

The make-believe world of real-world physics



MIT
Cambridge, MA, 17 May 2011



The make-believe world of real-world physics



@eric_mazur

MIT
Cambridge, MA, 17 May 2011



Dear Professor,

Dear Professor,

*I still don't believe heavy
and light things fall at the same speed.*

Dear Professor,

*I still don't believe heavy
and light things fall at the same speed.
A feather and a stone, for example.*

Dear Professor,

*I still don't believe heavy
and light things fall at the same speed.
A feather and a stone, for example.
You kept saying I'd get it
if I lived in a vacuum.*

Dear Professor,

*I still don't believe heavy
and light things fall at the same speed.*

A feather and a stone, for example.

*You kept saying I'd get it
if I lived in a vacuum.*

Do you live in a vacuum?

Nin Andrews, *Dear Professor* (Subito Press, 2008)

Does physics apply to the real world?

Does physics apply to the real world?

Does physics apply to the real world?

physicists



Does physics apply to the real world?

physicists



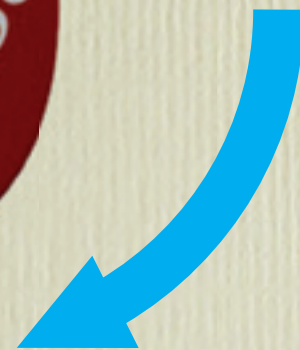
lay people

Does physics apply to the real world?

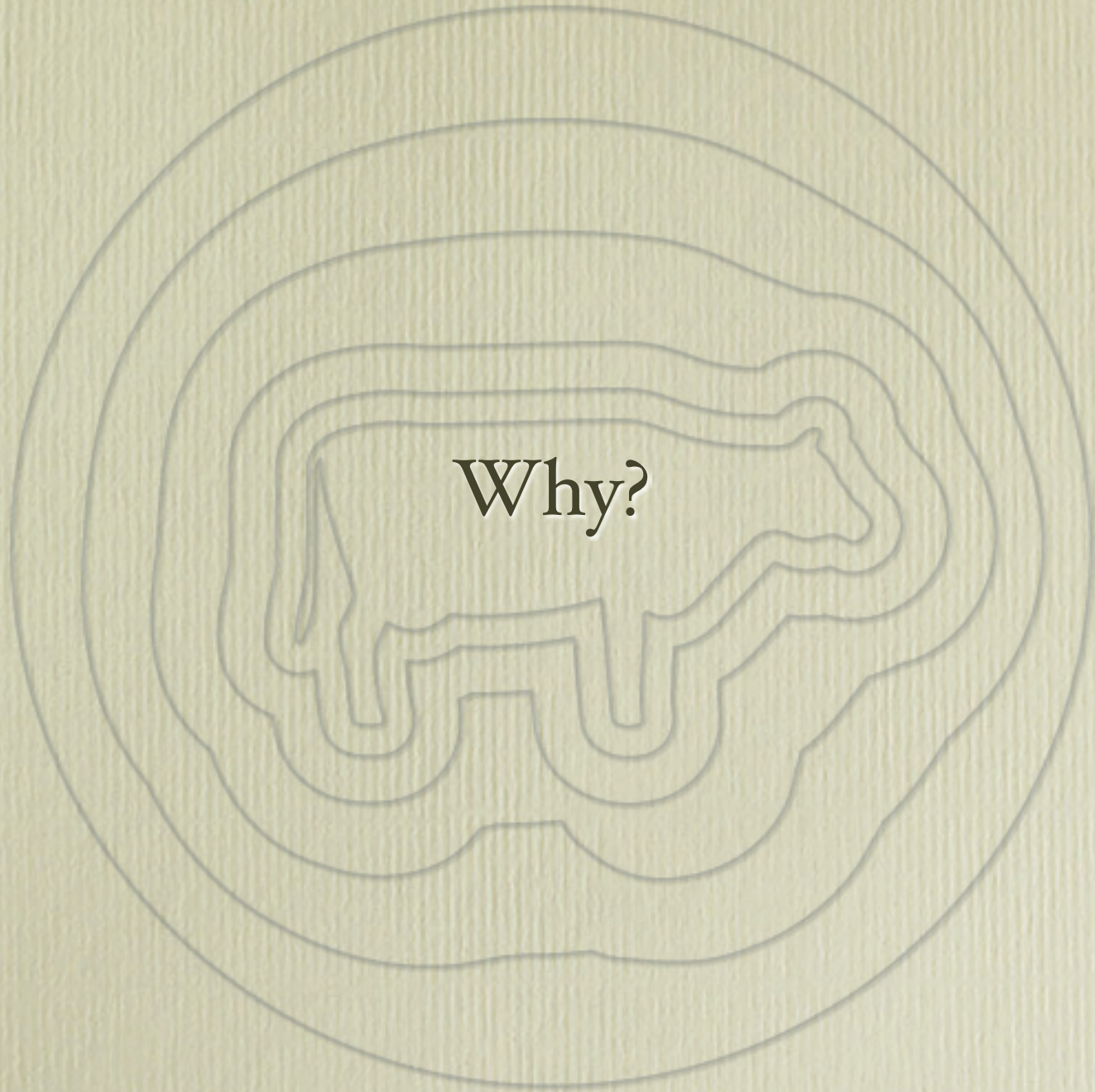
physicists



lay people



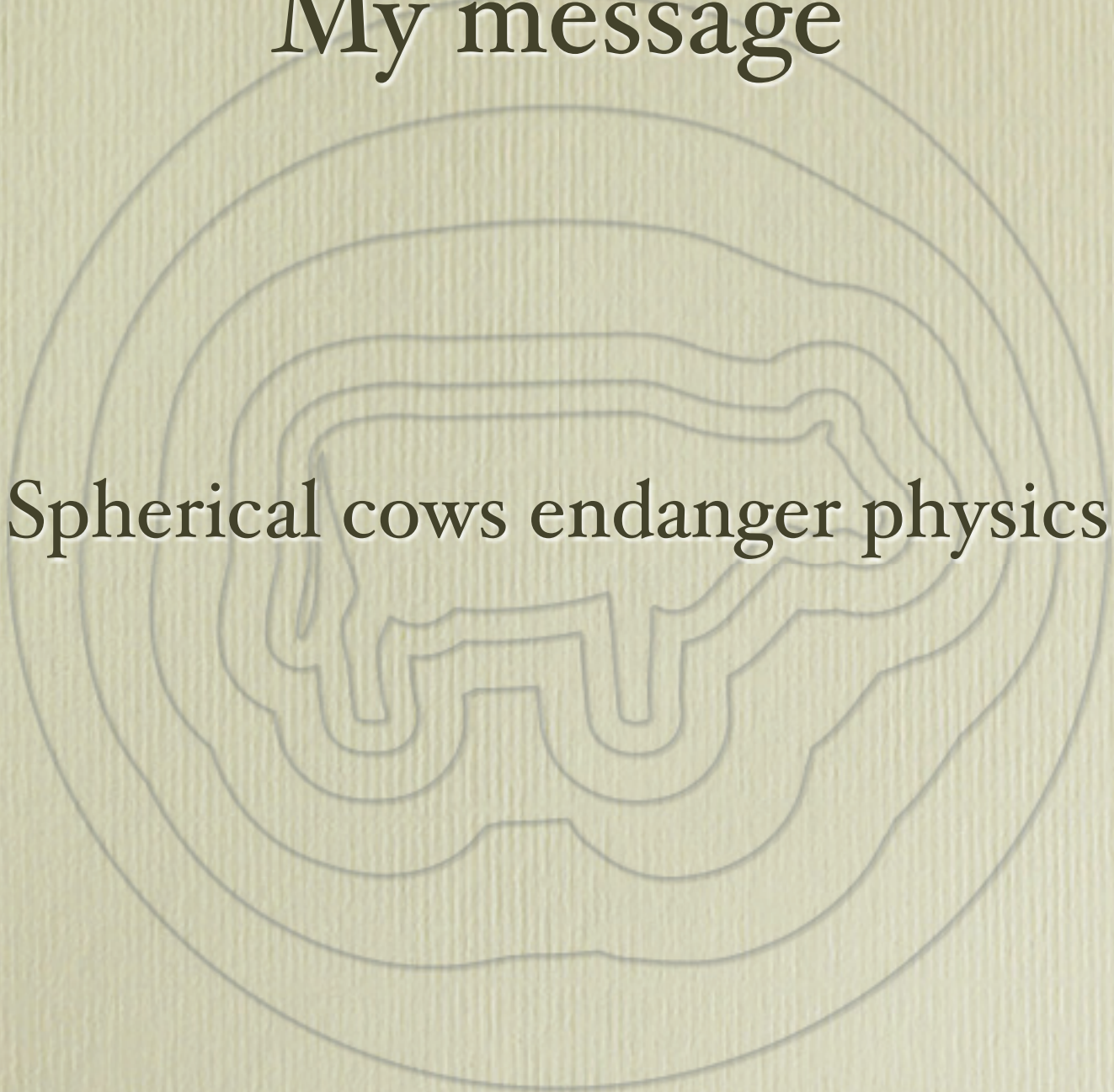
students



Why?

My message

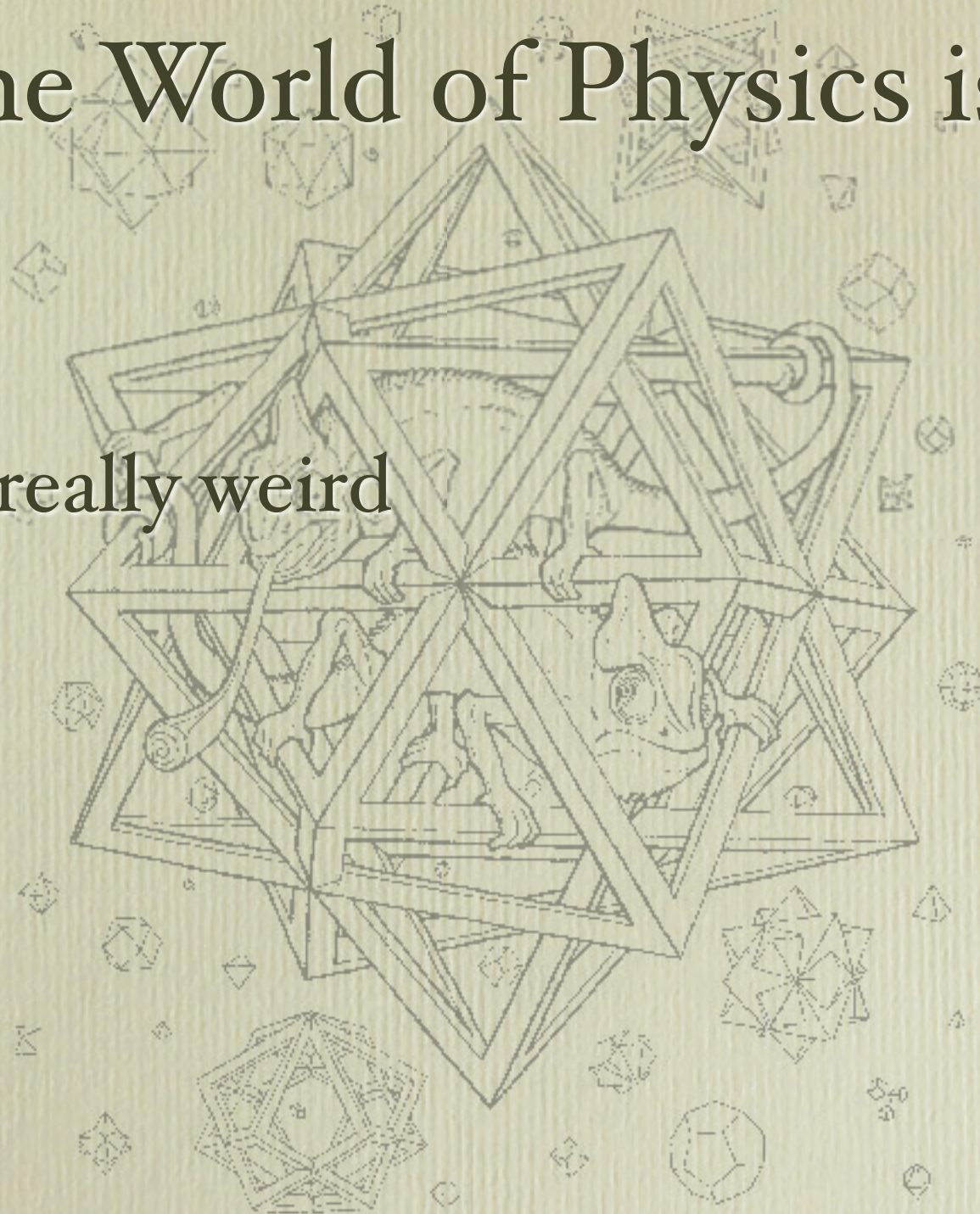
Spherical cows endanger physics



The World of Physics is...



really weird



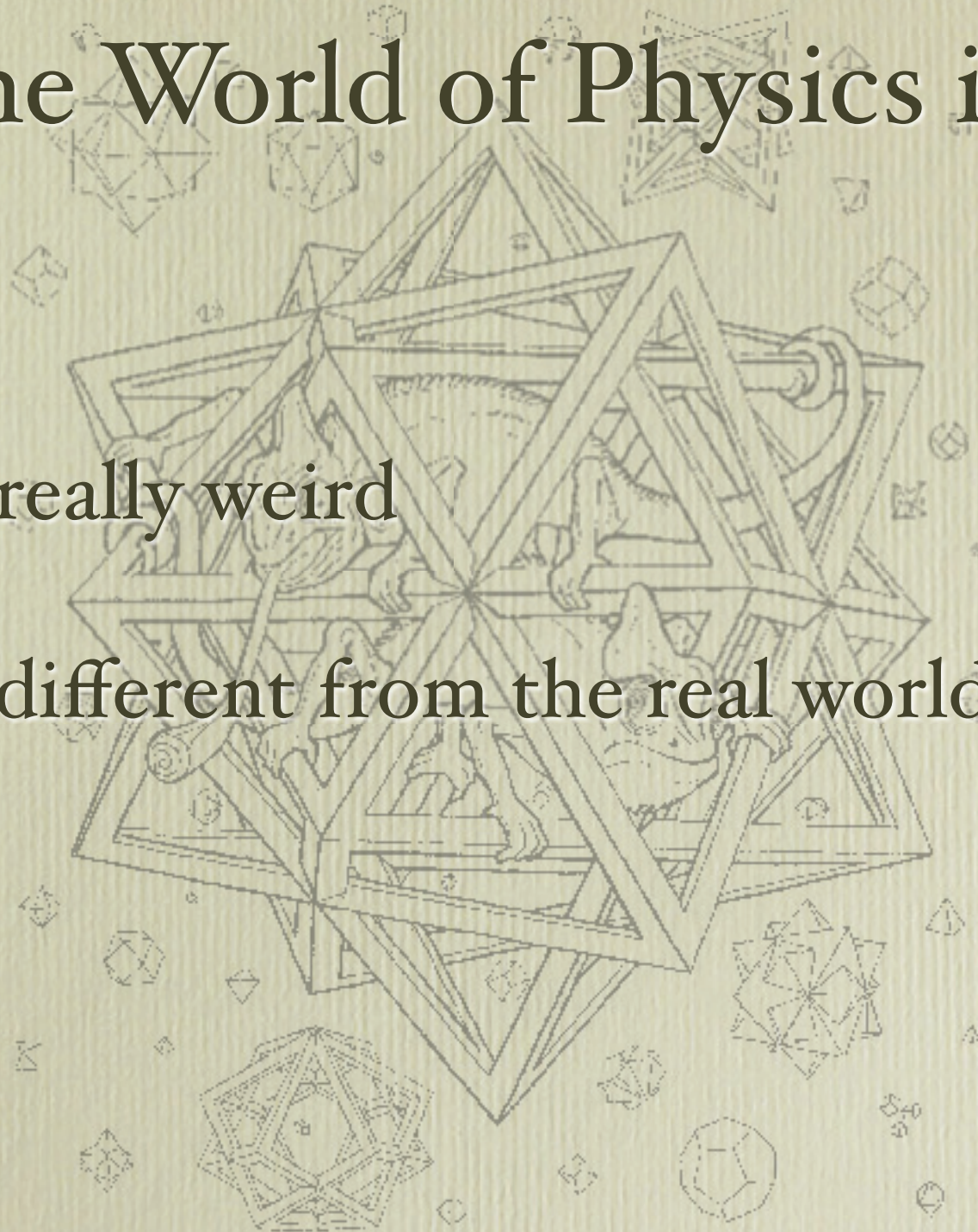
The World of Physics is...



really weird



different from the real world



The World of Physics is...



