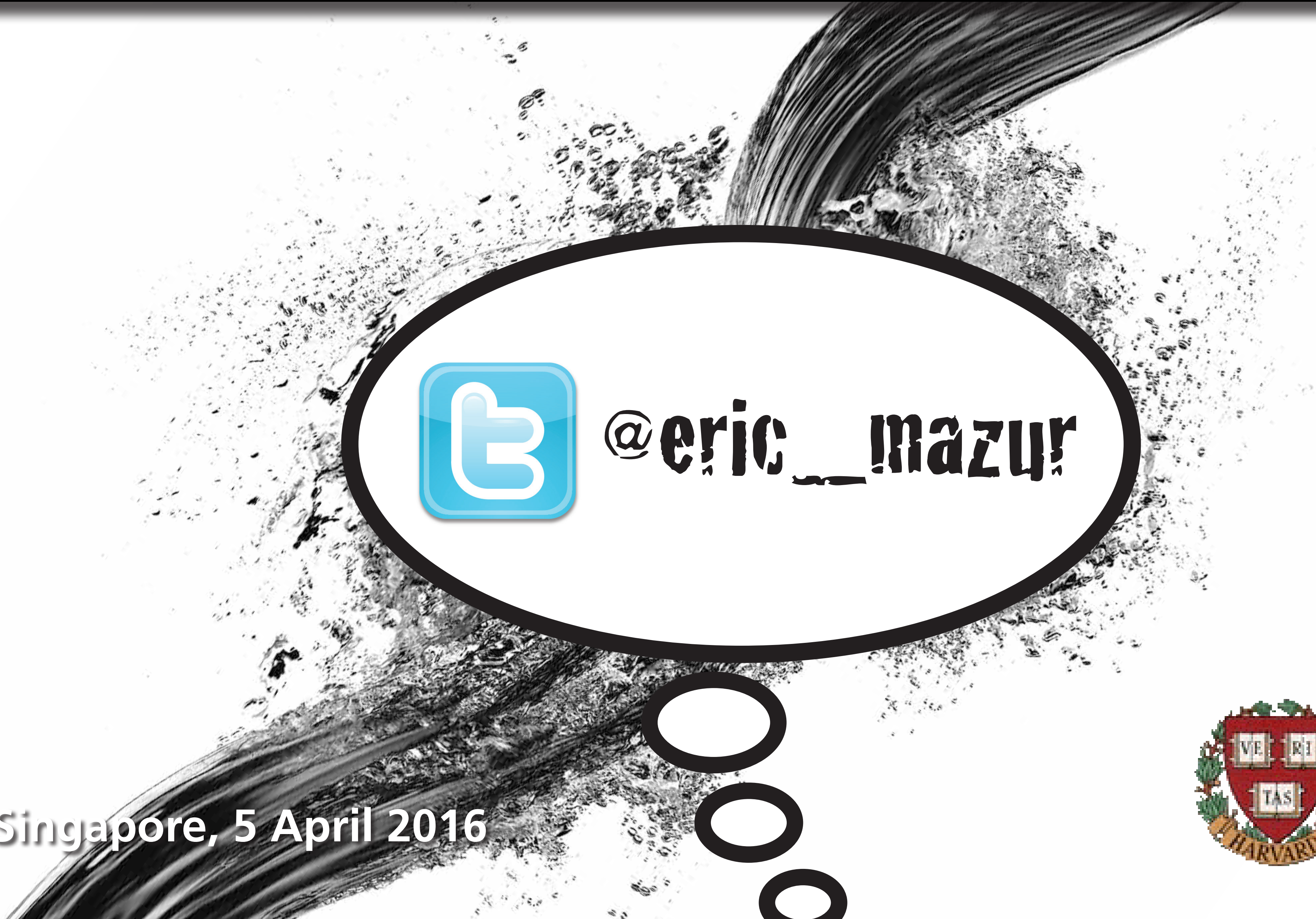
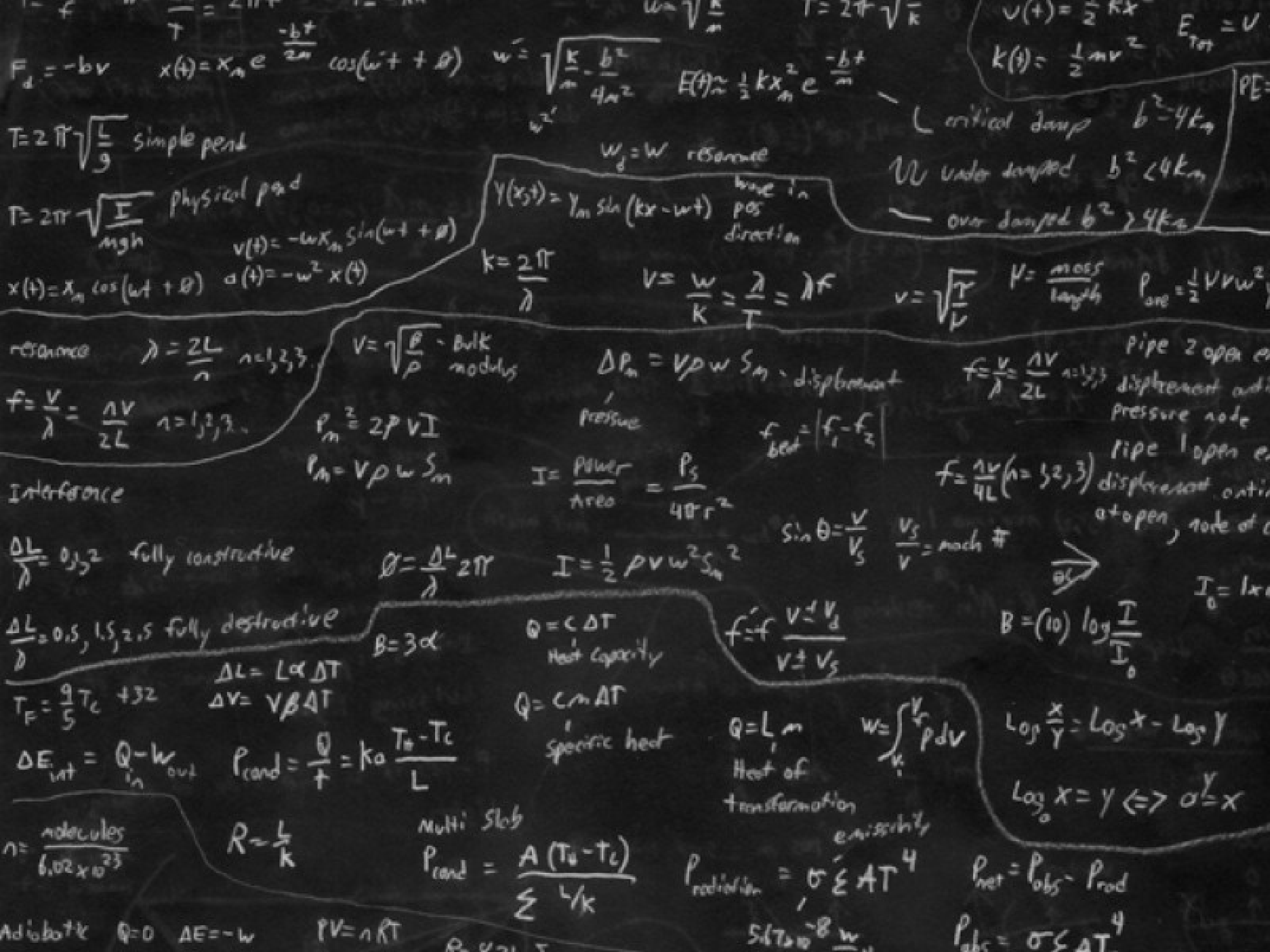
Teaching Physics, Conservation Laws First

Singapore, 5 April 2016

Teaching Physics, Conservation Laws First



Singapore, 5 April 2016



F_d = -bv
T=2π √(L/g) simple pend
T= 2π √(I/mgh) physical pend
x(t)=x_m cos(wt + ø)
v(t)= -wx_m sin(wt + ø)
a(t)= -w² x(t)
critical damp b²=4km
under damped b² <4km
over damped b² > 4km
w_d=w resonance
y(x,t) = y_m sin(kx - wt)
wave in pos direction
k= 2π/λ
v= w/k = λ/T = λf
v= √(τ/μ)
μ= mass/length
resonance
λ = 2L/n n=1,2,3
f= v/λ = nv/2L n=1,2,3
v= √(B/ρ) Bulk modulus
ΔP_m = vρw s_m
displacement
pressure
f_beat = |f_1-f_2|
pipe 2 open e
displacement anti
pressure node
pipe 1 open e
f= nv/4L (n=1,3,5)
Interference
ΔL/λ = 0,1,2 fully constructive
ΔL/λ = 0.5, 1.5, 2.5 fully destructive
ø= ΔL/λ 2π
I= power/Area = P_s/4πr²
I = ½ ρvw²s_m²
sin θ= v/v_s
v_s/v = mach #
B =(10) log I/I_0
Q=C ΔT
Heat capacity
B=3α
ΔL= Lα ΔT
ΔV= VβΔT
T_F = 9/5 T_C +32
Q= cmΔT
specific heat
Q=L m
Heat of transformation
W= ∫ pdV
Log x/y = Log x - Log y
Log_a x= y <=> a^y=x
ΔE_int = Q_in - W_out
P_cond = Q/t = kA (T_H - T_C)/L
Multi Slab
P_cond = A(T_H-T_C)/Σ L/k
R= L/k
n= molecules/6.02x10^23
emissivity
P_radiation = σεAT⁴
P_net = P_abs - P_rad
P_abs = σεAT⁴
Adiabatic Q=0 ΔE=-W
PV=nRT

vectors

vectors

Math, not Physics?!

kinematics

vectors

kinematics

vectors

Calculus…

kinematics

vectors

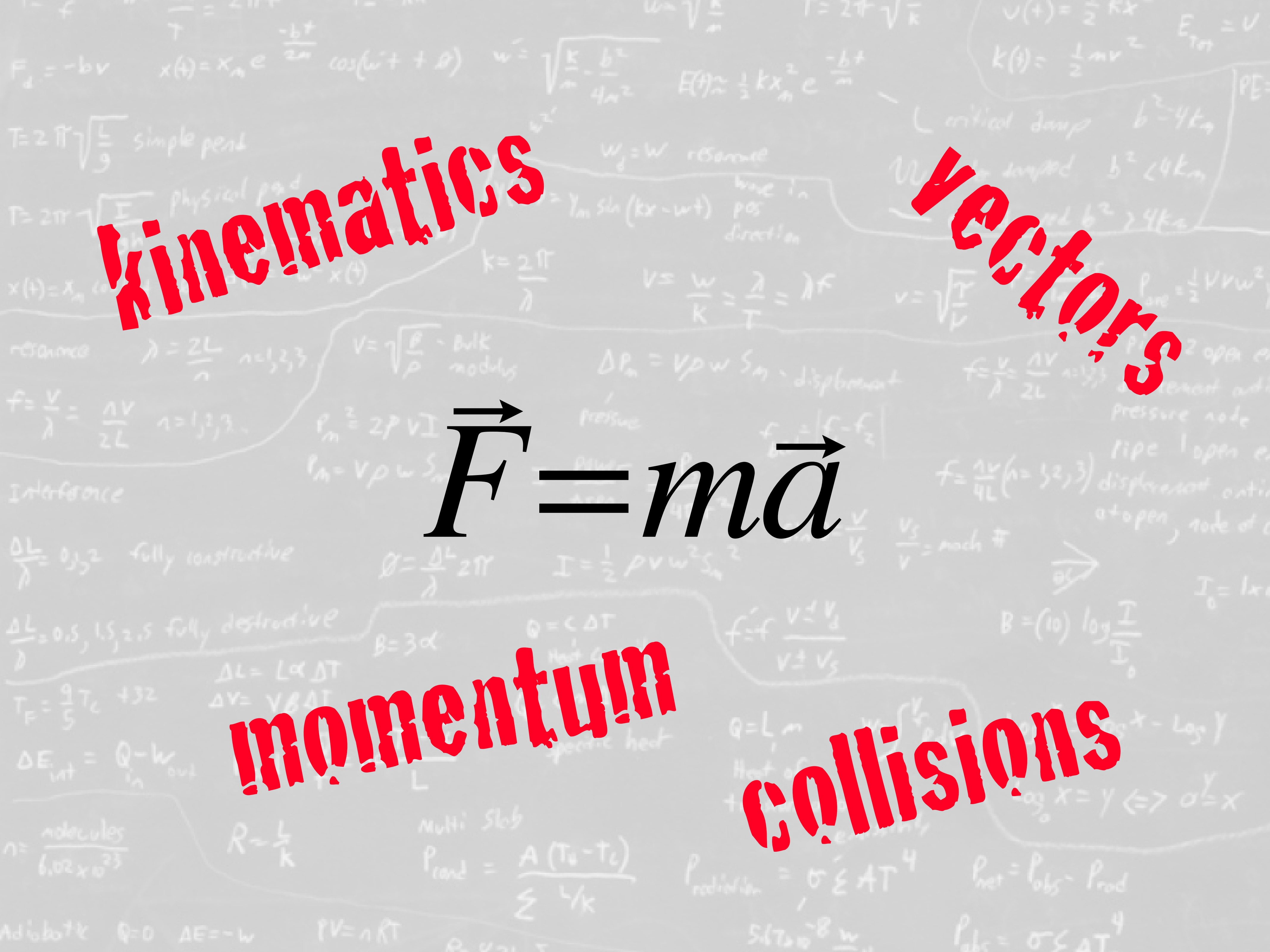
$$\vec{F}=m\vec{a}$$

kinematics

vectors

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

momentum


kinematics
vectors
$\vec{F} = m\vec{a}$
momentum
collisions

kinematics

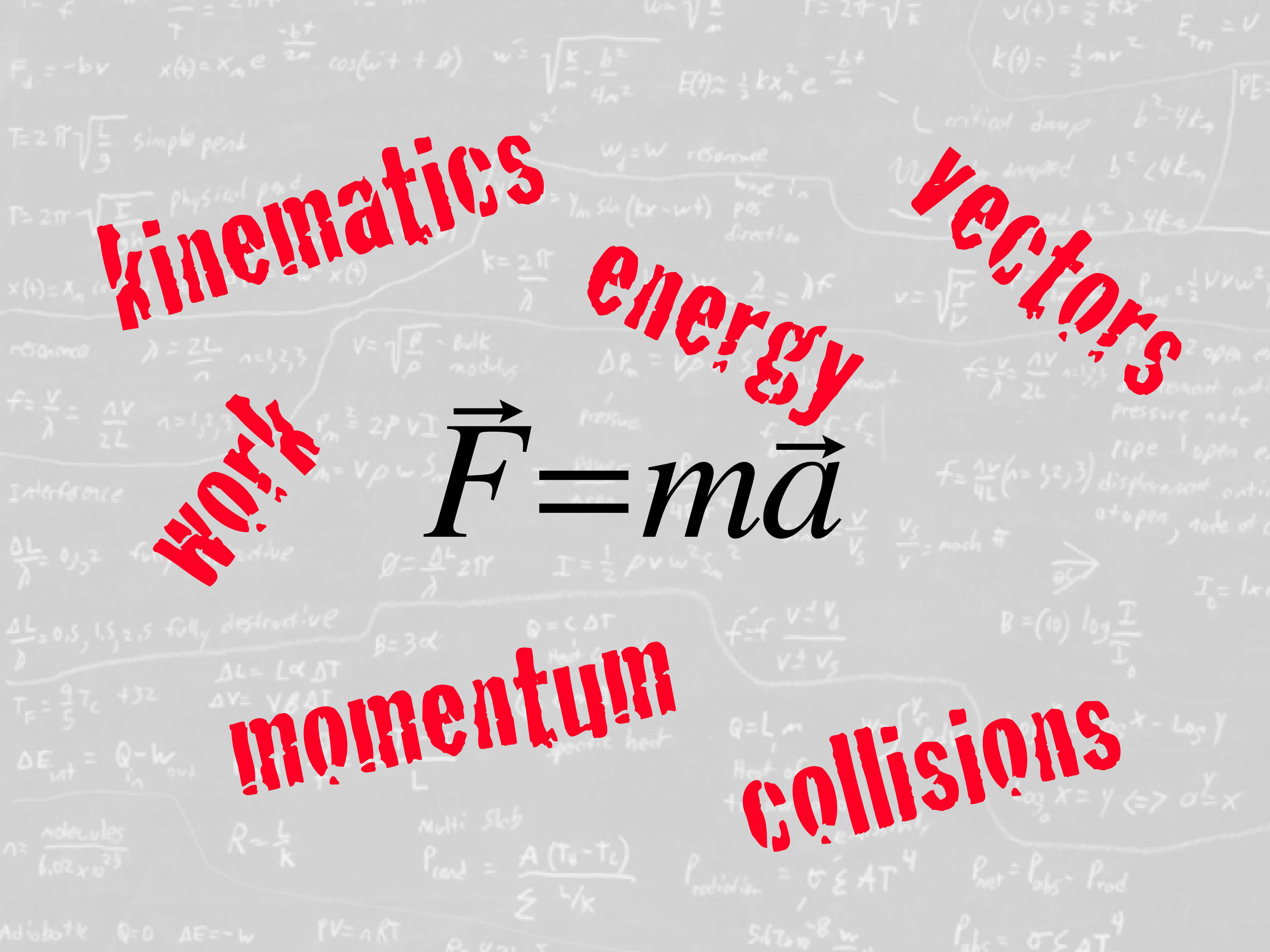
vectors

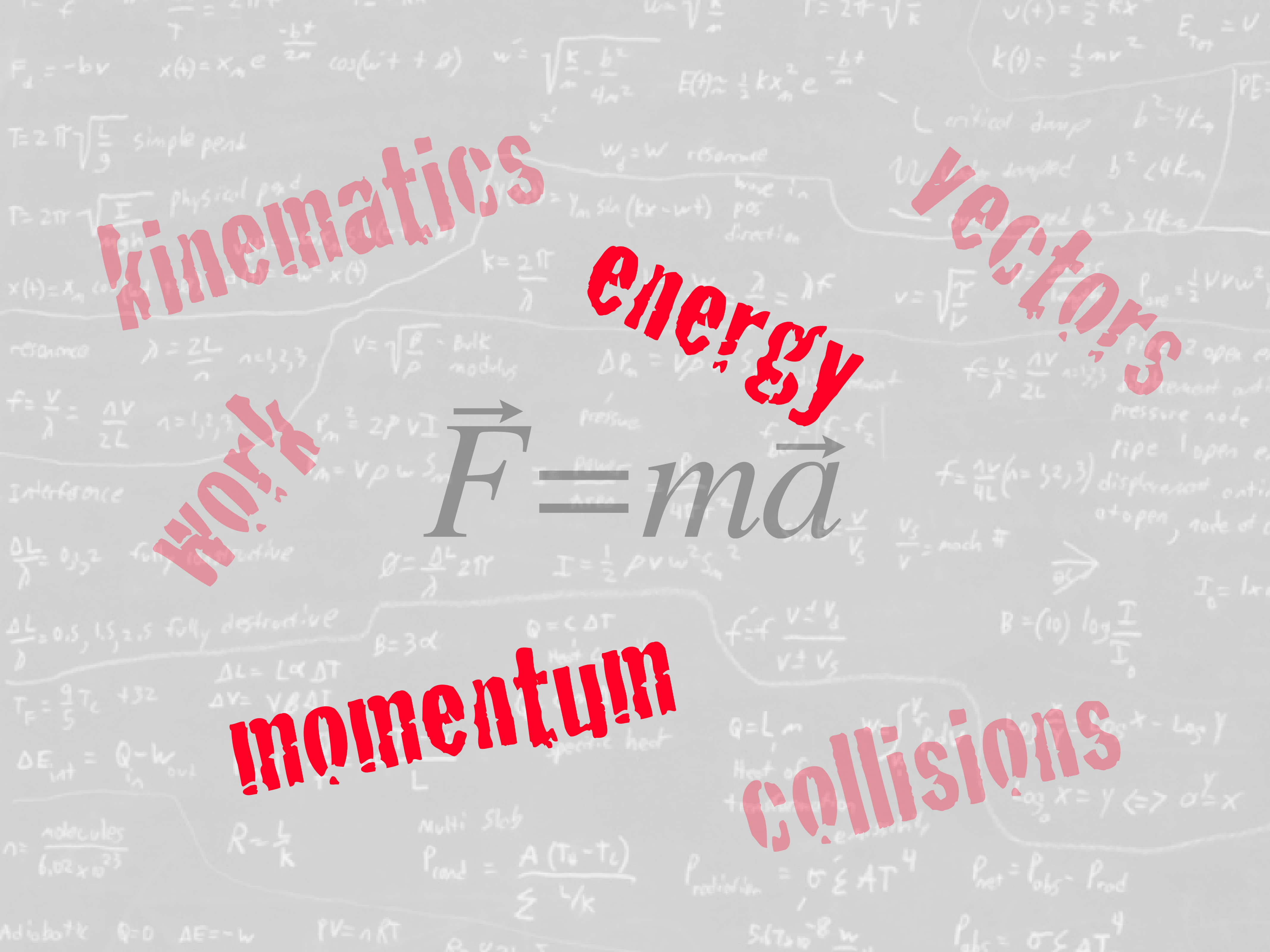
work

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

momentum

collisions


kinematics
energy
vectors
work
$\vec{F} = m\vec{a}$
momentum
collisions


kinematics
energy
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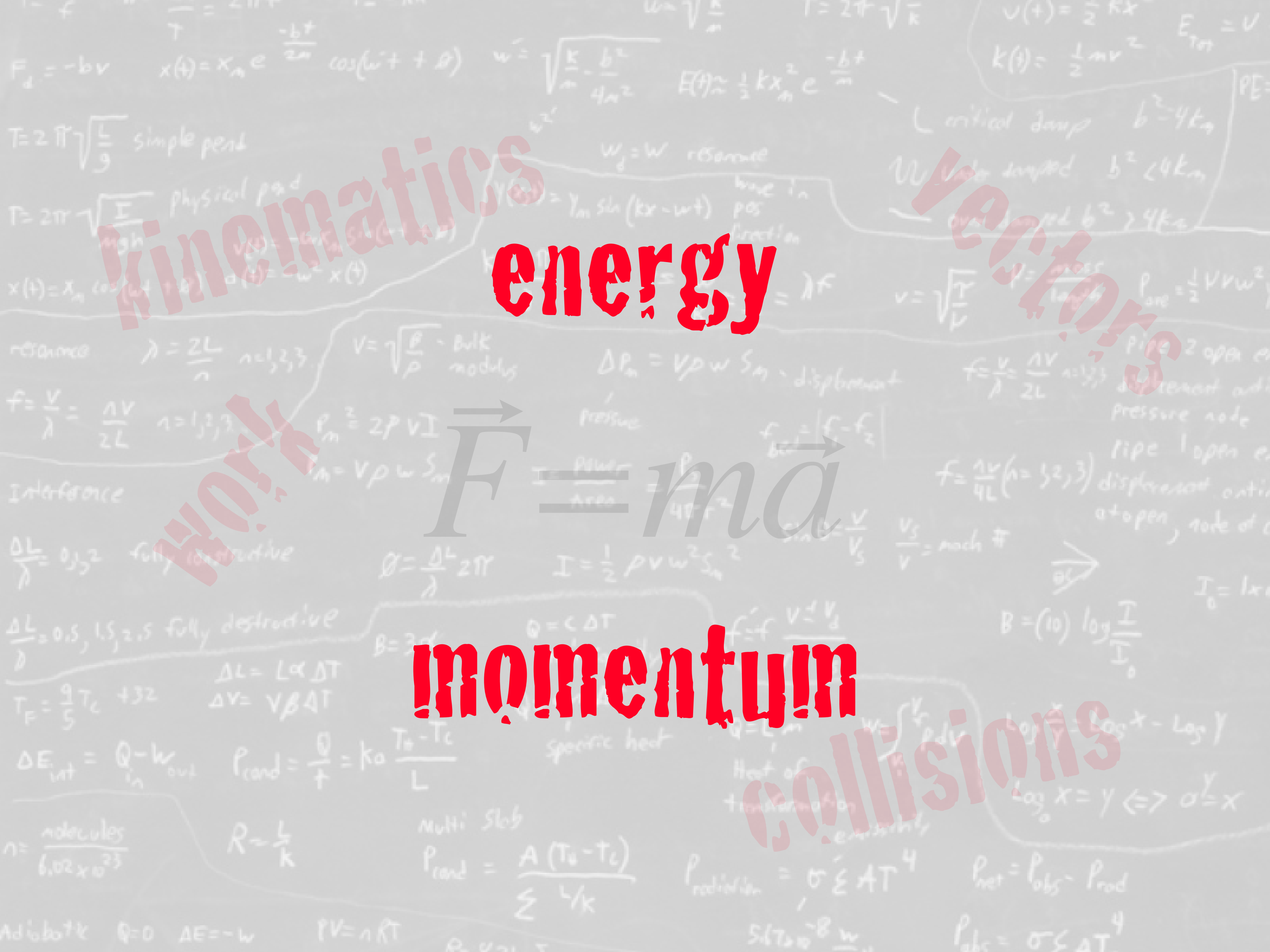
work
$\vec{F}=m\vec{a}$
momentum
collisions


kinematics
vectors
energy
work
$\vec{F} = m\vec{a}$
momentum
collisions

conservation of energy

kinematics

vectors

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

work

conservation of momentum

collisions

conservation of energy

Just algebra!

conservation of momentum

kinematics

vectors

conservation of energy

work

Why not START the easy way?

conservation of momentum

collisions

The historical approach

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

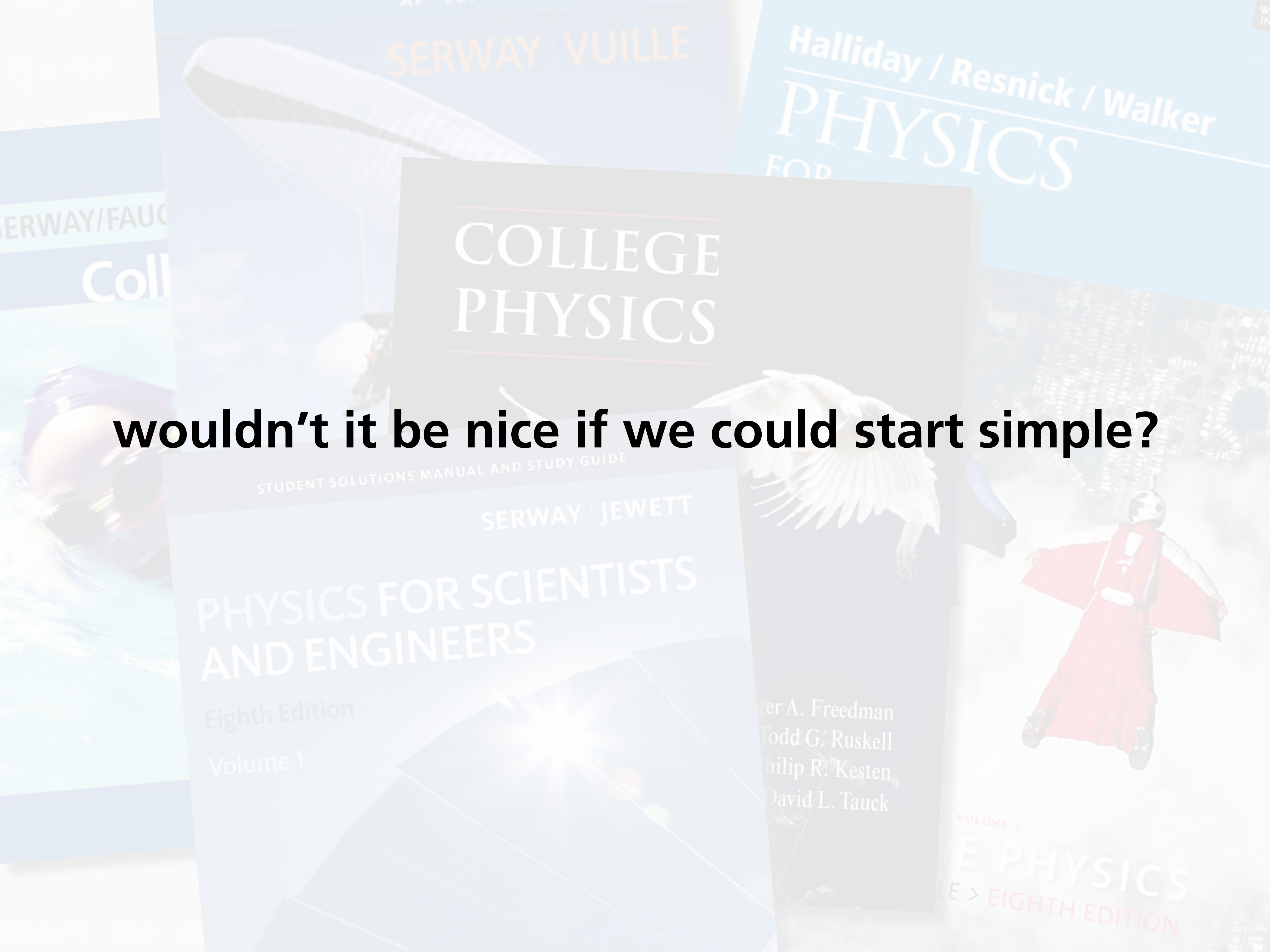
Ernst Mach (1838–1916)

