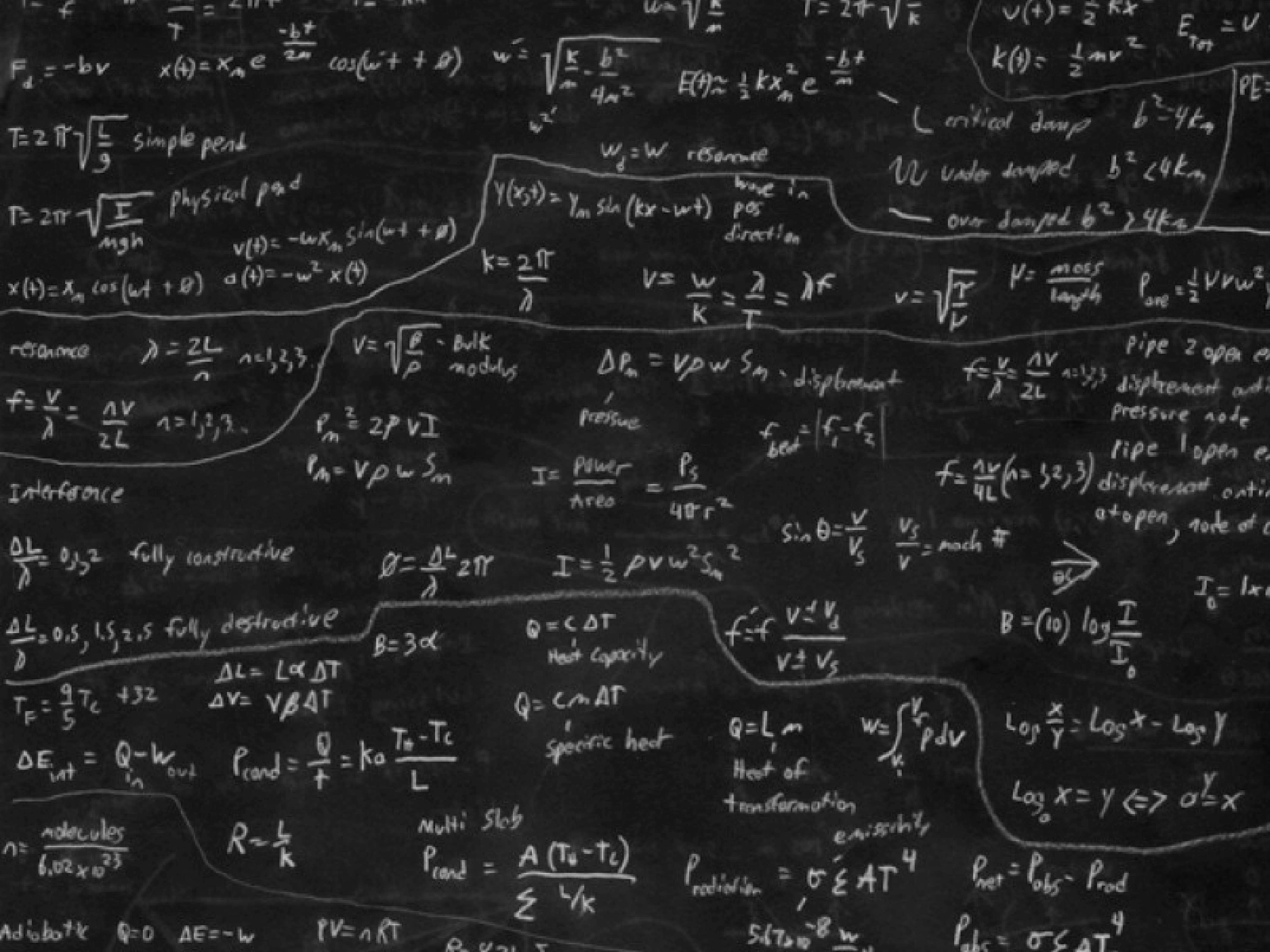
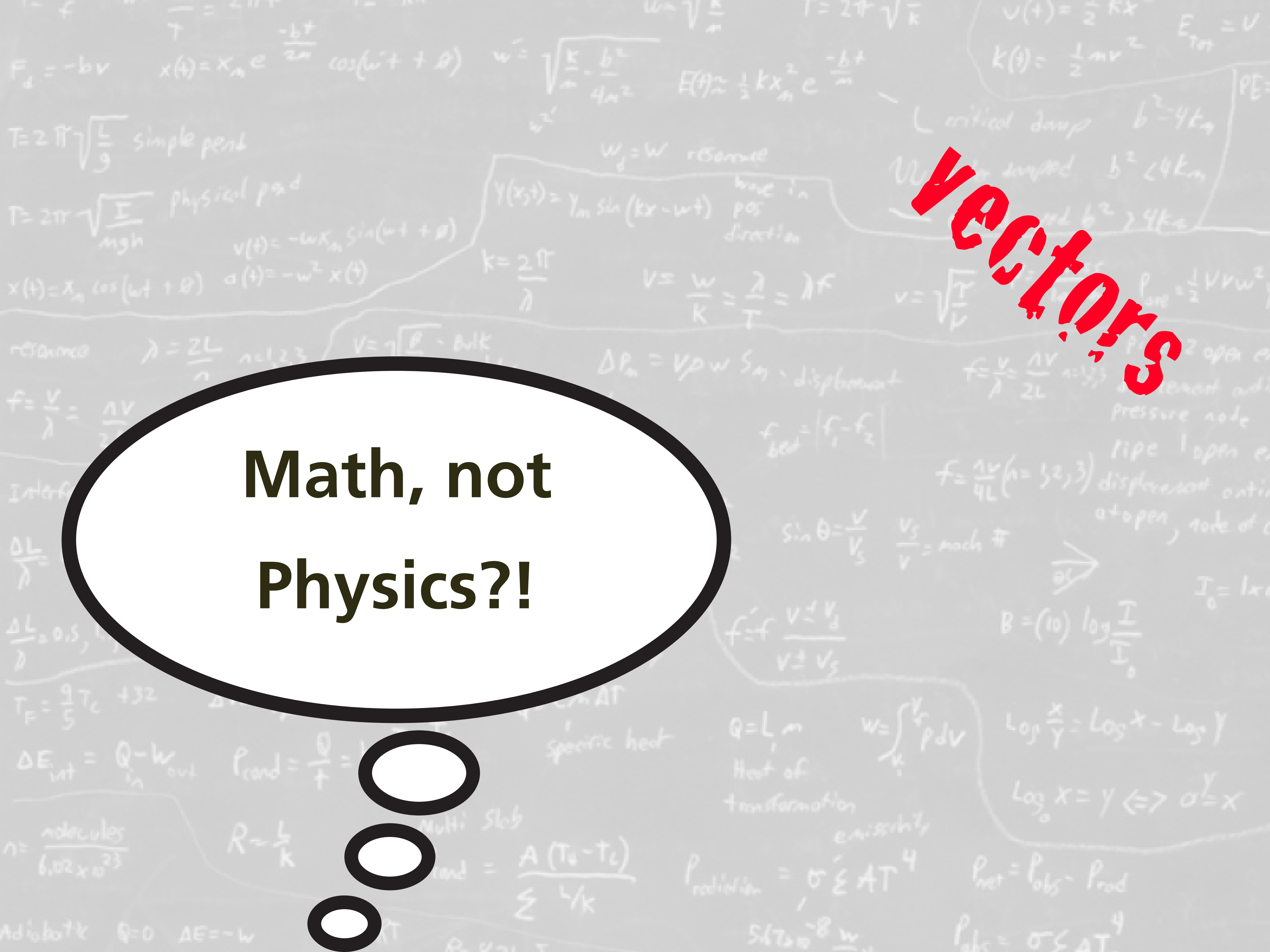
The Principles and Practice of Physics

University of Michigan
Ann Arbor, MI, 14 February 2014



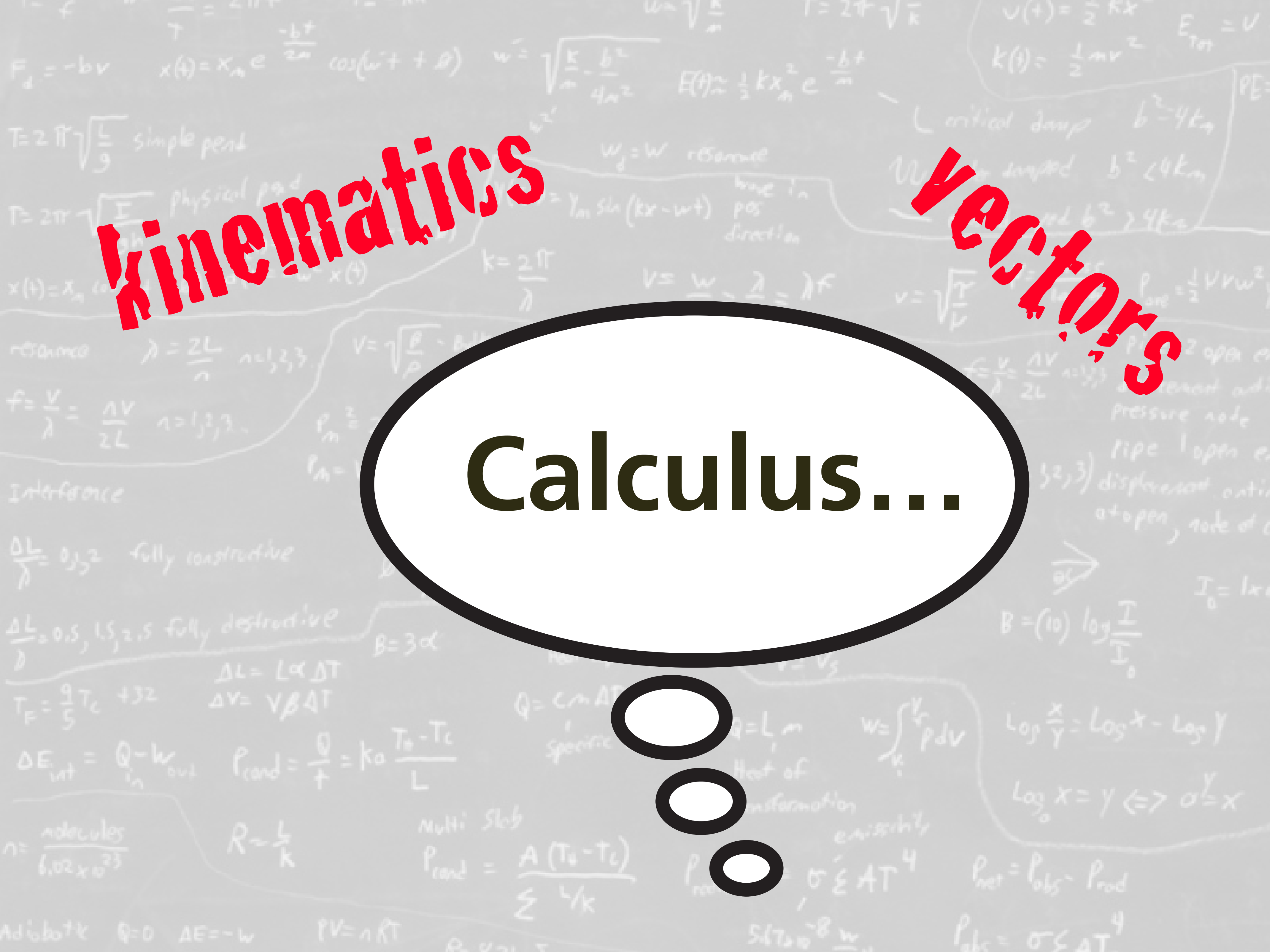
Fd = -bv
x(t) = xm e^(-bt/2m) cos(w't + ø)
w' = √(k/m - b²/4m²)
E(t) ≈ ½ k xm² e^(-bt/m)
T = 2π √(k/m)
v(t) = ½ kx²
k(t) = ½ mv²
E_Tot = U
critical damp b² = 4km
under damped b² < 4km
over damped b² > 4km
T = 2π √(L/g) simple pend
T = 2π √(I/mgh) physical pend
wd = w resonance
y(x,t) = ym sin(kx - wt)
wave in pos direction
v(t) = -wxm sin(wt + ø)
a(t) = -w² x(t)
x(t) = xm cos(wt + ø)
k = 2π/λ
v = w/k = λ/T = λf
v = √(τ/μ)
μ = mass/length
P_ave = ½ μvw² ym²
resonance λ = 2L/n n=1,2,3
f = v/λ = nv/2L n=1,2,3
v = √(B/ρ) Bulk modulus
ΔPm = vρw sm displacement
pressure
Pm² = 2ρvI
Pm = vρw sm
f_beat = |f1 - f2|
pipe 2 open ends
f = v/λ = nv/2L n=1,2,3
displacement antinode
pressure node
pipe 1 open end
f = nv/4L (n = 1,3,5)
displacement antinode at open, node at closed
Interference
I = power/Area = Ps/4πr²
sin θ = v/vs
vs/v = mach #
ΔL/λ = 0,1,2 fully constructive
ø = (ΔL/λ) 2π
I = ½ ρvw² sm²
I0 = 1×10⁻¹²
ΔL/λ = 0.5, 1.5, 2.5 fully destructive
B = 3α
Q = C ΔT
Heat capacity
f' = f (v ± vd)/(v ± vs)
B = (10) log I/I0
ΔL = Lα ΔT
ΔV = Vβ ΔT
TF = (9/5) TC + 32
Q = cm ΔT
specific heat
Q = L m
Heat of transformation
W = ∫ p dV
Log x/y = Log x - Log y
Loga x = y ⟺ a^y = x
ΔEint = Qin - Wout
Pcond = Q/t = kA (TH - TC)/L
n = molecules/6.02×10²³
R = L/k
Multi Slab
Pcond = A(TH - TC)/Σ L/k
emissivity
Pradiation = σεAT⁴
Pnet = Pabs - Prad
Adiabatic Q=0 ΔE=-W
PV = nRT
5.67×10⁻⁸ W
Pabs = σεAT⁴

vectors


vectors
Math, not Physics?!

kinematics

vectors


kinematics
vectors
Calculus…

kinematics

vectors

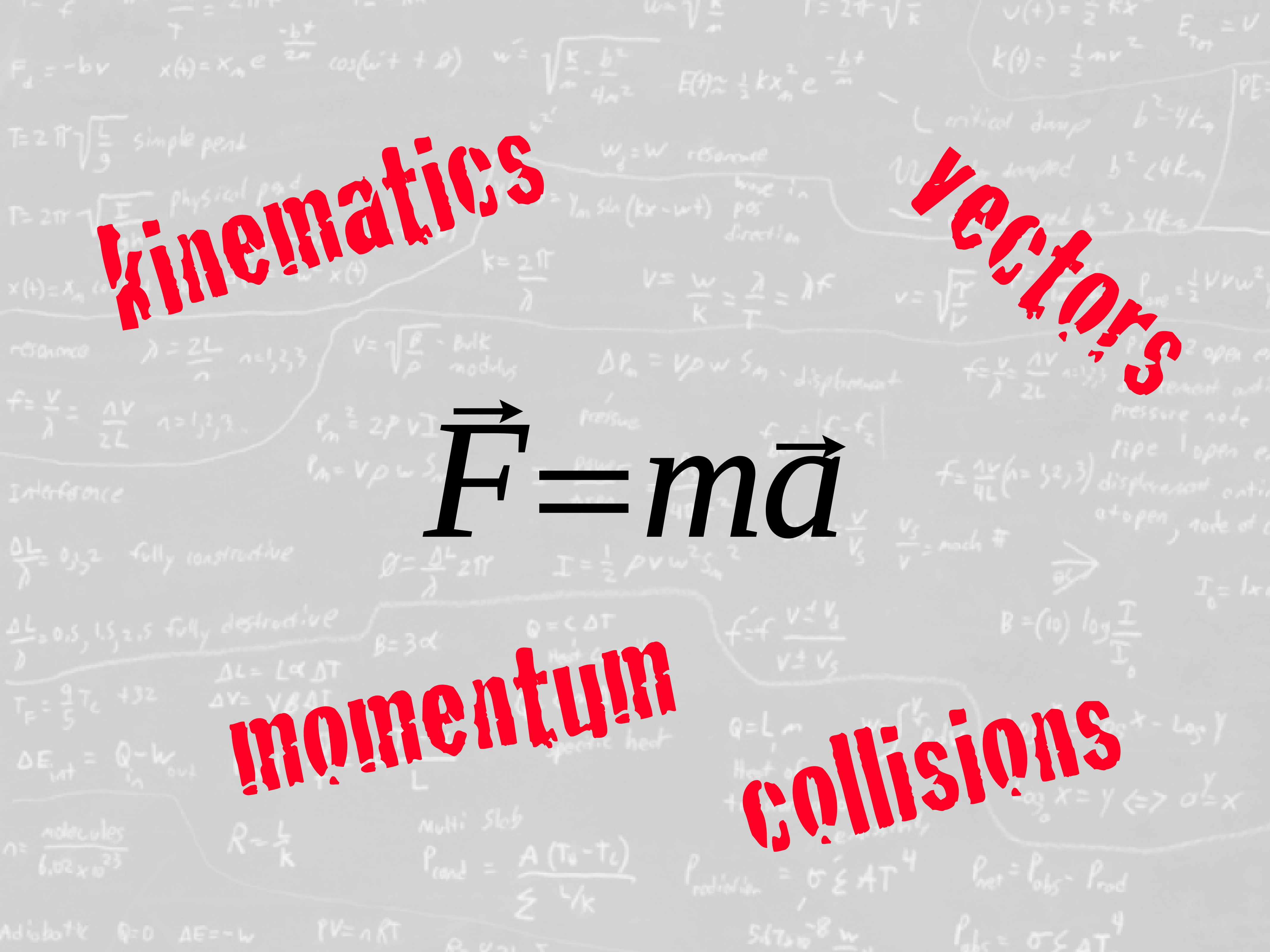
$$\vec{F} = m\vec{a}$$

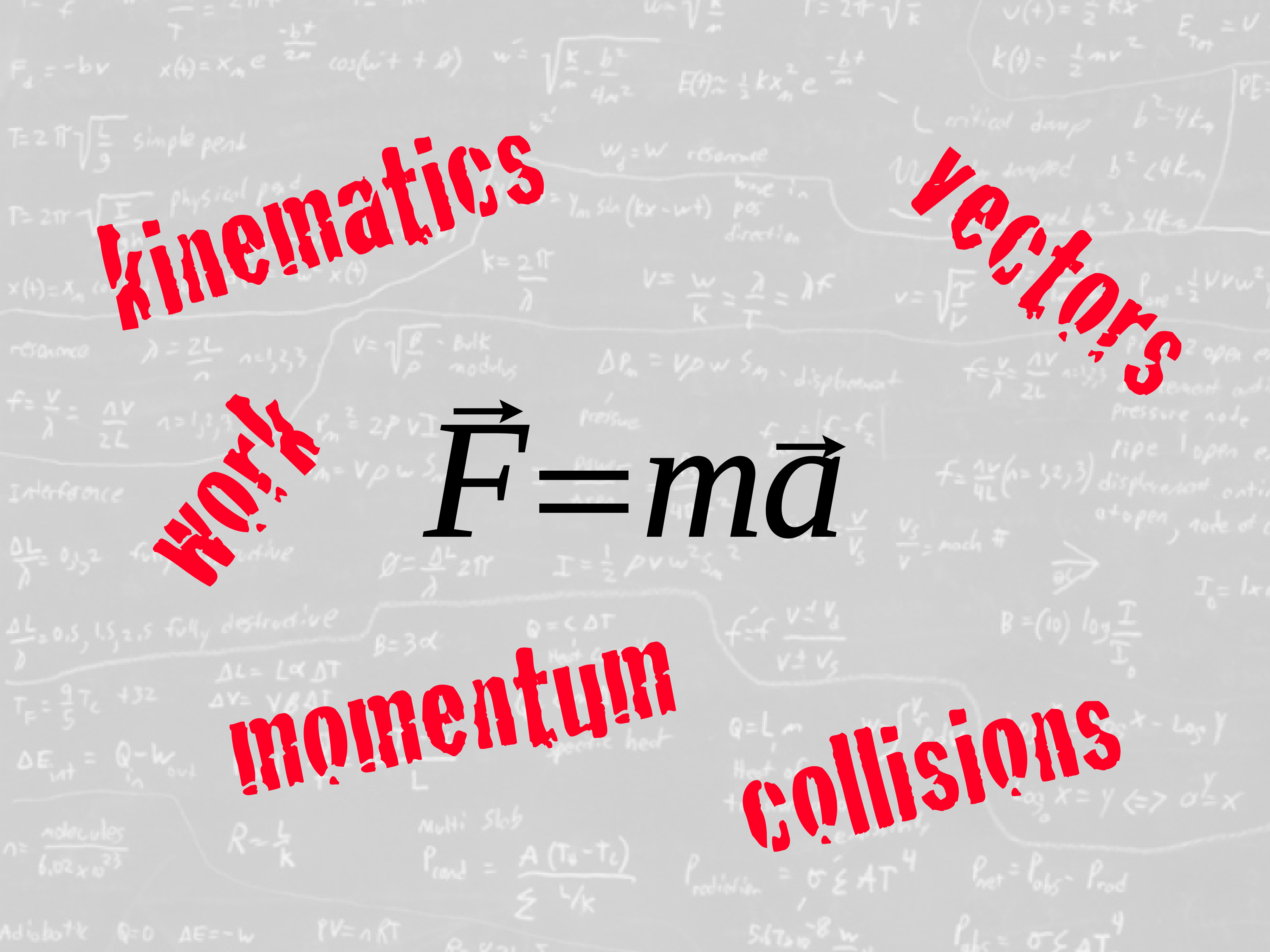
kinematics

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

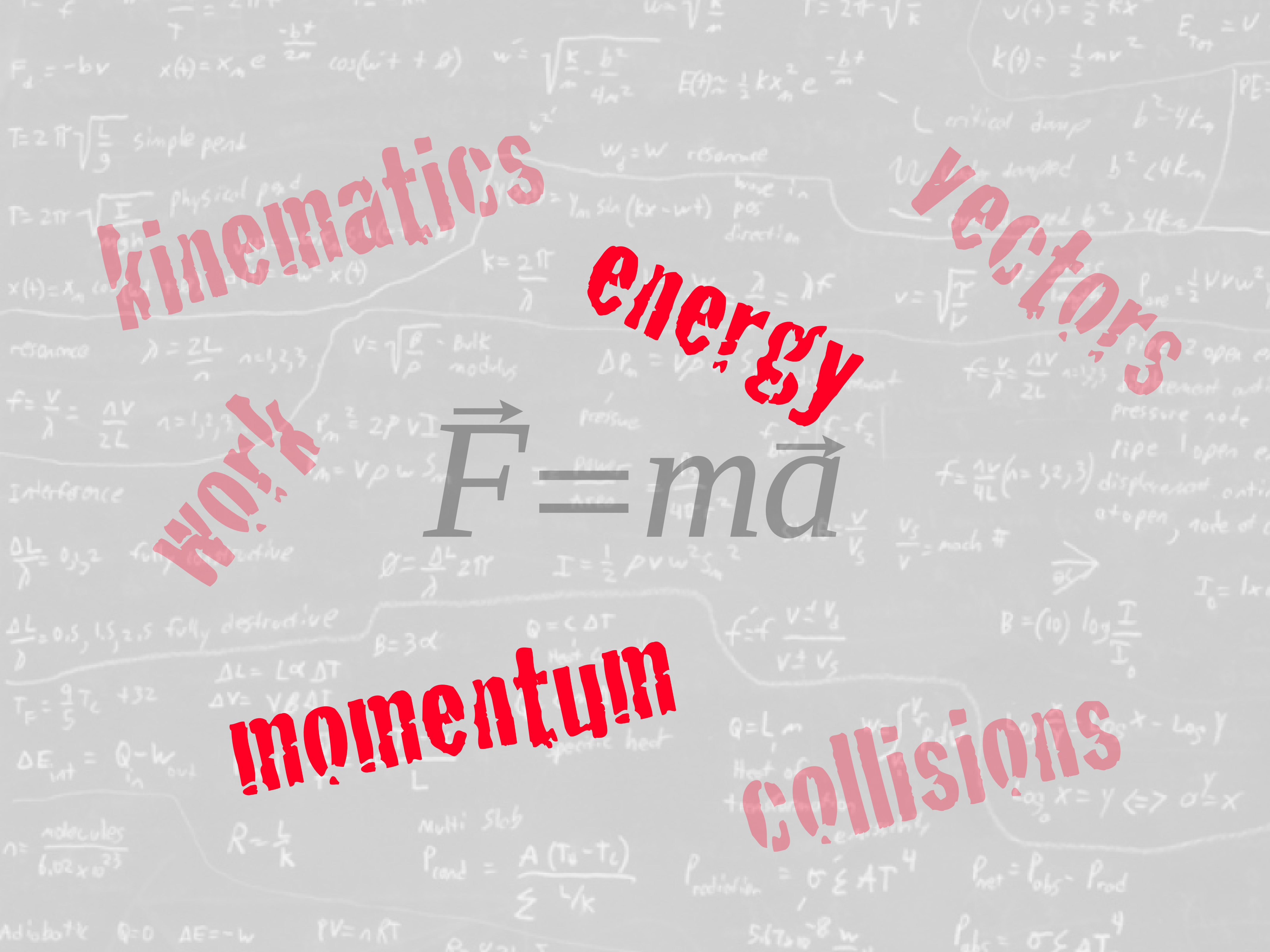
vectors

work

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

momentum

collisions


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

kinematics

vectors

energy

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

work

momentum

collisions

conservation of energy

kinematics

vectors

work

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

conservation of momentum

collisions

kinematics

vectors

conservation of energy

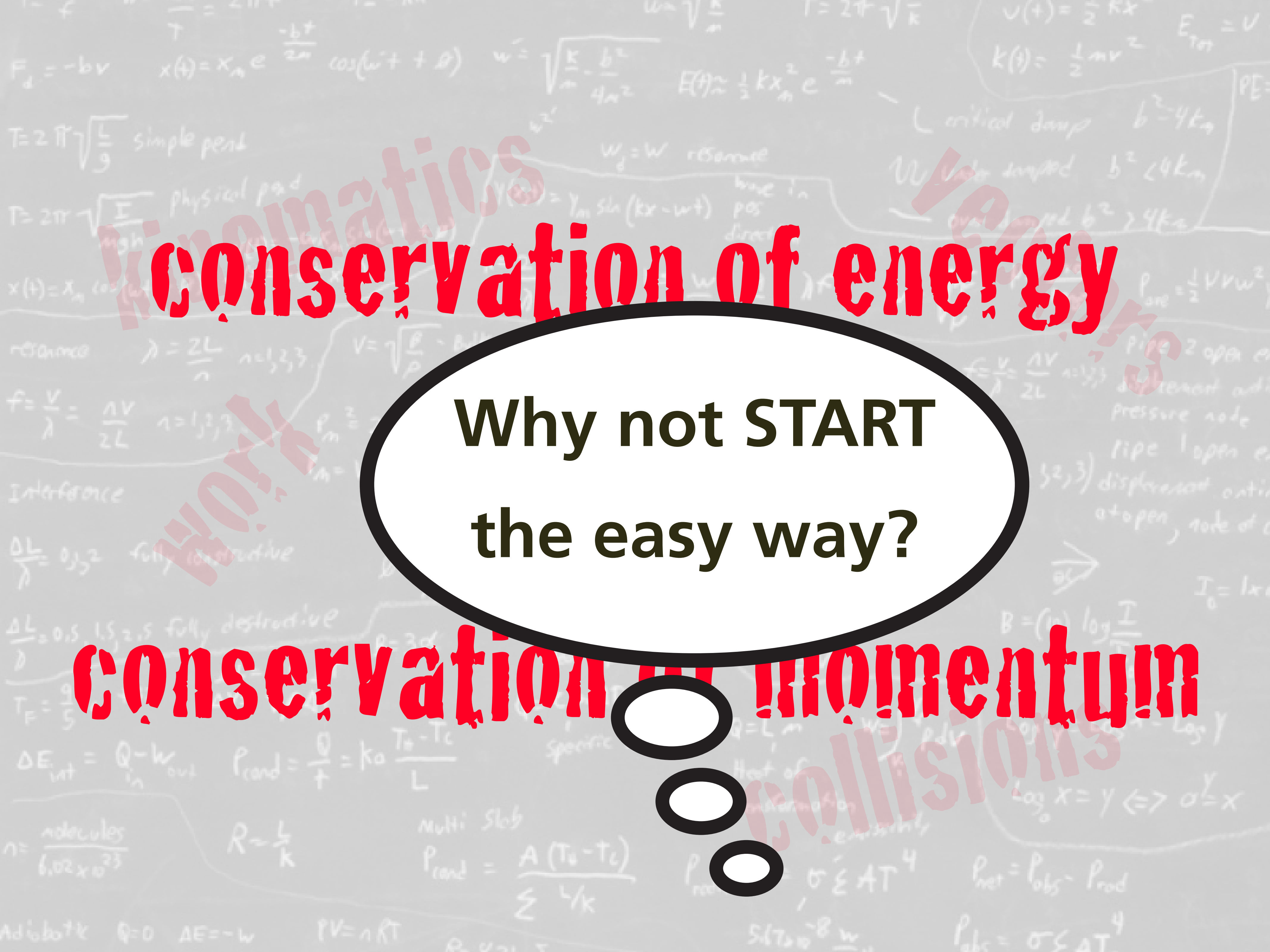
work

Just algebra!

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

conservation of momentum

collisions


kinematics
vectors
conservation of energy
work
Why not START
the easy way?
conservation
momentum
collisions

The historical approach

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

The historical approach

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

The historical approach

150 years of tradition

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

Ernst Mach (1838–1916)

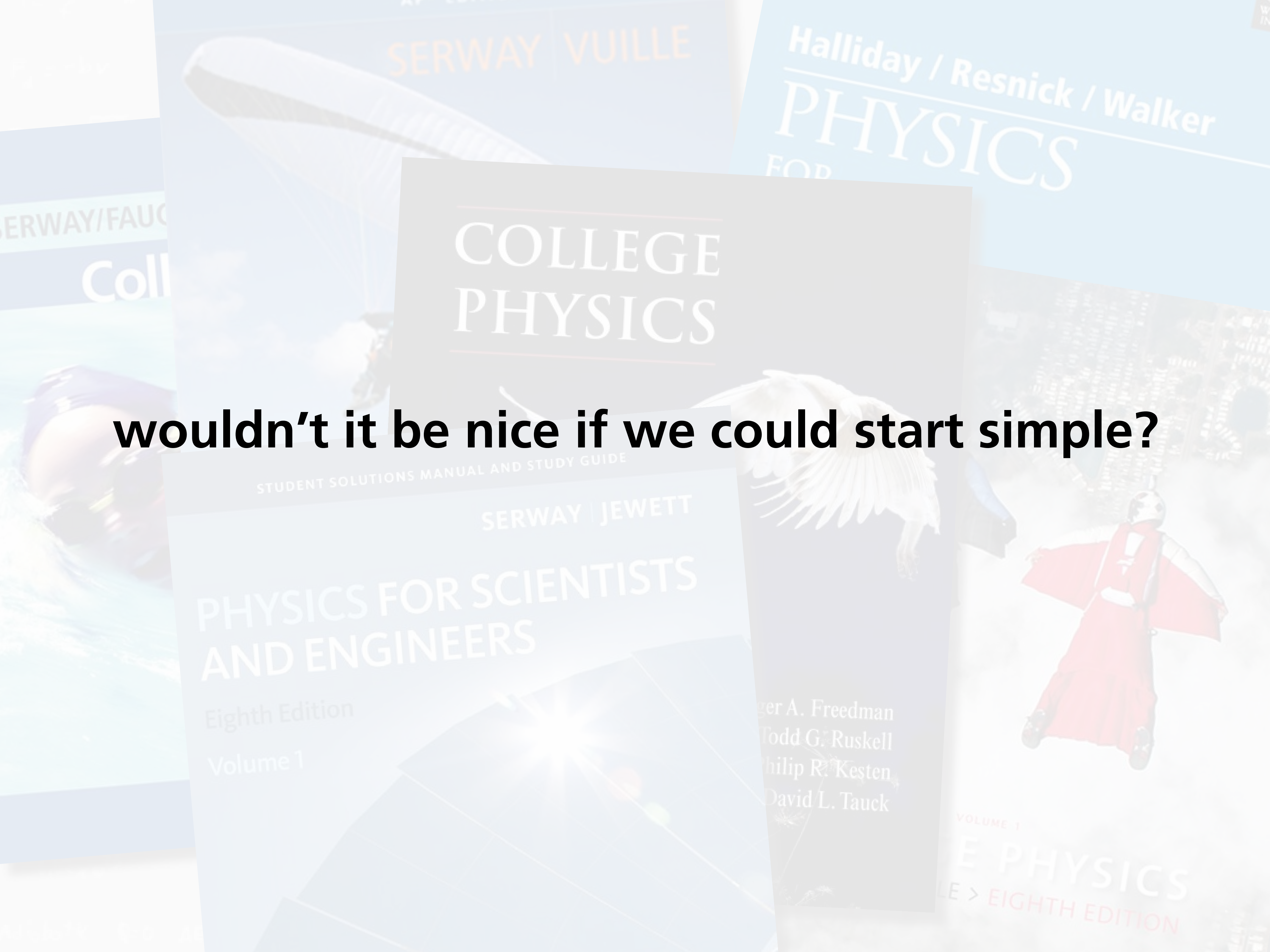
- Newton's laws
- Momentum (and conservation)
- Collisions
- Work and energy
- Conservation of energy

Ernst Mach (1838–1916)

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

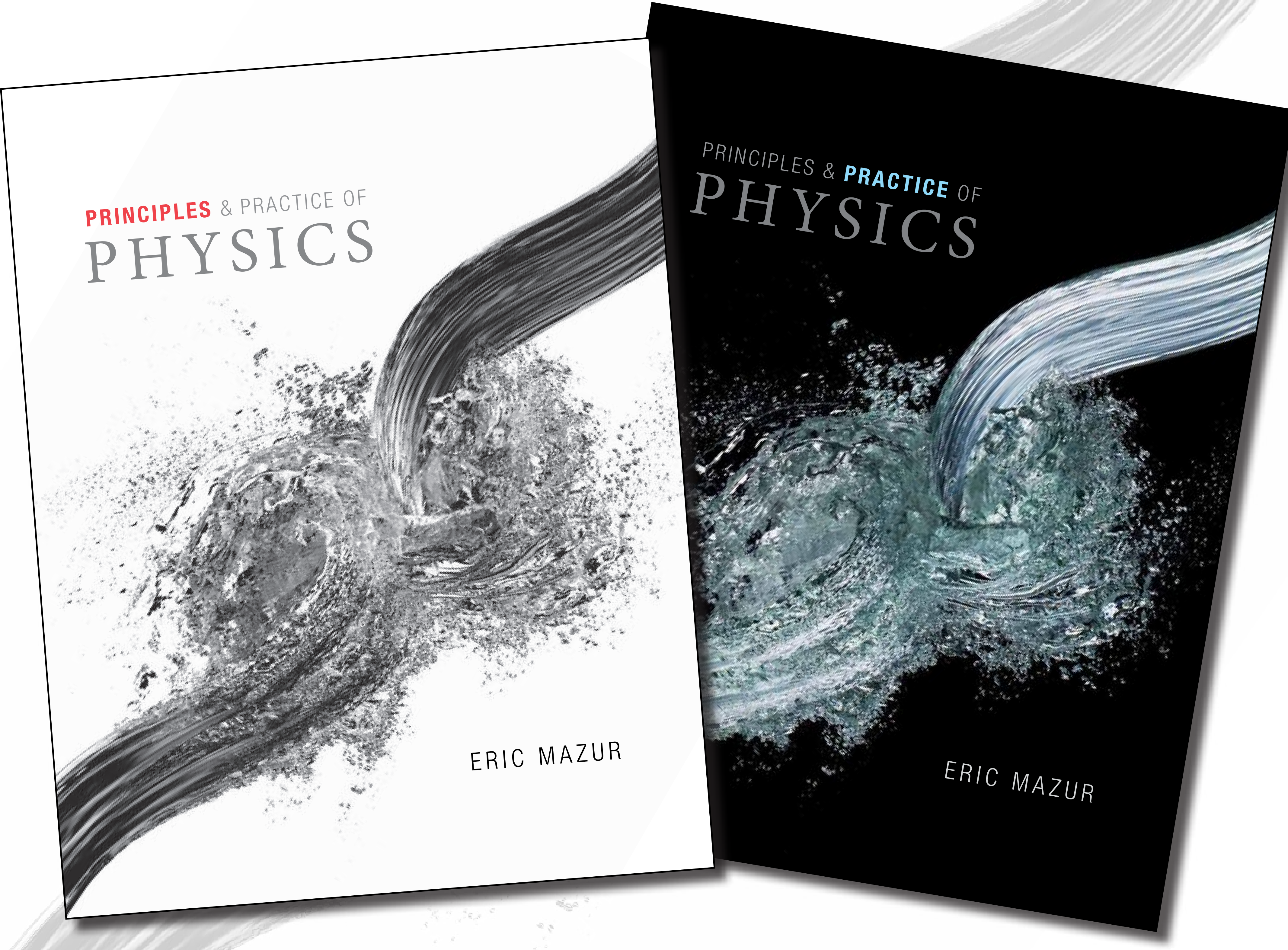
Ernst Mach (1838–1916)

- 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
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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

Principles and Practice of Physics

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

What about engineers?

Principles and Practice of Physics

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

Principles and Pr ysics

- C erimental)
- Co ntal)
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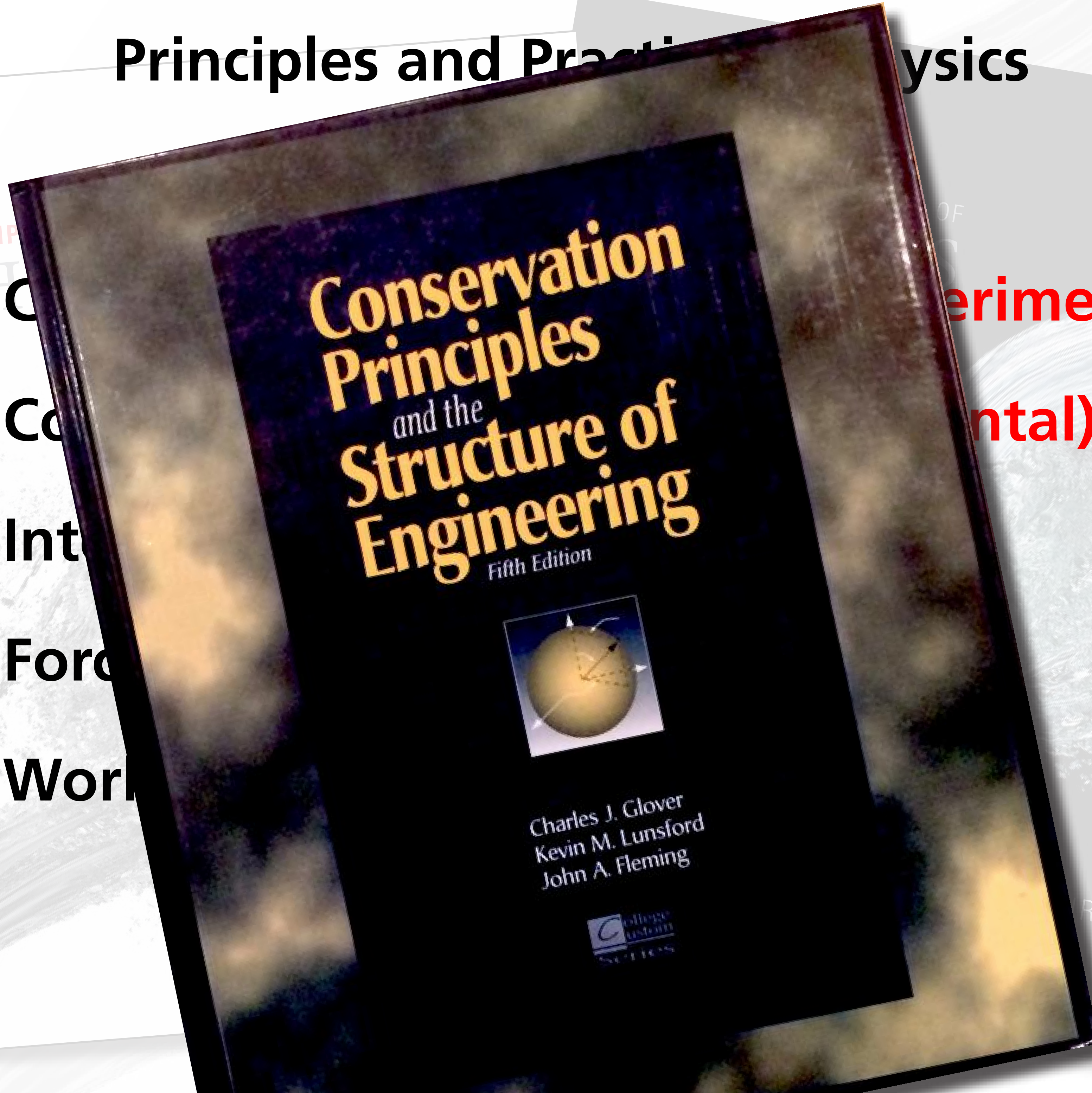
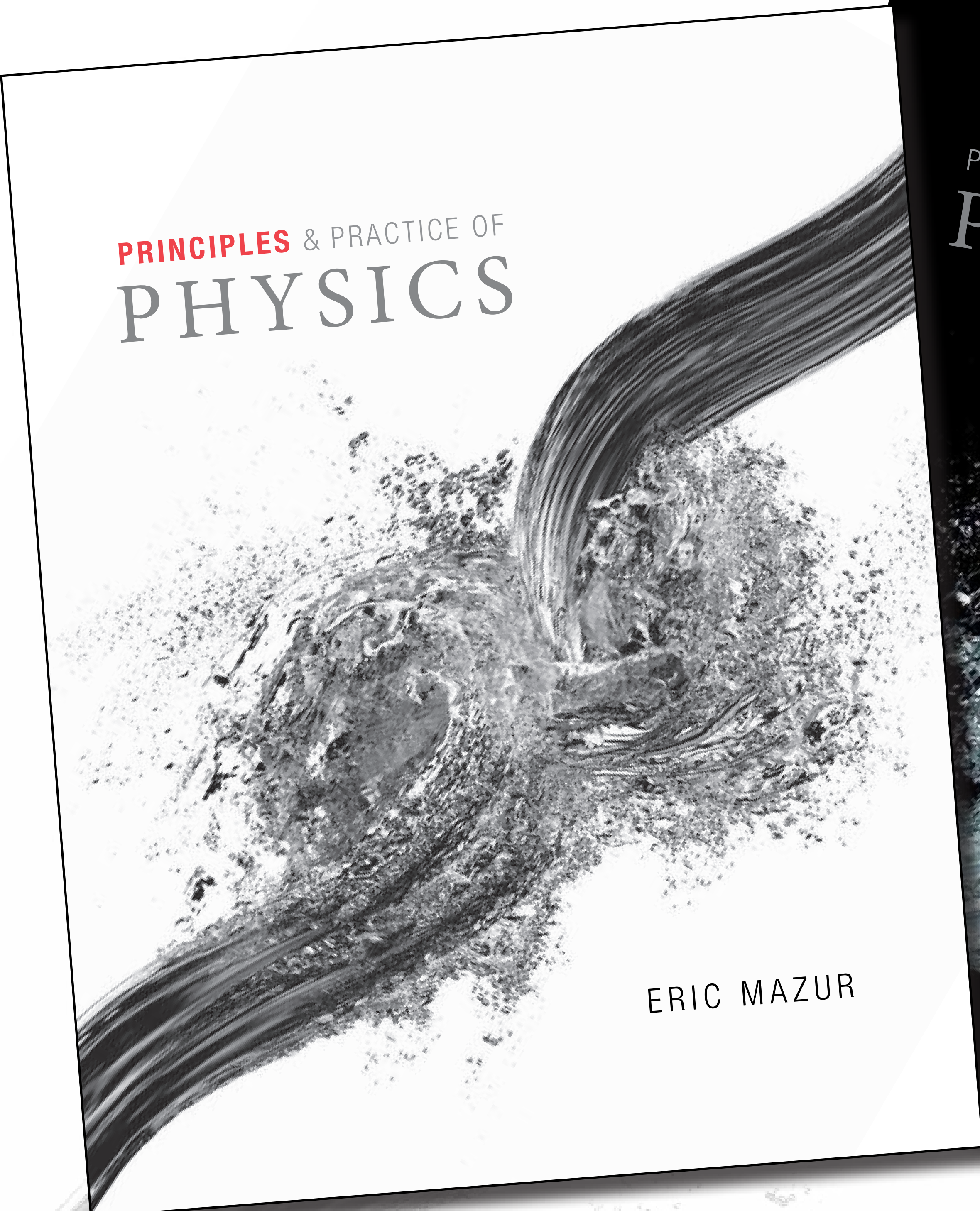
- Worl

