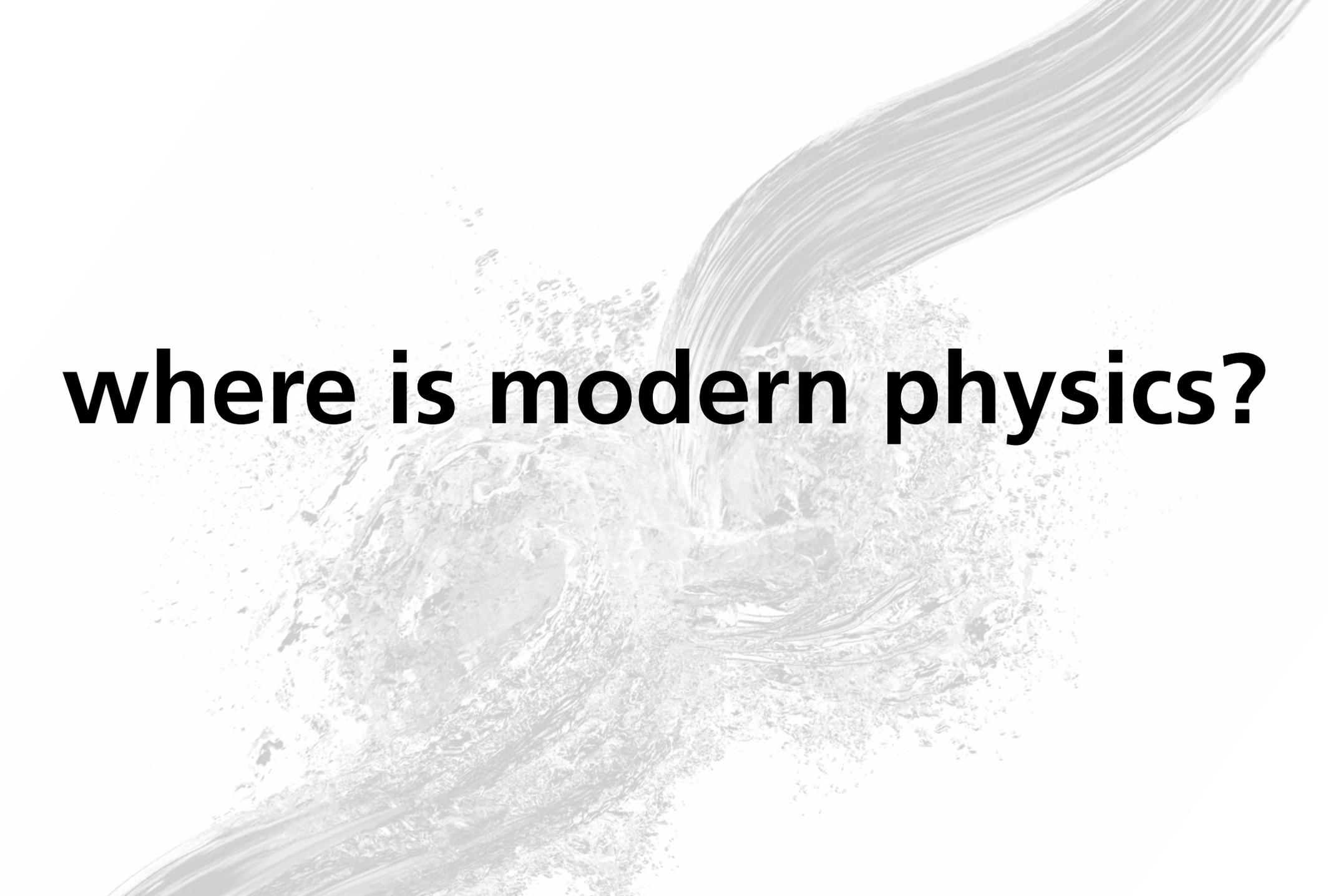
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aesthetically more appealing