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

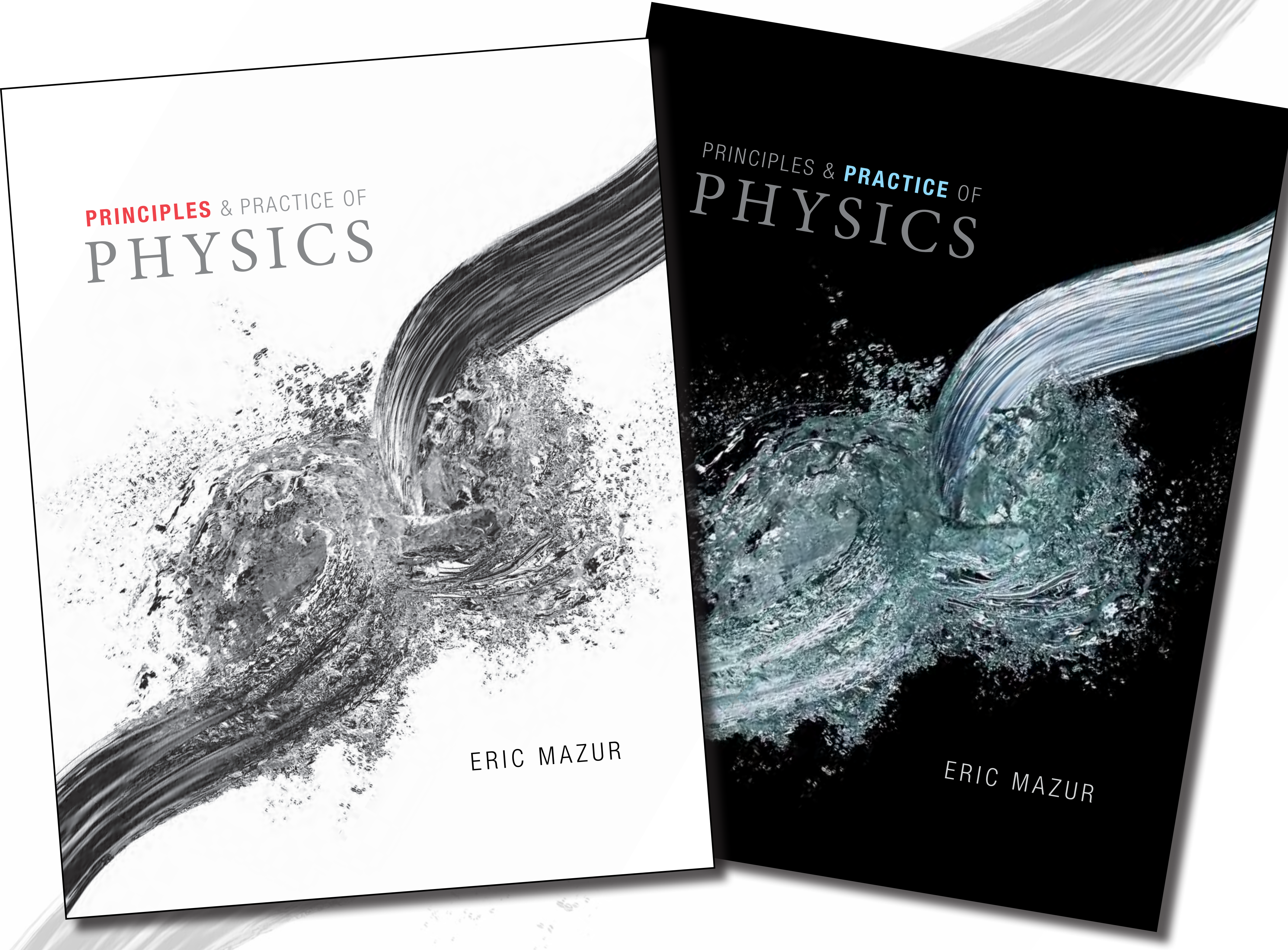
Ernst Mach (1838–1916)

- 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?



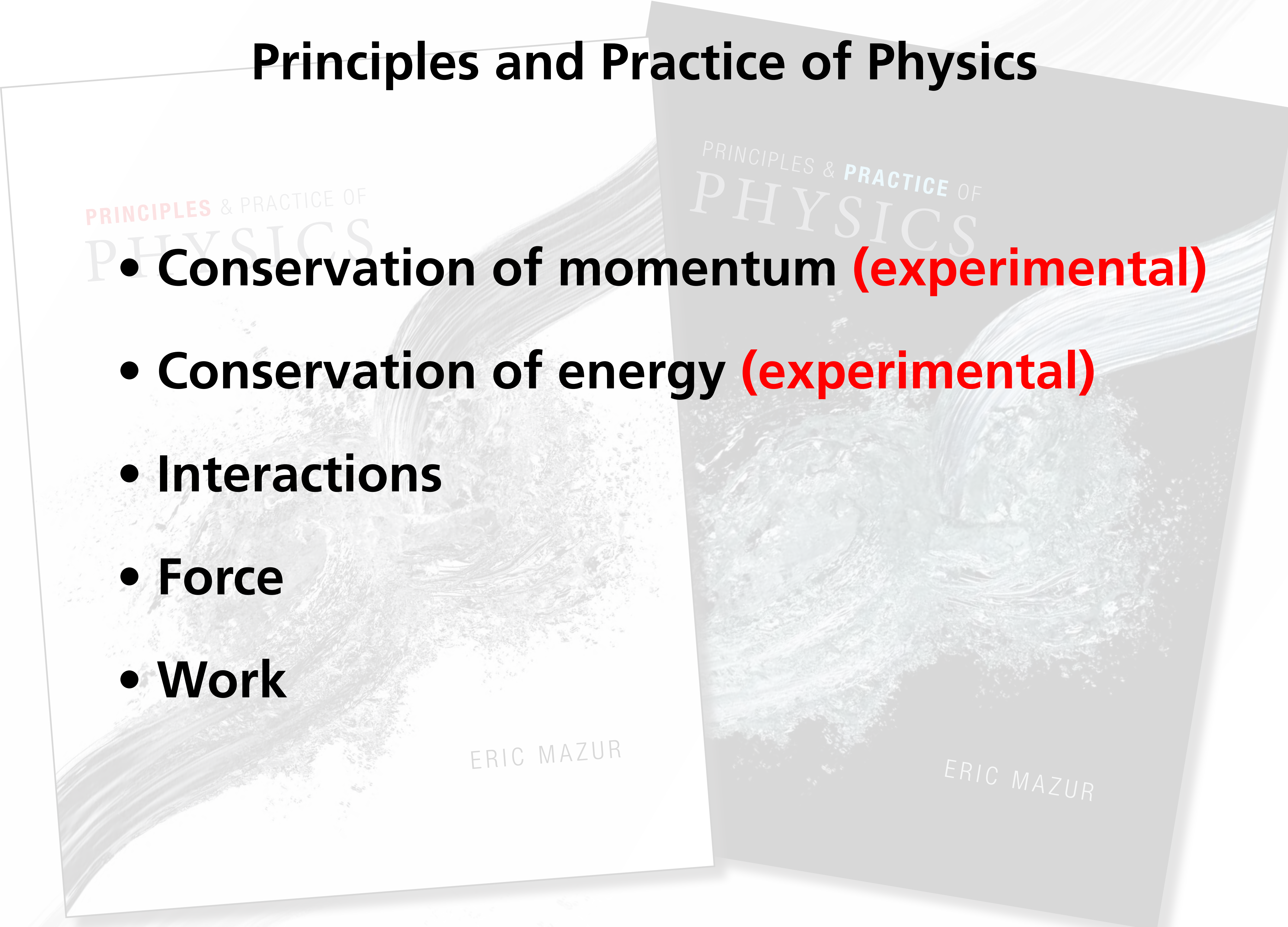

we can!


PRINCIPLES & PRACTICE OF
PHYSICS
ERIC MAZUR
PRINCIPLES & PRACTICE OF
PHYSICS
ERIC MAZUR

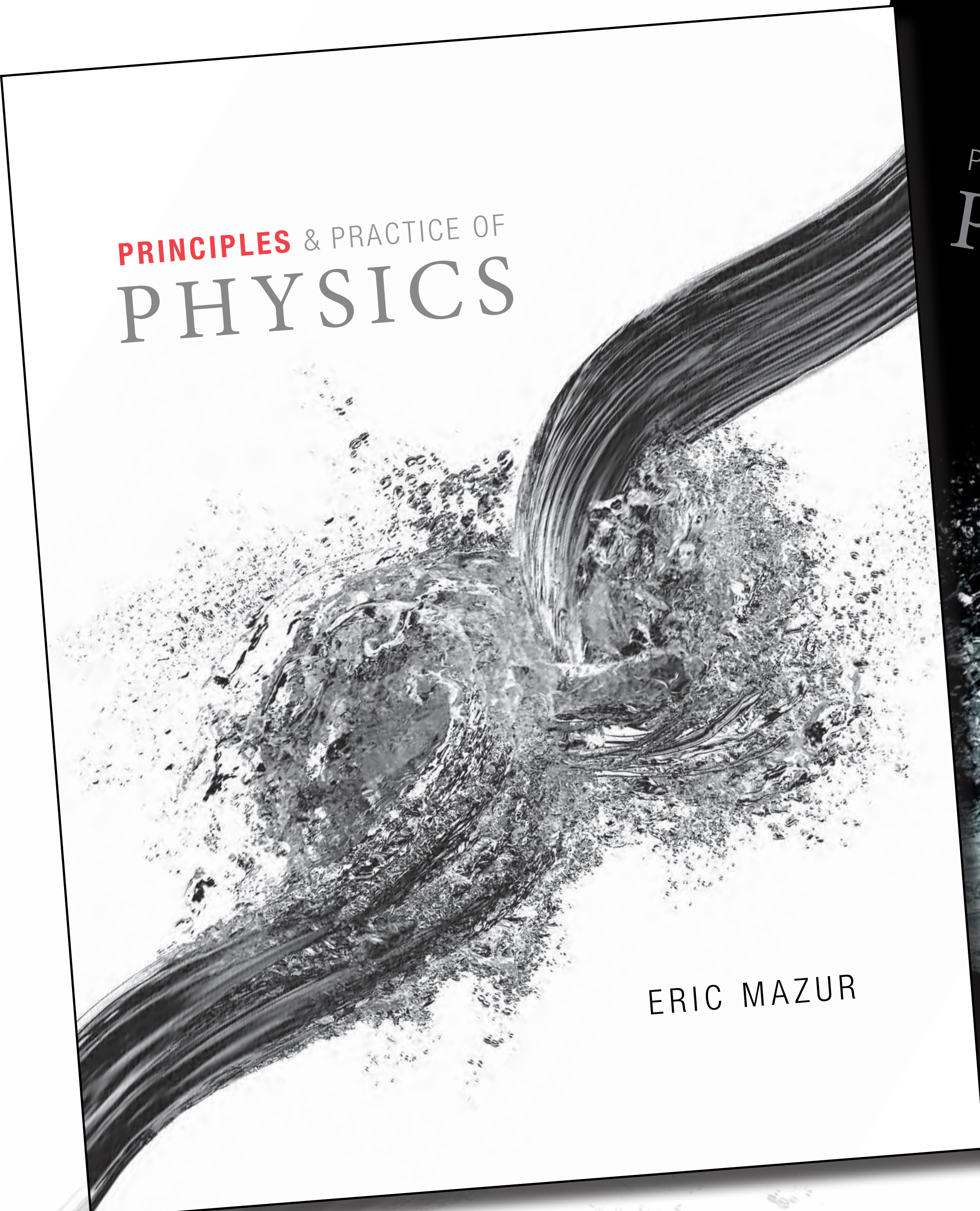
Principles and Practice of Physics

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

Principles and Practice of Physics



- **Conservation of momentum** **(experimental)**
- **Conservation of energy** **(experimental)**
- **Interactions**
- **Force**
- **Work**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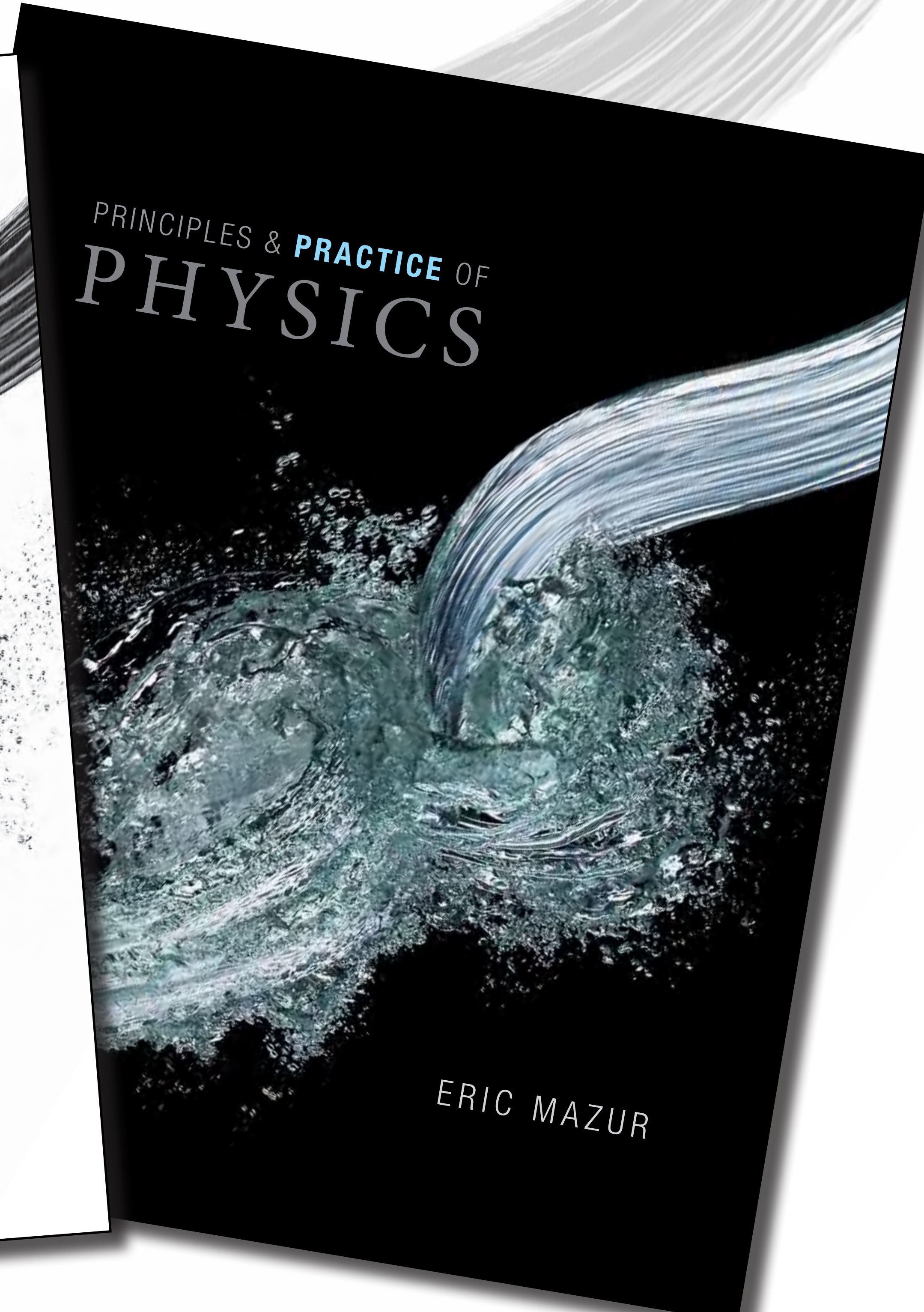
PRINCIPLES & PRACTICE OF
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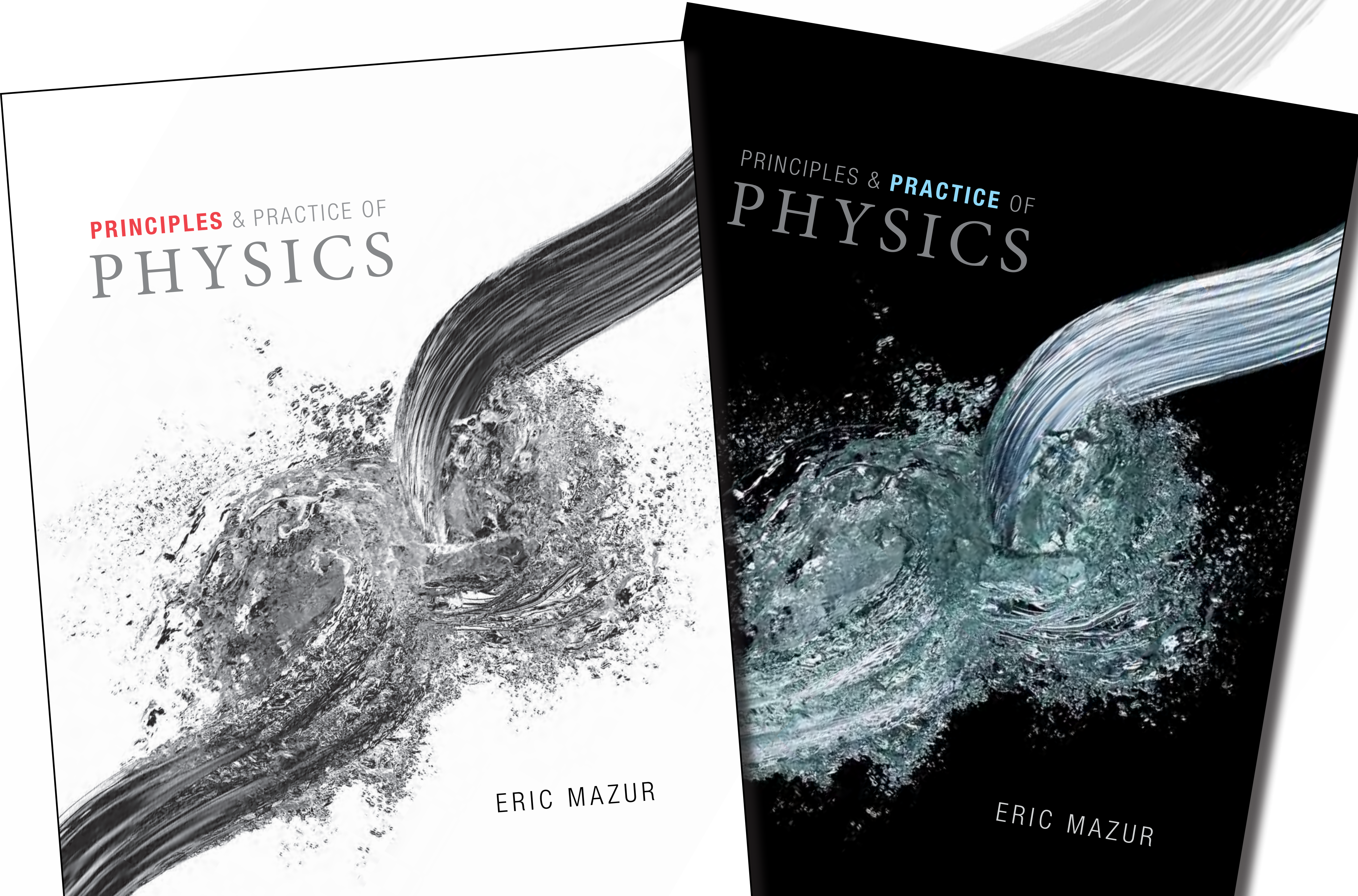
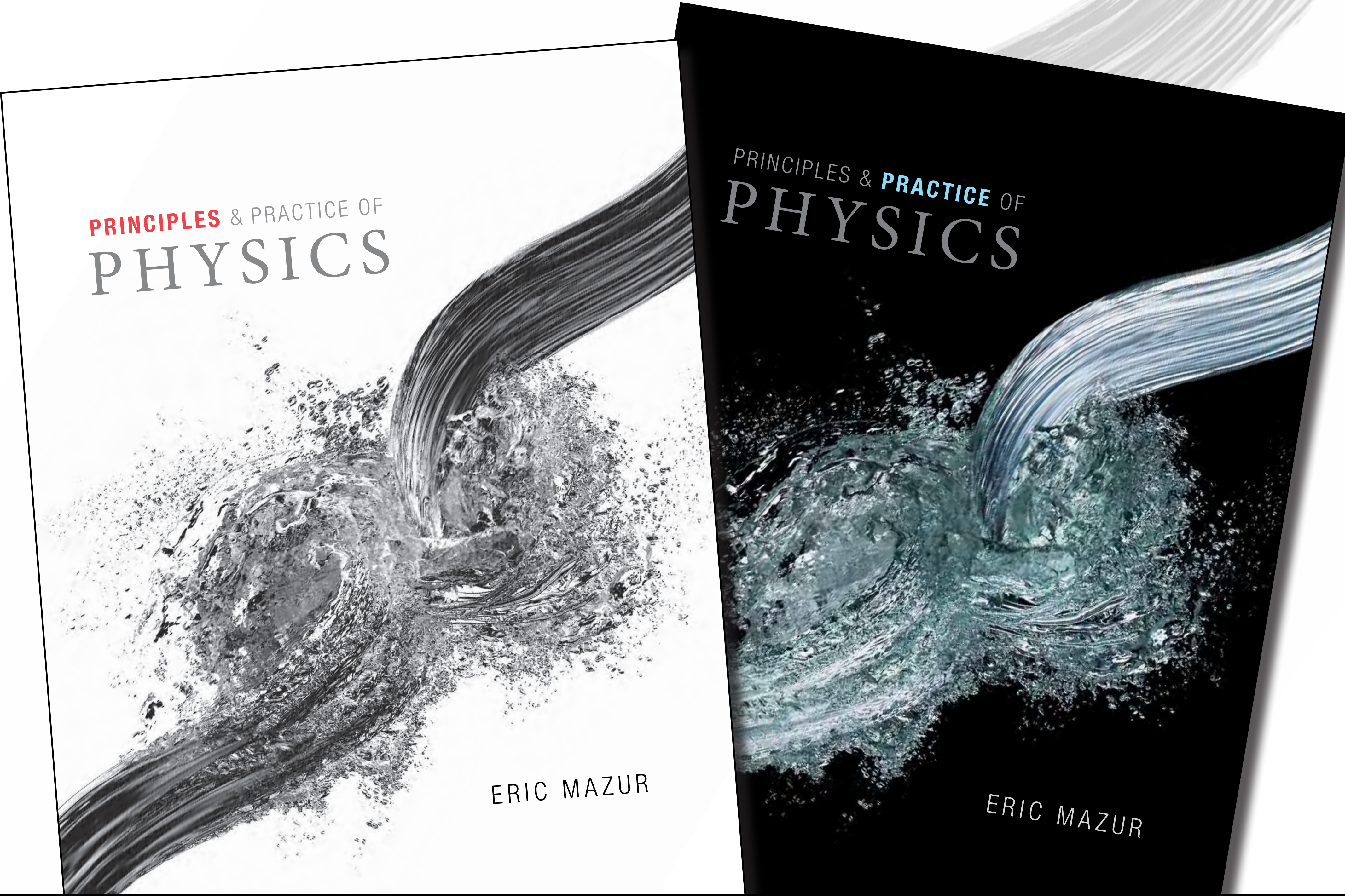
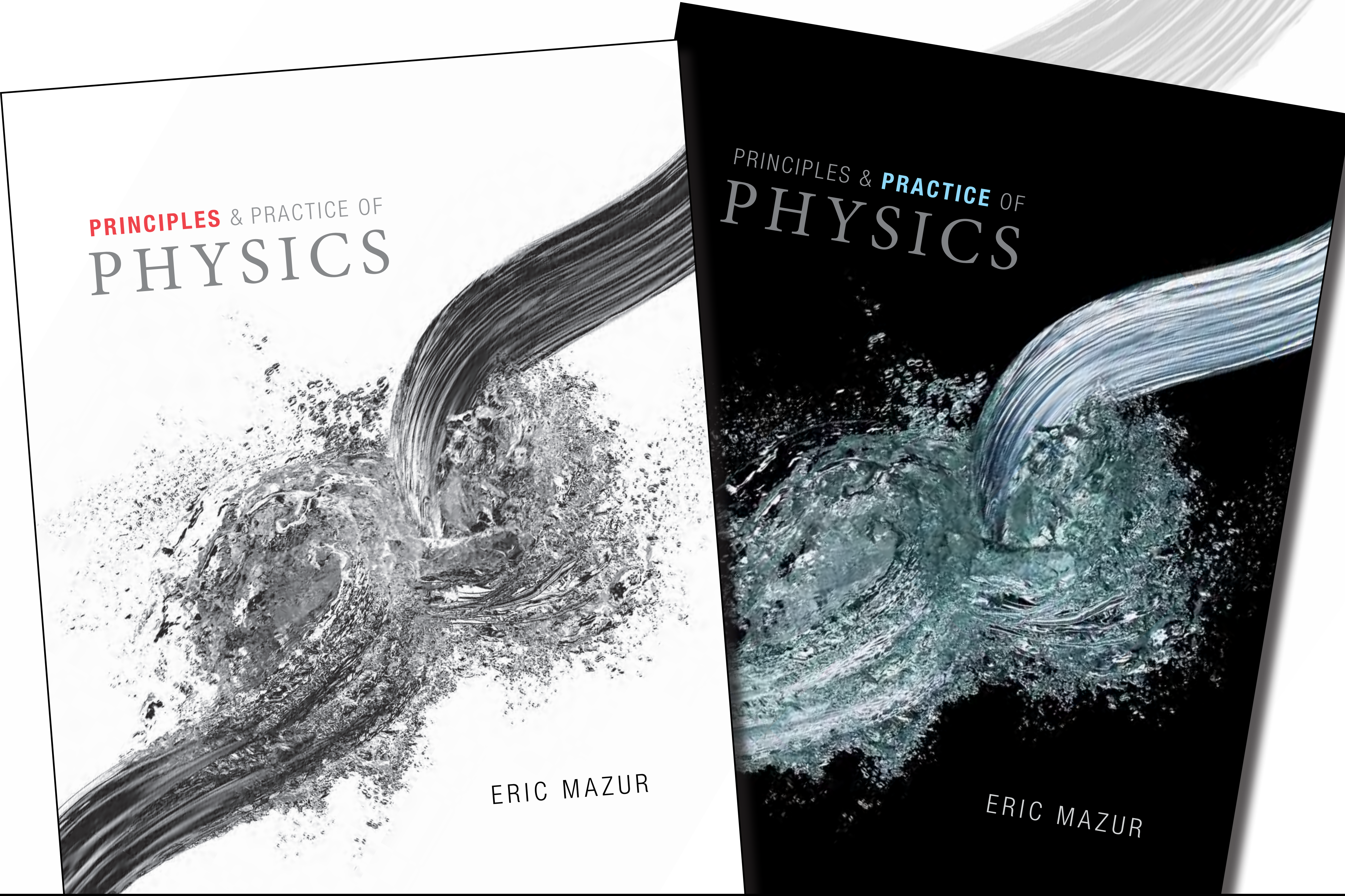