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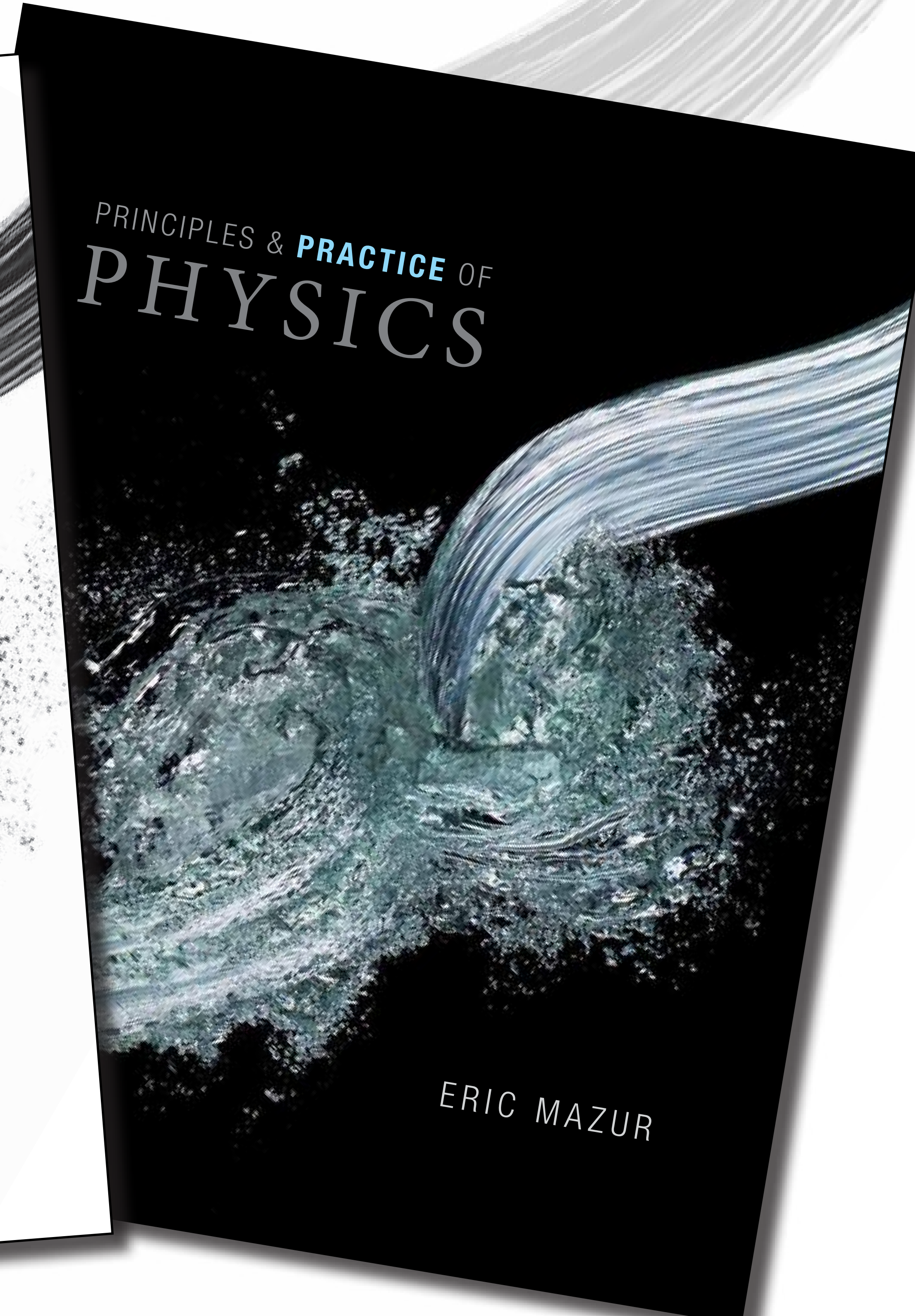
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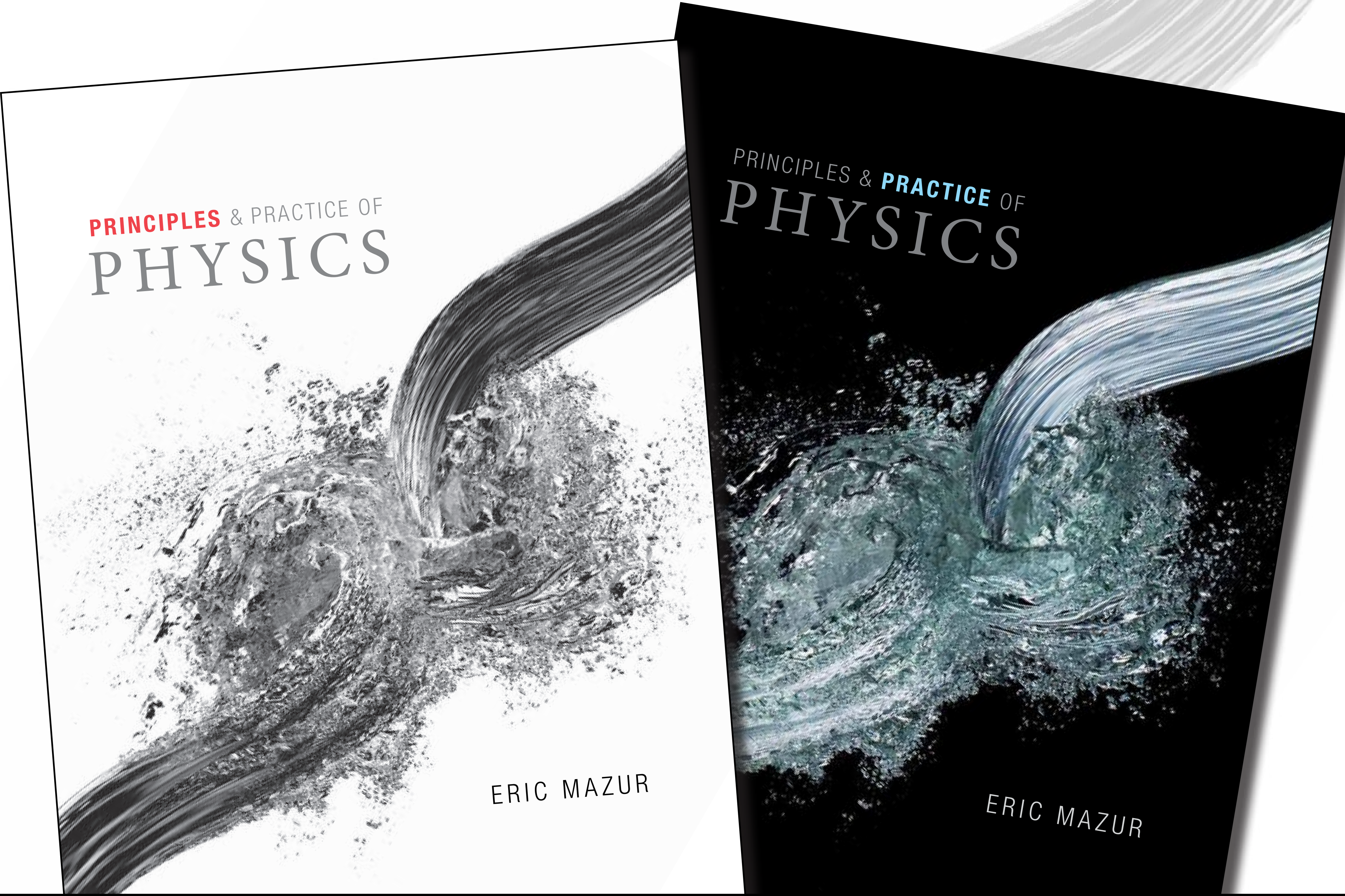
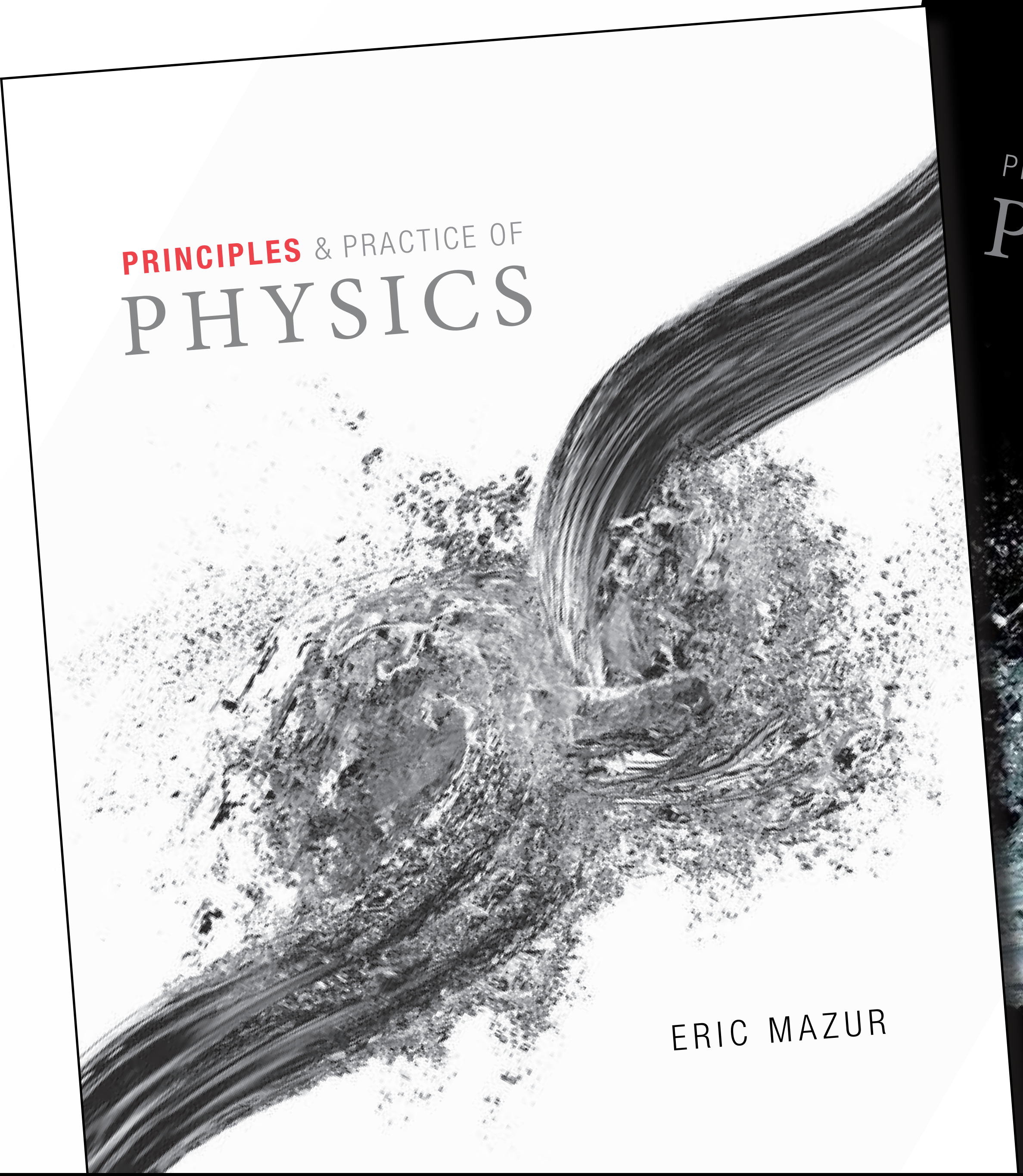
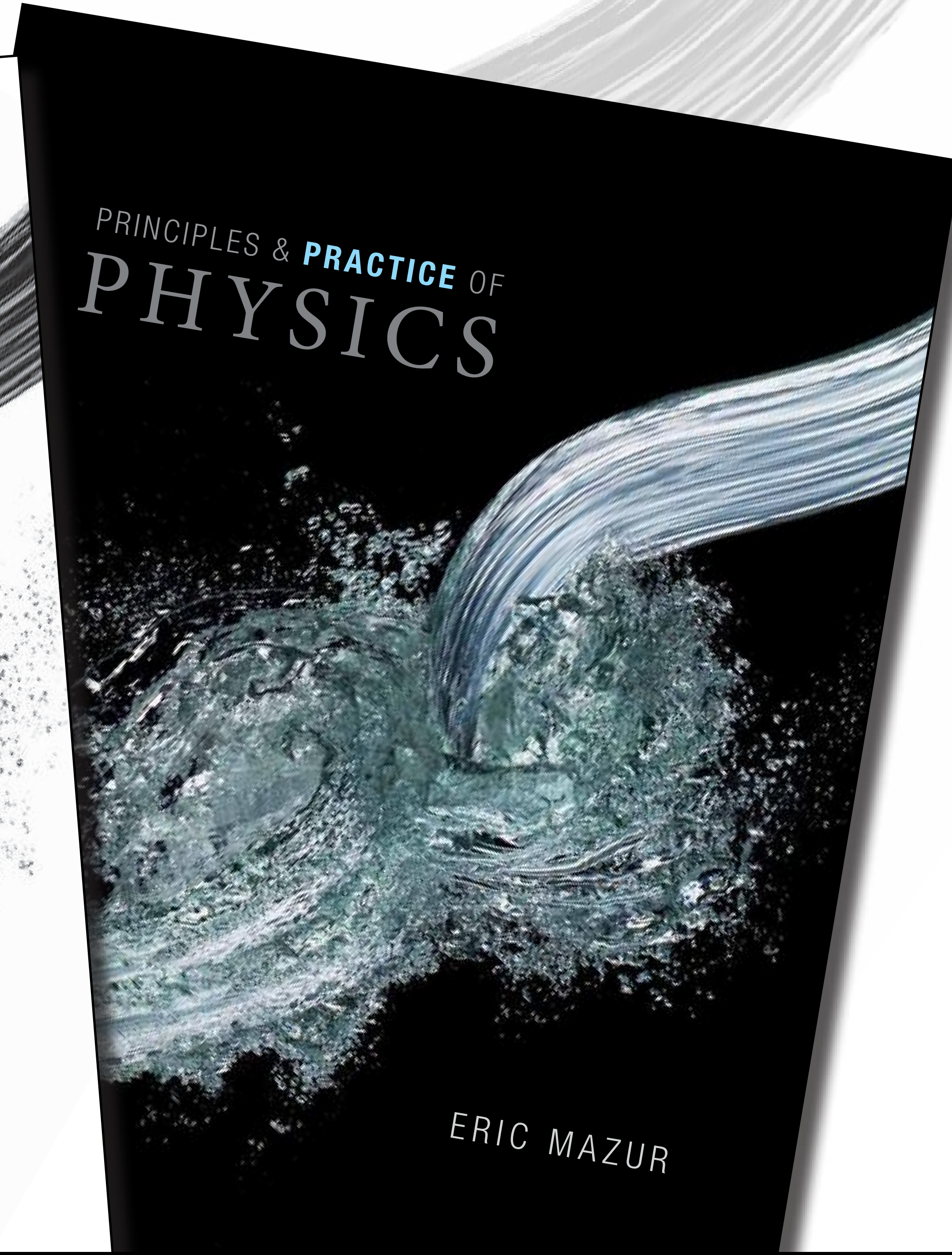


1 architecture





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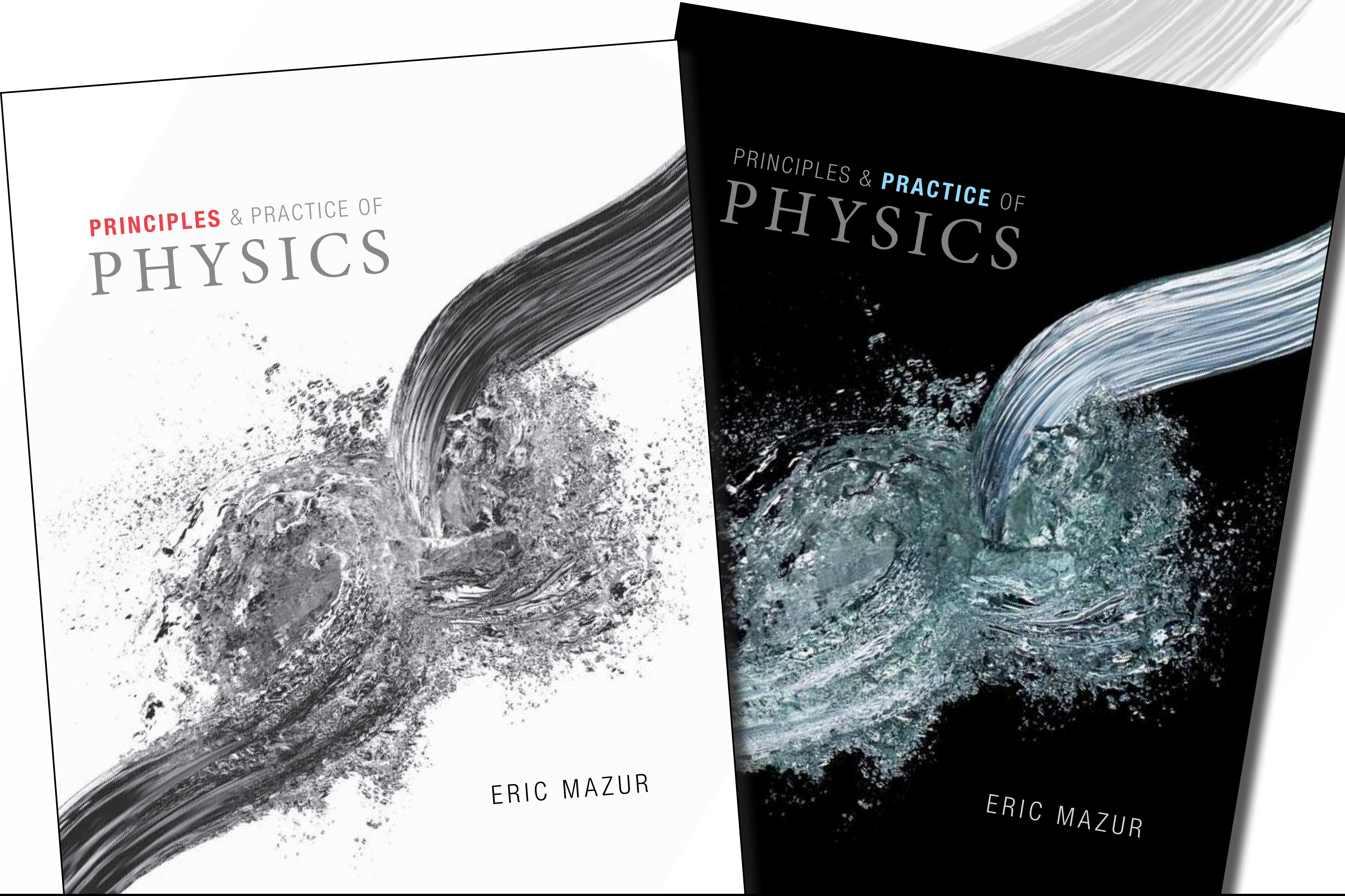
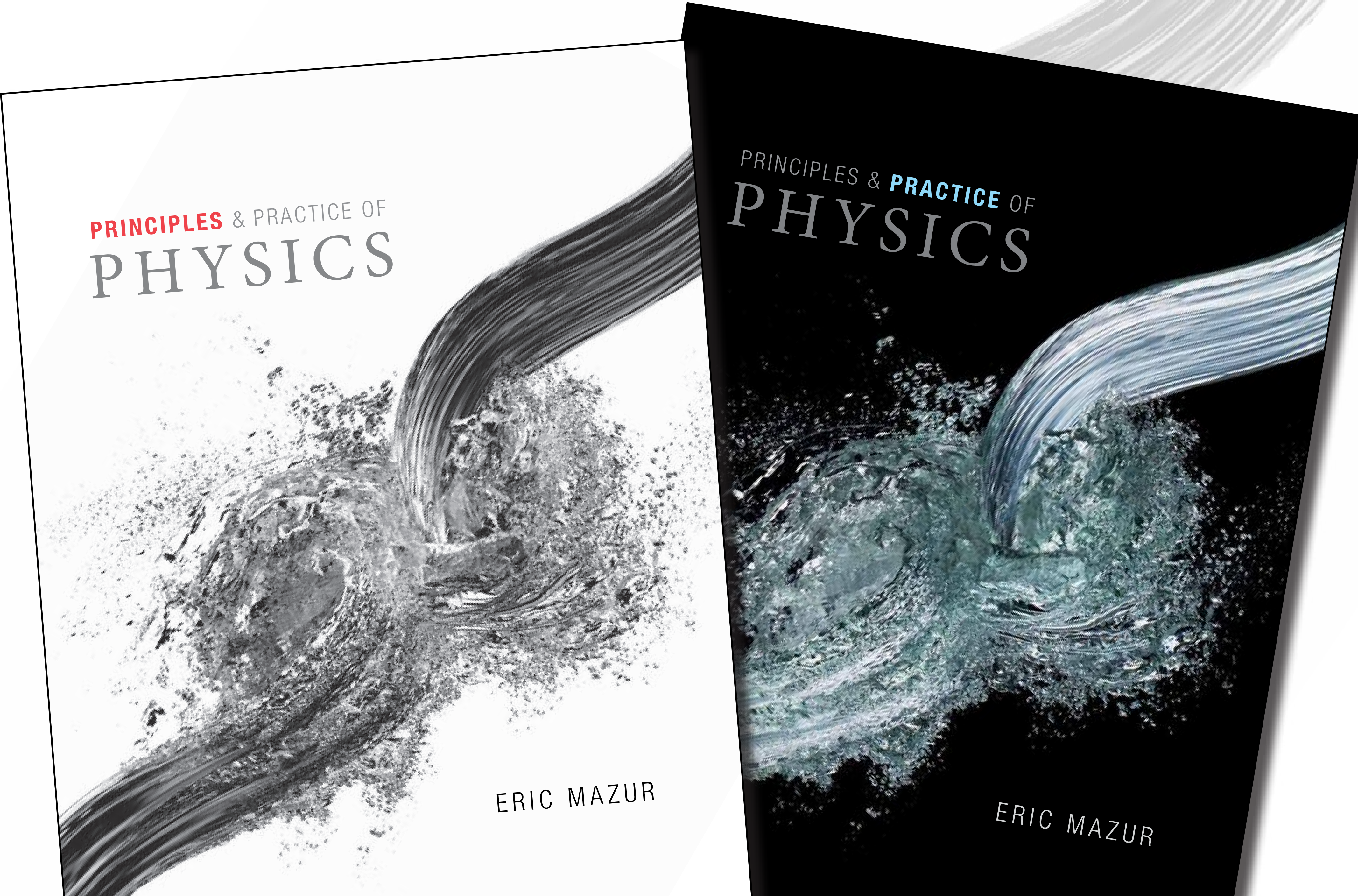
2 content

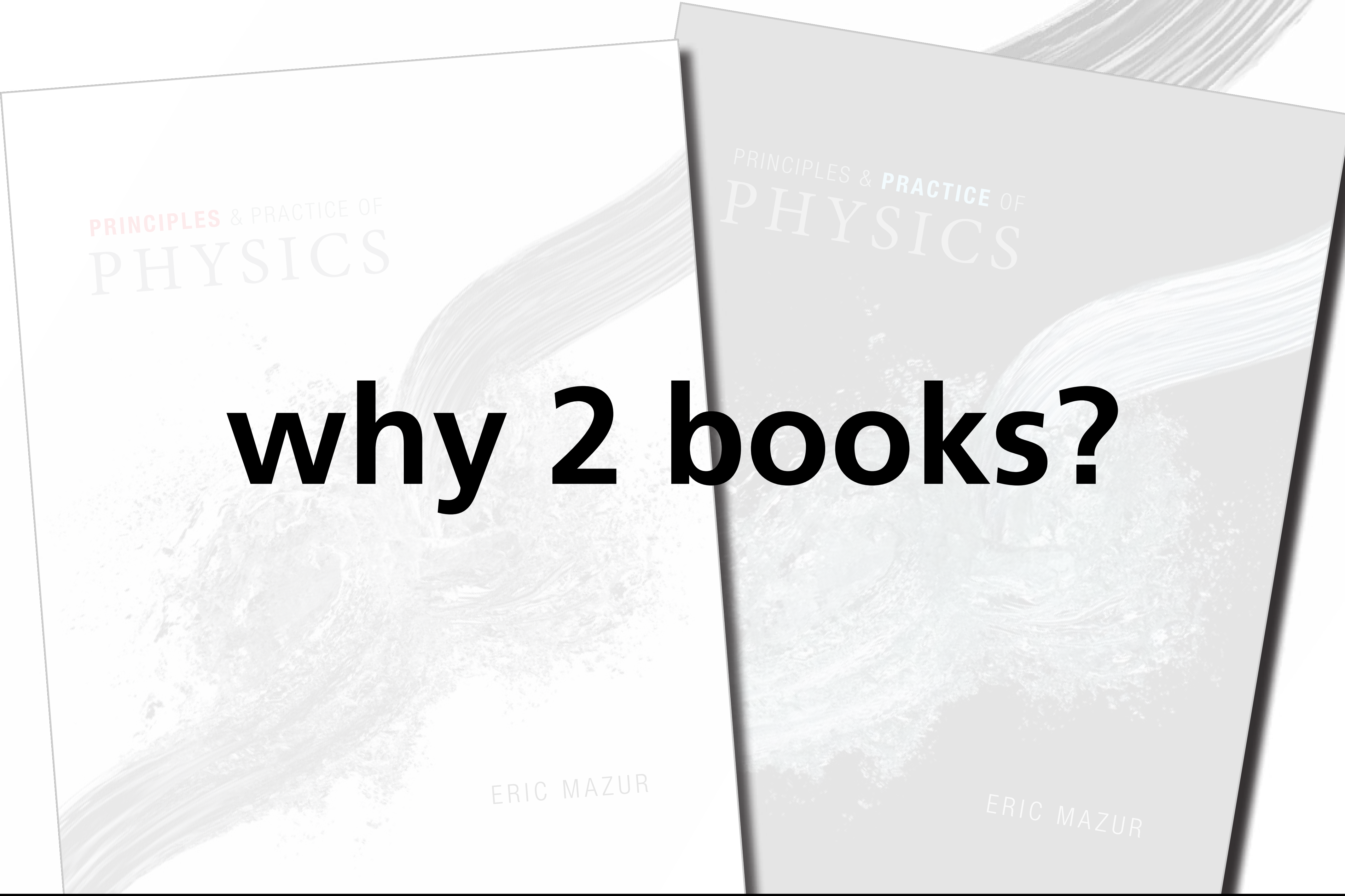


1 architecture 2 content 3 results



1 architecture

why 2 books?



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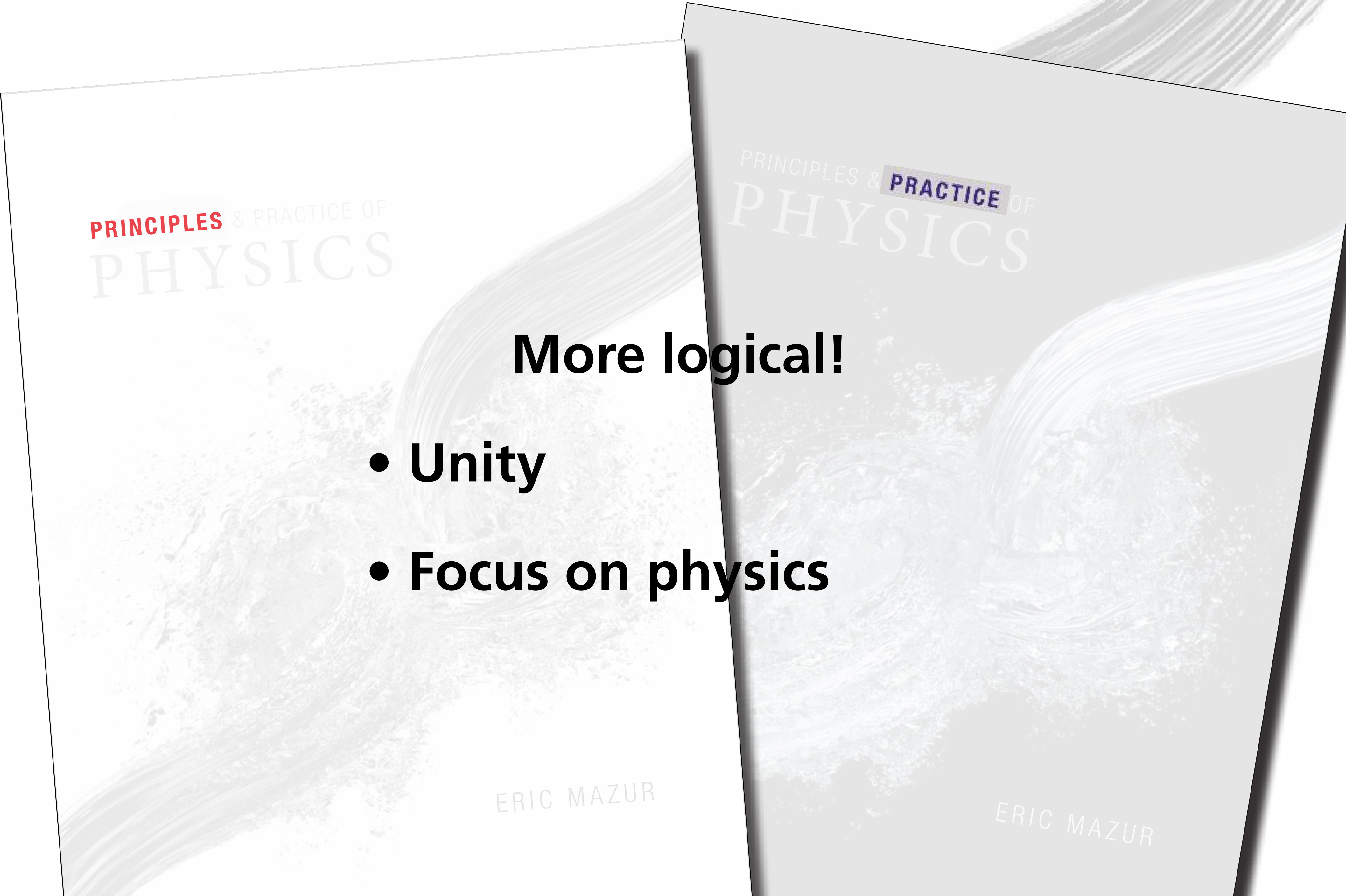
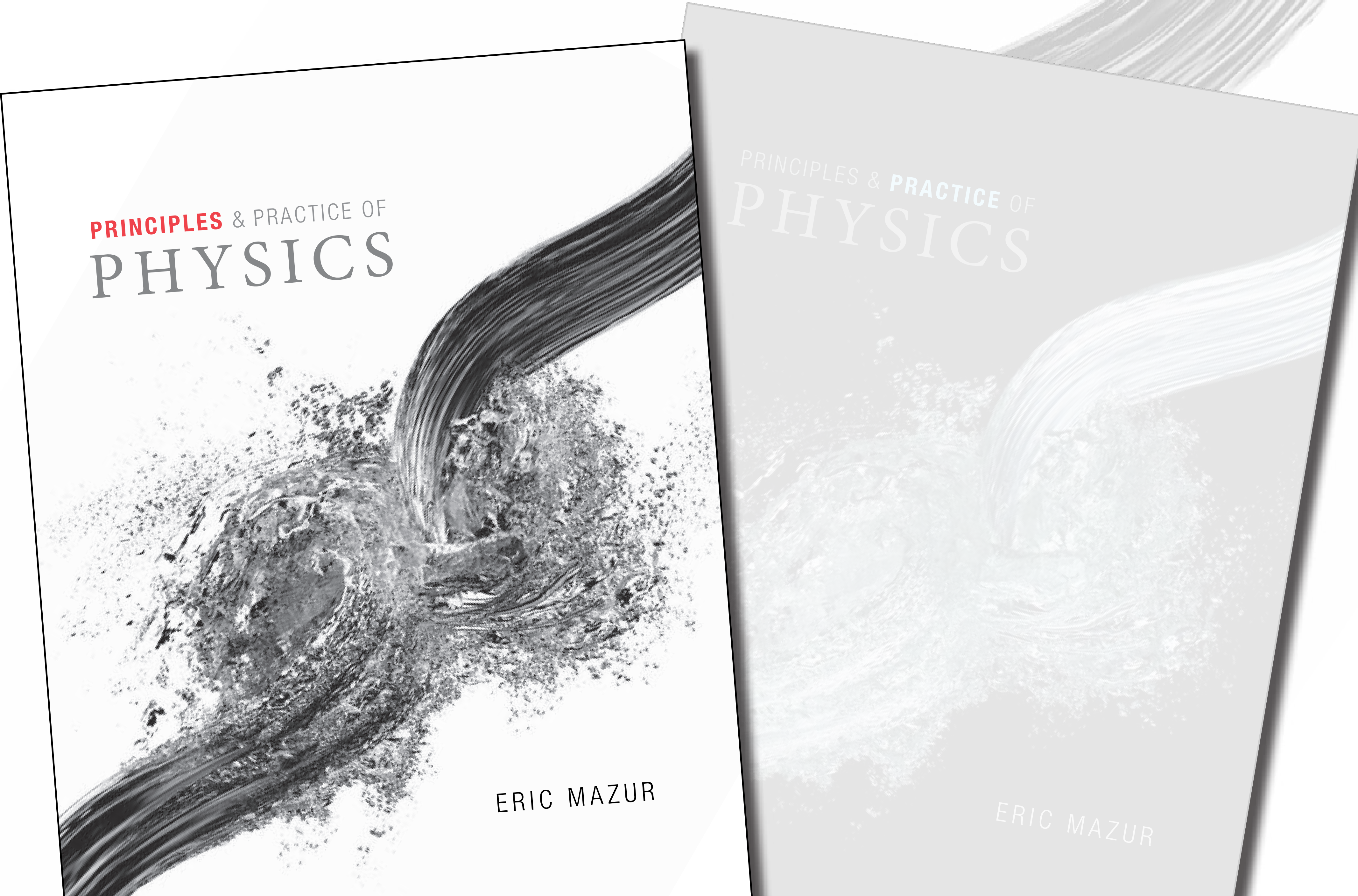


More logical!

- Unity
- Focus on physics

More practical!

- Contexts different
- Lighter



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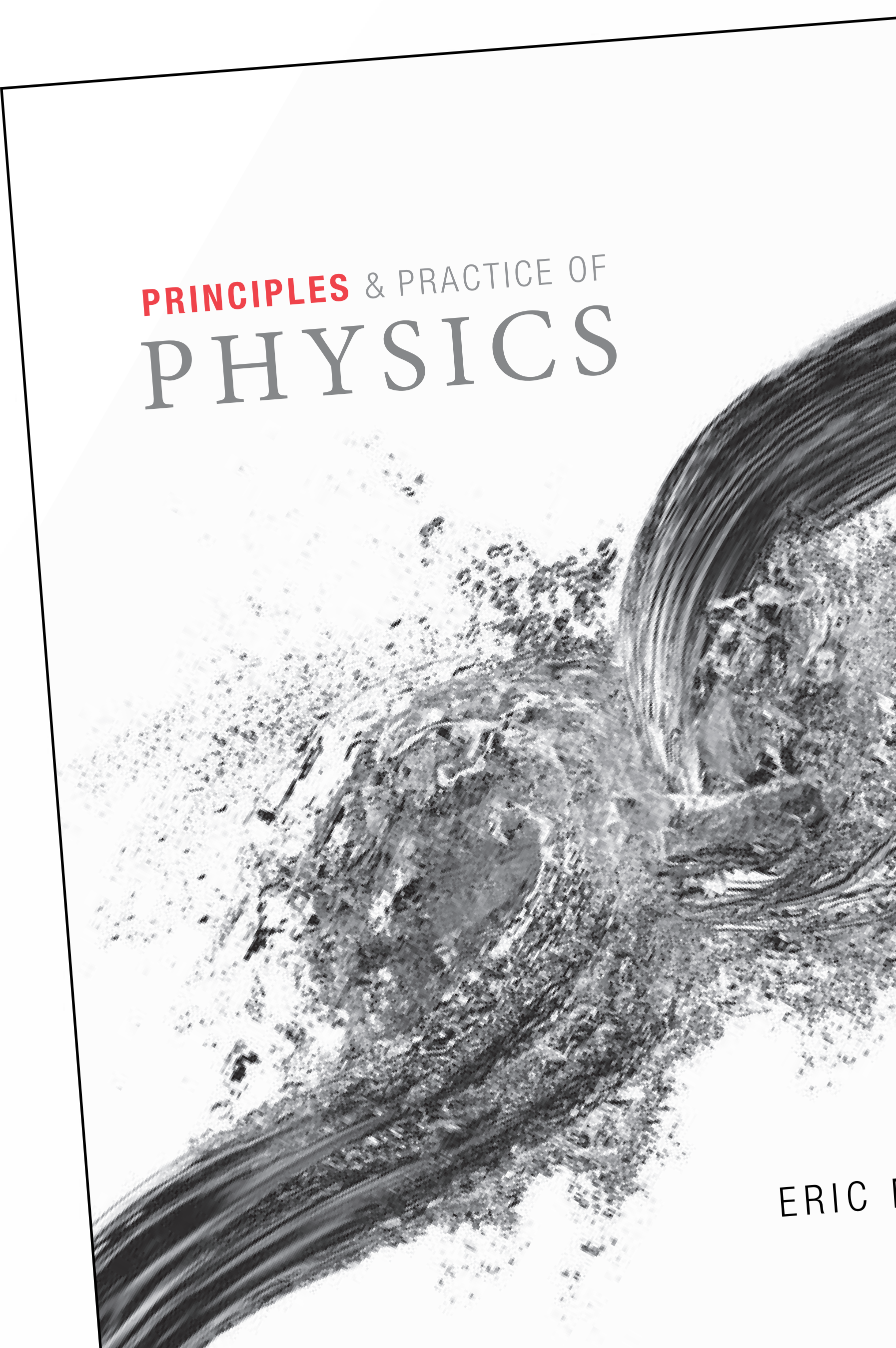

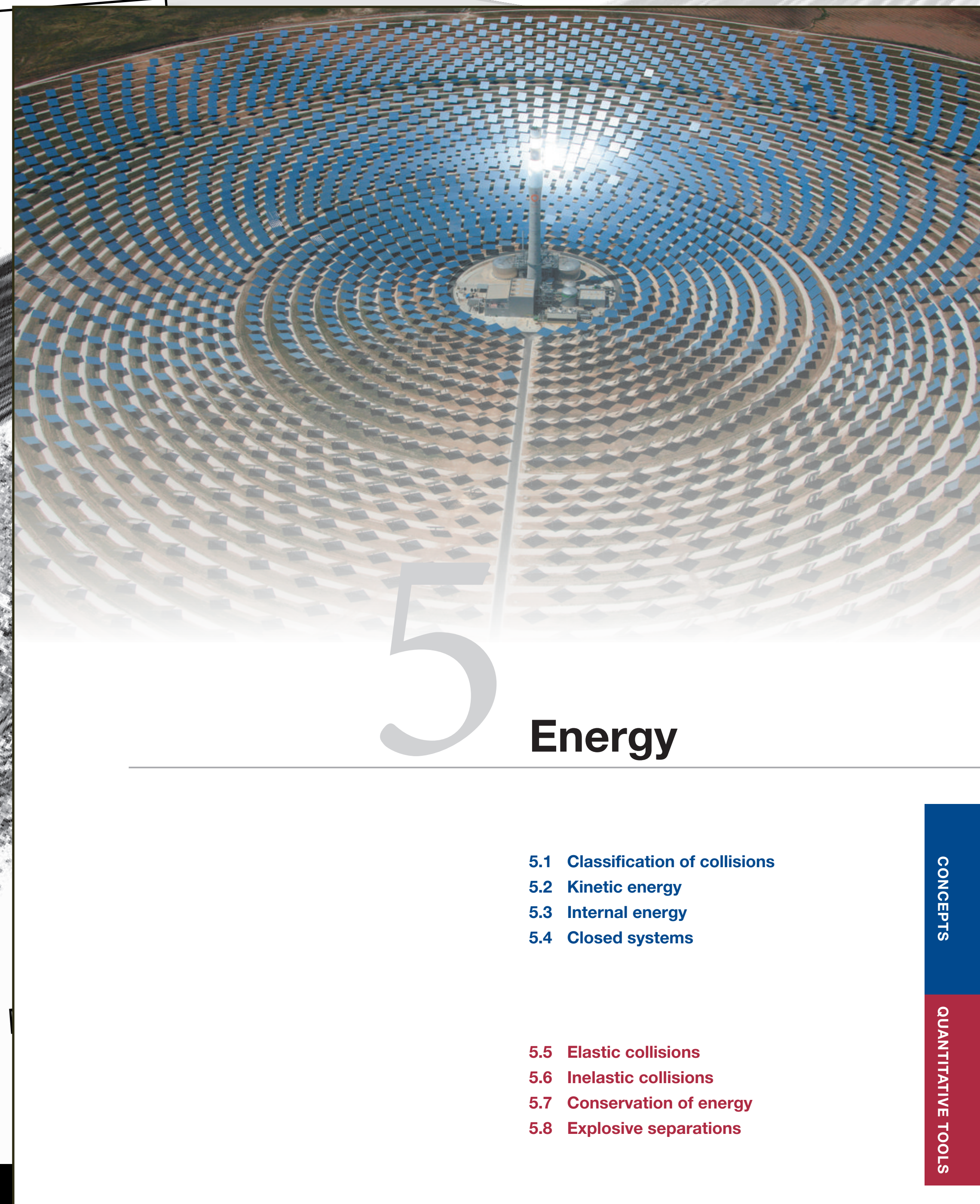

5 Energy

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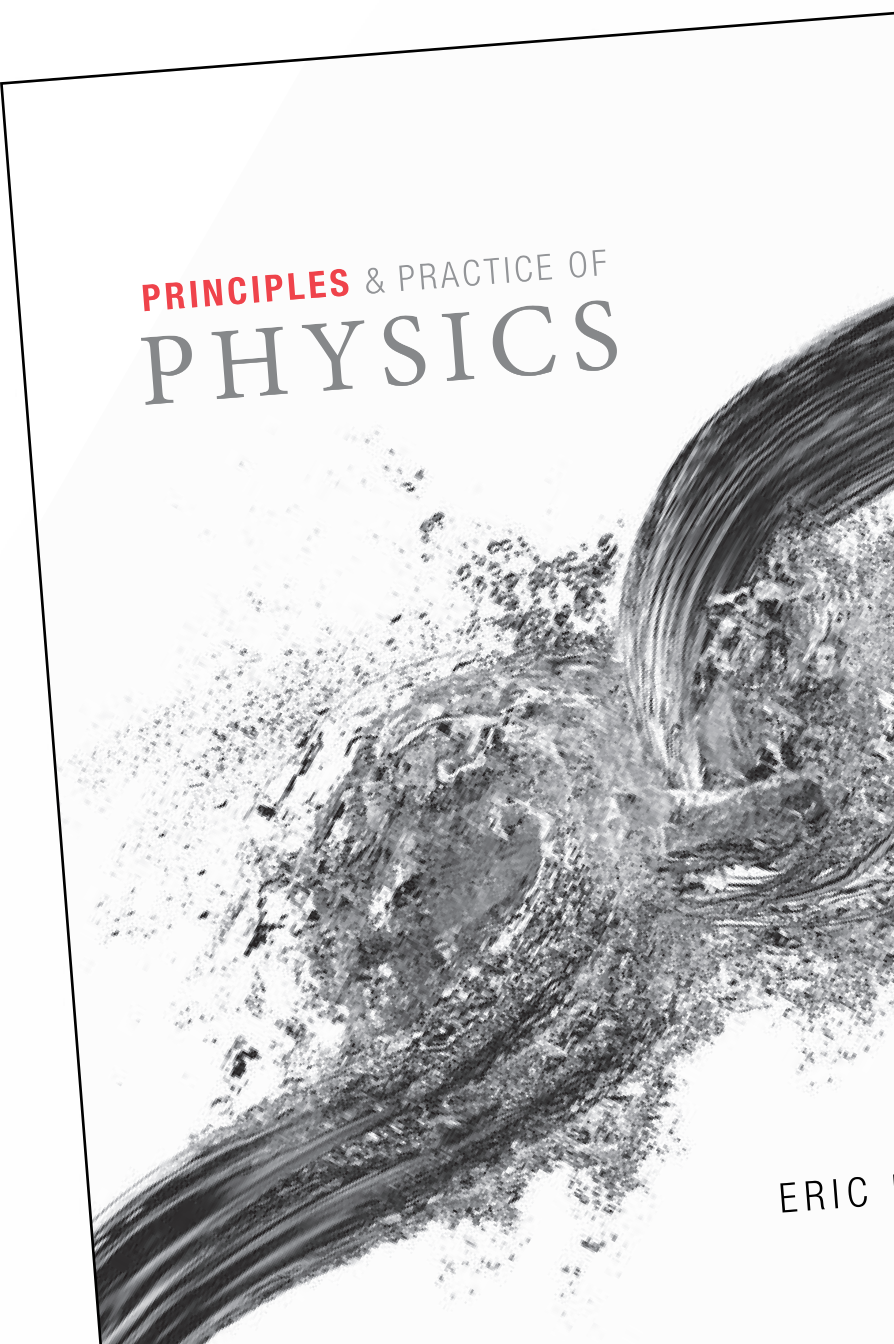