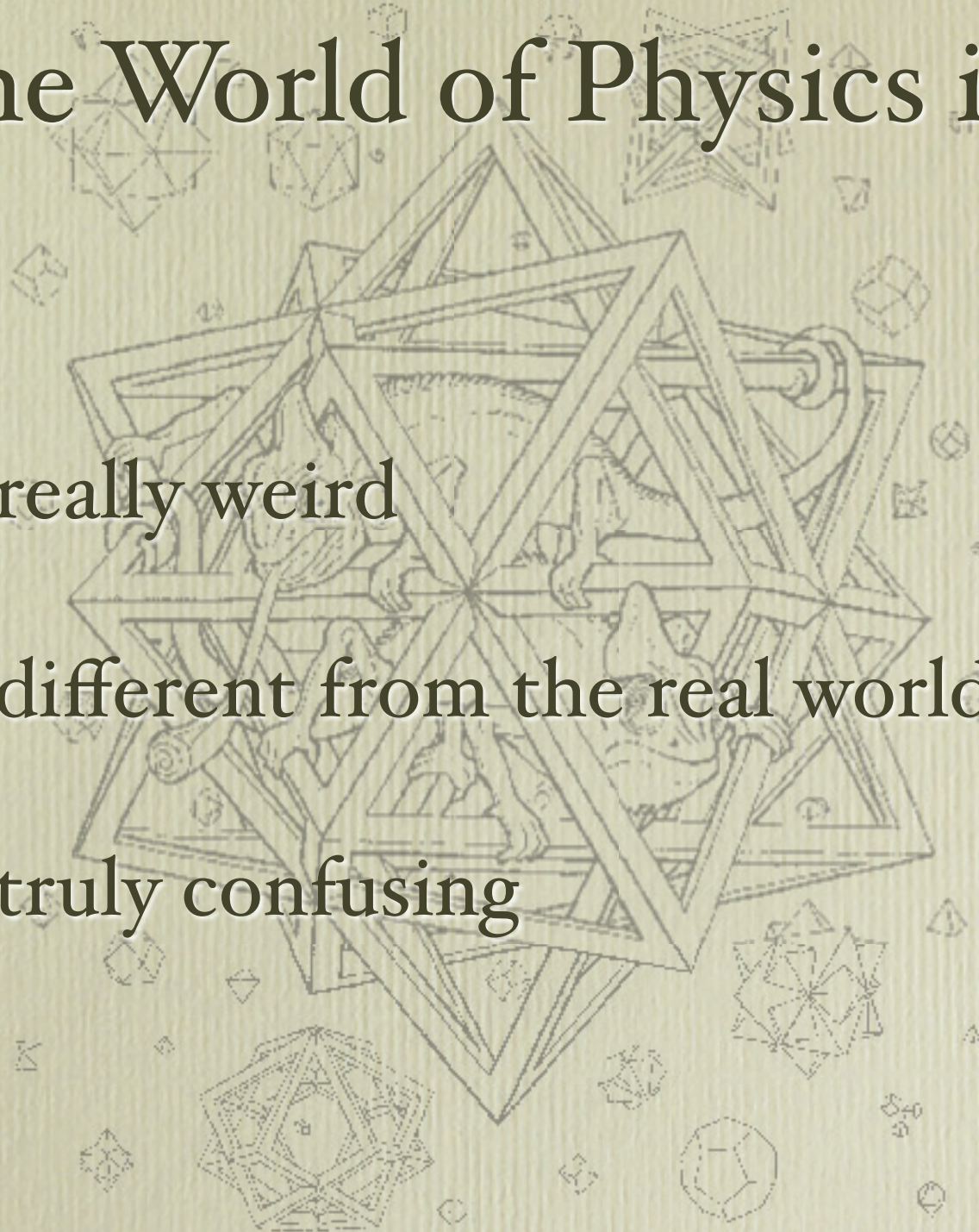
really weird



different from the real world



truly confusing



The weird world of physics



First impressions

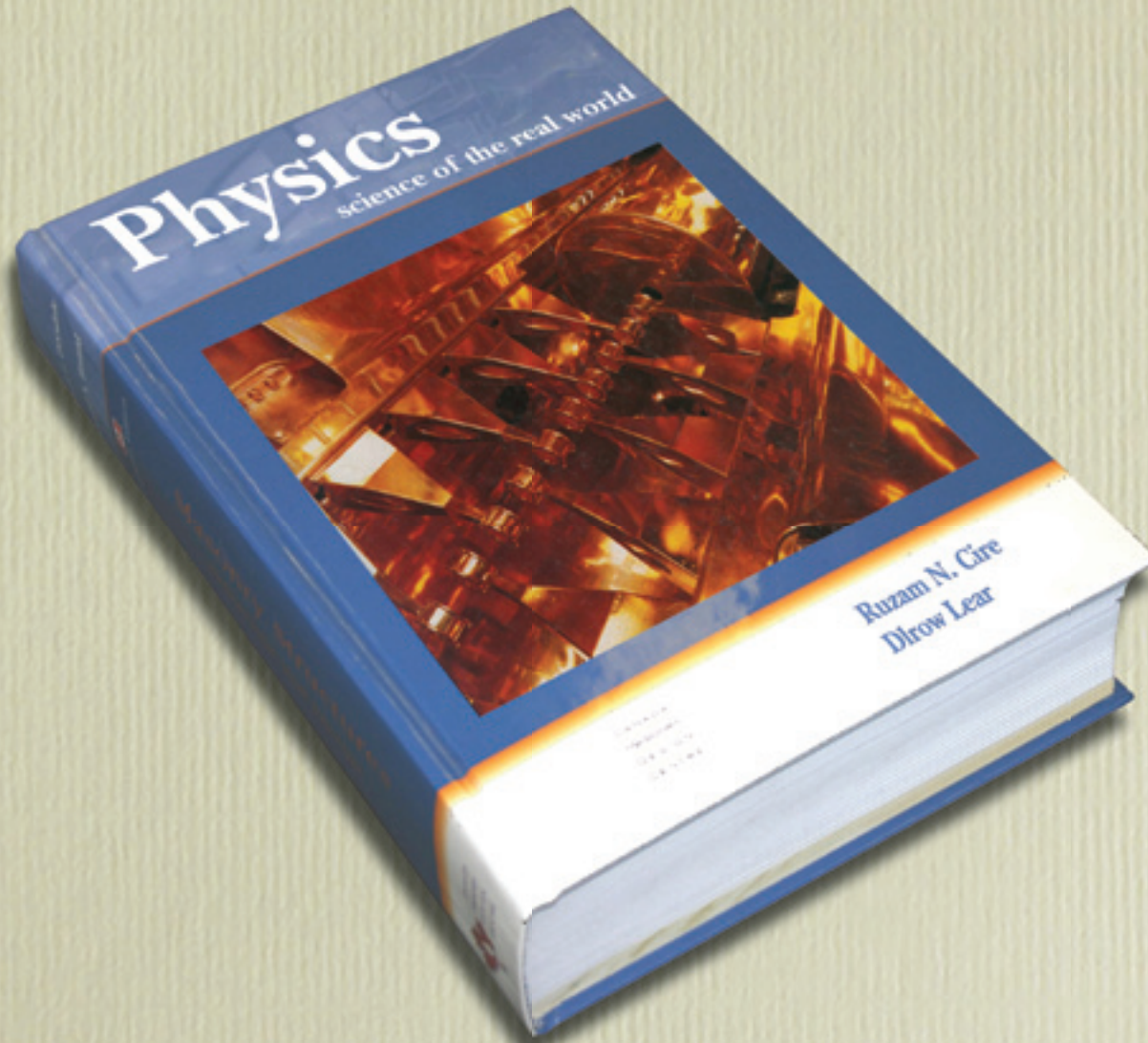


Table manners

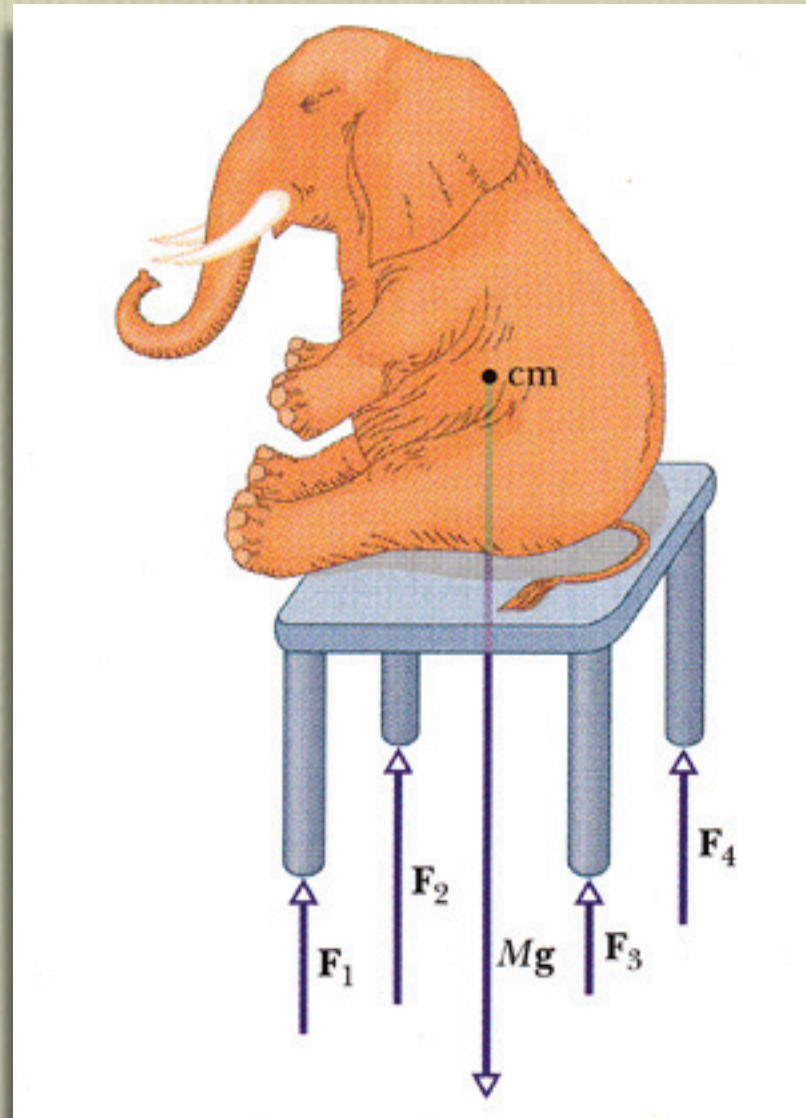
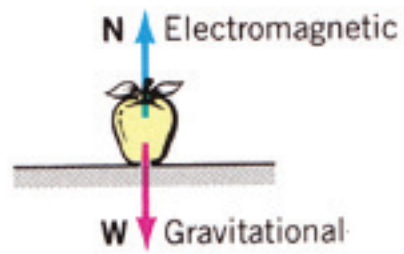
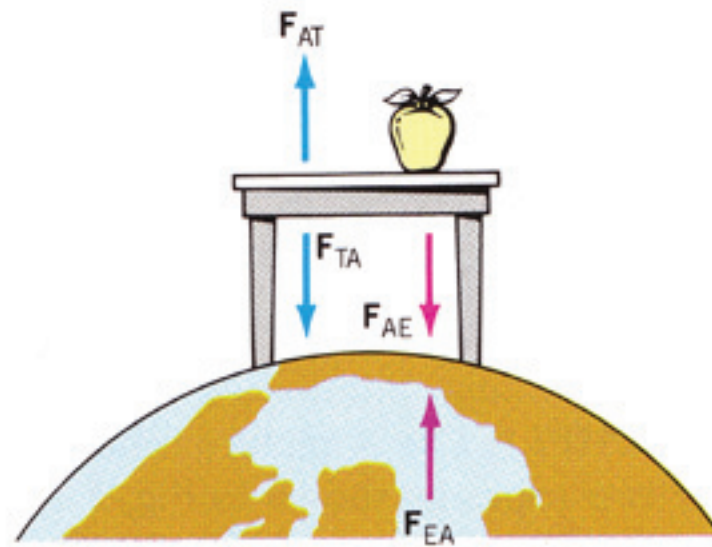


Table manners



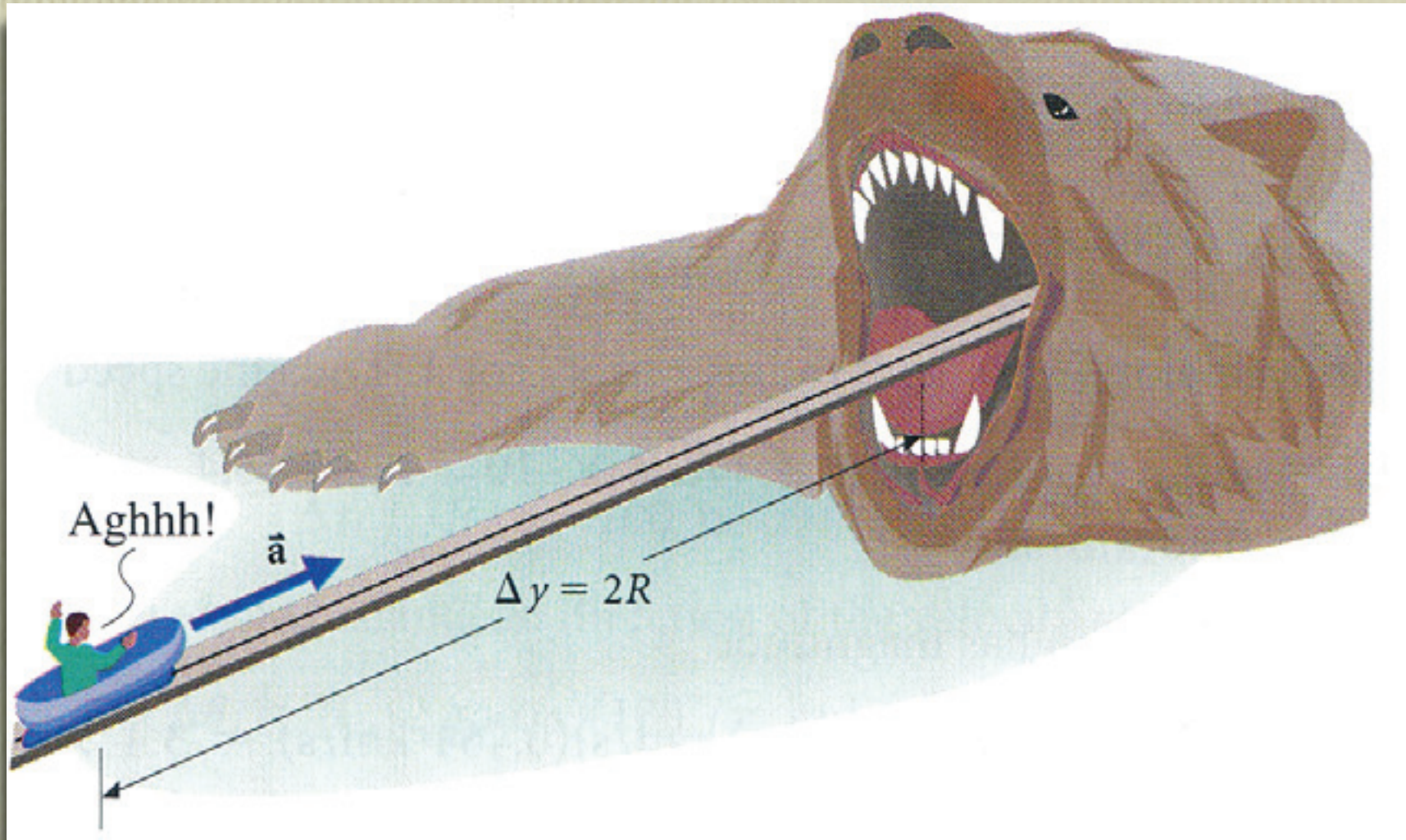
(a)



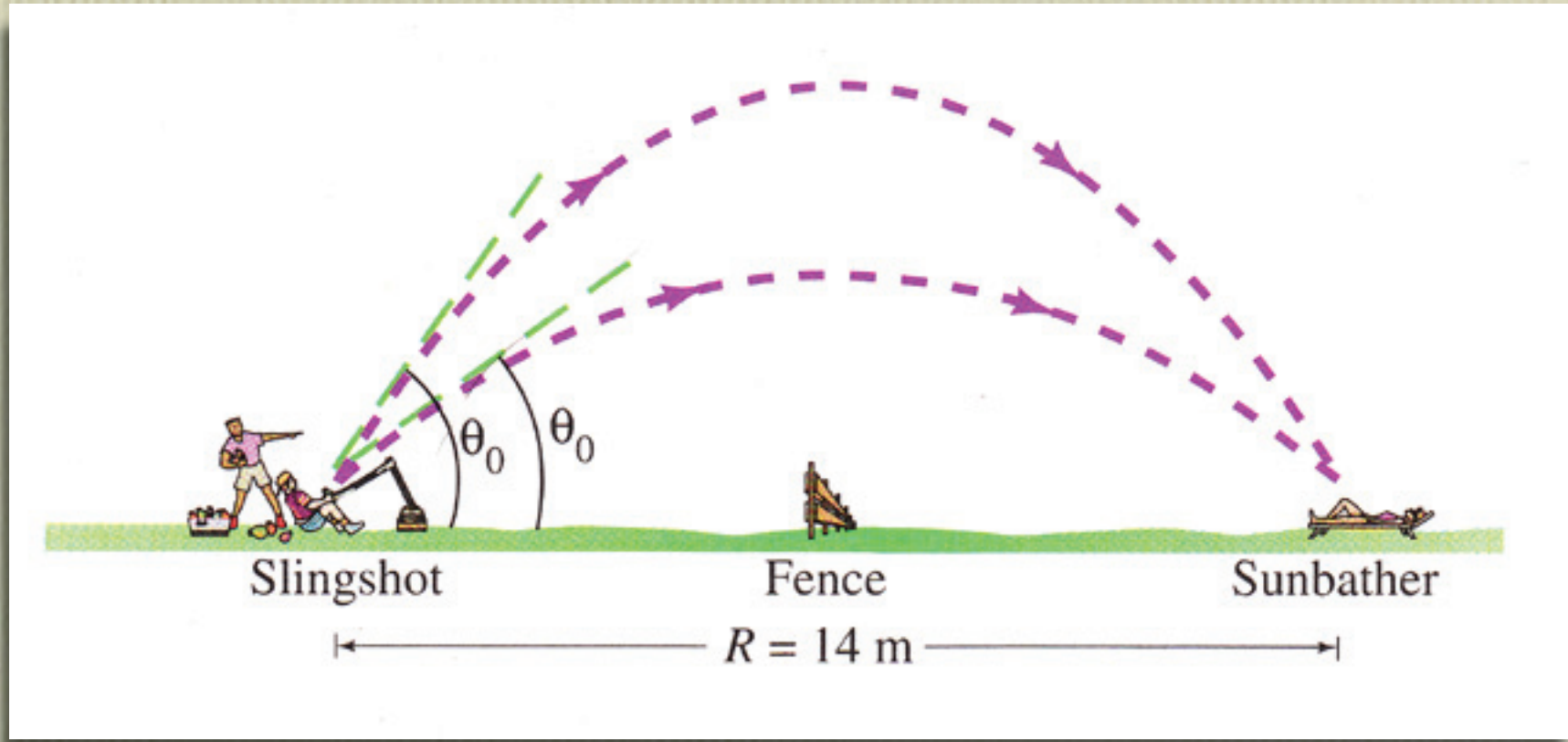
(b)



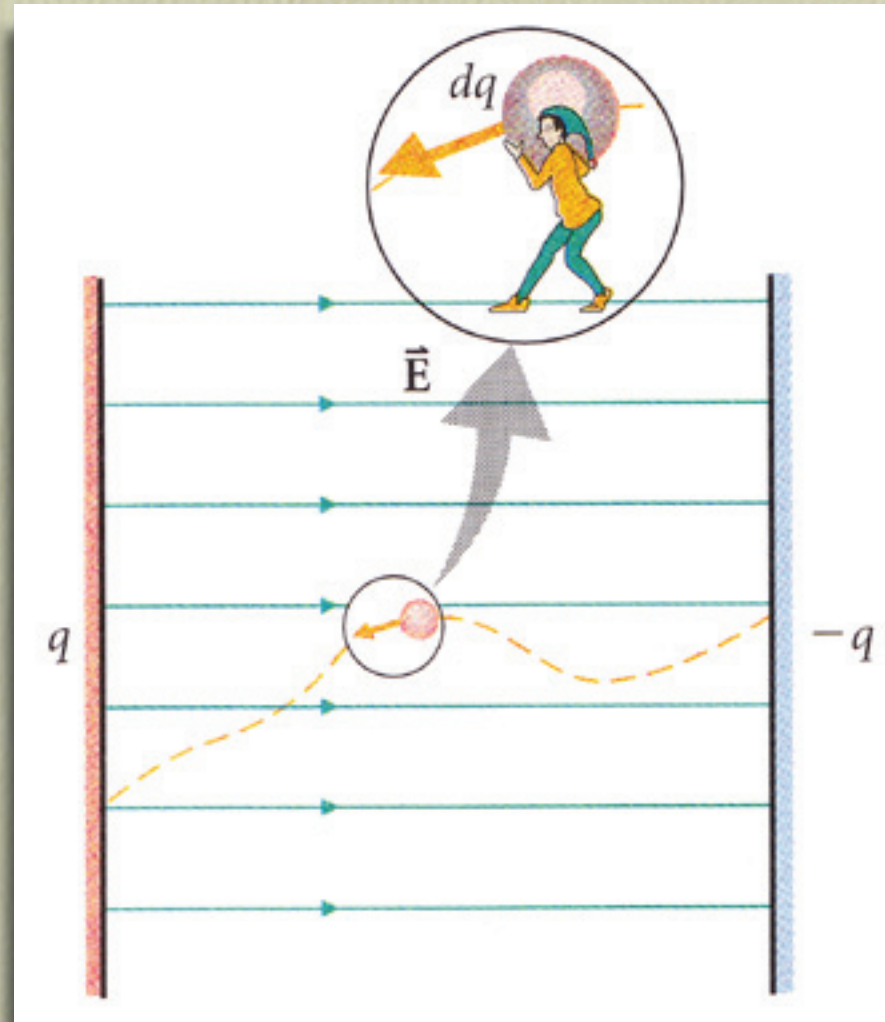
Leisure time activities



Leisure time activities



Leisure time activities



Leisure time activities

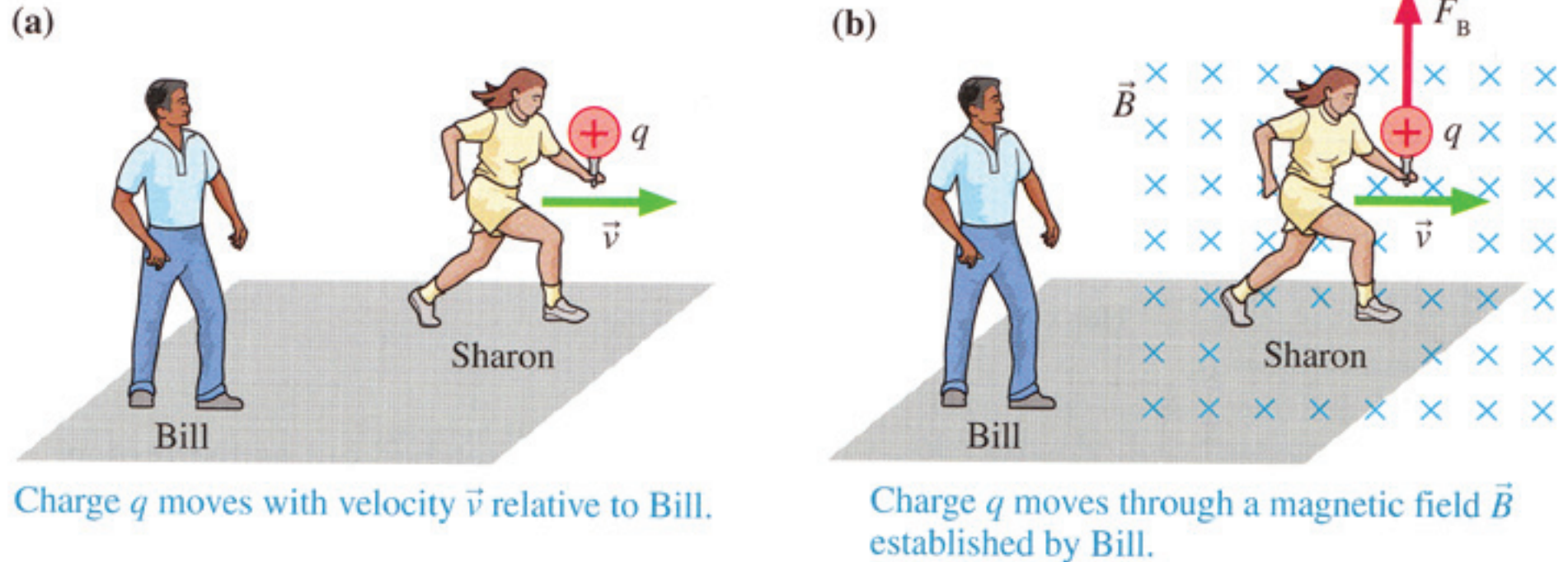
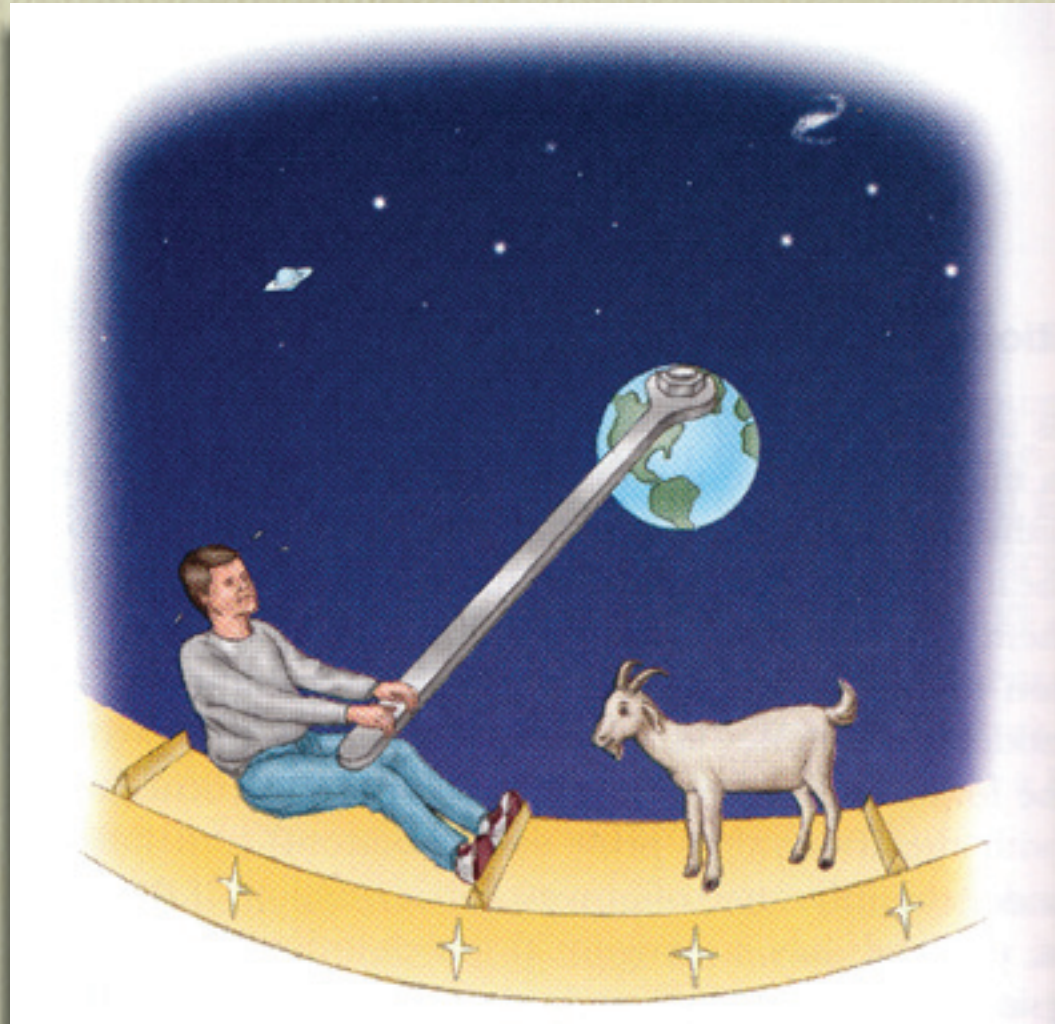


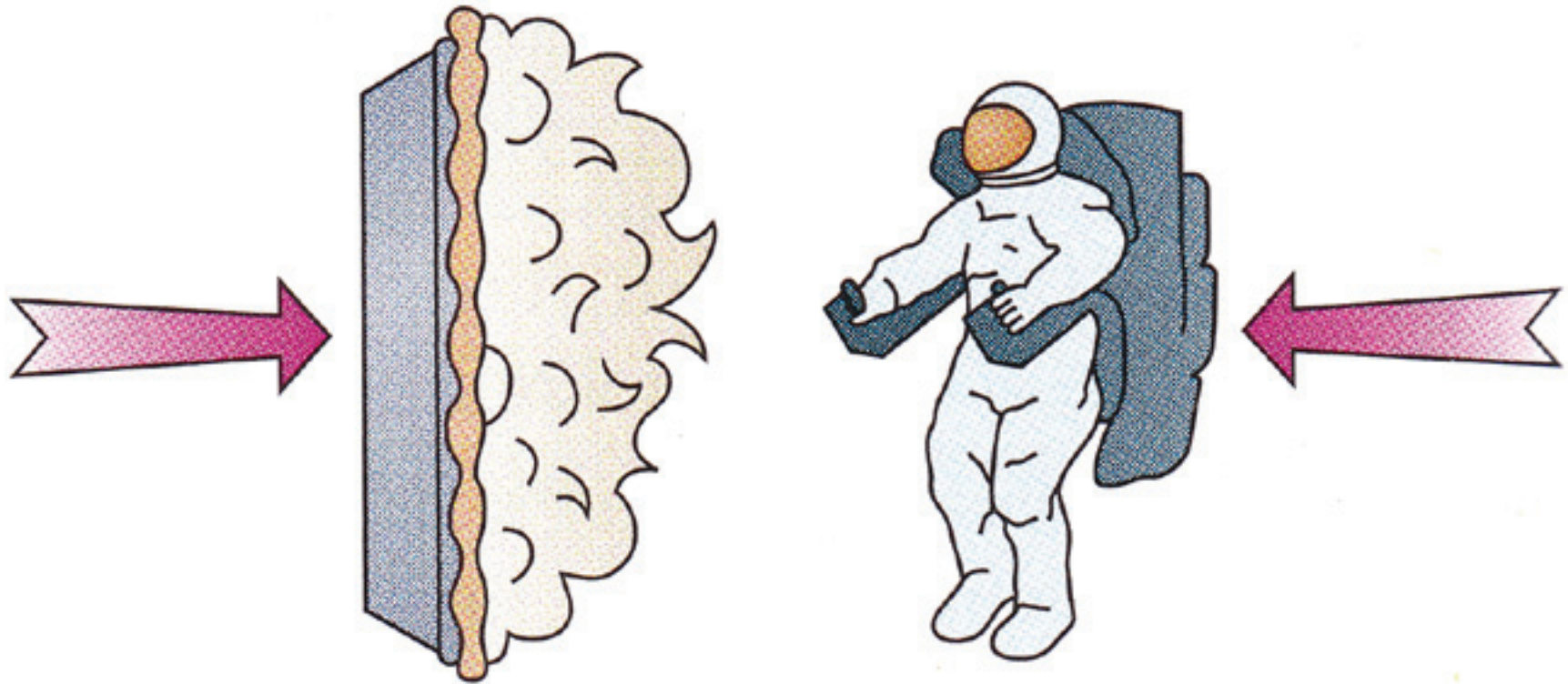
FIGURE 34.6 Sharon carries a charge past Bill.