1 architecture

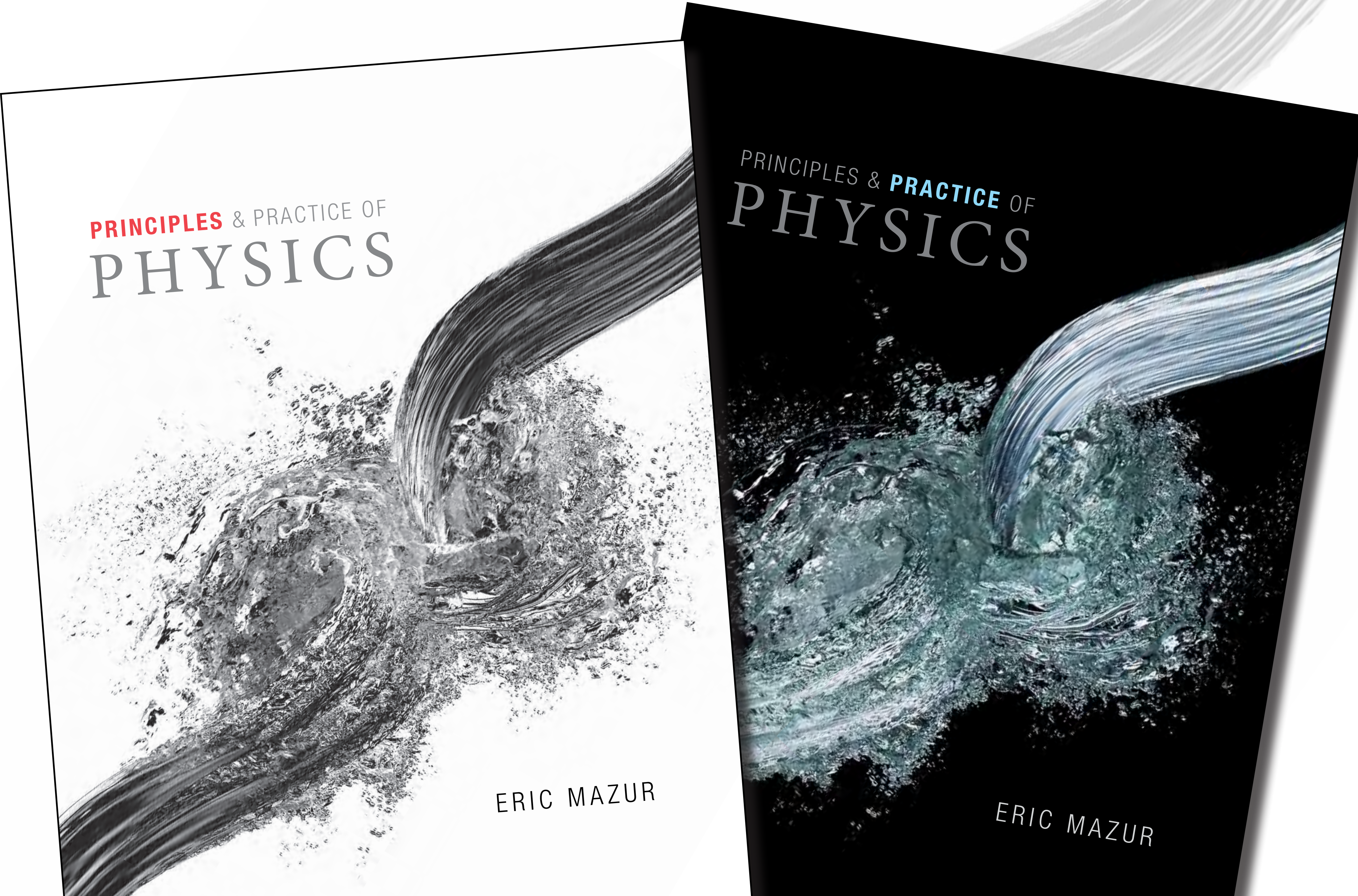


1 architecture

2 content



1. architecture
2. content
3. results



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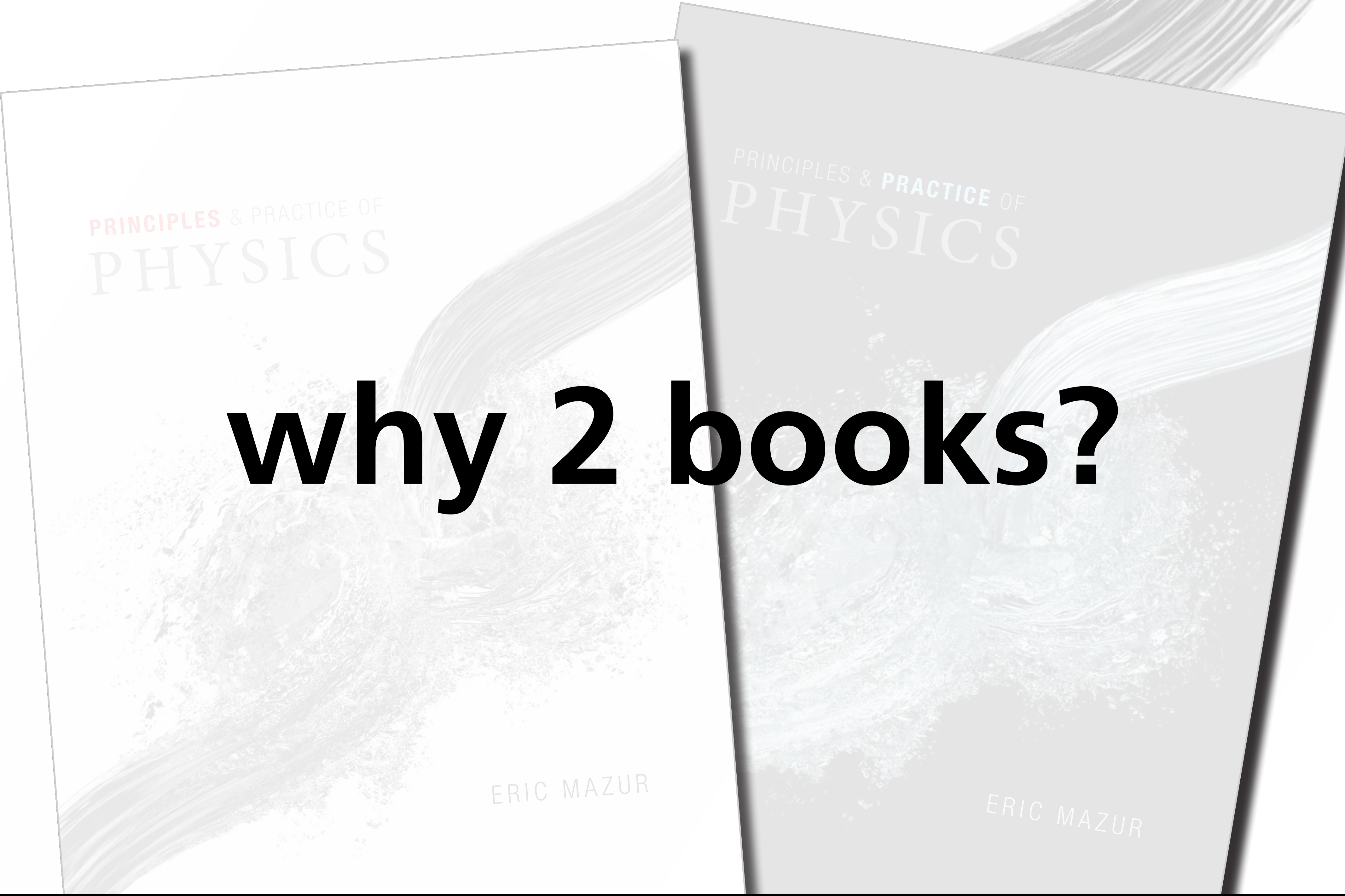
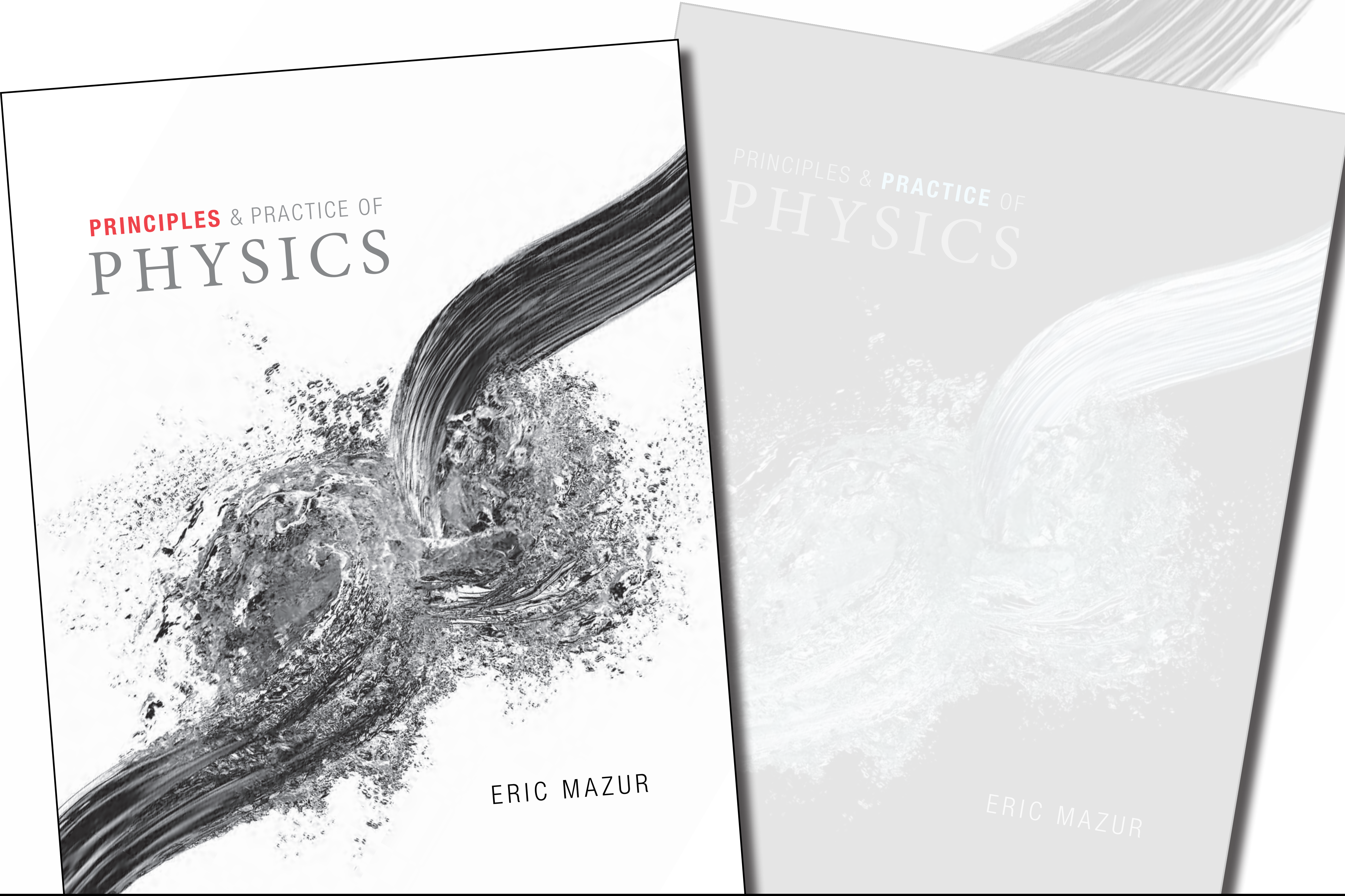


why 2 books?

1 architecture



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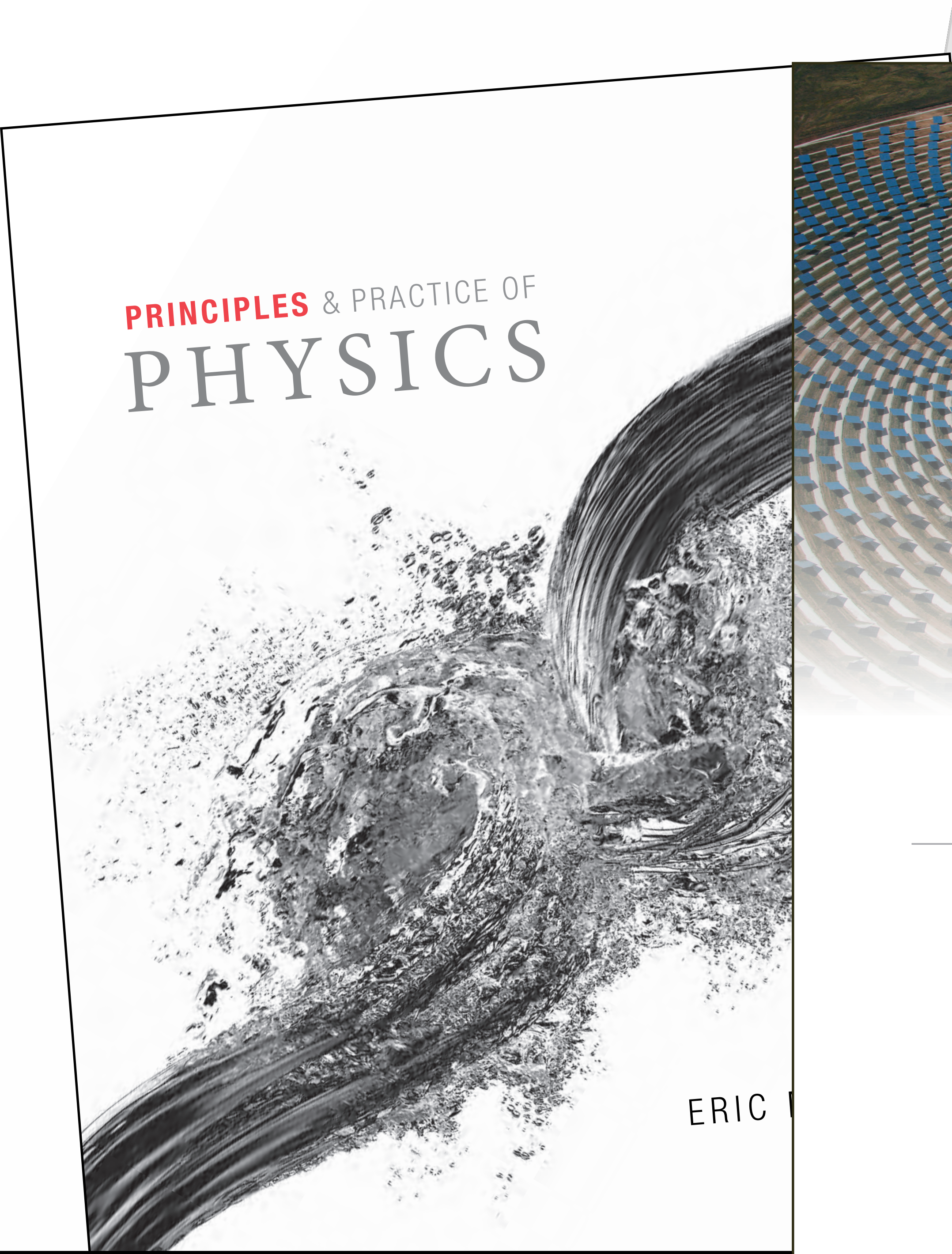
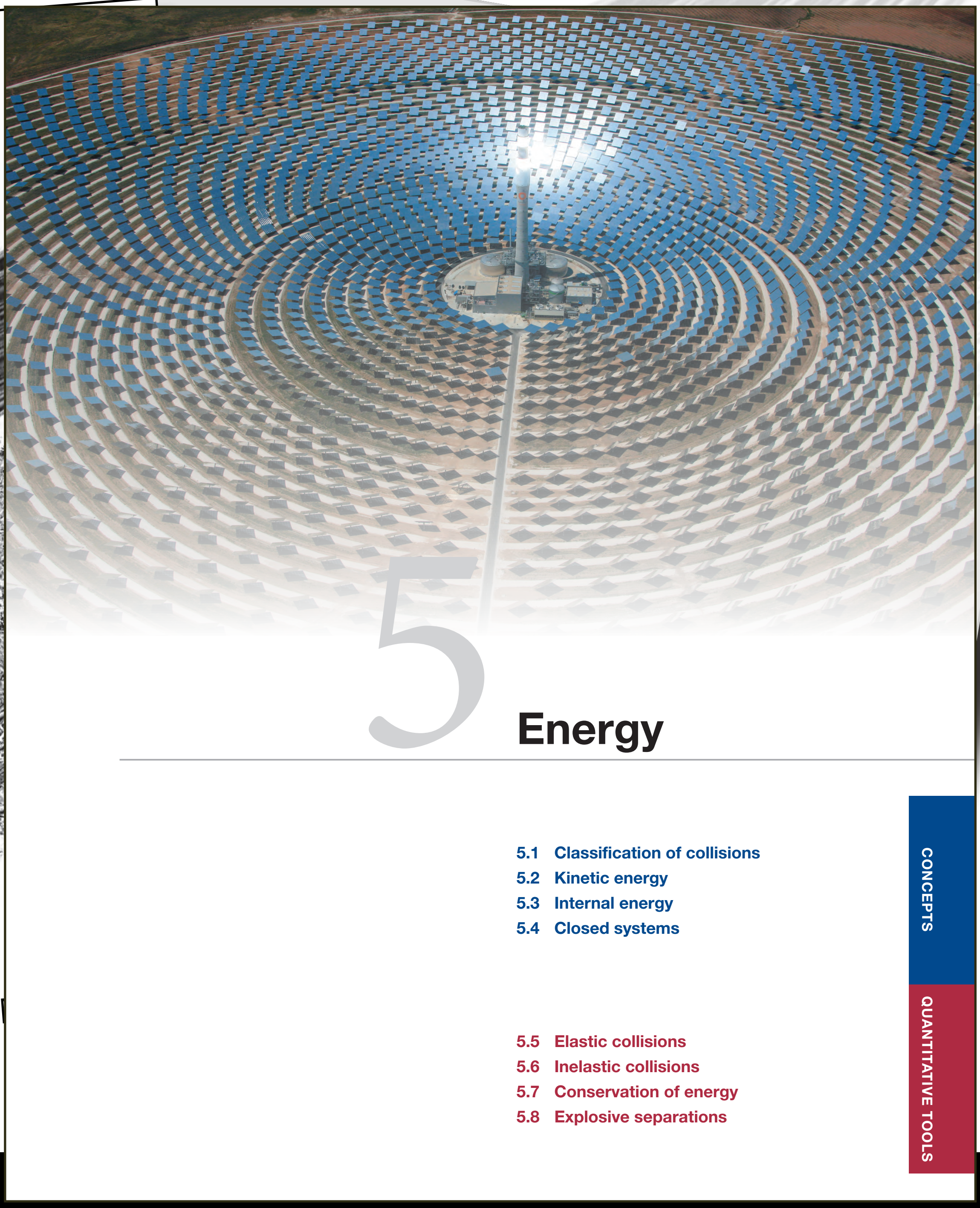




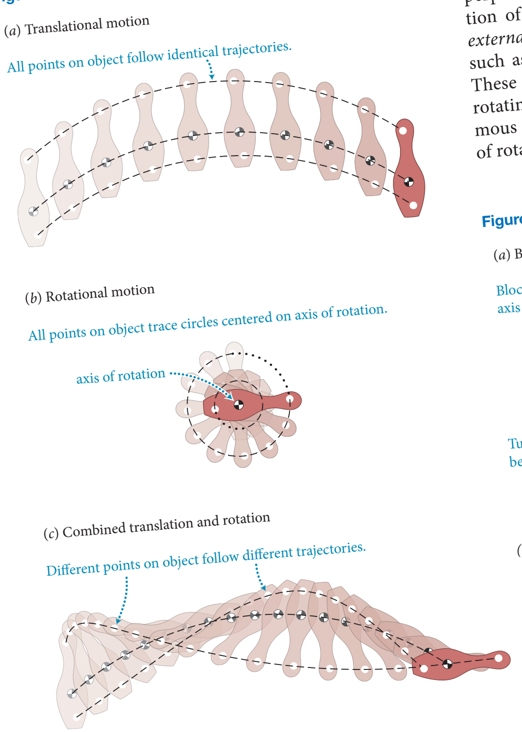
5 Energy

1 architecture

The motion we have been dealing with so far in this text is called **translational motion** (Figure 11.1*a*). 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 11.1*b*). Generally, the motion of rigid objects is a combination of these two types of motion (Figure 11.1*c*), 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 11.1*b* 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.

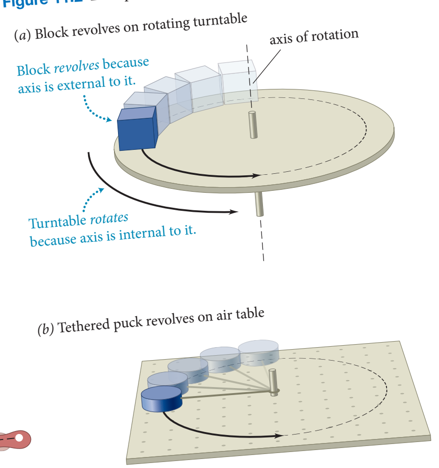
Figure 11.1 Translational and rotational motion of a rigid object.



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 puck and perpendicular to the plane of rotation. This is the definition of *revolve*—to move in circular motion around an *external* center. Objects that turn about an *internal* axis, such as the turntable in Figure 11.2*a*, 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 11.2 Examples of circular motion.



CONCEPTS

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CONCEPTS

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QUANTITATIVE TOOLS

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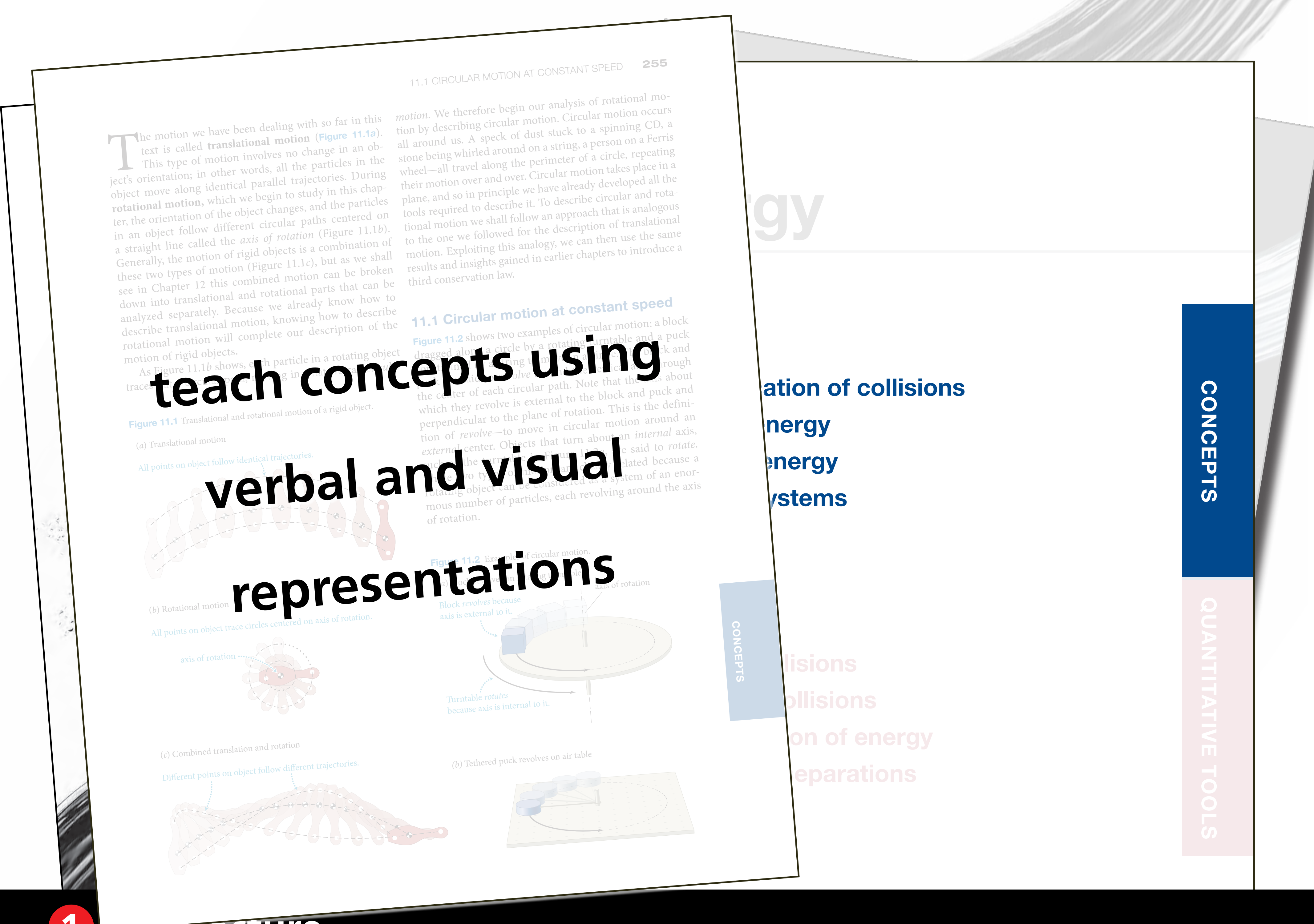
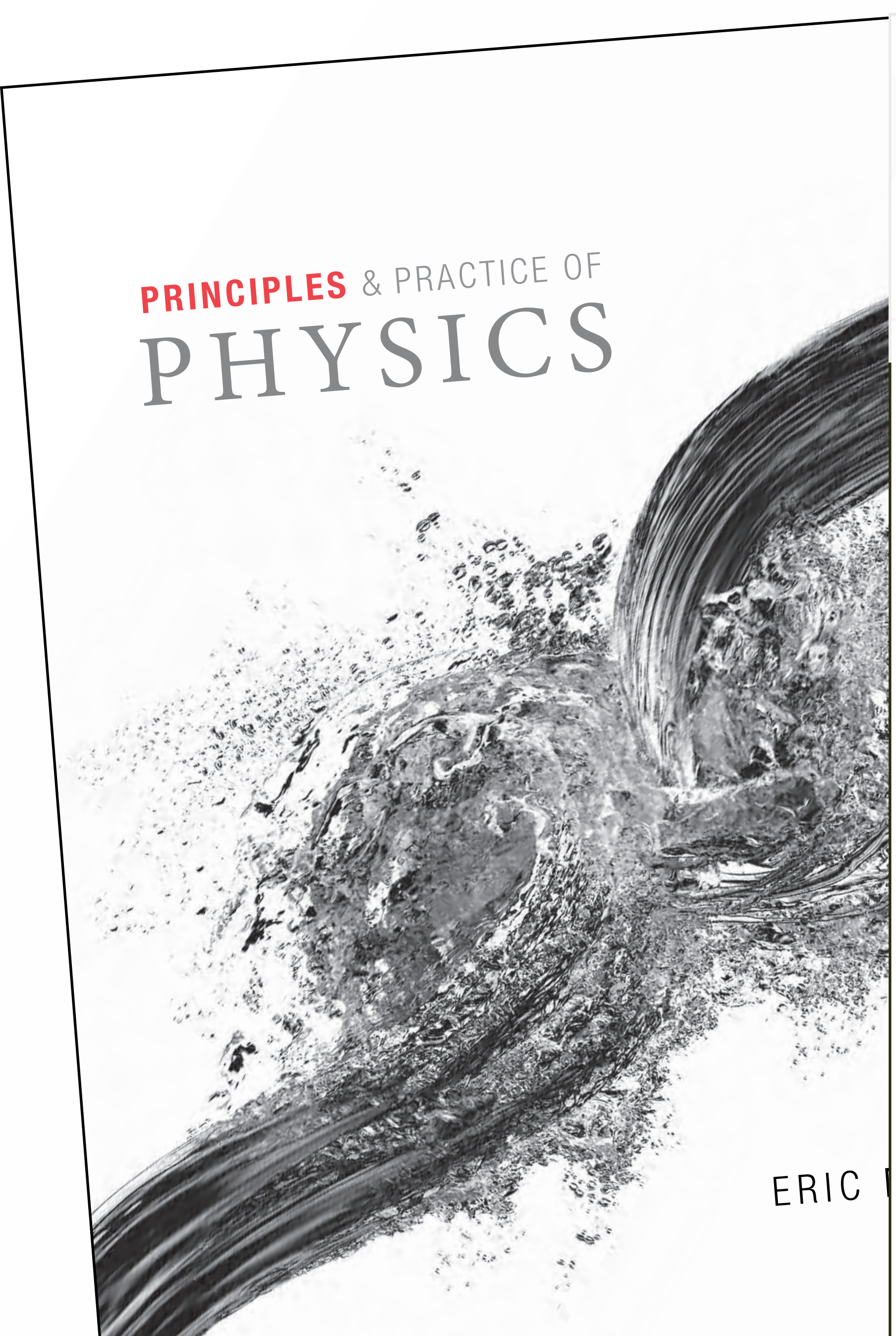


teach concepts using

verbal and visual

representations

1 architecture



Energy

CONCEPTS

QUANTITATIVE TOOLS

1 architecture

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 6.13*a*). Observer A sees the event as happening at position $\vec{r}_{Ae}$ at clock reading t_{Ae} (Figure 6.13*b*).* 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