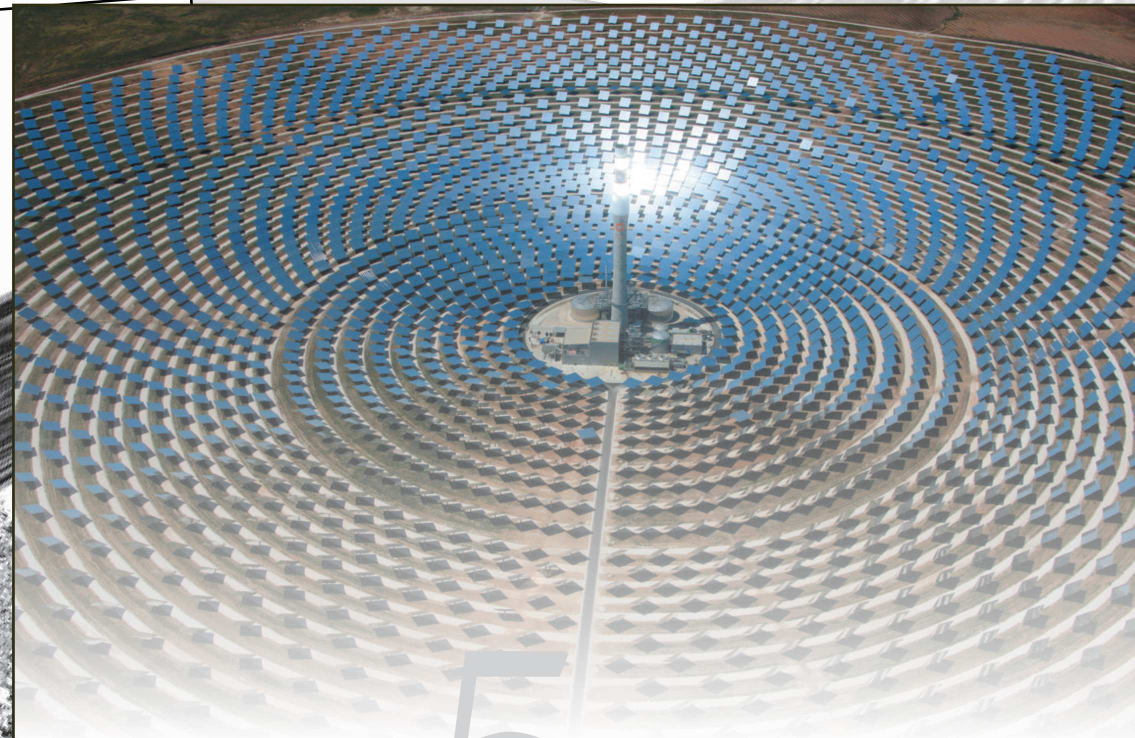

5 Energy

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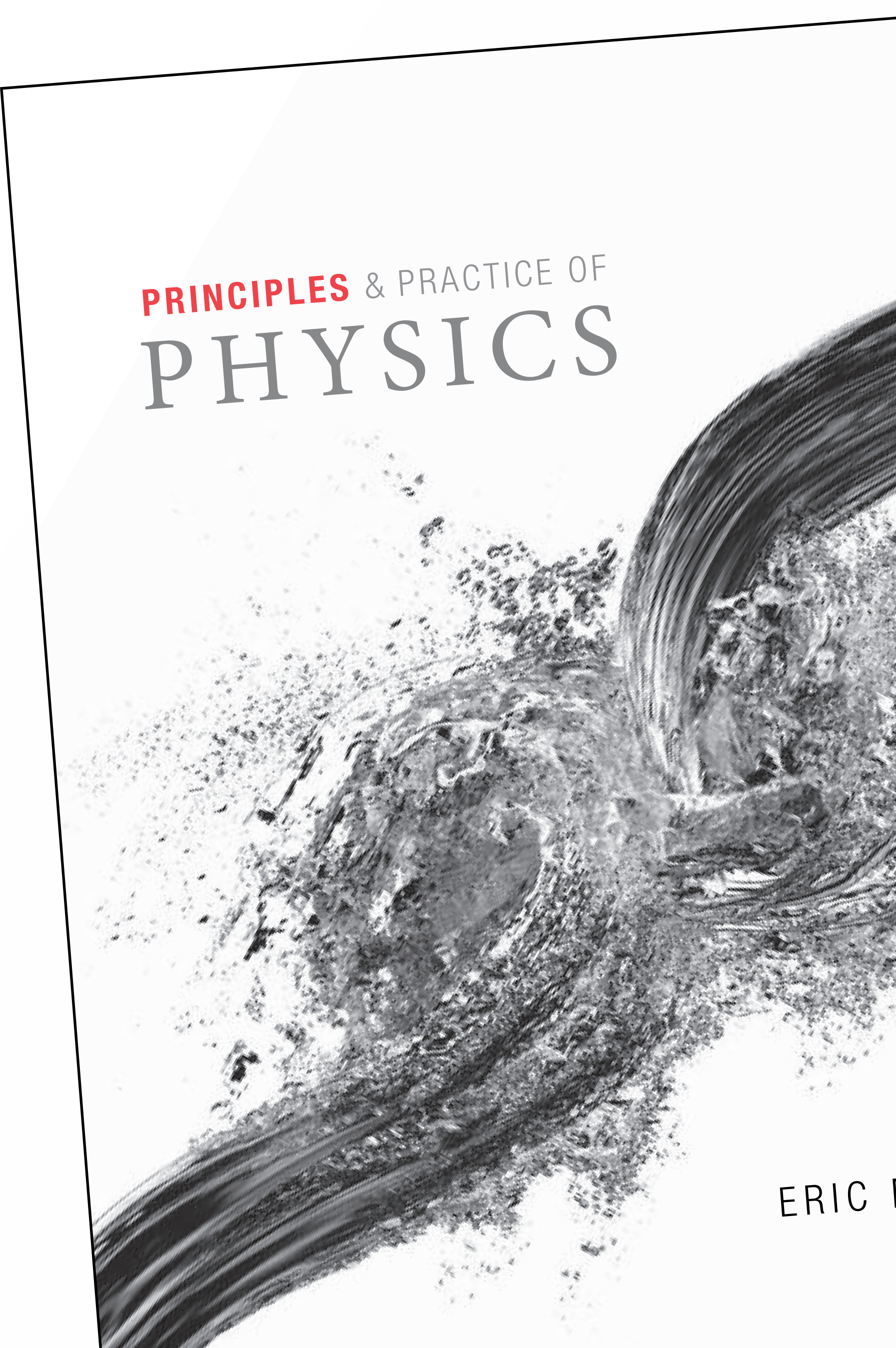
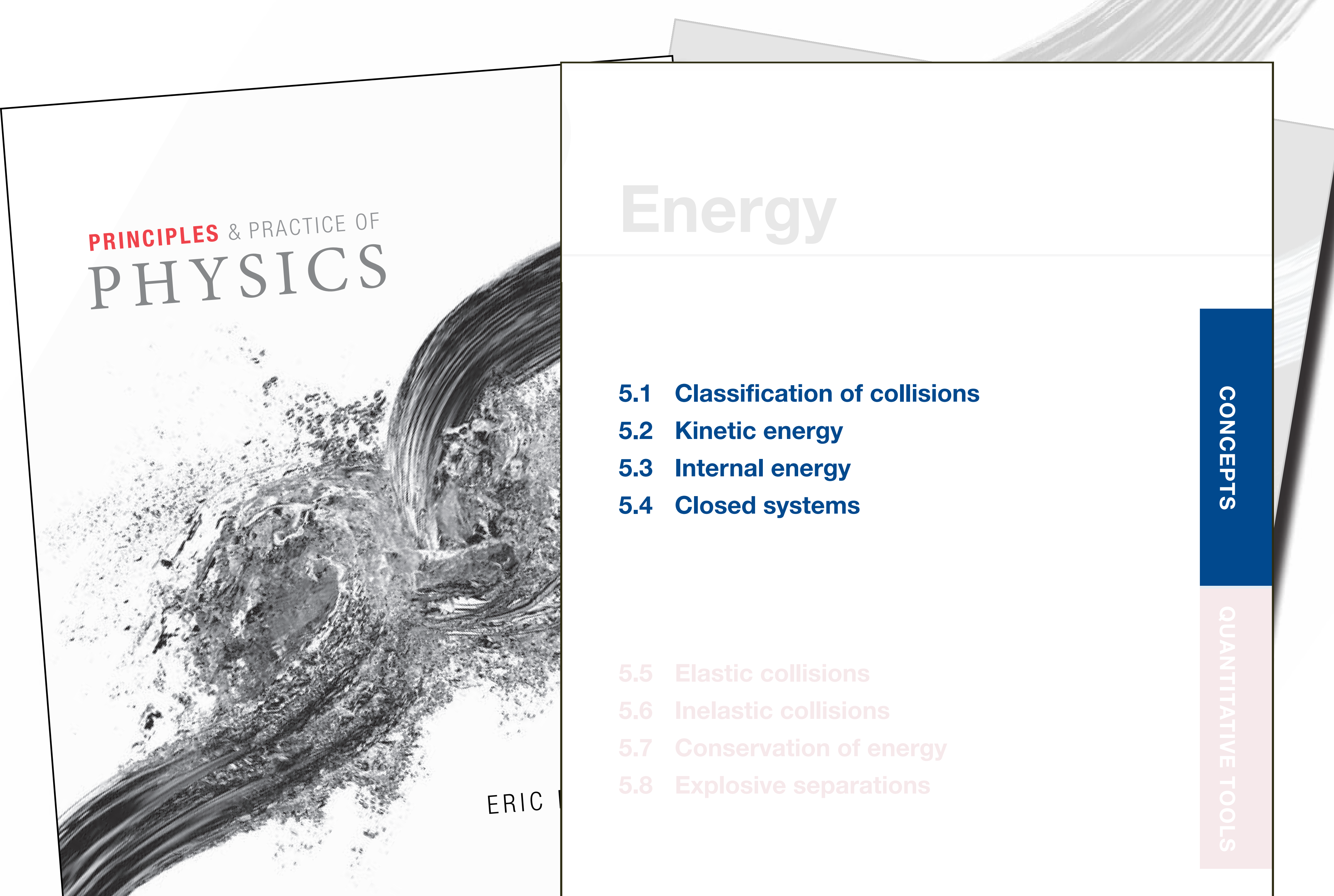


Energy

CONCEPTS

QUANTITATIVE TOOLS

1 architecture

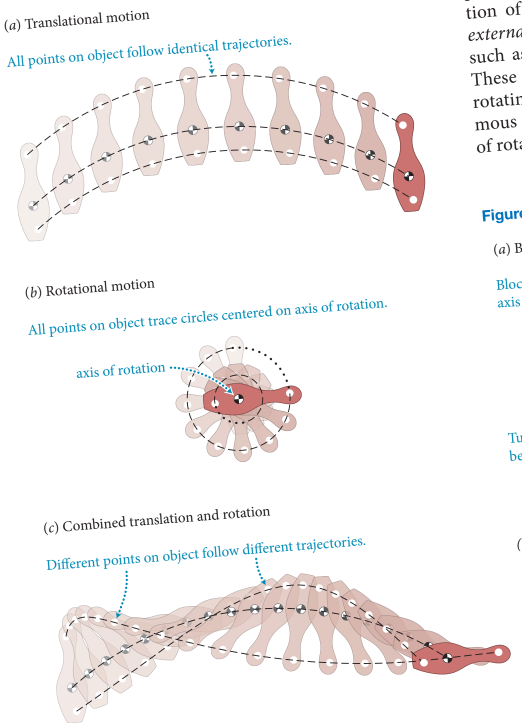


1 architecture

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.

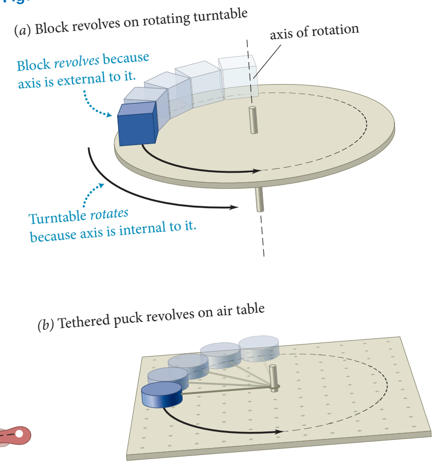
Figure 11.1 Translational and rotational motion of a rigid object.



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.



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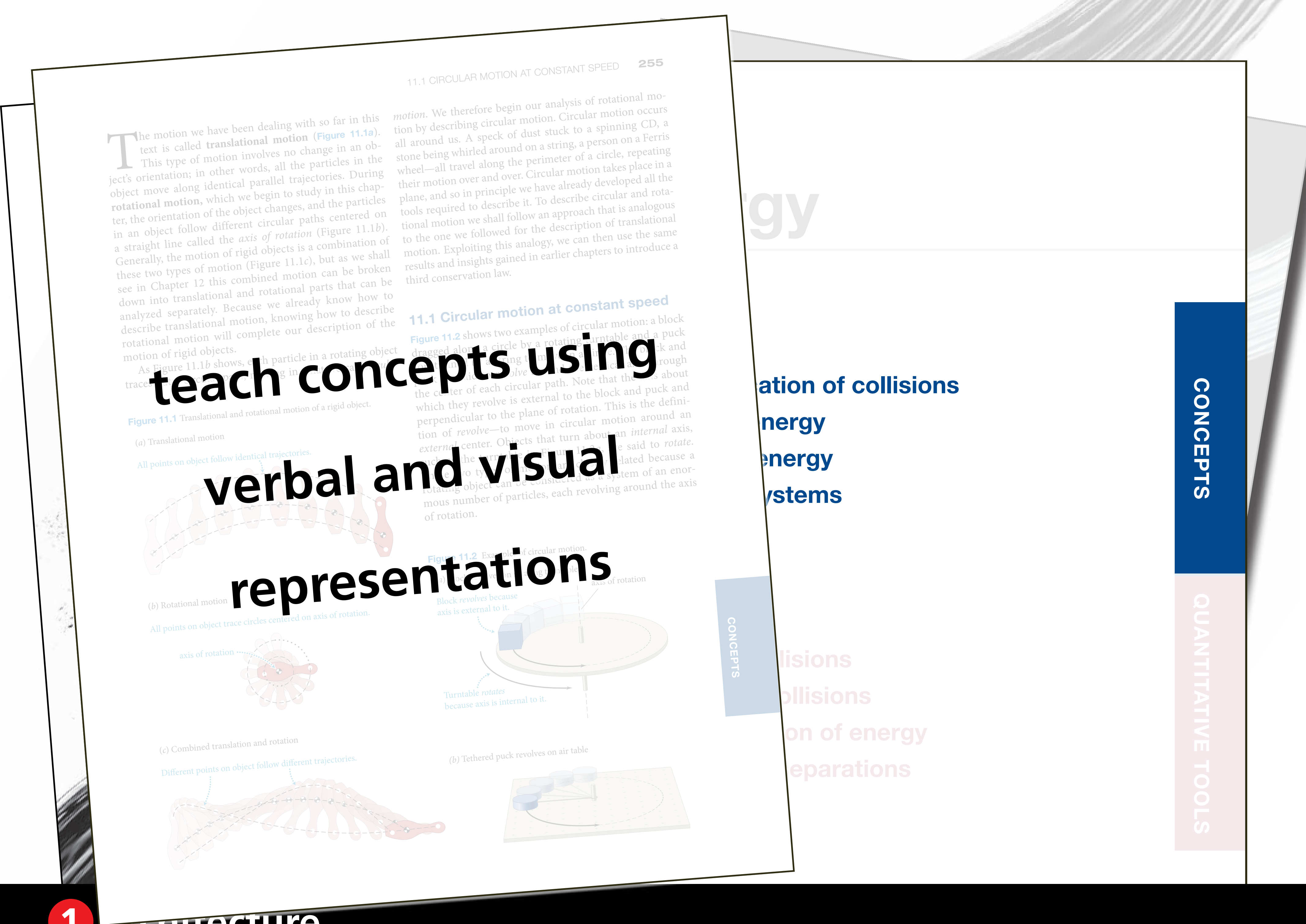


teach concepts using verbal and visual representations

1 architecture

Self-quiz

1. Two carts are about to collide head-on on a track. The inertia of cart 1 is greater than the inertia of cart 2, and the collision is elastic. The speed of cart 1 before the collision is higher than the speed of cart 2 before the collision. *(a)* Which cart experiences the greater acceleration during the collision? *(b)* Which cart has the greater change in momentum due to the collision? *(c)* Which cart has the greater change in kinetic energy during the collision?
2. Which of the following deformations are reversible and which are irreversible: *(a)* the deformation of a tennis ball against a racquet, *(b)* the deformation of a car fender during a traffic accident, *(c)* the deformation of a balloon as it is blown up, *(d)* the deformation of fresh snow as you walk through it?
3. Translate the kinetic energy graph in Figure 7.2 into three sets of energy bars: before the collision, during the collision, and after the collision. In each set, include a bar for K_1, a bar for K_2, and a bar for the internal energy of the system, and assume that the system is closed.
4. Describe a scenario to fit the energy bars shown in Figure 7.22. What happens during the interaction?

Figure 7.22

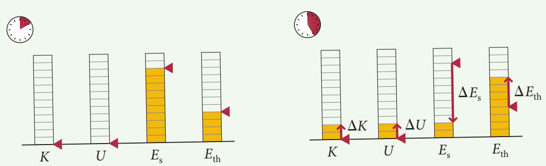
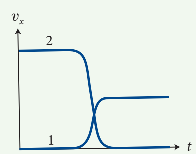


Figure 7.23

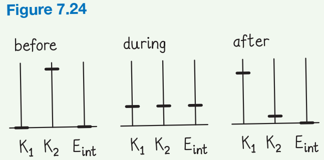


5. Describe a scenario to fit the velocity-versus-time curves for two colliding objects shown in Figure 7.23. What happens to the initial energy of the system of colliding objects during the interaction?

Answers

1. *(a)* The cart with the smaller inertia experiences the greater acceleration (see Figure 7.2). *(b)* The magnitude of $\Delta\vec{p}_1$ is the same as the magnitude of $\Delta\vec{p}_2$, but the changes are in opposite directions because the momentum of the system does not change during the collision. *(c)* $|\Delta K_1| = |\Delta K_2|$, but the changes are opposite in sign because the kinetic energy of the system before the elastic collision has to be the same as the kinetic energy of the system afterward.
2. *(a)* Reversible. The ball returns to its original shape. *(b)* Irreversible. The fender remains crumpled. *(c)* Irreversible. The balloon does not completely return to its original shape after deflation. *(d)* Irreversible. Your footprints remain.
3. See Figure 7.24. Before the collision $K_1 = 0$, K_2 is maximal, and $E_{int} = 0$; during the collision K_1, K_2, and E_{int} are all about one-third of the initial value of K_1; after the collision K_1 is about 7/8 of the initial value of K_1, K_2 is about 1/8 of the initial value of K_1, and $E_{int} = 0$. Because the system is closed, its energy is constant, which means the sum of the three bars is always the same.

Figure 7.24



4. During the interaction, eight units of source energy is converted to two units of kinetic energy, two units of potential energy, and four units of thermal energy. One possible scenario is the vertical launching of a ball. Consider the system comprising you, the ball, and Earth from just before the ball is launched until after it has traveled some distance upward: The source energy goes down (you exert some effort), thermal energy goes up (in the process of exerting effort you heat up), kinetic energy goes up (the ball was at rest before the launch), and so does potential energy (the distance between the ground and the ball increases).
5. The graph represents an inelastic collision because the relative velocity of the two objects decreases to about half its initial value. In order for the momentum of the system to remain constant, the inertia of object 1 must be twice that of object 2. Possible scenario: Object 2, inertia m, collides inelastically with object 1, inertia $2m$. The collision brings object 2 to rest and sets object 1 in motion. The interaction converts the initial kinetic energy of object 2 to kinetic energy of cart 1 and to thermal energy and/or incoherent configuration energy of both carts.

SELF-QUIZ

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CONCEPTS

QUANTITATIVE TOOLS

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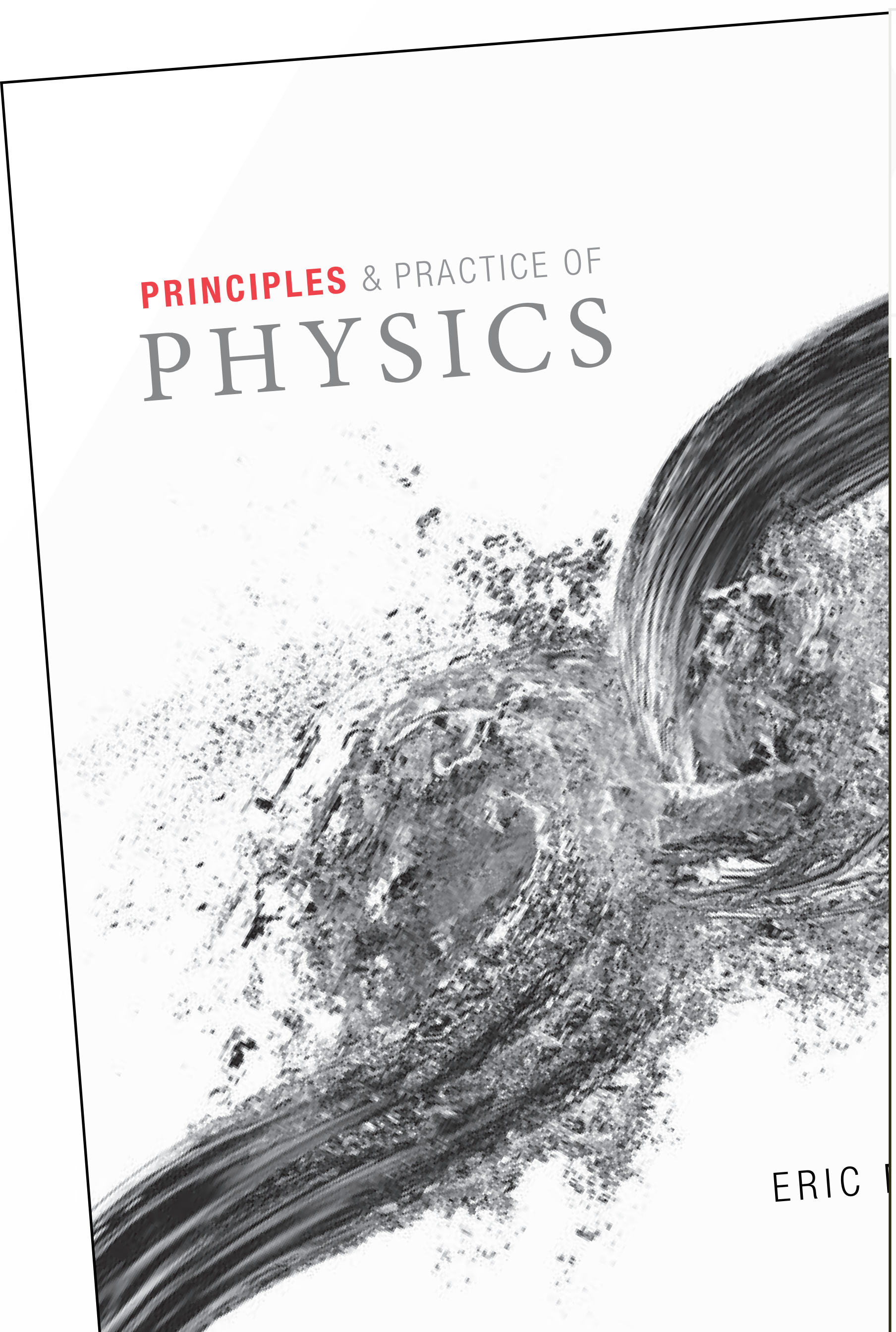

Energy

CONCEPTS

QUANTITATIVE TOOLS

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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 6.13*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:

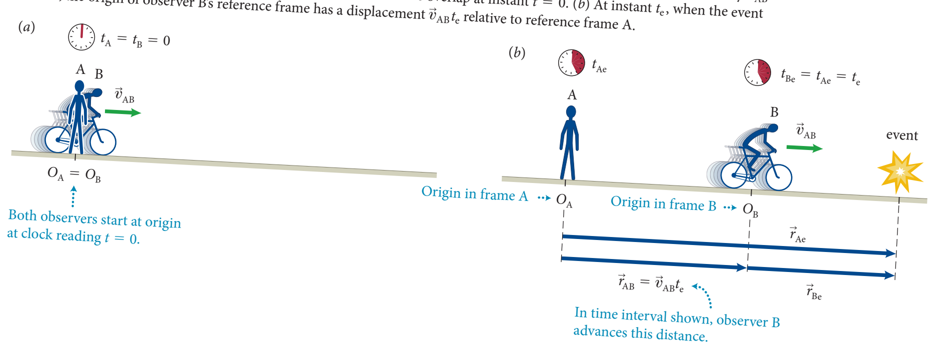
$$t_A = t_B = t. \tag{6.2}$$

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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QUANTITATIVE TOOLS

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build on conceptual underpinnings to effectively teach quantitative tools

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(*b*) From Figure 10.18 I see that $\tan\theta = |F^c_{sp\,x}|/|F^c_{sp\,y}|$. For $\theta < 45°$, $\tan\theta < 1$, and so $|F^c_{sp\,x}| < |F^c_{sp\,y}|$. Because $|F^c_{sp\,y}| = F^G_{Ep}$ and $|F^c_{sp\,x}| = F^c_{rp}$, I find that for $\theta < 45°$, $F^c_{rp} < F^G_{Ep}$. When $\theta > 45°$, $\tan\theta > 1$, and so $|F^c_{sp\,x}| > |F^c_{sp\,y}|$ and $F^c_{rp} > F^G_{Ep}$. ✔

(*c*) $|\vec{F}^c_{sp\,y}| = F^G_{Ep}$ and $F^c_{sp} = \sqrt{(F^c_{sp\,x})^2 + (F^c_{sp\,y})^2}$. Therefore, F^c_{sp} must always be larger than F^G_{Ep} when $\theta \neq 0$. ✔

❹ **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°, the forces $\vec{F}^c_{rp}$ and $\vec{F}^G_{Ep}$ on your friend make the same angle with the force $\vec{F}^c_{sp}$, and so $\vec{F}^c_{rp}$ and $\vec{F}^G_{Ep}$ 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°, $\vec{F}^c_{rp}$ is larger than $\vec{F}^G_{Ep}$. In part *c*, because the vertical component of the force $\vec{F}^c_{sp}$ exerted by the seat on your friend always has to be equal to the force of gravity, adding a horizontal component makes $\vec{F}^c_{sp}$ larger than $\vec{F}^G_{Ep}$, 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.

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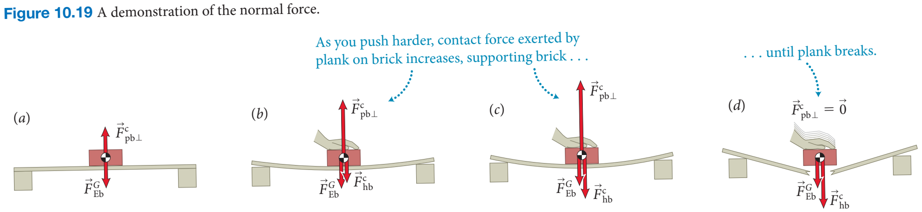
Even though the normal and tangential components of the contact force exerted by the floor on the cabinet belong to the same interaction, they behave differently and are usually treated as two separate forces: the normal component being called the **normal force** and the tangential component being called 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 10.19*a*). Because the brick is at rest, the normal force $\vec{F}^c_{pb\perp}$ 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 $\vec{F}^c_{hb}$. 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 10.19*b*). As you push down harder, the plank bends more, and the normal force continues to increase (Figure 10.19*c*) until you exceed the plank's capacity to provide support and it snaps, at which point the normal force suddenly disappears (Figure 10.19*d*). 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 10.19*a*, 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.**

Figure 10.19 A demonstration of the normal force.



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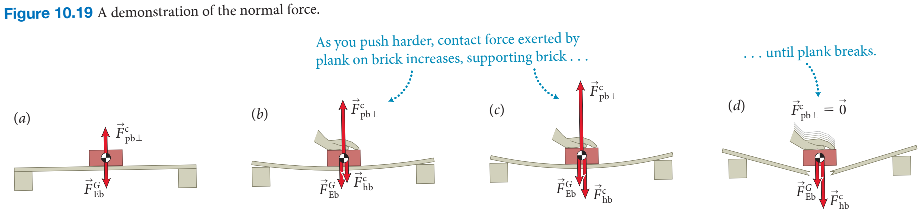

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Figure 10.19 A demonstration of the normal force.

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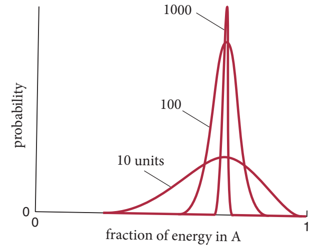
Figure 19.14 Probability of finding a given fraction of the system's energy in compartment A of the box in Figure 19.13. As the number of energy units increases from 10 to 1000, the probability distribution becomes narrower but remains centered about the mean energy.



basic states available to the system is obtained by multiplying Ω_A by Ω_B: $\Omega = \Omega_A\Omega_B$.

The probability of each macrostate is obtained by dividing Ω, the number of basic states associated with that macrostate, by Ω_{tot}, the number of basic states associated with all macrostates (2.00×10^7; see Table 19.2). The table shows you that this probability is greatest for the macrostate $E_A = 7$, as you would expect. Given that there are 14 particles in A and six in B, on average each particle has half an energy unit, and so the $E_A = 7$ macrostate corresponds to an equipartitioning of the energy. The curve labeled 10 units in **Figure 19.14** shows this probability as a function of the fraction of energy contained in A.

Example 19.6 Probability of macrostates

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 $E_A = 7$?

❶ **GETTING STARTED** Because all basic states are equally likely, the probability of finding the system in macrostate E_A is equal to the fraction Ω/Ω_{tot}, where Ω is the number of basic states of the system associated with the macrostate E_A and Ω_{tot} is the total number of basic states associated with all macrostates (2.00×10^7; Table 19.2).

❷ **DEVISE PLAN** To find the probability of a given macrostate E_A, I divide the value of Ω for that macrostate given in Table 19.2 by $\Omega_{tot} = 2.00 \times 10^7$.

❸ **EXECUTE PLAN** (*a*) For $E_A = 1$, Table 19.2 tells me that $\Omega = 2.80 \times 10^4$. The probability of macrostate $E_A = 1$ is thus $(2.80 \times 10^4)/(2.00 \times 10^7) = 1.40 \times 10^{-3}$. ✔

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

❹ **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 equipartition 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.

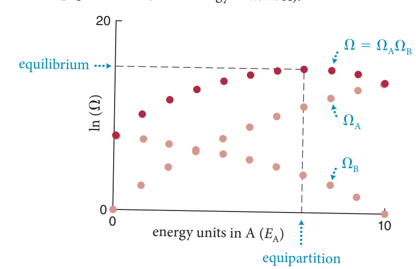
Note that the number of basic states is very large, even with just ten energy units and 20 particles. In a box of volume 1 m^3 containing air at atmospheric pressure and room temperature, there are on the order of 10^{25} particles and 10^{20} energy units per particle, and so the number of basic states 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 rightmost column in Table 19.2, the natural logarithm of the number of basic states is indeed much more manageable.

Figure 19.15 shows how the natural logarithms of Ω_A, Ω_B, and Ω vary with the number of energy units in compartment A in Figure 19.13. As you can see, the natural logarithm of the number of basic states changes much less rapidly than the number of basic states. Note that as E_A increases, the number of basic states Ω_A increases. As E_A increases, however, E_B decreases and so Ω_B decreases. The number of basic states Ω is maximum when $E_A = 7$ and $E_B = 3$, representing an equipartition of energy. The most probable macrostate (equilibrium) is achieved when there is equipartition of energy.

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 (2.80×10^4) 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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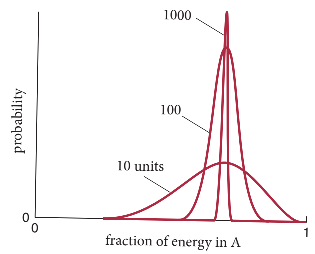

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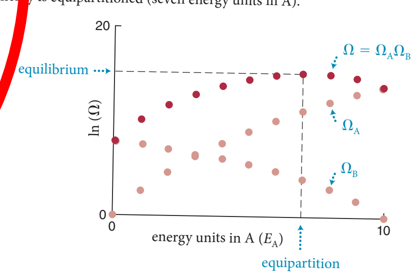

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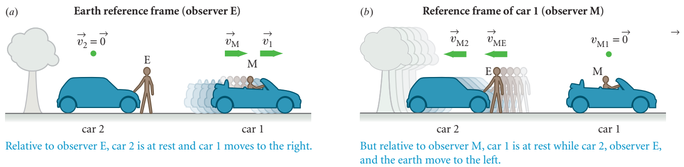
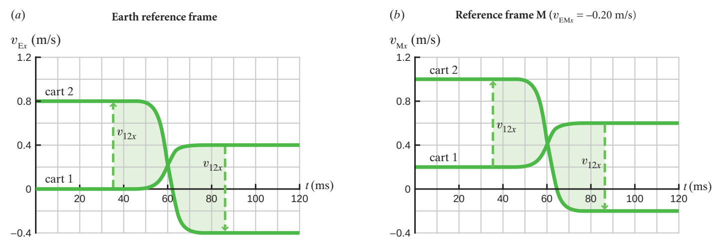
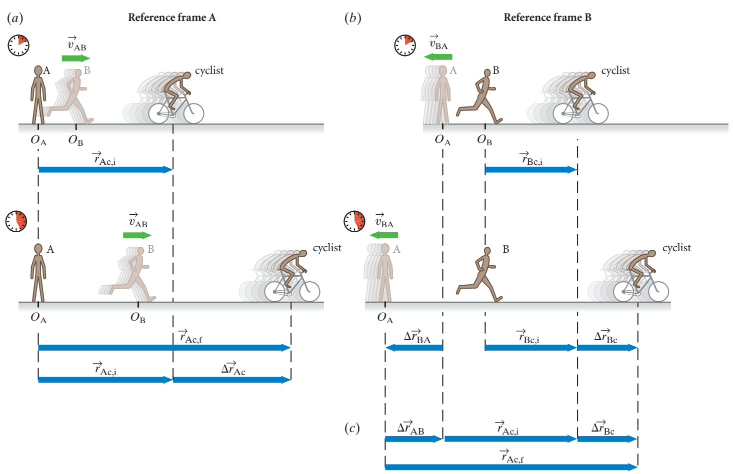
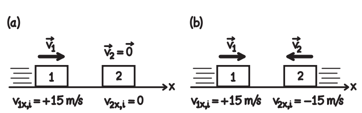
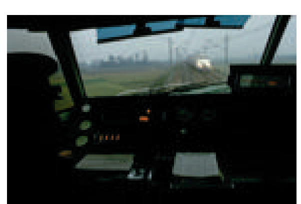
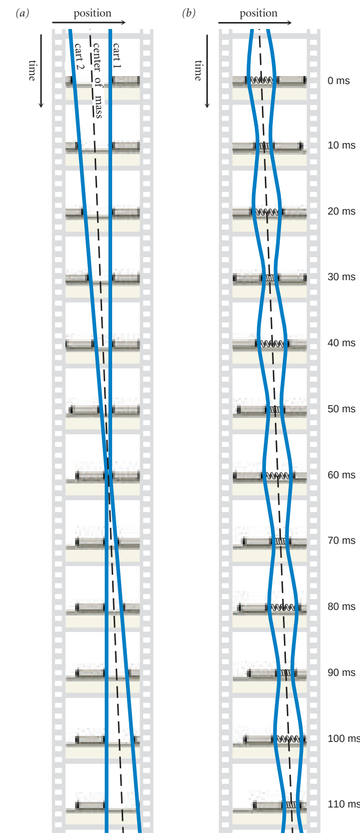

(a) Earth reference frame (observer E)
E
M
car 2
car 1
Relative to observer E, car 2 is at rest and car 1 moves to the right.
(b) Reference frame of car 1 (observer M)
E
M
car 2
car 1
But relative to observer M, car 1 is at rest while car 2, observer E, and the earth move to the left.

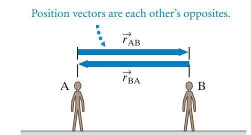

(a) Earth reference frame
cart 2
cart 1
t (ms)
(b) Reference frame M
cart 2
cart 1
t (ms)

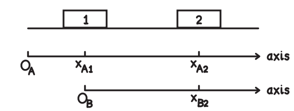

(a) Reference frame A
cyclist
A
B
(b) Reference frame B
cyclist
A
B
(c)

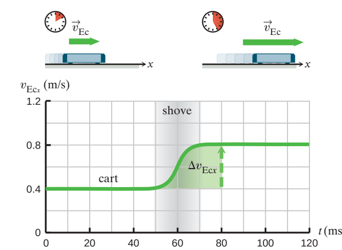

(a)
1
2
(b)
1
2

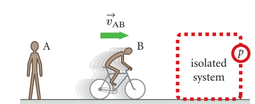


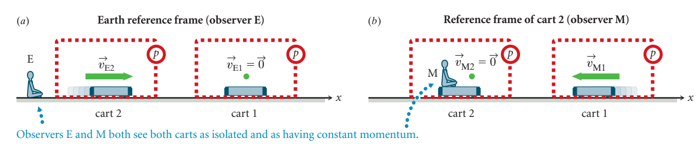

(a) position
time
cart 2
center of mass
cart 1
(b) position
time
0 ms
10 ms
20 ms
30 ms
40 ms
50 ms
60 ms
70 ms
80 ms
90 ms
100 ms
110 ms

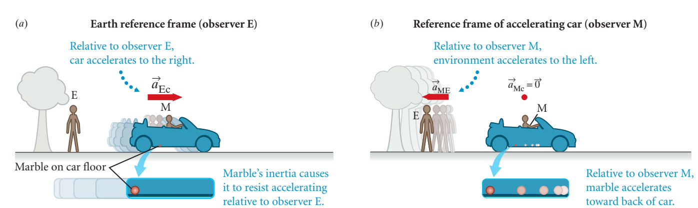

Position vectors are each other's opposites.
A
B

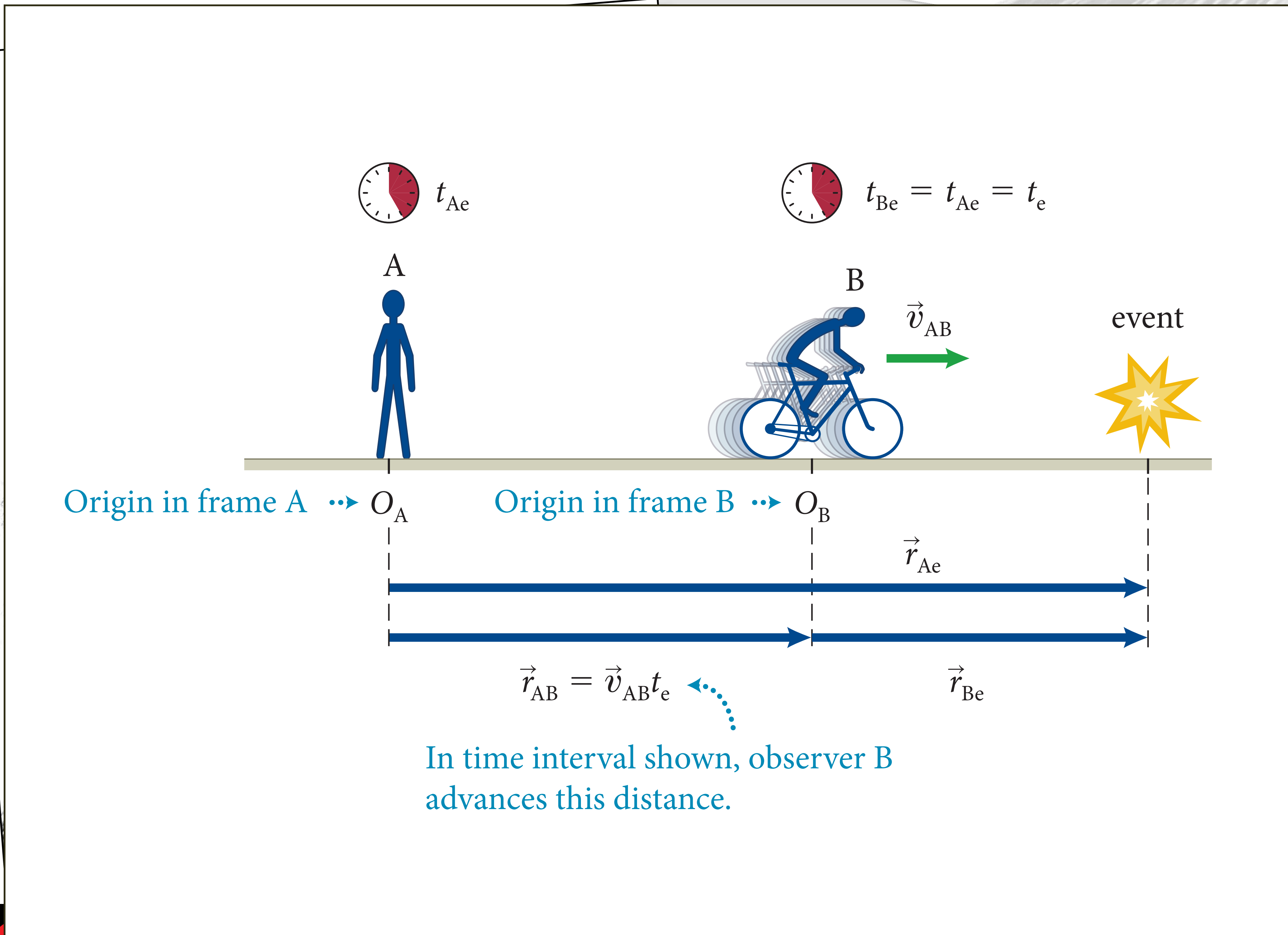

1
2
axis A
axis B


shove
cart
t (ms)

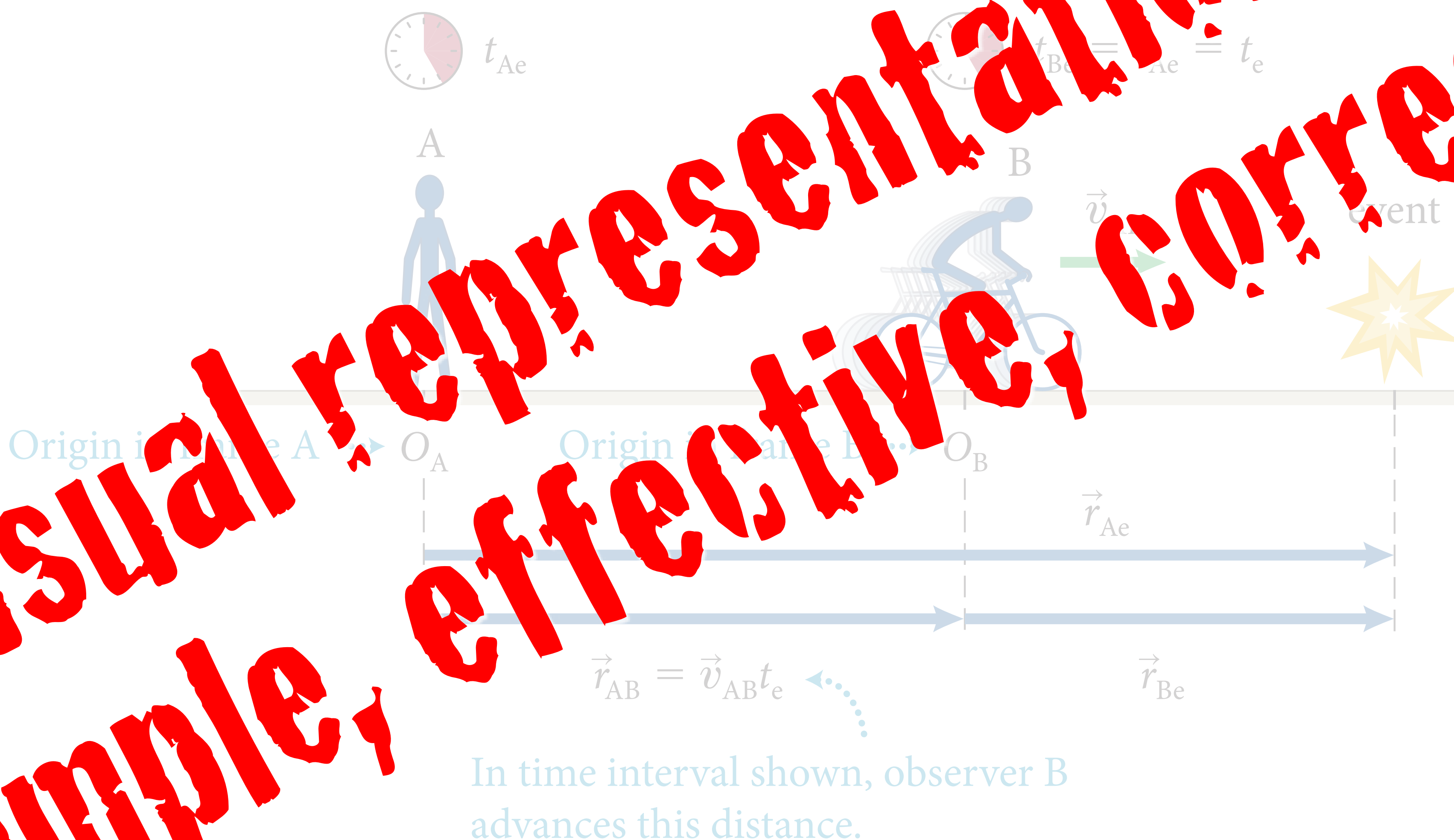

A
B
isolated system


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


(a) Earth reference frame (observer E)
Relative to observer E, car accelerates to the right.
E
M
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.
E
M
Relative to observer M, marble accelerates toward back of car.