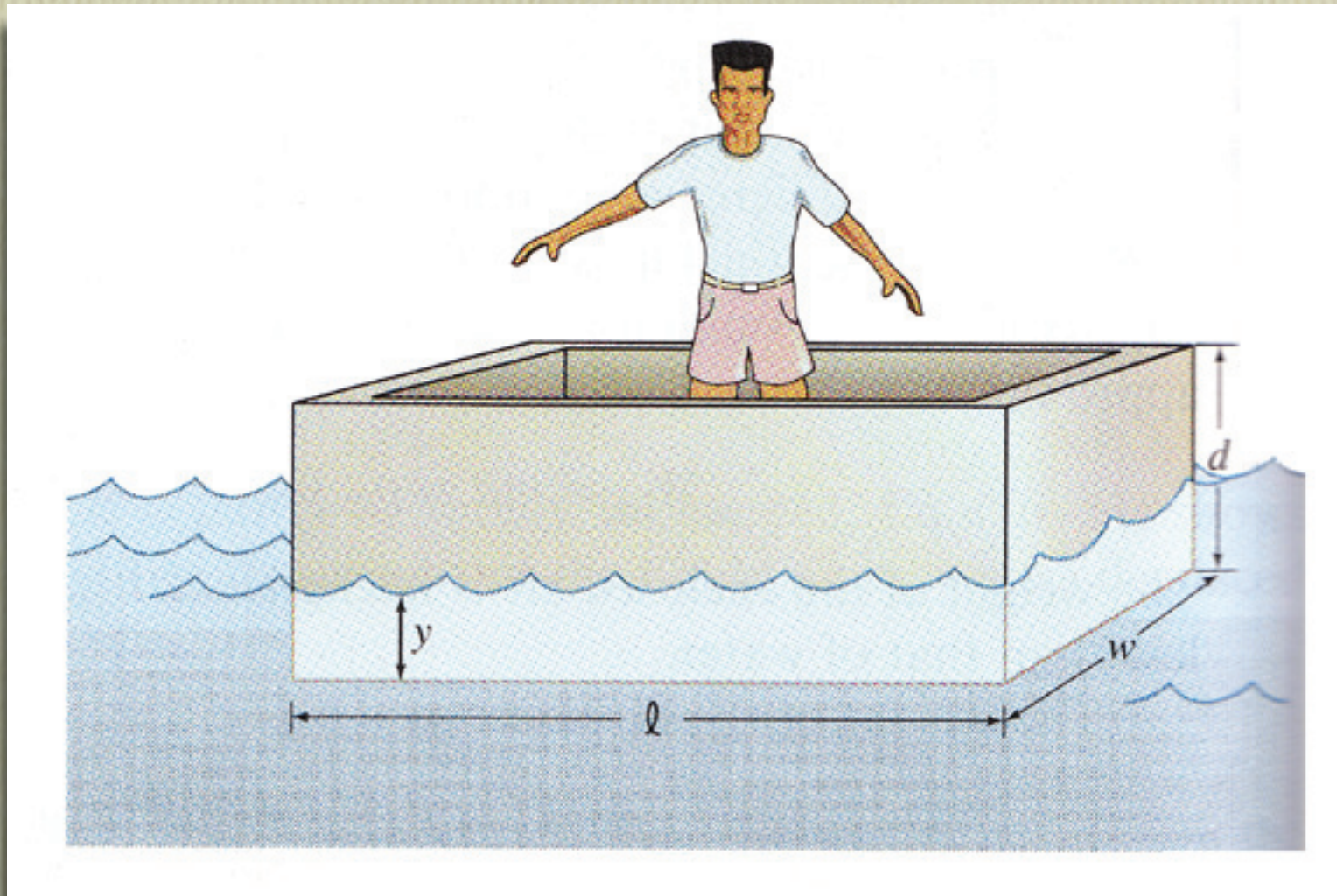
Leisure time activities



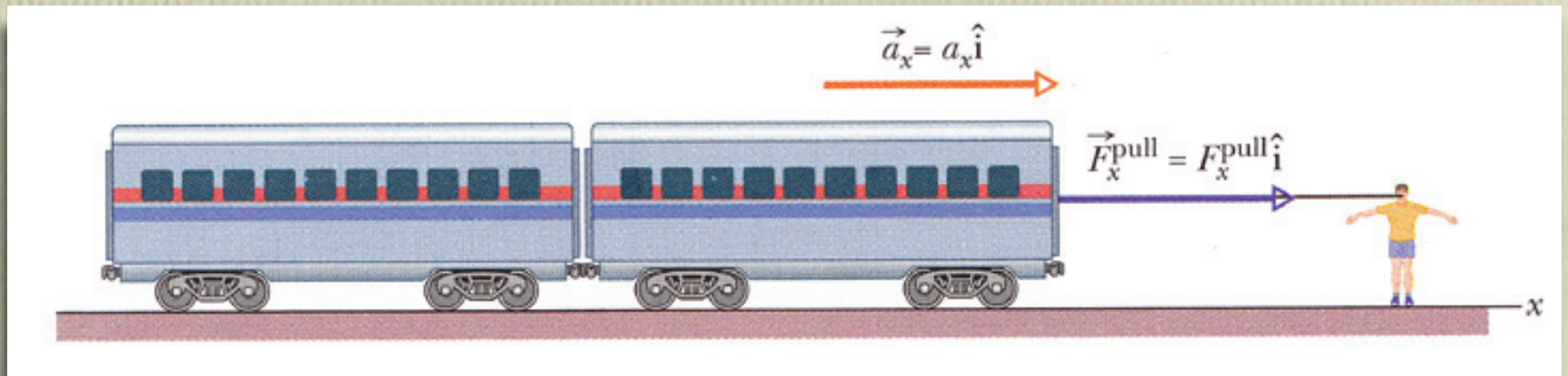
Leisure time activities



Leisure time activities



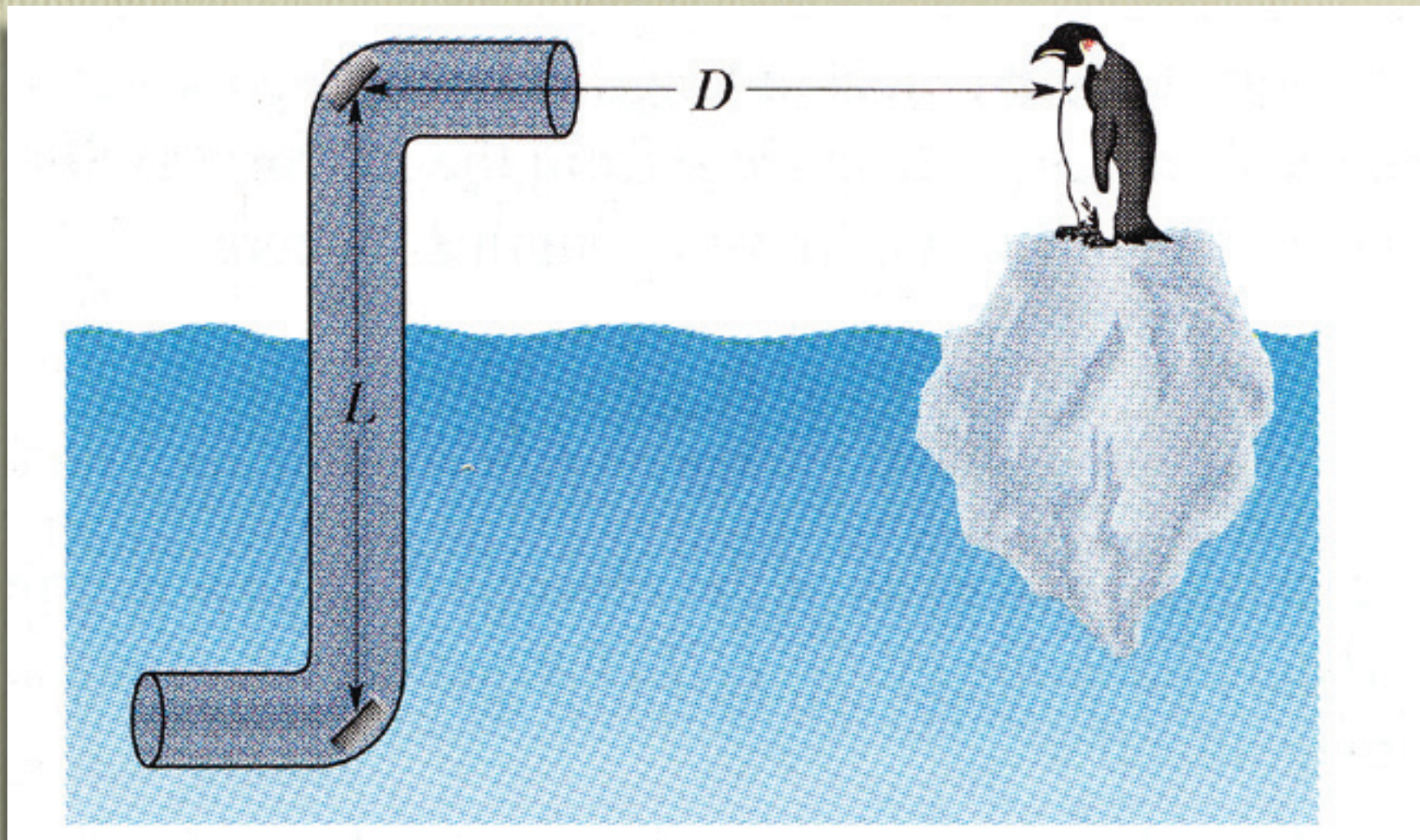
Leisure time activities



Fascinations



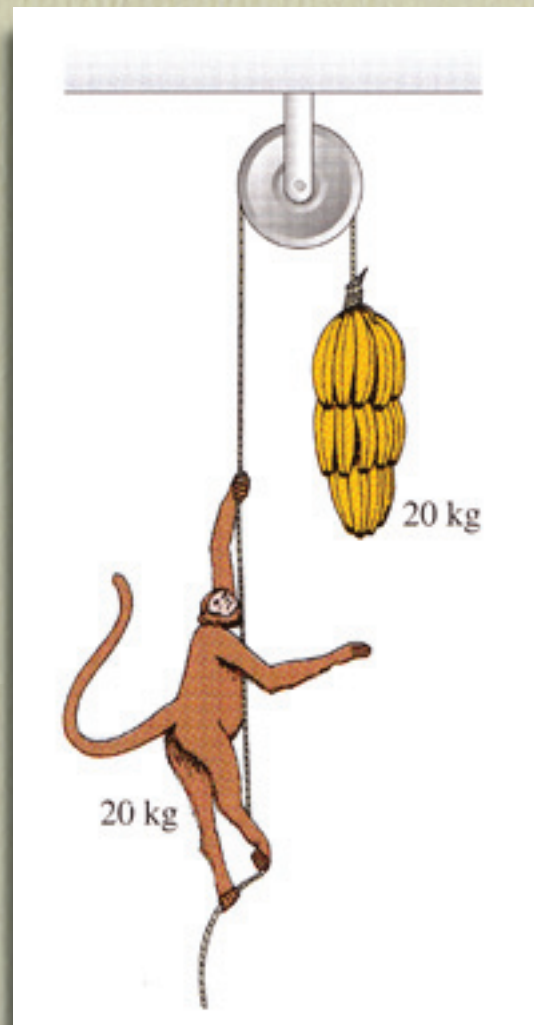
Fascinations



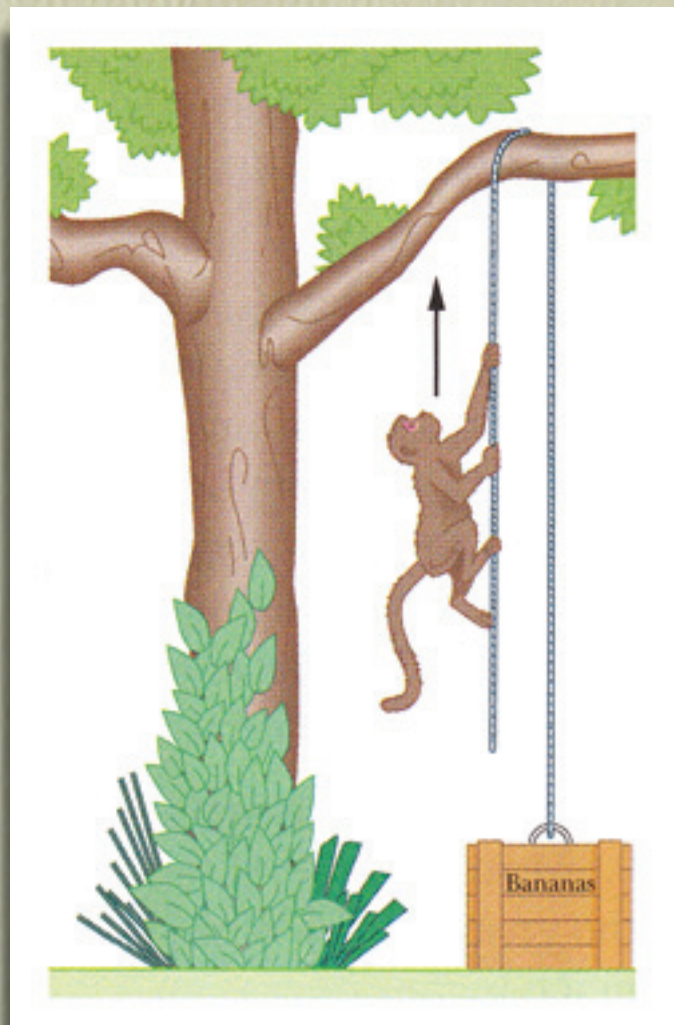
Fascinations



Fascinations



Fascinations



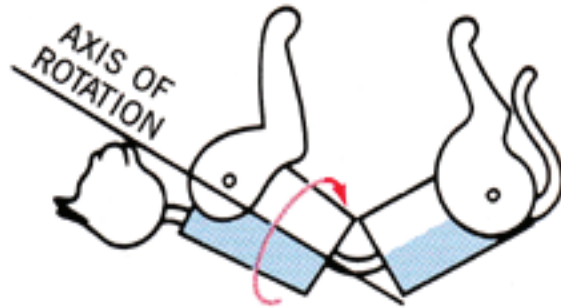
Fascinations



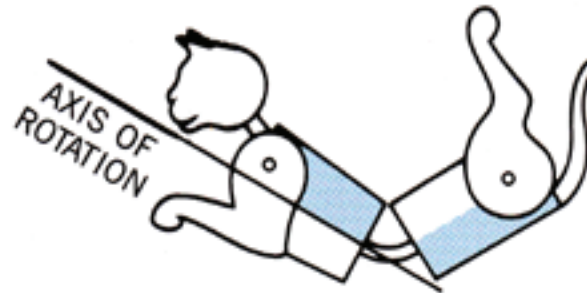
Spherical cows and...



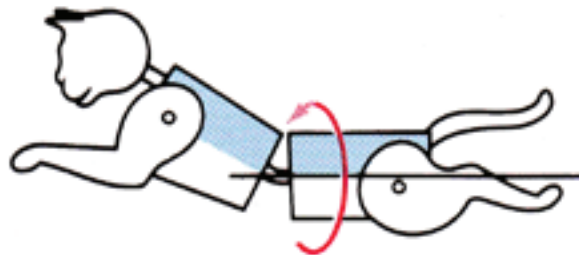
Spherical cows and...



POSITION 1. Flexion, at the waist.
Fore-part begins to turn.



POSITION 2. Fore-part rotated through
180°.



POSITION 3. Rear end rotating on
fore-end.



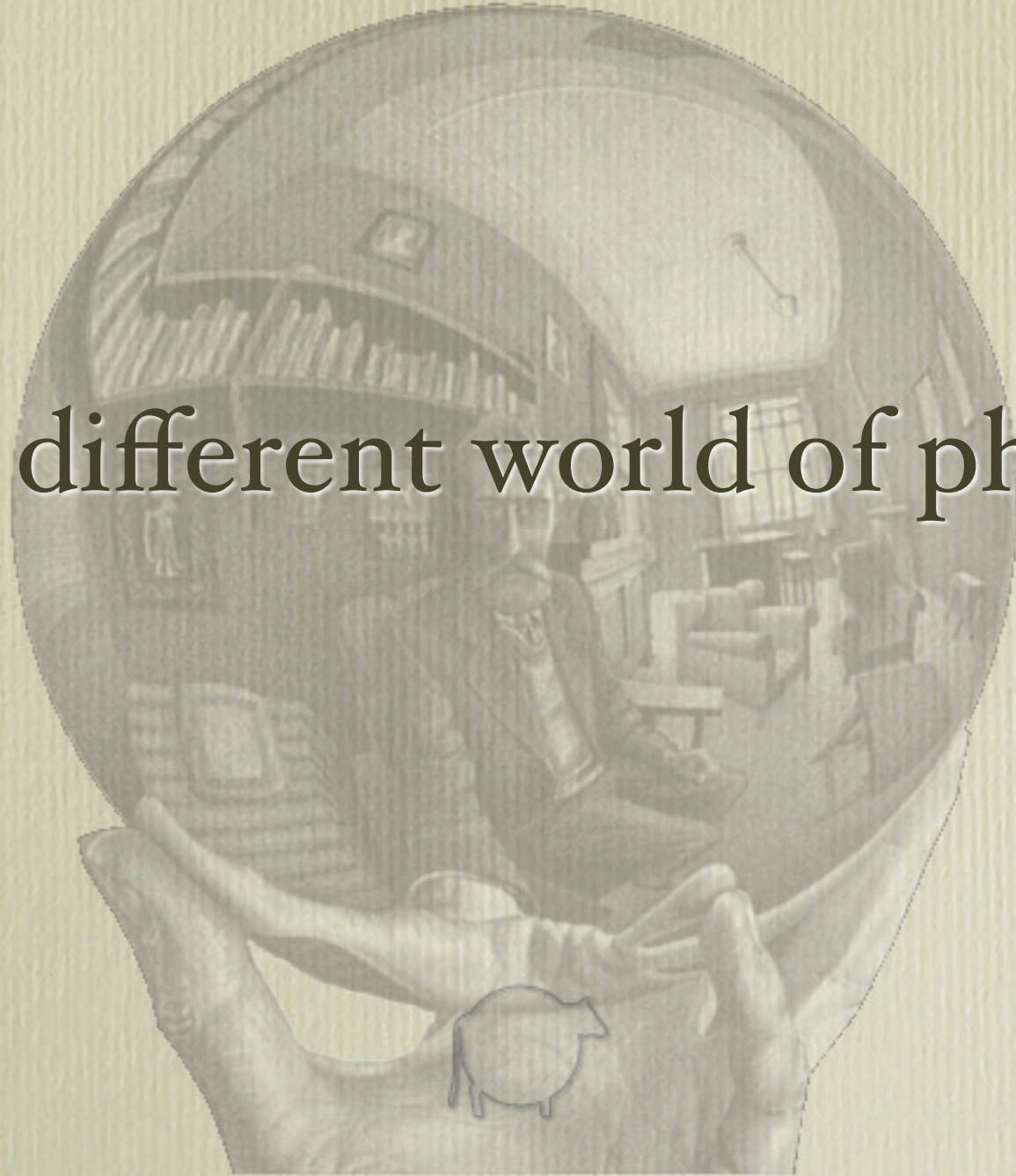
POSITION 4. Back arched. Legs
extended for landing.
Tail circling for "trim."