$$t_{Ae} = t_{Be}. \tag{6.1}$$

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

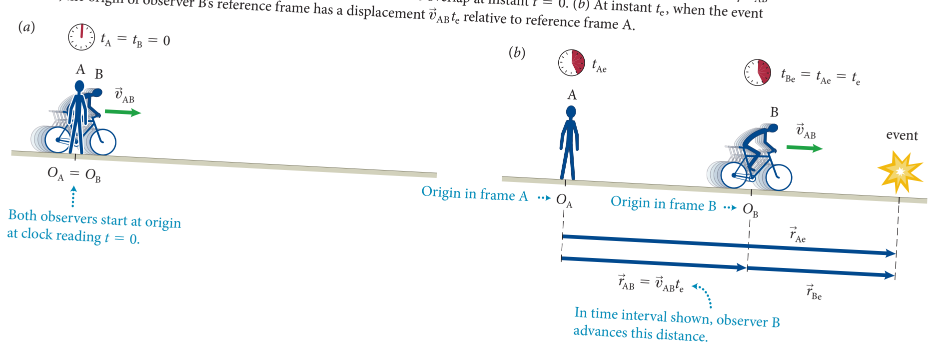
$$t_A = t_B = t. \tag{6.2}$$

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

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

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

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



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

QUANTITATIVE TOOLS

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systems

CONCEPTS

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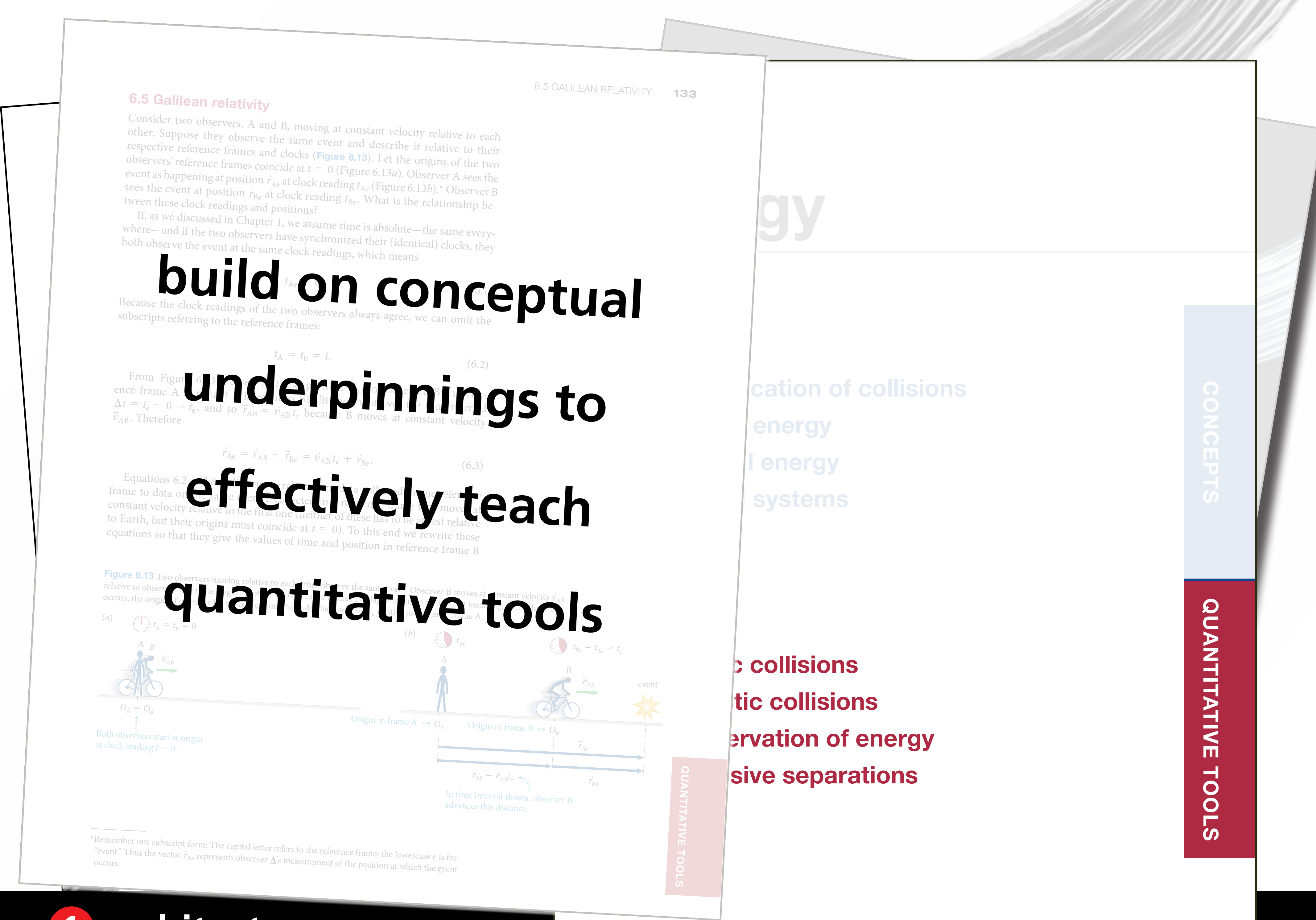
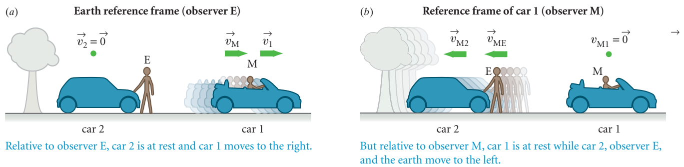
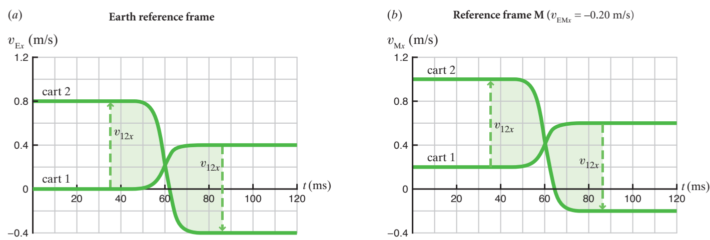
QUANTITATIVE TOOLS

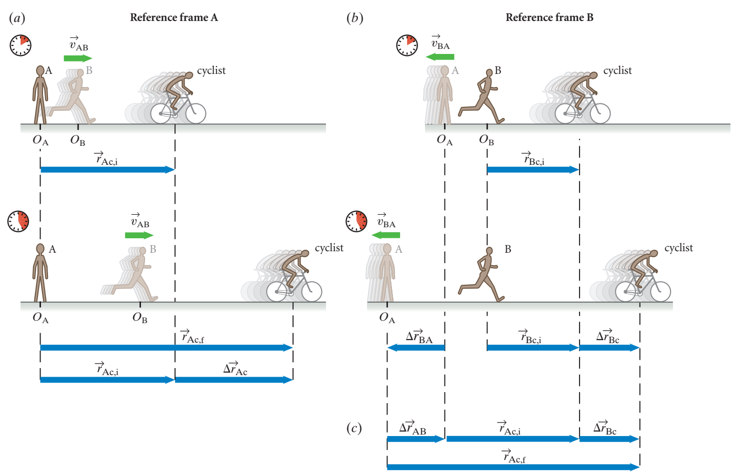
1 architecture

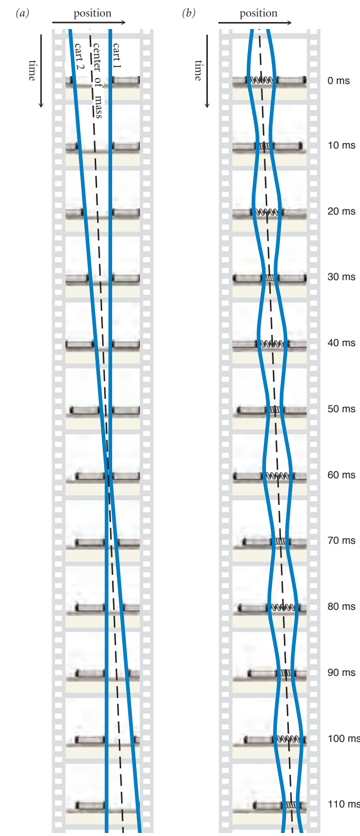


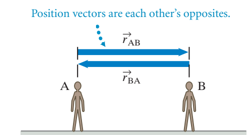
1 architecture

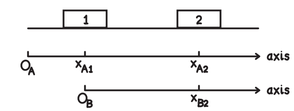

(a) Earth reference frame (observer E)
car 2
car 1
Relative to observer E, car 2 is at rest and car 1 moves to the right.
(b) Reference frame of car 1 (observer M)
car 2
car 1
But relative to observer M, car 1 is at rest while car 2, observer E, and the earth move to the left.

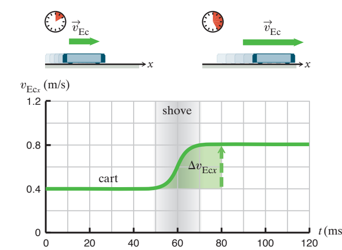

(a) Earth reference frame
cart 2
cart 1
t (ms)
(b) Reference frame M
cart 2
cart 1
t (ms)

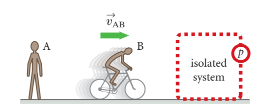

(a) Reference frame A
cyclist
(b) Reference frame B
cyclist
(c)

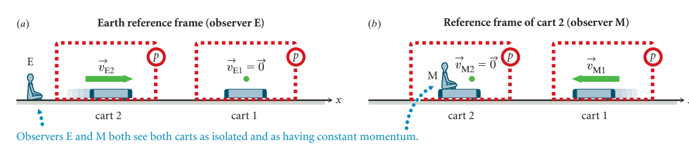

(a) position
time
cart 2
center of mass
cart 1
(b) position
time
0 ms
10 ms
20 ms
30 ms
40 ms
50 ms
60 ms
70 ms
80 ms
90 ms
100 ms
110 ms

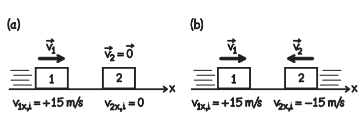

Position vectors are each other's opposites.
A
B

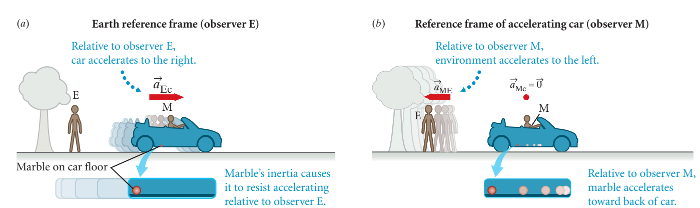

1
2
axis A
axis B


shove
cart
t (ms)


A
B
isolated system

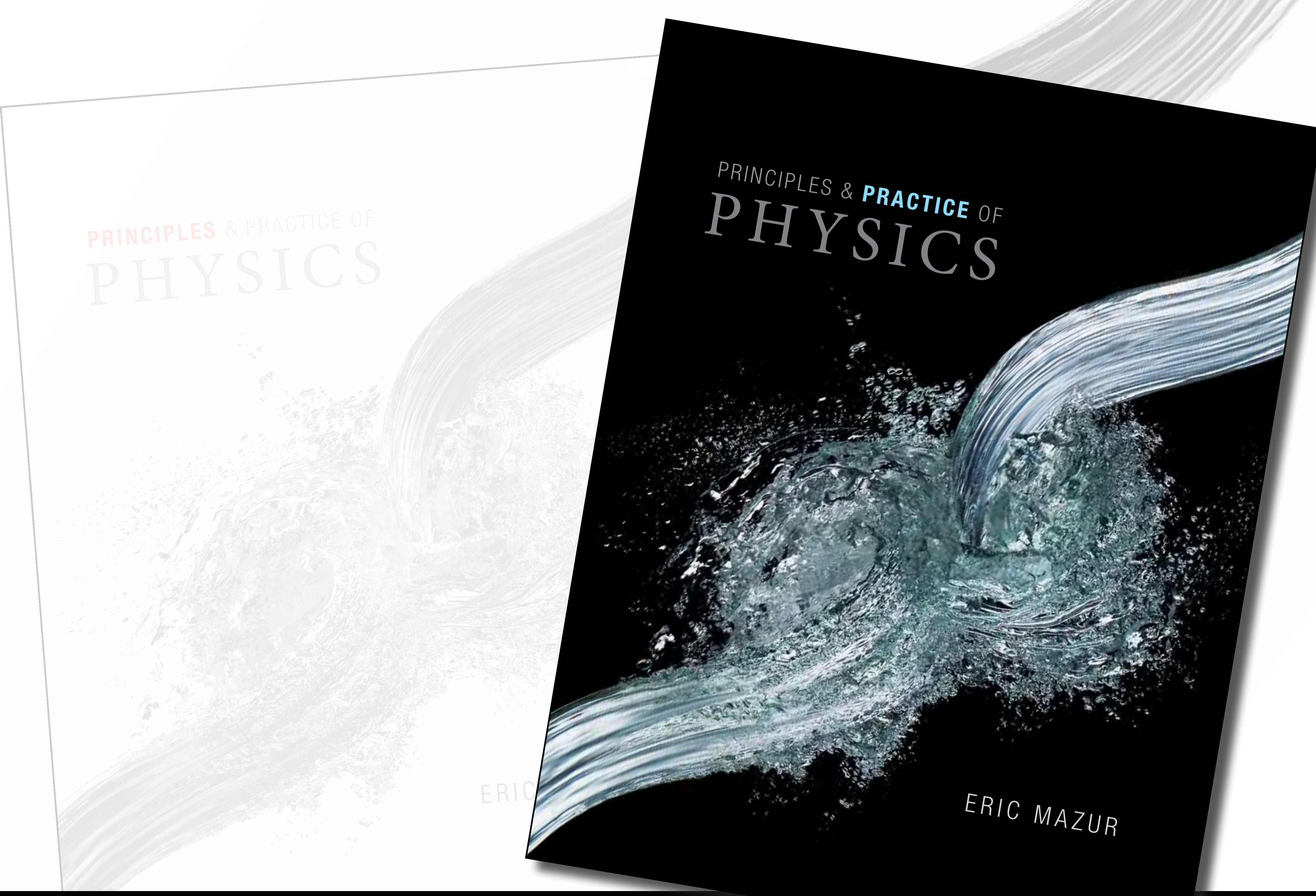

(a) Earth reference frame (observer E)
cart 2
cart 1
(b) Reference frame of cart 2 (observer M)
cart 2
cart 1
Observers E and M both see both carts as isolated and as having constant momentum.


(a)
1
2
(b)
1
2


(a) Earth reference frame (observer E)
Relative to observer E, car accelerates to the right.
Marble on car floor
Marble's inertia causes it to resist accelerating relative to observer E.
(b) Reference frame of accelerating car (observer M)
Relative to observer M, environment accelerates to the left.
Relative to observer M, marble accelerates toward back of car.

PRINCIPLES VOLUME

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



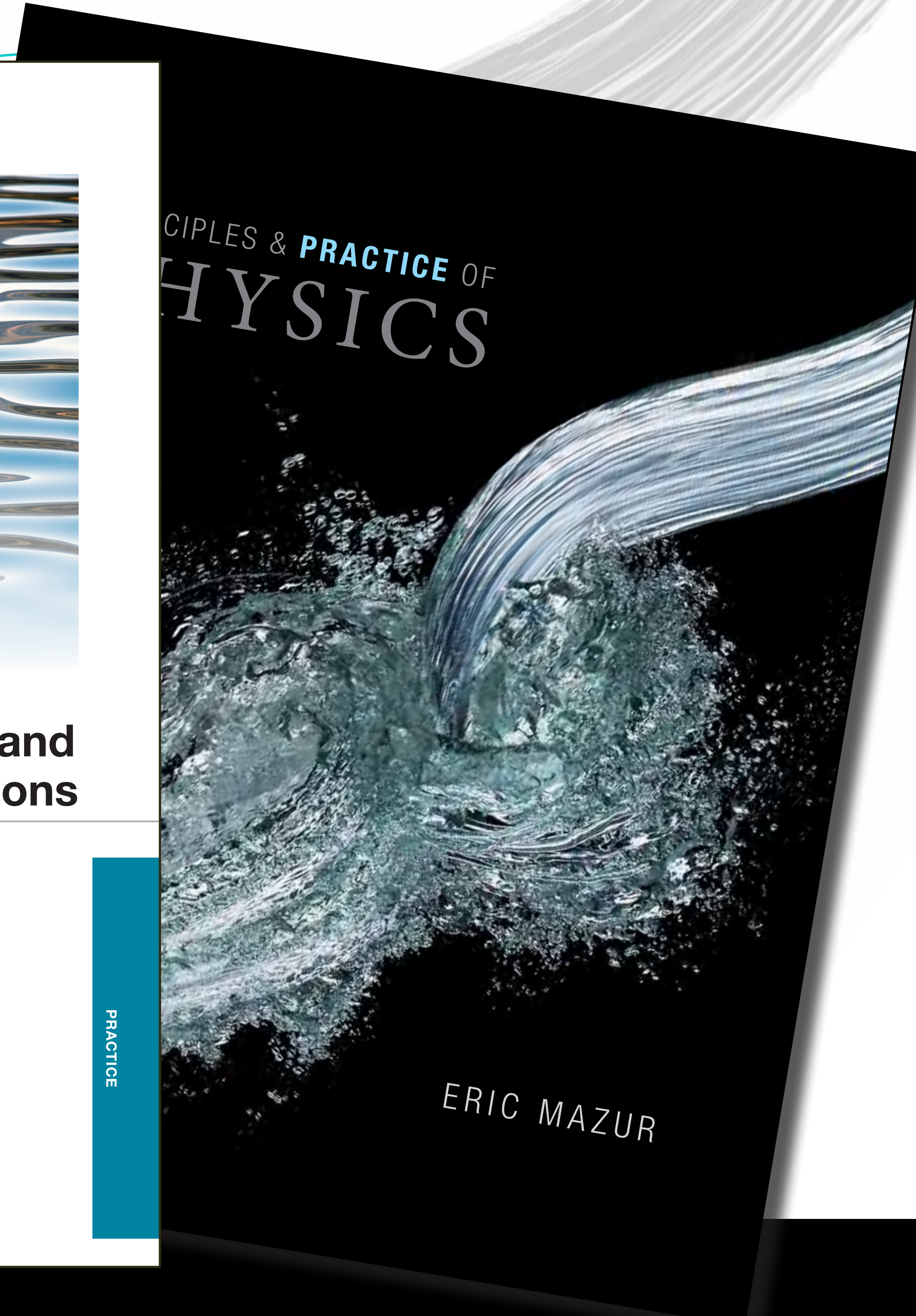
1 architecture

17

PRACTICE

Waves in Two and Three Dimensions

PRACTICE



architecture

PRACTICE

Waves in Two
Three Dimens

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)

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PRACTICE

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Waves in Two Three Dimens

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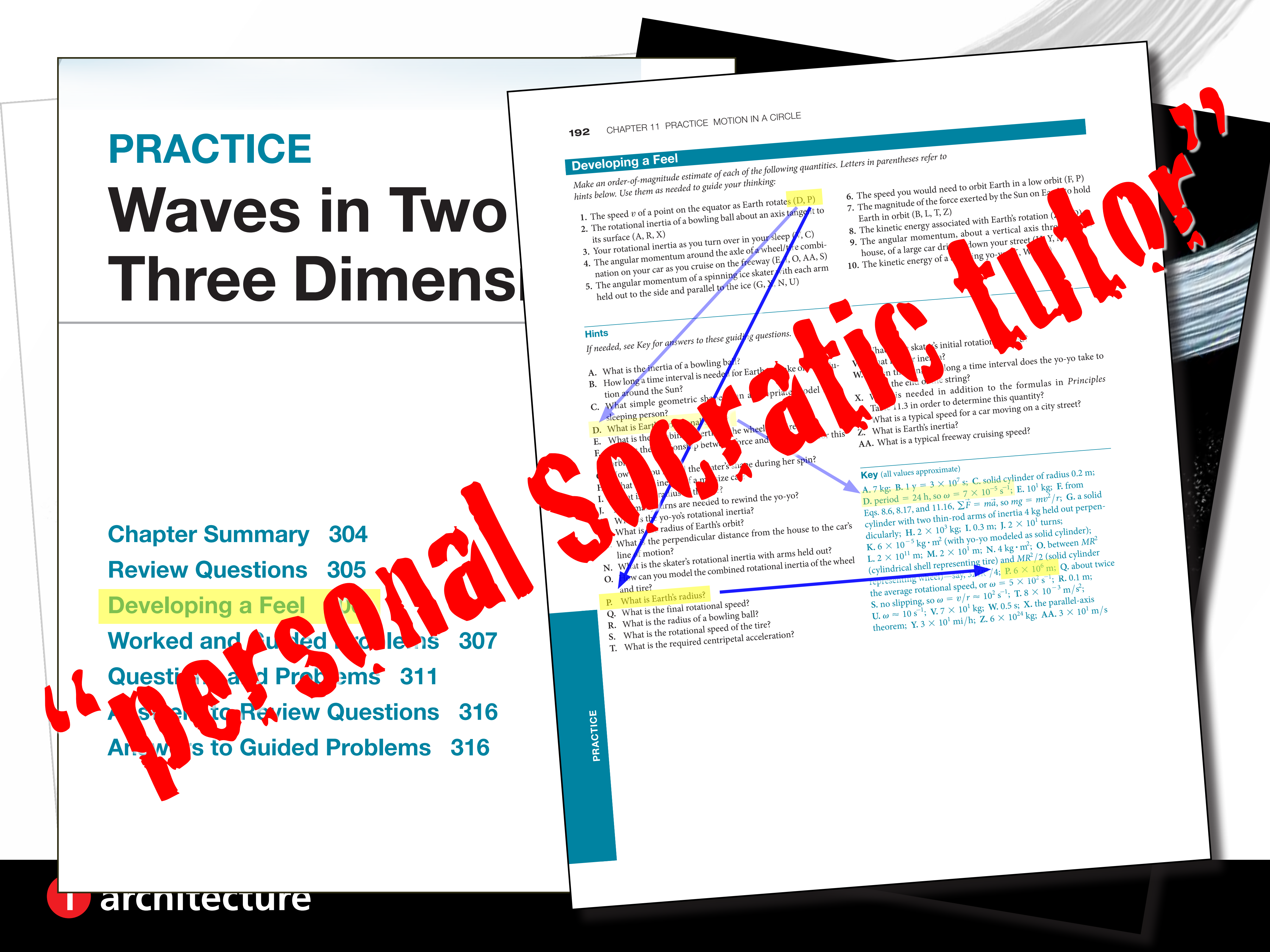
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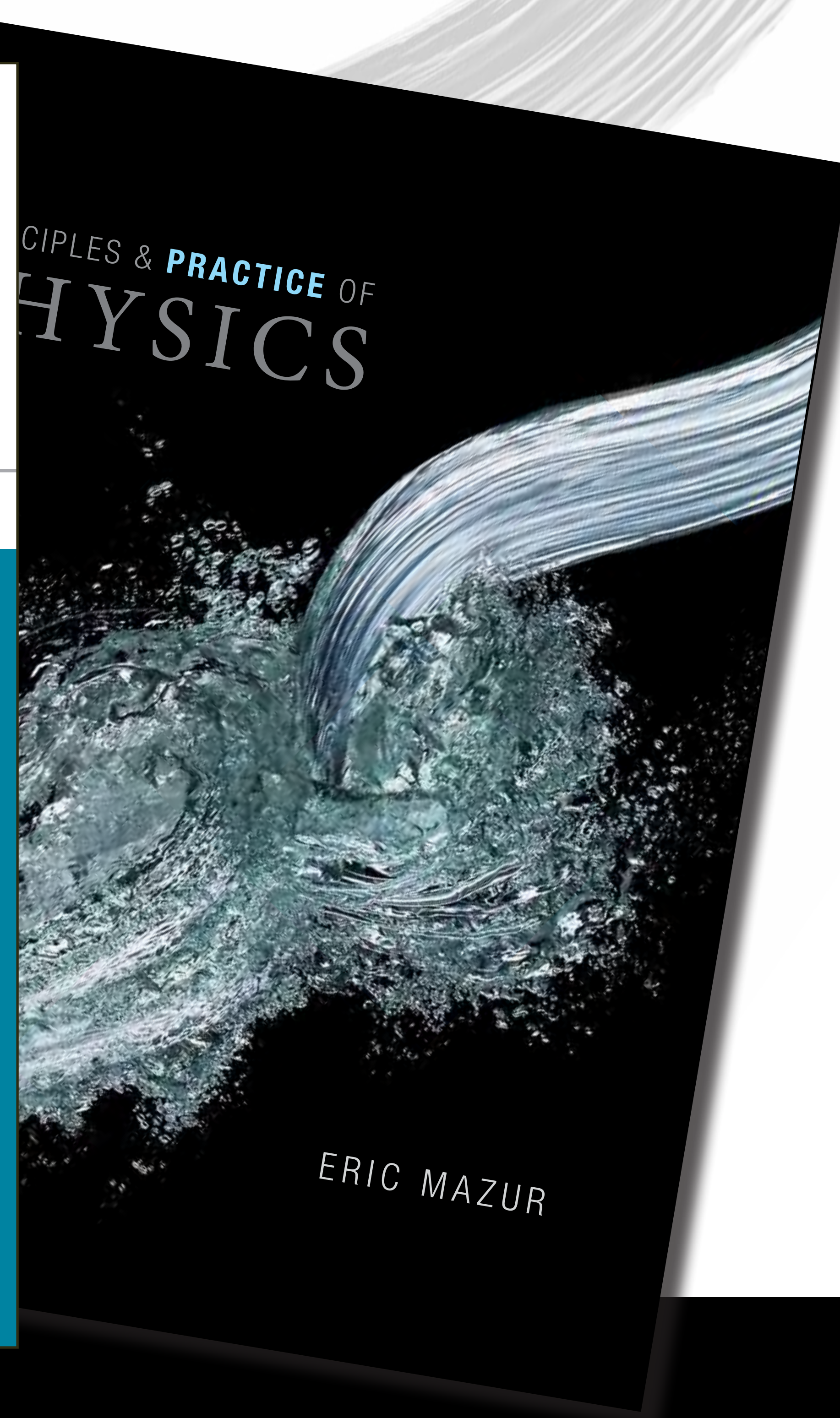

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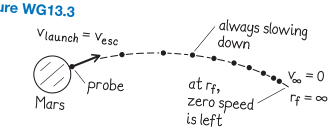
Worked Problem 13.3 Escape at last

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

❶ **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



❷ **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.

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

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

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

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

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

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

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.

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

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

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

Guided Problem 13.4 Spring to the stars

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

❶ **GETTING STARTED**

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

❷ **DEVISE PLAN**

4. What law of physics should you invoke?
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?

❸ **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.

❹ **EVALUATE RESULT**

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

PRACTICE

PRACTICE

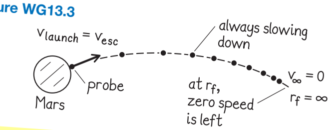
Waves in Two a[nd] Three Dimensi[ons]

Worked Problem 13.3 Escape at last

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

❶ **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



❷ **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.

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

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

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

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

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

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

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

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.

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

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

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

Guided Problem 13.4 Spring to the stars

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

❶ **GETTING STARTED**

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

❷ **DEVISE PLAN**

4. What law of physics should you invoke?
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?

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PRACTICE

4-step procedure

PRACTICE

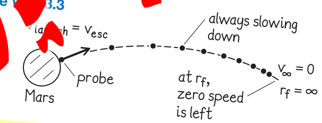
Waves in Two a[illegible] Three Dimensi[illegible]

Worked Problem 13.3 Escape at last

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

❶ GETTING STARTED Let us do a quick sketch to help [illegible]ink-ing (Figure WG13.3). We select the Mars-probe system for [illegible]sis. In order to reach "deep space," the probe must attain a ver[illegible] distance from Mars. This will require a significant amount [illegible] kinetic energy, which the probe must acquire during lau[illegible] launch, the kinetic energy immediately begi[illegible]crea[illegible] potential energy of the Mars-probe system [illegible] tion distance increases. We assume a refe[illegible] is fixed and only the probe [illegible]hen [illegible] is far en[illegible] away (infinity, really, but pr[illegible]cally [illegible] to g[illegible]uite far), the kinetic energy has [illegible]nimum value [illegible] an take to be zero beca[illegible] any more ene[illegible] supply tationa[illegible] he pr[illegible]e out there. The gravi-[illegible]e, which is also zero. [illegible] also ass[illegible] Sun and other planets have a negli-gible [illegible]ence on o[illegible]tem, and we ignore the rotation of Mars.