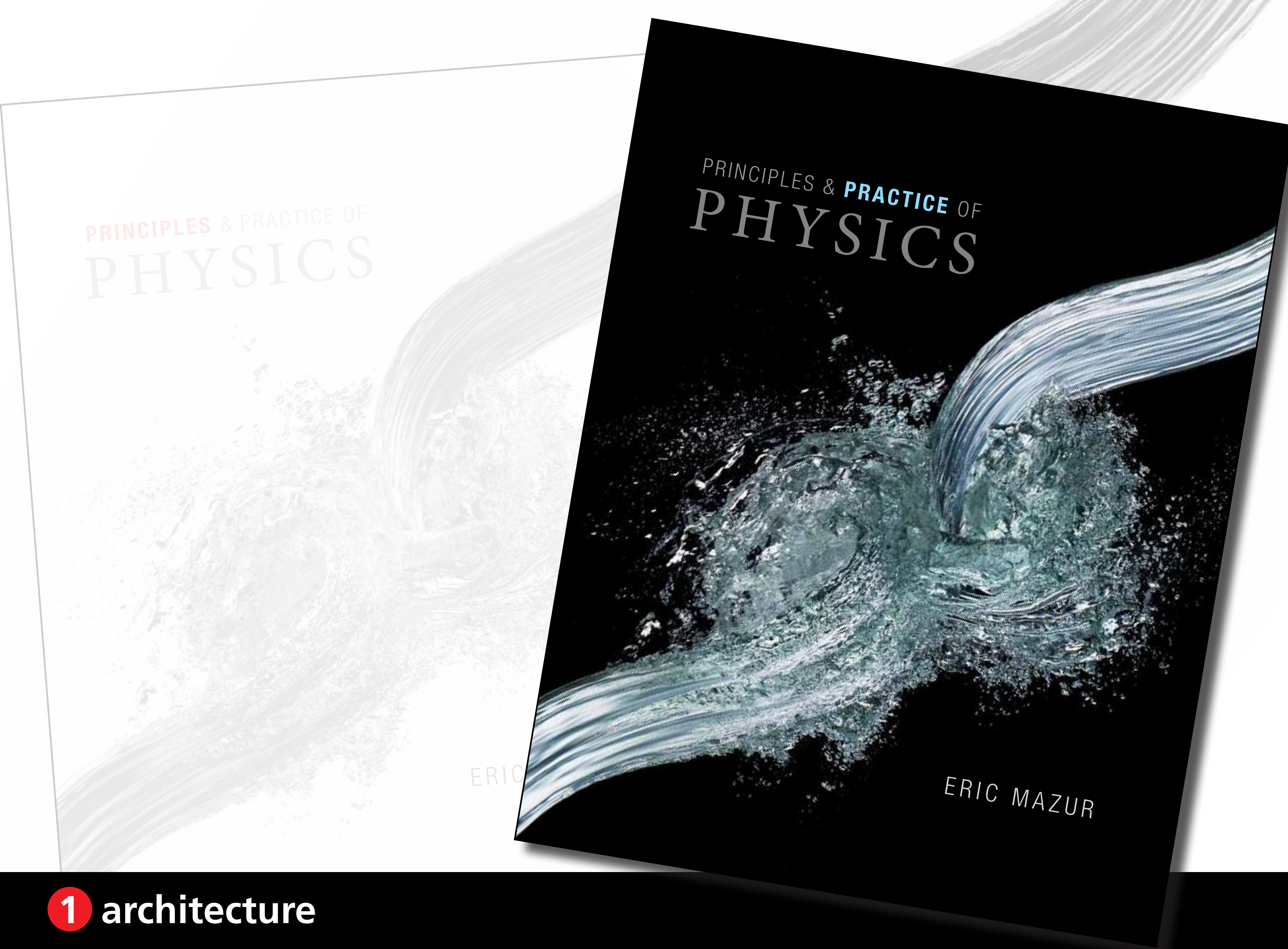

t_{Ae}
$t_{Be} = t_{Ae} = t_e$
A
B
$\vec{v}_{AB}$
event
Origin in frame A
O_A
Origin in frame B
O_B
$\vec{r}_{Ae}$
$\vec{r}_{AB} = \vec{v}_{AB} t_e$
$\vec{r}_{Be}$
In time interval shown, observer B
advances this distance.
architecture

visual representations: simple, effective, correct



PRINCIPLES VOLUME

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



1 architecture

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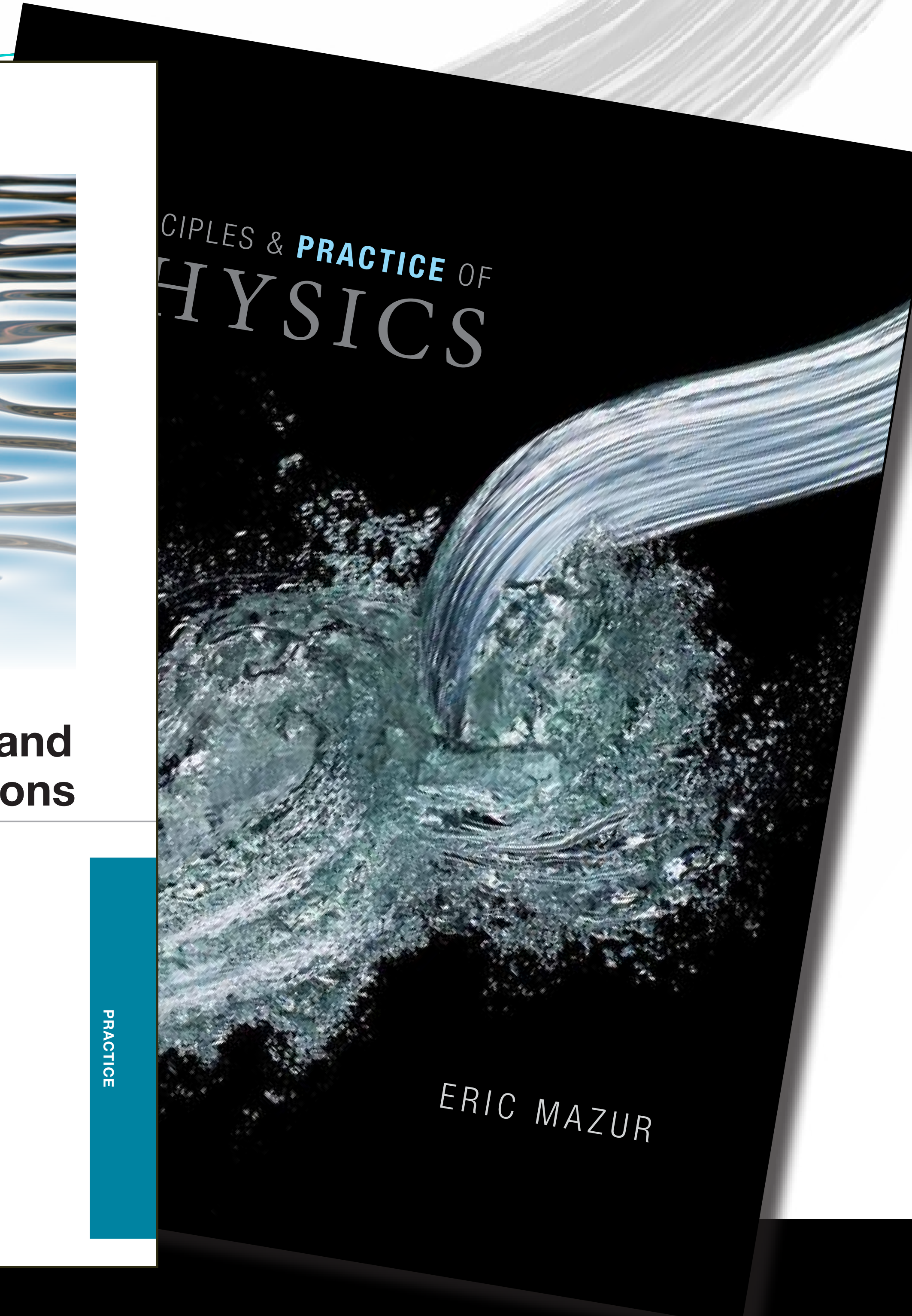
PRACTICE
Waves in Two and Three Dimensions

PRACTICE



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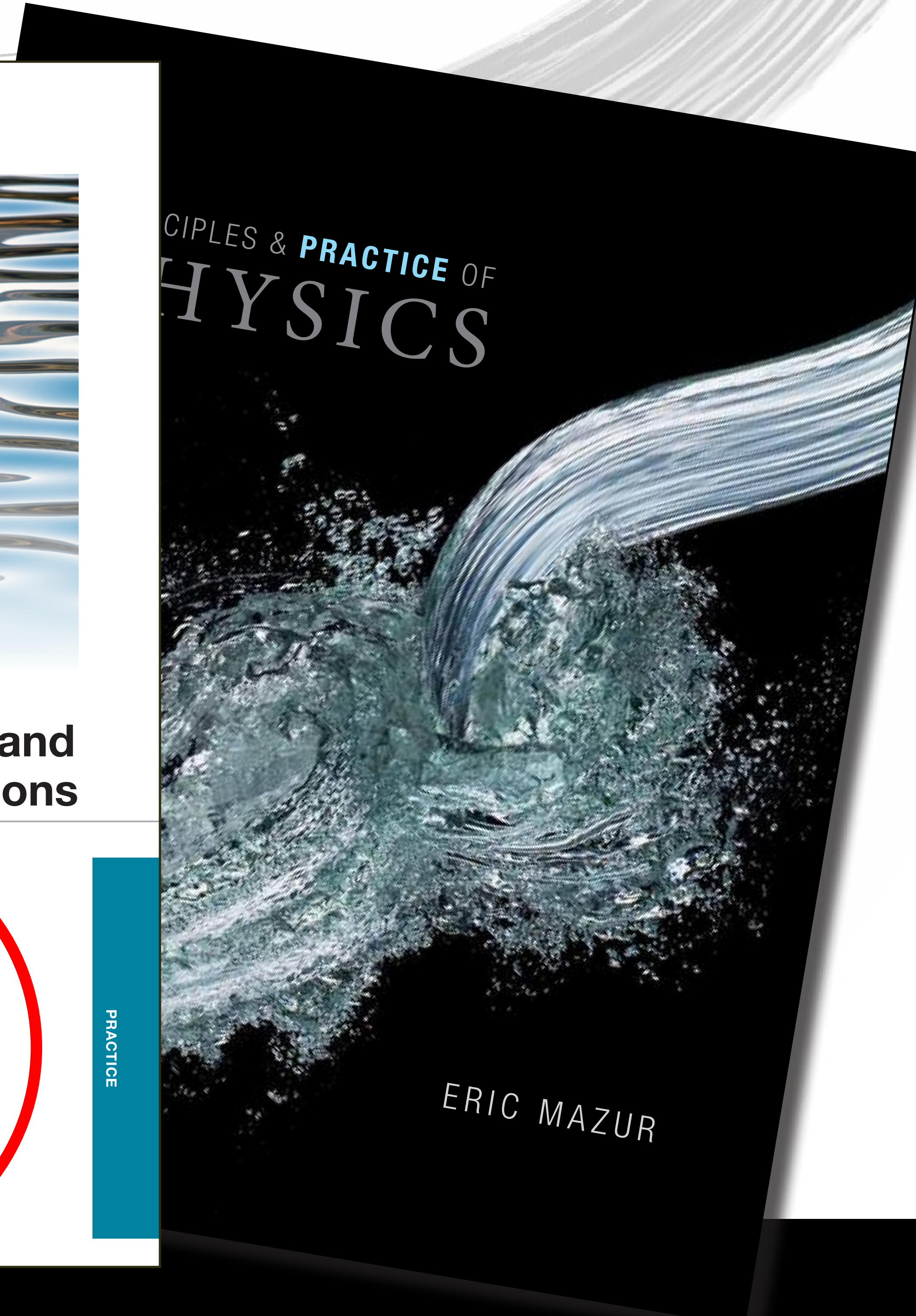
PRACTICE

Waves in Two and Three Dimensions

PRACTICE

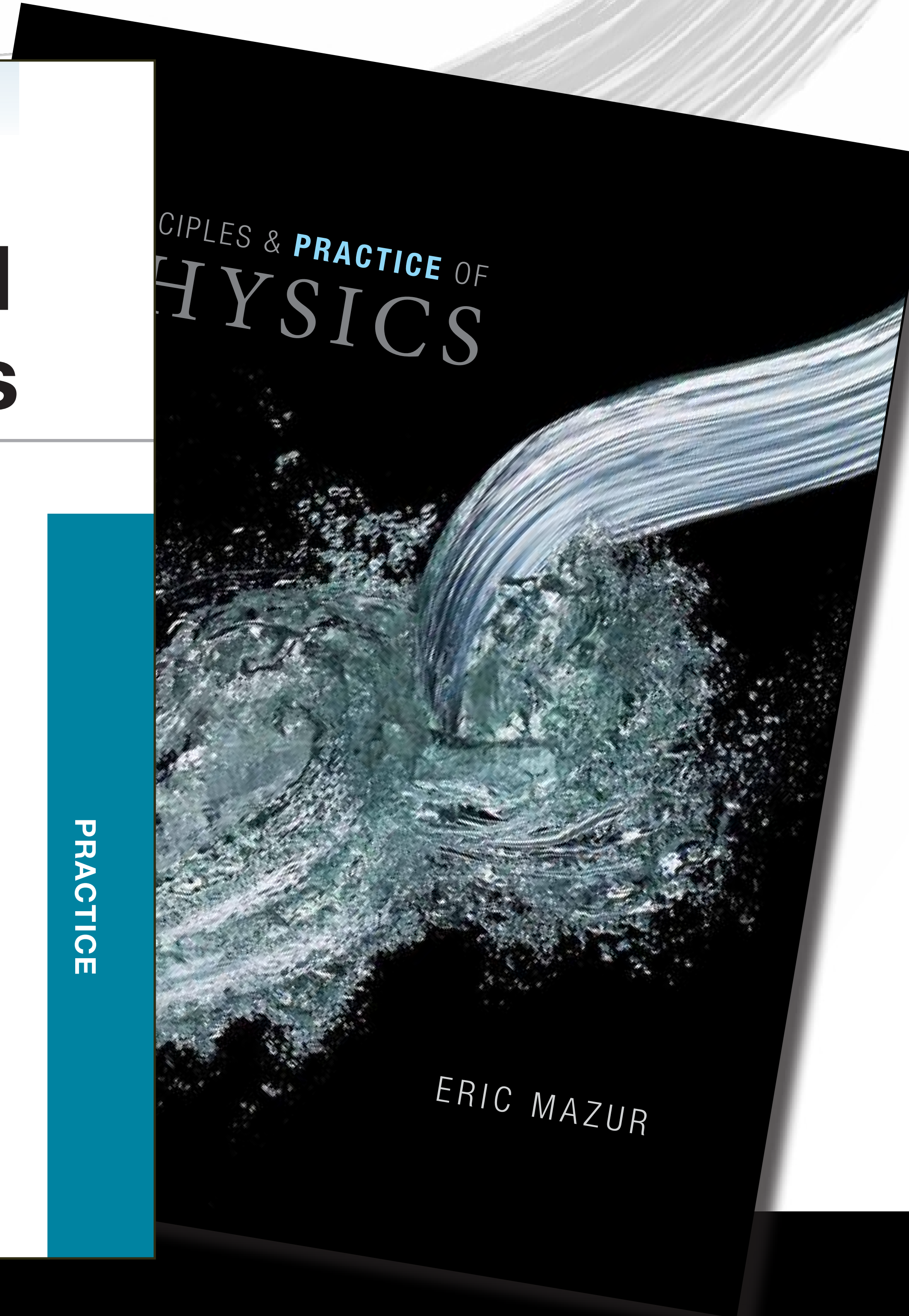


architecture

PRACTICE

Waves in Two and Three Dimensions

PRACTICE

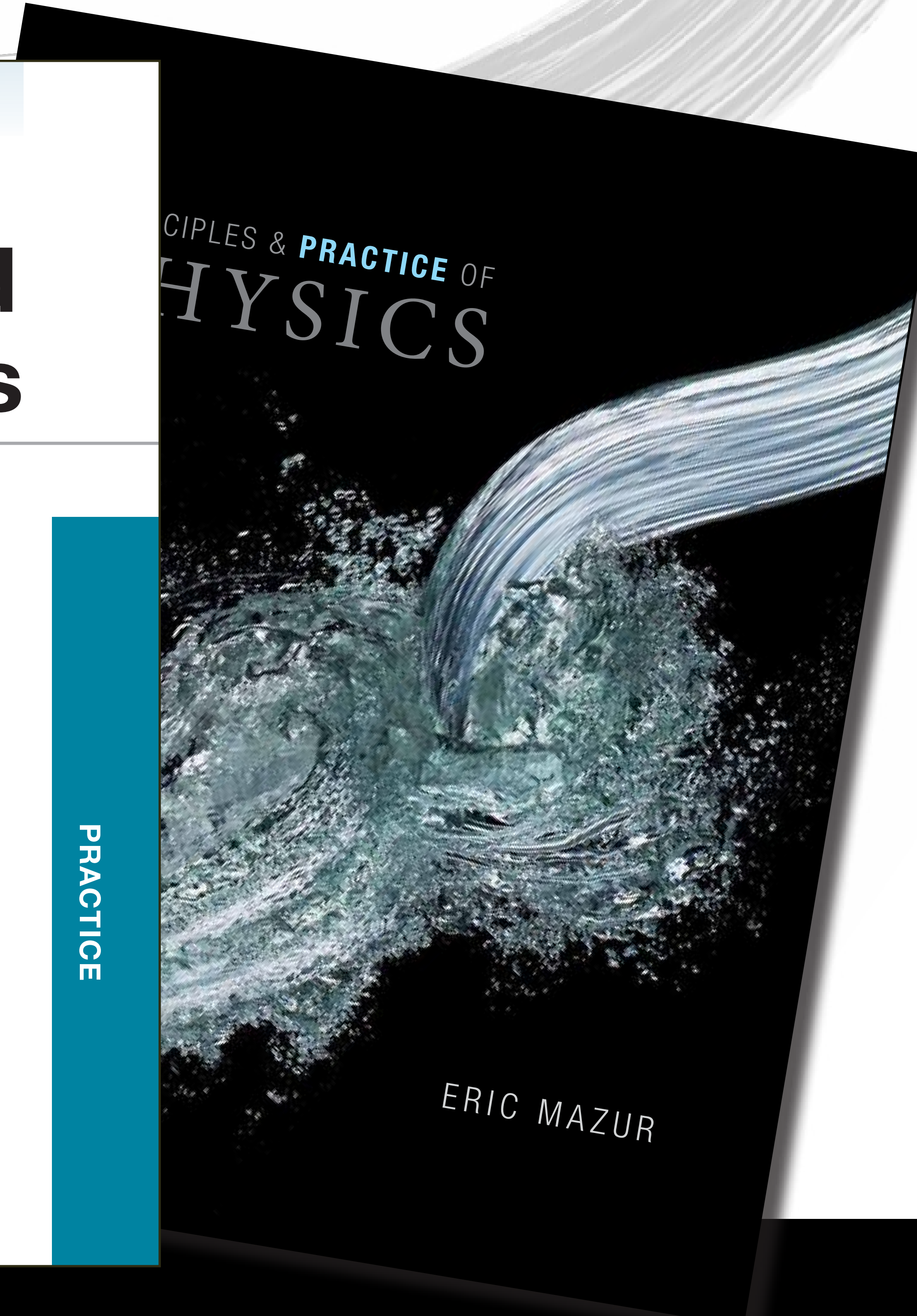


architecture

PRACTICE

Waves in Two and Three Dimensions

PRACTICE



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)

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

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PRACTICE

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PRACTICE

architecture

PRACTICE

Waves in Two Three Dimens

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AA. What is a typical freeway cruising speed?

Key (all values approximate)

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

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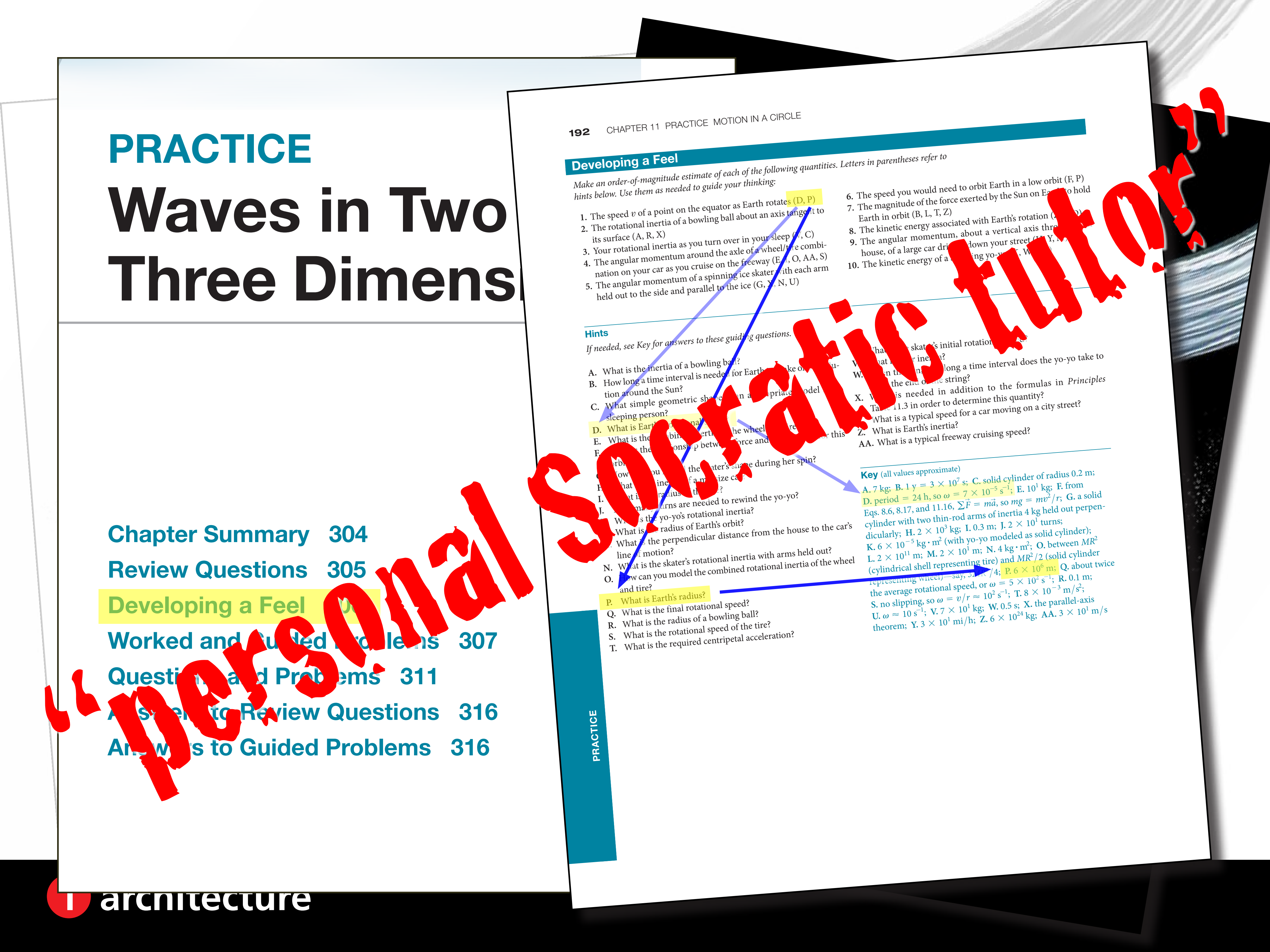

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Developing a Feel
Make an order-of-magnitude estimate of each of the following quantities. Letters in parentheses refer to hints below. Use them as needed to guide your thinking.
1. The speed v of a point on the equator as Earth rotates (D, P)
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Hints
If needed, see Key for answers to these guiding questions.
A. What is the inertia of a bowling ball?
D. What is Earth's
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?
Z. What is Earth's inertia?
AA. What is a typical freeway cruising speed?
Key (all values approximate)
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PRACTICE

Waves in Two and Three Dimensions

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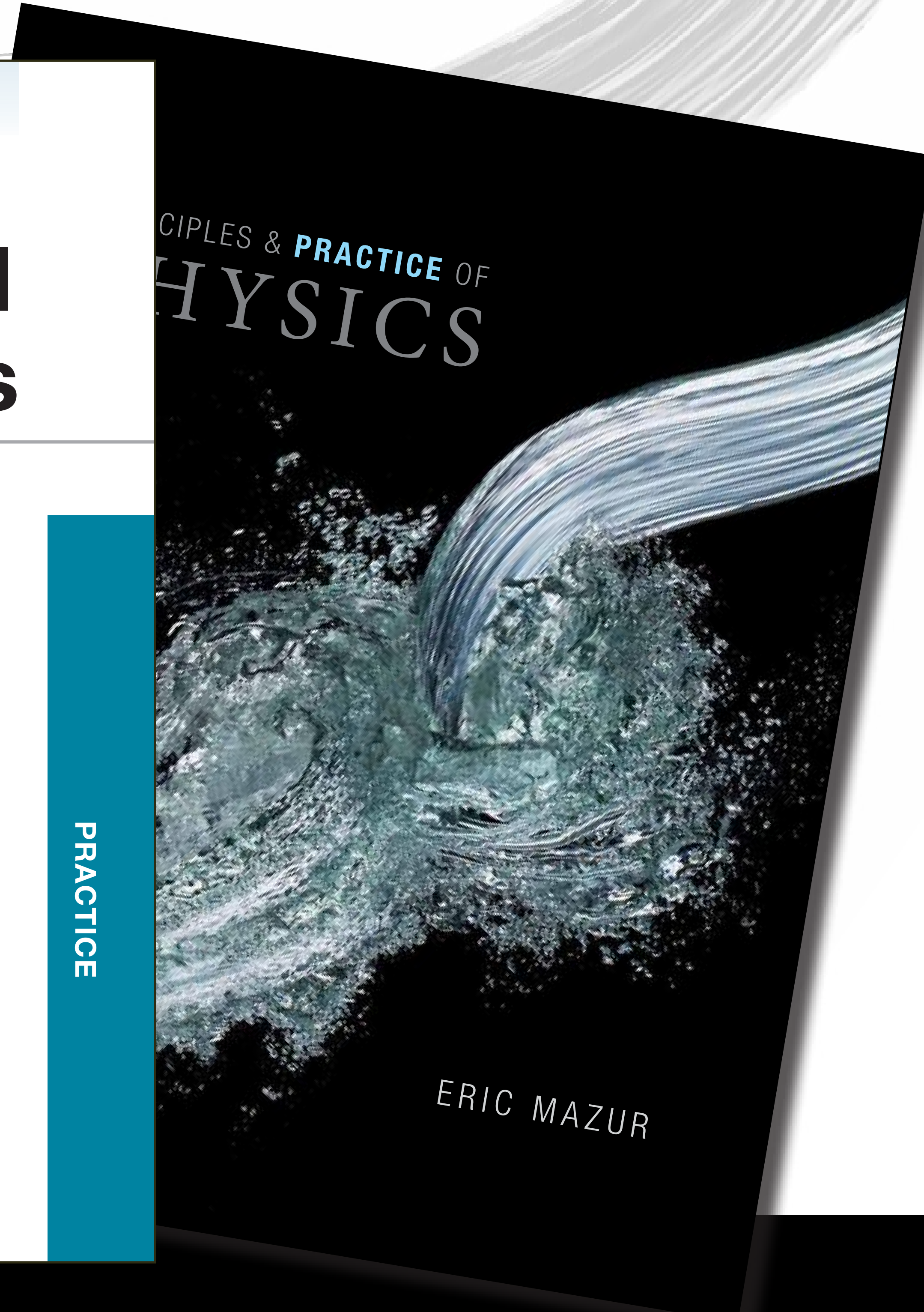

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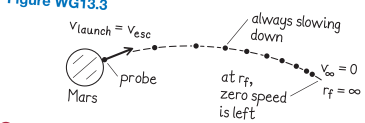
Worked Problem 13.3 Escape at last

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:

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

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

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

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

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

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?

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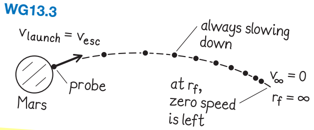
Worked Problem 13.3 Escape at last

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

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

Figure WG13.3



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

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

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

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

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Guided Problem 13.4 Spring to the stars

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

1 GETTING STARTED

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

2 DEVISE PLAN

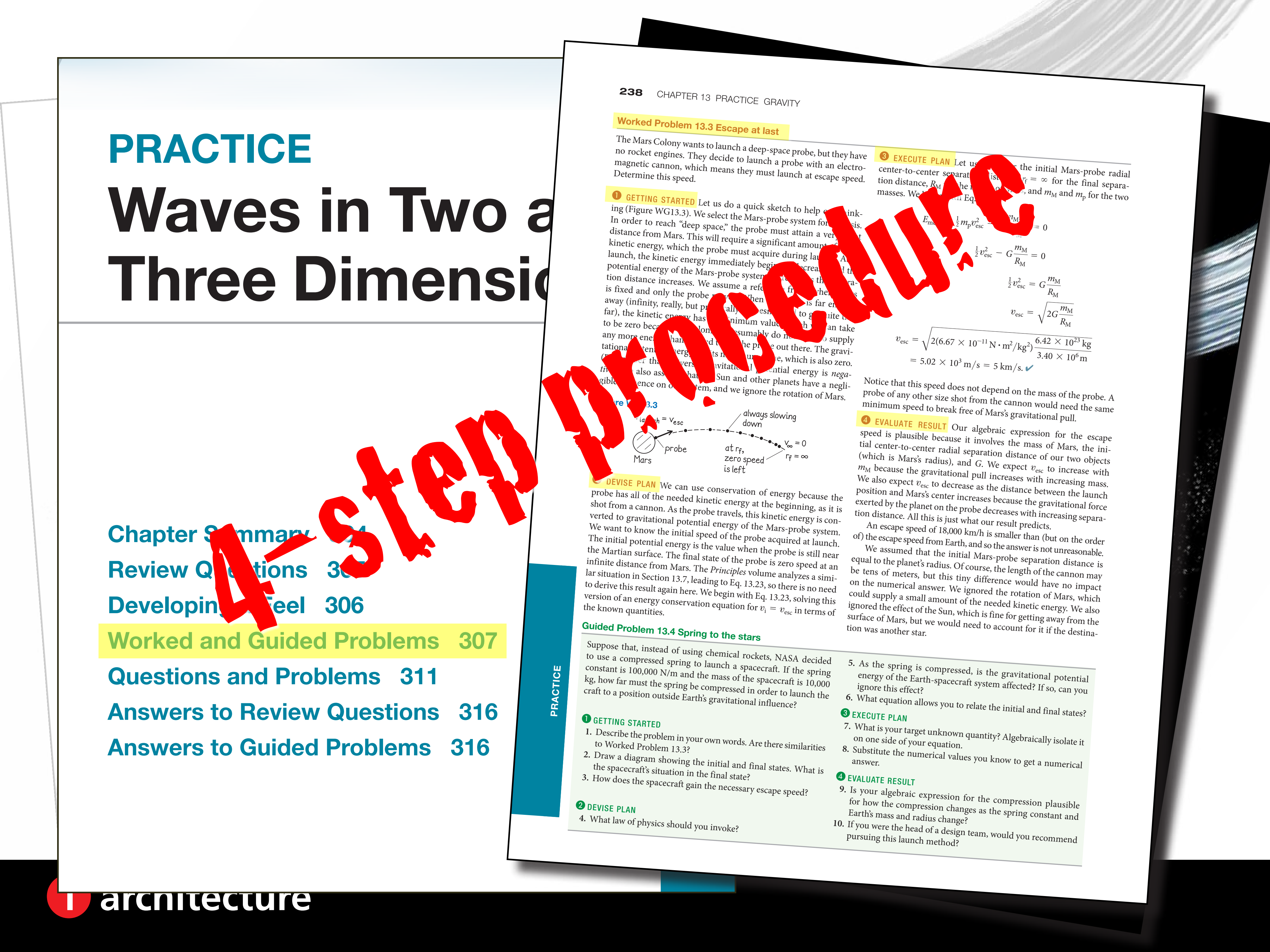
4. What law of physics should you invoke?
5. As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you ignore this effect?
6. What equation allows you to relate the initial and final states?

3 EXECUTE PLAN

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

4 EVALUATE RESULT

9. Is your algebraic expression for the compression plausible for how the compression changes as the spring constant and Earth's mass and radius change?
10. If you were the head of a design team, would you recommend pursuing this launch method?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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.
GETTING STARTED
EXECUTE PLAN
EVALUATE RESULT
DEVISE PLAN
always slowing down
probe
Mars
at rf, zero speed is left
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Worked Problem 13.3 Escape at last

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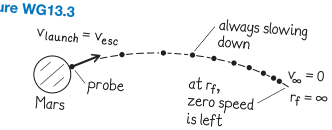
Figure WG13.3



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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:

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

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.

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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**

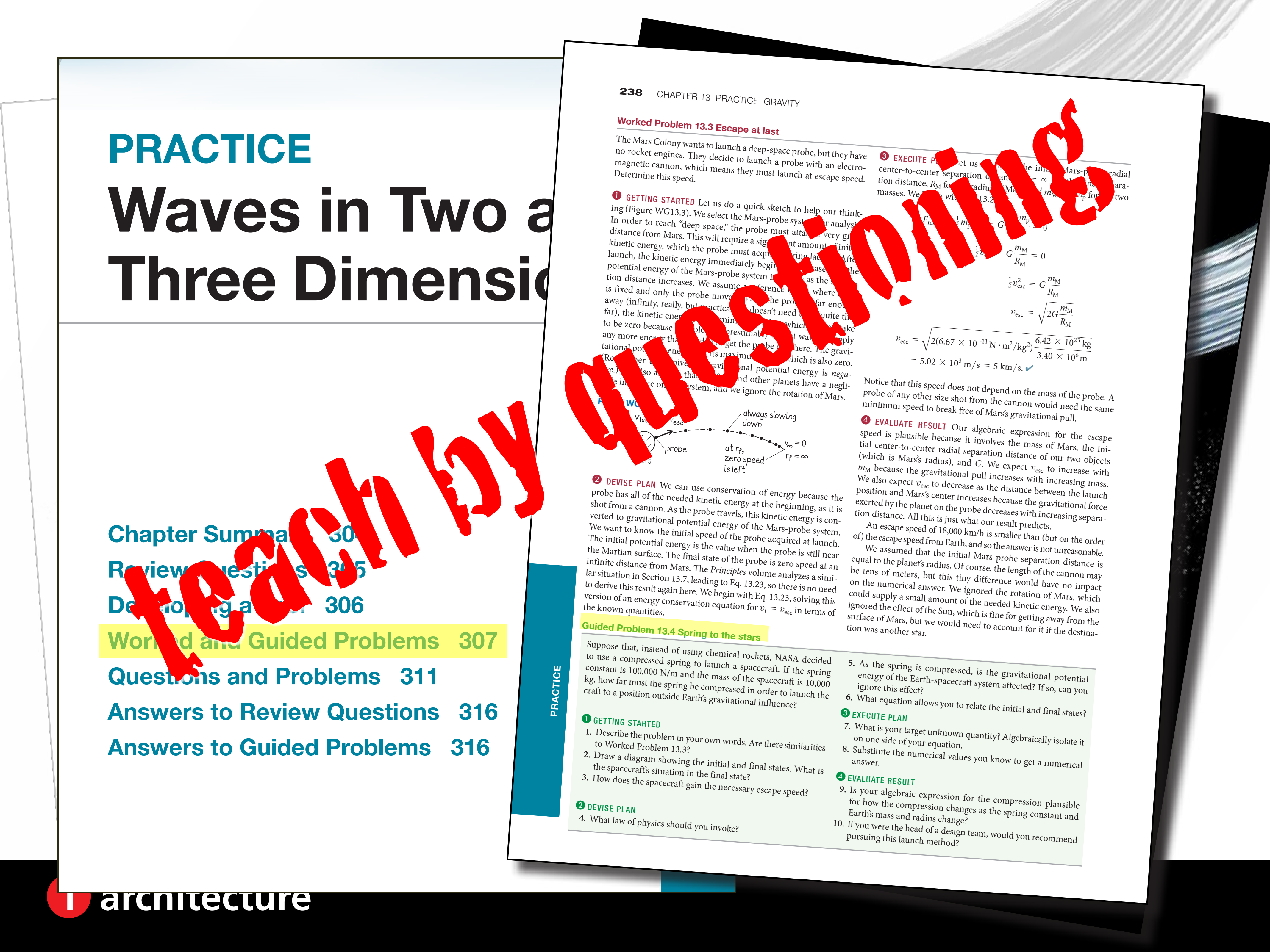
4. What law of physics should you invoke?
5. As the spring is compressed, is the gravitational potential energy of the Earth-spacecraft system affected? If so, can you ignore this effect?
6. What equation allows you to relate the initial and final states?

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?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Worked Problem 13.3 Escape at last
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GETTING STARTED
DEVISE PLAN
EXECUTE PLAN
EVALUATE RESULT
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always slowing down
probe
at rf, zero speed is left
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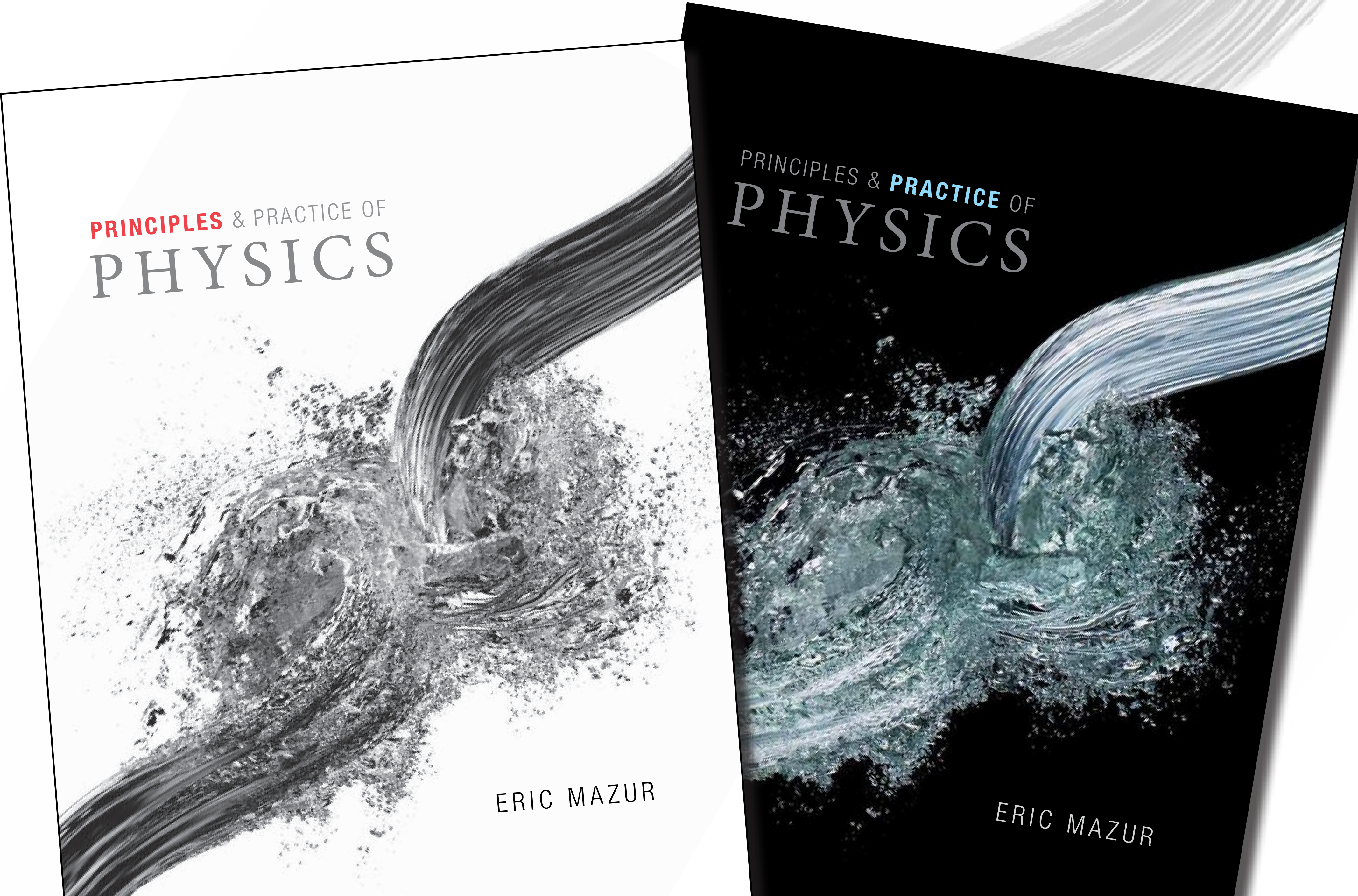
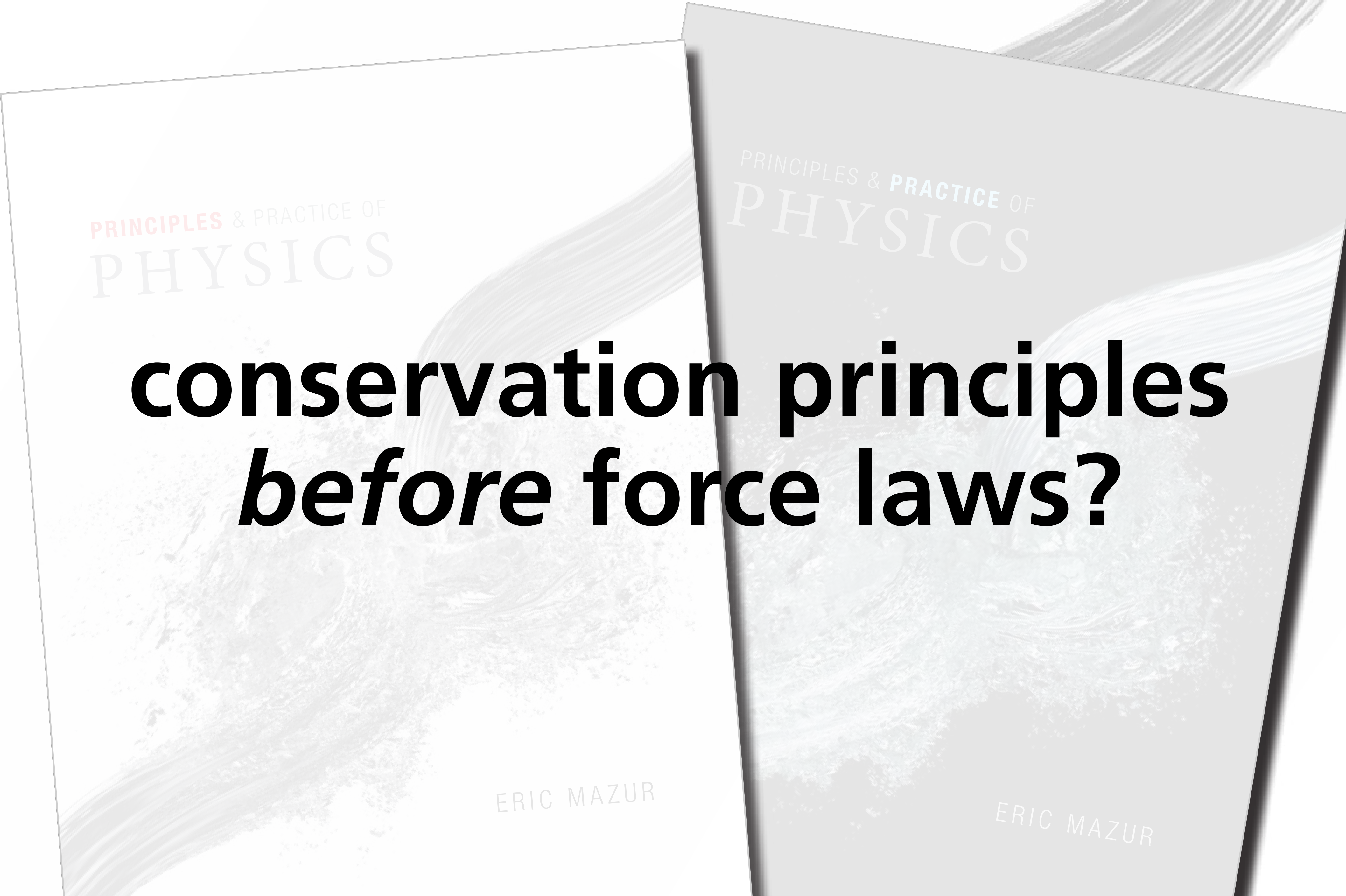
- many innovative features
- teaches authentic problem solving

1 architecture



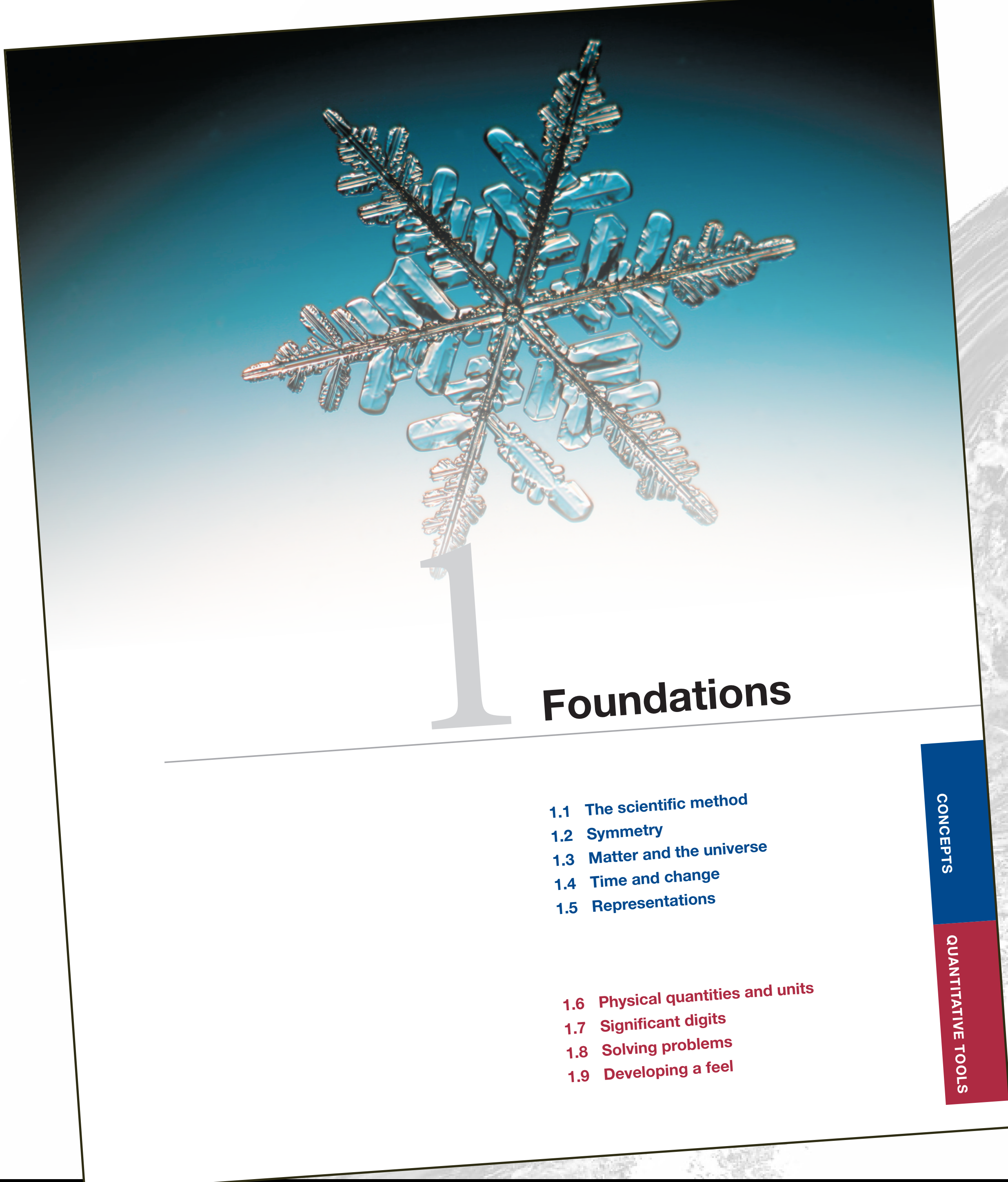
1 architecture

2 content



conservation principles *before* force laws?