1 architecture

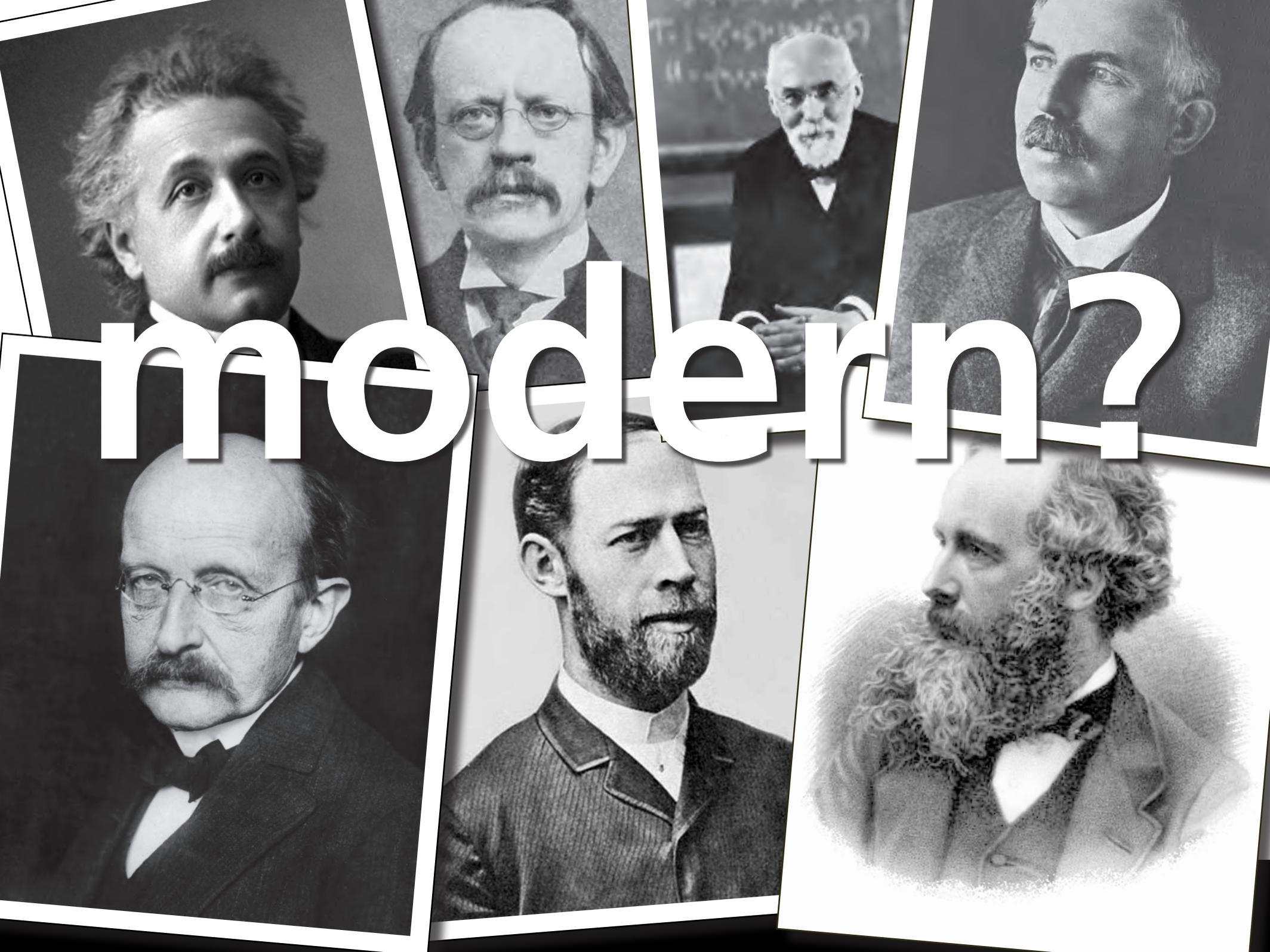
2 content



# where is modern physics?

**1** architecture

**2** content



modern?

where is modern physics?

**ALL physics is modern!**

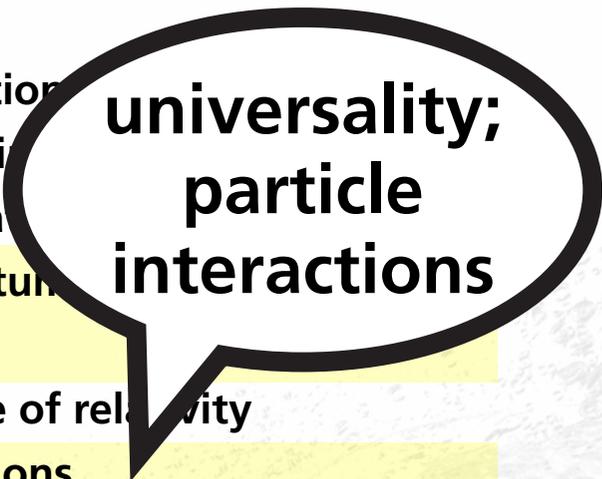
1 architecture

2 content



**conservation  
as modern  
foundation**

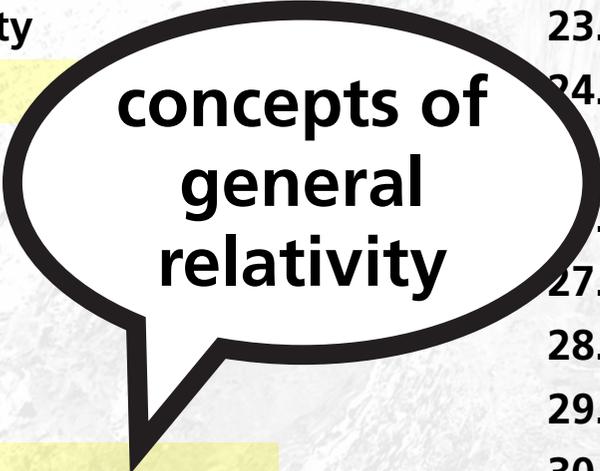
1. Foundations
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27. Magnetic interactions
28. Magnetic fields of charged particles in motion
29. Changing magnetic fields
30. Changing electric fields
31. Electric circuits
32. Electronics
33. Ray optics
34. Wave and particle optics



**universality;  
particle  
interactions**

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4. Momentum
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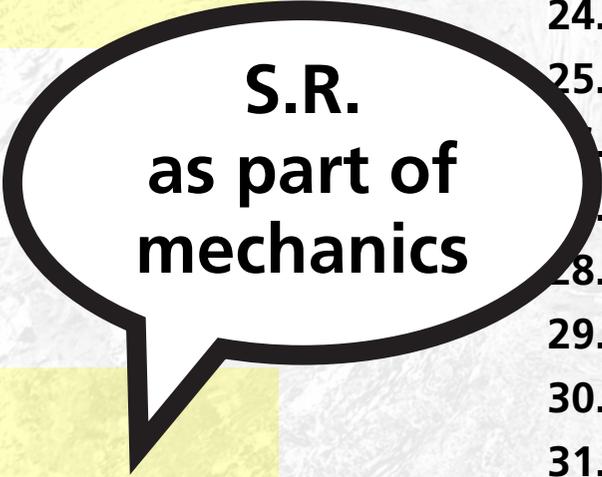
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**concepts of  
general  
relativity**

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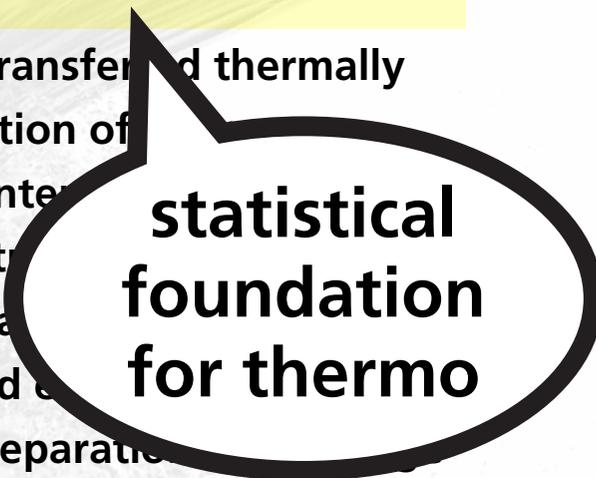


**S.R.**  
**as part of**  
**mechanics**

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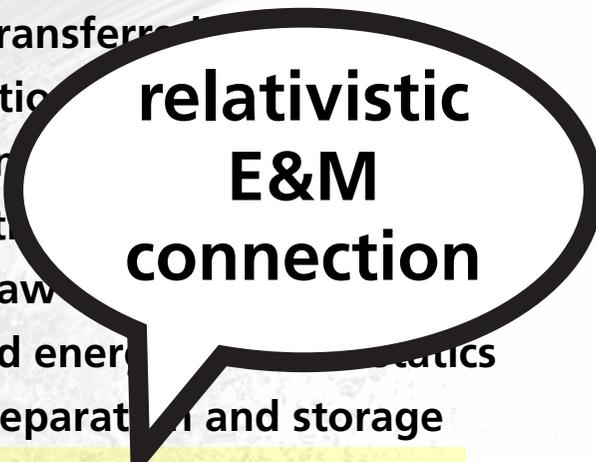
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**statistical  
foundation  
for thermo**