[illegible]re [illegible]3.3



❷ 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 con-verted 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 simi-lar 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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PRACTICE

PRACTICE

Waves in Two a
Three Dimensi

Worked Problem 13.3 Escape at last

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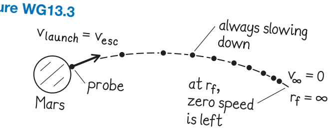
Figure WG13.3



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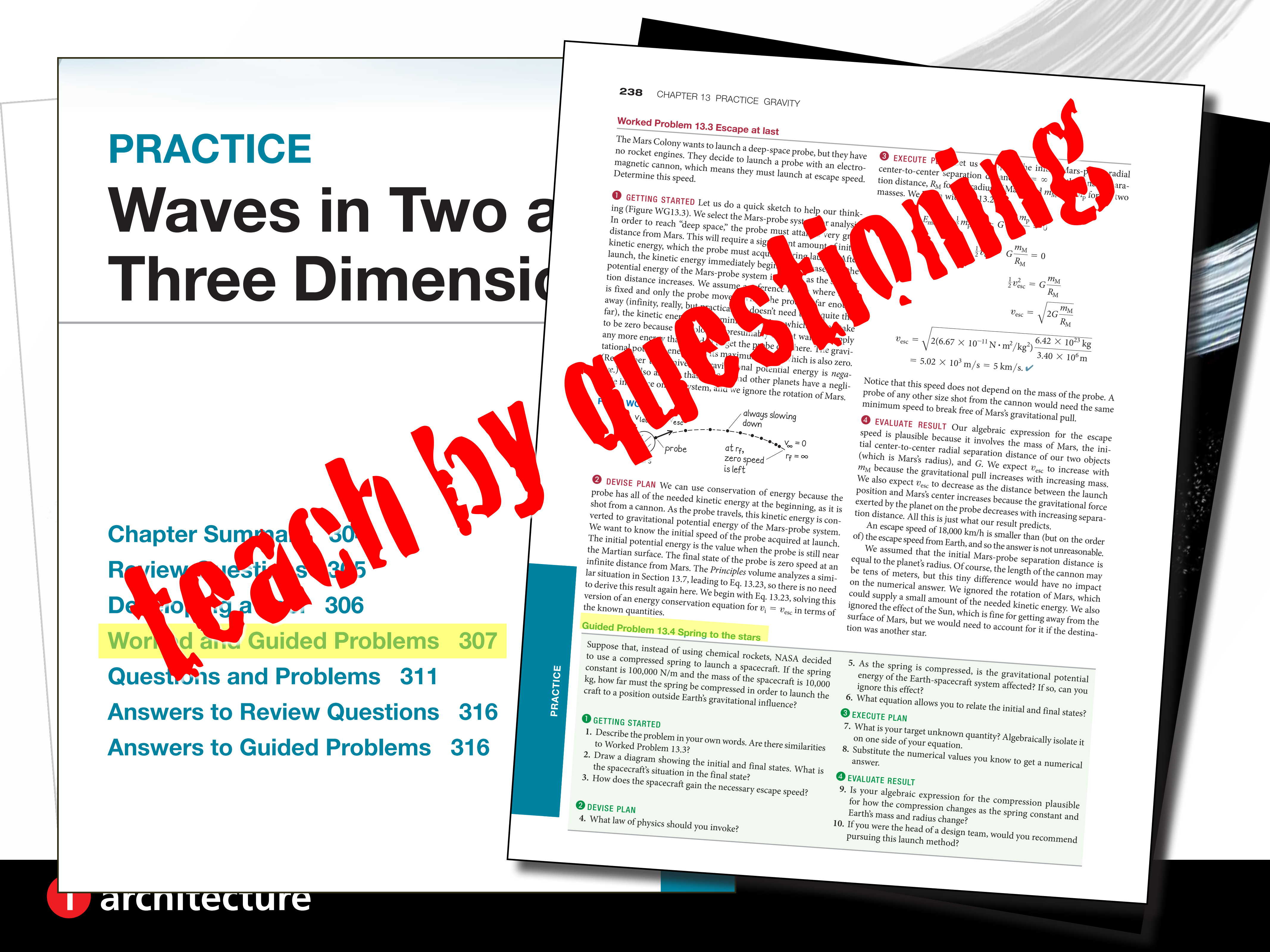
PRACTICE

architecture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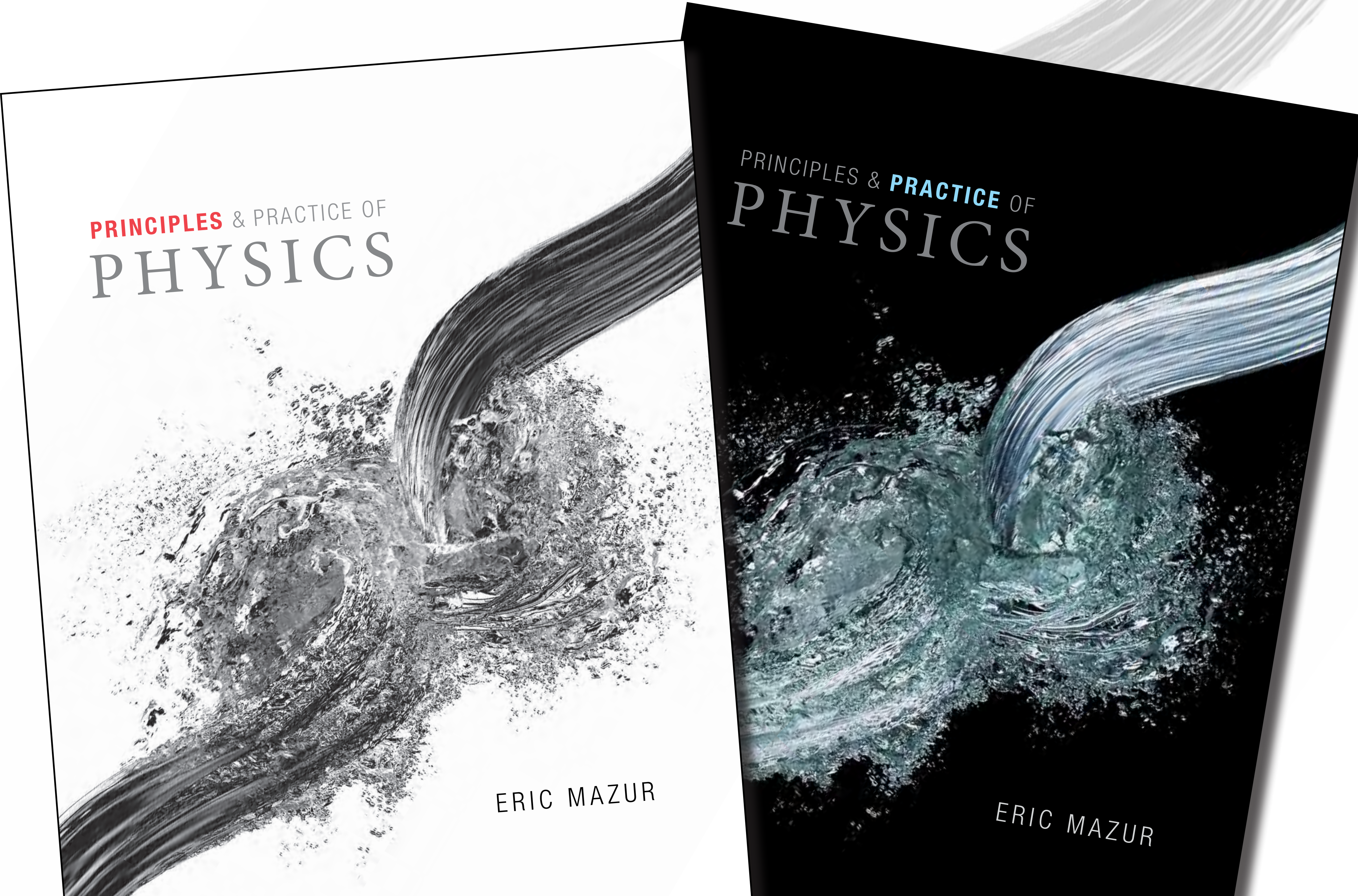
PRACTICE
teach by questioning
architecture

PRACTICE VOLUME

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

1 architecture



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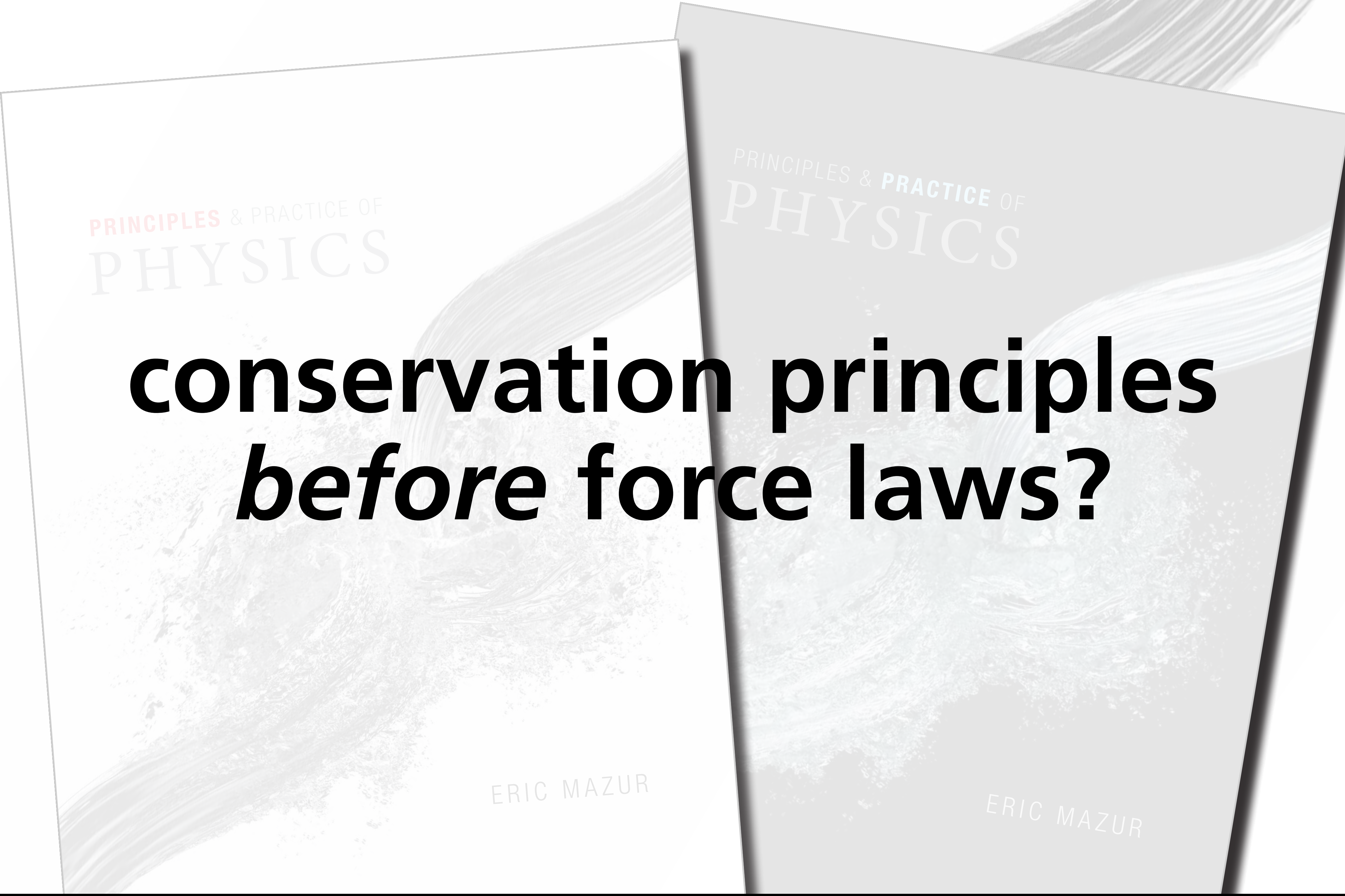
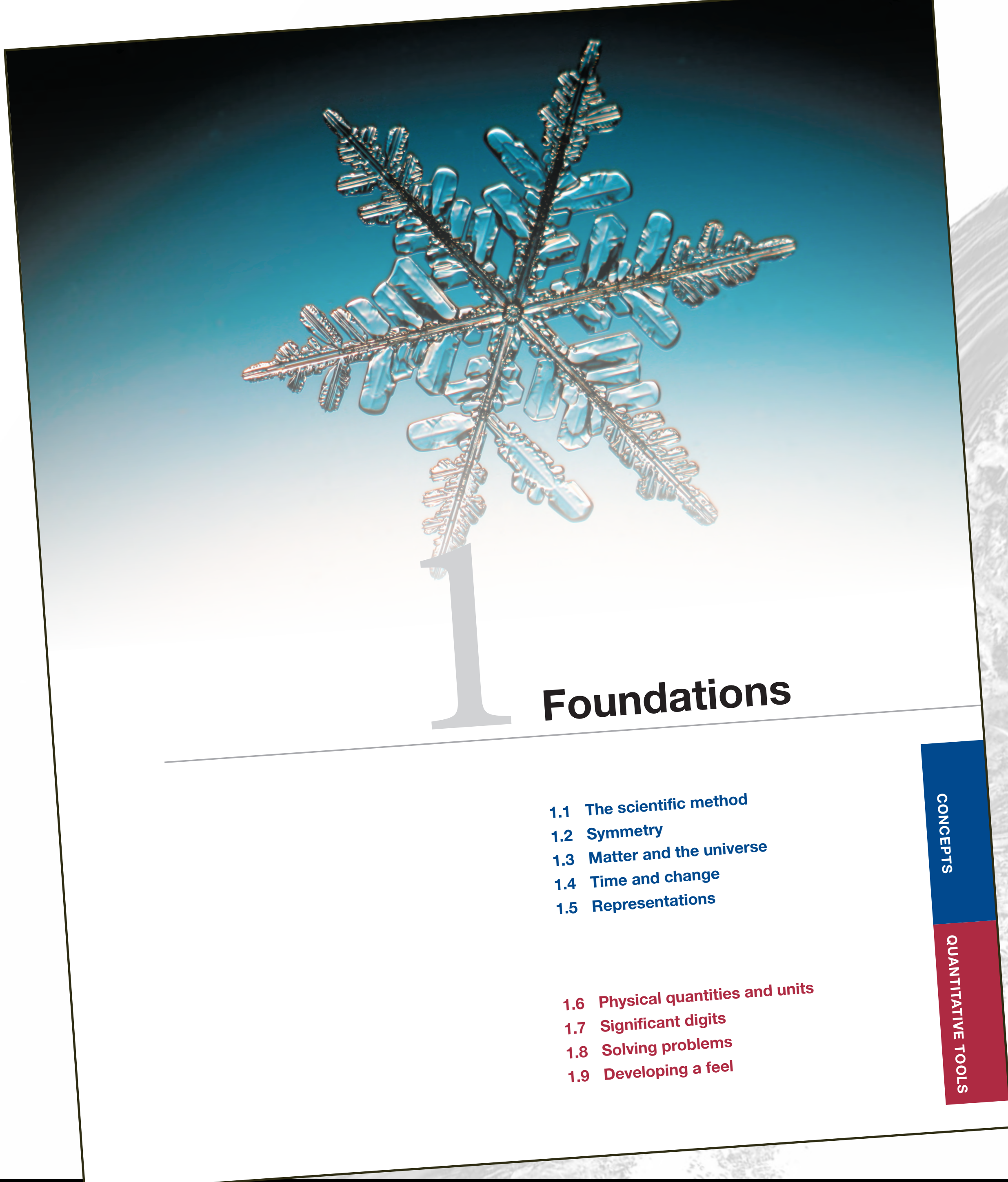


conservation principles *before* force laws?

1 architecture 2 content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Foundations

CONCEPTS

1.1 The scientific method
1.2 Symmetry
1.3 Matter and the universe
1.4 Time and change
1.5 Representations

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

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1 architecture

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2

Motion in
Dimensi

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Acceleration

CONCEPTS

QUANTITATIVE TOOLS

1 architecture

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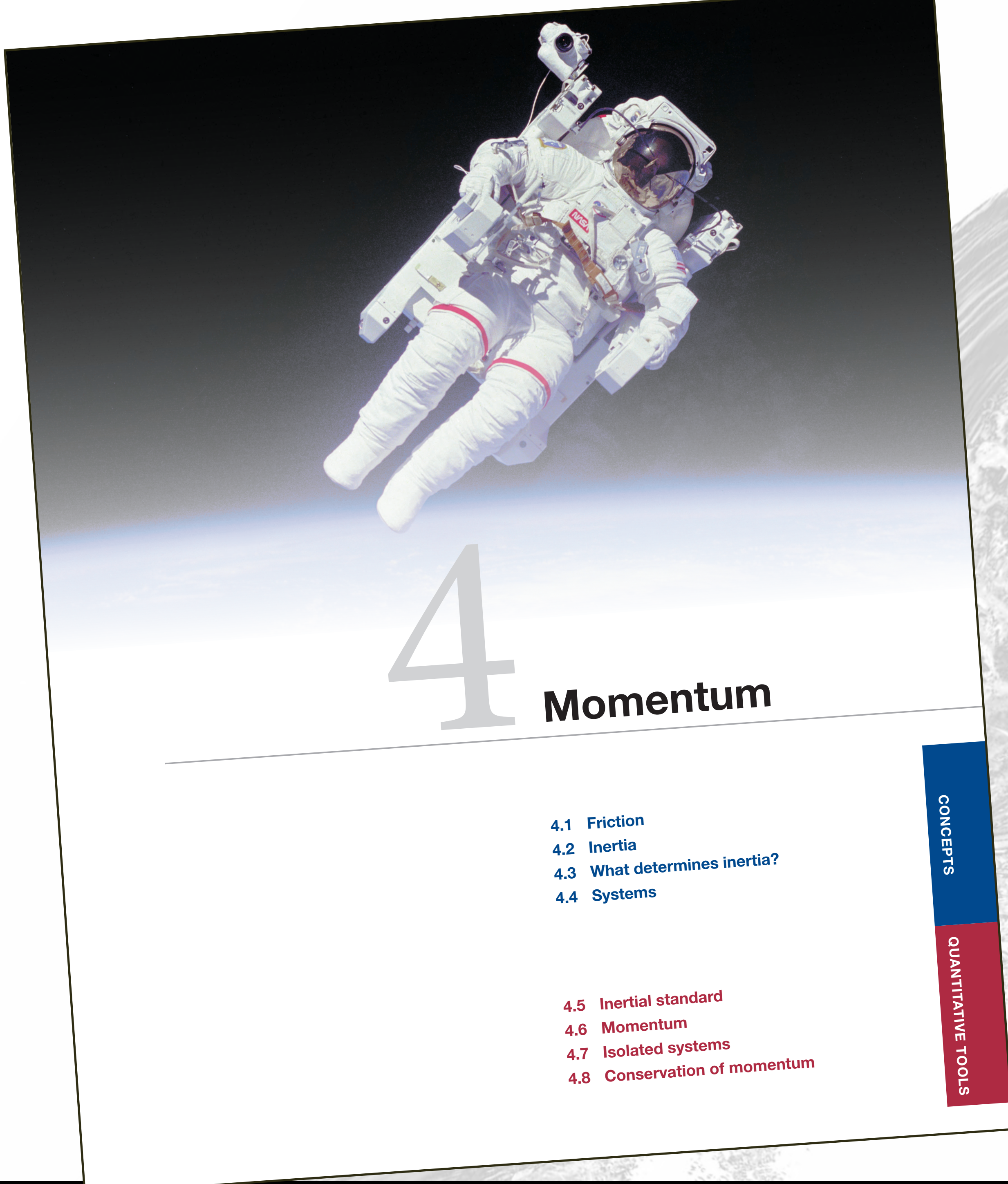

4 Momentum

1 architecture 2 content

4.1 Friction

4.2 Inertia

4.3 What determines inertia?

4.4 Systems

4.5 Inertial standard

4.6 Momentum

4.7 Isolated systems

4.8 Conservation of momentum

1 architecture

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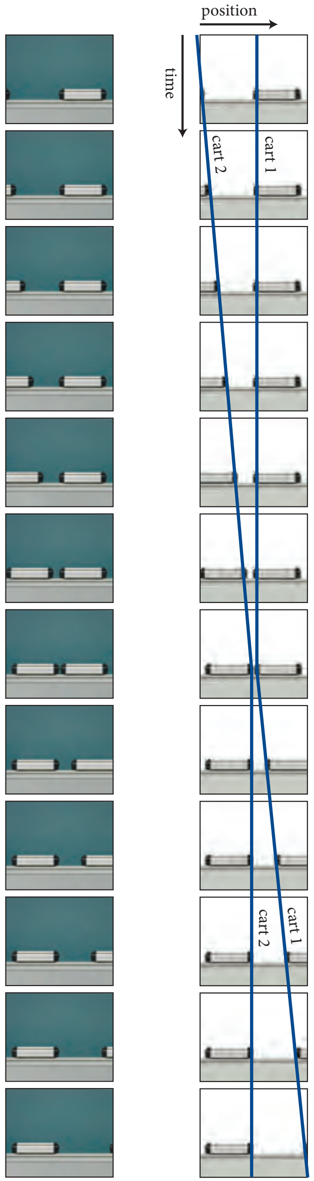

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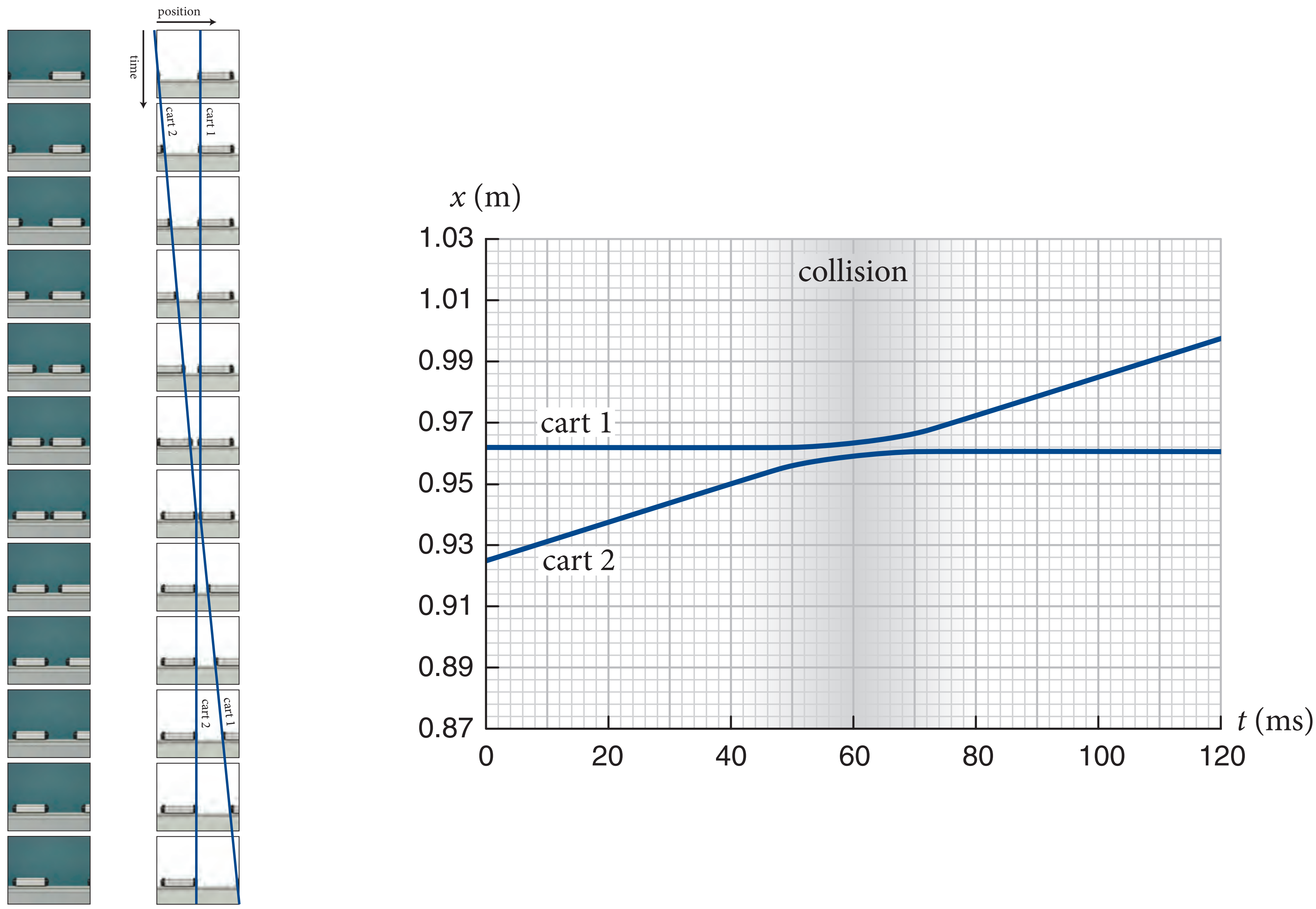

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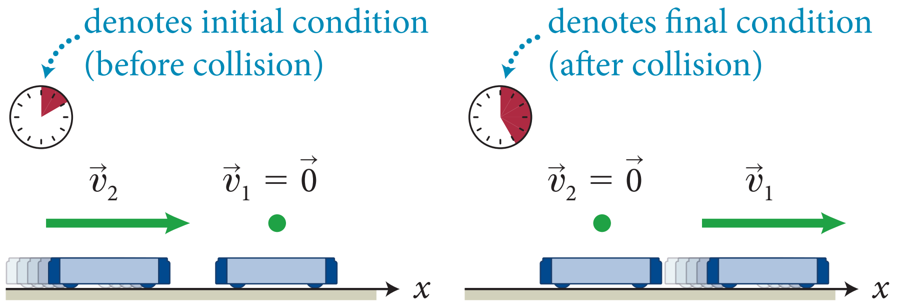

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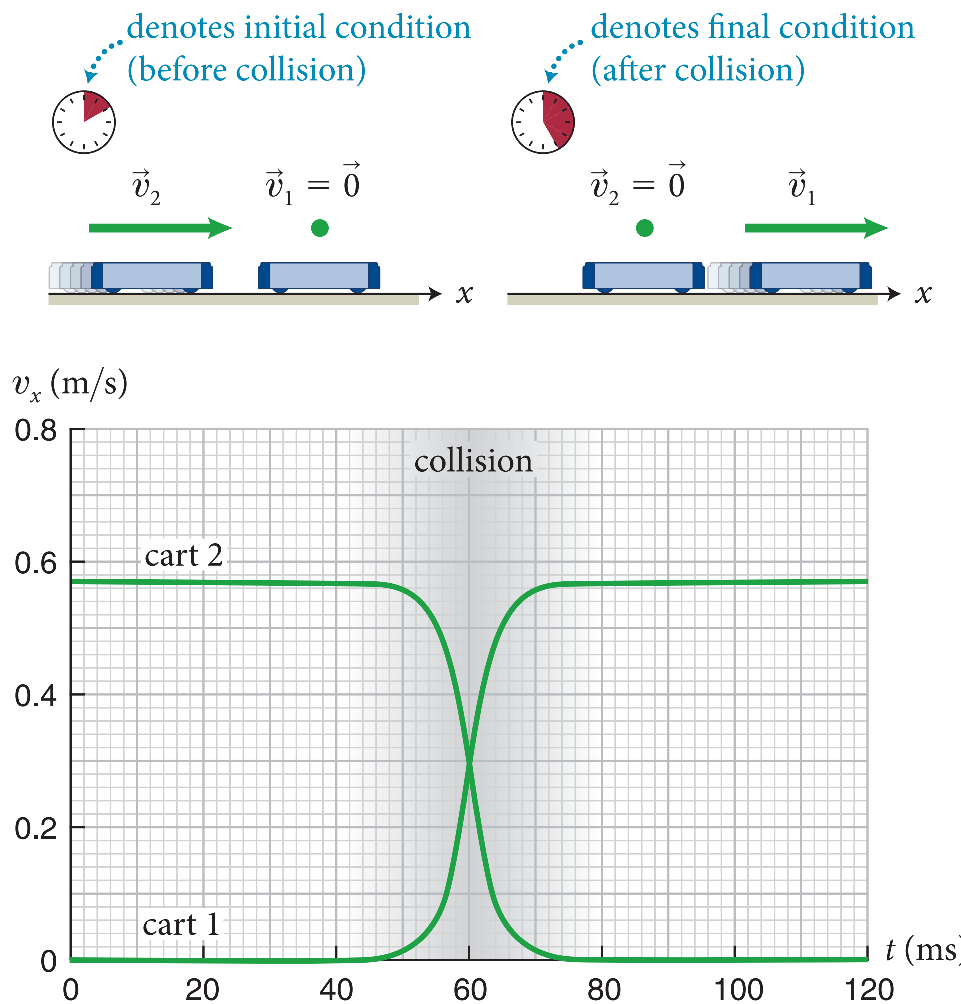