❶ architecture ❷ content



1 Foundations

CONCEPTS

QUANTITATIVE TOOLS

1 architecture

2 content

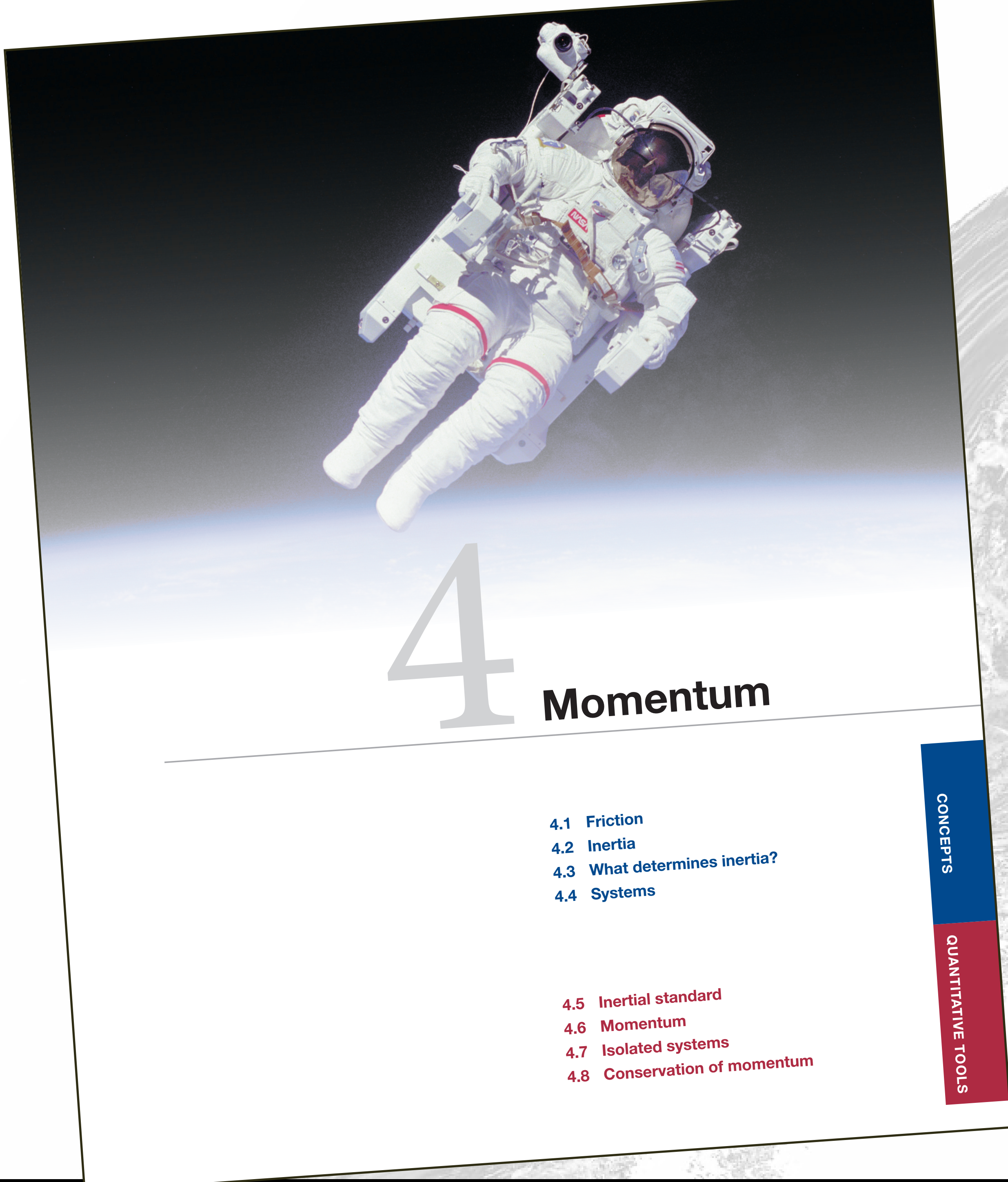
1.1 The scientific method
1.2 Symmetry
1.3 Matter and the universe
1.4 Time and change
1.5 Representations

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

1 architecture
2 content

1 architecture

2 content



1 architecture

2 content

4.1 Friction

4.2 Inertia

4.3 What determines inertia?

4.4 Systems

4.5 Inertial standard

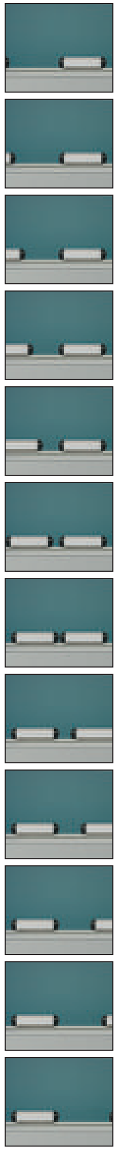
4.6 Momentum

4.7 Isolated systems

4.8 Conservation of momentum

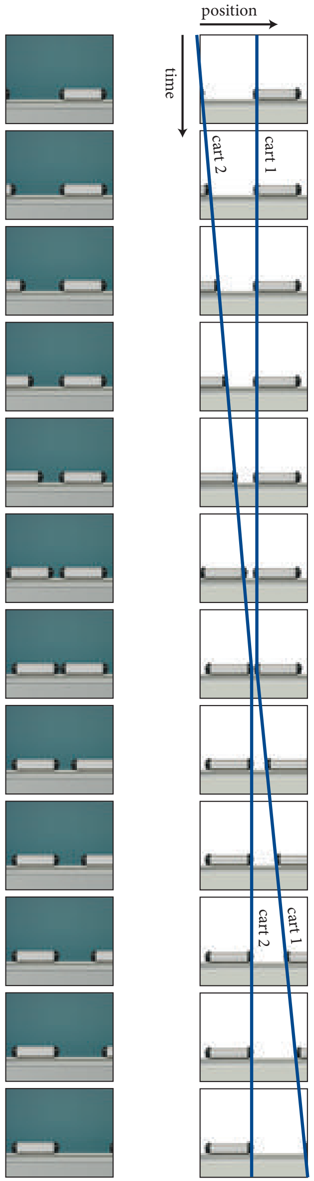
1 architecture

2 content

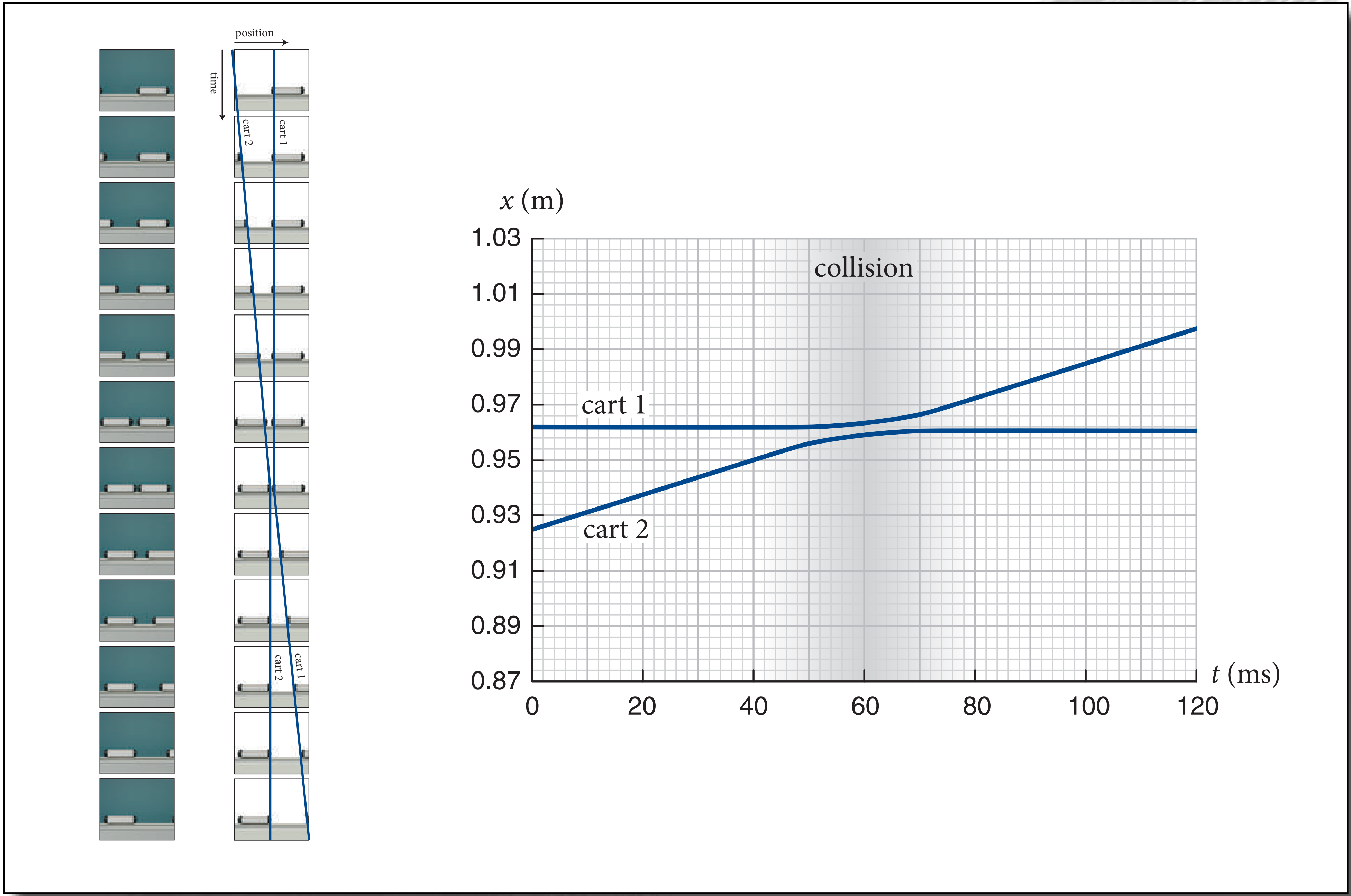


1 architecture

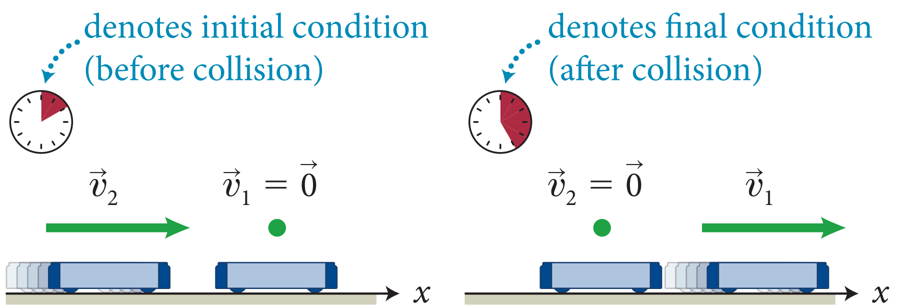
2 content



1 architecture 2 content

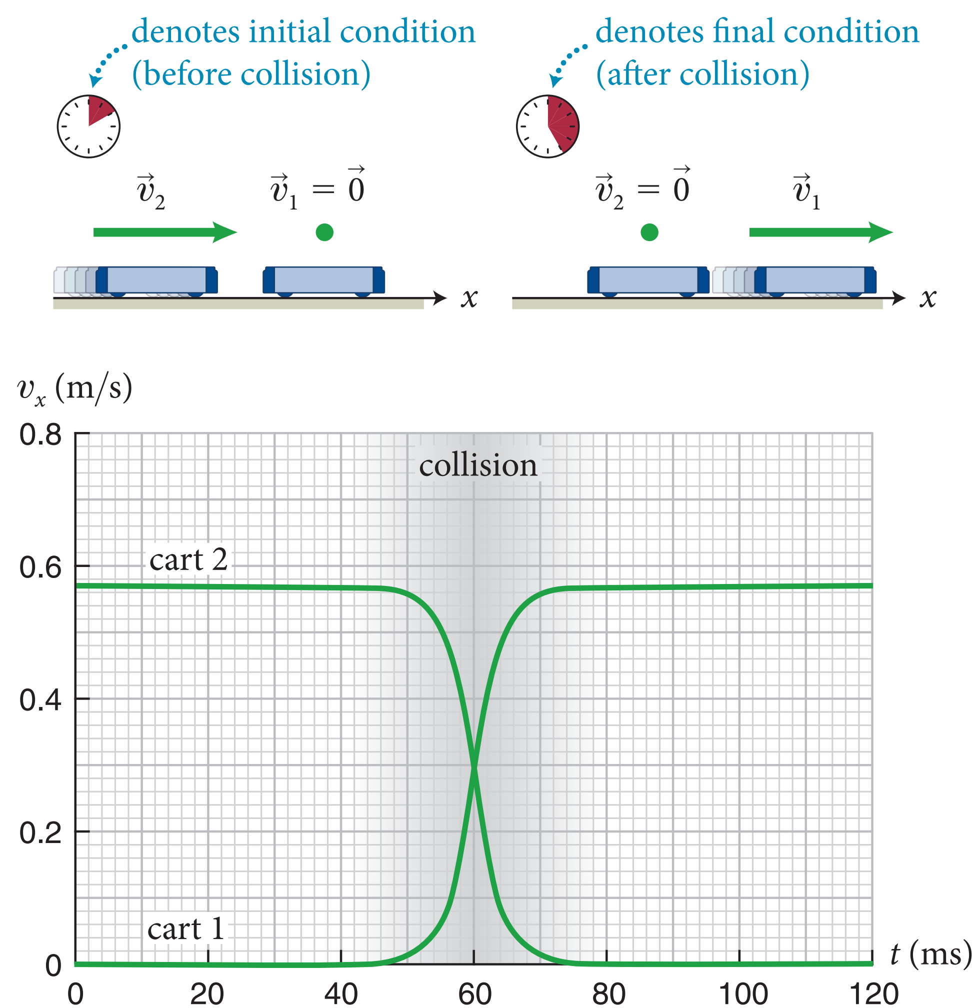


1 architecture   2 content



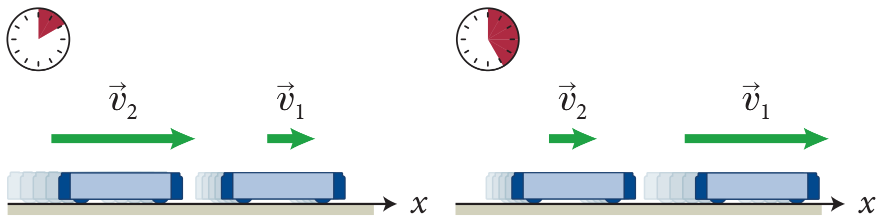
1 architecture

2 content



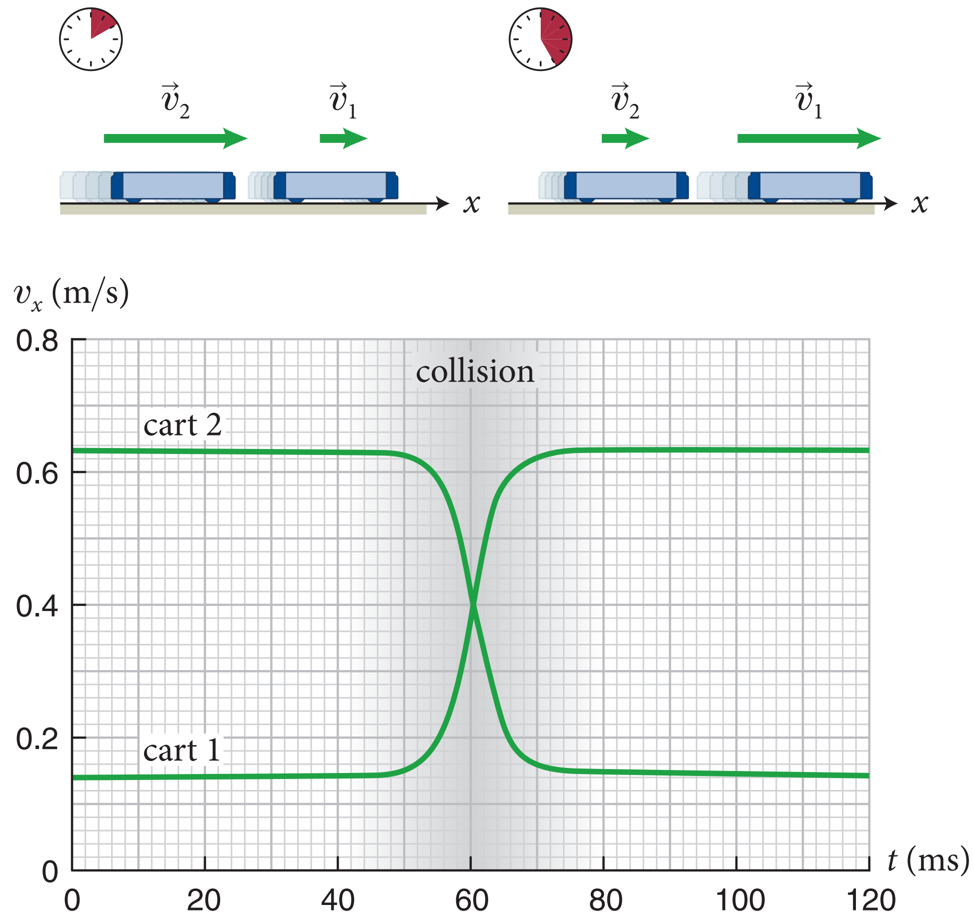
1 architecture

2 content



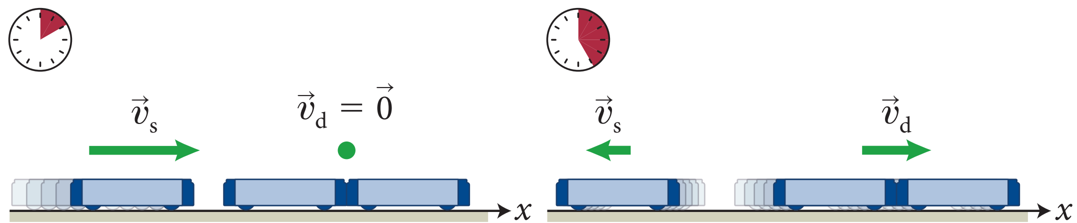
1 architecture

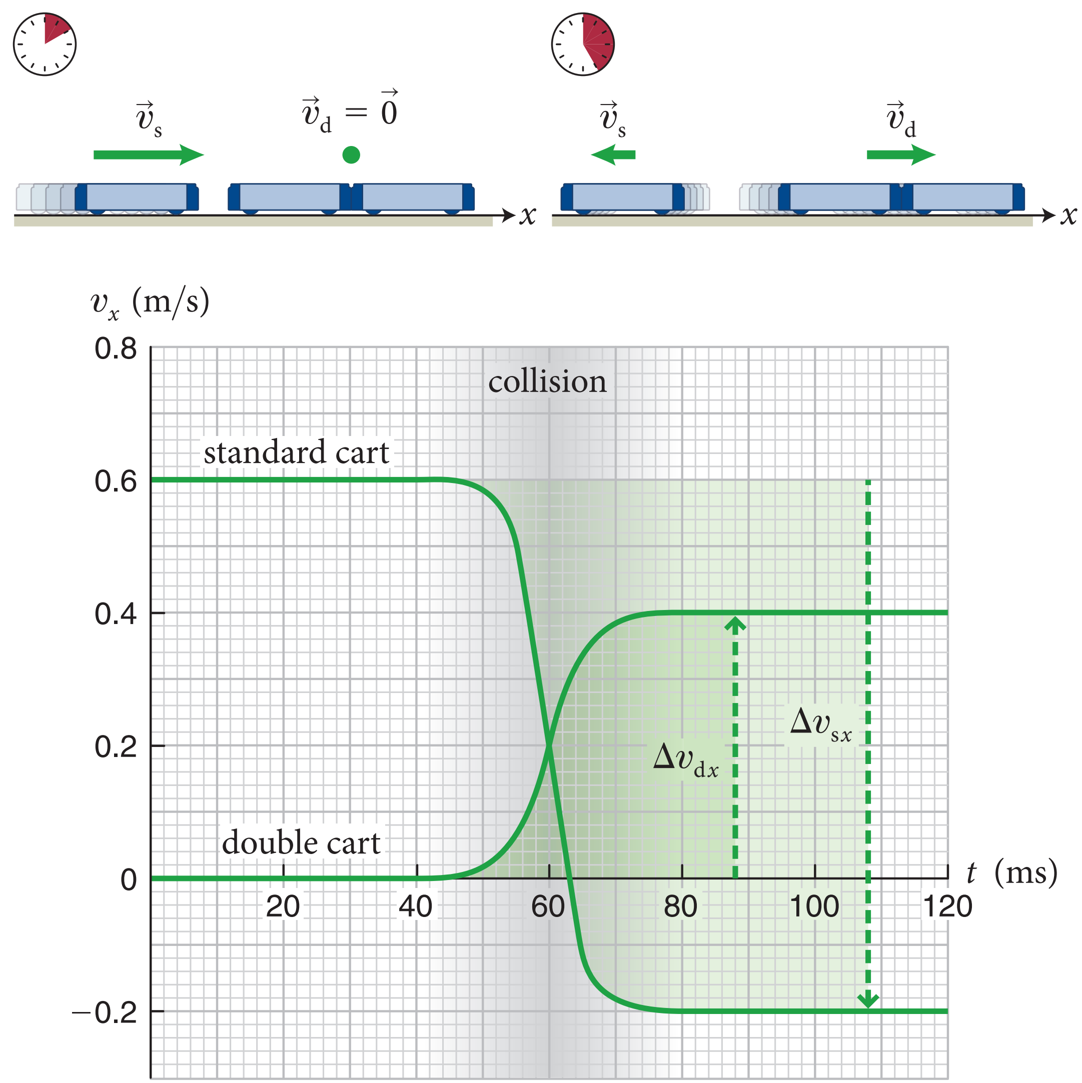
2 content



1 architecture

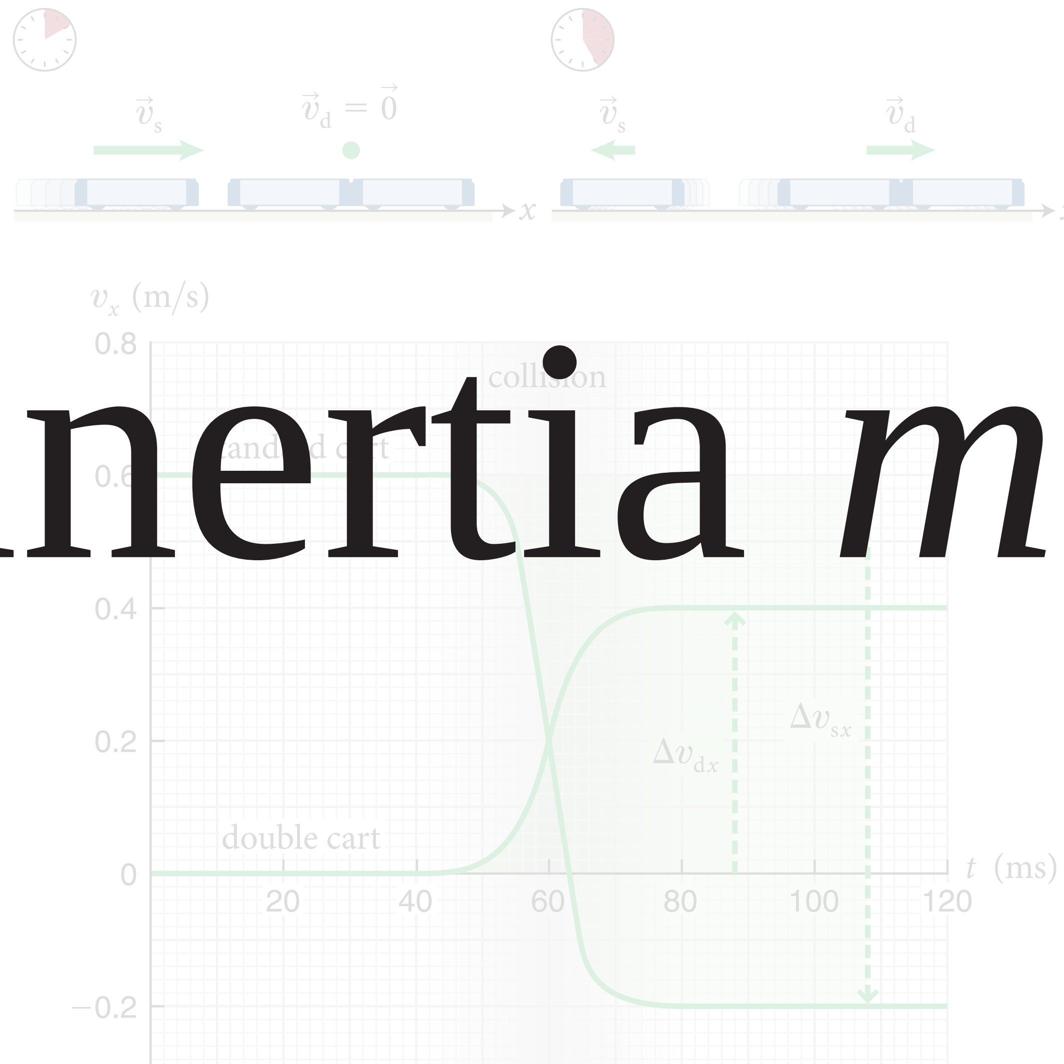
2 content


$\vec{v}_s$
$\vec{v}_d = \vec{0}$
x
$\vec{v}_s$
$\vec{v}_d$
x



1 architecture

2 content



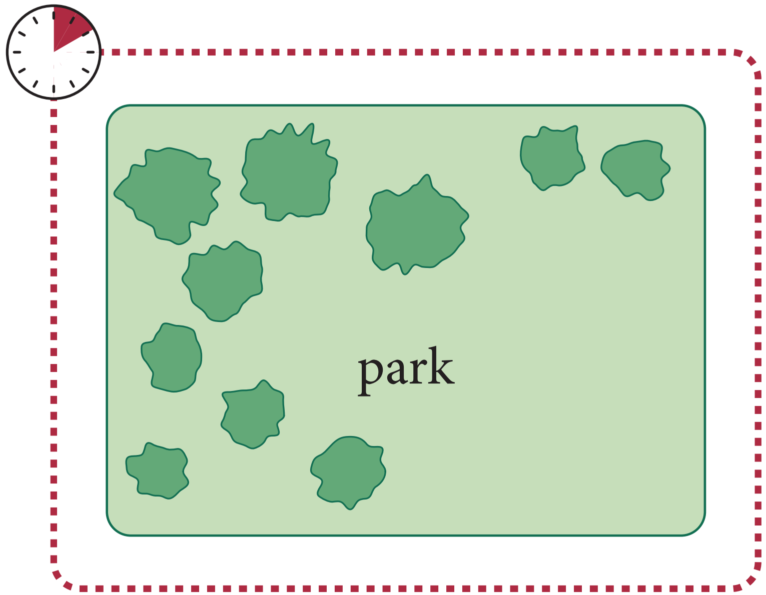
inertia m

1 architecture

2 content

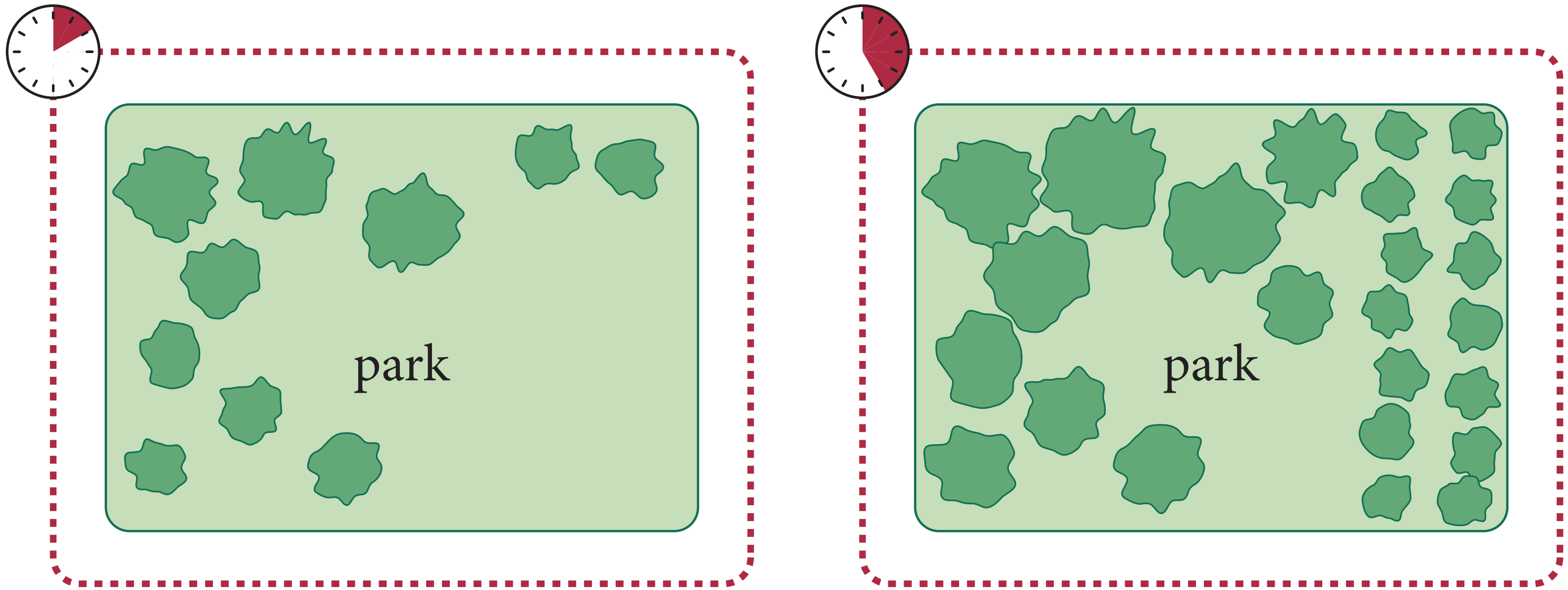
systems & extensive quantities

systems & extensive quantities



1 architecture 2 content

systems & extensive quantities



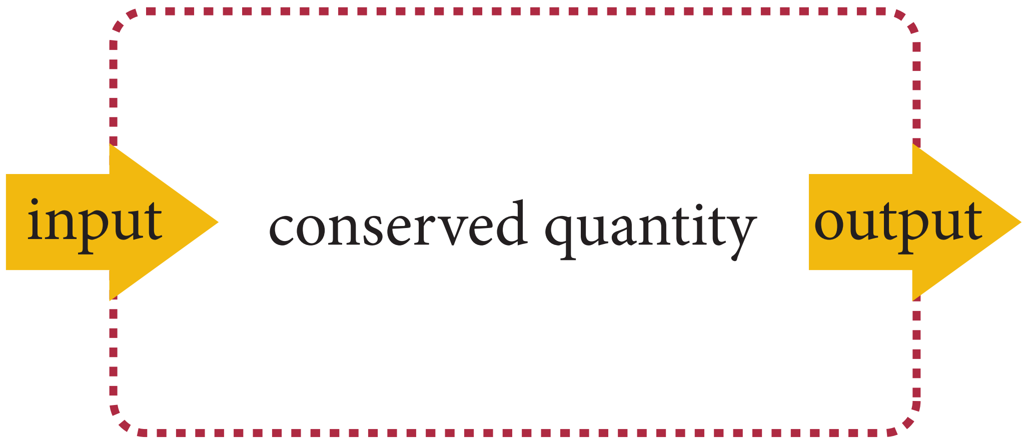
1 architecture 2 content

systems & extensive quantities

systems & extensive quantities

systems & extensive quantities

systems & extensive quantities



1 architecture 2 content

systems & extensive quantities

conserved quantity

systems & extensive quantities

conserved quantity in isolated system

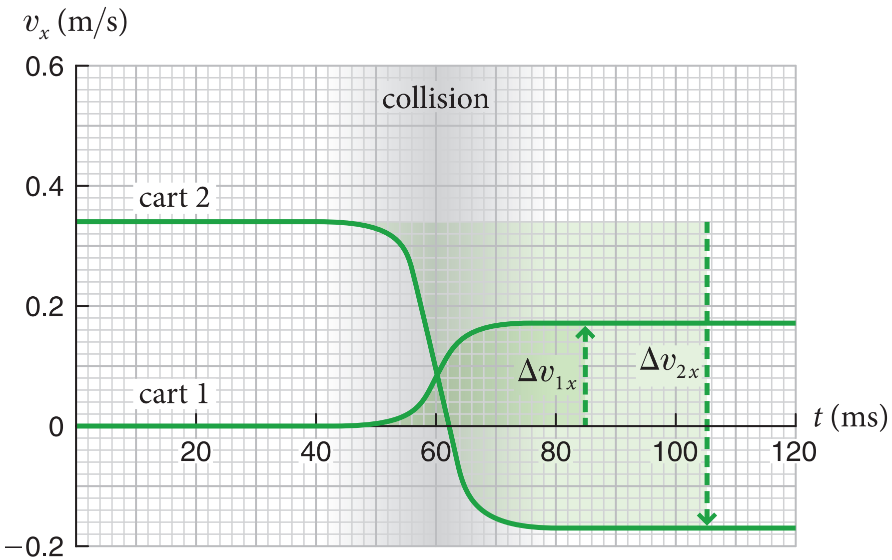
conserved quantity

can't change (constant)

systems & extensive quantities

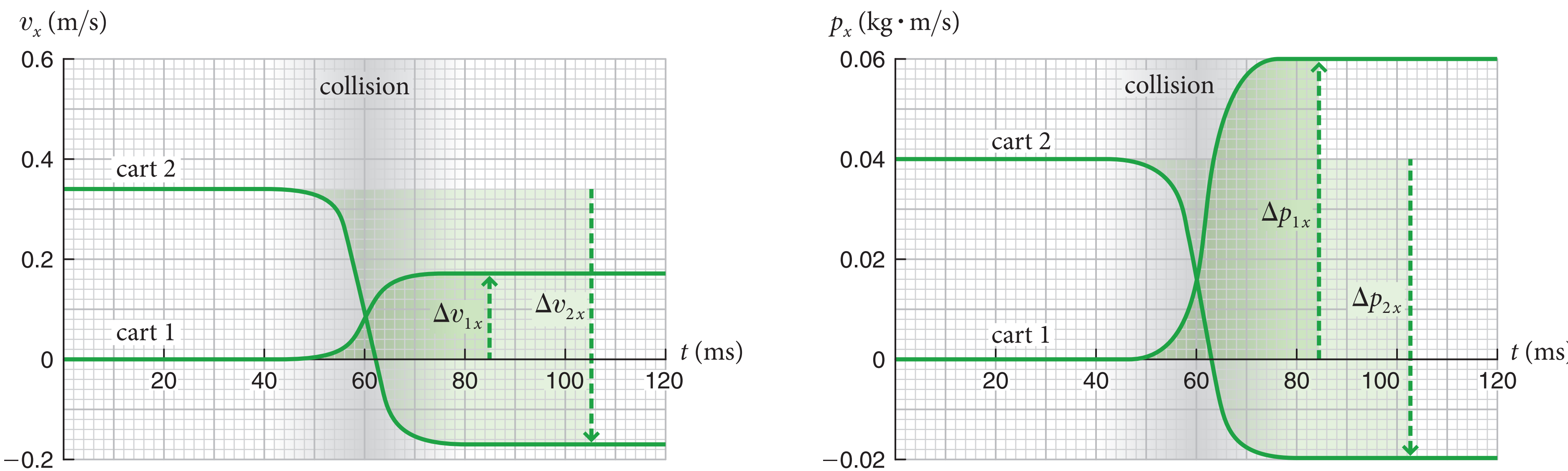
$$\vec{p} \equiv m\vec{v}$$

conserved quantity

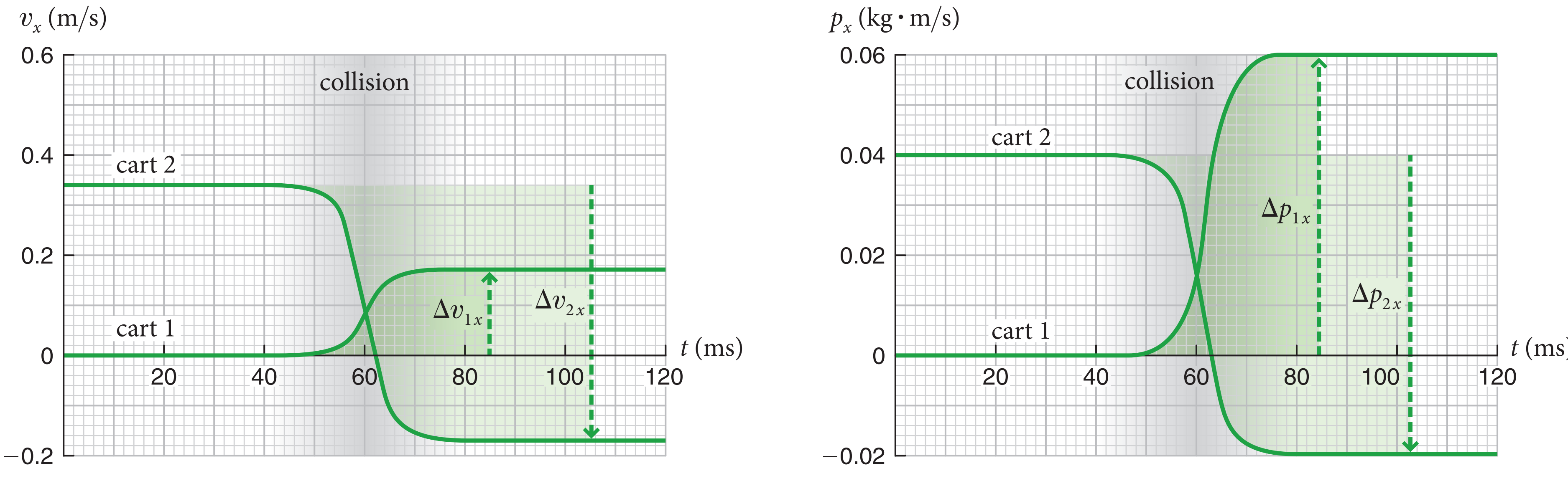


1 architecture

2 content

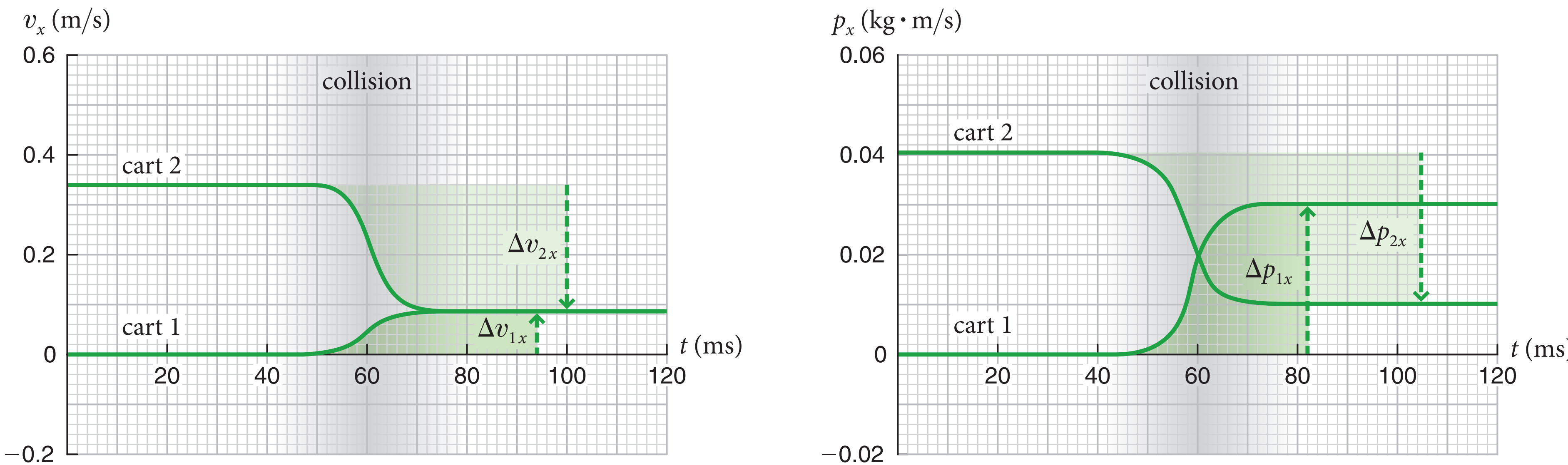


1 architecture 2 content



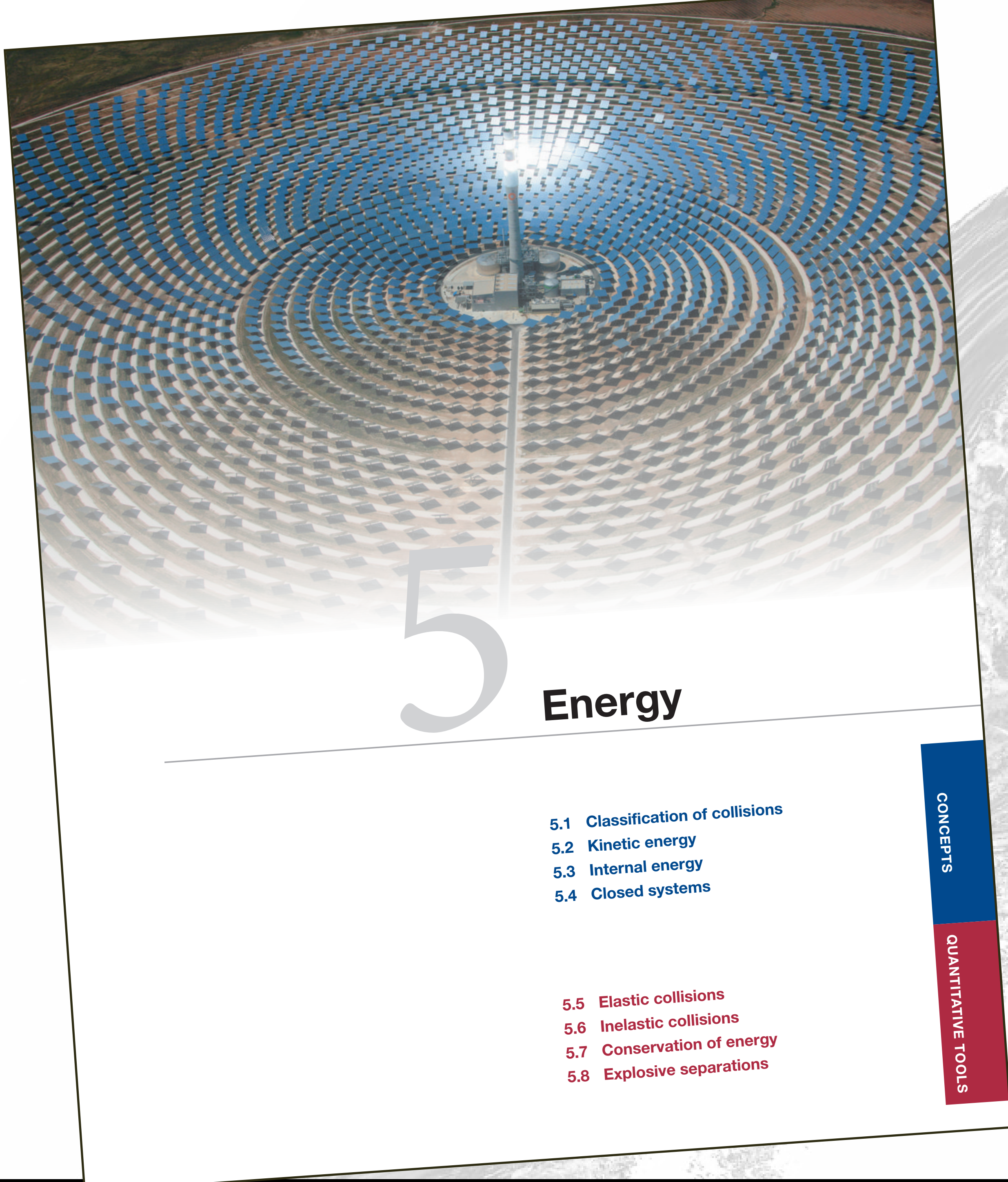
$$\Delta \vec{p} \equiv \Delta \vec{p}_1 + \Delta \vec{p}_2 = \vec{0}.$$

1 architecture **2** content



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

1 architecture   2 content



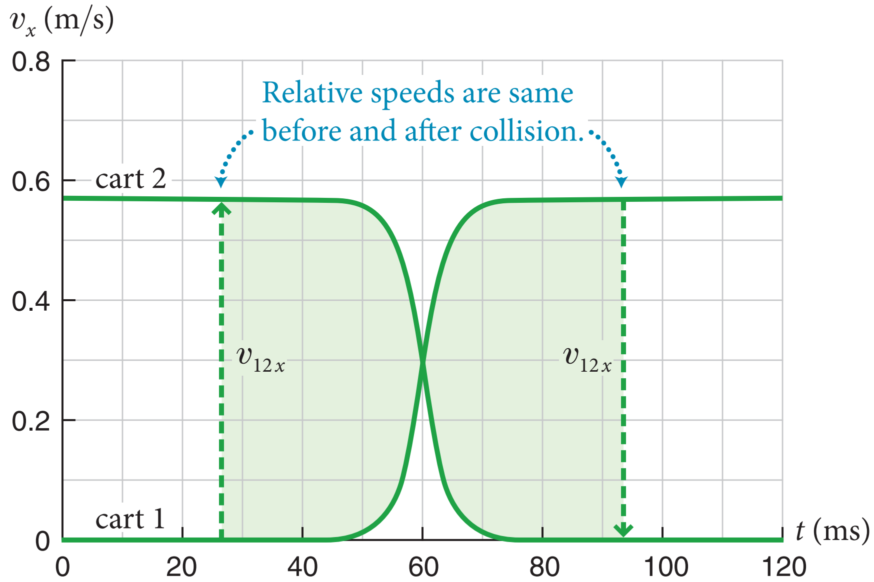
5 Energy

CONCEPTS

QUANTITATIVE TOOLS

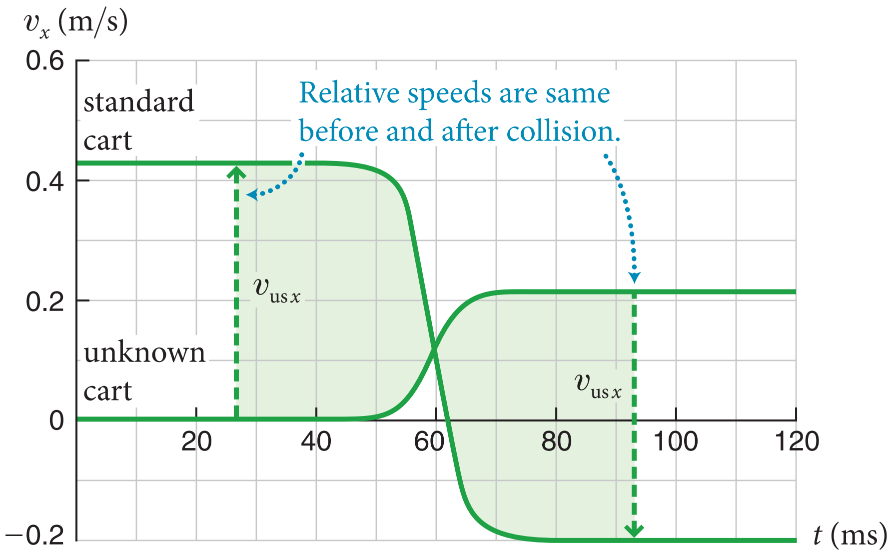
1 architecture 2 content

elastic: relative speed unchanged



1 architecture
2 content

elastic: relative speed unchanged



1 architecture
2 content

elastic: relative speed unchanged

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

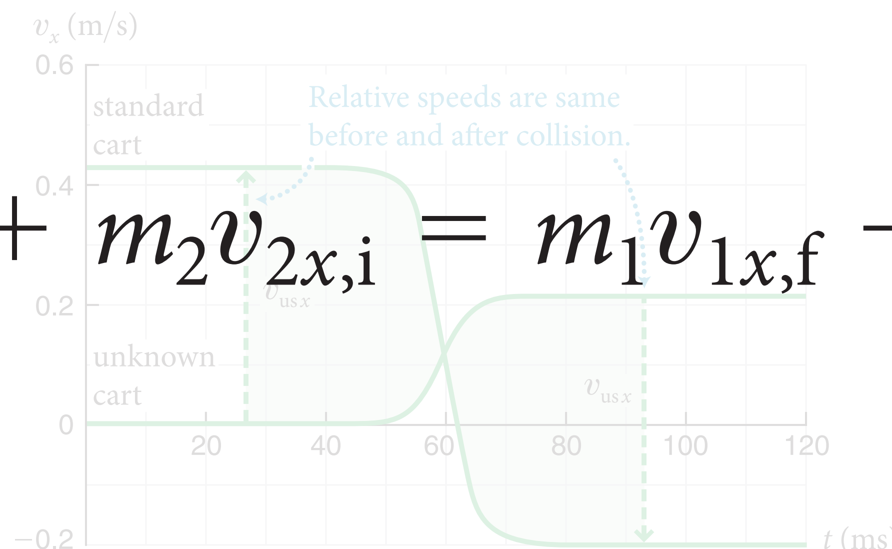
1 architecture

2 content

elastic: relative speed unchanged

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

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

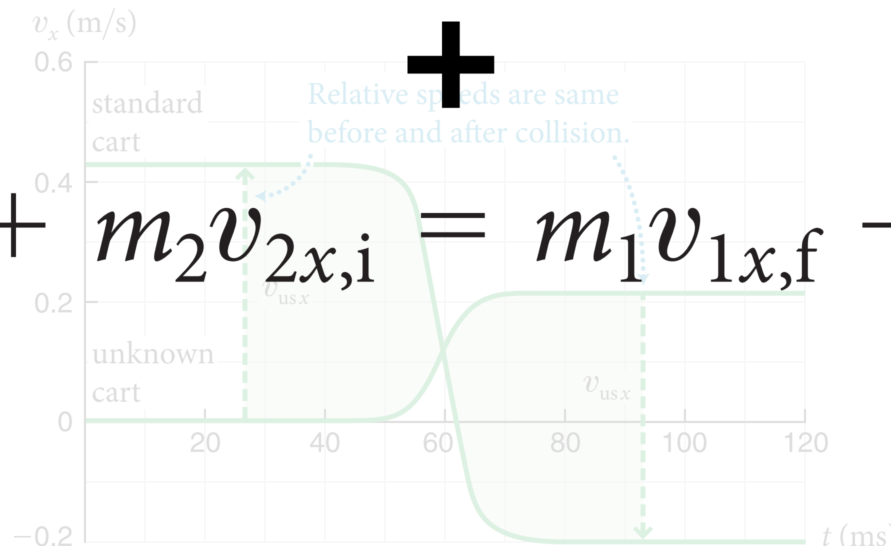


elastic: relative speed unchanged

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

+

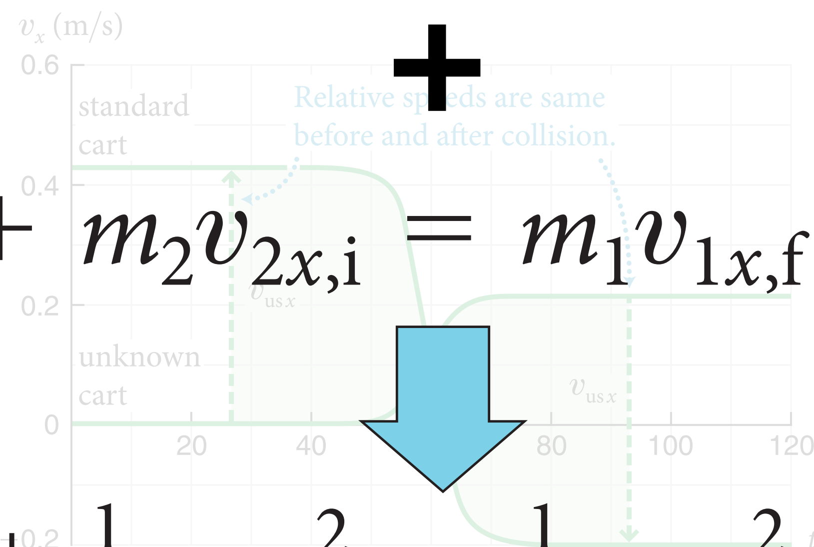
$$m_1 v_{1x,\mathrm{i}} + m_2 v_{2x,\mathrm{i}} = m_1 v_{1x,\mathrm{f}} + m_2 v_{2x,\mathrm{f}}$$



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

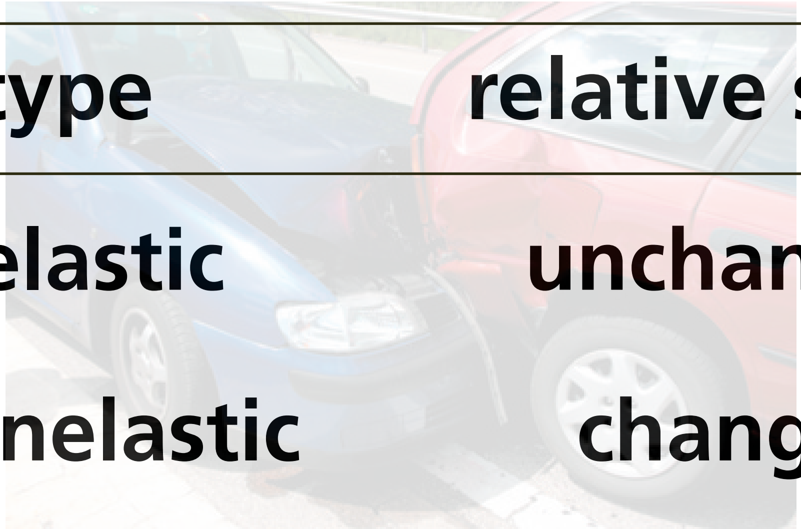
before or after?