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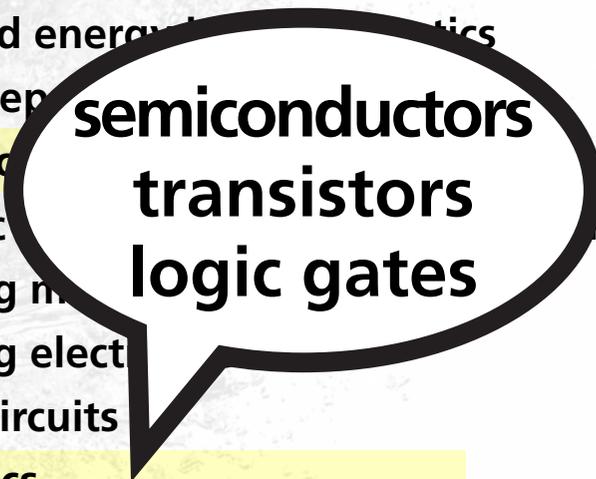
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**relativistic  
E&M  
connection**

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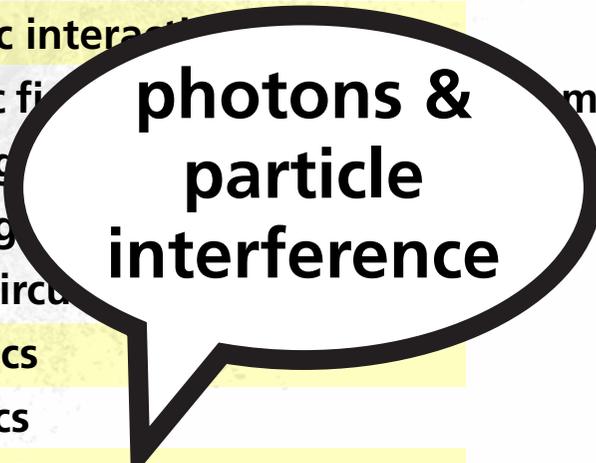
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semiconductors  
transistors  
logic gates

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**photons &  
particle  
interference**

## CHAPTER

# 1

## Foundations

### Strategy

This book is developed with the goal of engaging students in developing a conceptual framework for the topics presented in introductory physics and to develop in students the reasoning and problem-solving skills that will help them in and beyond the study of physics. Throughout this book, the focus is on change, the transition from one state to another. Conservation principles naturally become the focus as they arise from those properties that are observed to remain unchanged. The mathematics requirements are initially minimized to allow students to develop a better grasp of the physics without getting sidetracked by mathematics. For that reason, the first nine chapters only deal with physics in one dimension. Once students have a solid grasp of physics in one dimension, they can better begin to explore two- and three-dimensional problems. This also gives students an opportunity to develop the required math skills in a concurrent mathematics course. Taking mathematics concurrent to physics, rather than as a prerequisite, can increase students' understanding of the mathematical concepts. Further, some concepts are often so transparent to an instructor that they are not taught explicitly, creating difficulty for students who do not have the same background. These foundational ideas, such as symmetry, and tools, such as representations, are spelled out so that students can explicitly engage in their use. Language is used and developed very carefully to avoid introducing confusion. Although they may sometimes seem formal or wordy, these choices have been carefully made to avoid common misconceptions by students.

### Overview

The presentation of physics begins by defining it and its scope of the study of "all there is in the universe." The skills developed in studying physics to other aspects of life also is discussed. This chapter launches with a discussion of the concepts of physics that are taught in grade school.

CHAPTER

1

Foundations

- **Strategy**
- **Overview**
- **Topics that are not covered**
- **Terminology**
- **Notation and visual representations**
- **Cautionary notes**
- **Common student difficulties and concerns**
- **Sample recommendations from Practice Vol**

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Eric Mazur | Harvard University | Log out

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Courses Questions Classrooms Tour Help Student view

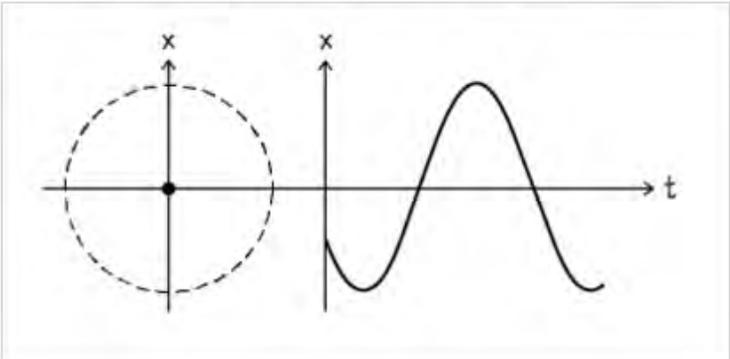
My Courses > AP50a F2013 > Chapters 14-15 in class

Start session Edit Review results Create PDF Delete module

Jump to 1 2 3 4 5 6 7 8 9 10

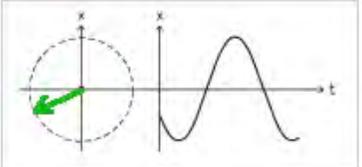
3. direction

In the reference circle on the left, draw a phasor representing the oscillation shown on the right.



The diagram shows a reference circle on the left and a graph of displacement  $x$  versus time  $t$  on the right. The reference circle is a dashed circle centered at the origin of a coordinate system with a vertical  $x$ -axis and a horizontal  $t$ -axis. The graph shows a sinusoidal wave starting at a negative value at  $t=0$ , reaching a minimum, crossing the  $t$ -axis, reaching a maximum, and crossing the  $t$ -axis again.

Answer



The answer diagram shows the same reference circle and graph, but with a green arrow (phasor) drawn on the circle. The arrow points from the center to the left edge of the circle, representing the initial phase of the oscillation.

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

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PHYSICS

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1 architecture

2 content

3 results

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PRINCIPLES & PRACTICE OF  
PHYSICS

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PHYSICS

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1 architecture

2 content

3 results

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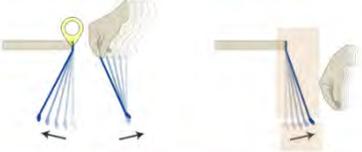
Perusall Unit 6 Page 595 Eric Mazur

22.2 ELECTRICAL CHARGE 595

**Figure 22.2** Strips of tape just pulled out of a dispenser repel each other. The repulsive force is great enough to keep the strips apart even when they are weighted down by paper clips.



**Figure 22.4** Tape strips prepared according to Figure 22.3 repel each other... but are attracted to your hand.



Let us call the attribute responsible for the electric interaction **electrical charge**, or simply **charge**. Saying that something carries an electrical charge is just another way of saying that that object interacts electrically with other objects that carry electrical charge. Freshly pulled strips of tape carry electrical charge, and two such strips interact because each possesses an electrical charge, just as your body and Earth interact because each possesses mass. The general term for any microscopic object that carries an **electrical charge**, such as an electron or ion, is **charge carrier**.