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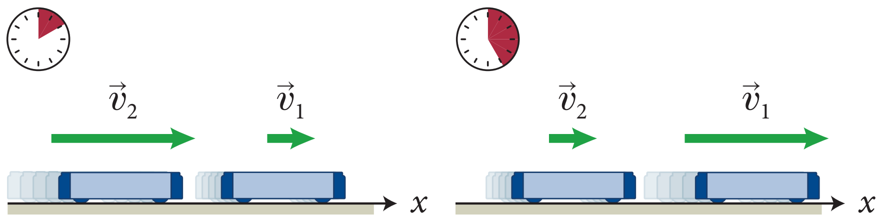

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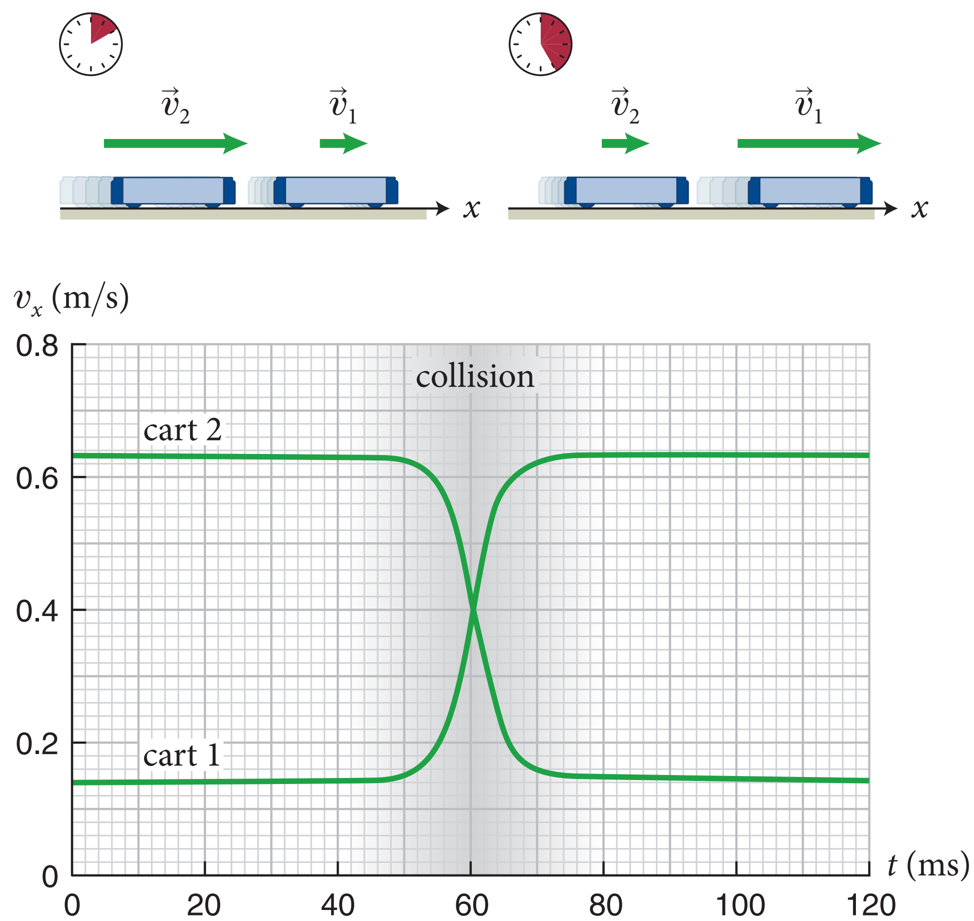

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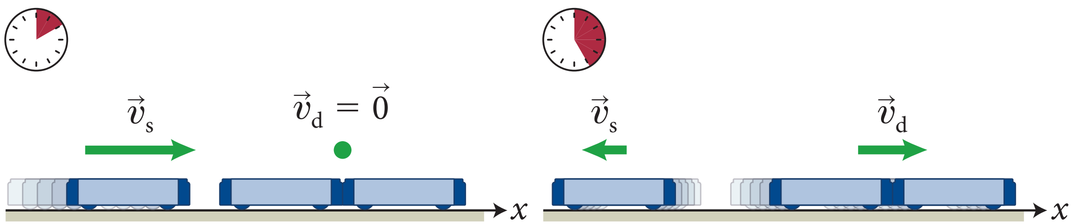

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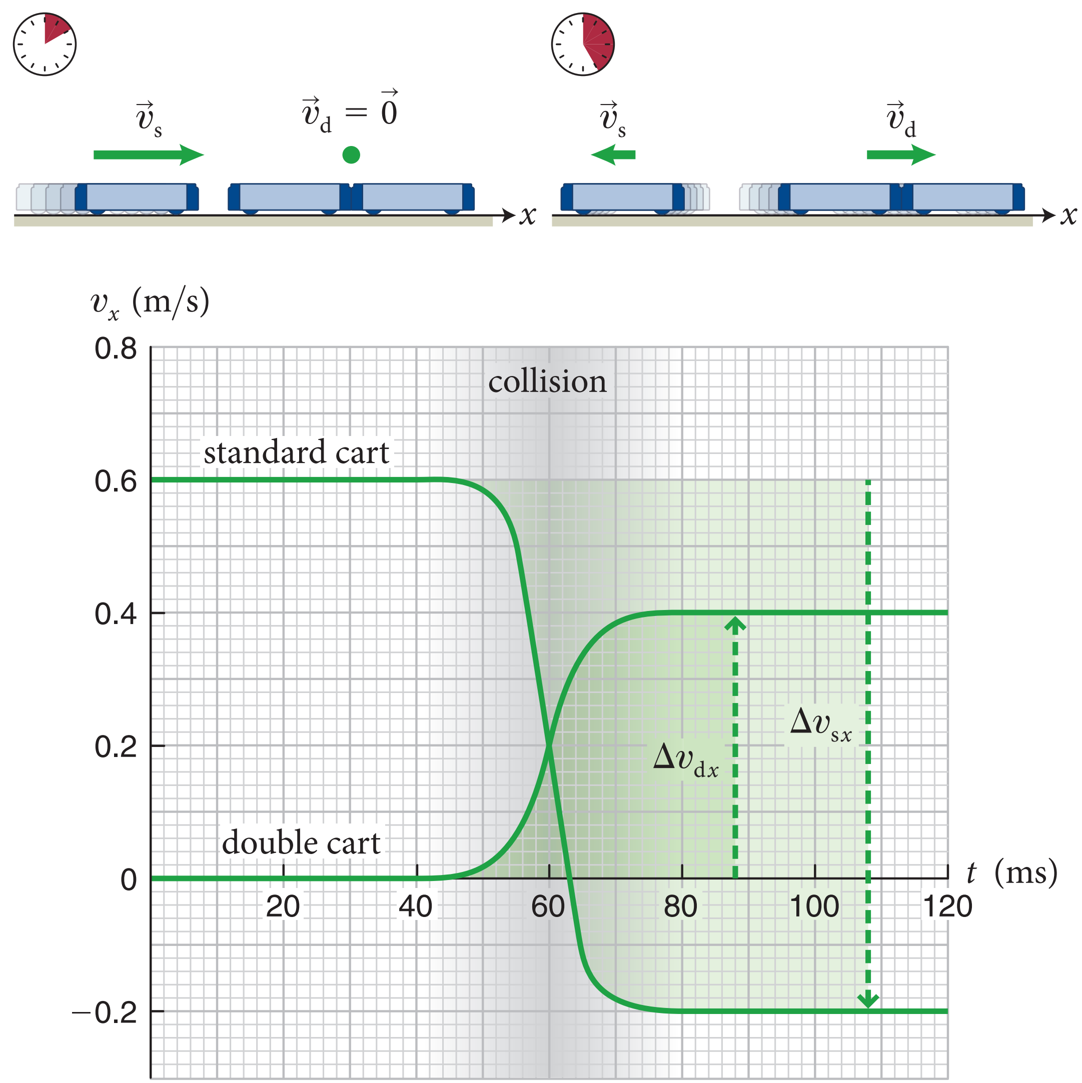

1 architecture

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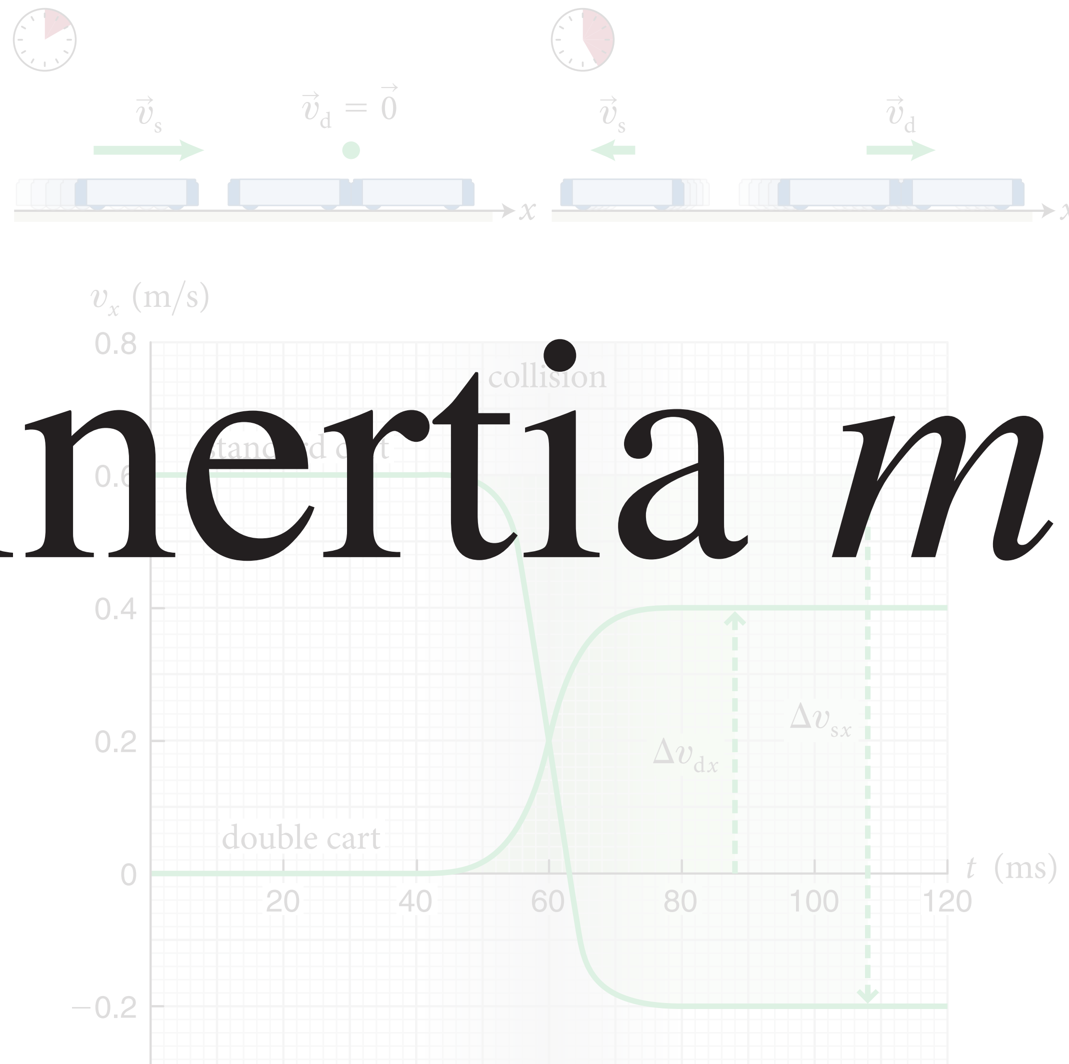
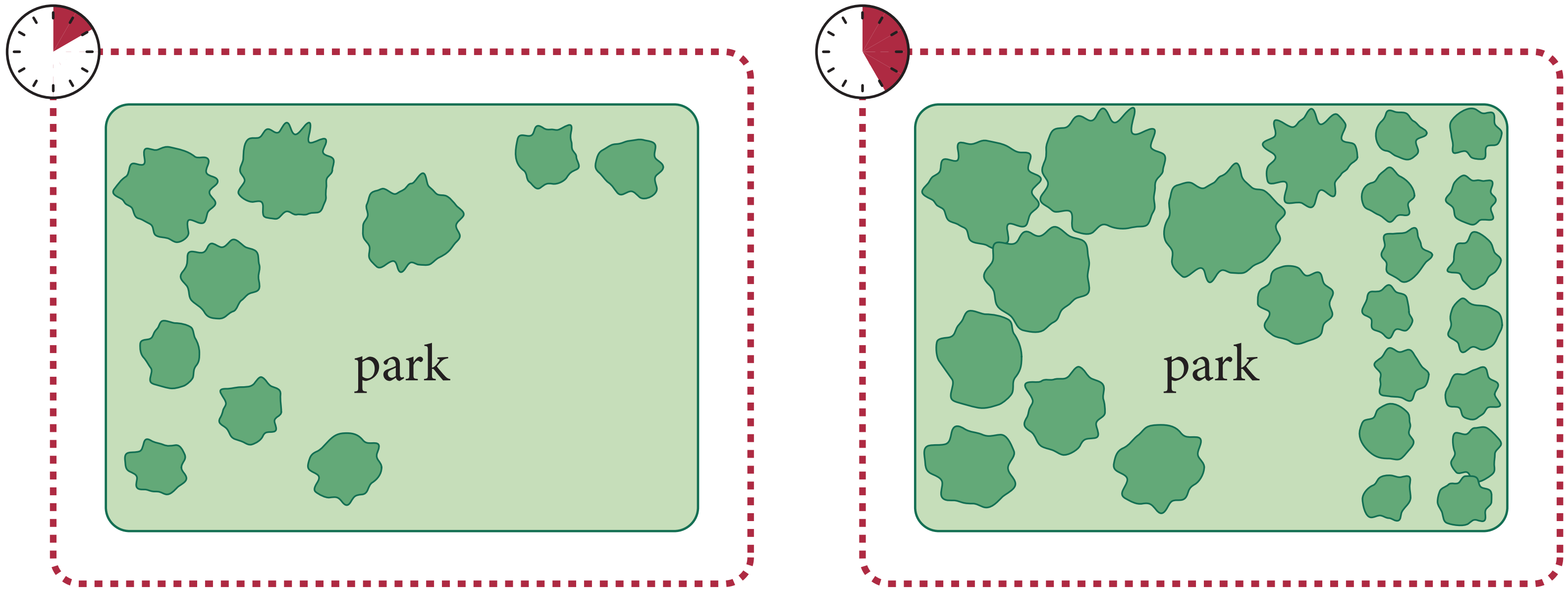
inertia m



$\vec{v}_s$
$\vec{v}_d = \vec{0}$
$\vec{v}_s$
$\vec{v}_d$
x
x
v_x (m/s)
0.8
0.6
0.4
0.2
0
−0.2
collision
double cart
Δv_{dx}
Δv_{sx}
t (ms)
20
40
60
80
100
120

systems & extensive quantities



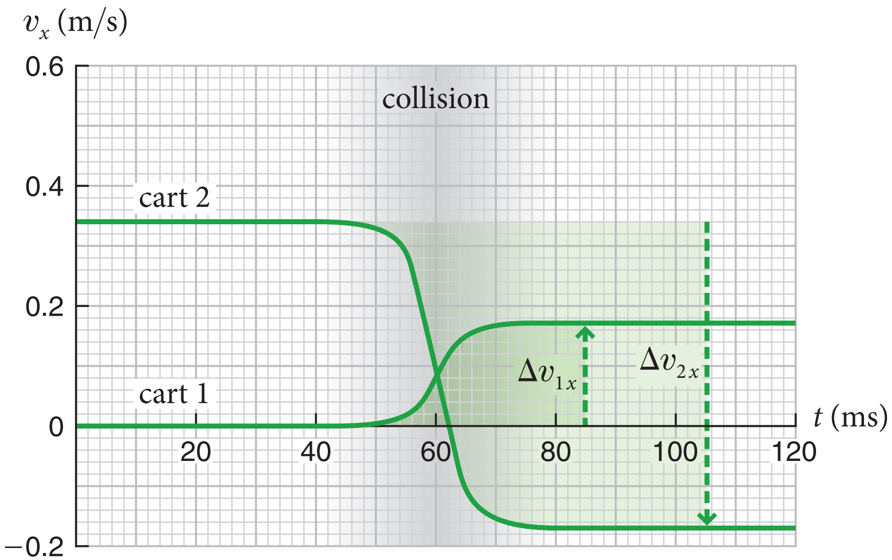
1 architecture   2 content

systems & extensive quantities

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

conserved quantity

1 architecture   2 content



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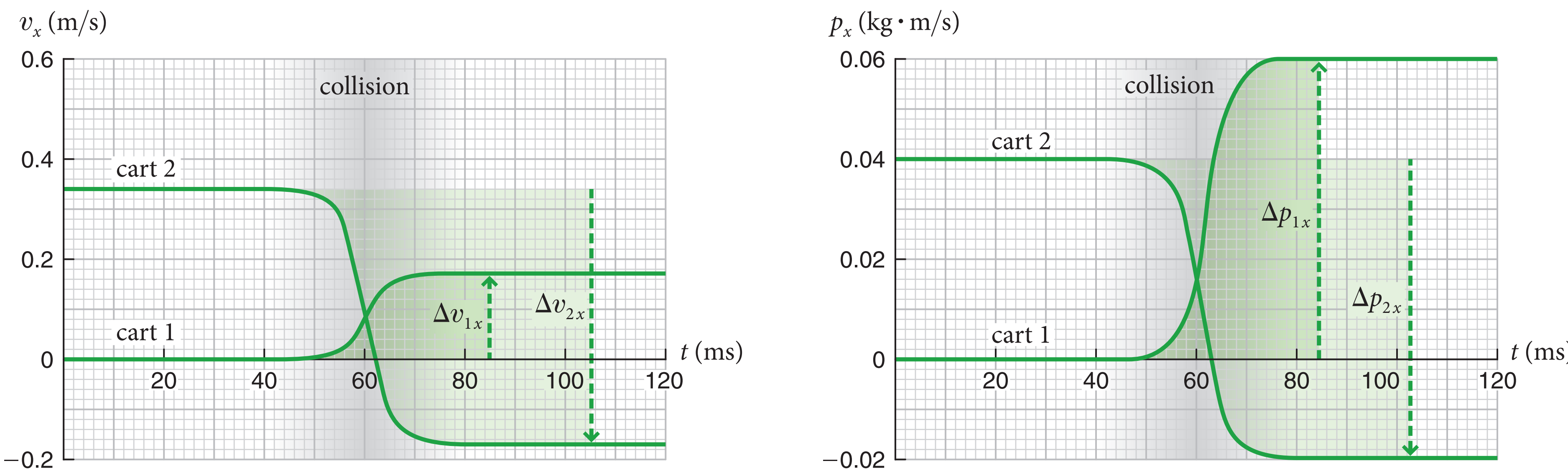

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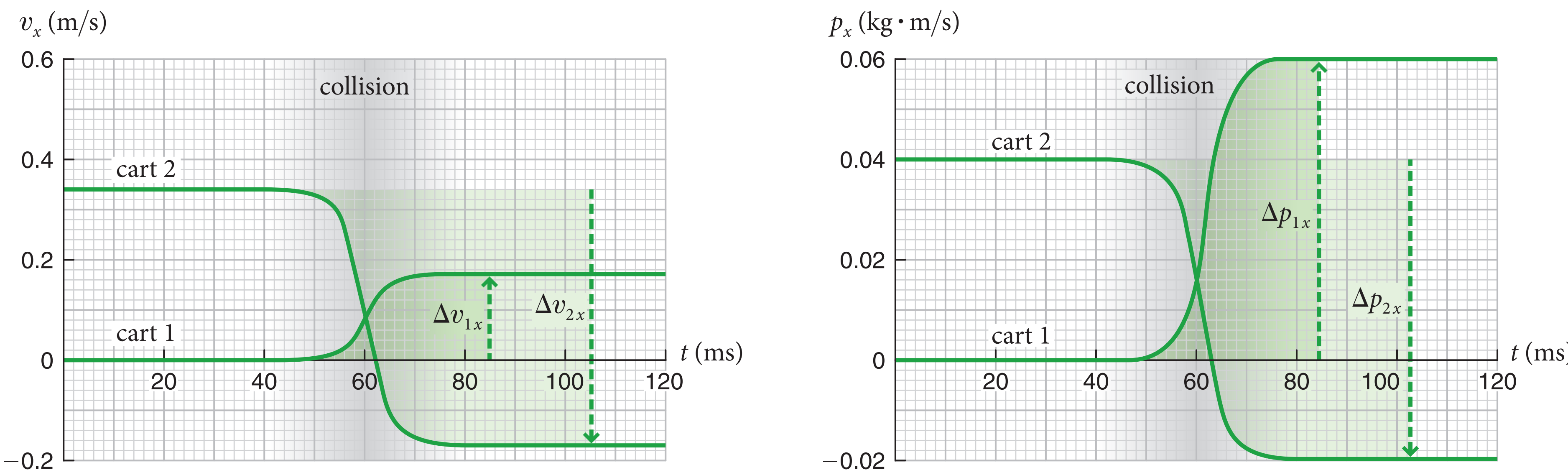
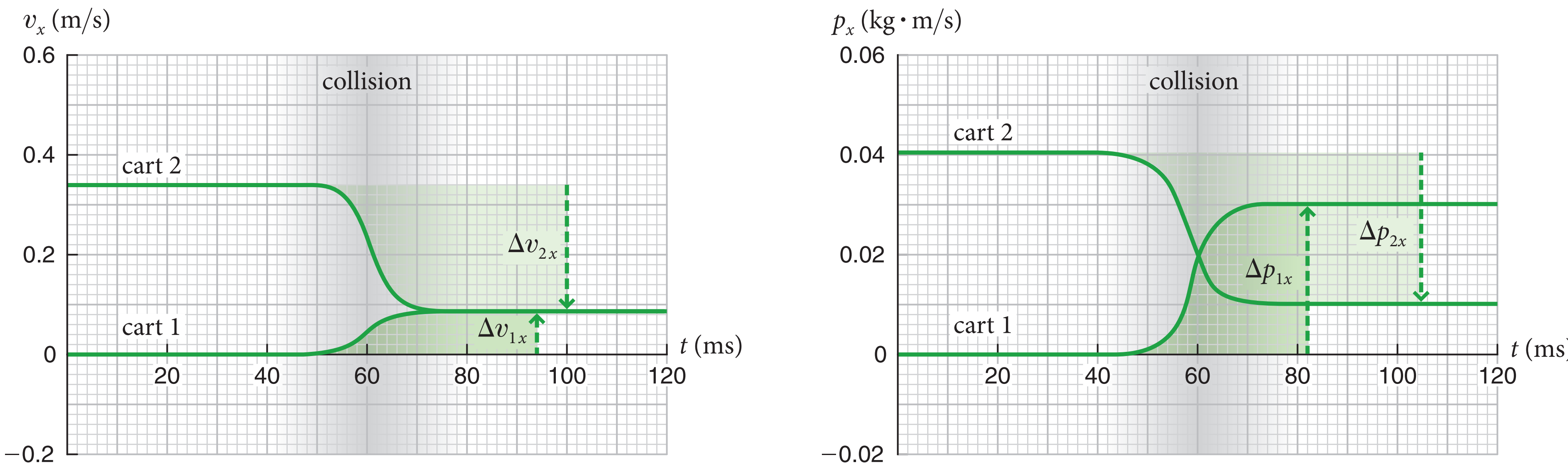


$$\Delta\vec{p} \equiv \Delta\vec{p}_1 + \Delta\vec{p}_2 = \vec{0}.$$



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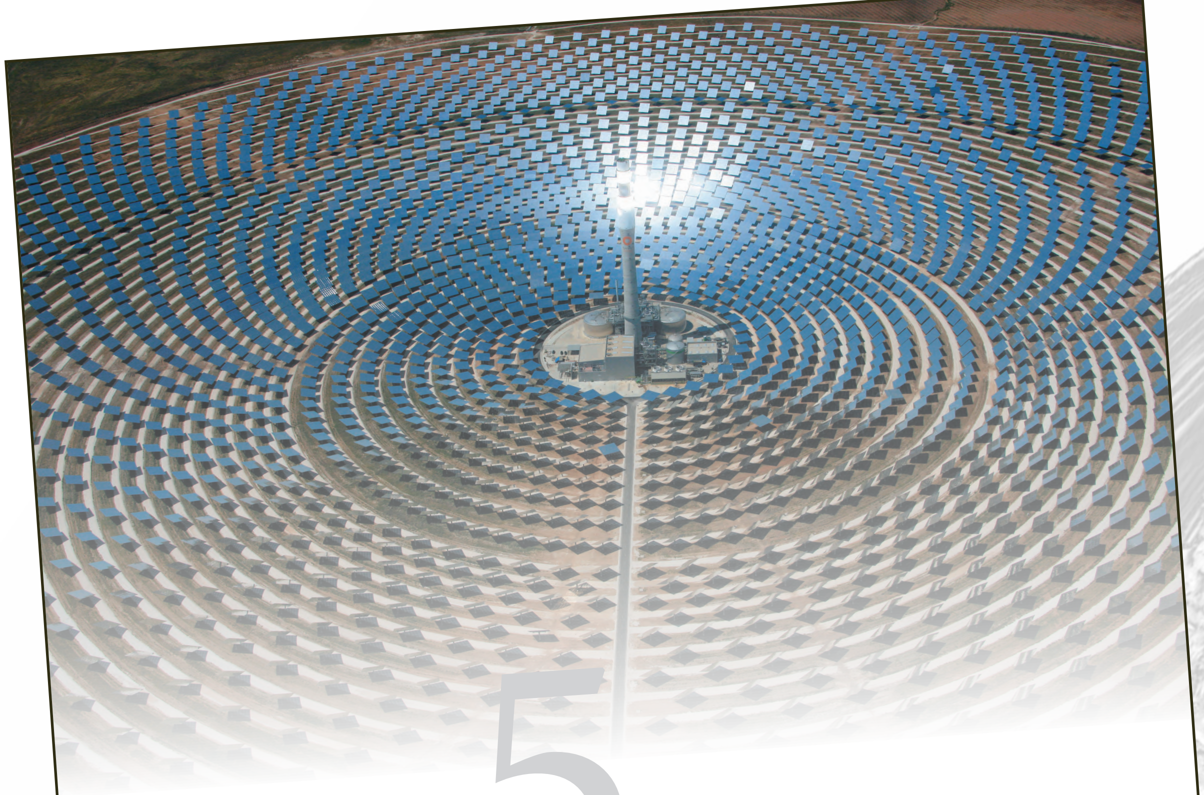