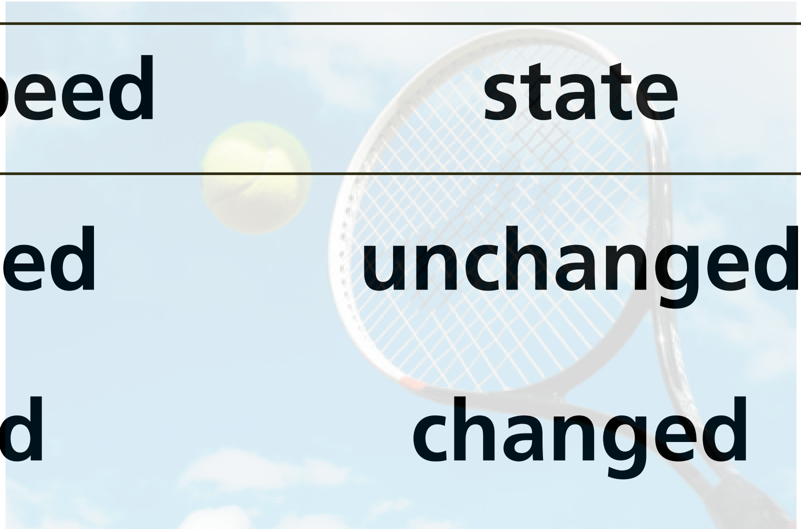
elastic vs. inelastic


elastic: reversible

inelastic: irreversible

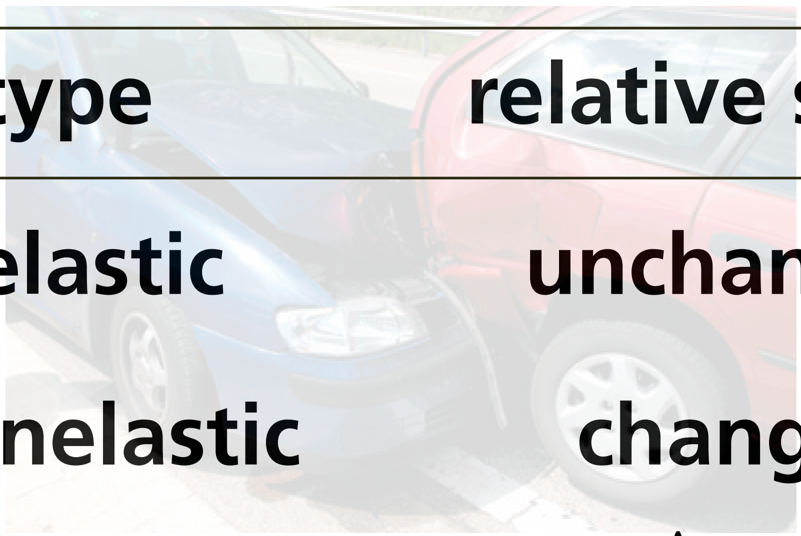
elastic vs. inelastic

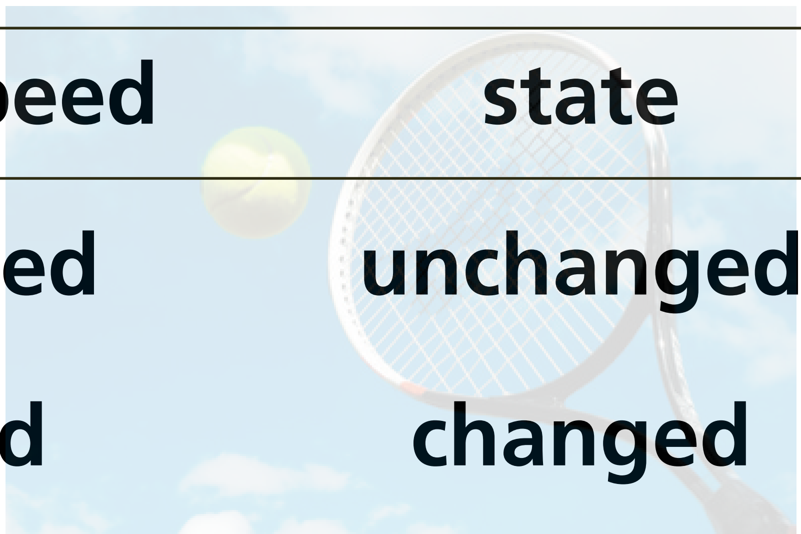




type	relative speed	state
elastic	unchanged	unchanged
inelastic	changed	changed

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

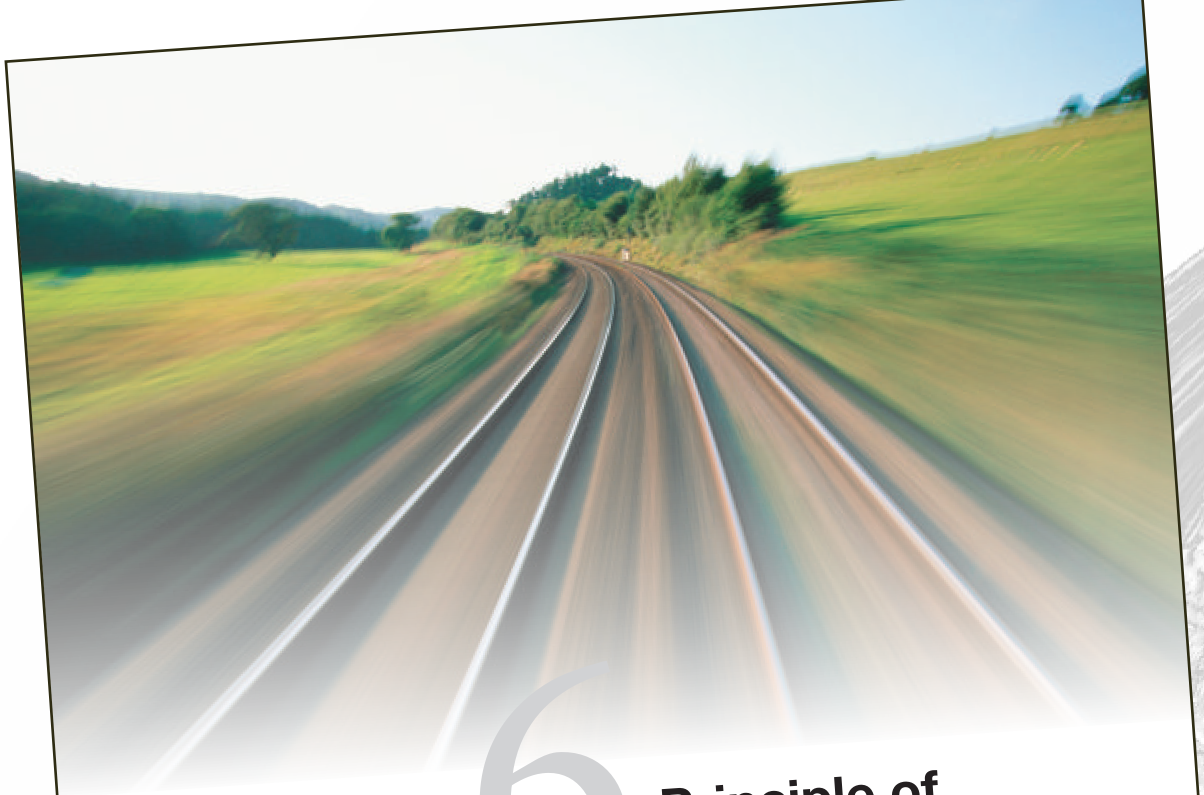
$$E = K + E_{\text{int}}$$

conservation of energy

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

closed system:

$$\Delta E = 0$$

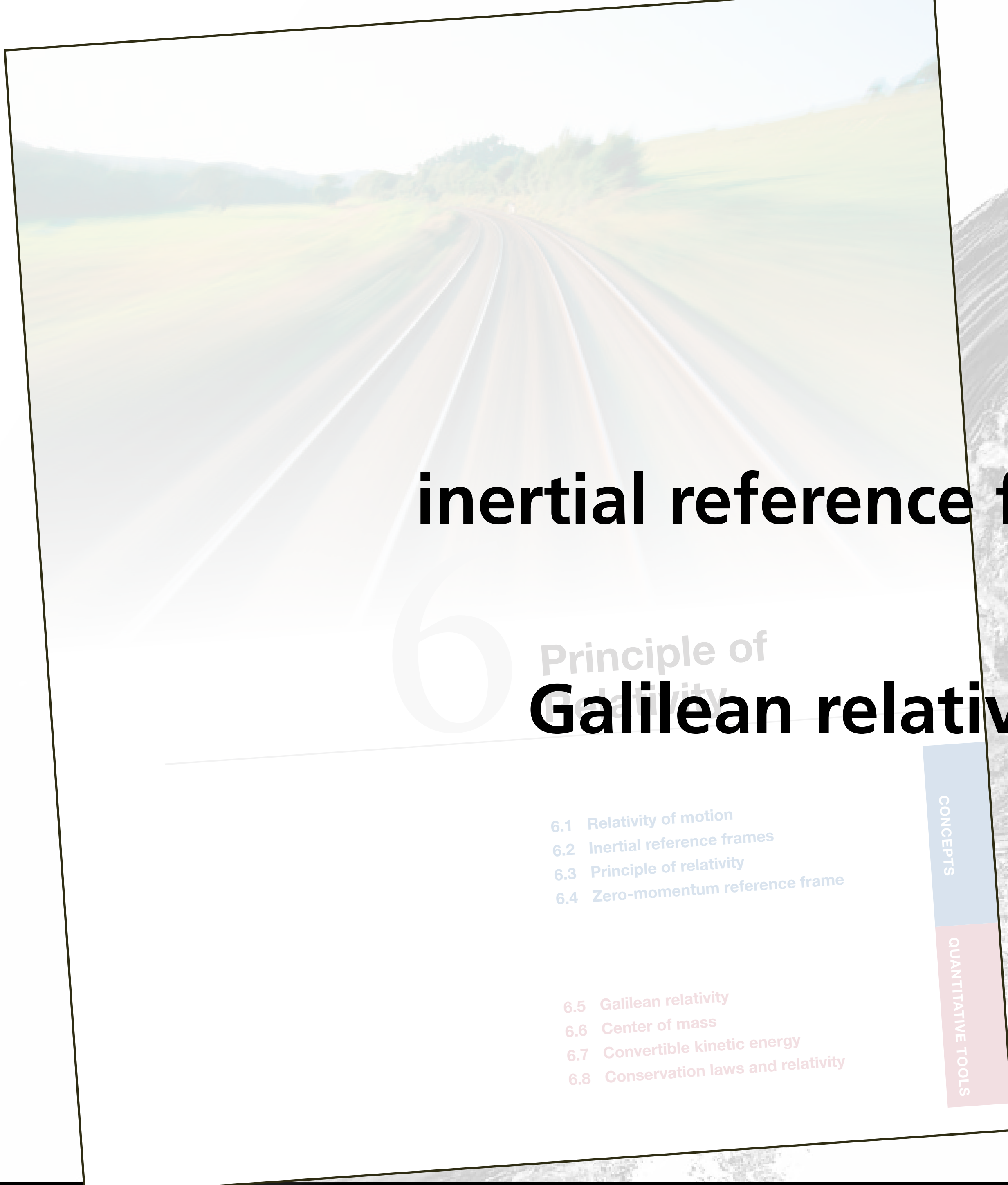


6 Principle of Relativity

CONCEPTS

QUANTITATIVE TOOLS

1 architecture 2 content



inertial reference frames

Galilean relativity

1 architecture

2 content

7 Interactions

CONCEPTS

QUANTITATIVE TOOLS

1 architecture

2 content

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

7.7 Interactions and accelerations

7.8 Nondissipative interactions

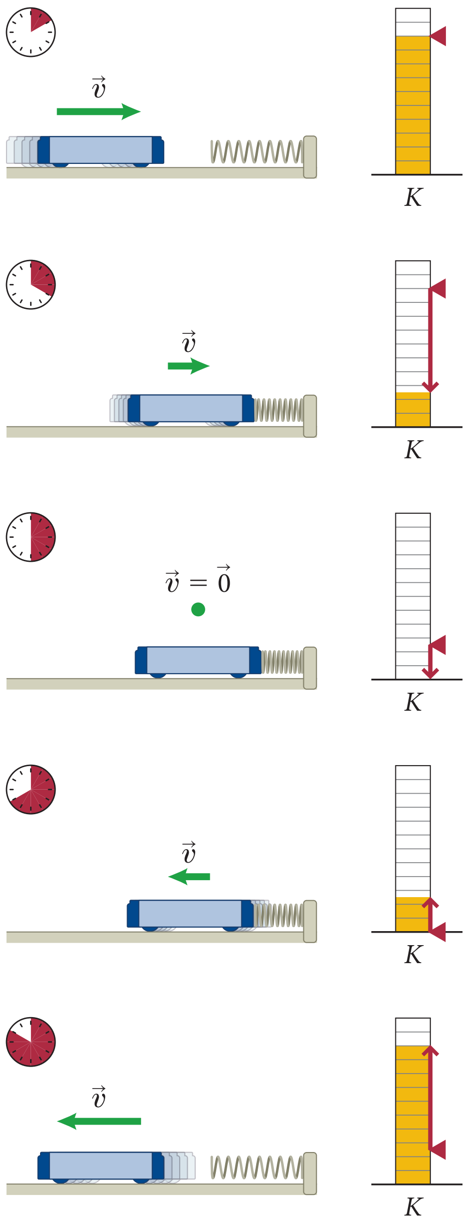
7.9 Potential energy near Earth's surface

7.10 Dissipative interactions

1 architecture

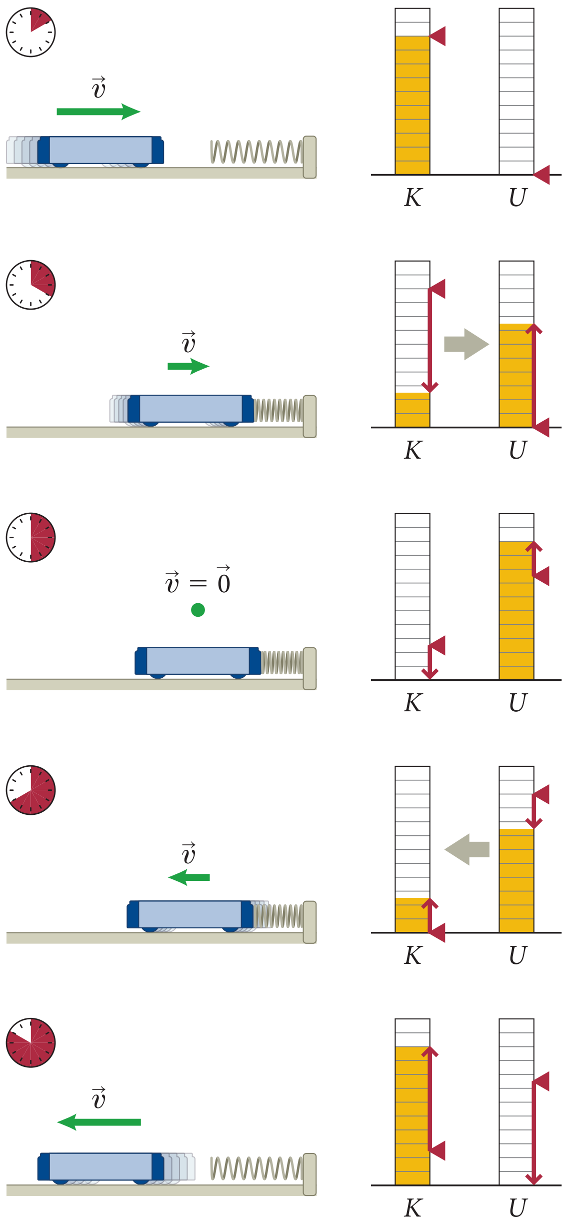
2 content

potential energy



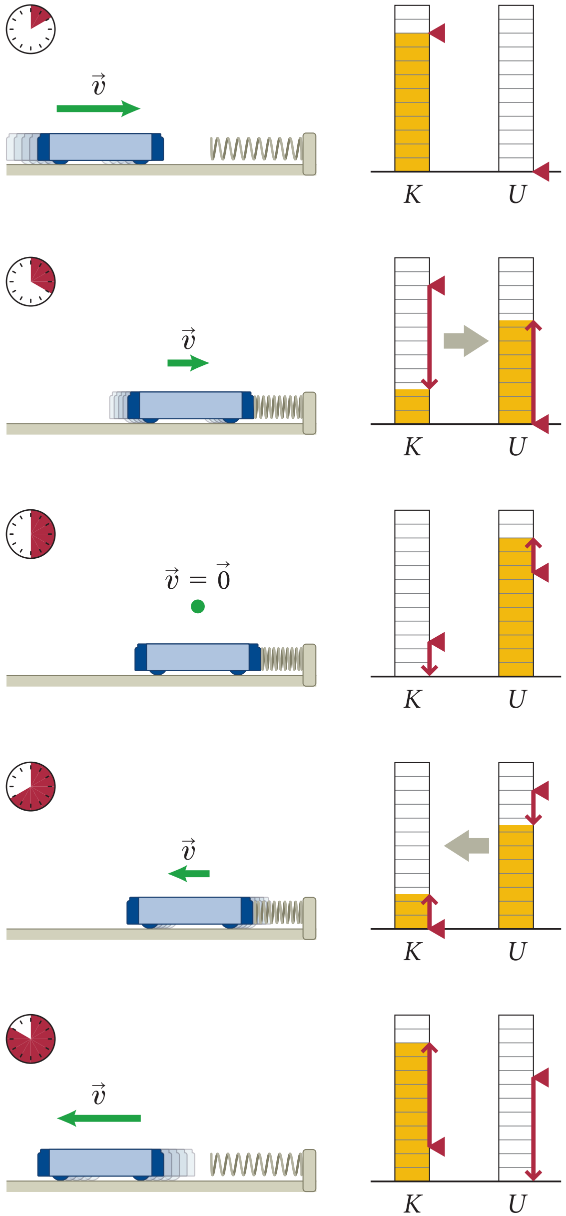
1 architecture   2 content

potential energy



1 architecture 2 content

potential energy



reversible

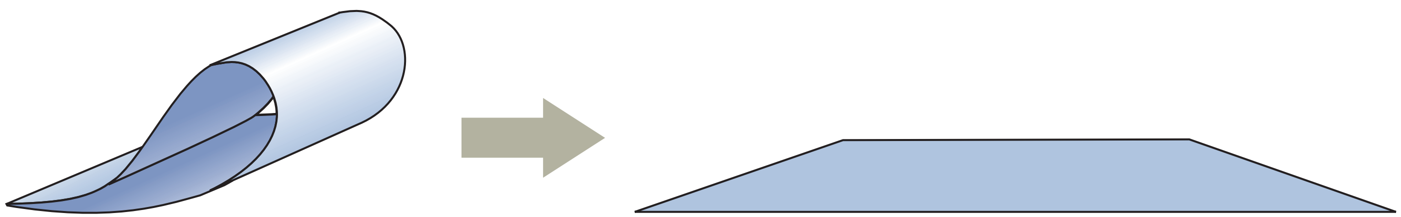
state change

1 architecture

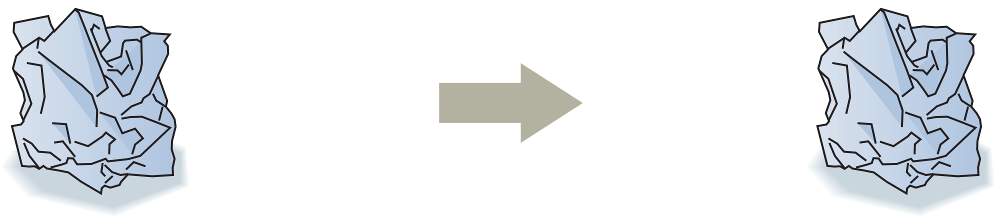
2 content

reversible and irreversible state changes

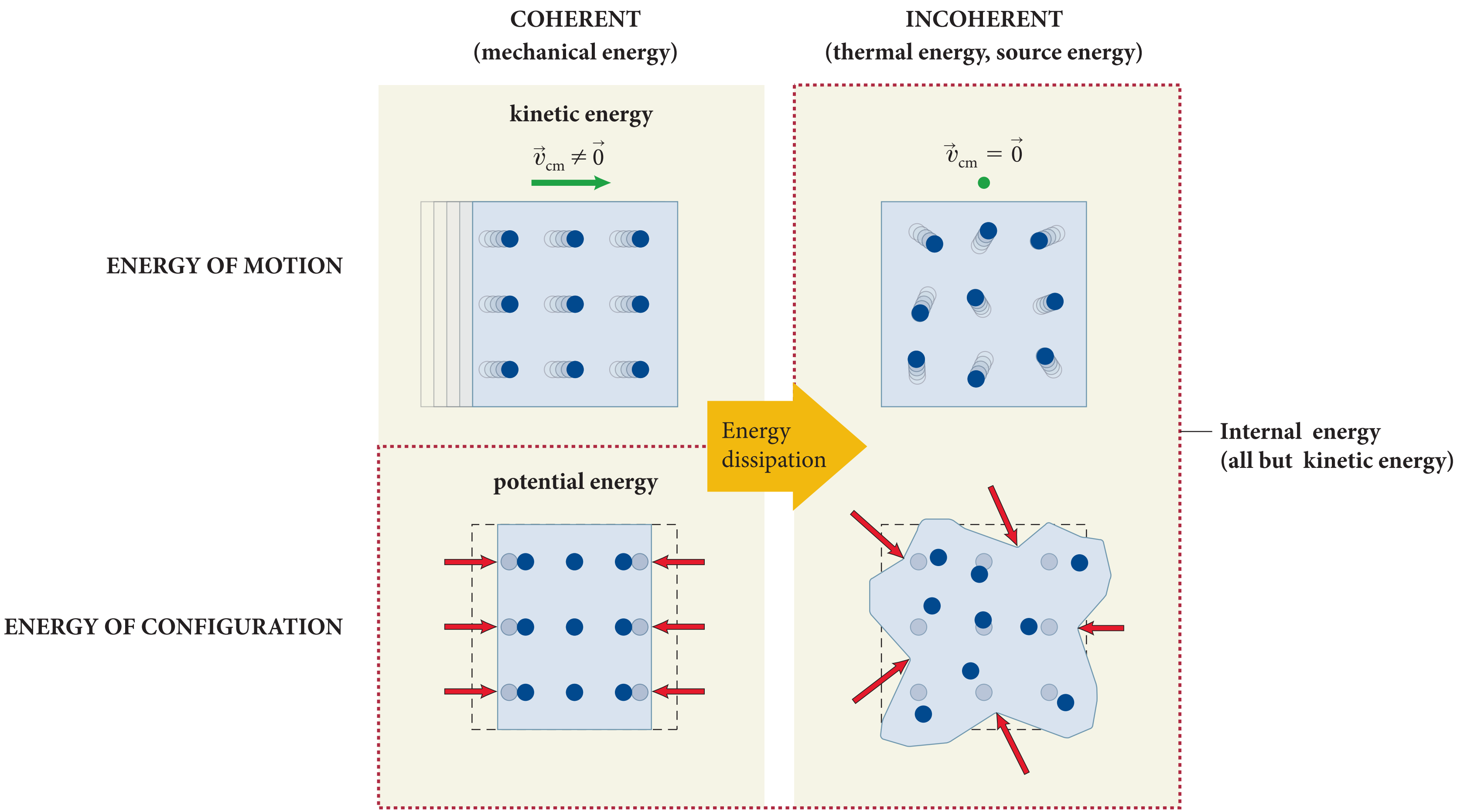
(*a*) Coherent deformation: reversible



(*b*) Incoherent deformation: irreversible

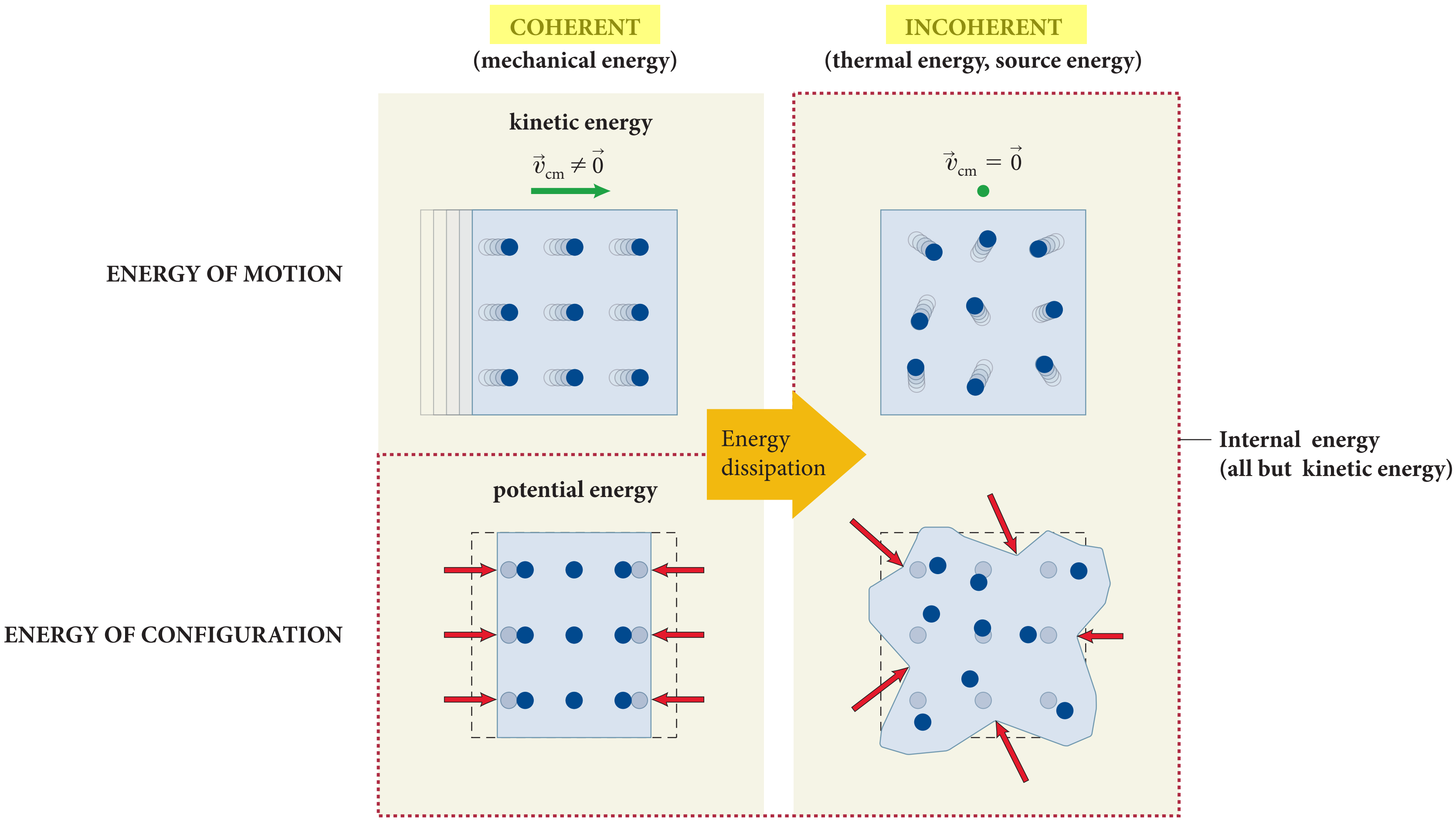


classification of energy



1 architecture 2 content

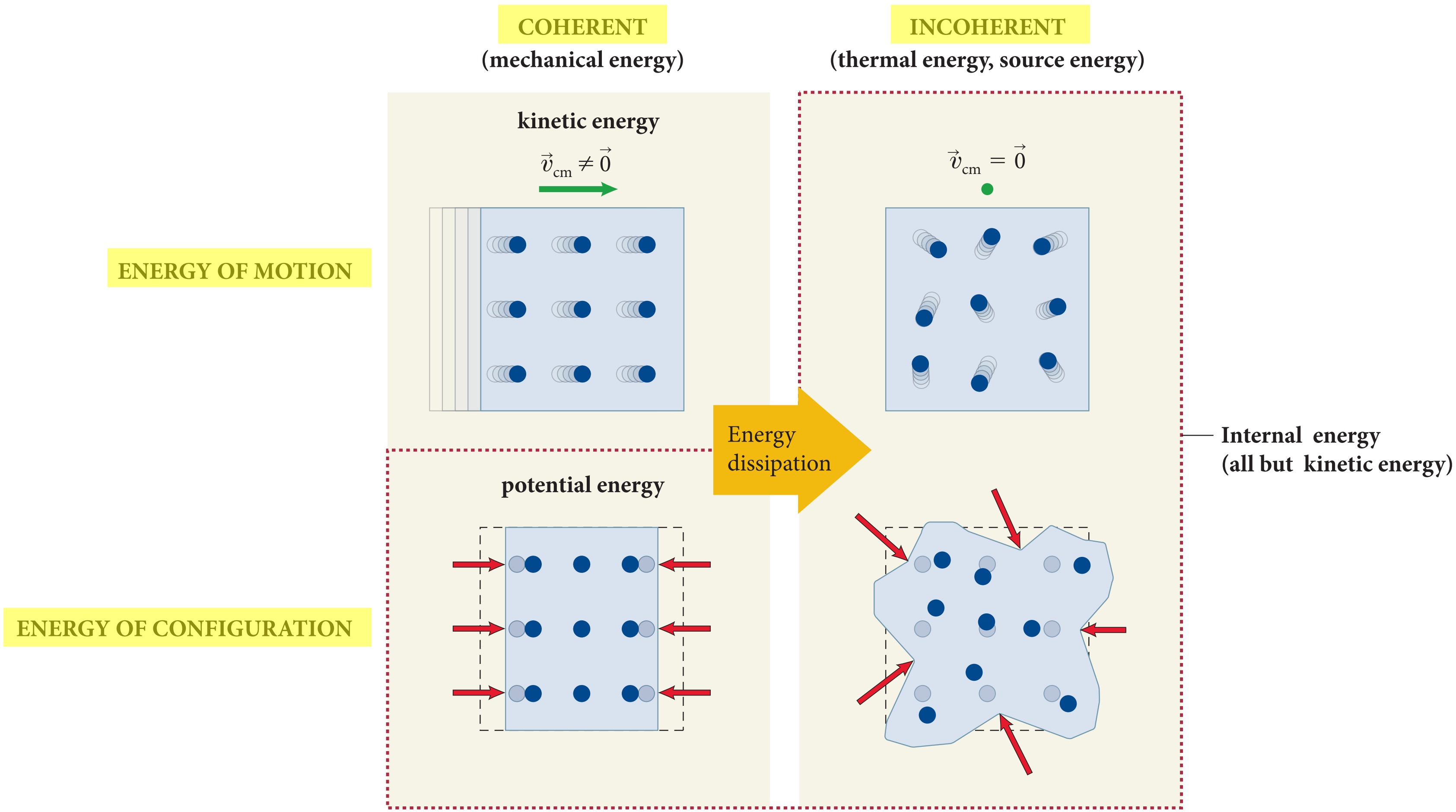
classification of energy



1 architecture

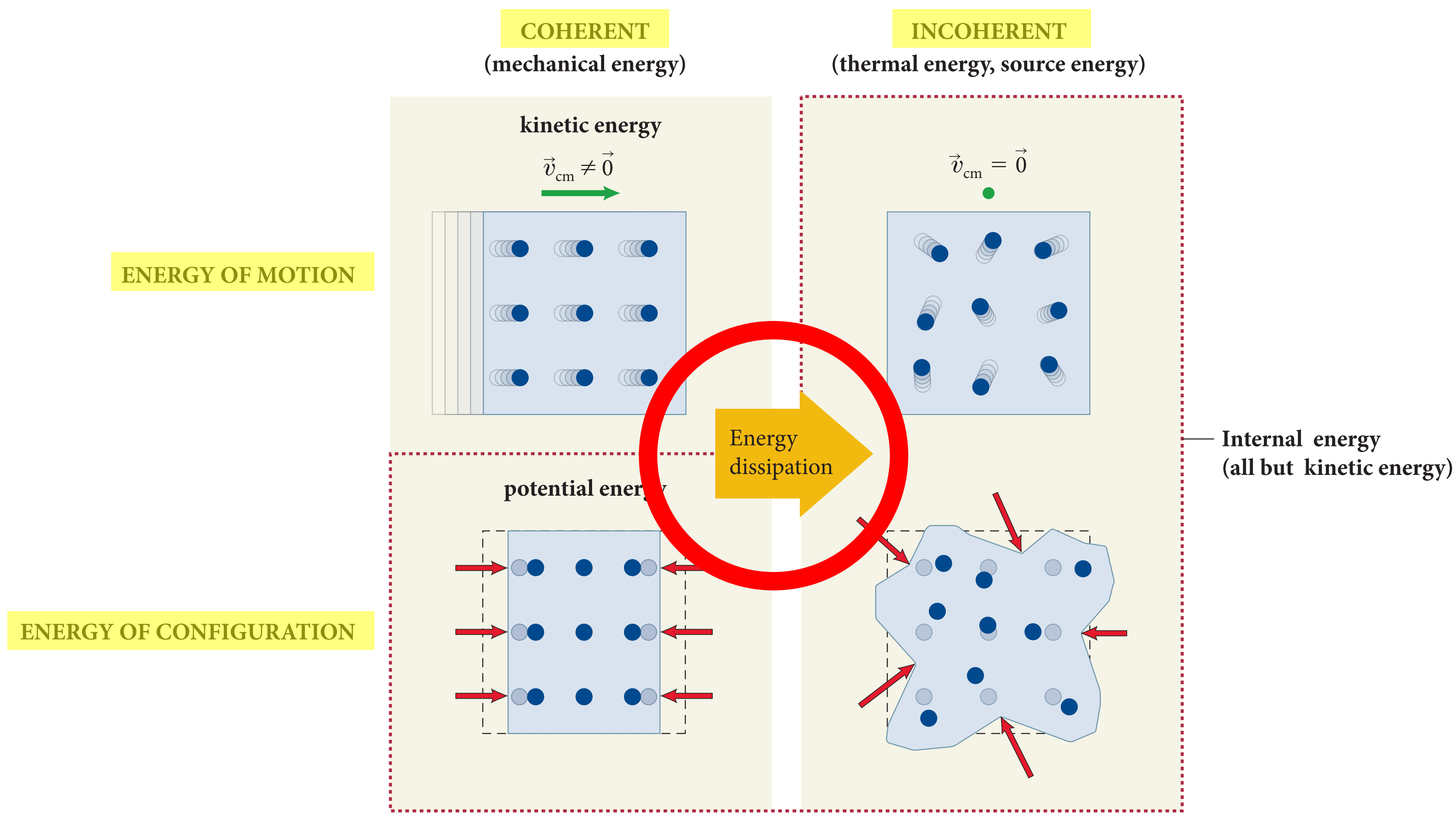
2 content

classification of energy



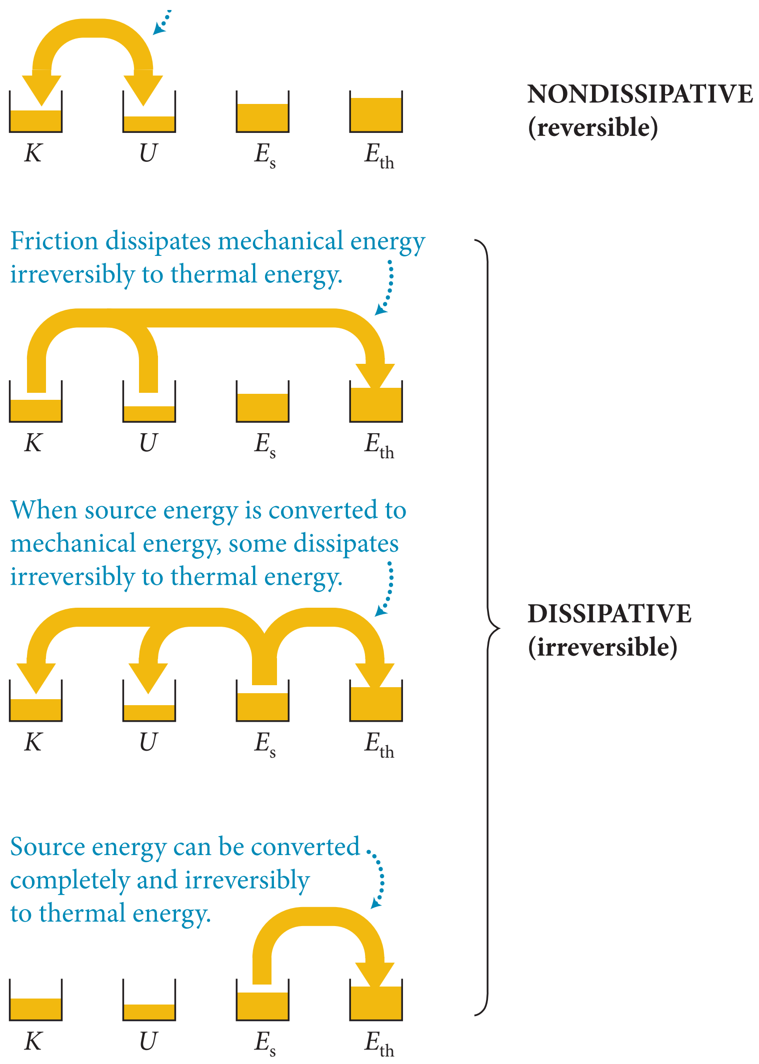
1 architecture 2 content

classification of energy



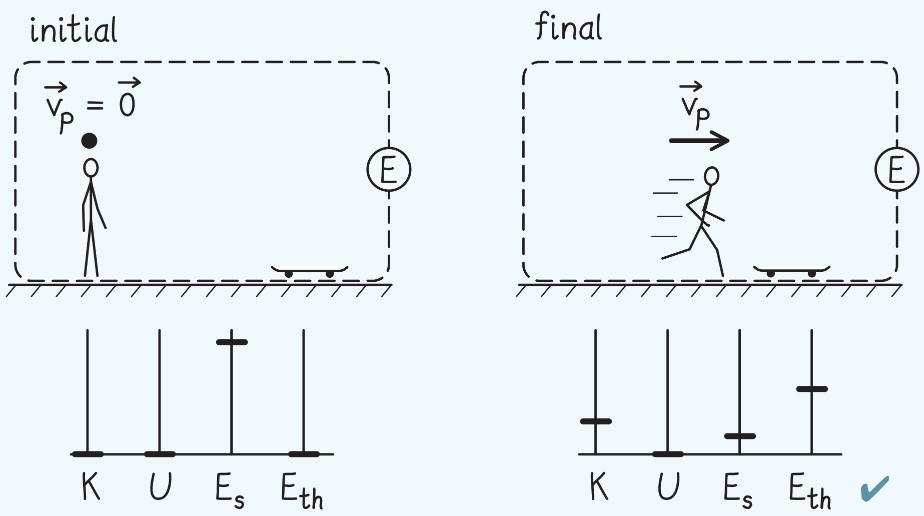
1 architecture 2 content

energy conversions



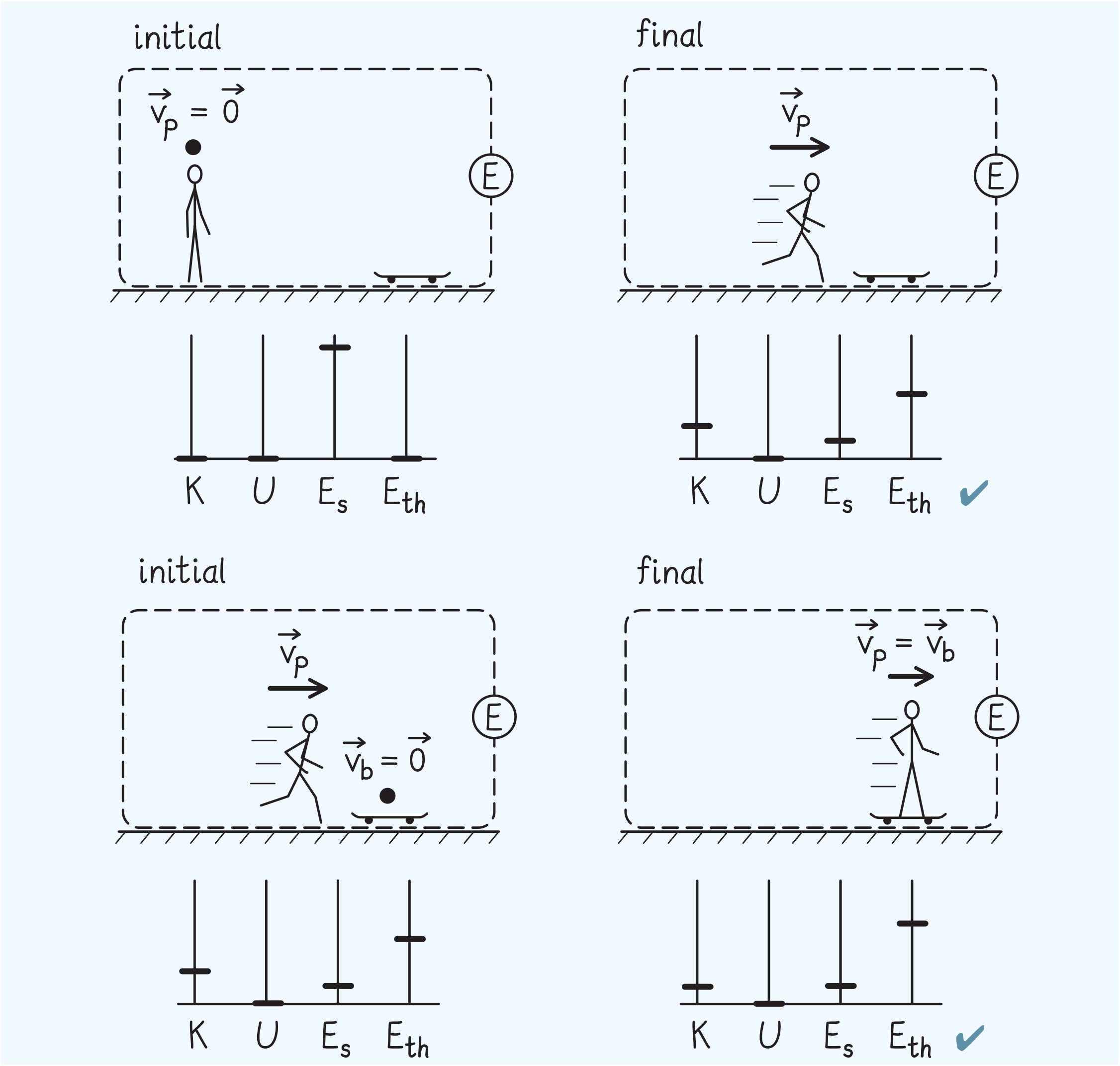
1 architecture   2 content

energy conversions

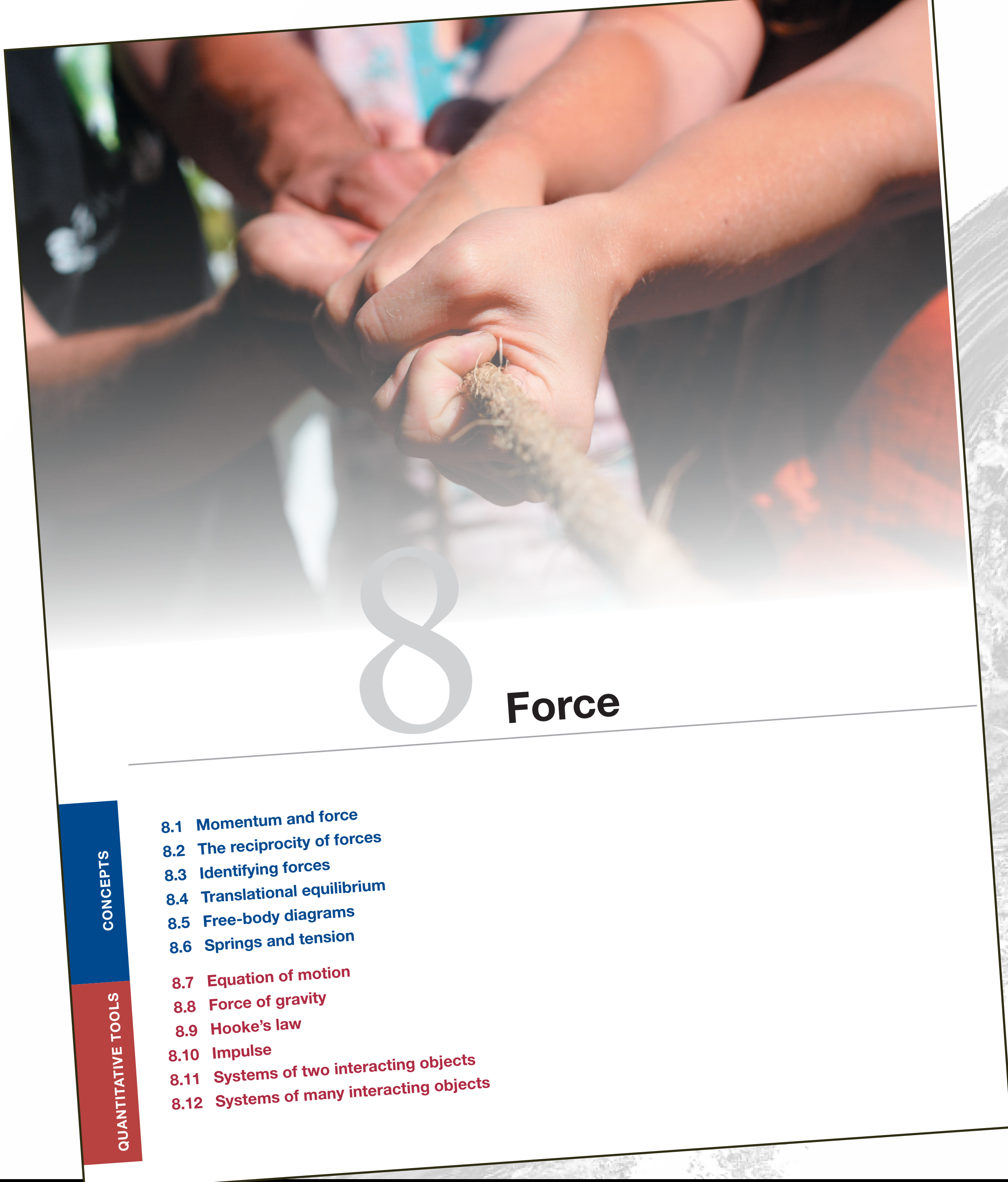


1 architecture 2 content

energy conversions



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

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 interact
8.12 Systems of many intera