It is not immediately clear what attributes to assign to objects that do not interact electrically with each other but do interact with a charged tape strip—a strip of paper, your hand, an eraser, you name it. All we know for now is that the interaction between these objects and a charged tape is attractive rather than repulsive.

The electric charge on an object is not a permanent property; if you let a charged strip of tape hang for a while, it loses its ability to interact electrically. In other words, the strip is no longer charged—it is *discharged*. Depending on the humidity of the air, the discharging can take minutes or hours, but you can speed up the discharging by rubbing your fingers a few times over the entire length of a suspended charged strip of tape.\* (The rubbing allows the charge to “leak away” from the tape by distributing itself over your body.)

\*If rubbing your fingers along the tape doesn't do the job, try licking them before rubbing them over the tape.

**22.2 Electrical charge**

As we saw in the preceding section, electric interactions are sometimes attractive and sometimes repulsive. In addition, the experiment you performed in Checkpoint 22.3 demonstrates that paper strips, which do not interact electrically with each other, do interact electrically with transparent tape. What causes these interactions? To answer this question, we need to carry out a systematic sequence of experiments.

**Figure 22.3** illustrates a simple procedure for reproducibly creating strips of tape that interact electrically. A suspended strip created according to this procedure interacts in the following ways: It repels another strip created in the same manner, and it attracts any other object that does not itself interact electrically with other objects (**Figure 22.4**).

**Figure 22.3** Procedure for making strips of transparent tape that interact electrically. The purpose of the foundation strip is simply to provide a standard surface.

- 1 On flat surface, stick down tape strip as foundation; flatten with thumb.
- 2 Fold end of second strip to make handle, smooth onto foundation strip.
- 3 Pull second strip off in one quick motion.
- 4 Holding both ends of strip to prevent curling, hang strip on table edge.



CONCEPTS

PRACTICE OF  
ICS



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1 architecture

2 content

3 results

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Perusall Unit 6 22.2 ELECTRICAL CHARGE 595

**Figure 22.2** Strips of tape just pulled out of a dispenser repel each other. The repulsive force is great enough to keep the strips apart even when they are weighted down by paper clips.



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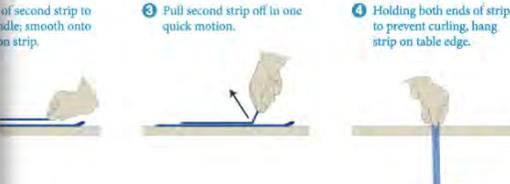
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\*If rubbing your fingers along the tape doesn't do the job, try licking them before rubbing them over the tape.

CONCEPTS

1. Pull second strip off in one quick motion.

2. Holding both ends of strip to prevent curling, hang strip on table edge.



Enter your comment or question and press Enter

PRACTICE OF  
ICS



1 architecture

2 content

3 results

# AP50: no lectures, students read book only

The screenshot shows a Perusall page for '22.2 ELECTRICAL CHARGE' on page 595. It features two figures: Figure 22.2 shows two strips of tape repelling each other, and Figure 22.4 shows a strip of tape being attracted to a hand. The text explains electrical charge and charge carriers. A comment thread on the left discusses the attraction of a neutral object to a charged one. The page includes a 'CONCEPTS' sidebar and a 'PRACTICE OF PHYSICS' header.

PRACTICE OF  
PHYSICS

- Quality
- Quantity
- Timeliness

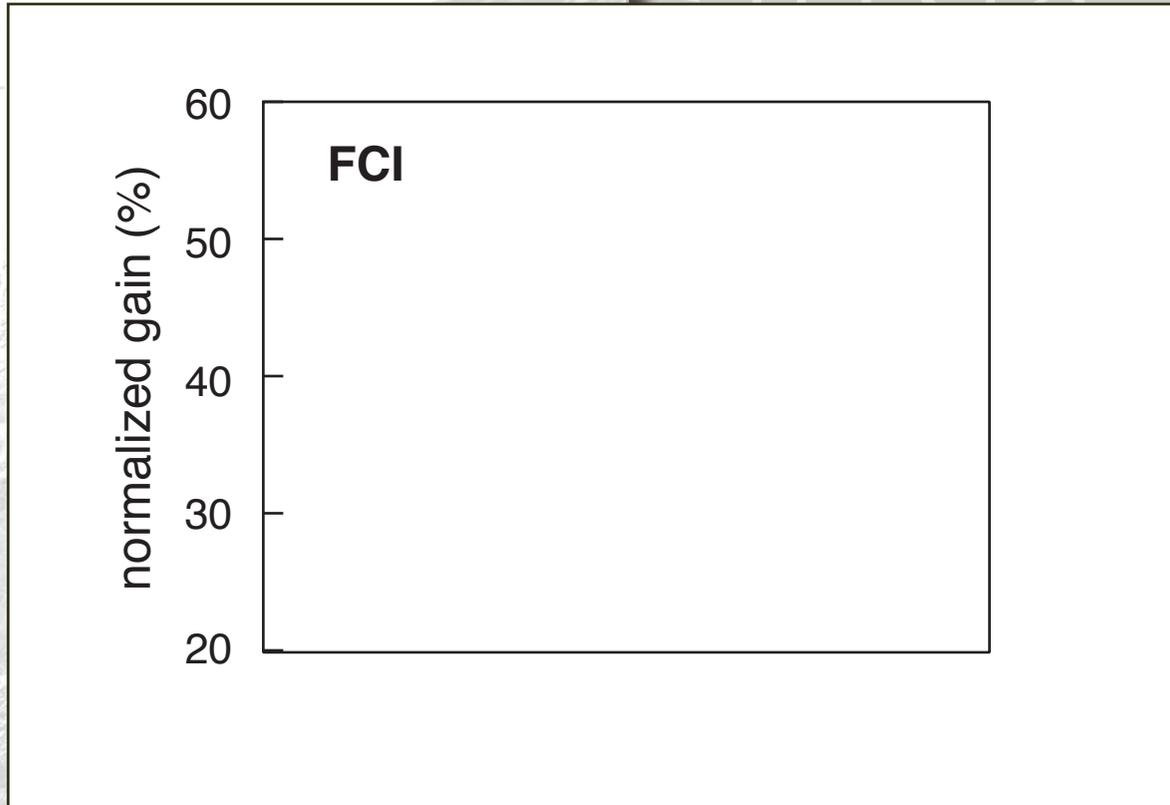
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Perusall.com