5 Energy

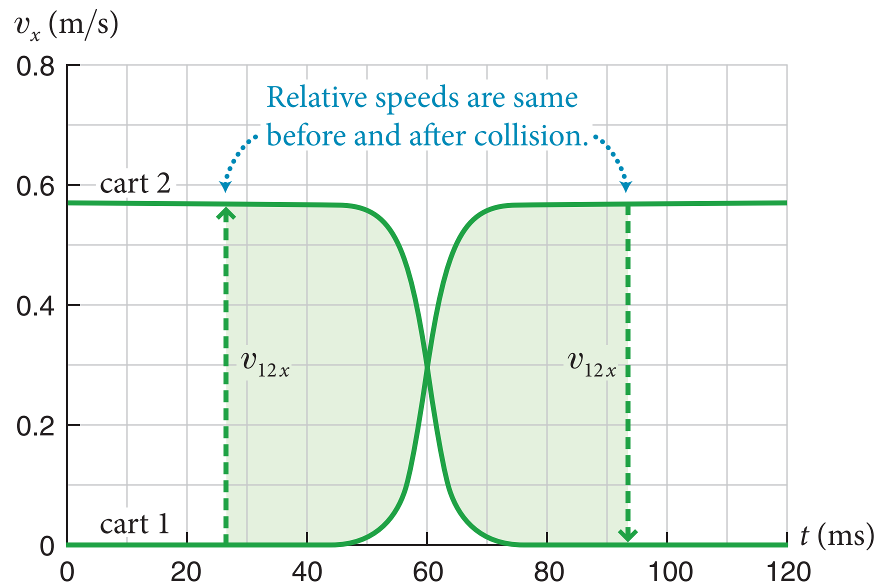
CONCEPTS

QUANTITATIVE TOOLS

1 architecture

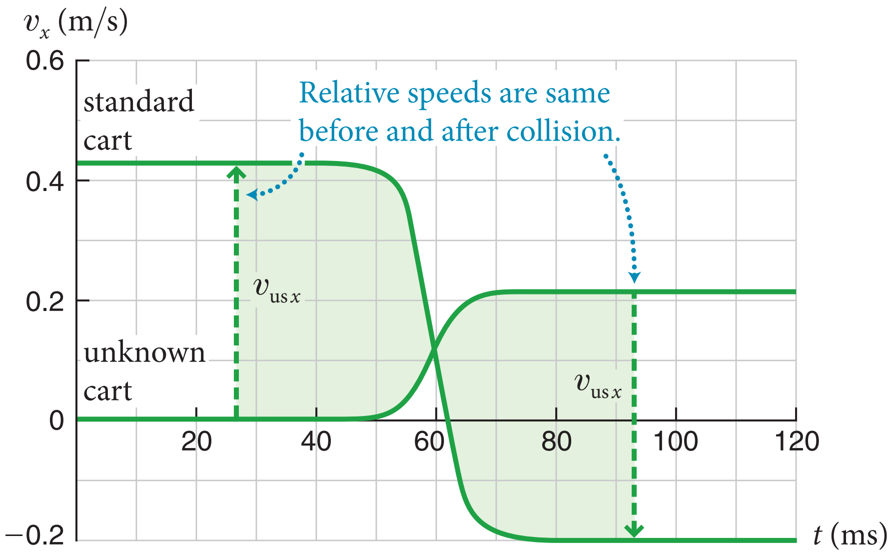
2 content

elastic: relative speed unchanged



1 architecture
2 content

elastic: relative speed unchanged



1 architecture **2** content

elastic: relative speed unchanged

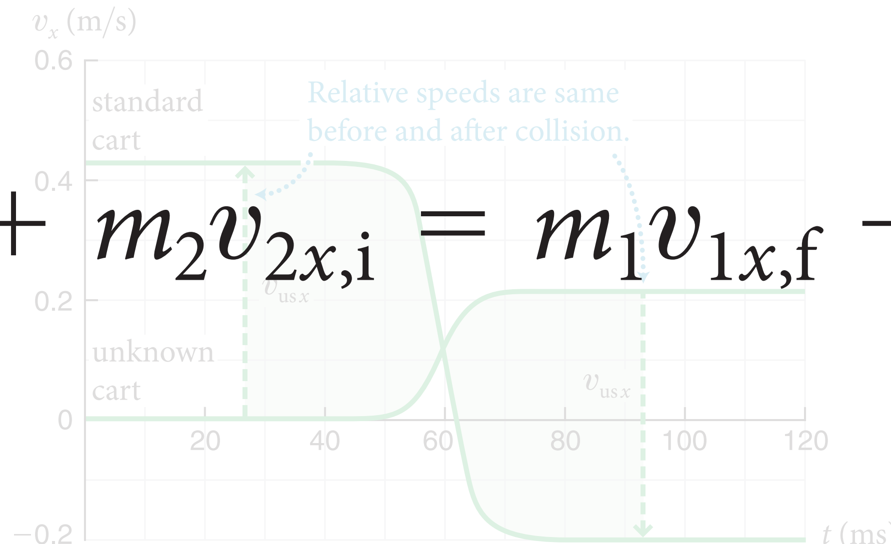
$$v_{12\text{i}} = v_{12\text{f}}$$

1 architecture
2 content

elastic: relative speed unchanged

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

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



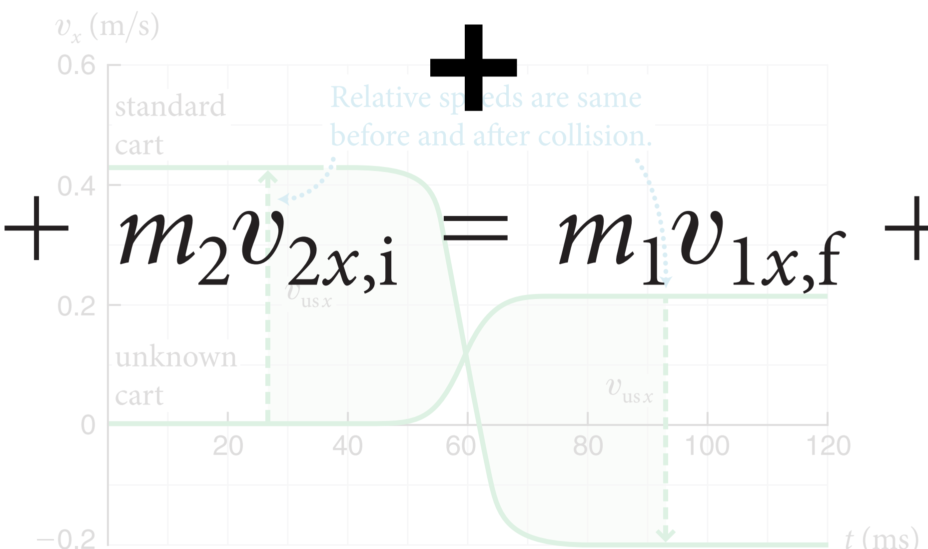
1 architecture   2 content

elastic: relative speed unchanged

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

+

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



1 architecture

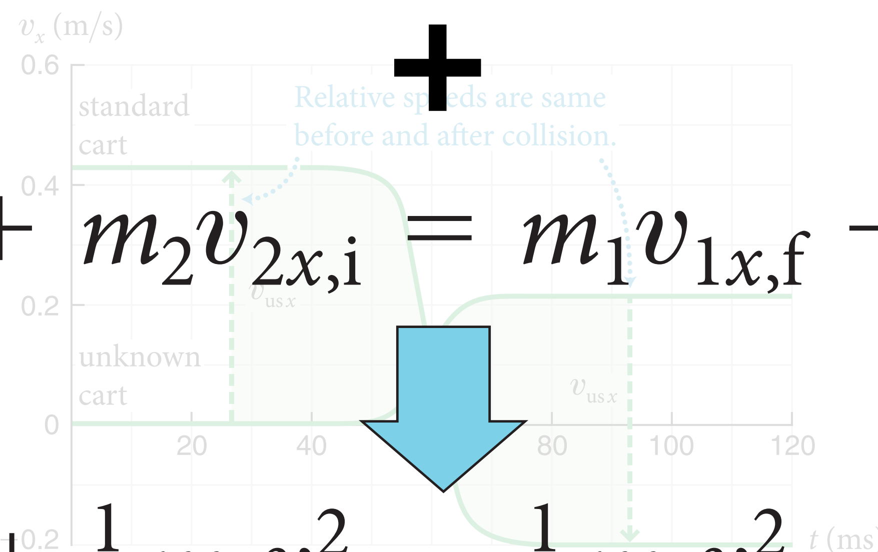
2 content

elastic: relative speed unchanged

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

+

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



$$\tfrac{1}{2} m_1 v_{1\mathrm{i}}^2 + \tfrac{1}{2} m_2 v_{2\mathrm{i}}^2 = \tfrac{1}{2} m_1 v_{1\mathrm{f}}^2 + \tfrac{1}{2} m_2 v_{2\mathrm{f}}^2.$$

elastic vs. inelastic

1 architecture **2** content

elastic vs. inelastic

before or after?

elastic vs. inelastic

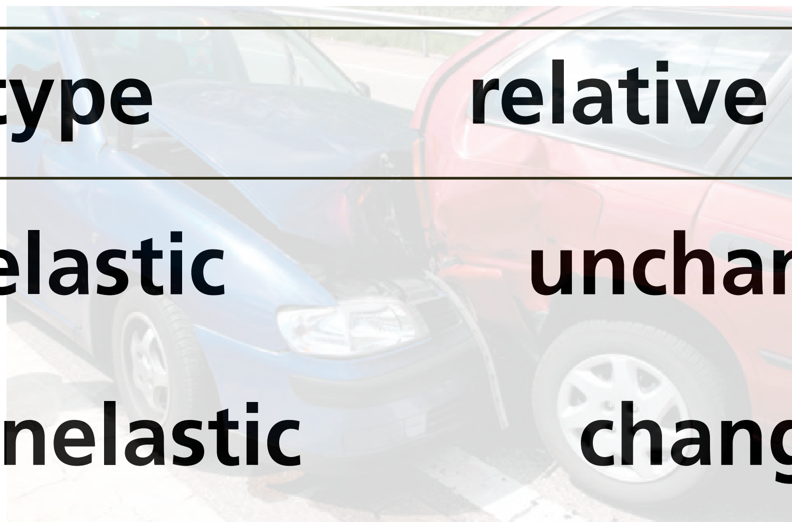
elastic: reversible

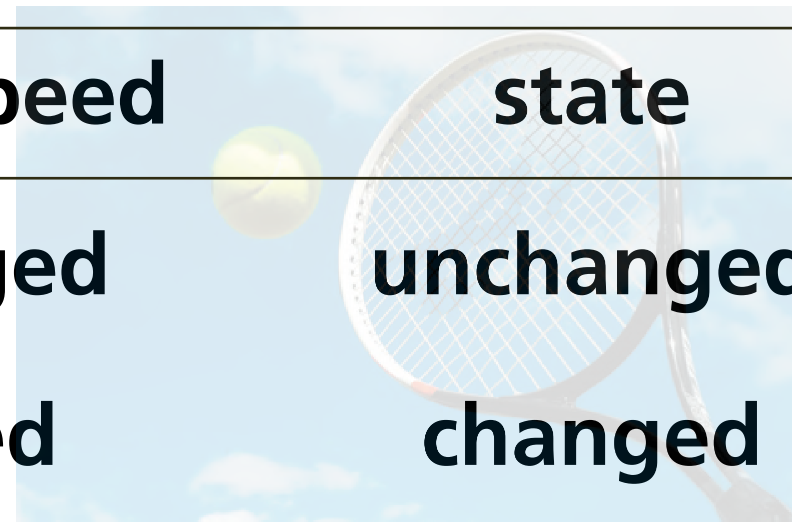
inelastic: irreversible

elastic vs. inelastic

type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

elastic vs. inelastic

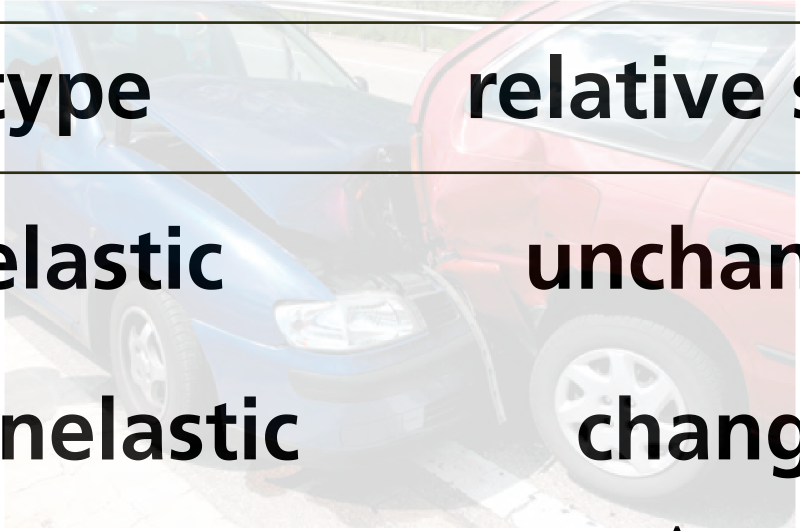


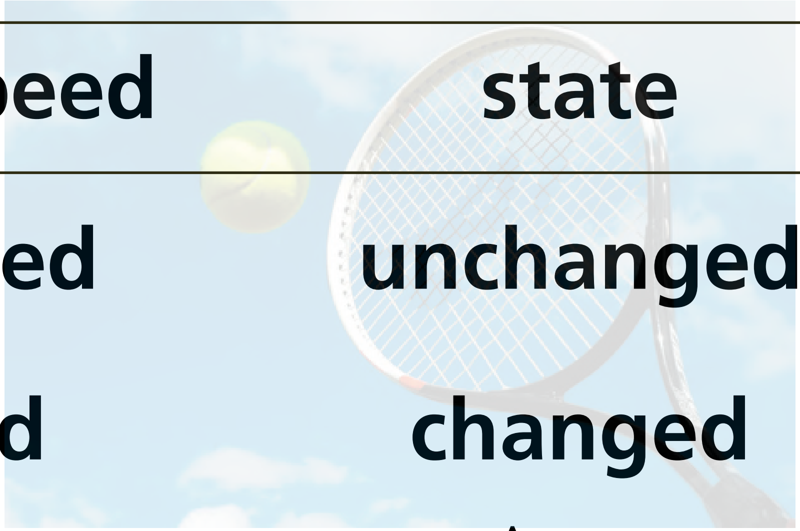


type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

$$\Delta K$$

elastic vs. inelastic





type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

ΔK ΔE_{int}

conservation of energy

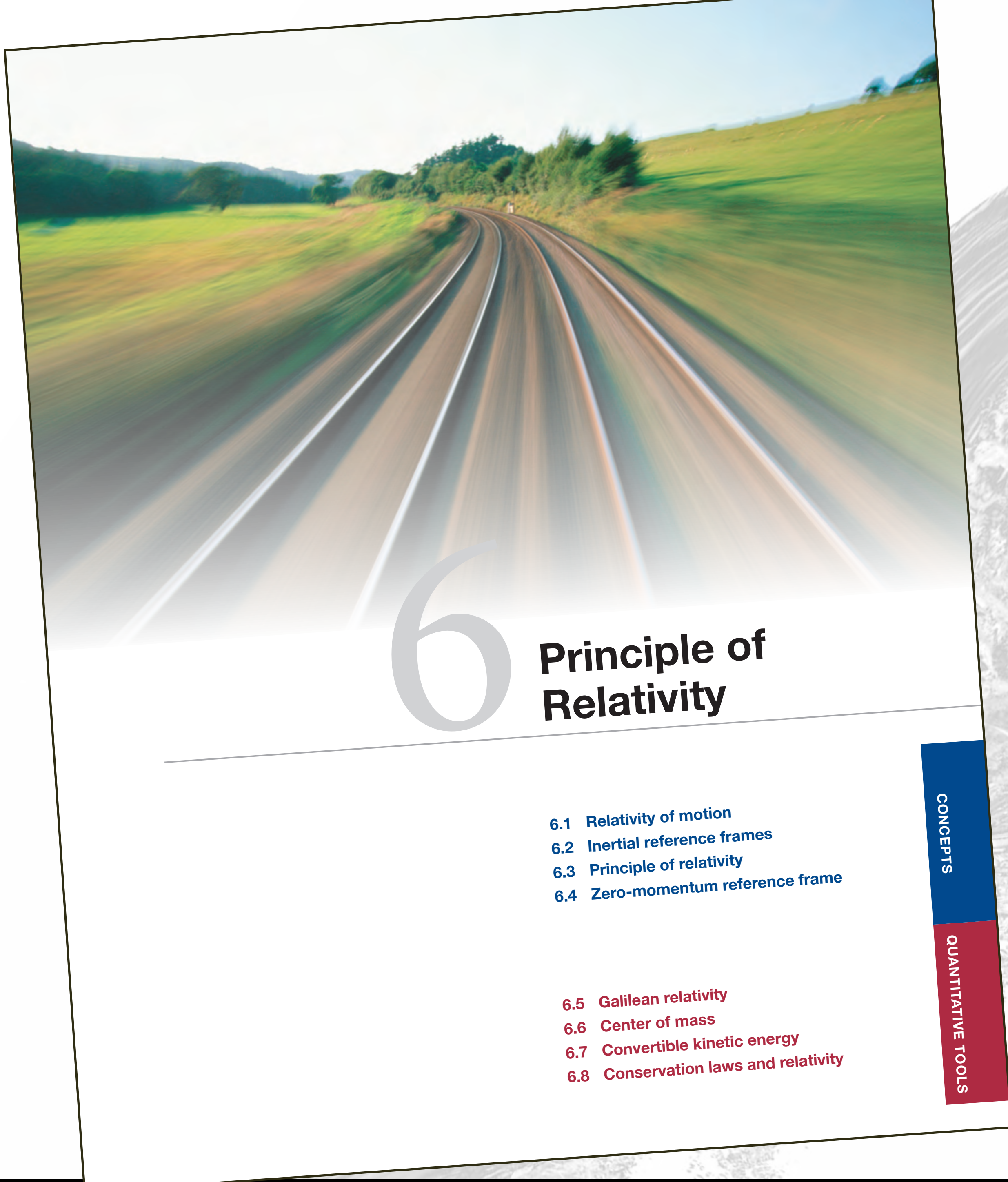
$$E = K + E_{\text{int}}$$

conservation of energy

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

closed system:

$$\Delta E = 0$$



6 Principle of Relativity

CONCEPTS

QUANTITATIVE TOOLS

1 architecture

2 content

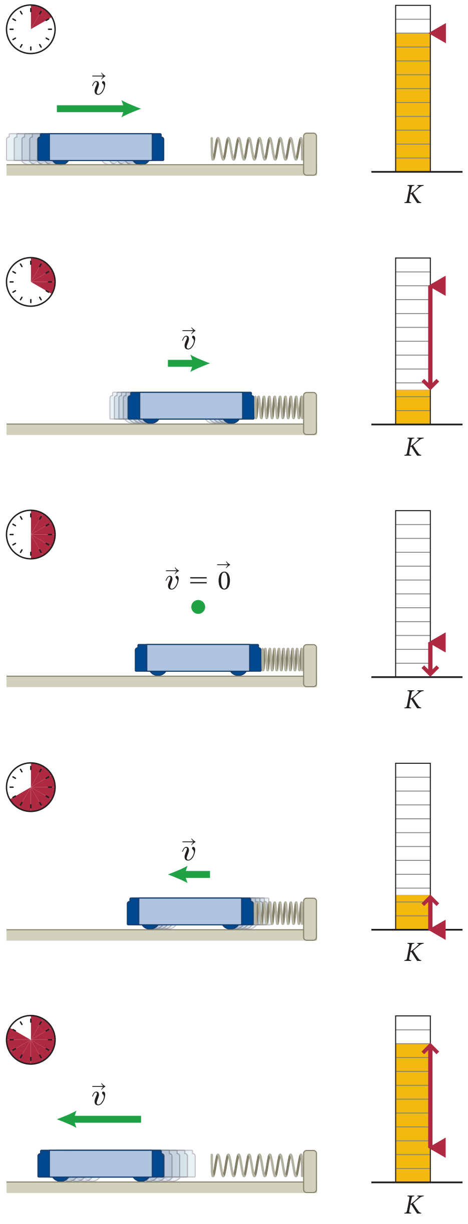
7 Interactions

CONCEPTS

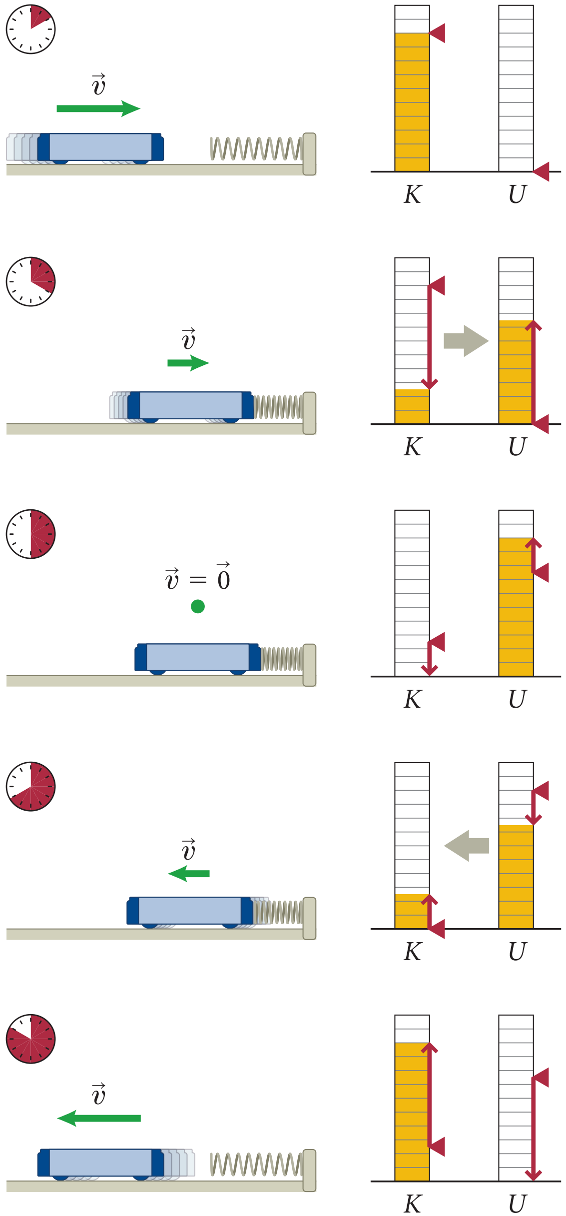
QUANTITATIVE TOOLS

1 architecture 2 content

potential energy



potential energy



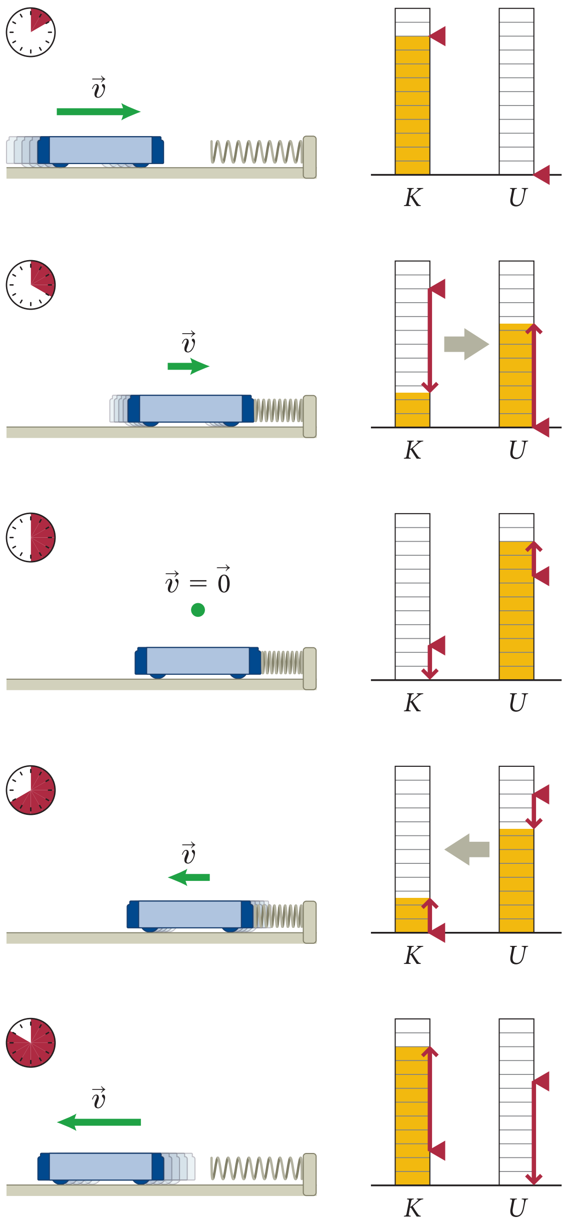
1 architecture

2 content

potential energy

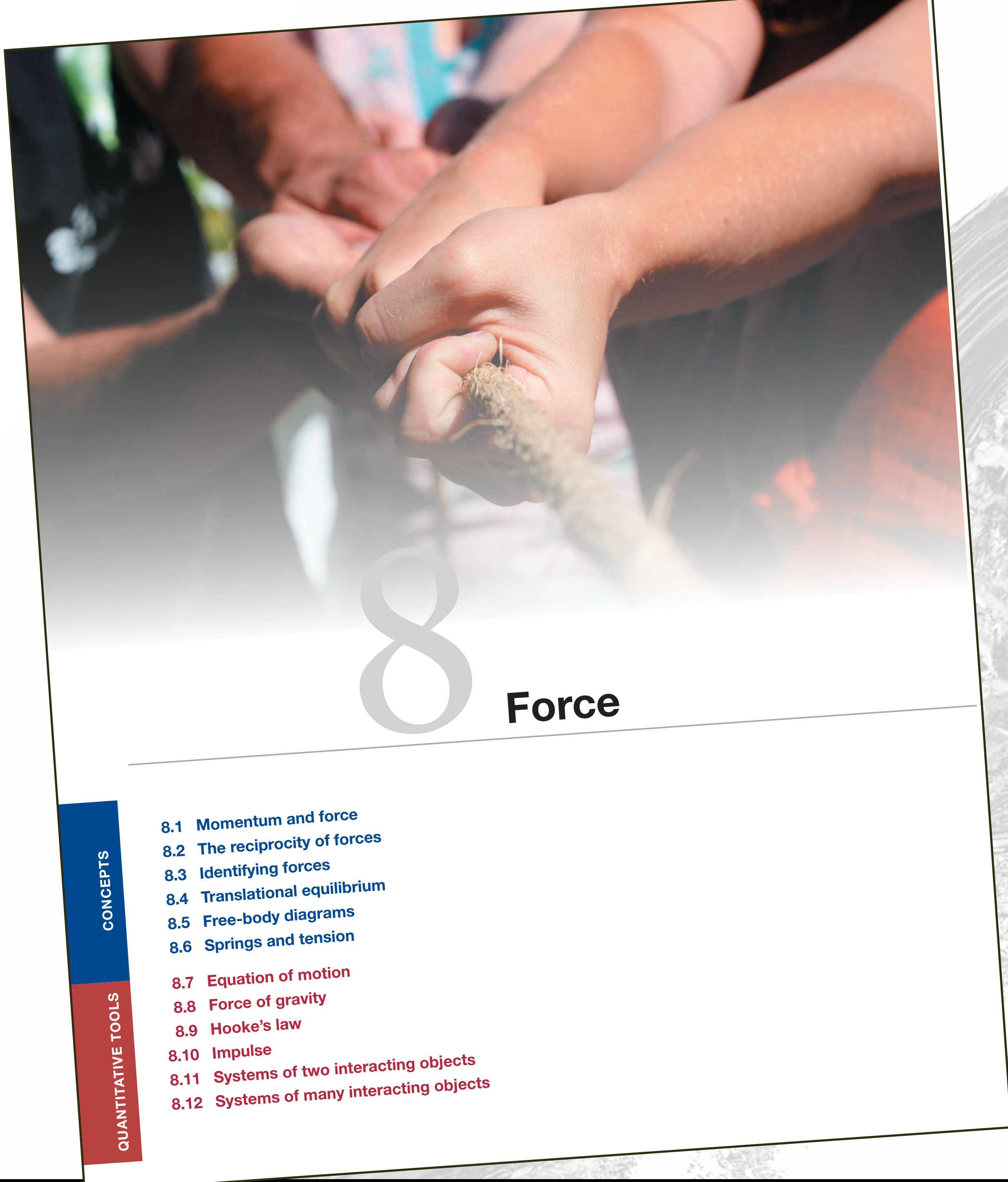
reversible

state change



1 architecture

2 content



8 Force

CONCEPTS

QUANTITATIVE TOOLS

1 architecture

2 content

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

1 architecture 2 content

9 Work

CONCEPTS

QUANTITATIVE TOOLS

1 architecture 2 content

how much work is it to switch?