1 architecture

2 content

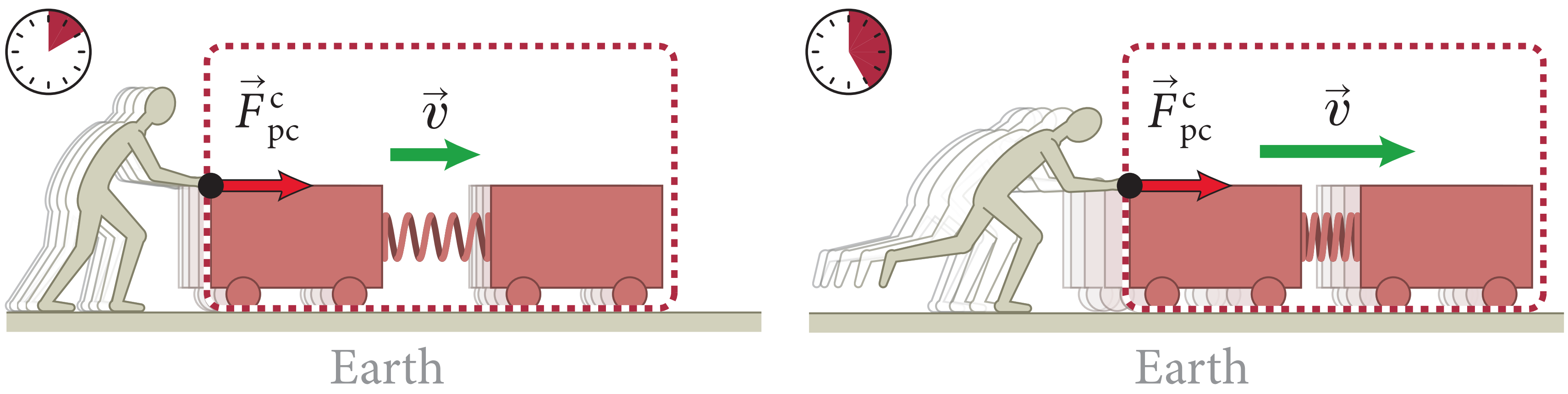
9 Work

CONCEPTS

QUANTITATIVE TOOLS

1 architecture 2 content

energy diagram

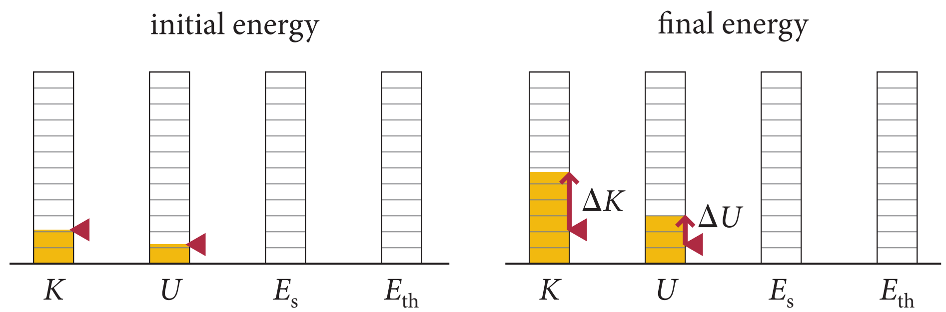


1 architecture

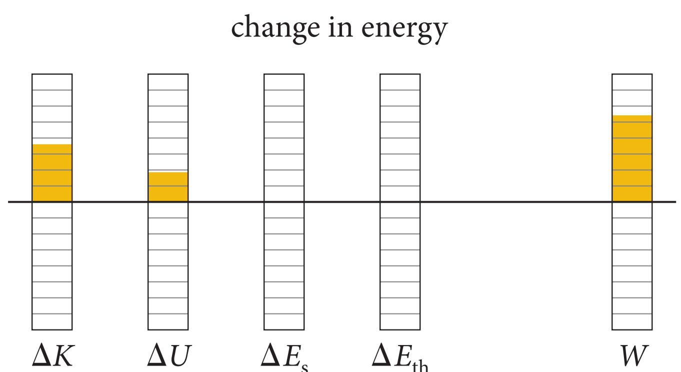
2 content

energy diagram

We can represent the changes in energy by initial and final bar diagrams . . .



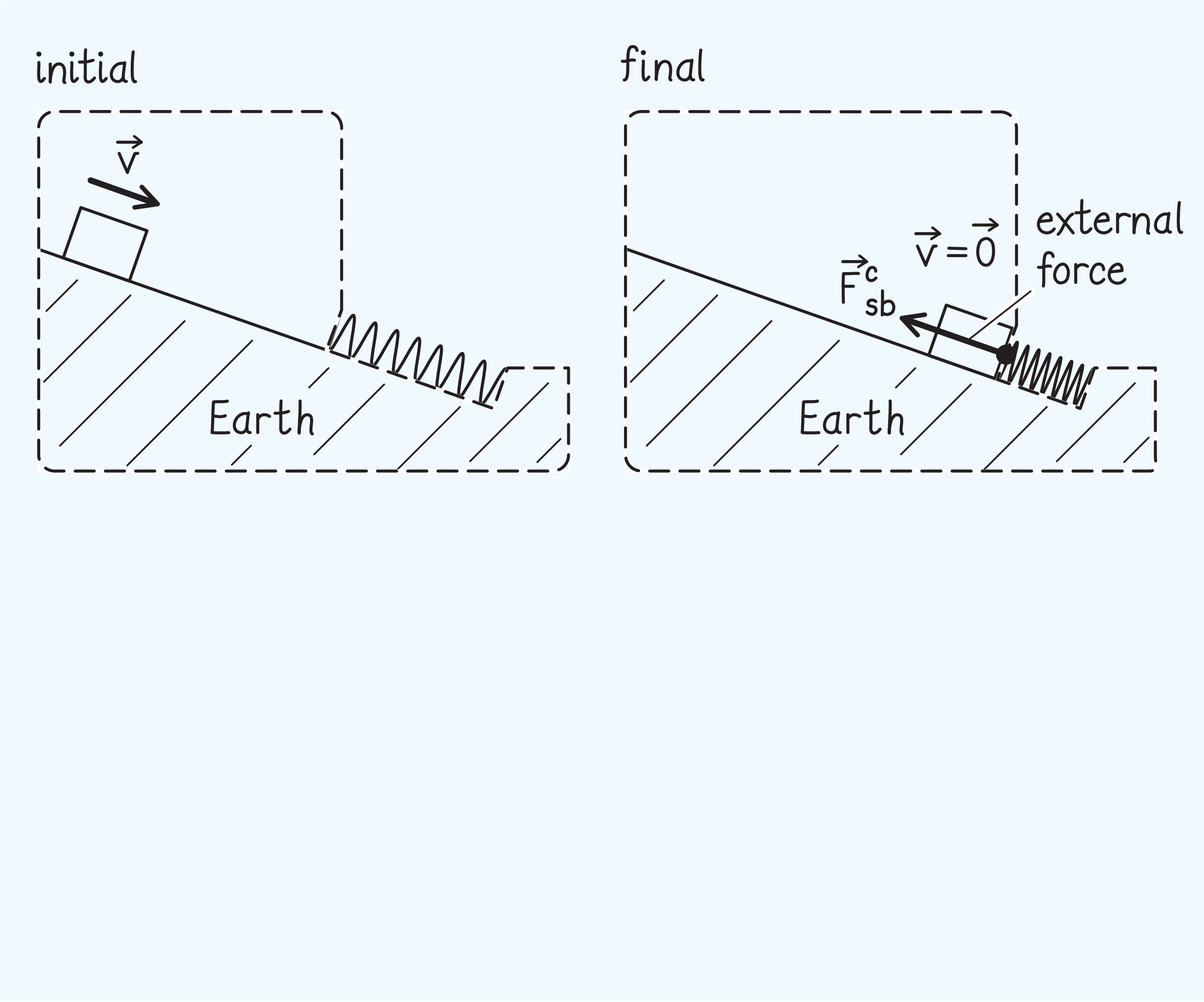
(*c*) . . . or by a single **energy diagram**.



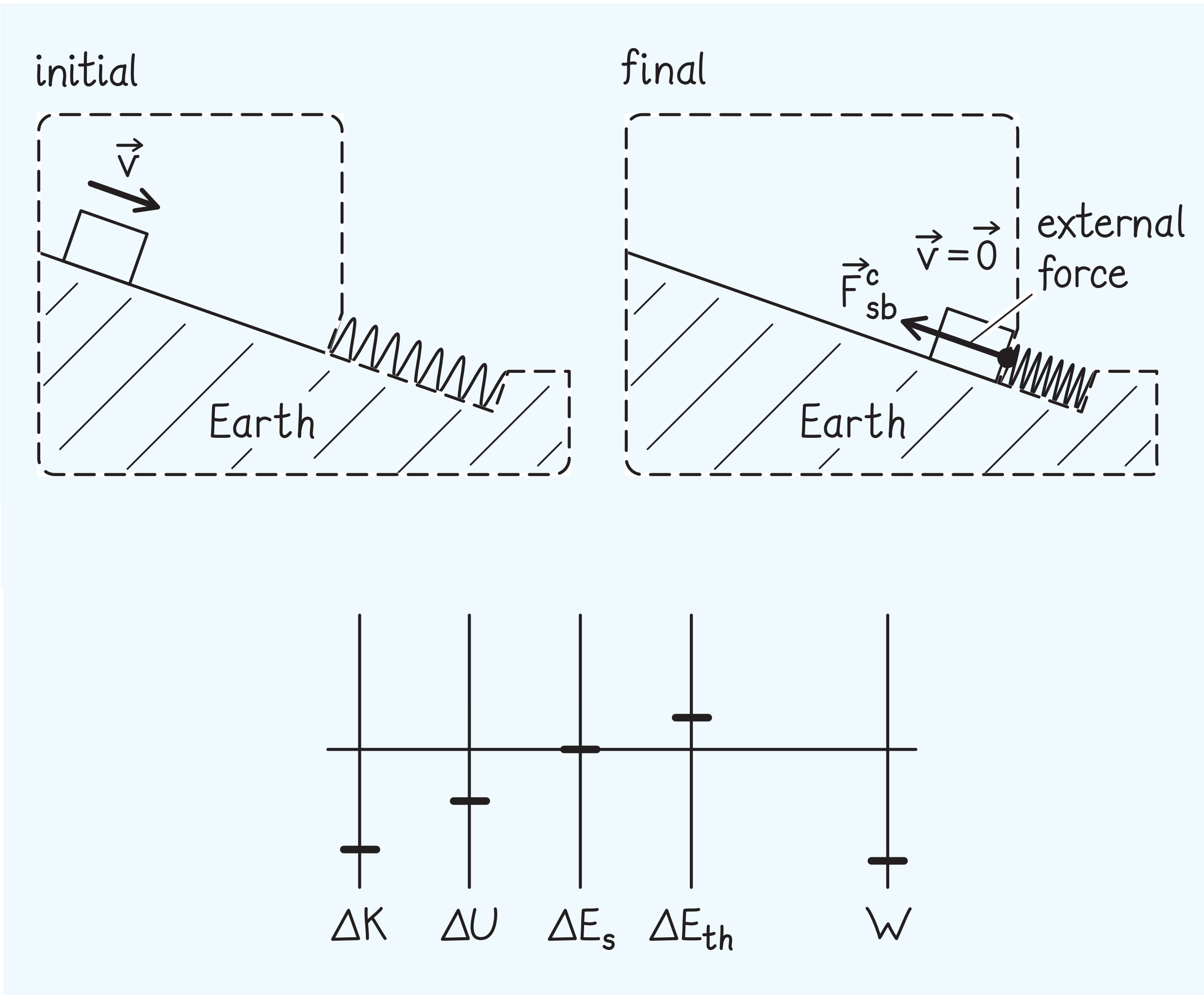
Changes in system's energy . . . . . . equal work done on system.

1 architecture 2 content

energy diagram



energy diagram

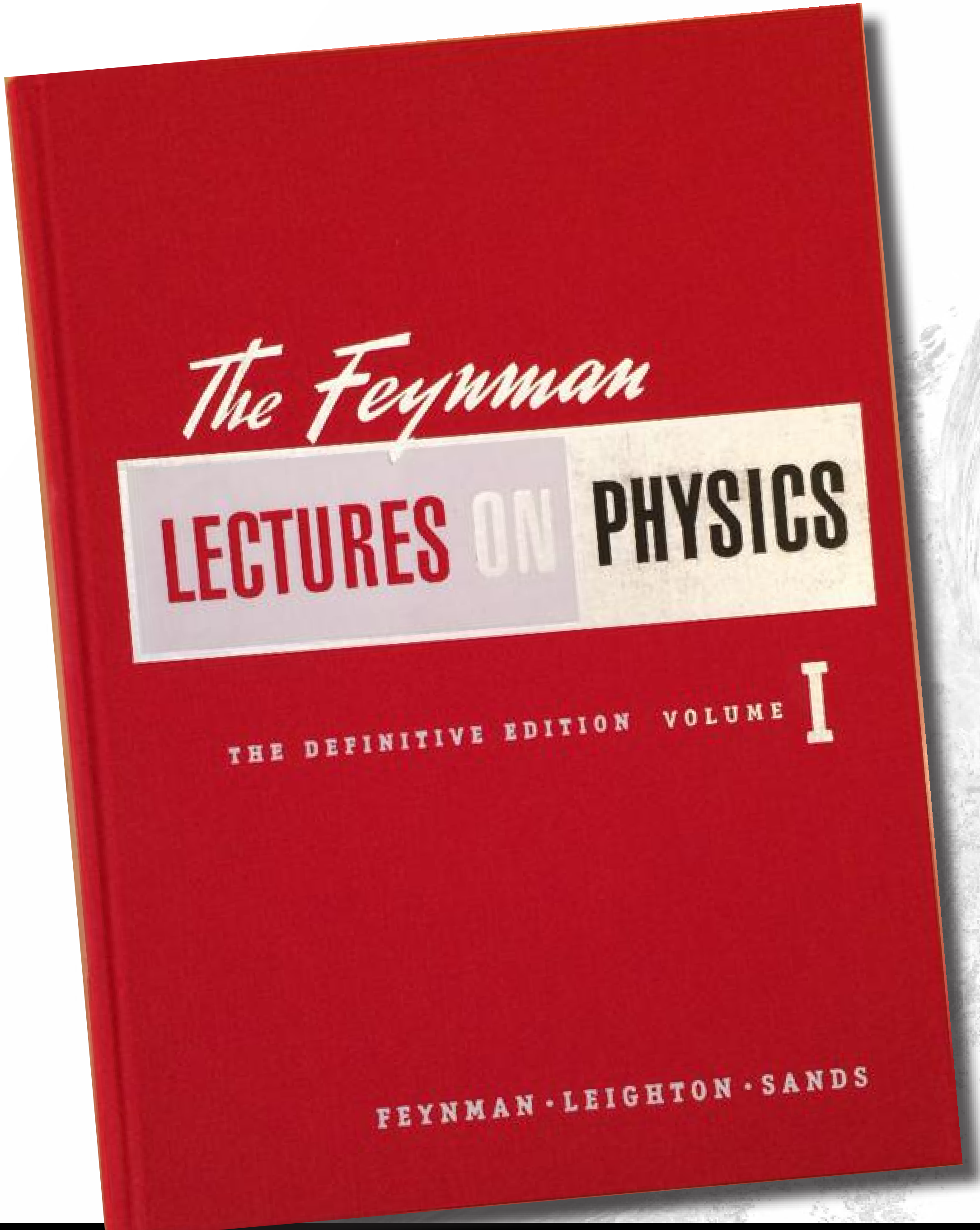


1 architecture

2 content

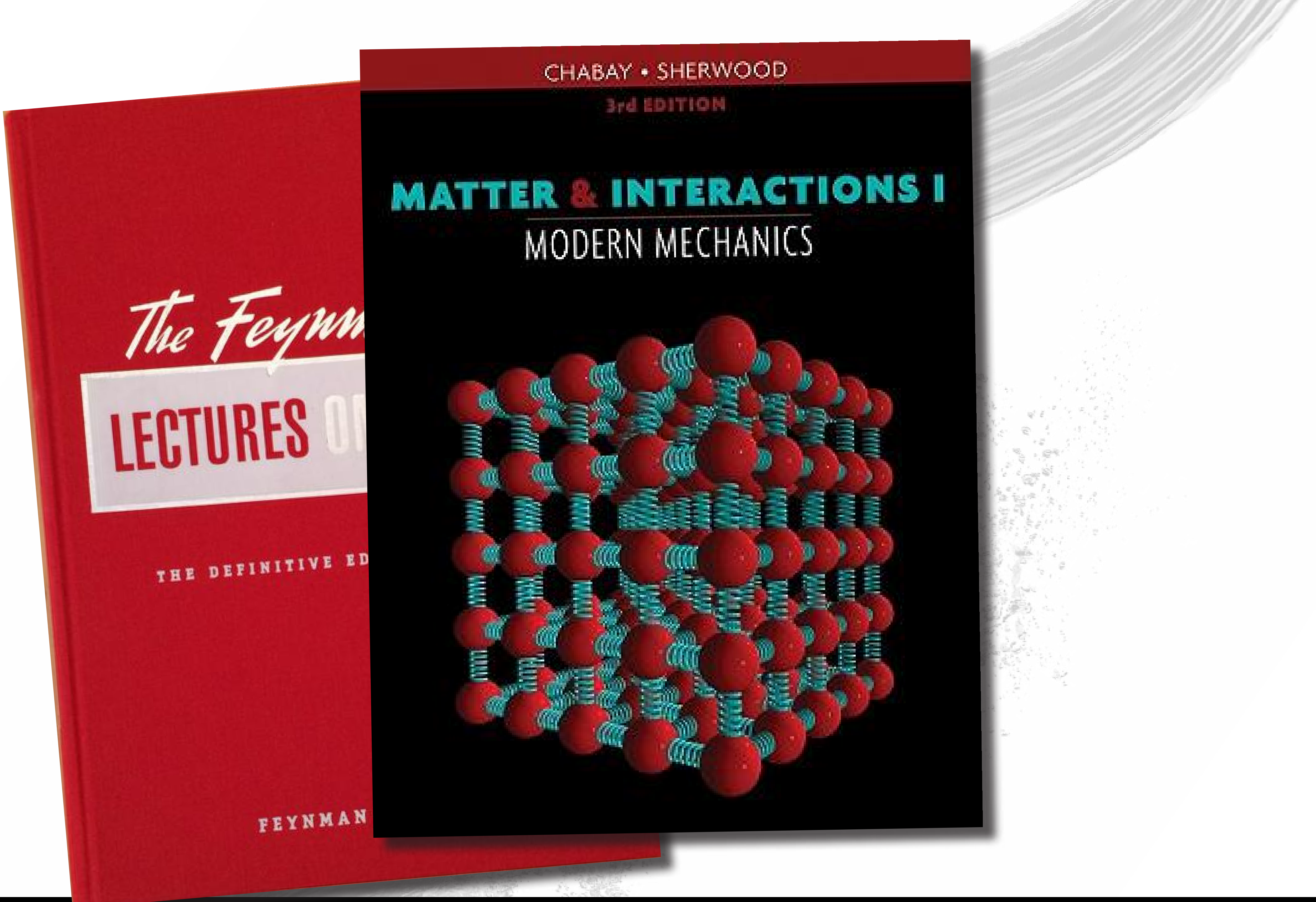
how much work is it to switch?

1 architecture   2 content

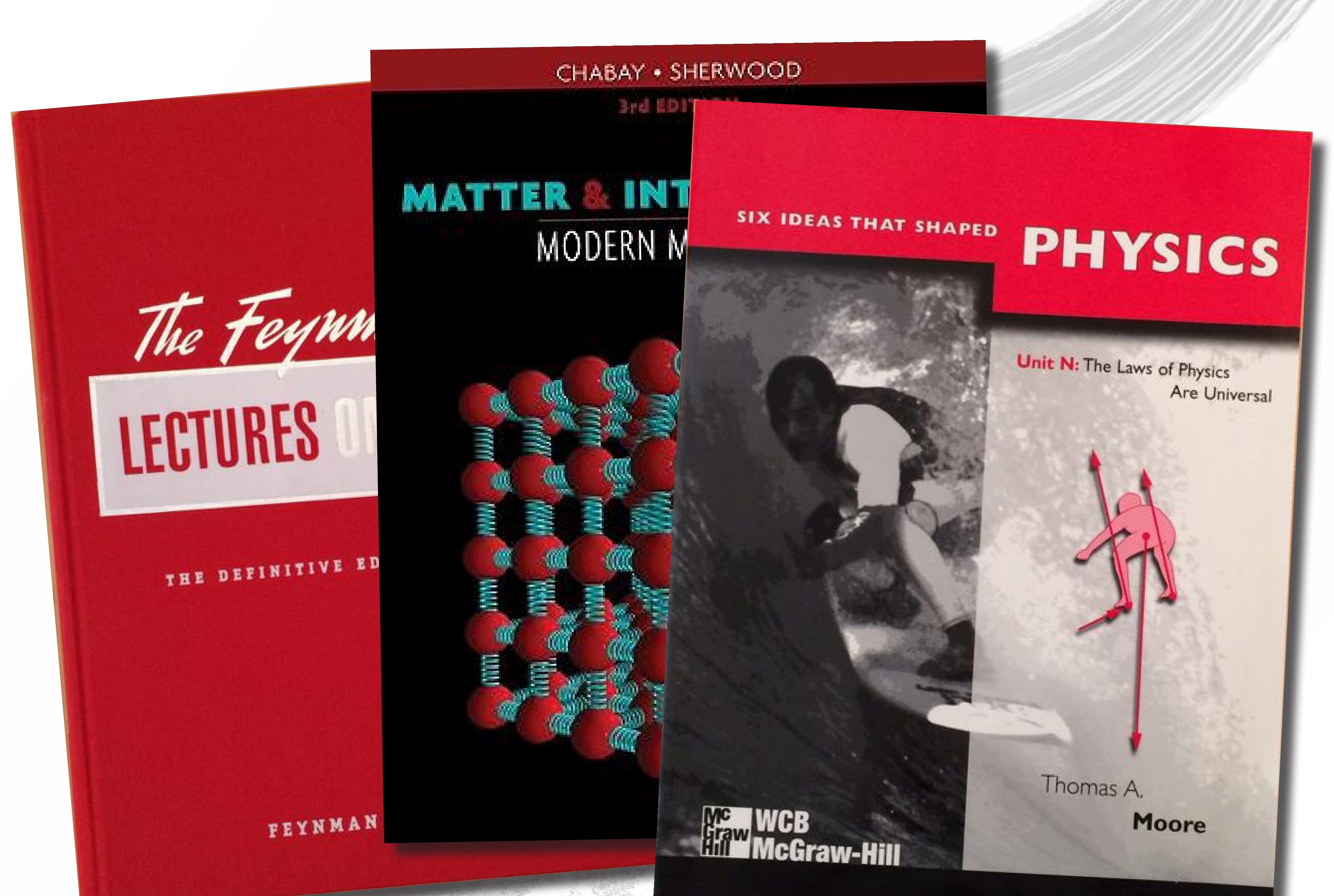


1 architecture

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	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	
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
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
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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

1D (Principles and Practice 2–9)

3D (Principles and Practice 10–13)

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	
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
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3. Vectors	3. Acceleration
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1D

3D

1 architecture 2 content

Traditional	Principles and Practice
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conservation

dynamics

1 architecture

2 content

Traditional	Principles and Practice
1. Physics and measurement	1. Foundations
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3. Vectors	3. Acceleration
4. Motion in two dimensions	4. Momentum
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rotation

1 architecture

2 content

Traditional	Principles and Practice
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periodic

1 architecture   2 content

mostly minor rearrangements!

easily custom tailored

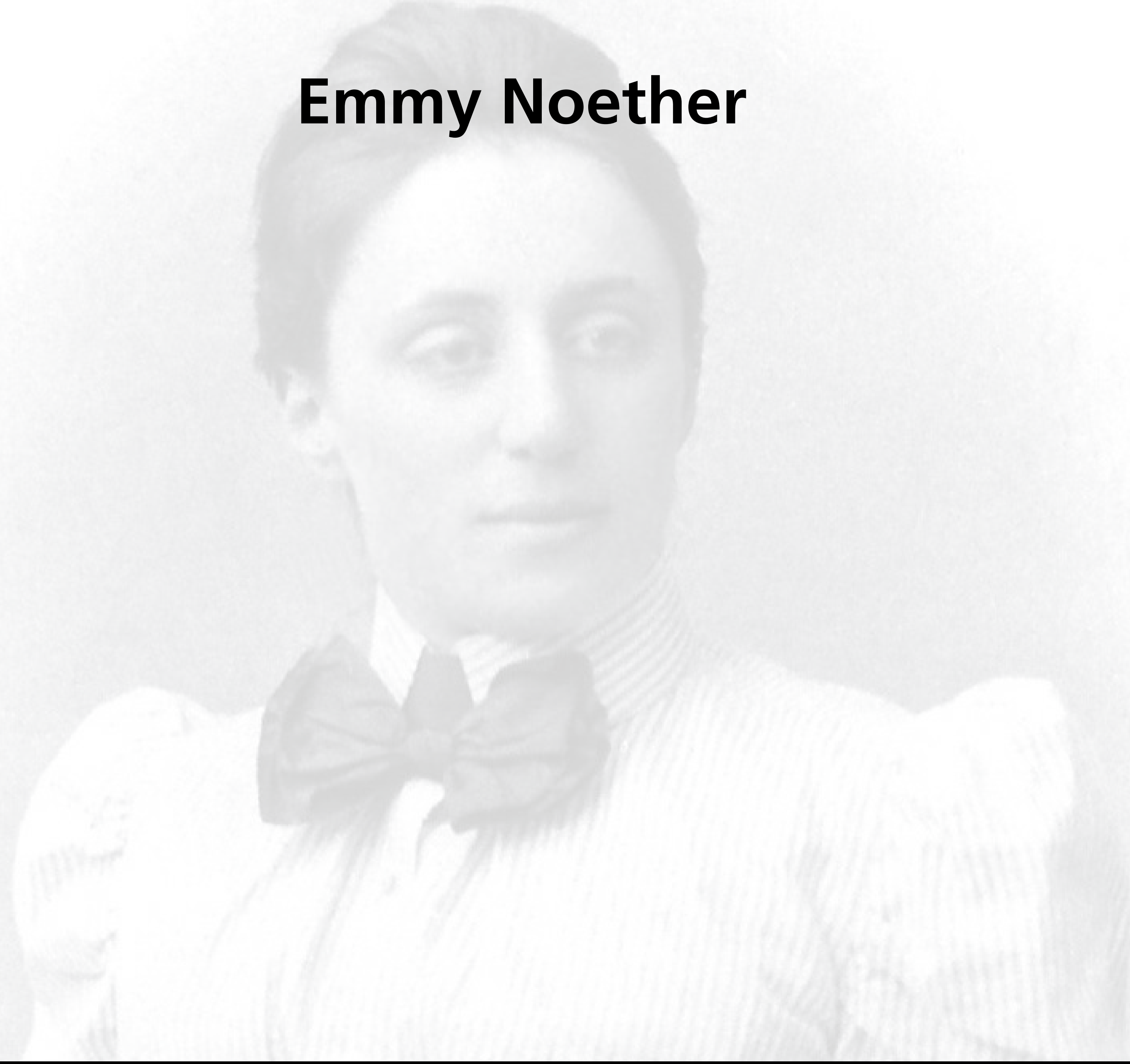
Table 1 Scheduling matrix

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

1 architecture

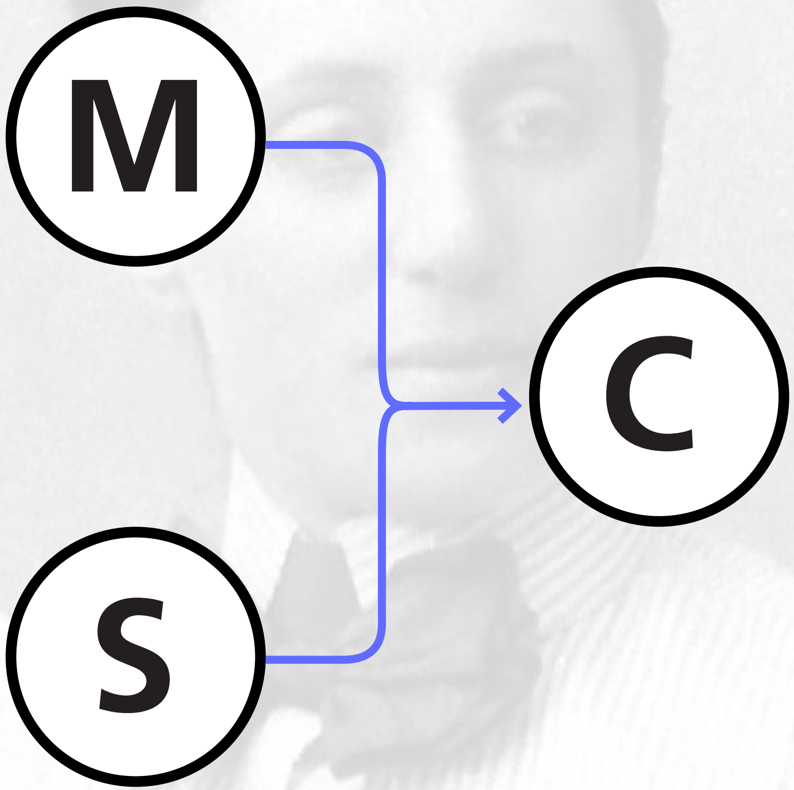
2 content

Emmy Noether



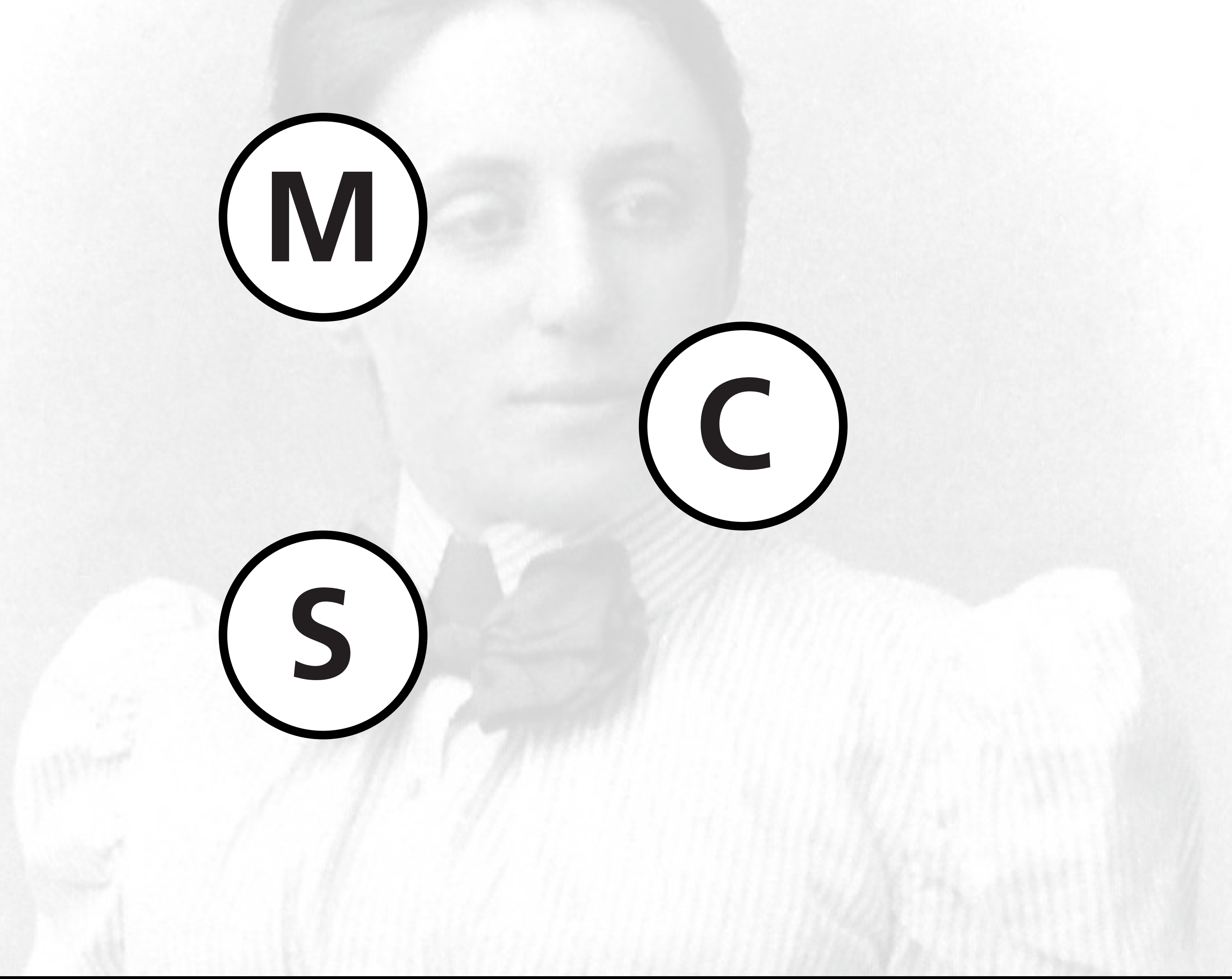
1 architecture **2 content**

Emmy Noether



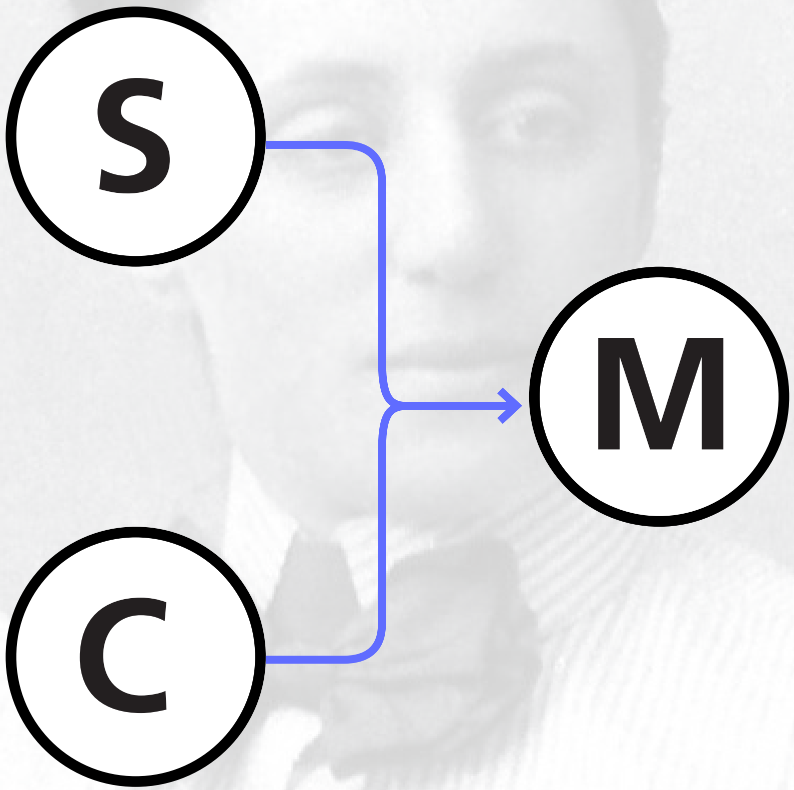
❶ architecture ❷ content

Emmy Noether



❶ architecture ❷ content

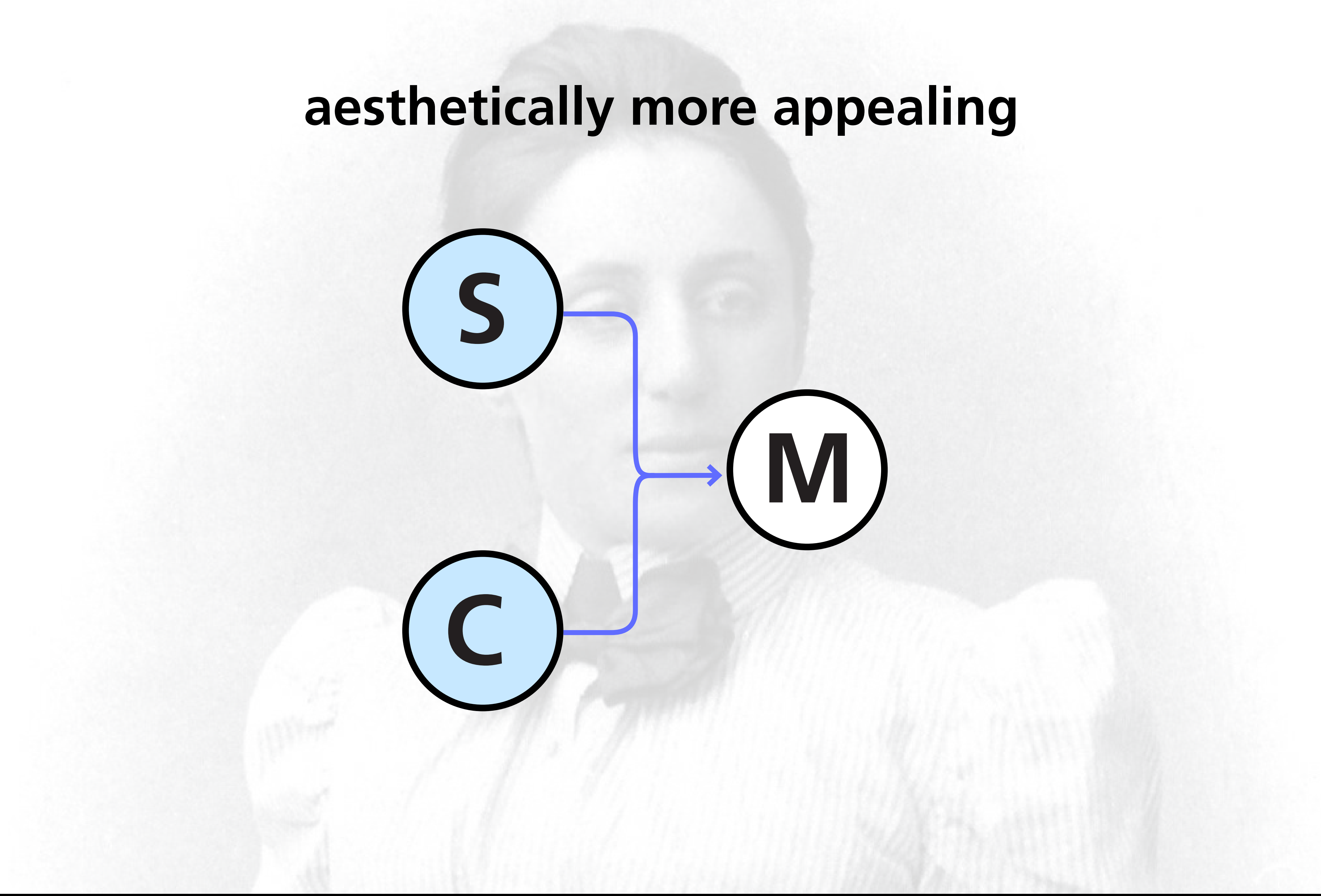
Noether inverted



1 architecture

2 content

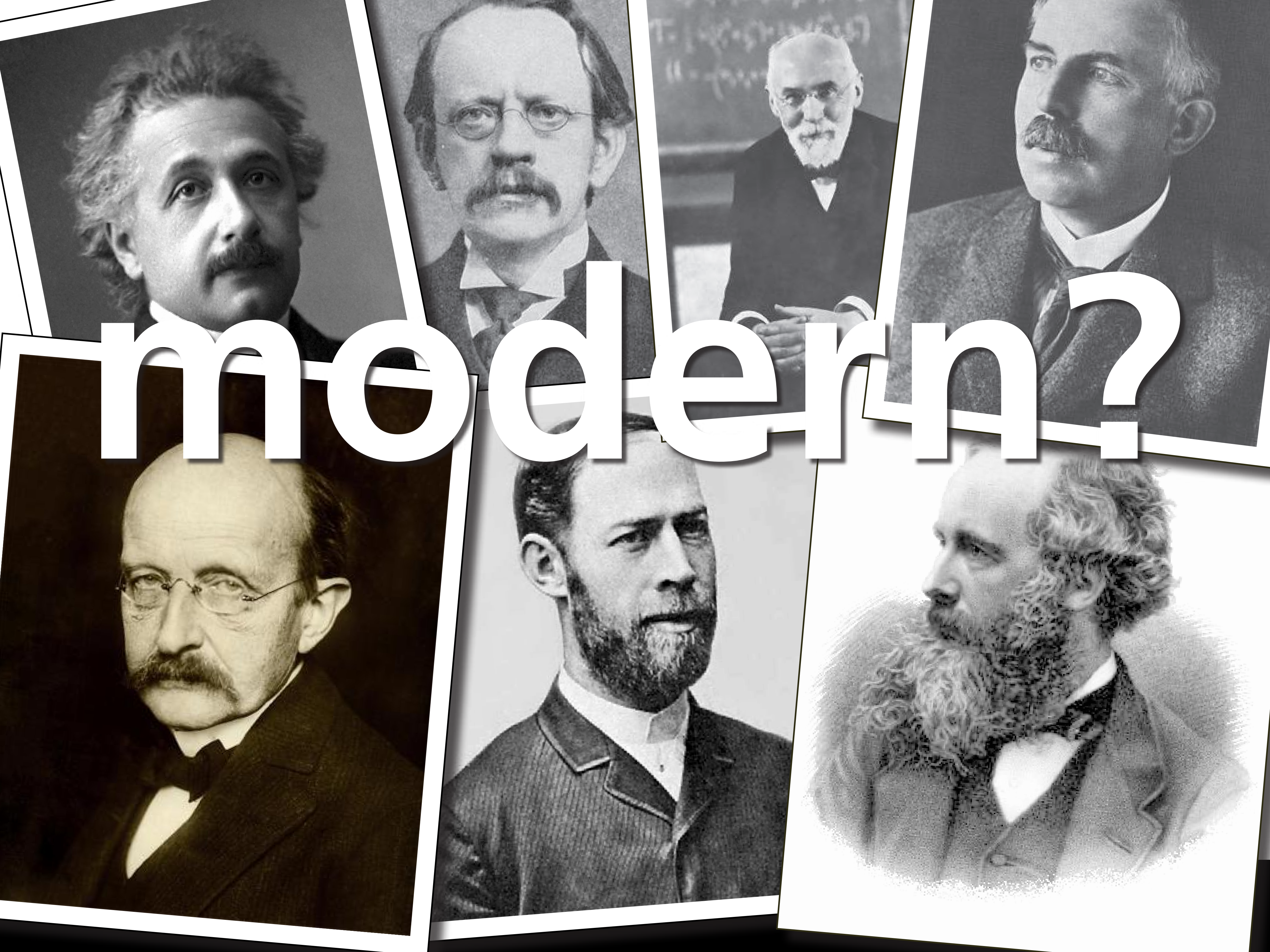
aesthetically more appealing



❶ architecture ❷ 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. Foundatio
2. Motion in one
3. Acceleration
4. Momentum
5. Energy
6. Principle of relativity
7. Interactions
8. Force
9. Work
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24. Gauss’s law
25. Work and energy in electrostatics
26. Charge separation and storage
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