1 architecture

2 content

3 results

# AP50: no lectures, students read book only

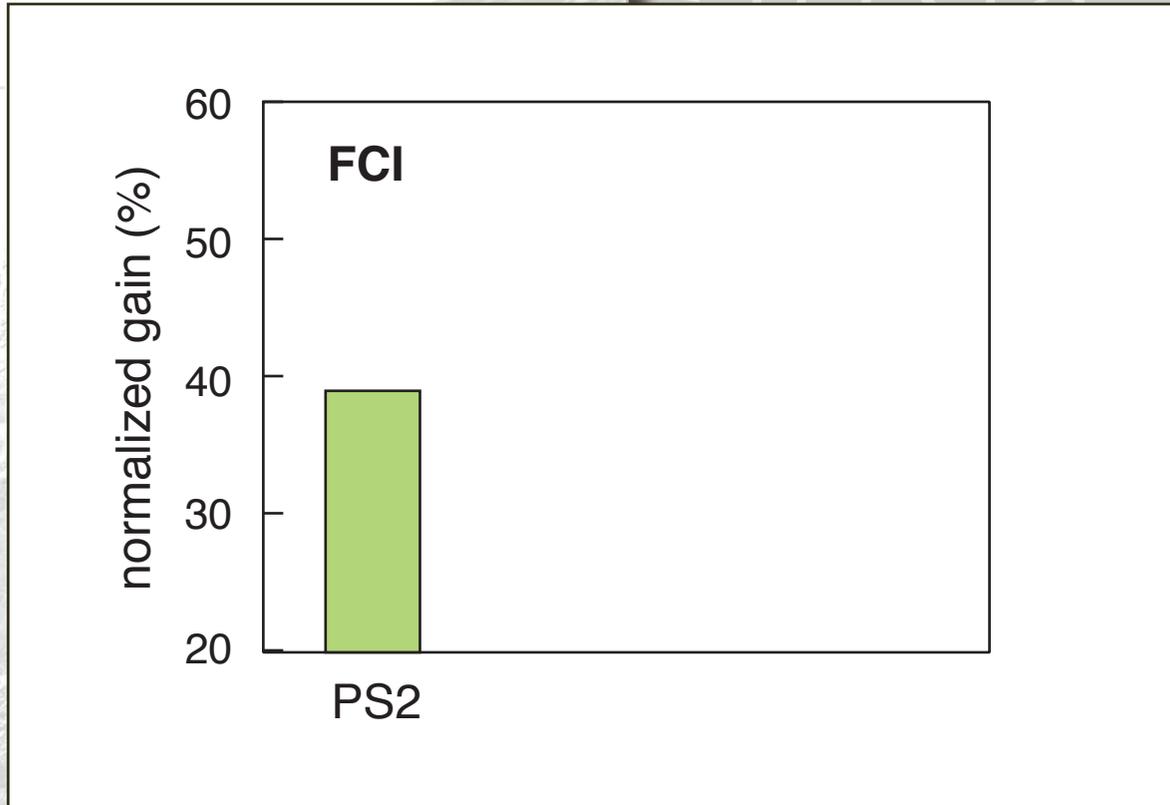


1 architecture

2 content

3 results

# AP50: no lectures, students read book only

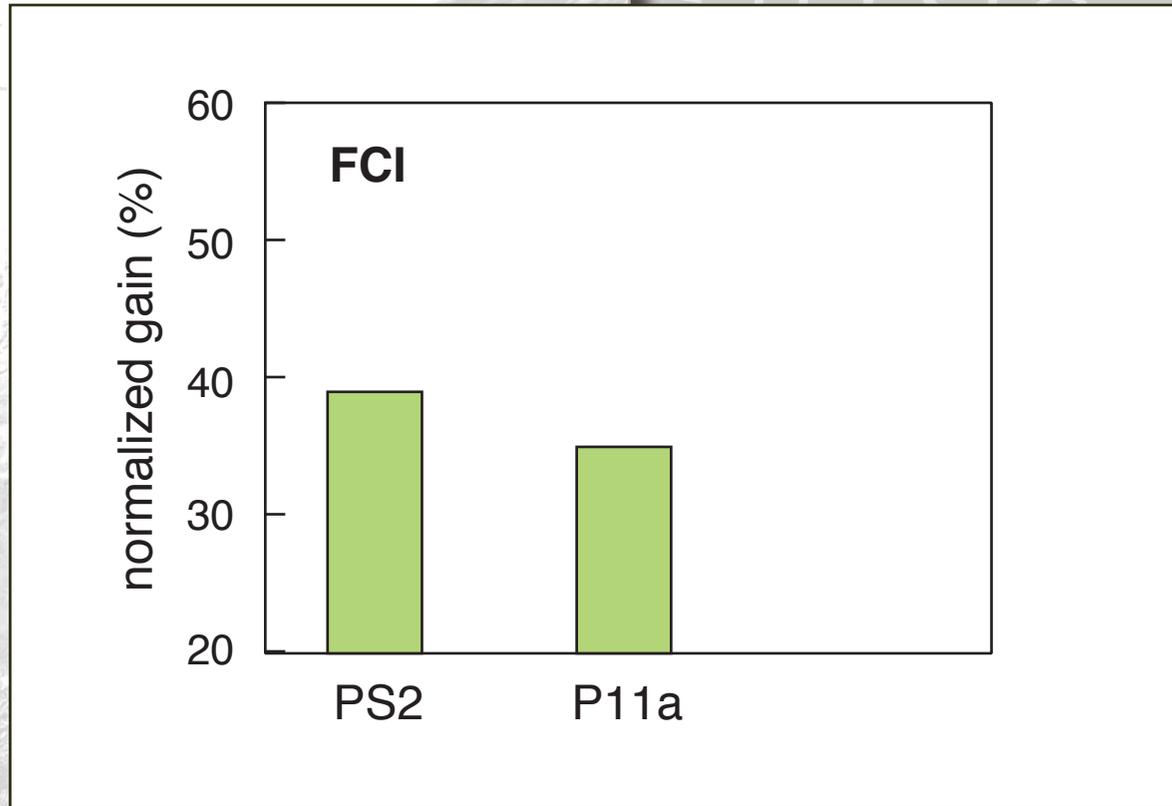


1 architecture

2 content

3 results

# AP50: no lectures, students read book only

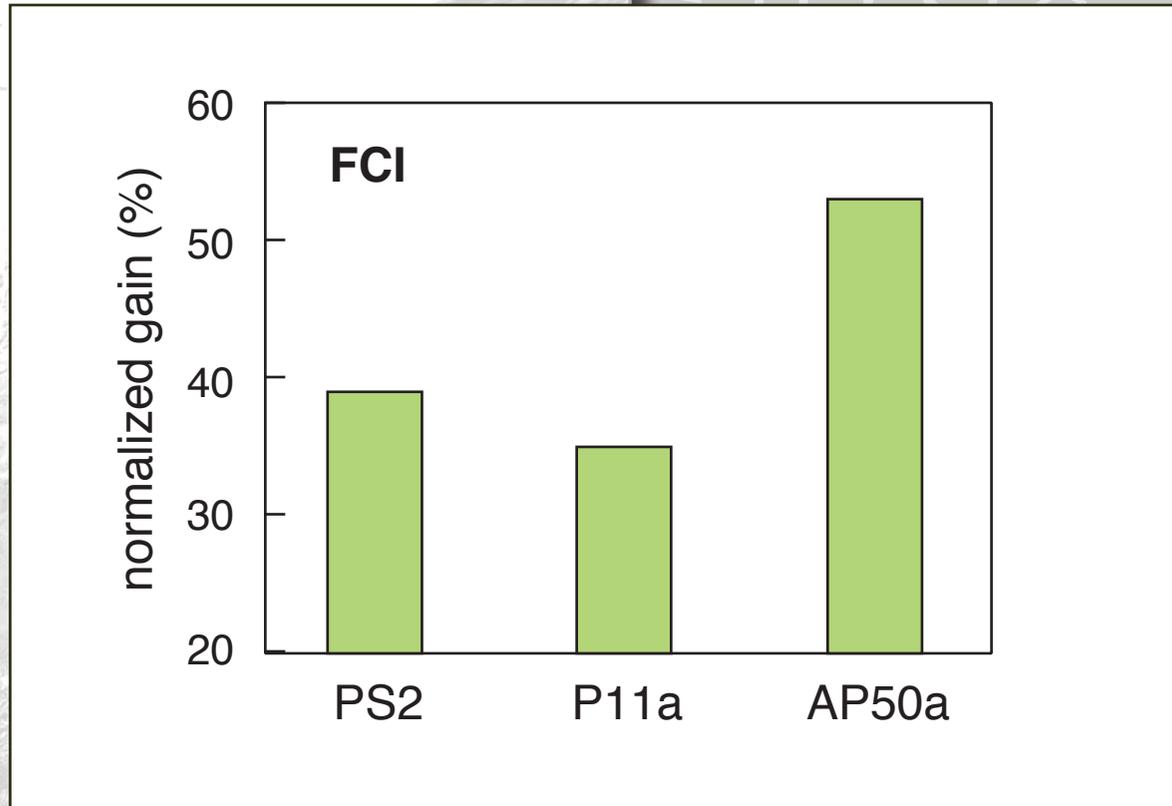