1 architecture

2 content

Traditional	Principles and Practice
1. Physics and measurement	1. Foundations
2. Motion in one dimension	2. Motion in one dimension
3. Vectors	3. Acceleration
4. Motion in two dimensions	4. Momentum
5. The laws of motion	5. Energy
6. Circular motion	6. Principle of relativity
7. Work and kinetic energy	7. Interactions
8. Potential energy and CoE	8. Force
9. Momentum and collisions	9. Work
10. Rotation about a fixed axis	10. Motion in a plane
11. Rolling motion and angular momentum	11. Motion in a circle
12. Static equilibrium and elasticity	12. Torque
13. Oscillatory motion	13. Gravity
14. The law of gravity	14. Special Relativity
15. Fluid mechanics	15. Periodic Motion
16. Wave motion	16. Waves in one dimension
17. Sound waves	17. Waves in 2 and 3 dimensions
18. Superposition and standing waves	18. Fluids

1 architecture   2 content

Traditional	Principles and Practice	
1. Physics and measurement	1. Foundations	
2. Motion in one dimension	2. Motion in one dimension	1D
3. Vectors	3. Acceleration	
4. Motion in two dimensions	4. Momentum	
5. The laws of motion	5. Energy	
6. Circular motion	6. Principle of relativity	
7. Work and kinetic energy	7. Interactions	
8. Potential energy and CoE	8. Force	
9. Momentum and collisions	9. Work	
10. Rotation about a fixed axis	10. Motion in a plane	3D
11. Rolling motion and angular momentum	11. Motion in a circle	
12. Static equilibrium and elasticity	12. Torque	
13. Oscillatory motion	13. Gravity	
14. The law of gravity	14. Special Relativity	
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17. Sound waves	17. Waves in 2 and 3 dimensions	
18. Superposition and standing waves	18. Fluids	

1 architecture 2 content

Traditional	Principles and Practice	
1. Physics and measurement	1. Foundations	
2. Motion in one dimension	2. Motion in one dimension	1D
3. Vectors	3. Acceleration	1D
4. Motion in two dimensions	4. Momentum	1D
5. The laws of motion	5. Energy	1D
6. Circular motion	6. Principle of relativity	1D
7. Work and kinetic energy	7. Interactions	1D
8. Potential energy and CoE	8. Force	1D
9. Momentum and collisions	9. Work	1D
10. Rotation about a fixed axis	10. Motion in a plane	3D
11. Rolling motion and angular momentum	11. Motion in a circle	3D
12. Static equilibrium and elasticity	12. Torque	3D
13. Oscillatory motion	13. Gravity	3D
14. The law of gravity	14. Special Relativity	
15. Fluid mechanics	15. Periodic Motion	
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1 architecture 2 content

Traditional	Principles and Practice	
1. Physics and measurement	1. Foundations	
2. Motion in one dimension	2. Motion in one dimension	1D
3. Vectors	3. Acceleration	1D
4. Motion in two dimensions	4. Momentum	1D
5. The laws of motion	5. Energy	1D
6. Circular motion	6. Principle of relativity	1D
7. Work and kinetic energy	7. Interactions	1D
8. Potential energy and CoE	8. Force	1D
9. Momentum and collisions	9. Work	1D
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1 architecture 2 content

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1D

3D

1 architecture

2 content

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conservation

dynamics

1 architecture 2 content

Traditional	Principles and Practice
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2. Motion in one dimension	2. Motion in one dimension
3. Vectors	3. Acceleration
4. Motion in two dimensions	4. Momentum
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rotation

1 architecture   2 content

Traditional	Principles and Practice
1. Physics and measurement	1. Foundations
2. Motion in one dimension	2. Motion in one dimension
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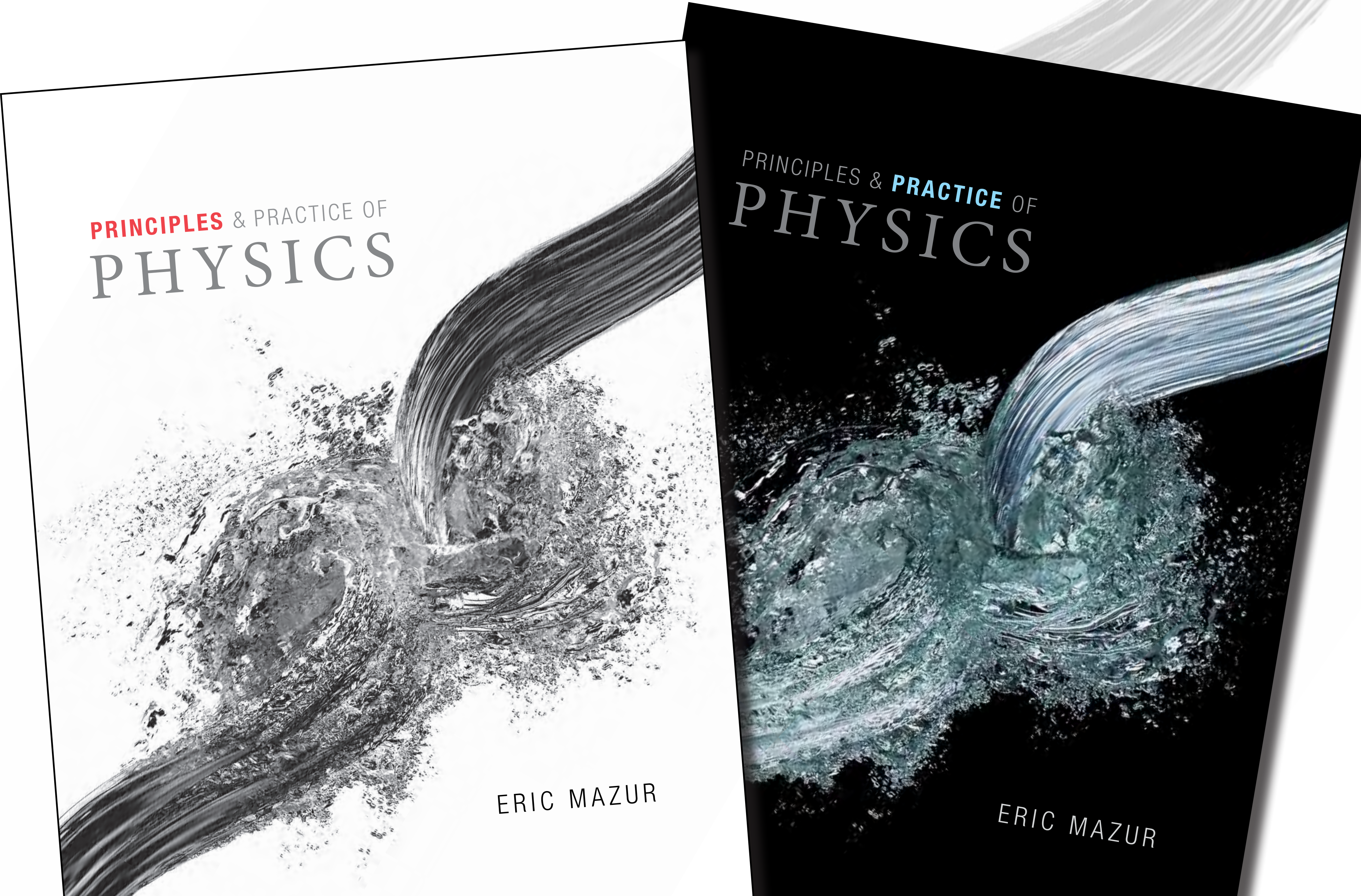
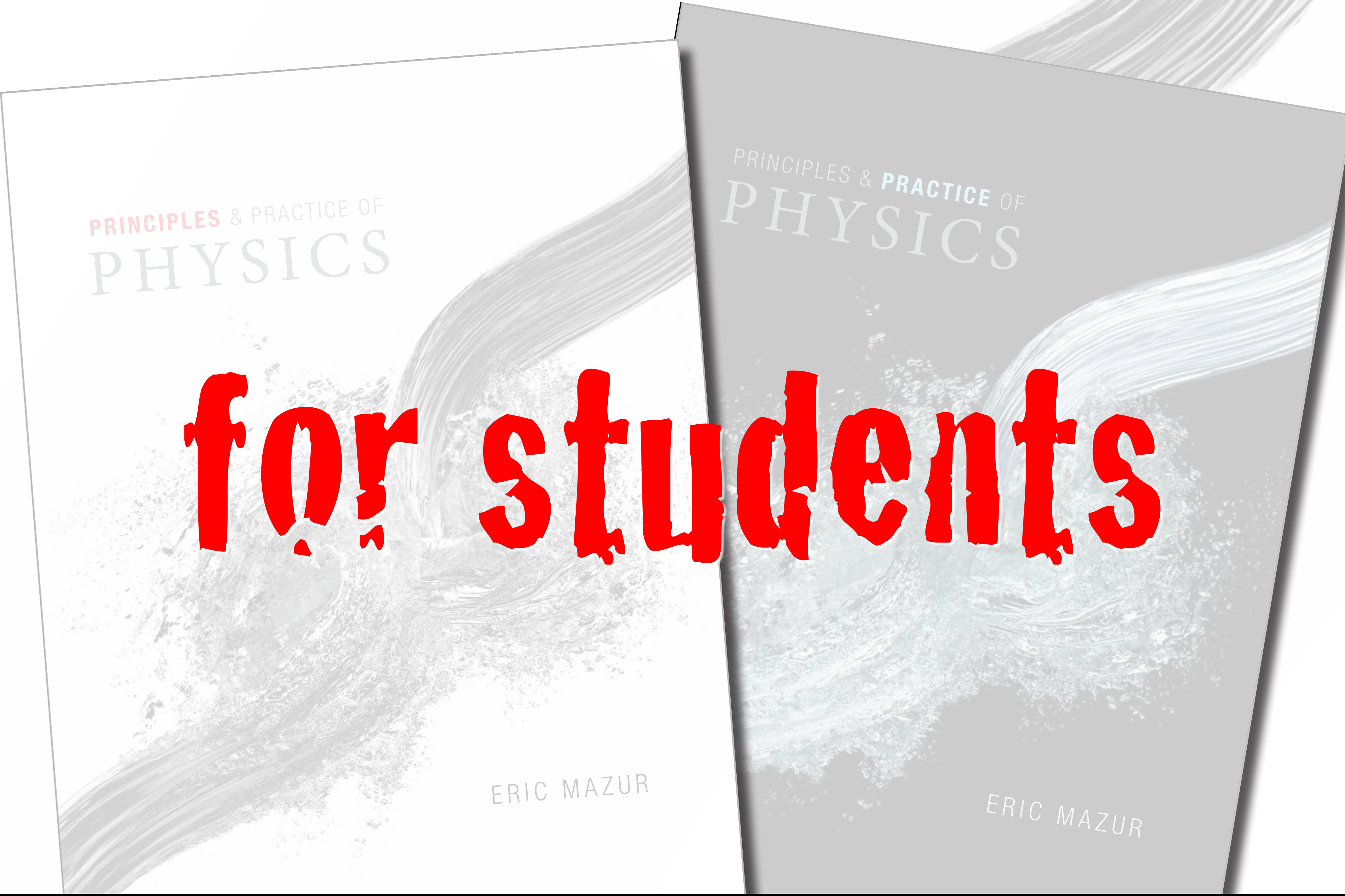
periodic

1 architecture 2 content

mostly minor rearrangements!



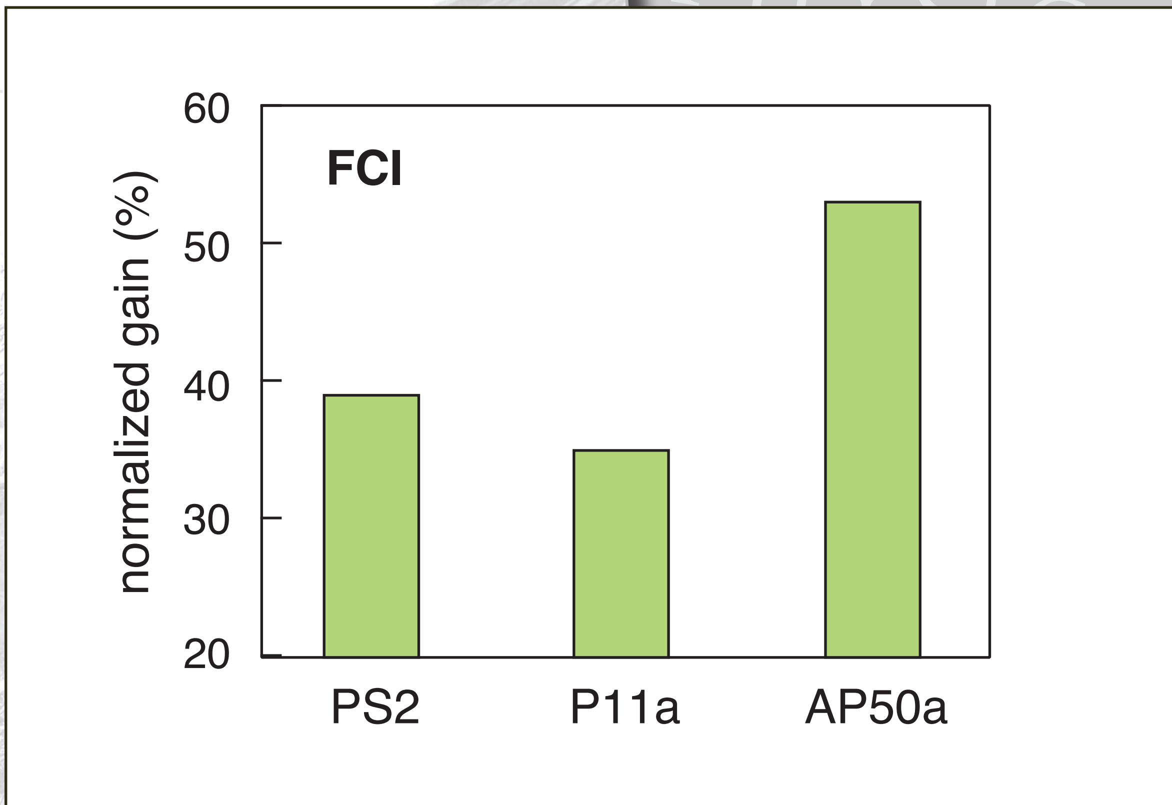
1 architecture
2 content
3 results



for students

1 architecture   2 content   3 results

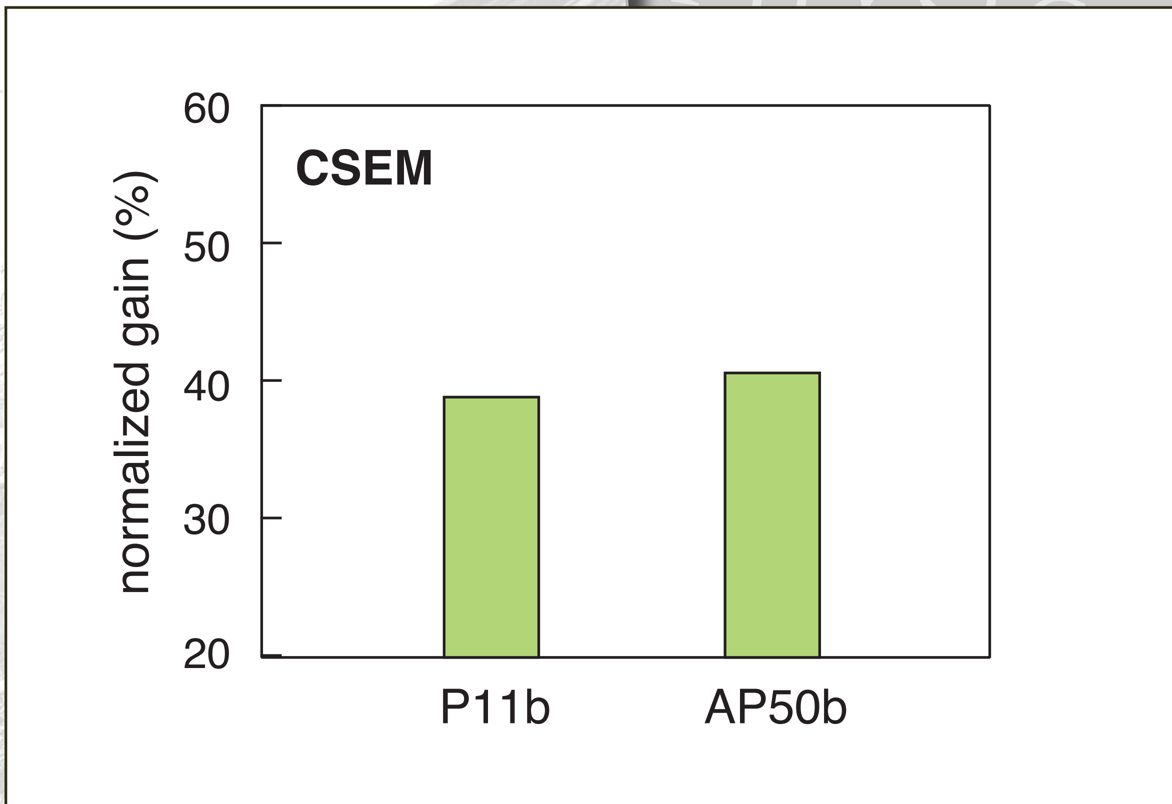
AP50: no lectures, students read book only



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

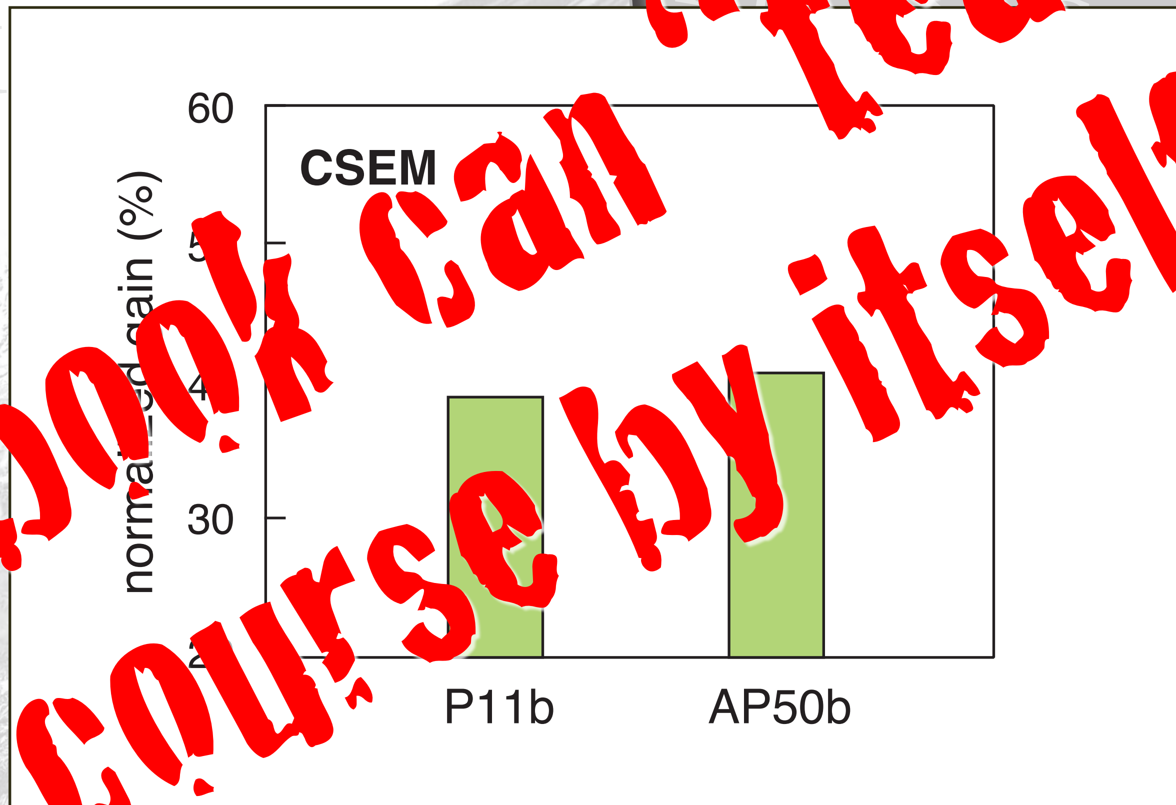
1 architecture 2 content 3 results

AP50: no lectures, students read book only



as good as when I do my best teaching!

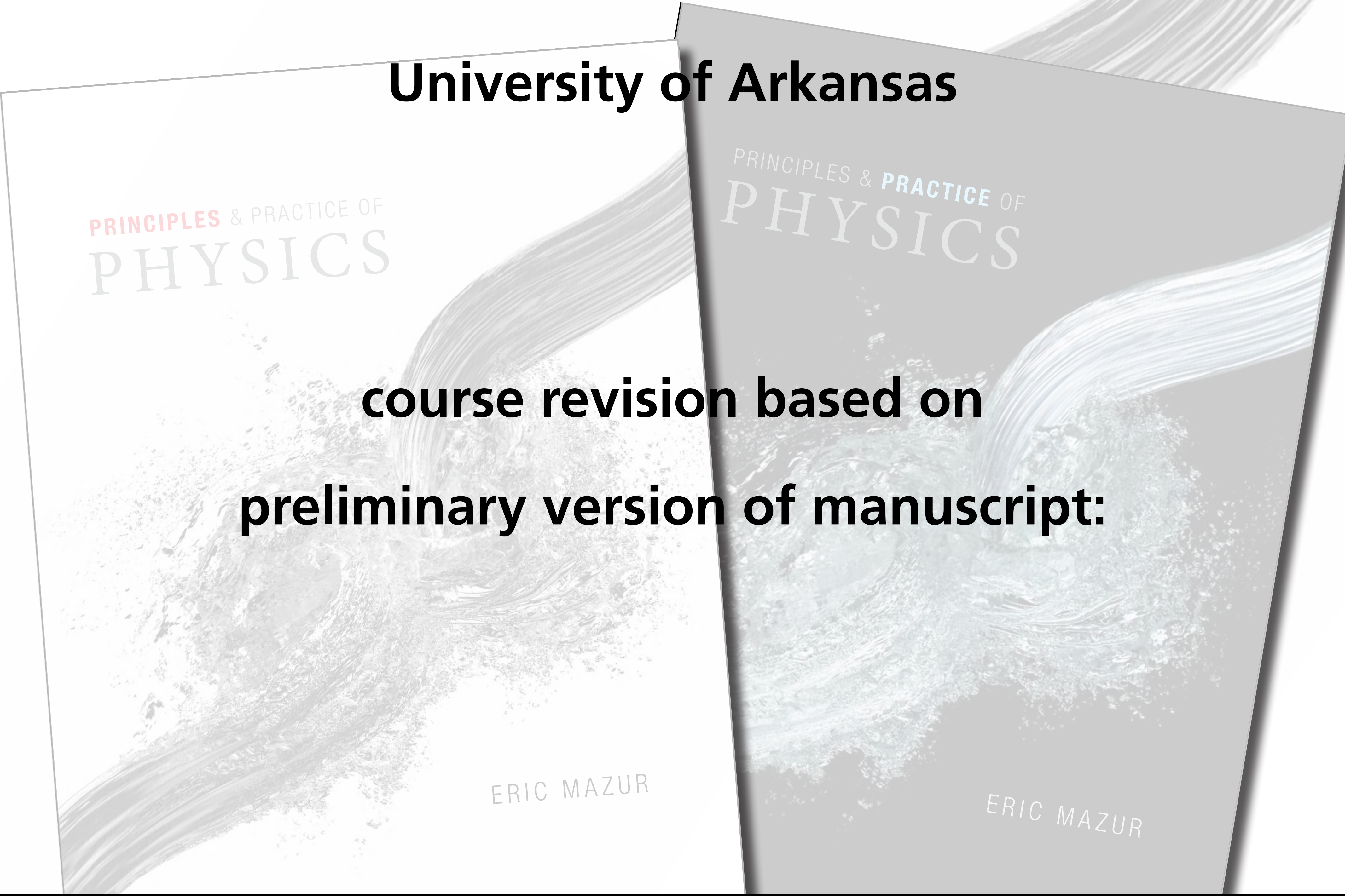
AP50: no lectures, students read book only



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

as good as when I do my best teaching!

University of Arkansas



course revision based on

preliminary version of manuscript:

1 architecture **2** content **3** results

University of Arkansas

course revision based on

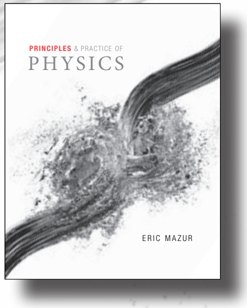
preliminary version of manuscript:

normalized FCI gain DOUBLED

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)

approach	before class	in class
traditional	–	

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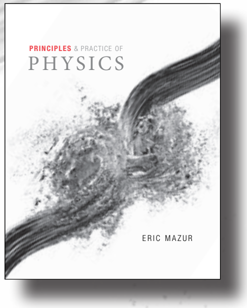
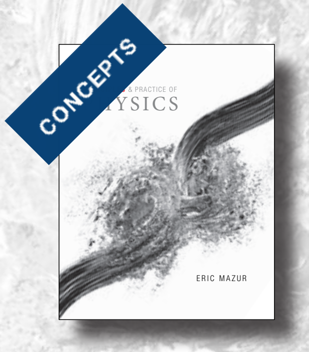
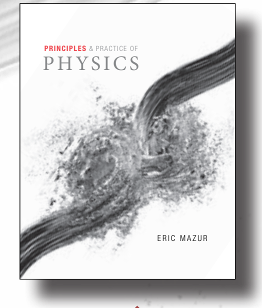
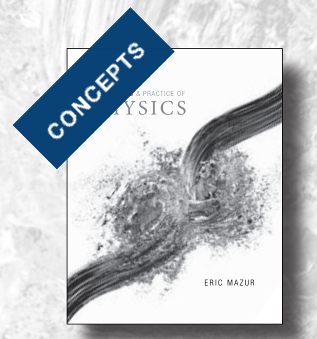
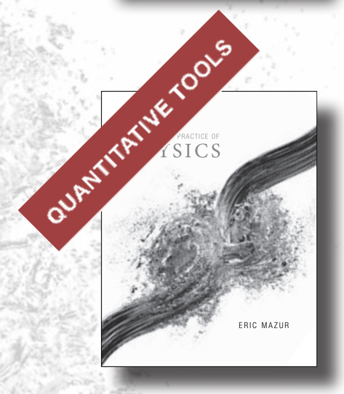
traditional	–	
partially flipped		

approach	before class	in class
traditional	–	
partially flipped		

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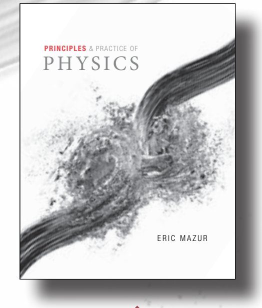
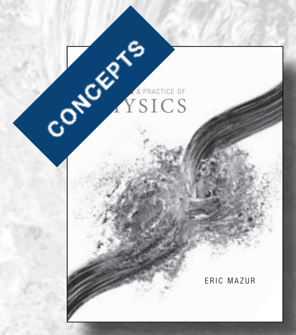
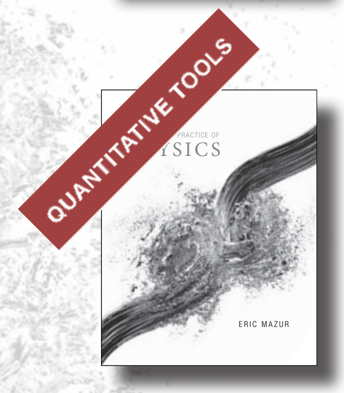
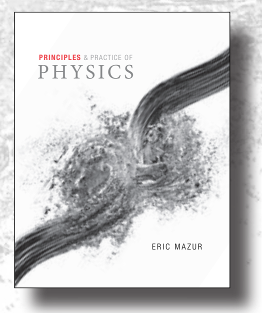
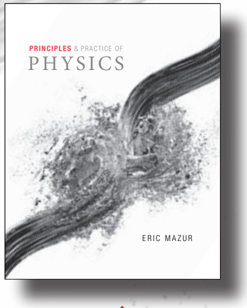
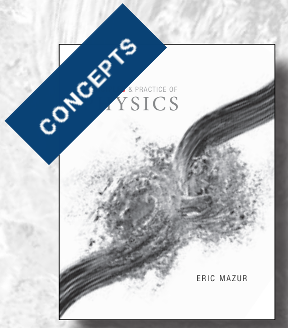
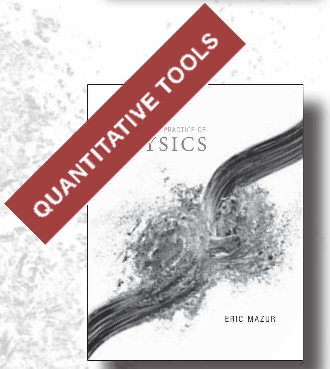
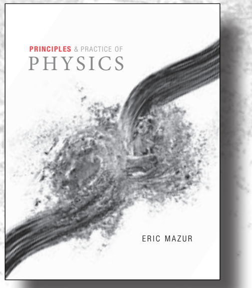
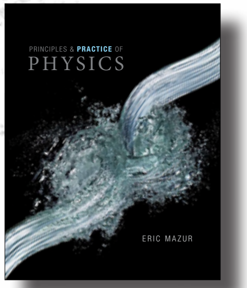
traditional	–	
partially flipped		
fully flipped		

approach	before class	in class
traditional	–	
partially flipped		
fully flipped		

1 architecture 2 content 3 results

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