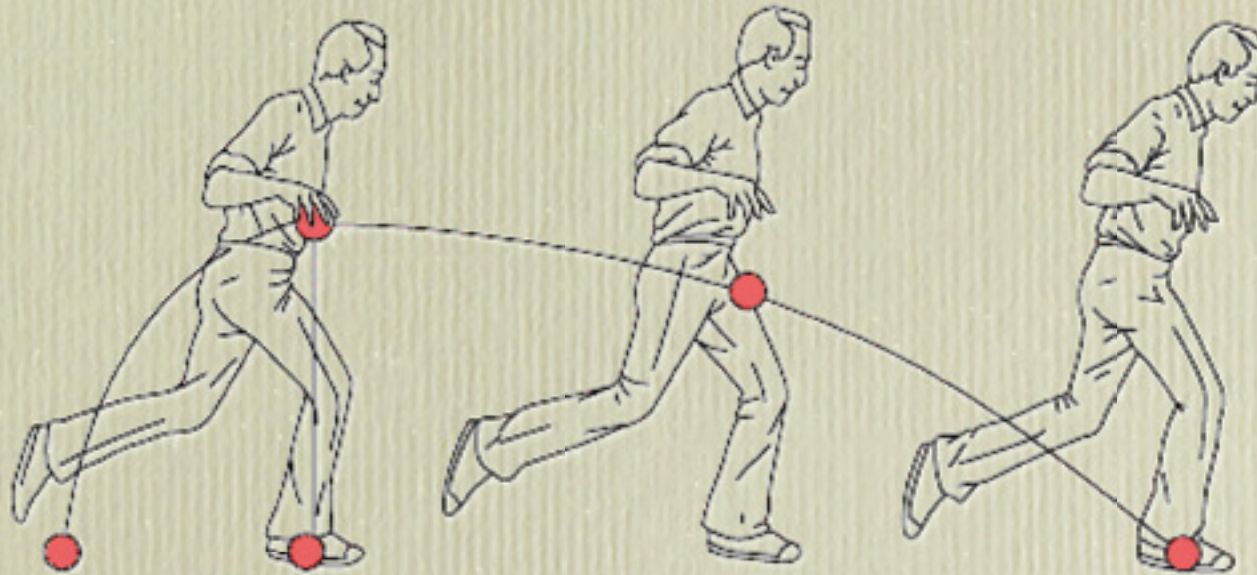
Silly art makes us look weird



The different world of physics



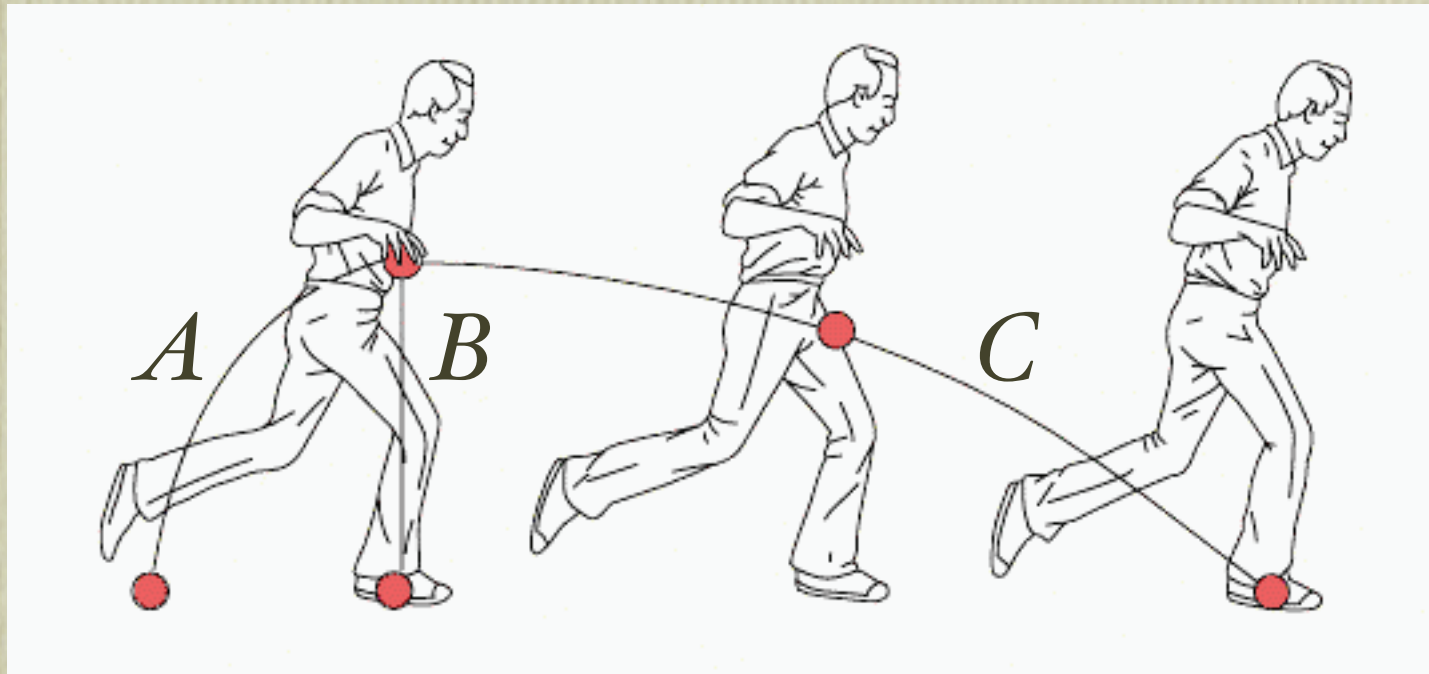
Parabolic motion



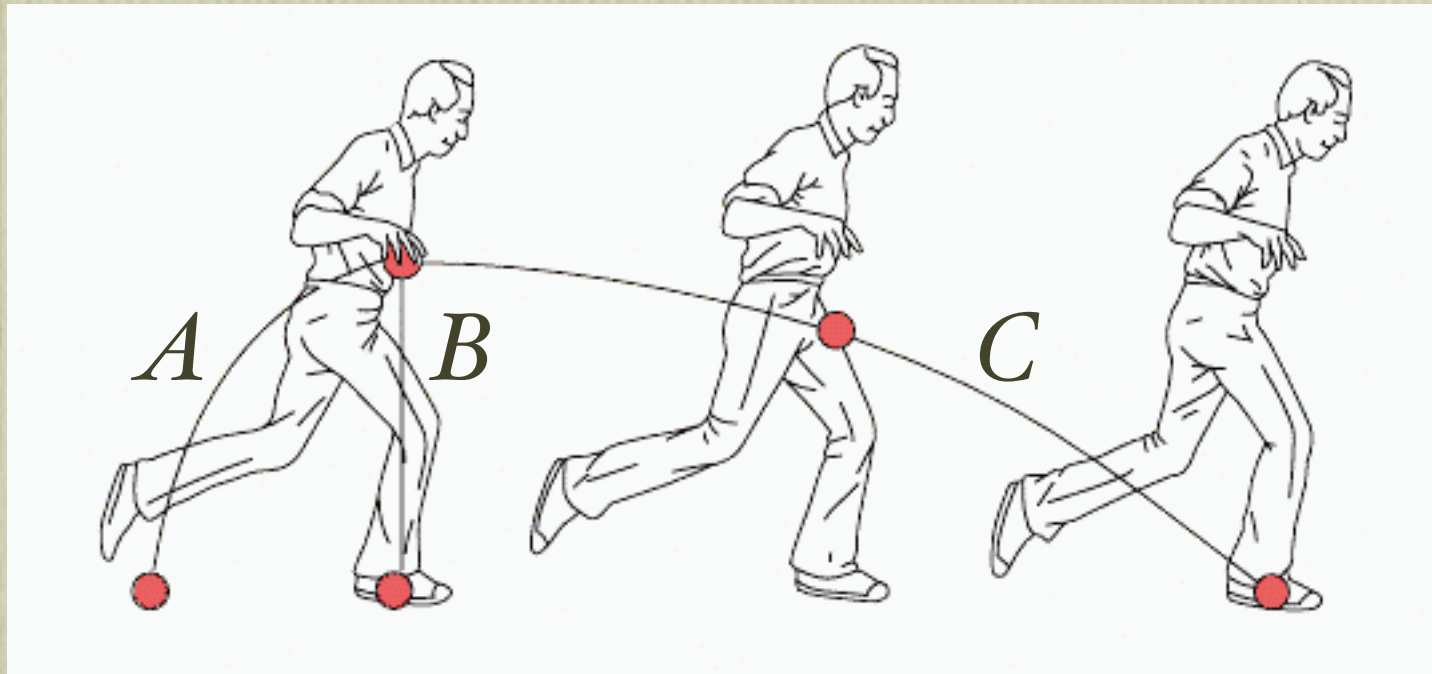
M. McCloskey, *Intuitive Physics*
Scientific American 248 (1983), pp. 122-130



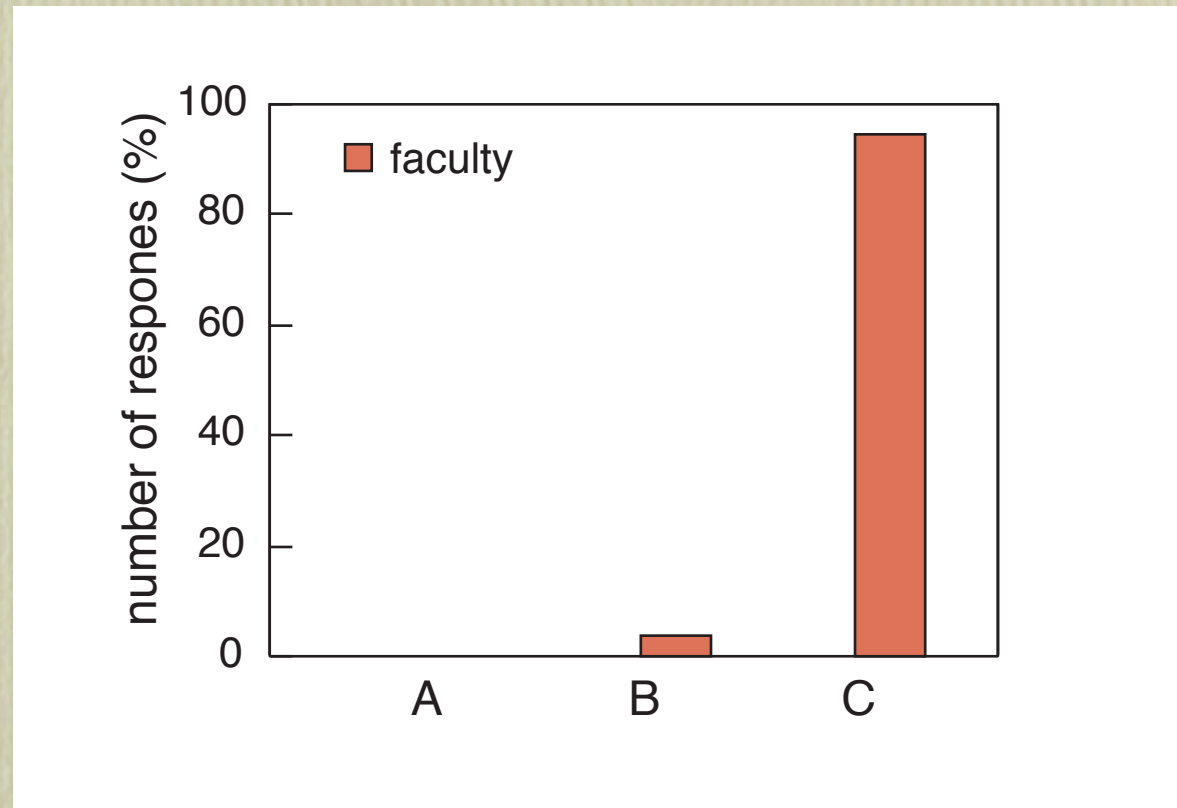
Which of the three paths shown (*A*–*C*) most closely resembles the path taken by the ball?



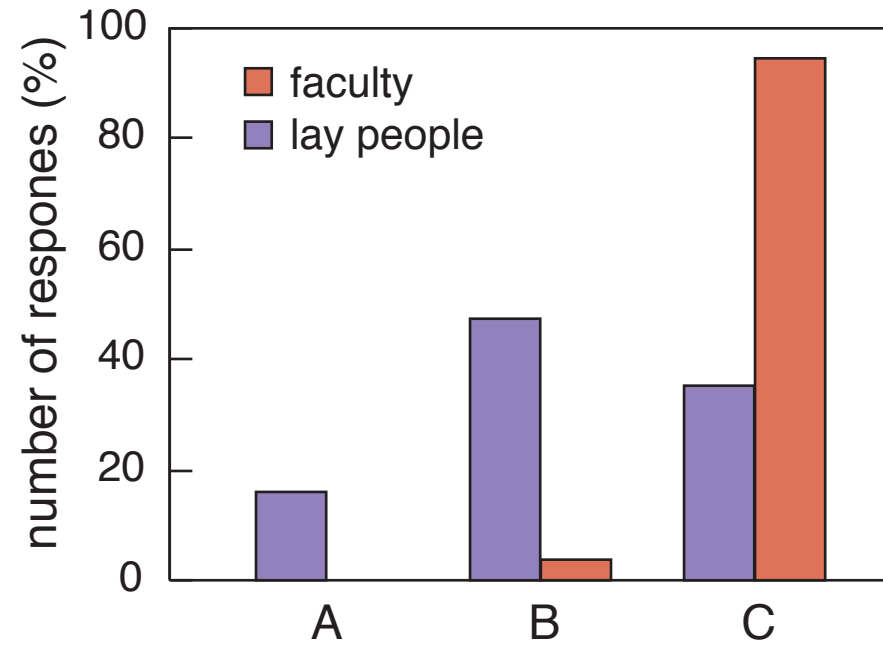
Which trajectory does the lay person select?



Predictions



Predictions



“The ball can’t go that far forward.”



“My eyes can’t lie; I’ve seen B.”



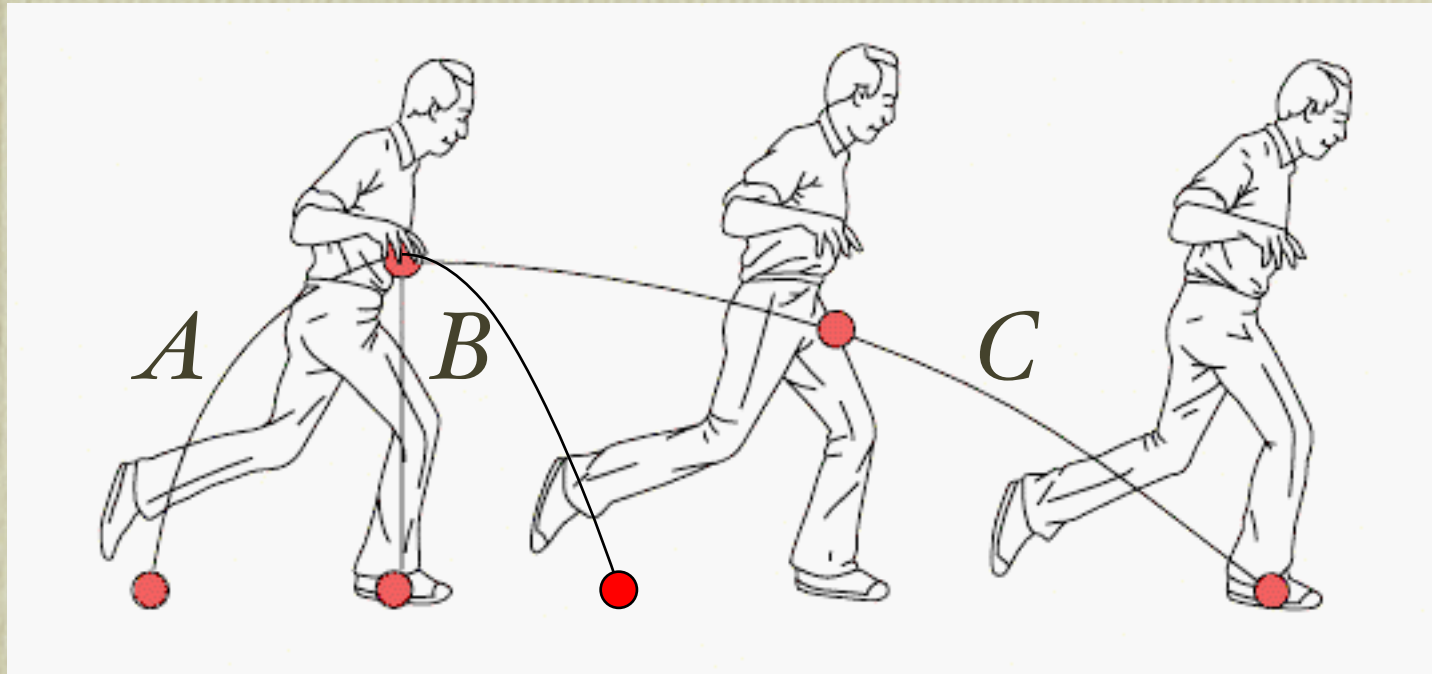
“I’d like to see it.”



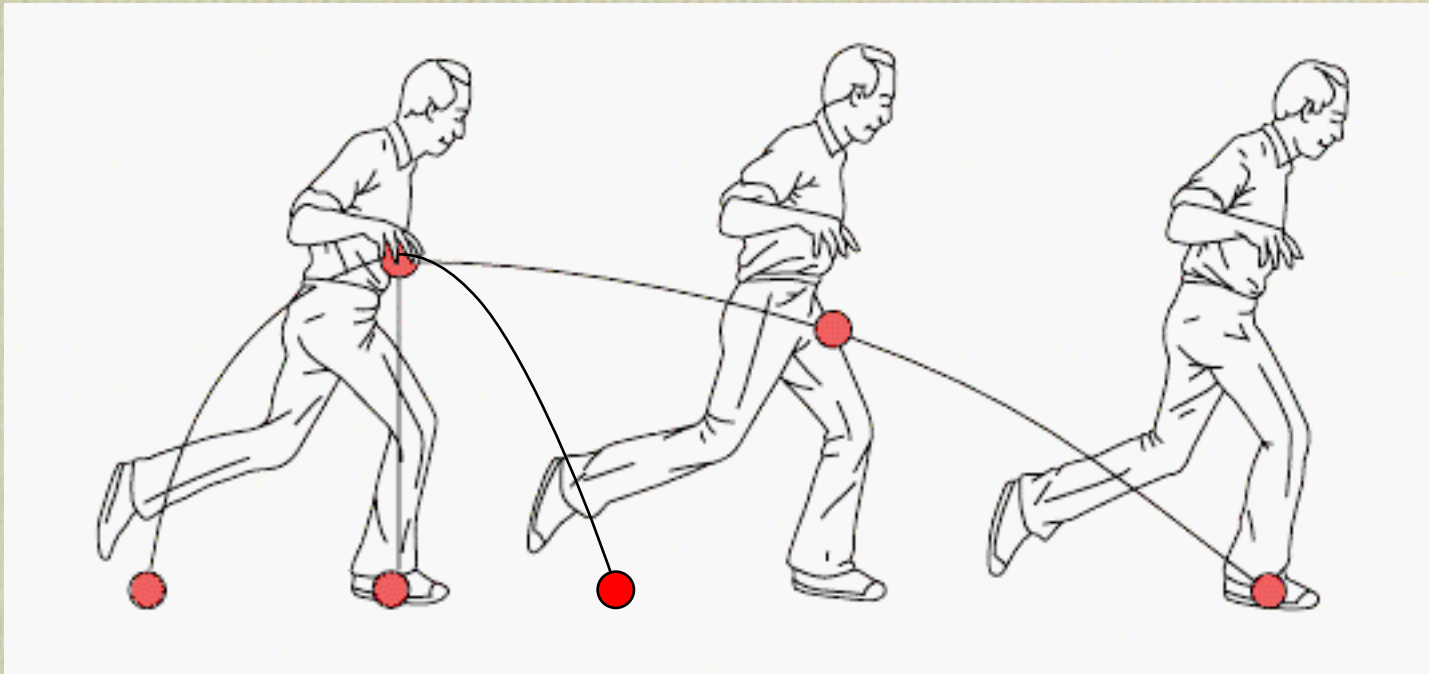
“Give me a proof.”



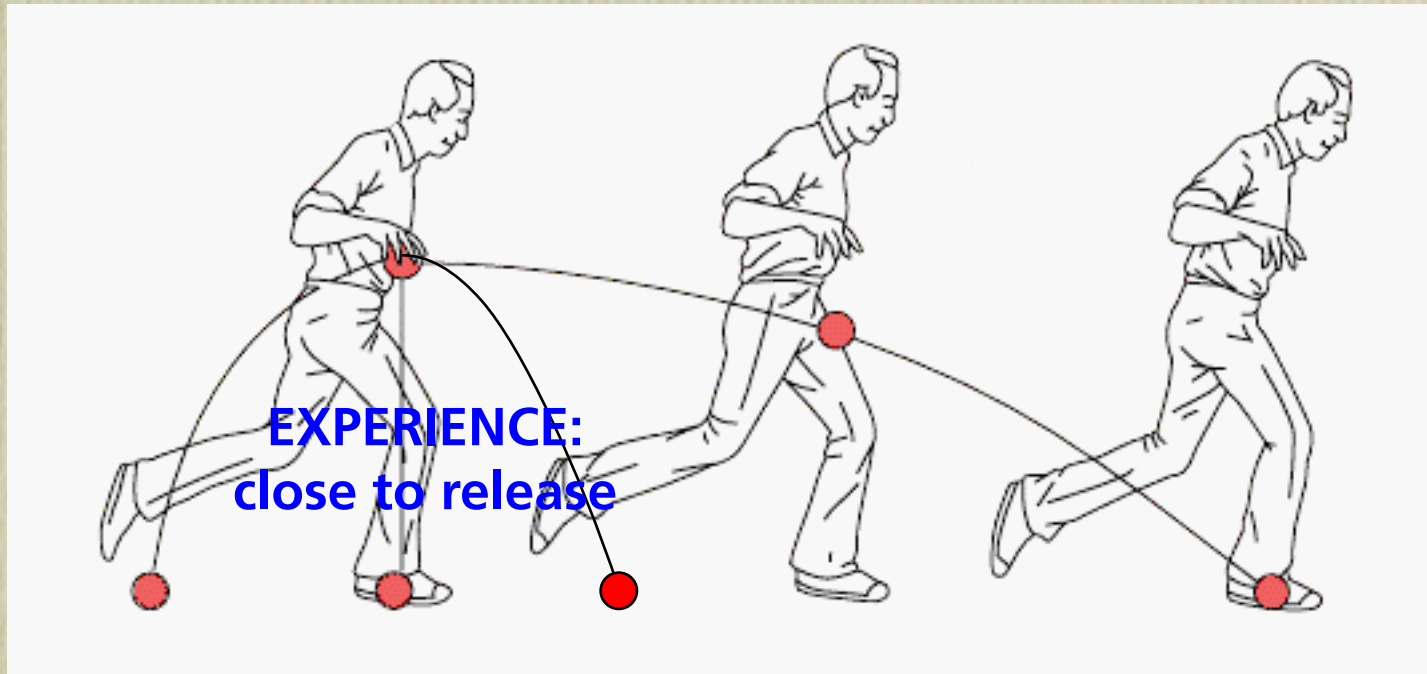
B is closest!