1 architecture

2 content

3 results

# AP50: no lectures, students read book only

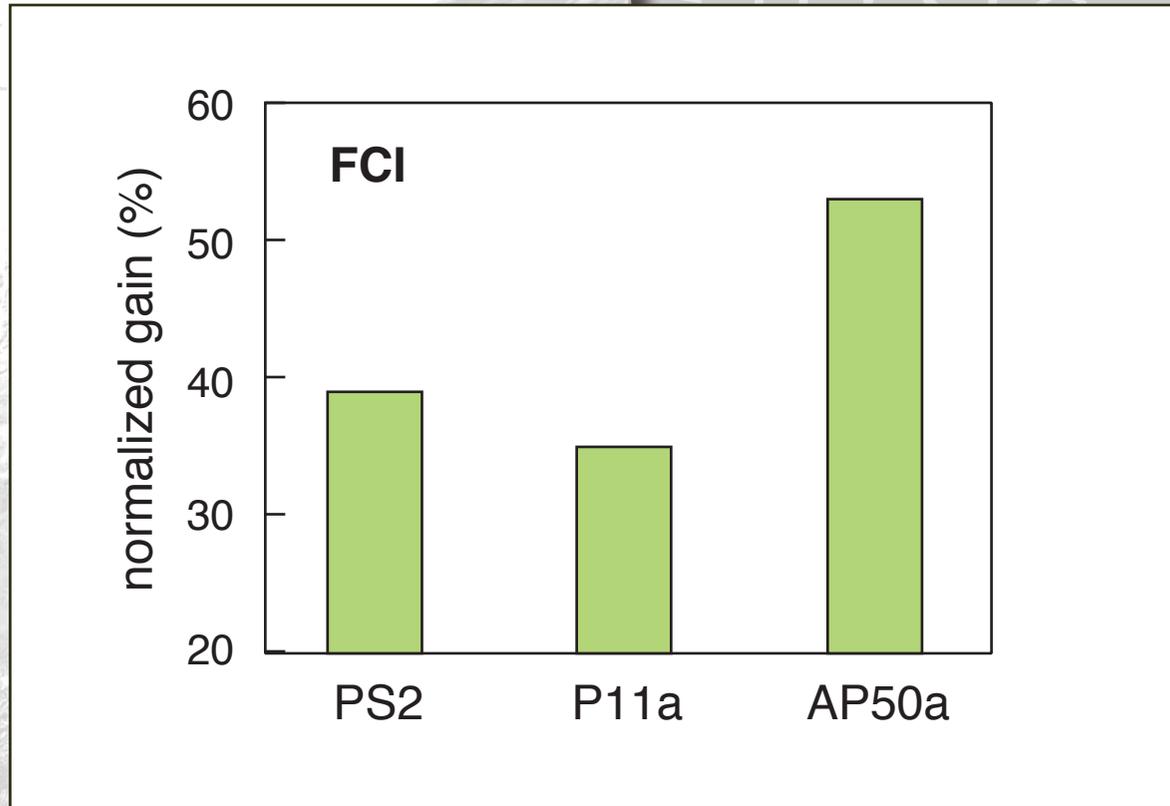


1 architecture

2 content

3 results

# AP50: no lectures, students read book only



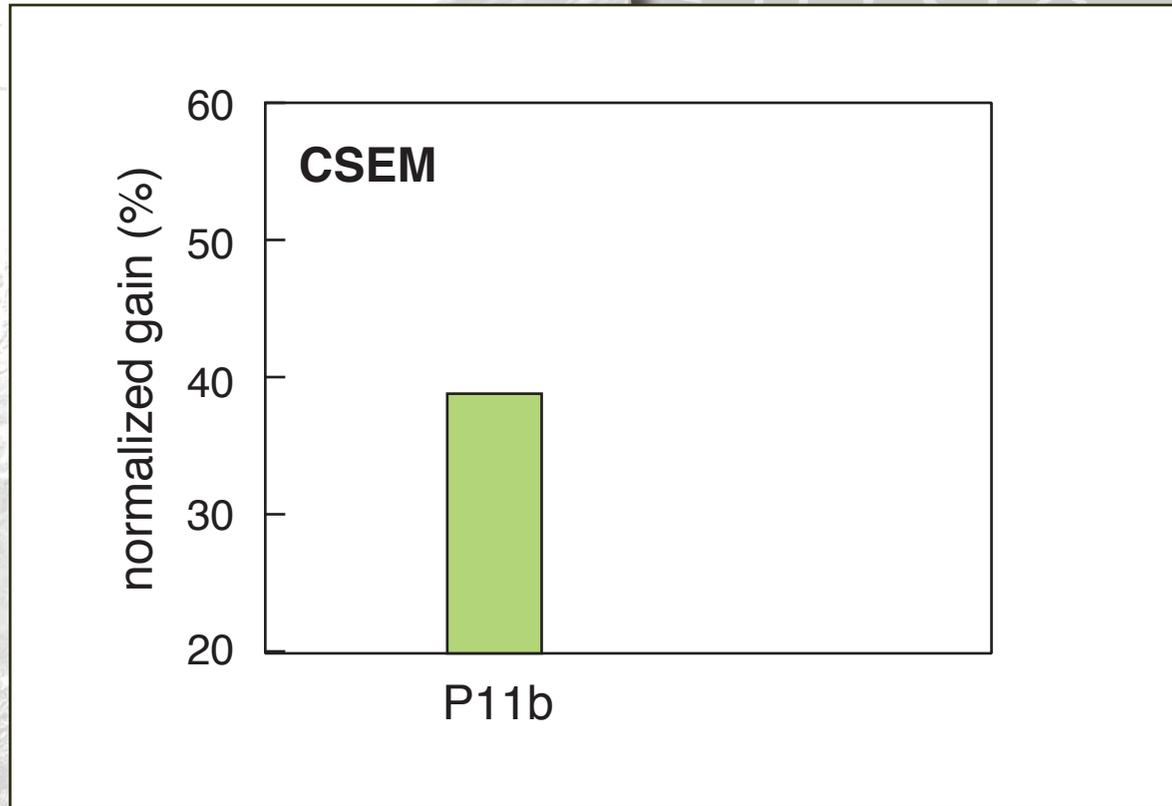
largest conceptual gain in *any* course past 6 yrs!