1. Foundatio
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universality; particle interactions

1 architecture 2 content

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concepts of general relativity

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S.R. as part of mechanics

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statistical foundation for thermo

1 architecture   2 content

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relativistic
E&M
connection

1 architecture

2 content

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34. Wave and particle optics

semiconductors
transistors
logic gates

1 architecture

2 content

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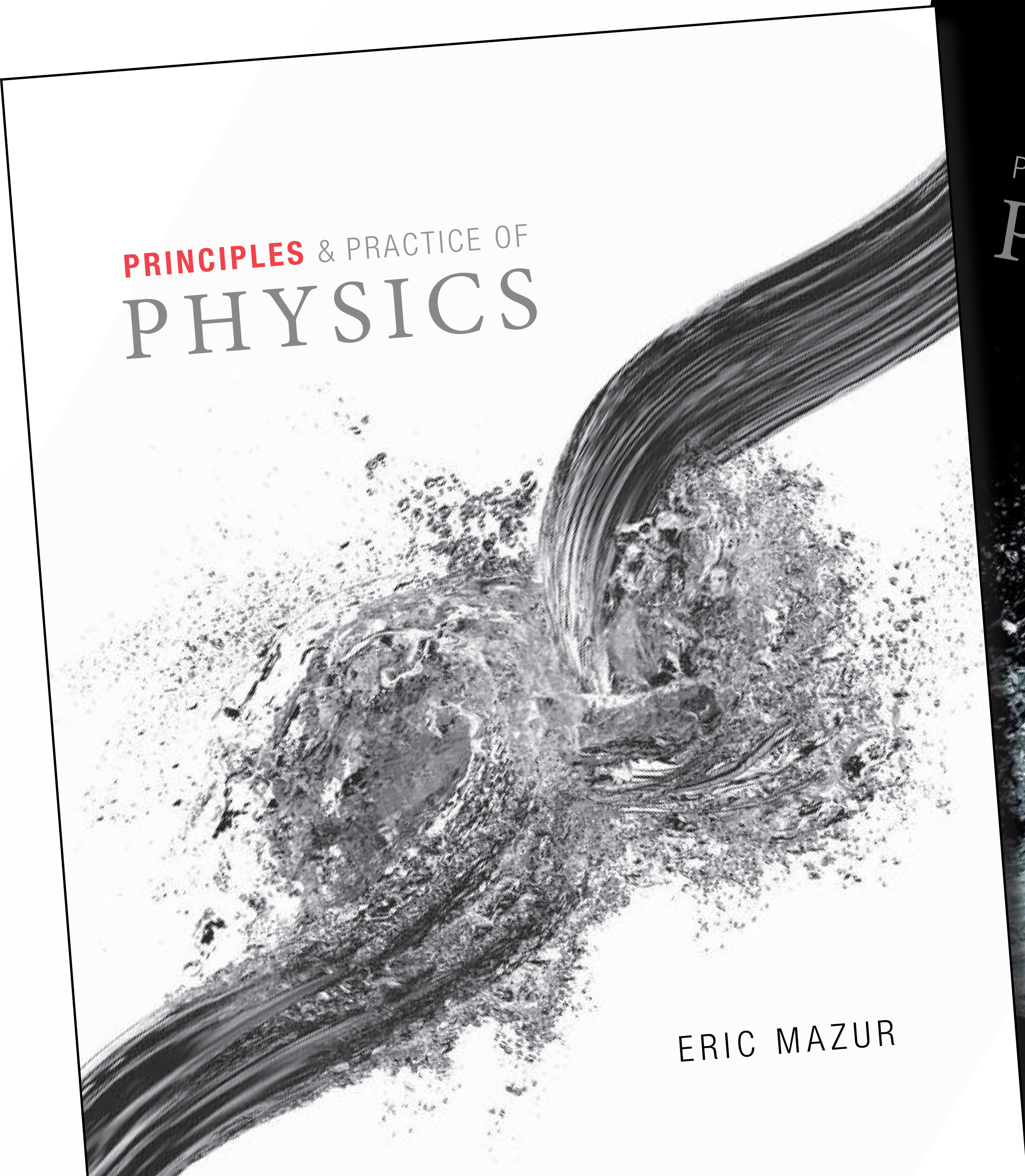
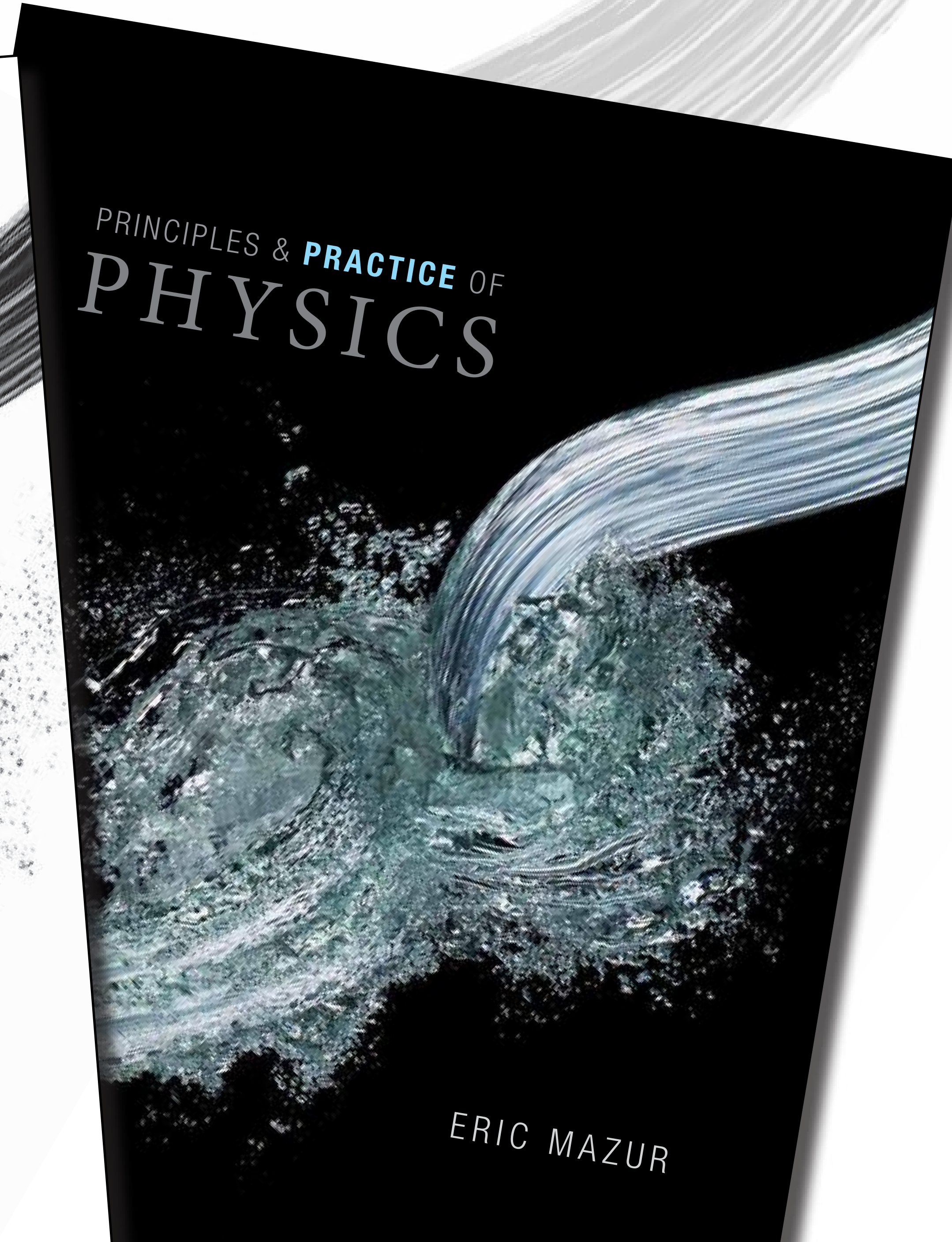
photons & particle interference

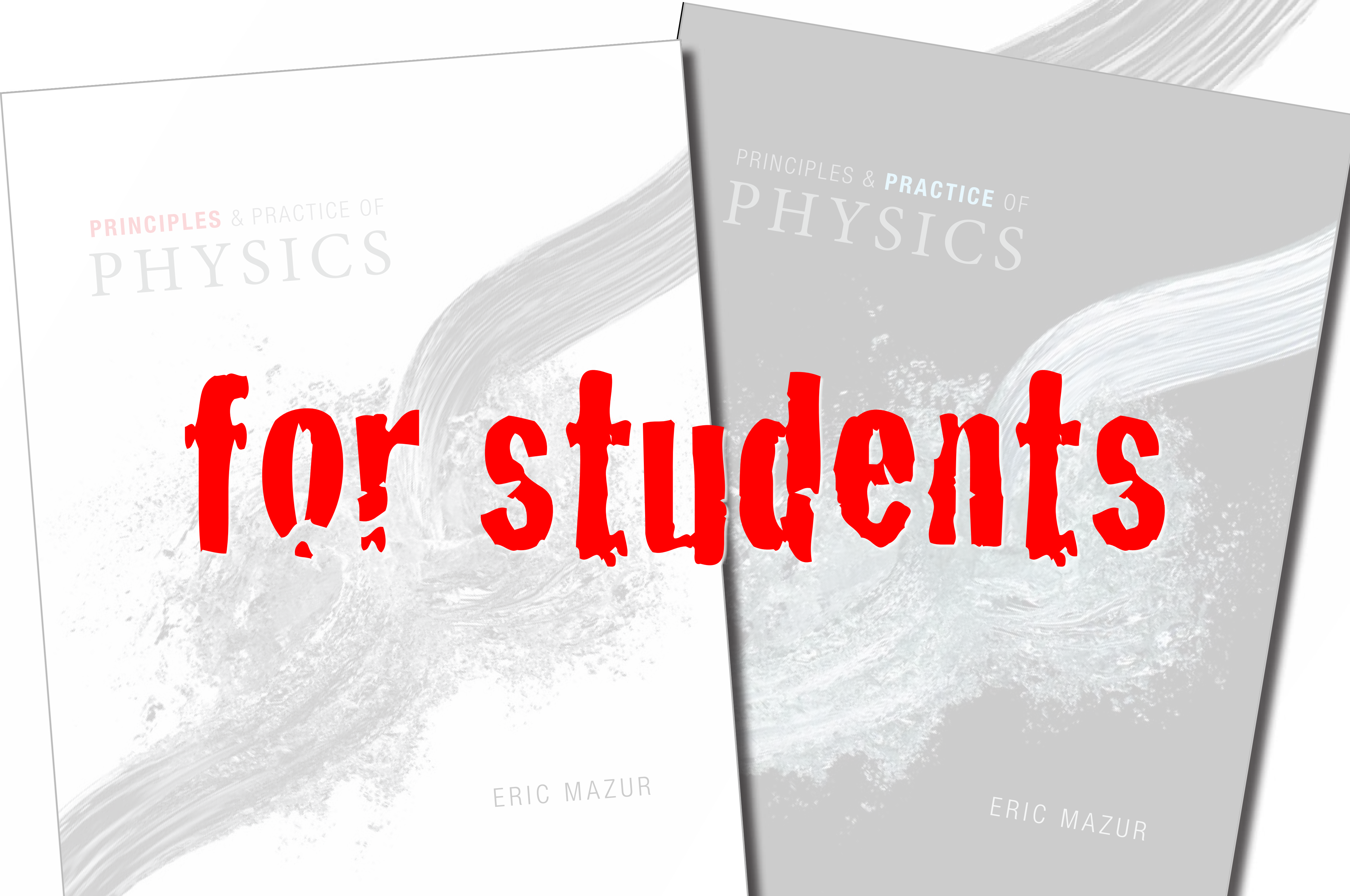
1 architecture

2 content





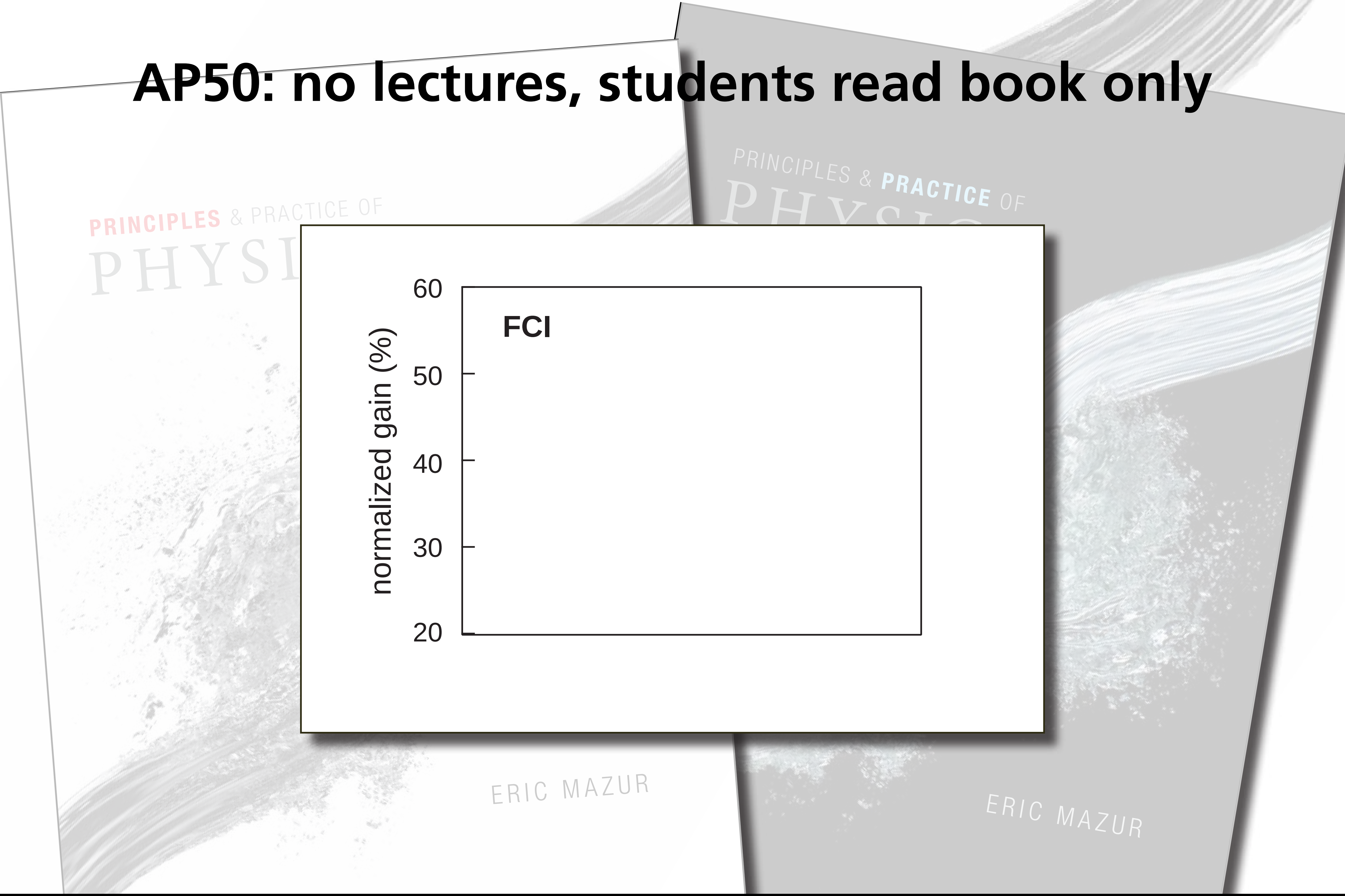
1 architecture 2 content 3 results



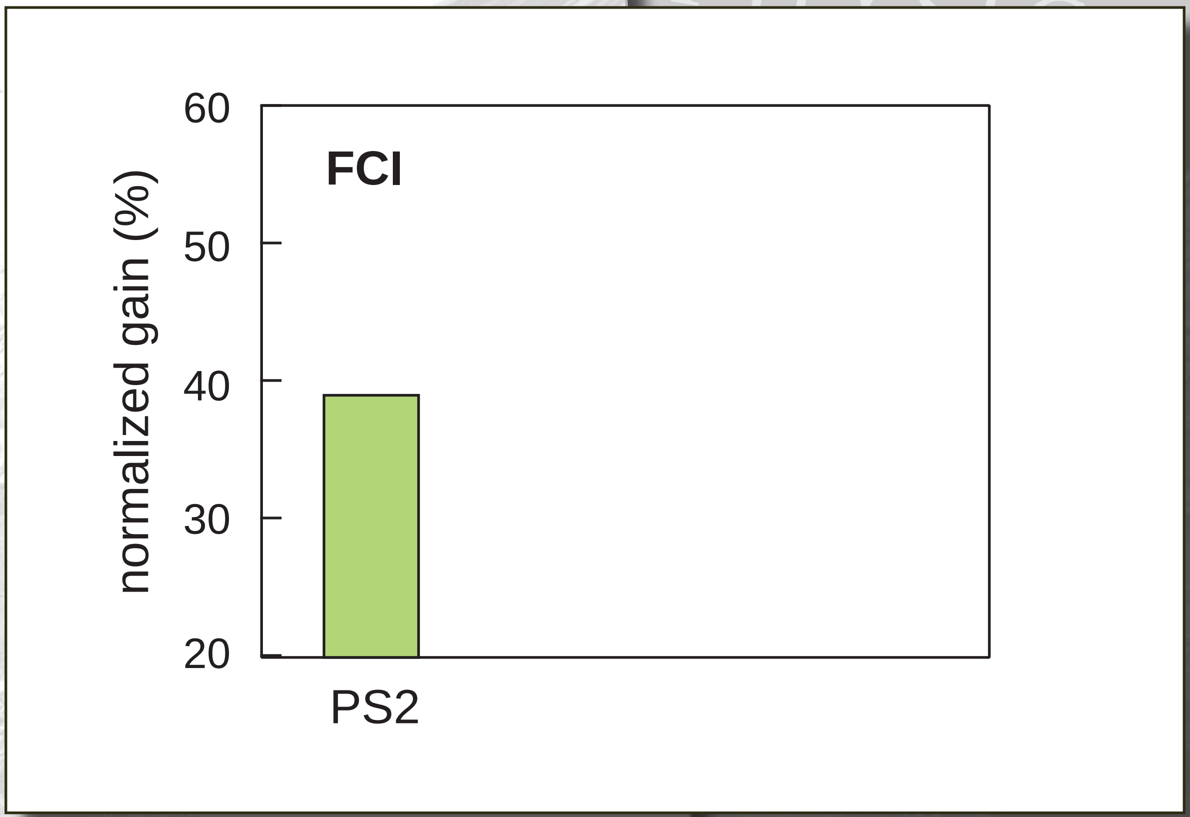
for students

1 architecture   2 content   3 results

AP50: no lectures, students read book only



AP50: no lectures, students read book only



1 architecture 2 content 3 results

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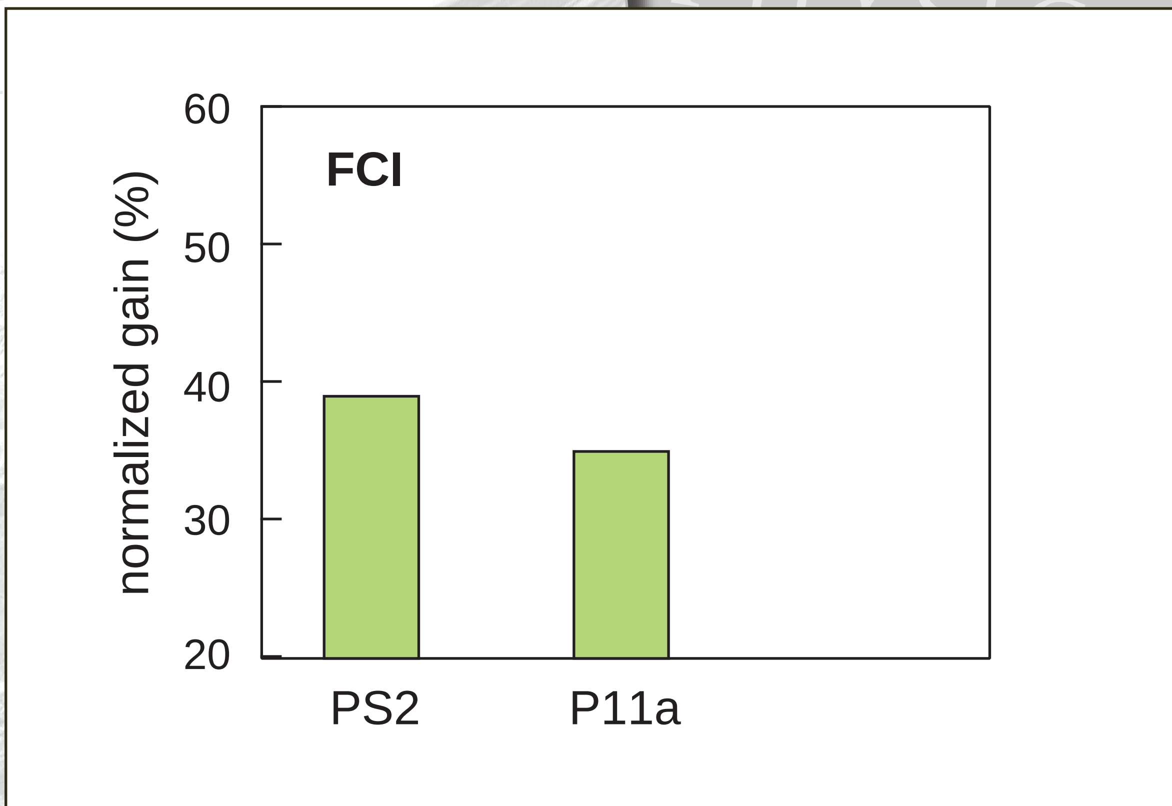

1 architecture 2 content 3 results

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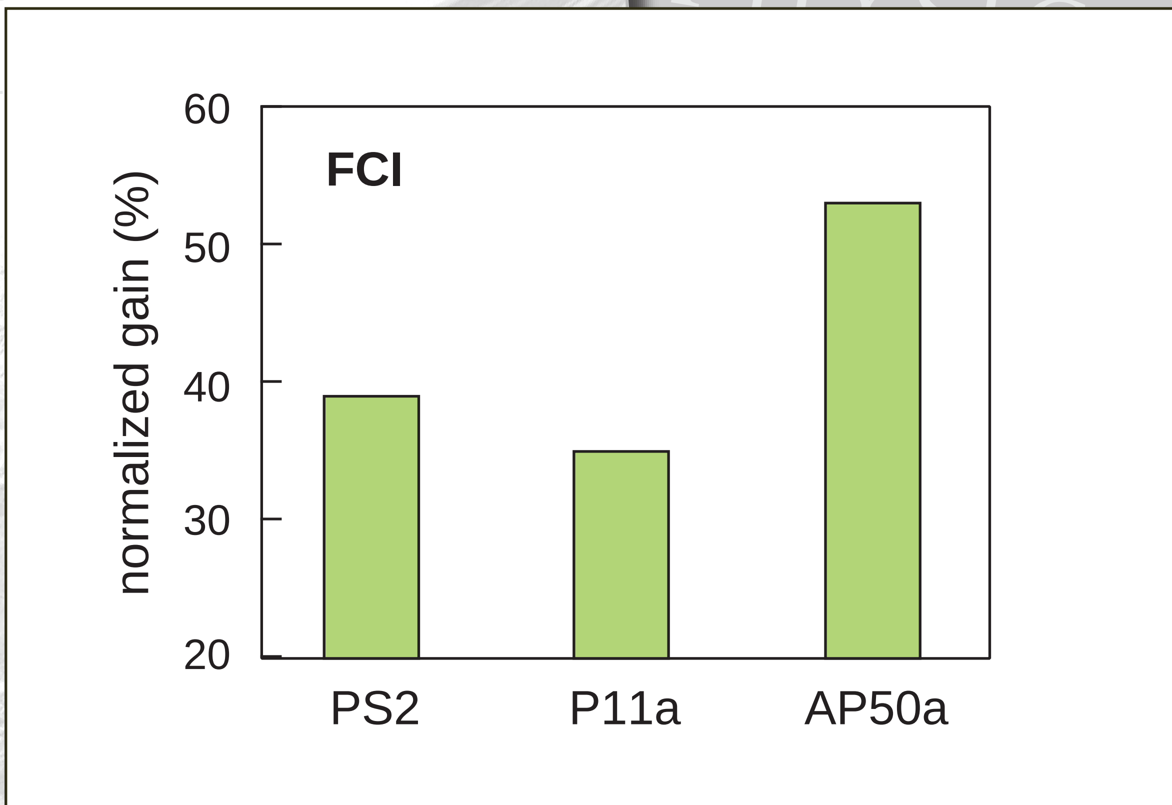

1 architecture　2 content　3 results

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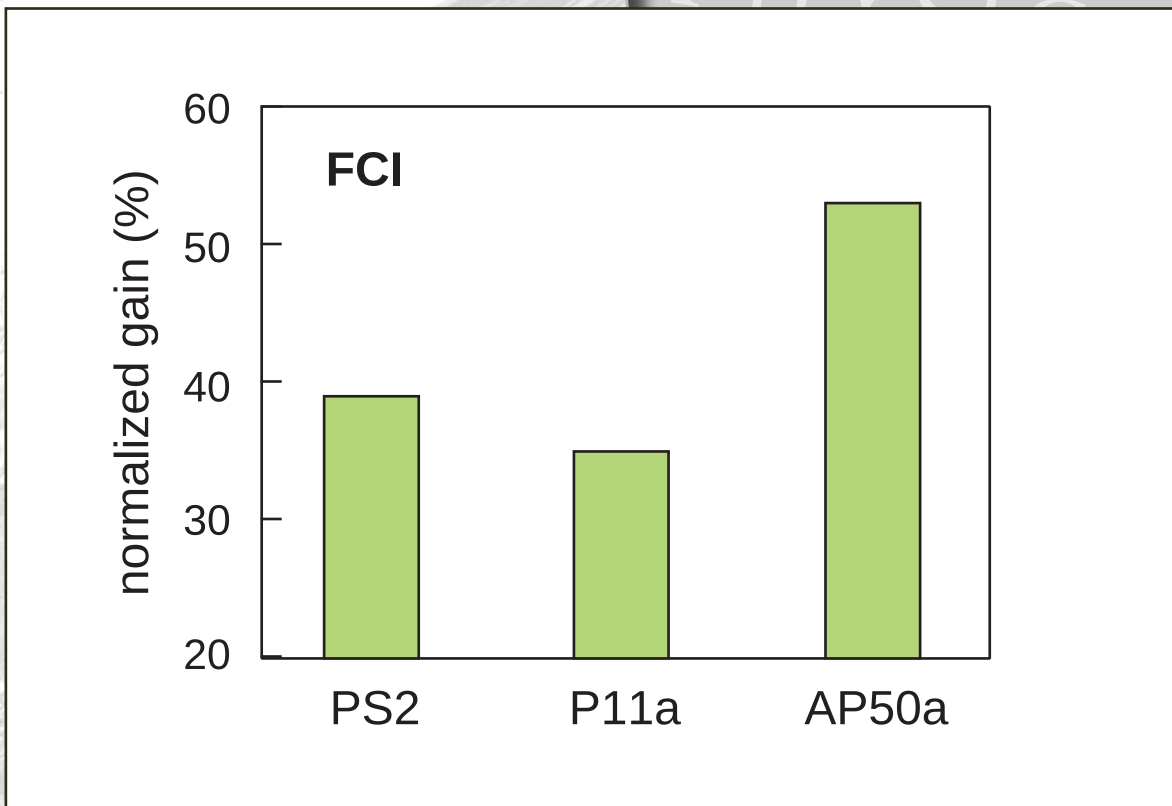

largest conceptual gain in *any* course past 6 yrs!

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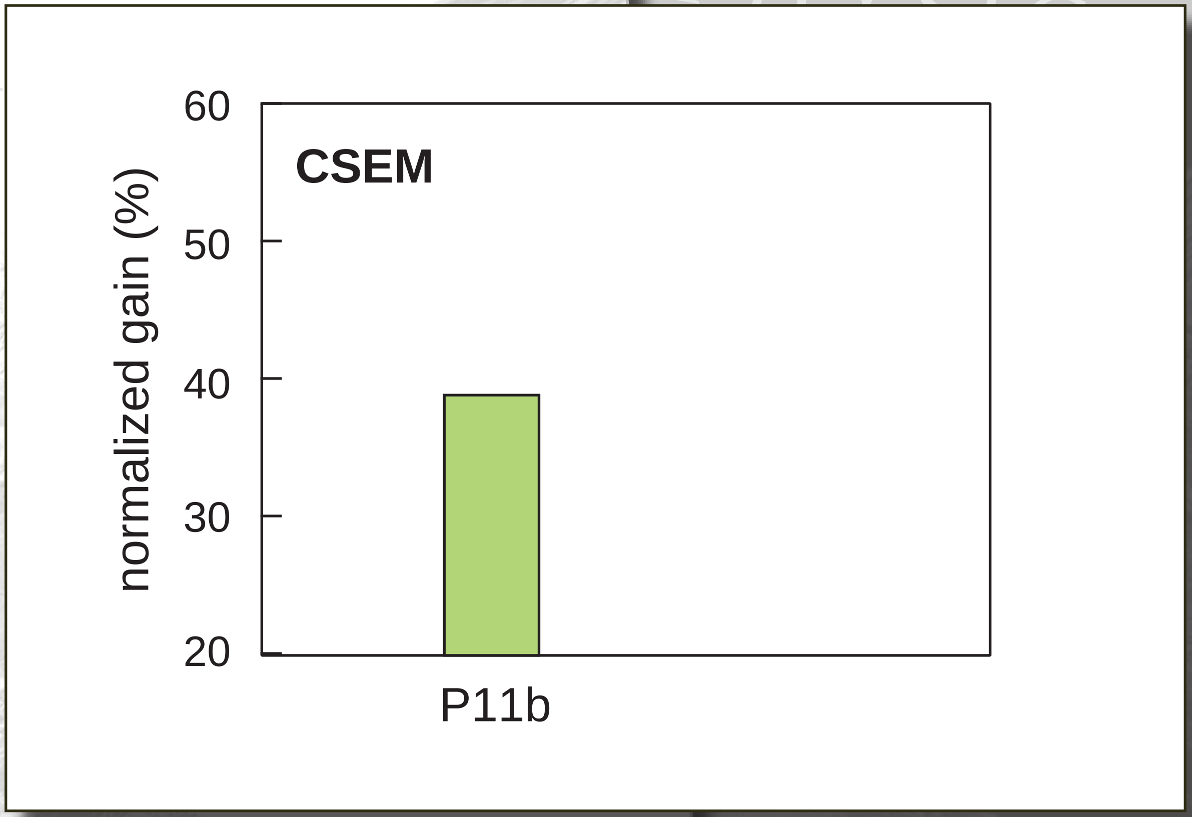
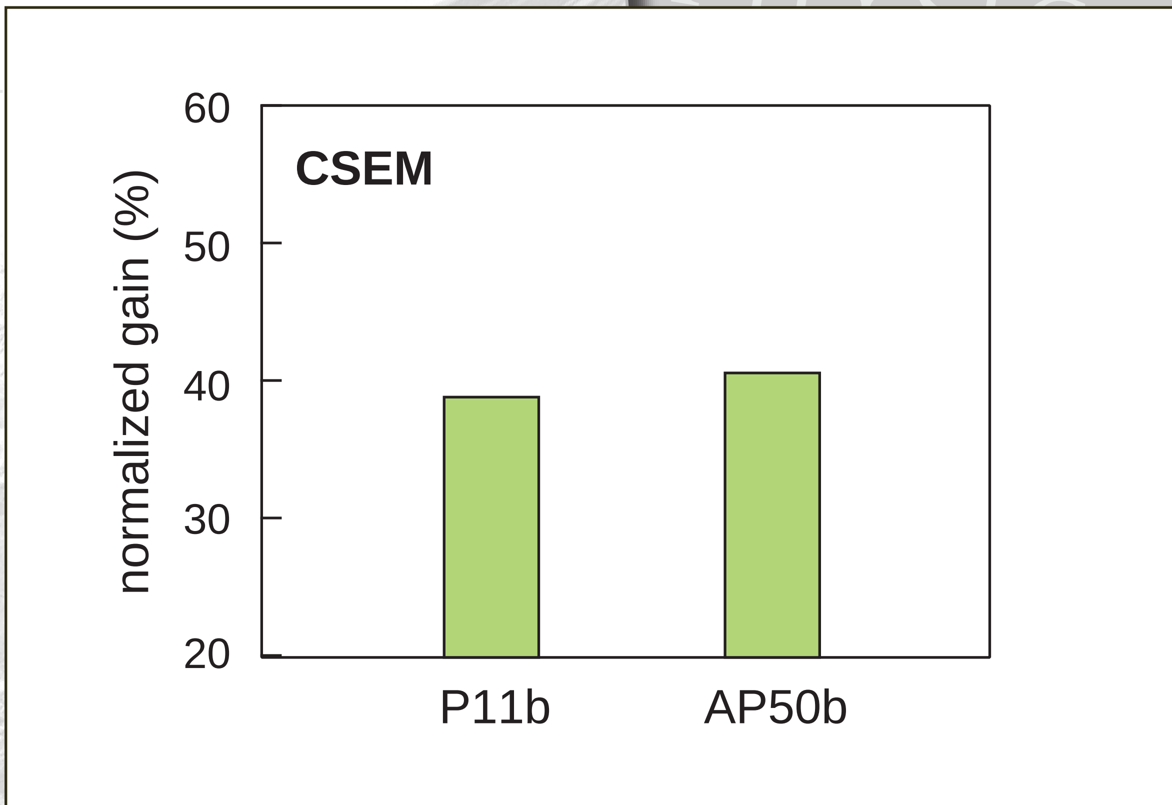


1 architecture **2** content **3** results

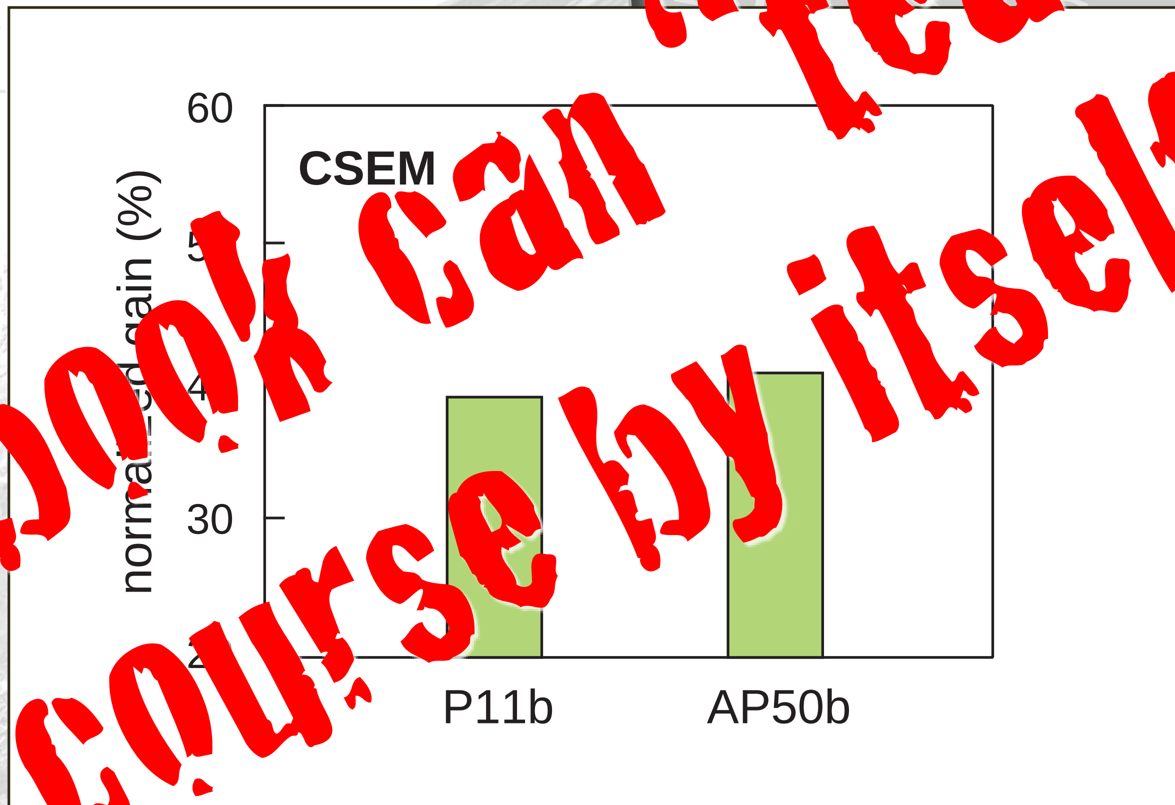
AP50: no lectures, students read book only



as good as when I do my best teaching!

1 architecture 2 content 3 results

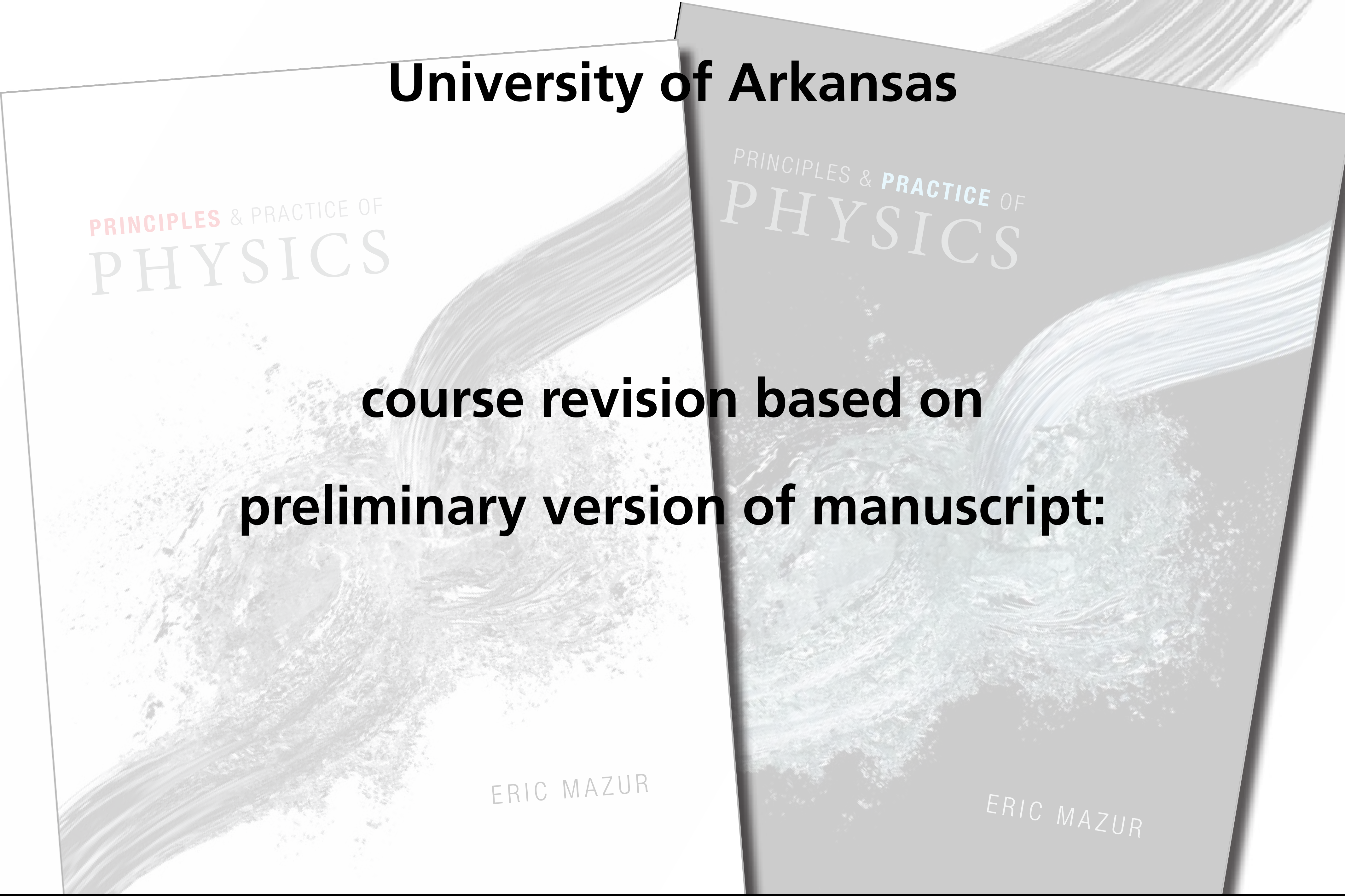
AP50: no lectures, students read book only



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

as good as when I do my best teaching!

University of Arkansas

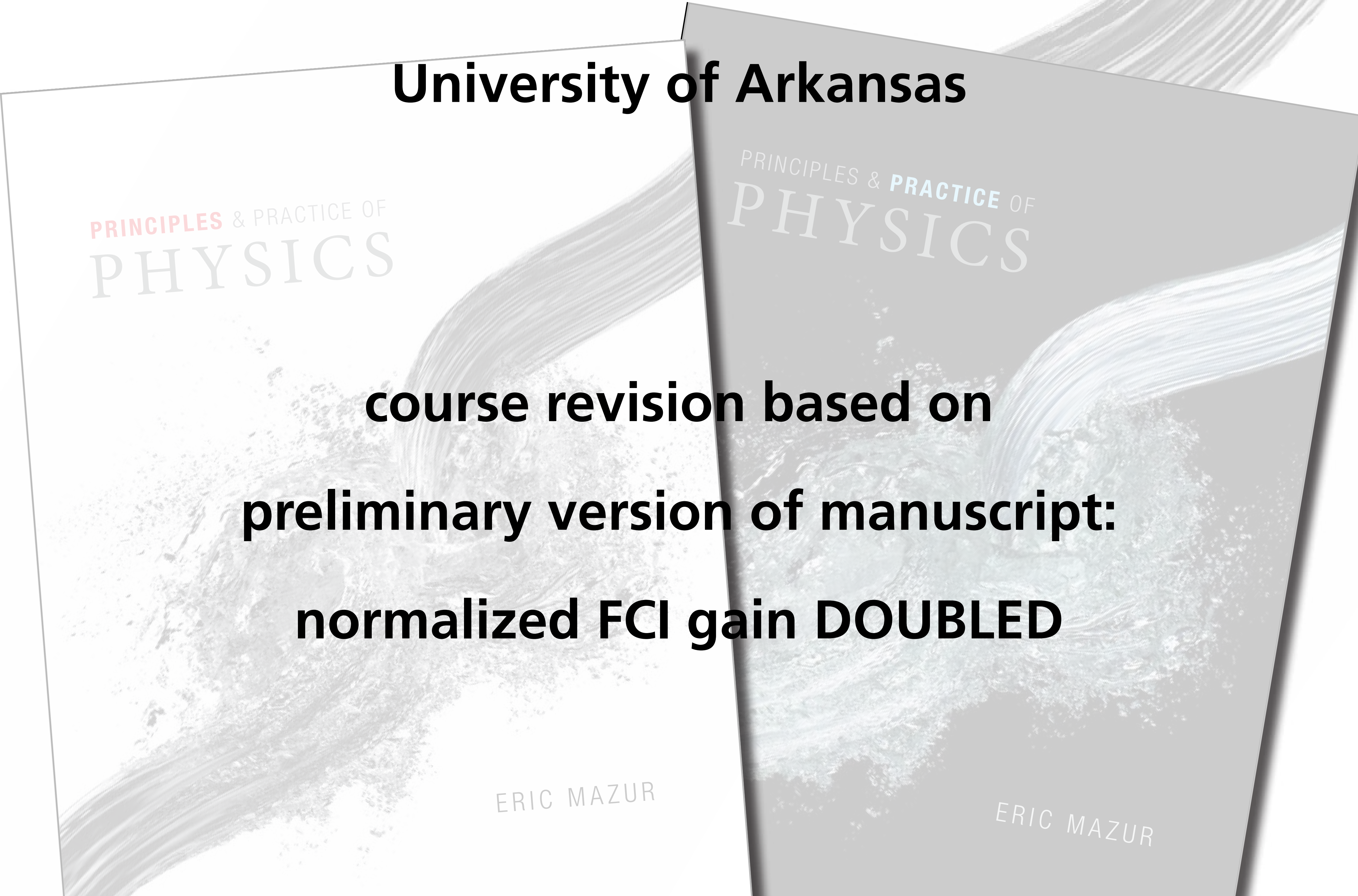


course revision based on

preliminary version of manuscript:

1 architecture   2 content   3 results

University of Arkansas



course revision based on

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normalized FCI gain DOUBLED


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