The lay person



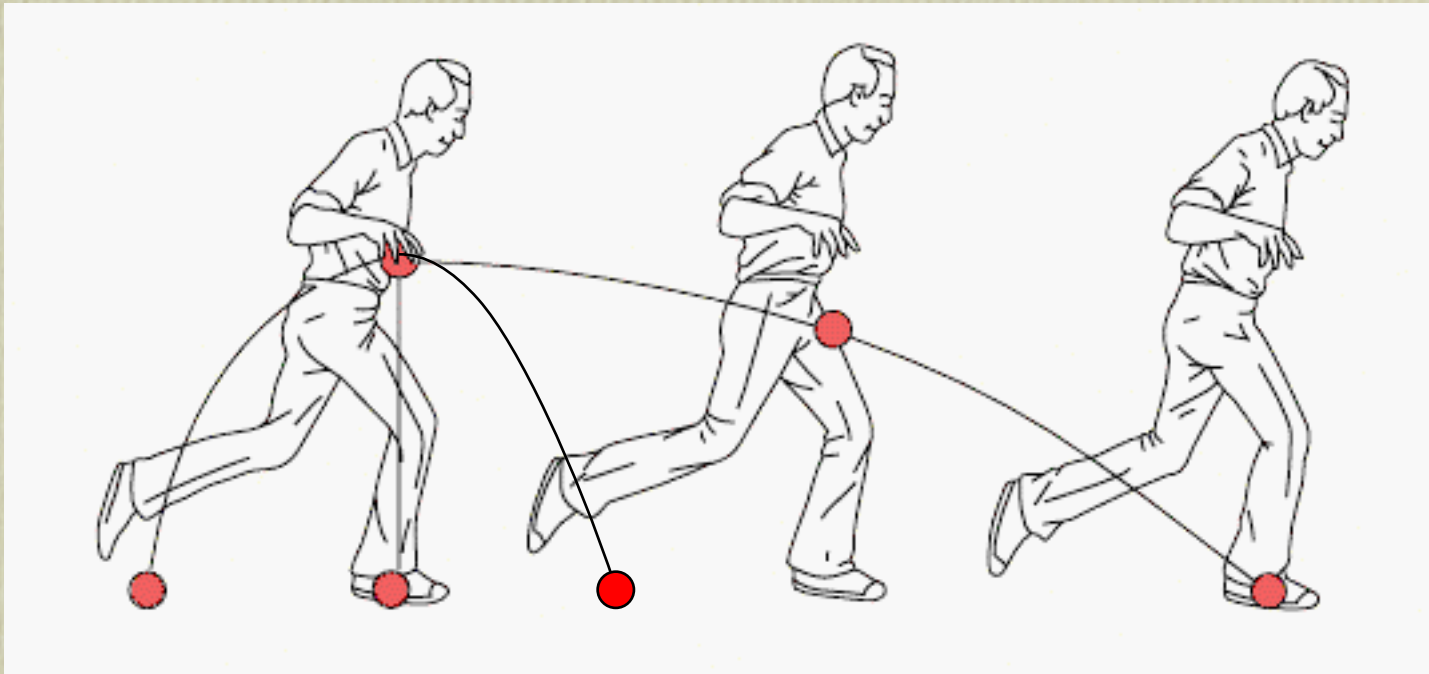
The lay person



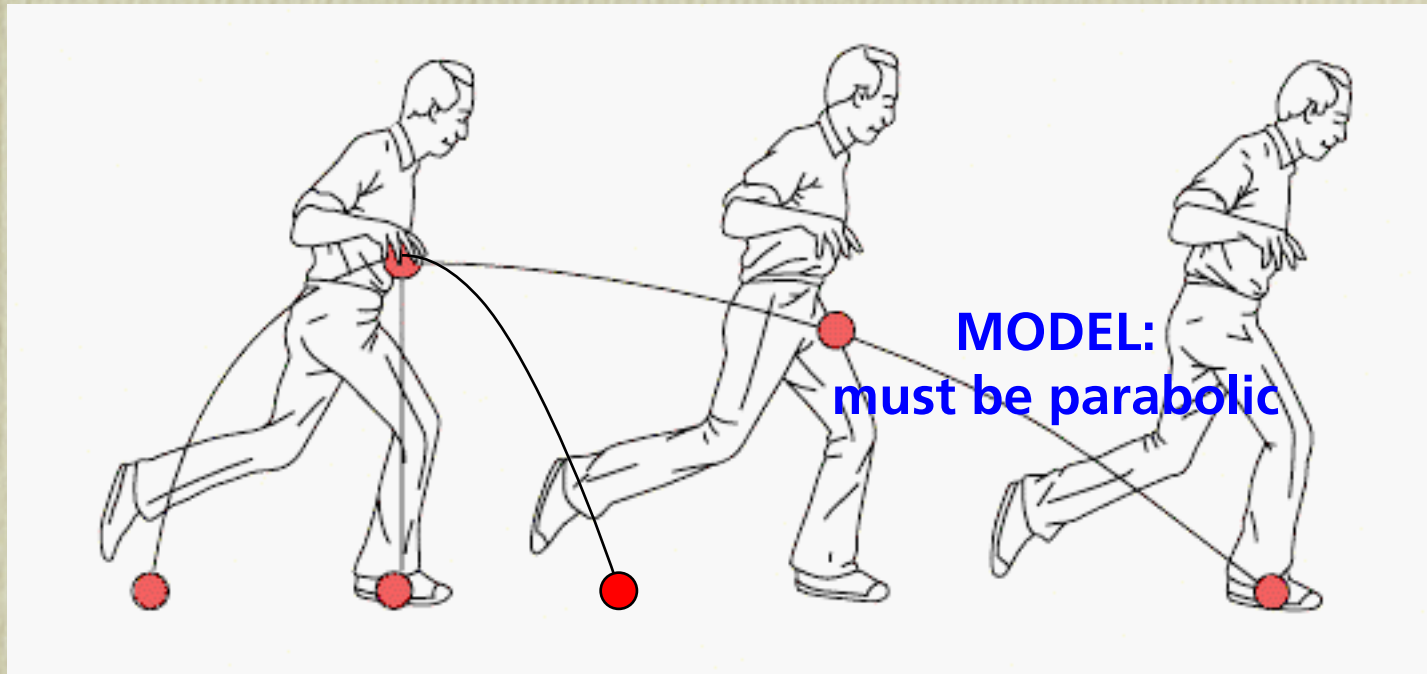
Choice dictated by experience



The physicist



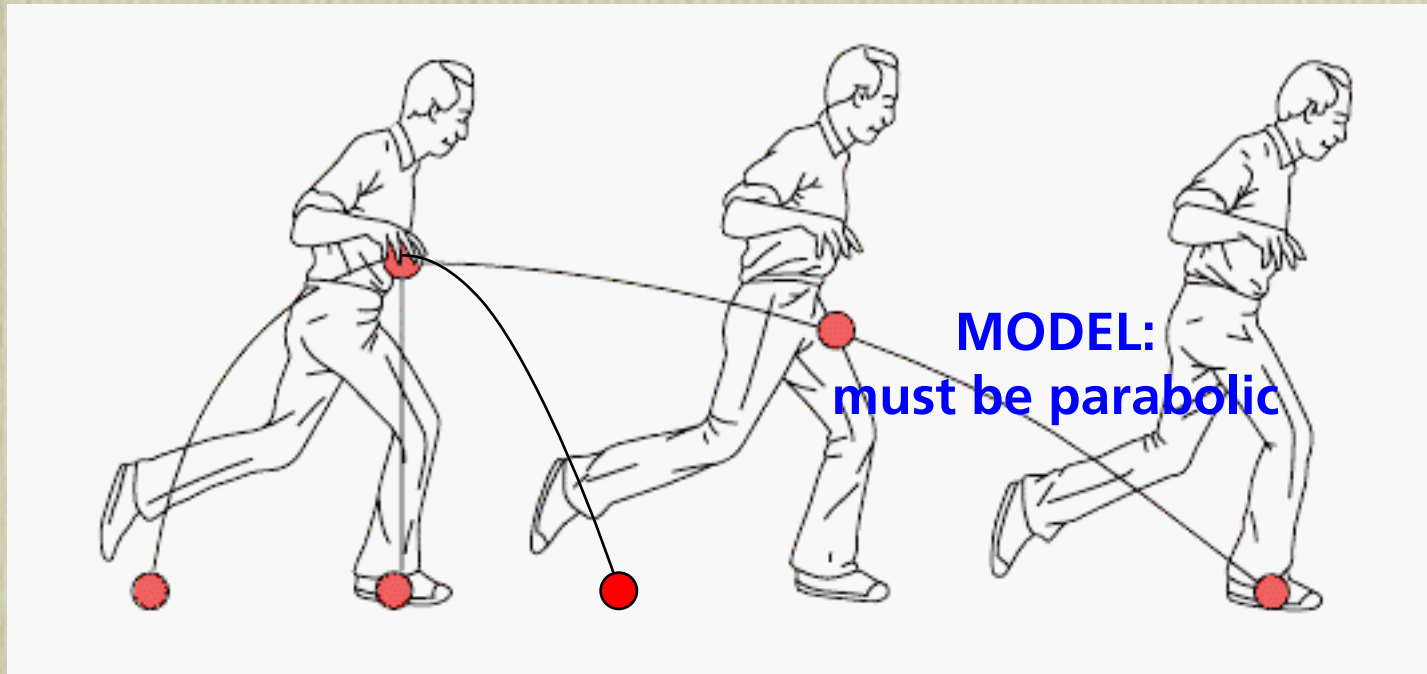
The physicist



Choice dictated by the model...



The physicist



...even if representation of model is *wrong*



“Knowing the answer? Or should I stick to my intuition? My intuition *still* tells me that B must be the closest to how it works. But I know perfectly well that path C *must* be the right answer.”



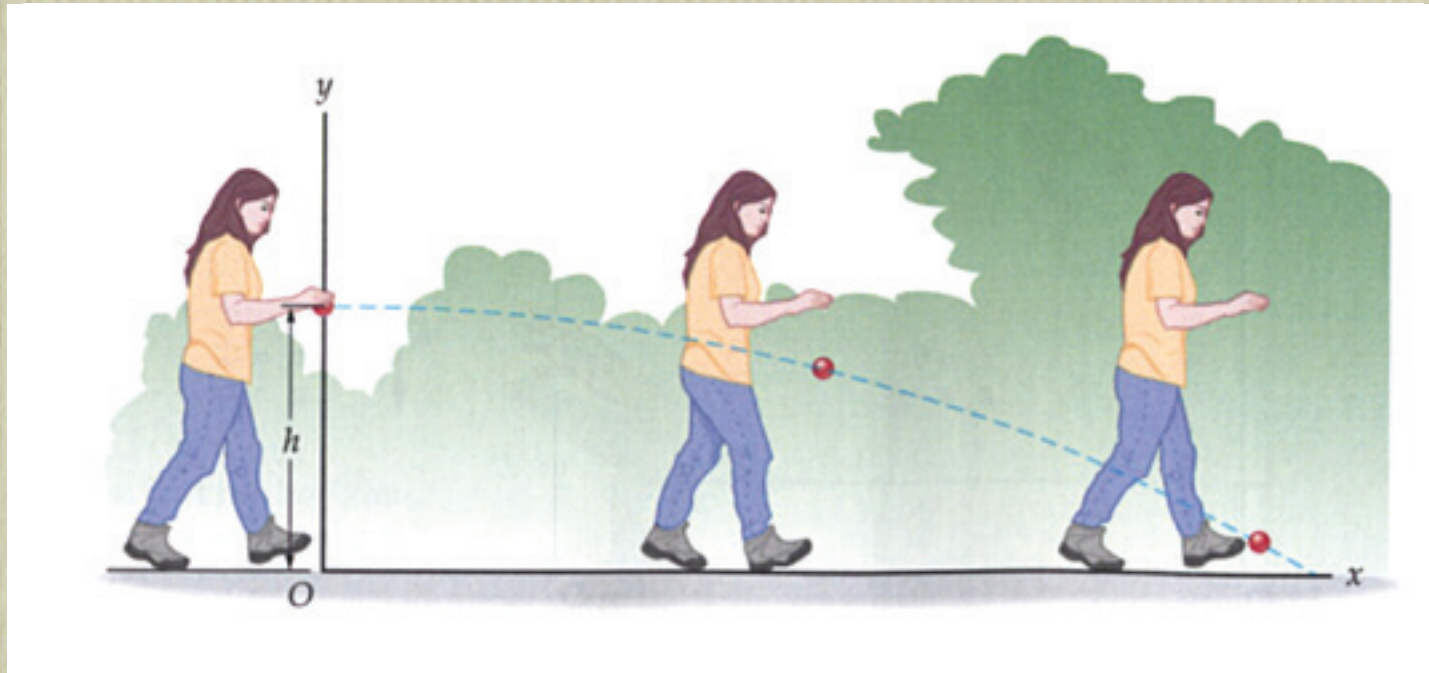
Model overrides experience



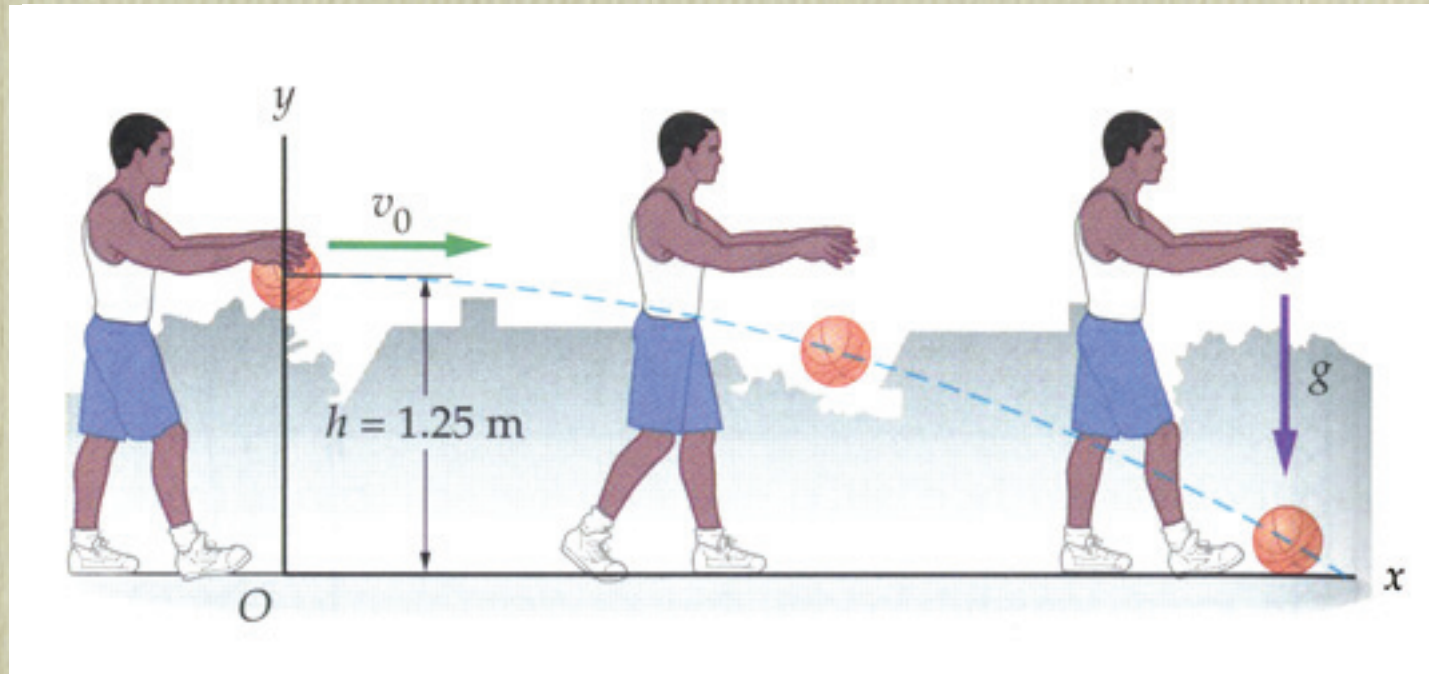
What do our students see?



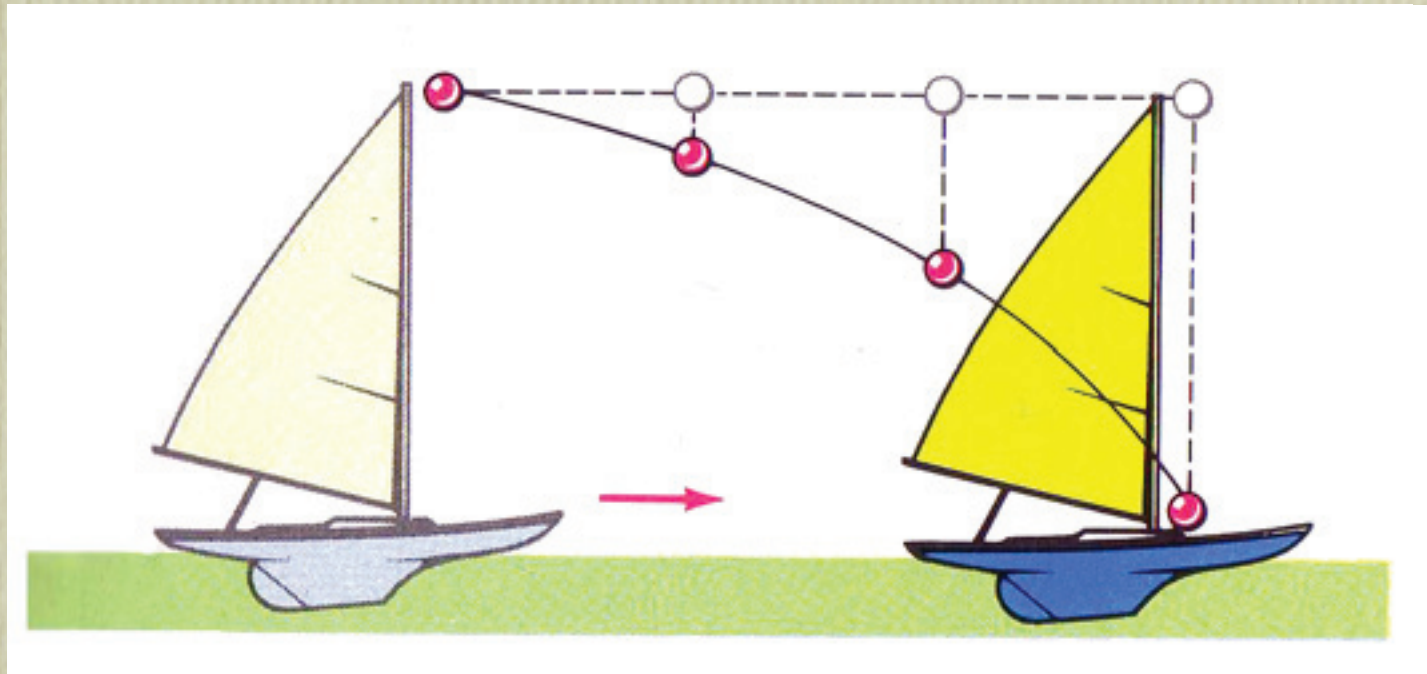
Microgravity



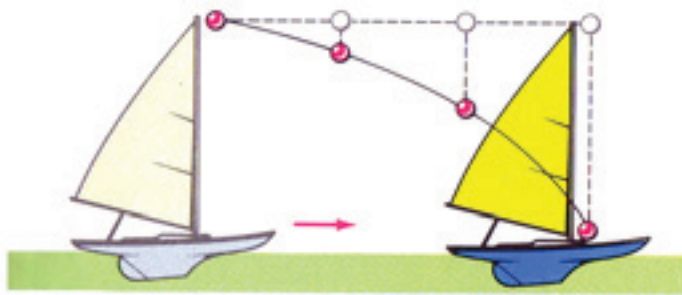
Microgravity



Microgravity



Microgravity



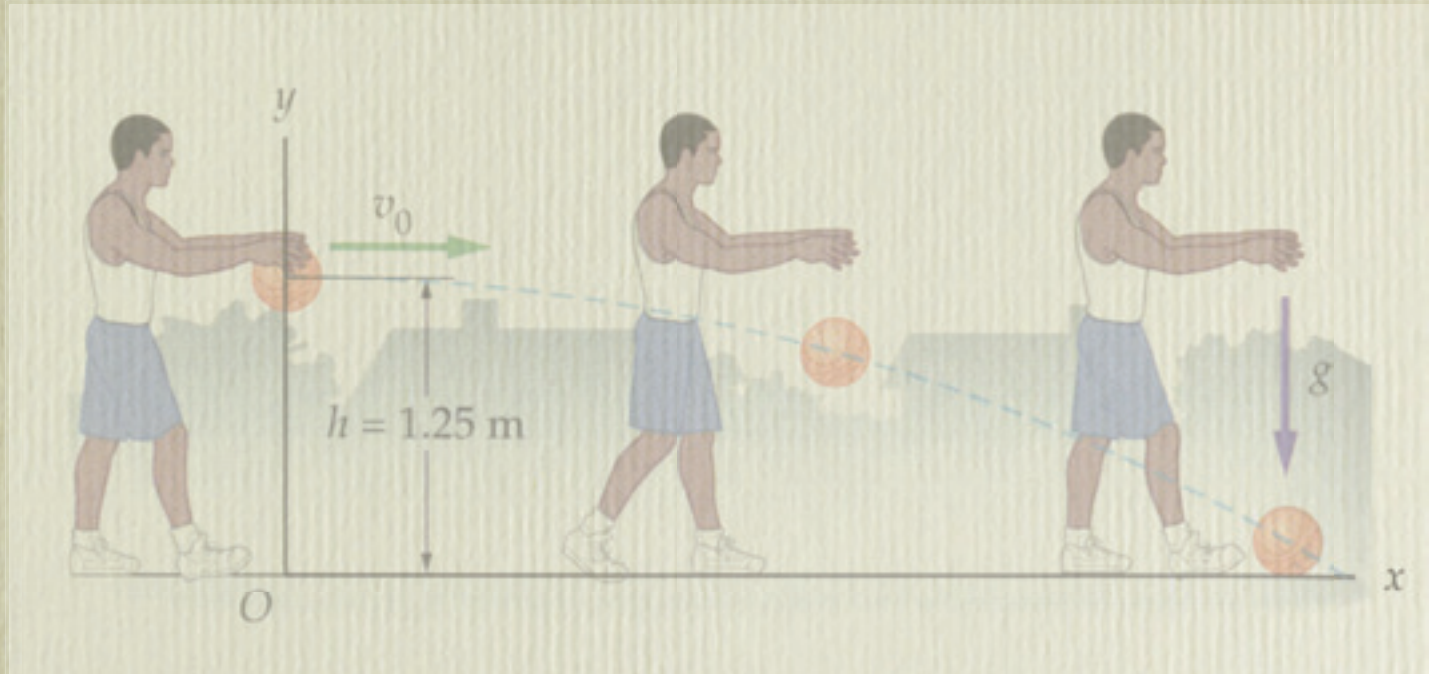
(a)



(b)