1 architecture

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3 results

# AP50: no lectures, students read book only

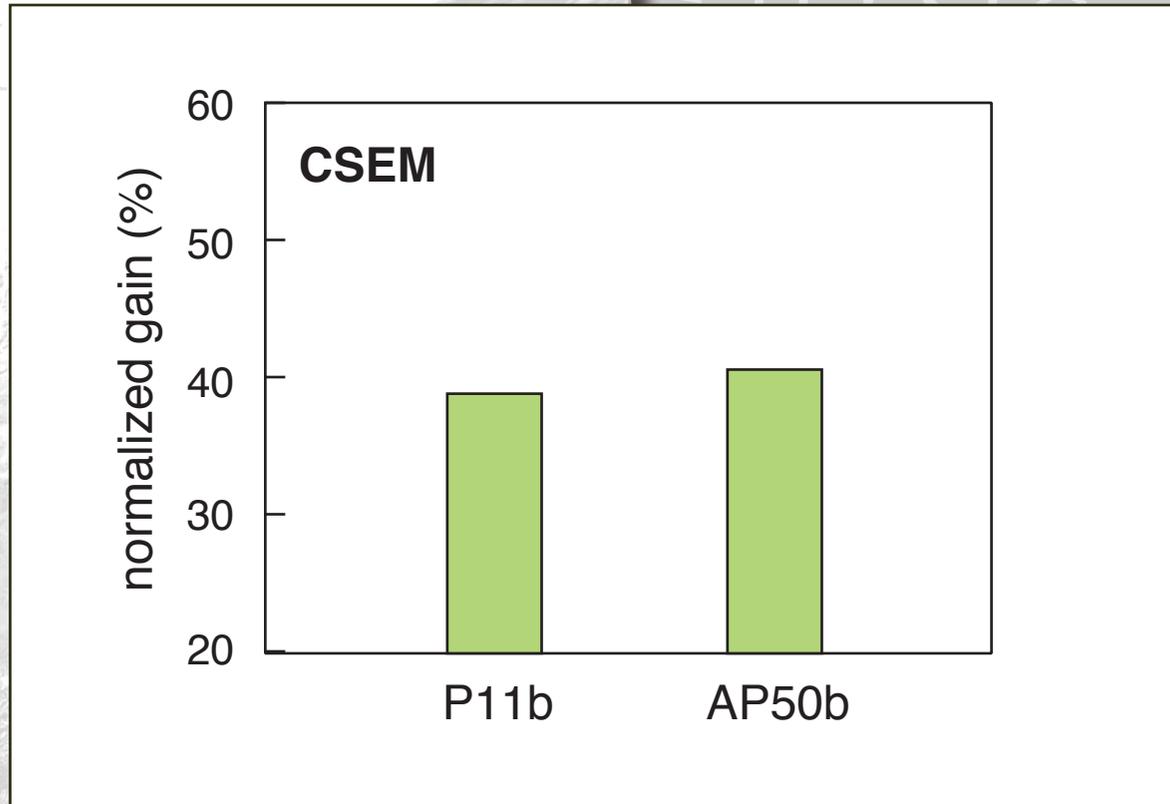


1 architecture

2 content

3 results

# AP50: no lectures, students read book only



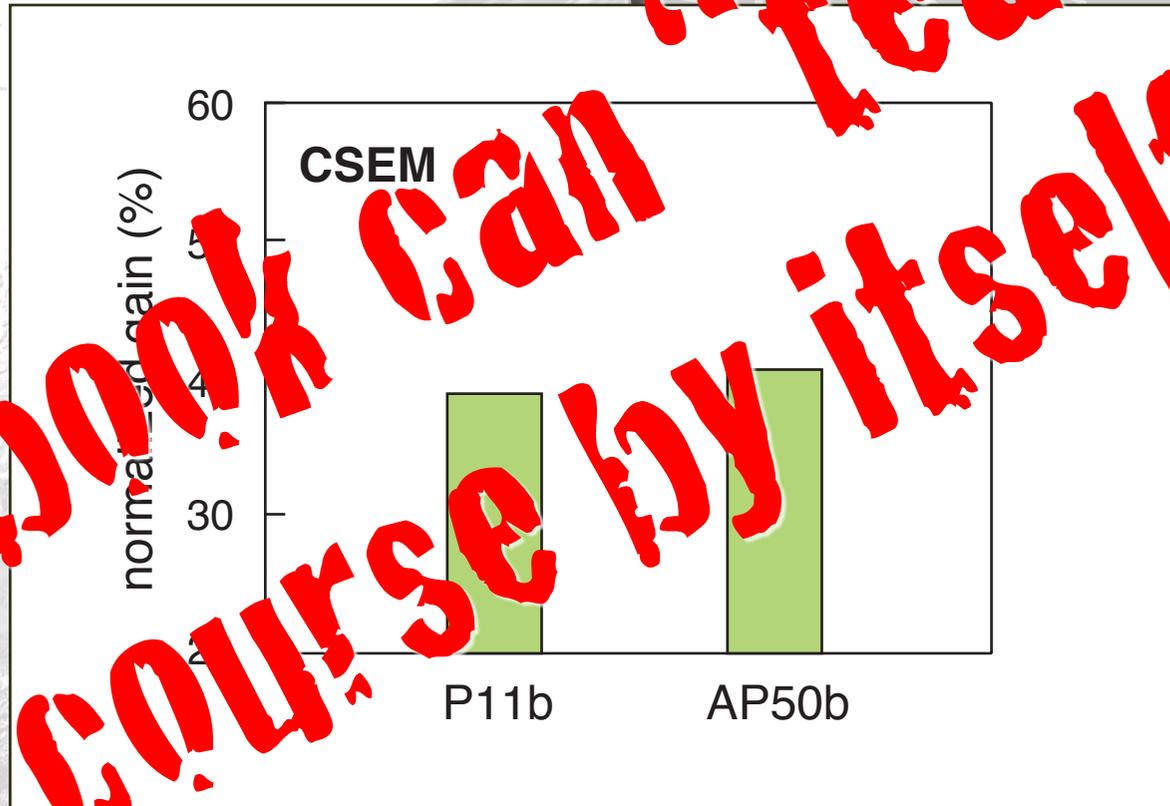
as good as when I do my best teaching!