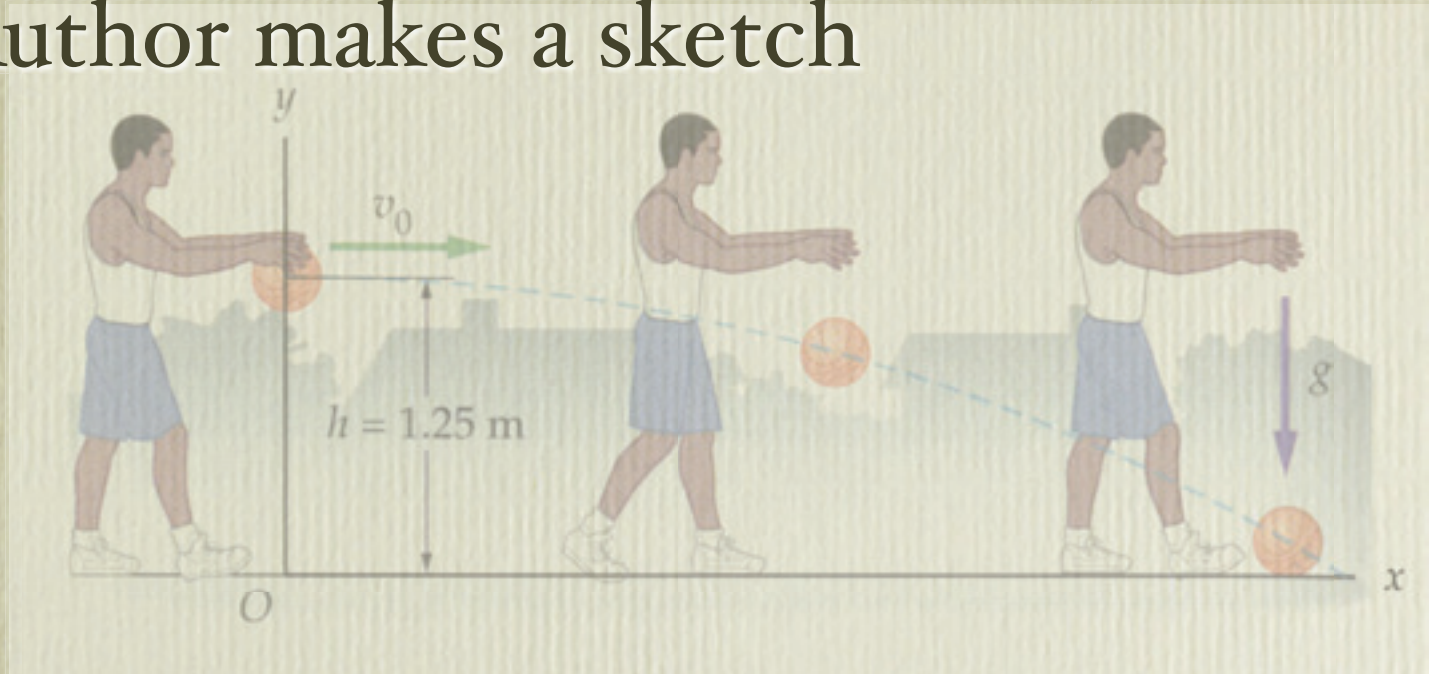


Microgravity



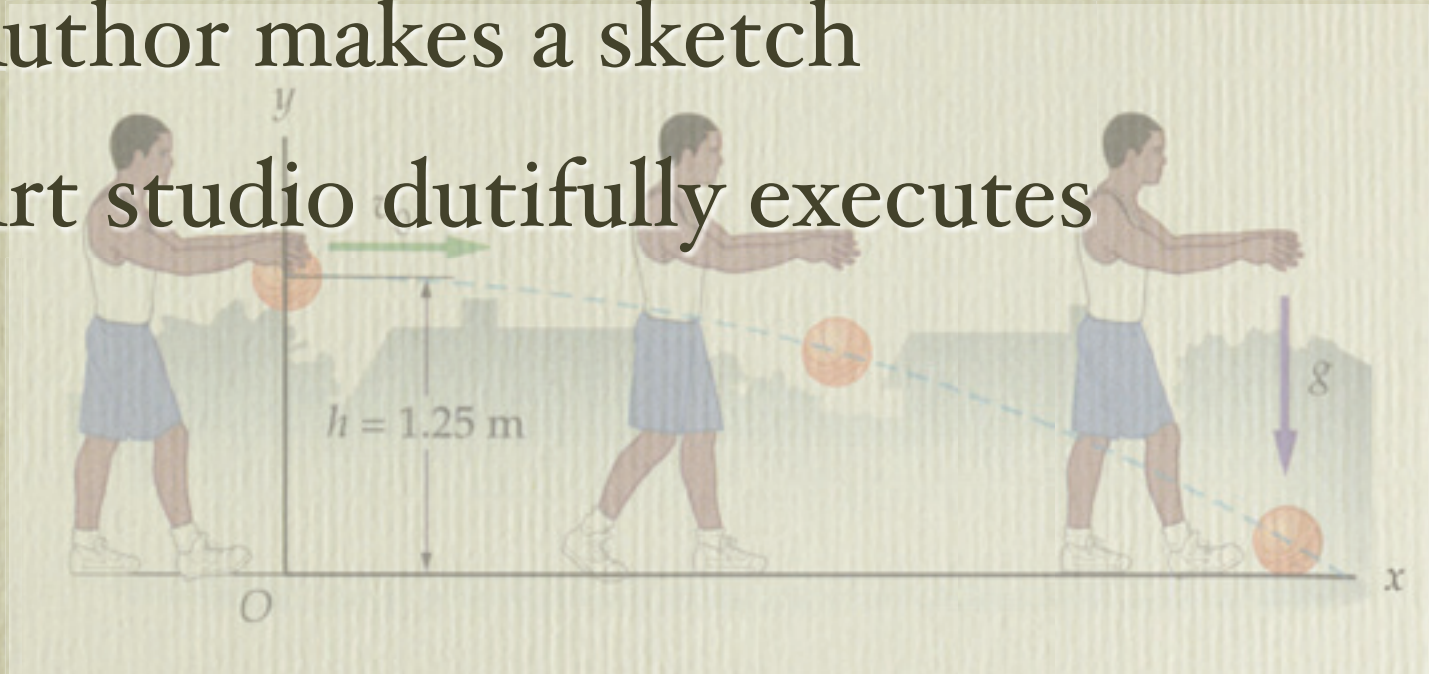
Microgravity

- Author makes a sketch



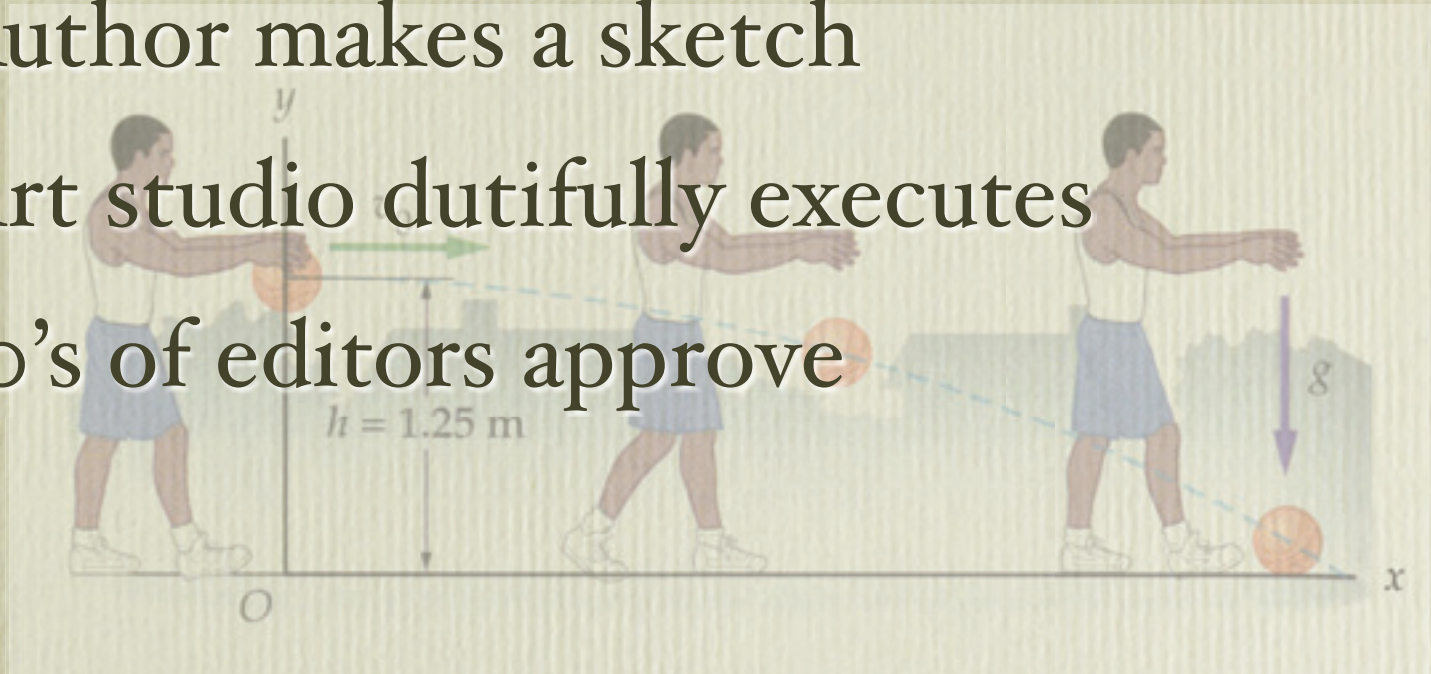
Microgravity

- Author makes a sketch
- Art studio dutifully executes



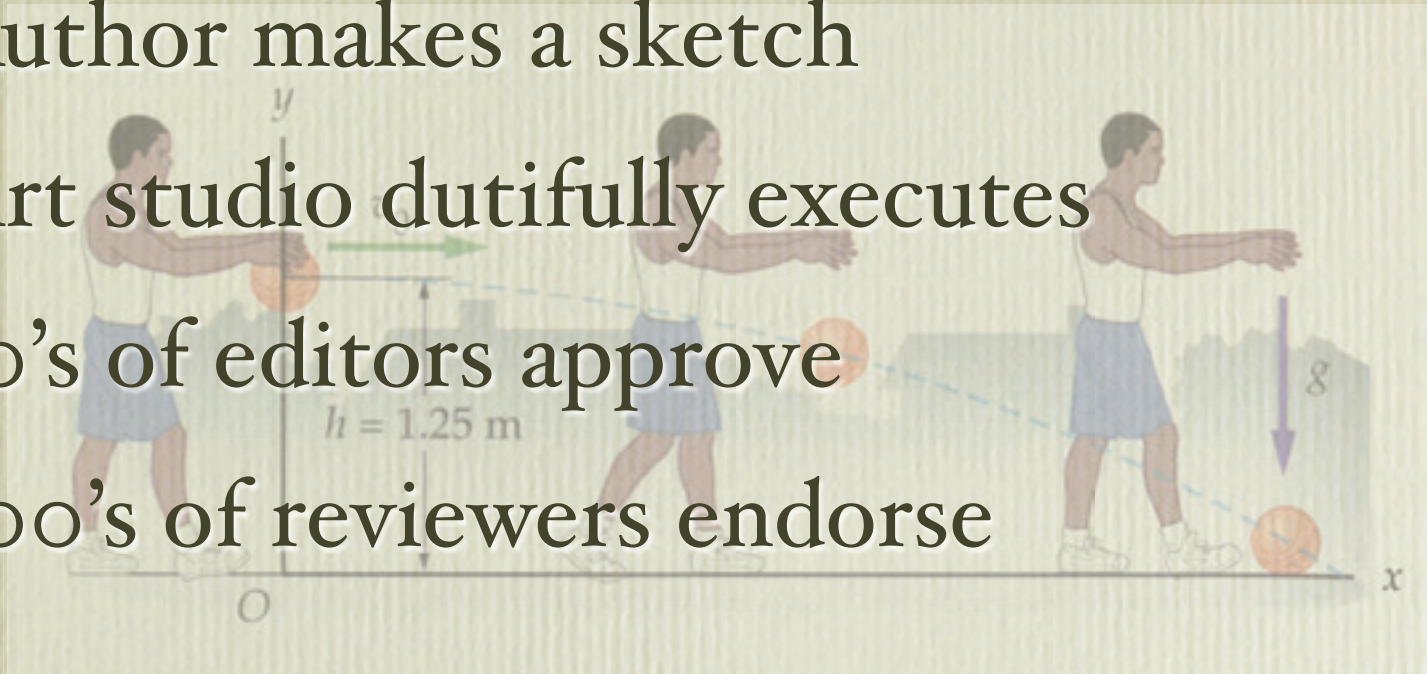
Microgravity

- Author makes a sketch
- Art studio dutifully executes
- 10's of editors approve



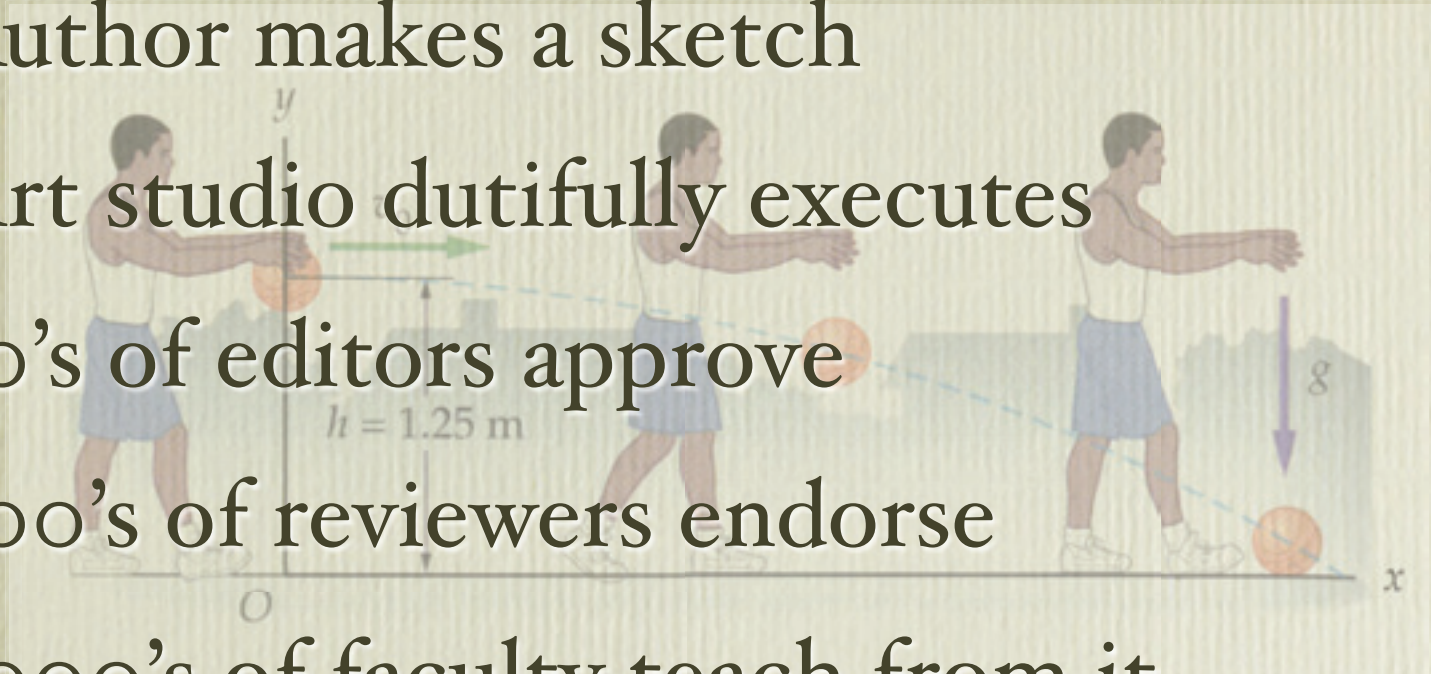
Microgravity

- Author makes a sketch
- Art studio dutifully executes
- 10's of editors approve
- 100's of reviewers endorse



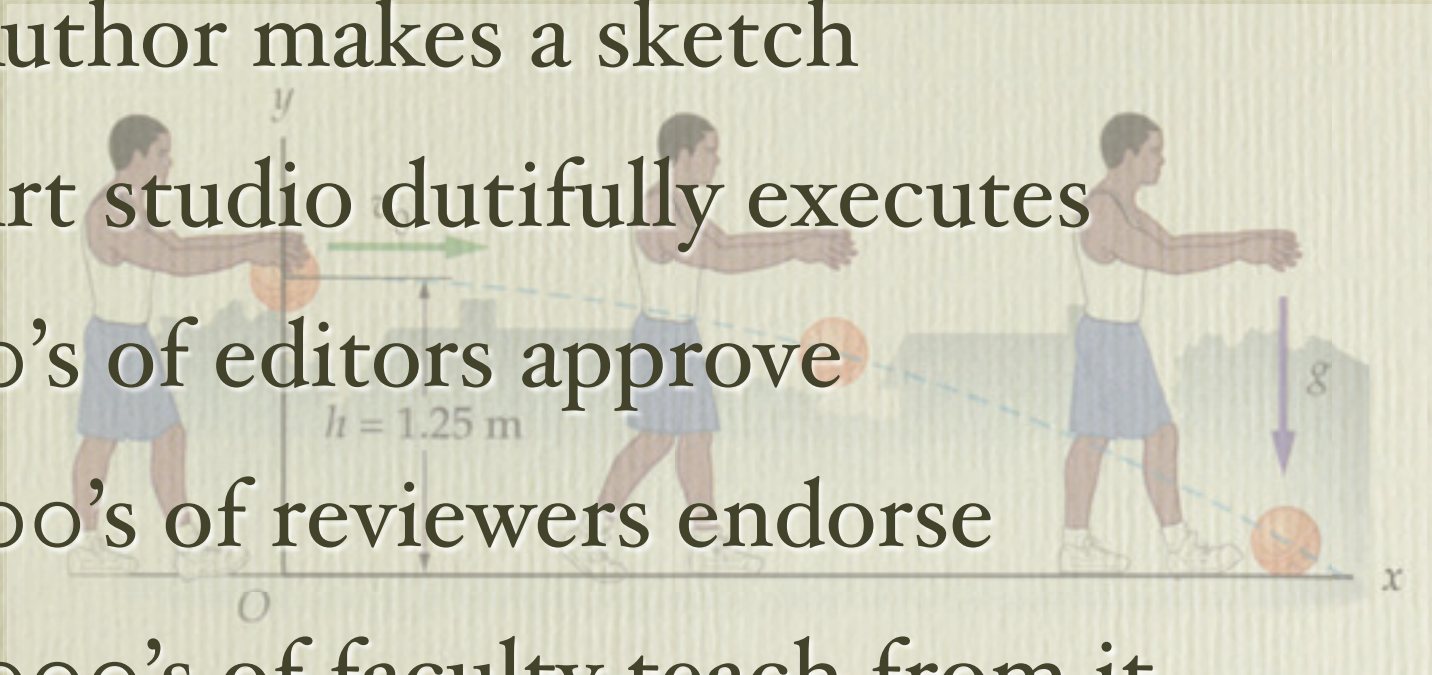
Microgravity

- Author makes a sketch
- Art studio dutifully executes
- 10's of editors approve
- 100's of reviewers endorse
- 1000's of faculty teach from it



Microgravity

- Author makes a sketch
- Art studio dutifully executes
- 10's of editors approve
- 100's of reviewers endorse
- 1000's of faculty teach from it
- 10,000's of students grudgingly regurgitate

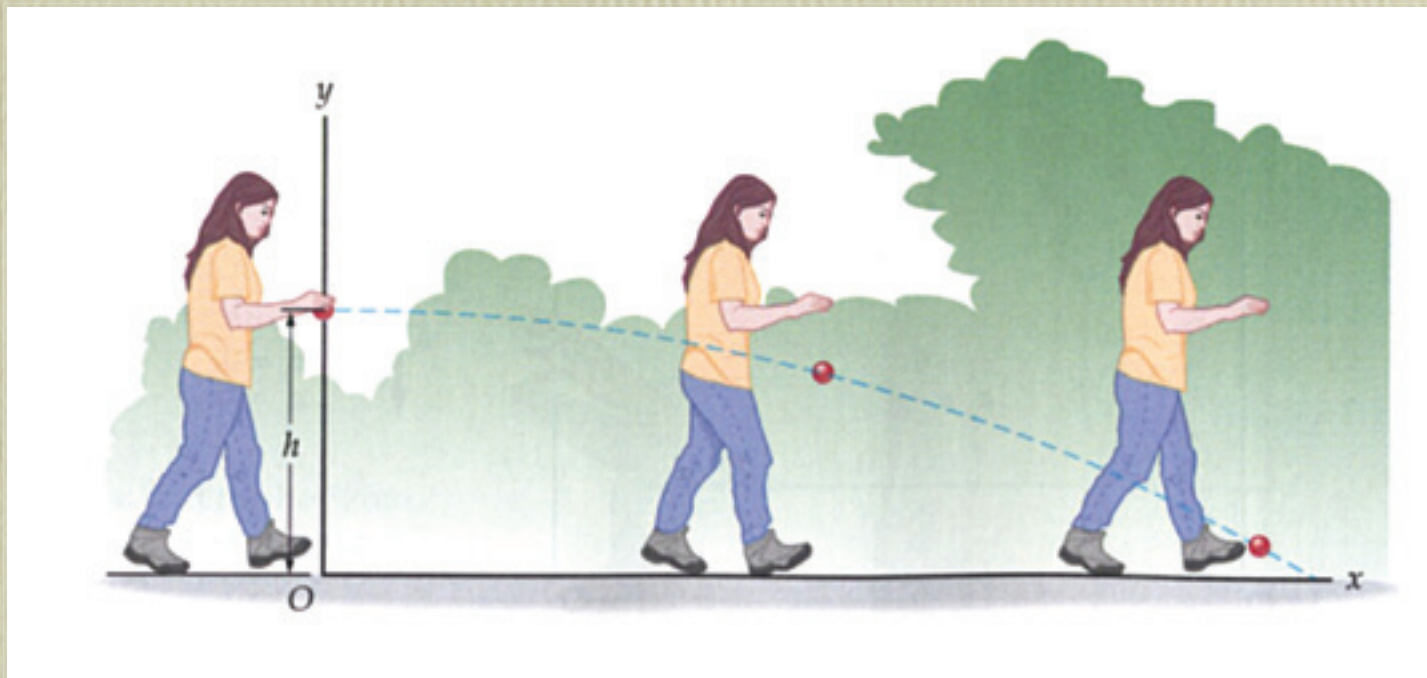


Physics is...

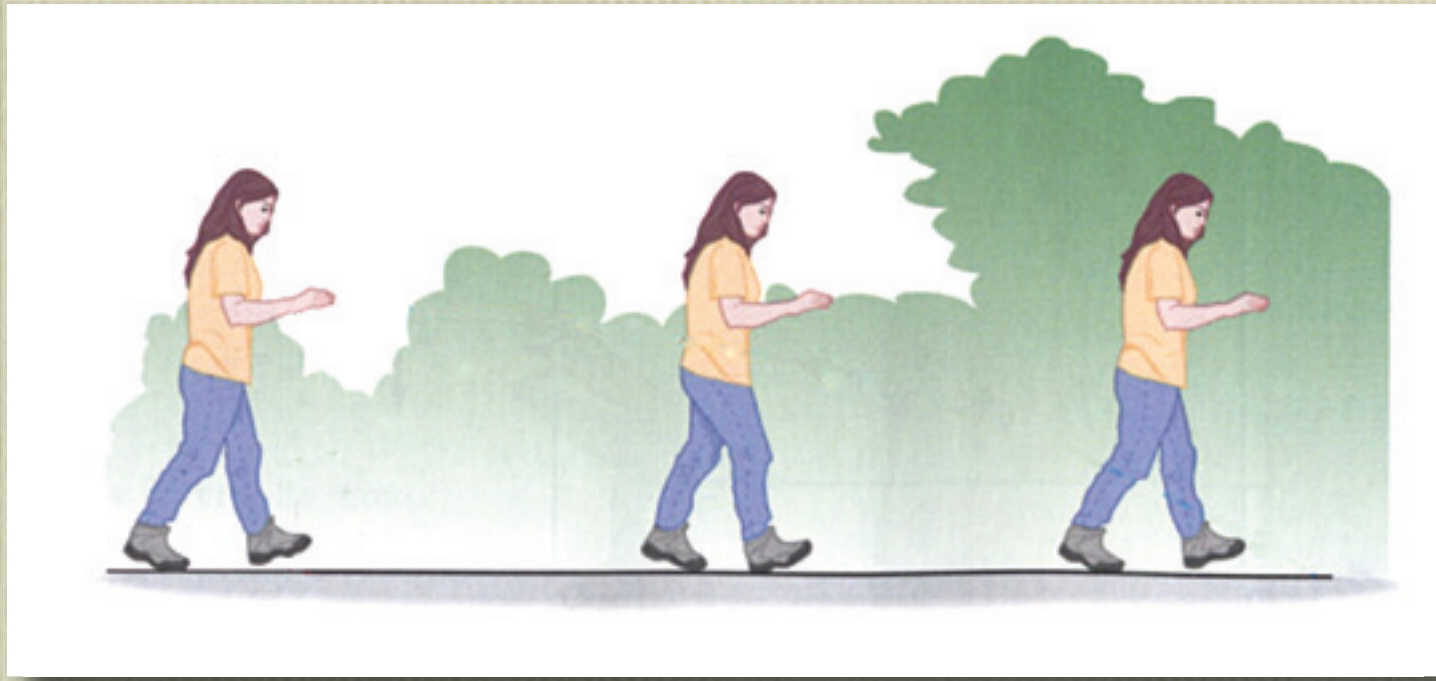
“almost on a totally different plane of existence.”



Realism



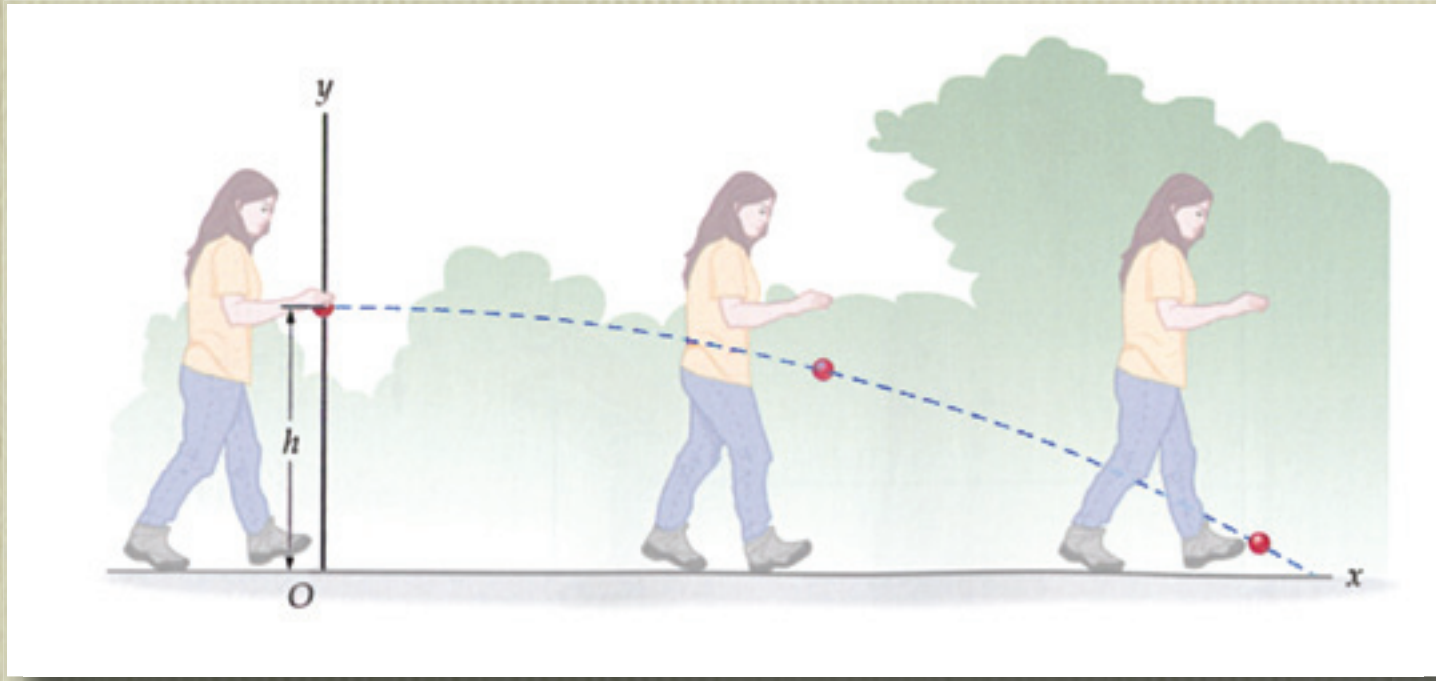
Realism



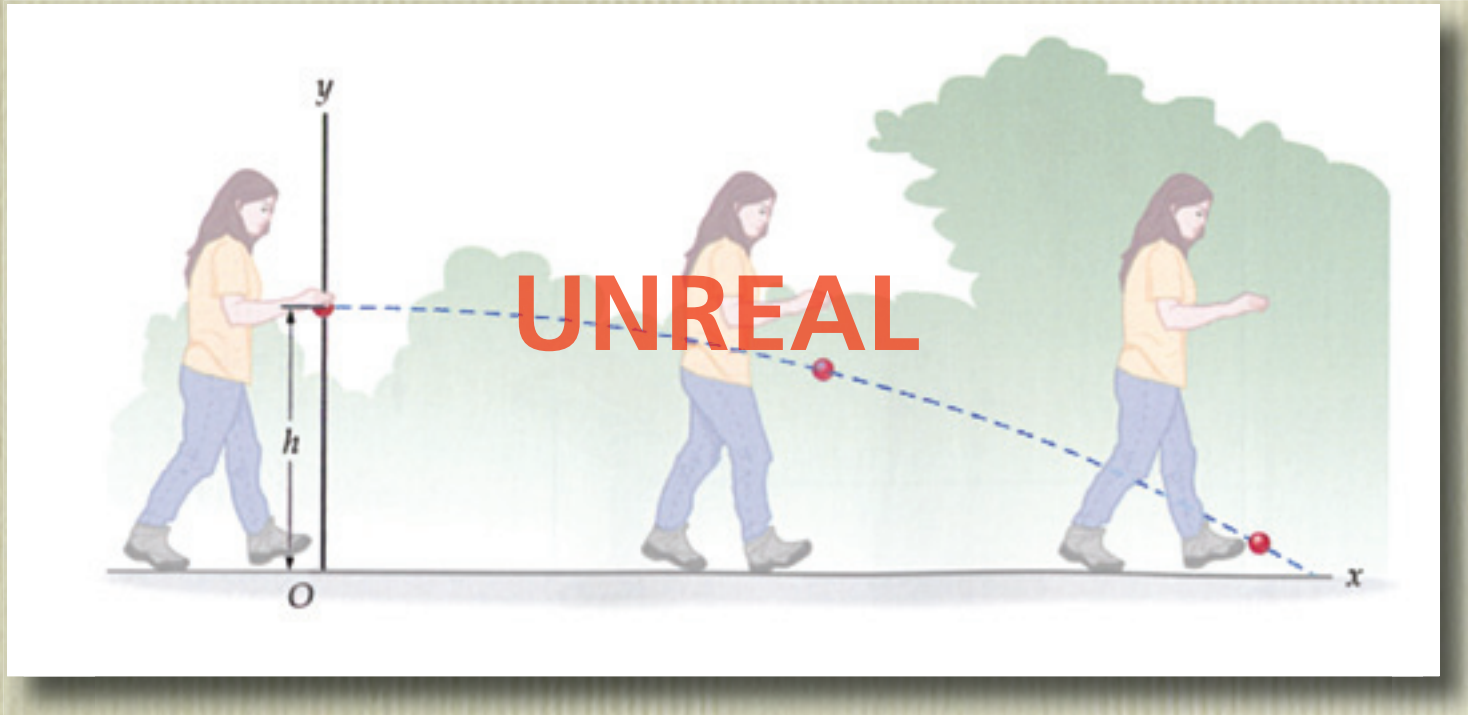
Realism



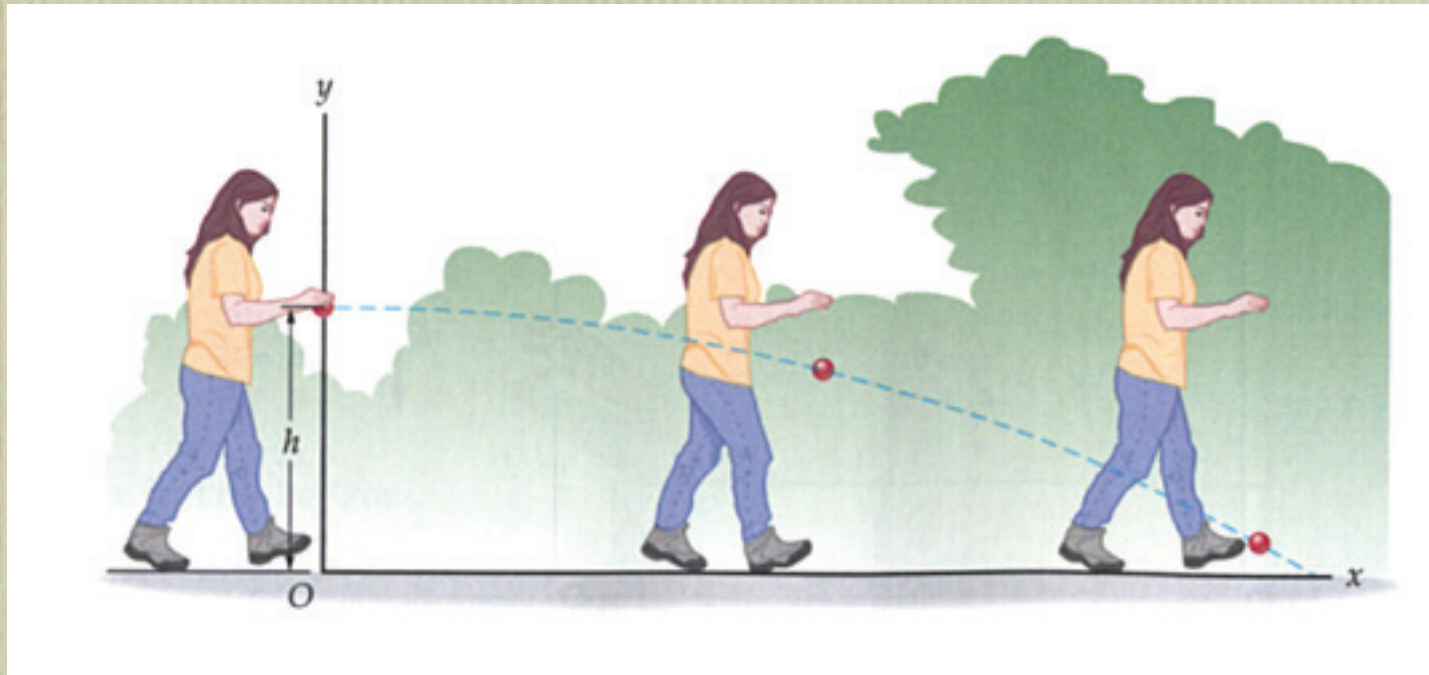
Realism



Realism



Realism



background:

realistic

physics:

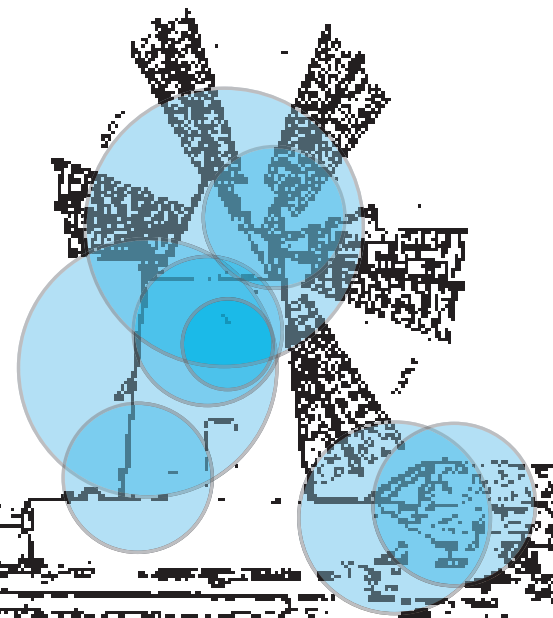
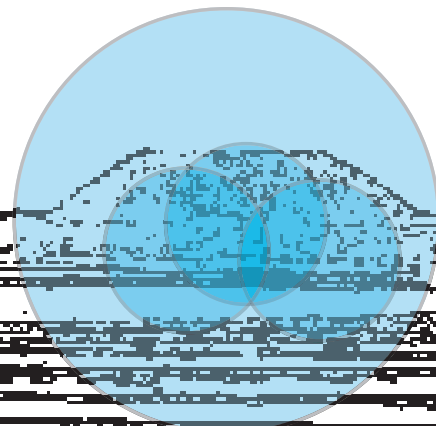
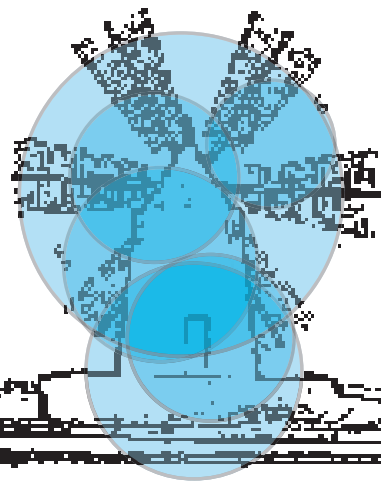
unrealistic



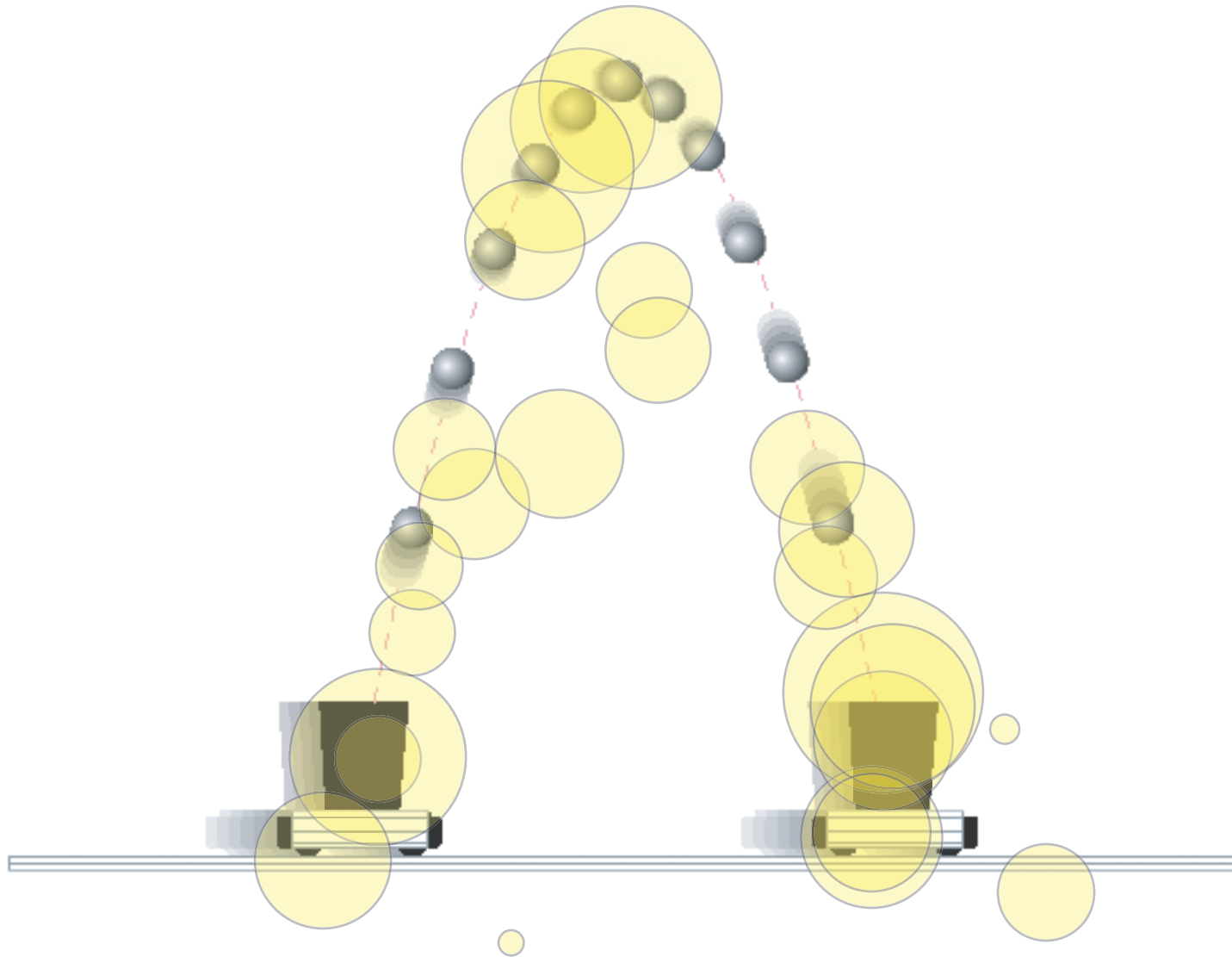
What do people look at?