1 architecture

2 content

3 results

AP50: no lectures, students read book only



as good as when I do my best teaching!

1 architecture

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3 results

# University of Arkansas

PRINCIPLES & PRACTICE OF  
PHYSICS

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PHYSICS

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**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**

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**1** architecture

**2** content

**3** results

# Current Adoptions

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

Spokane Falls Community College  
St Olaf College  
Suffolk University  
University of Arkansas  
University of Central Florida  
University of Florida  
University of Connecticut–Storrs  
University of Maine at Orono  
University of Minnesota  
University of Pennsylvania  
University of Washington  
Victoria College  
Virginia Tech University  
Washington University  
Williams College  
  
John Abbott College (Canada)  
Helsinki University (Finland)  
McMaster University (Canada)  
Monash University (Australia)  
Mount Saint Vincent University (Canada)  
University of British Columbia (Canada)  
University of Toronto (Canada)  
University of Waterloo (Canada, 2016)

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**approach**

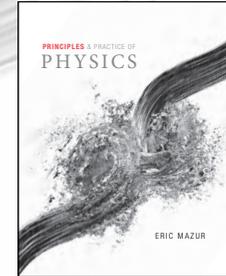
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**before class**

**in class**

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**traditional**



**1 architecture**

**2 content**

**3 results**

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approach

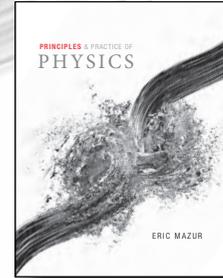
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before class

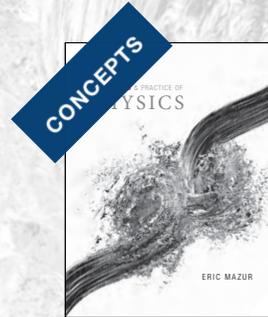
in class

---

traditional



partially flipped



1 architecture

2 content

3 results

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approach

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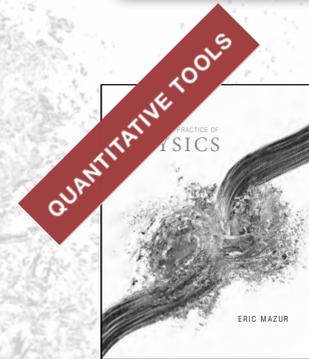
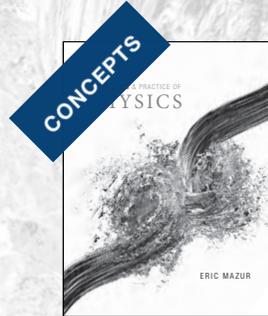
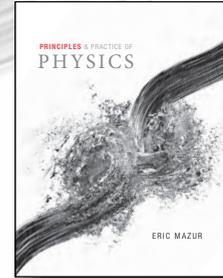
before class

in class

---

traditional

partially flipped



1 architecture

2 content

3 results

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approach

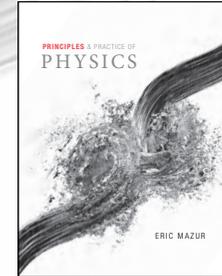
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before class

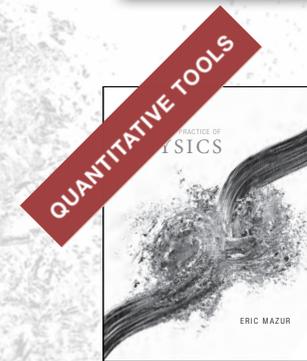
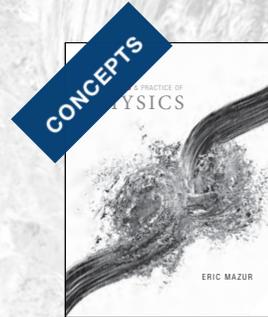
in class

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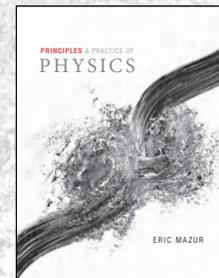
traditional



partially flipped



fully flipped



**1** architecture

**2** content

**3** results

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approach

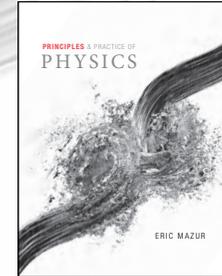
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before class

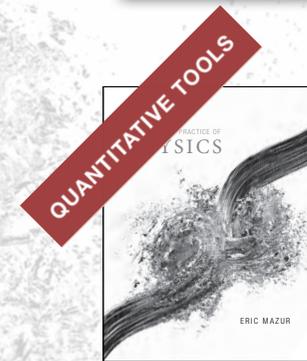
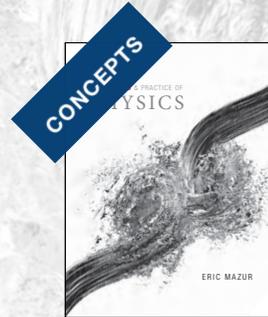
in class

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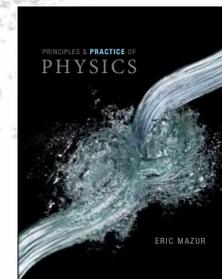
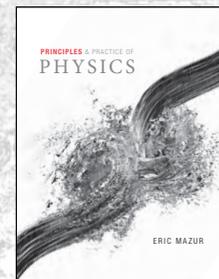
traditional



partially flipped



fully flipped



1 architecture

2 content

3 results



physics can be fun!



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