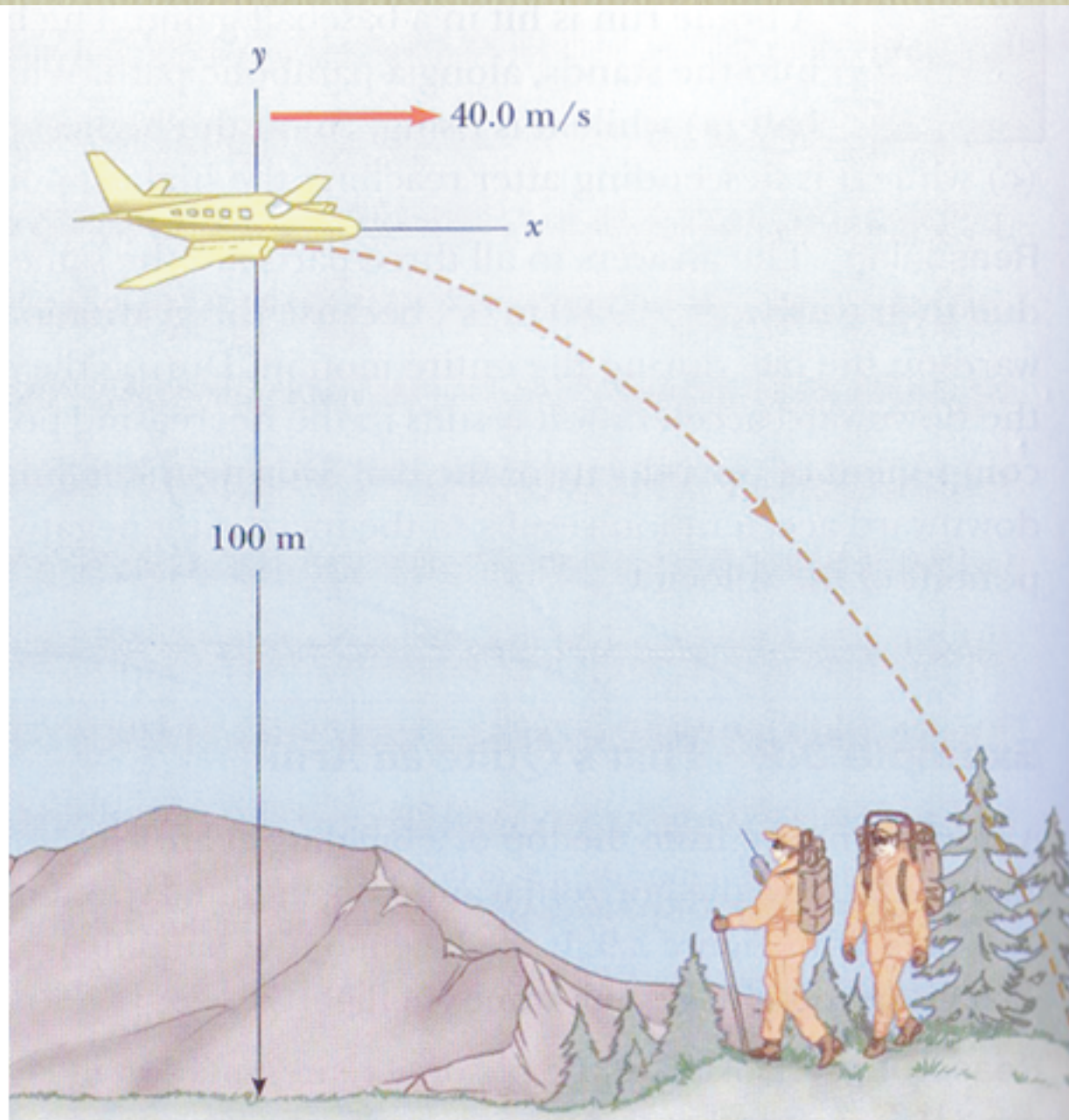


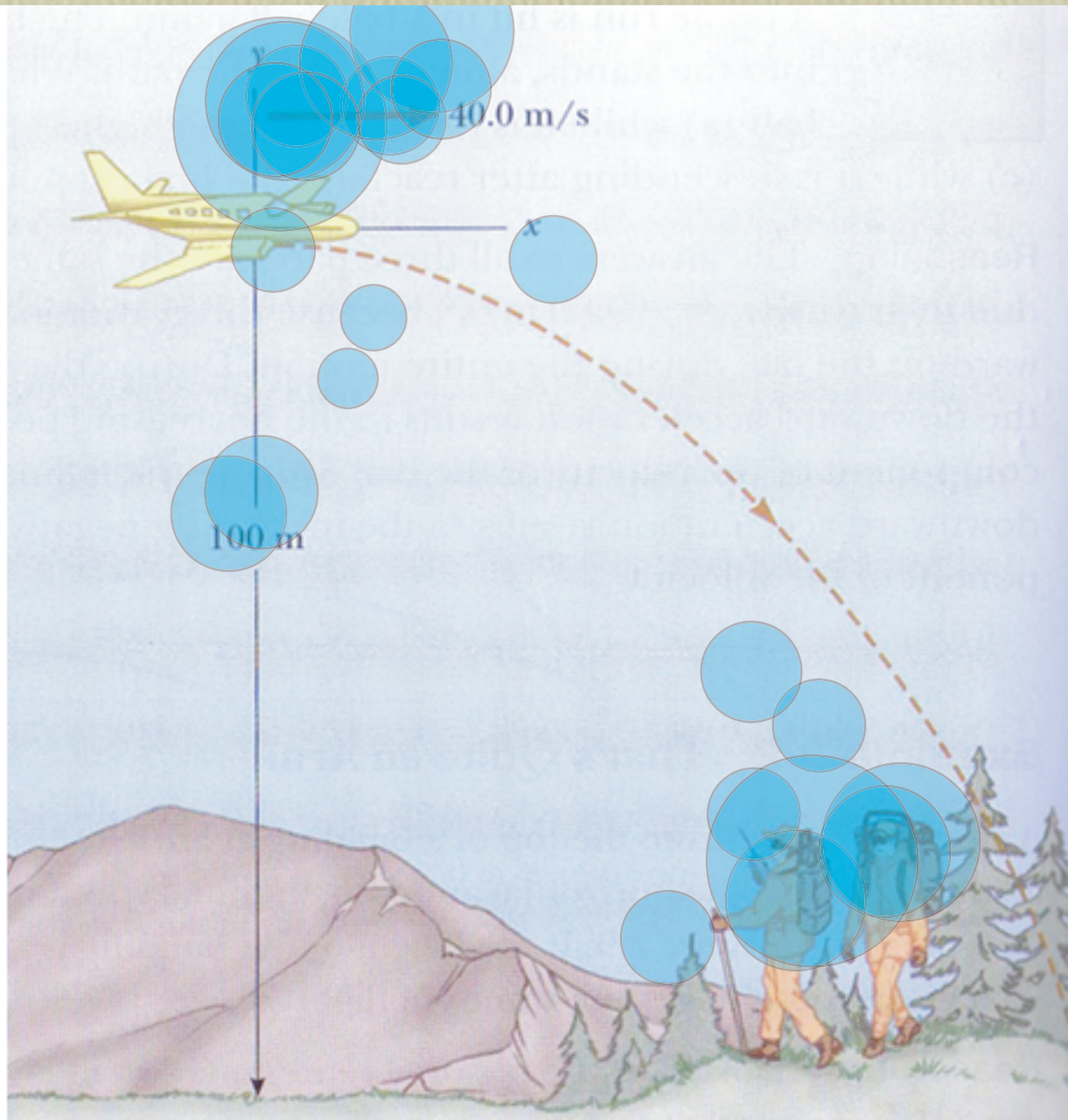


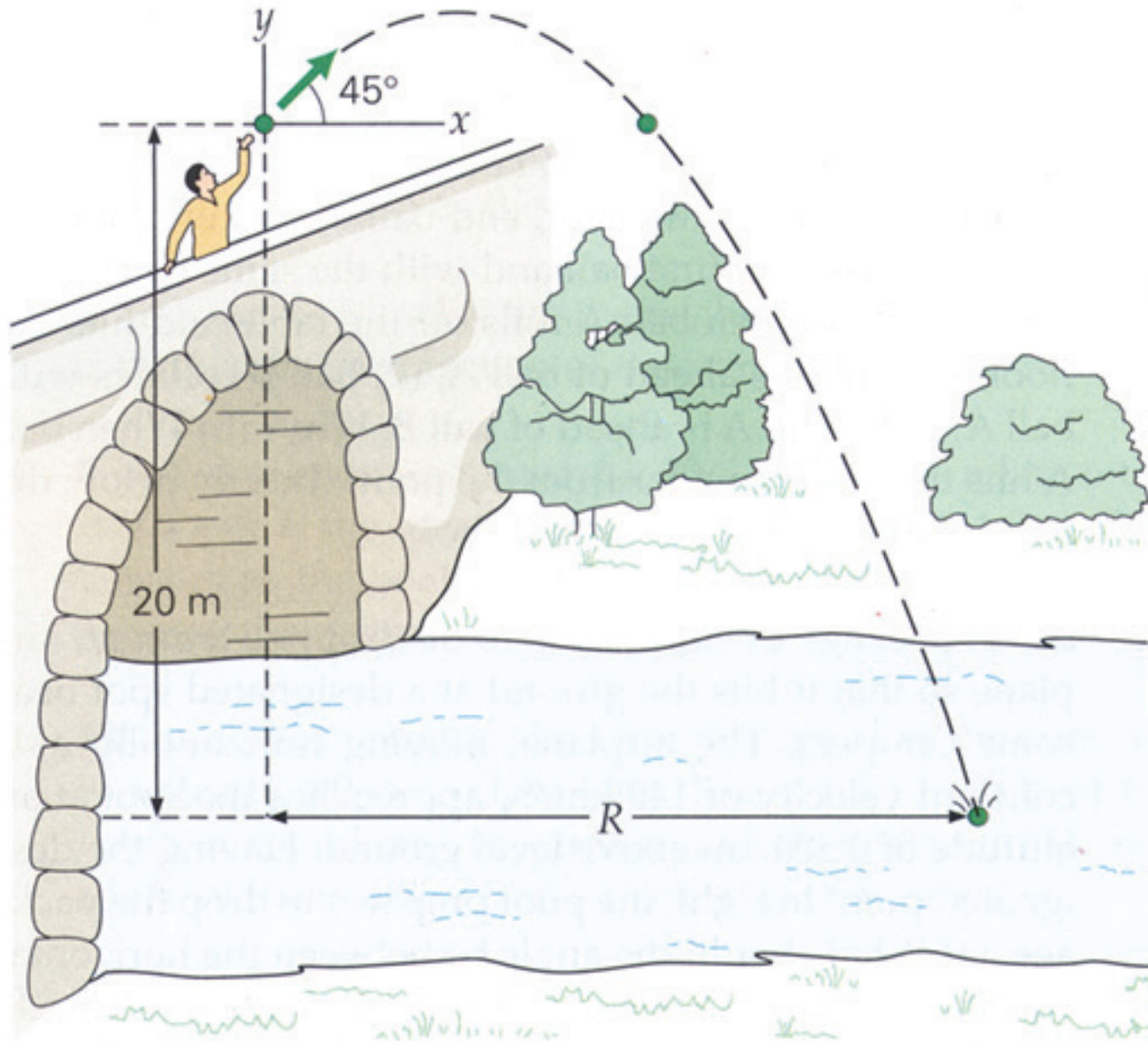
People look at

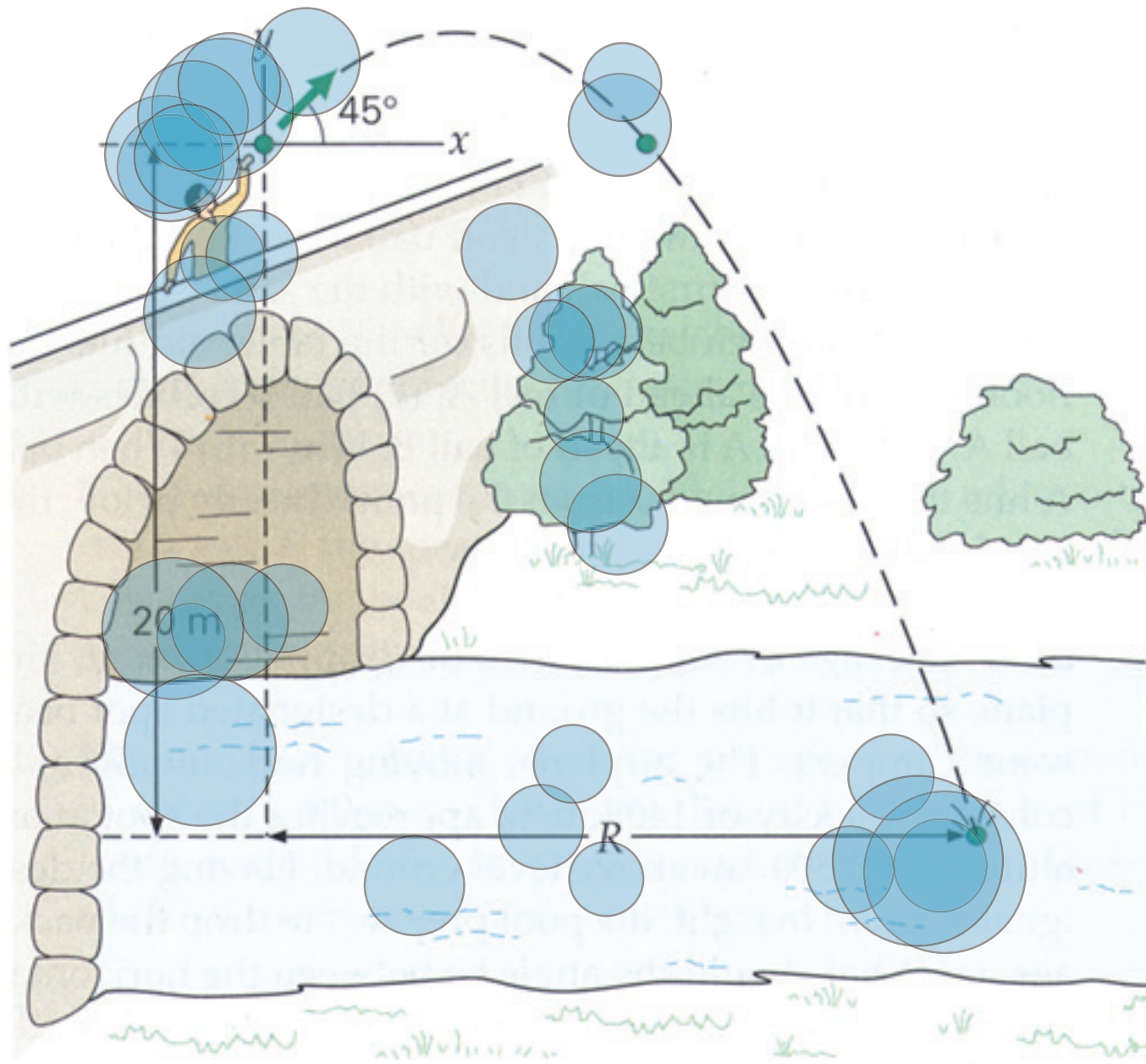
- Parabolic motion of ball
- Carts

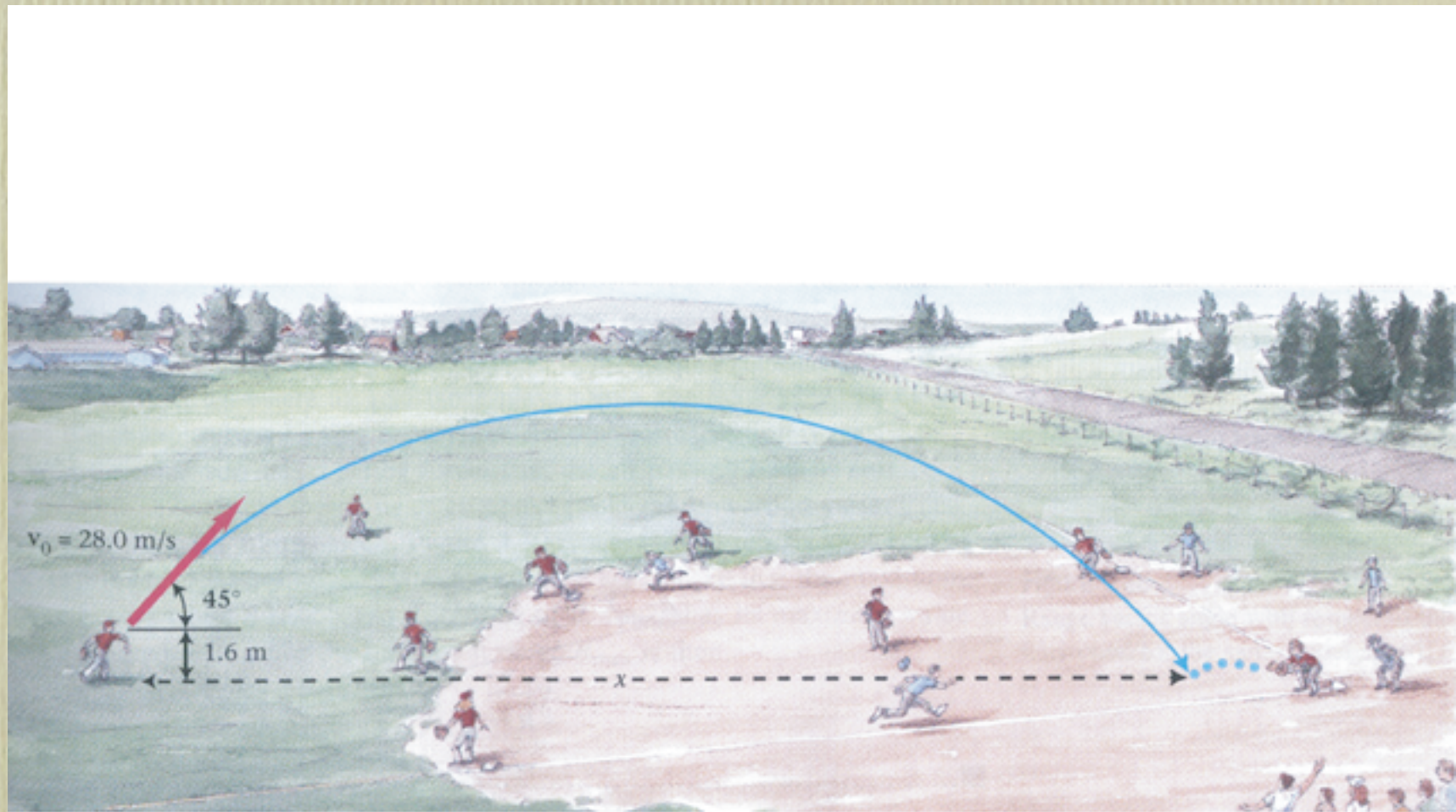


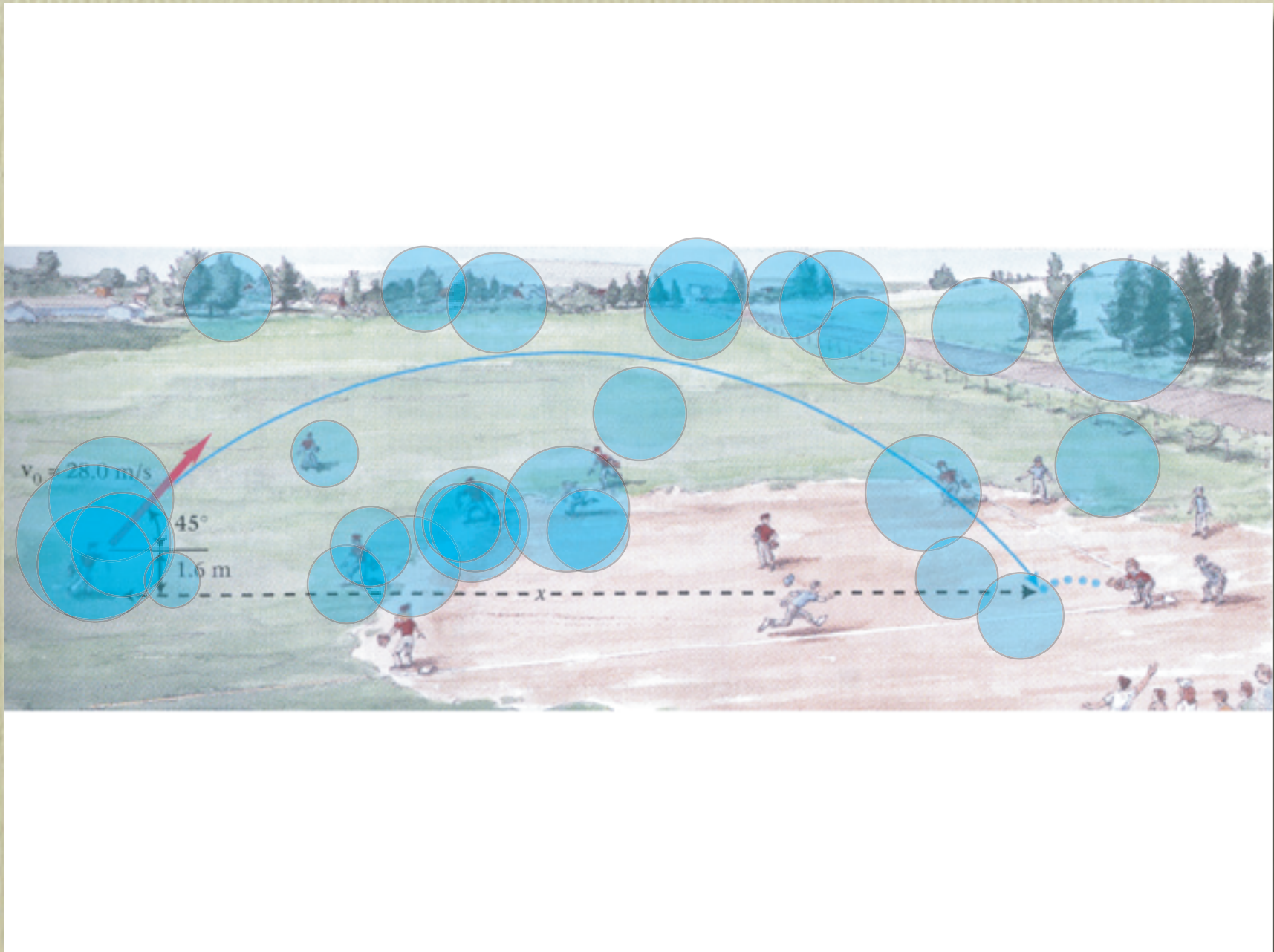


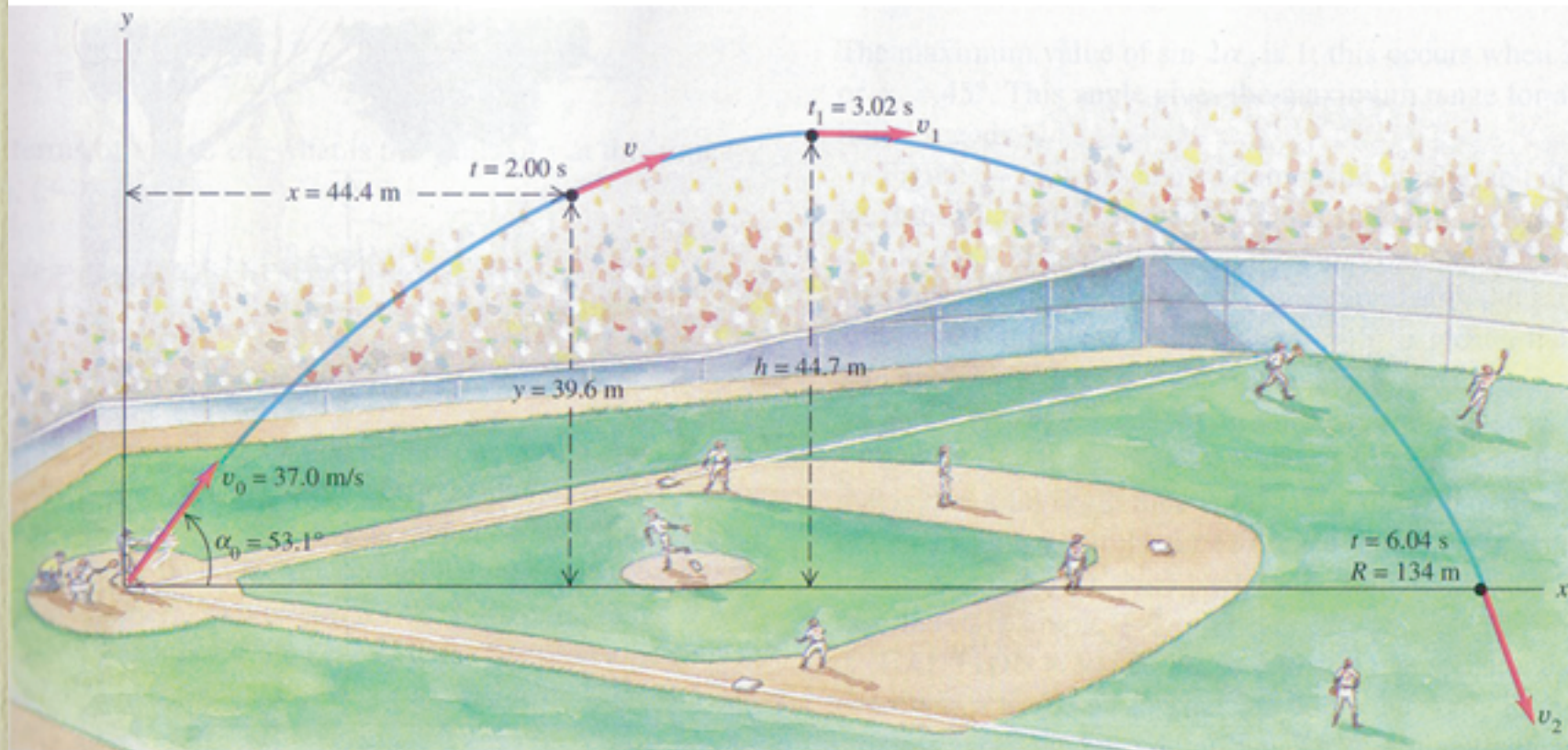


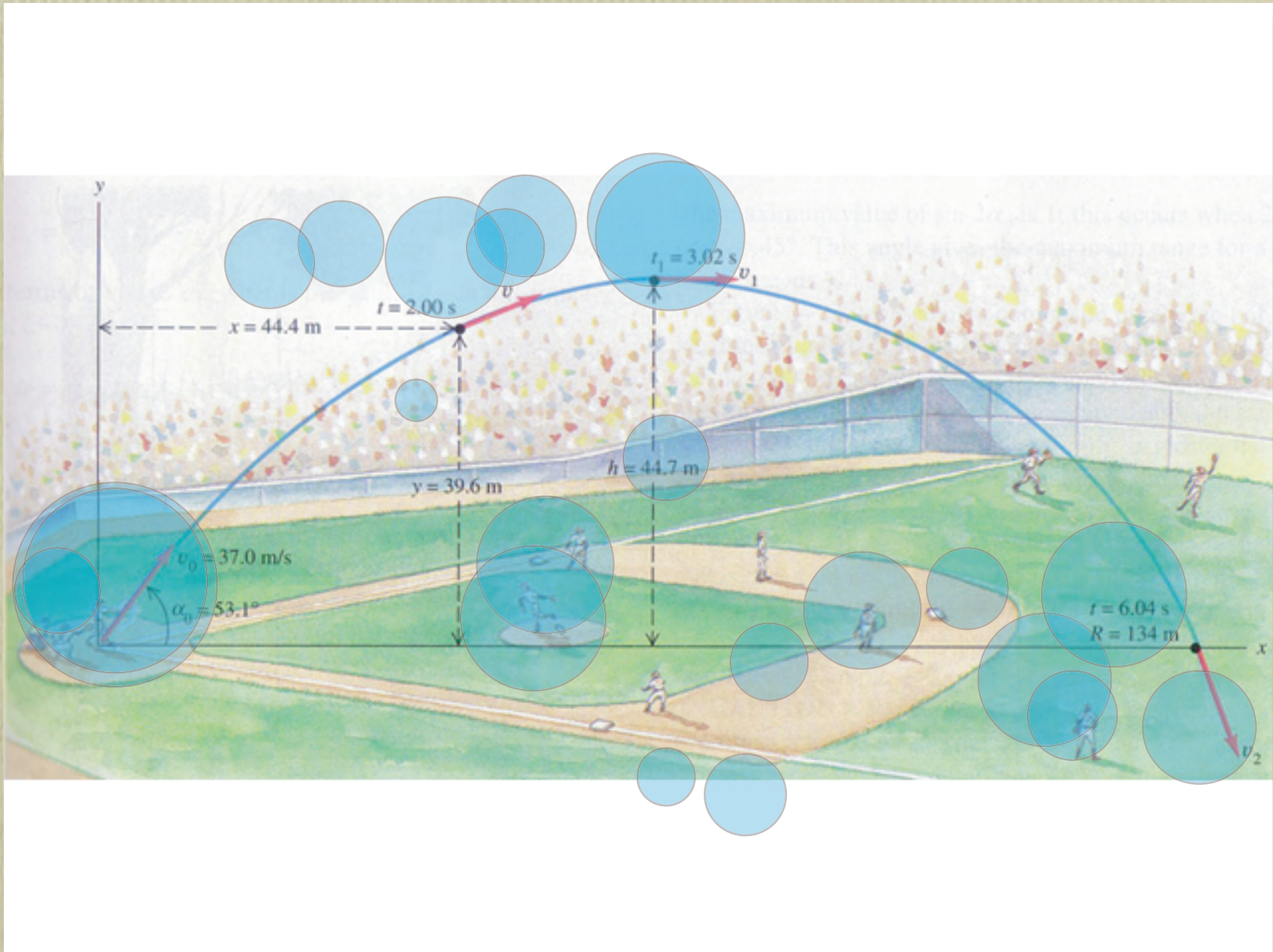












People look at

- People
- Text labels
- Other (distracting) elements



People look at

- People
- Text labels
- Other (distracting) elements

but not the parabolic motion!



Misplaced realism disconnects
physics from the real world





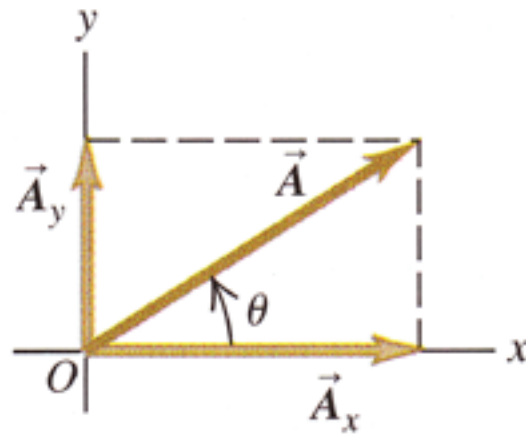
The confusing world of physics

Are vector components vectors?



Yes

18

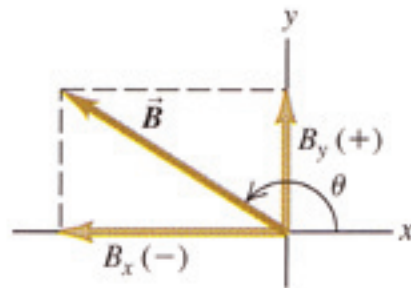


1.13 Vectors \vec{A}_x and \vec{A}_y are the rectangular component vectors of \vec{A} in the directions of the x - and y -axes. For the vector \vec{A} shown here, the components A_x and A_y are both positive.

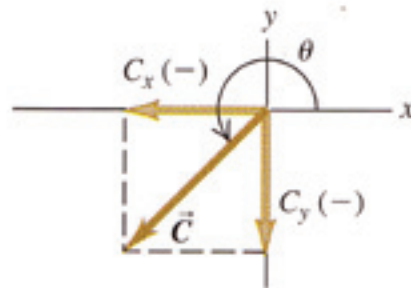


No

19



(a)



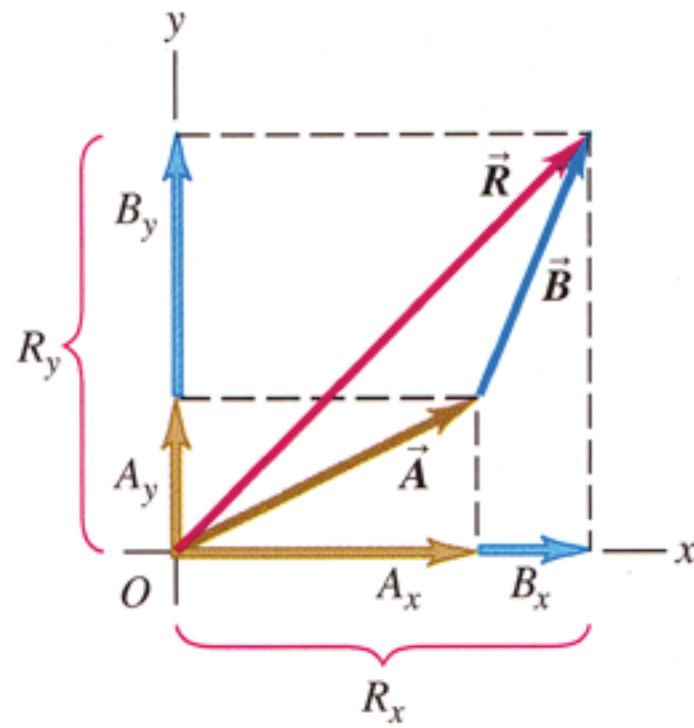
(b)

1.14 The components of a vector may be positive or negative numbers.



No

21

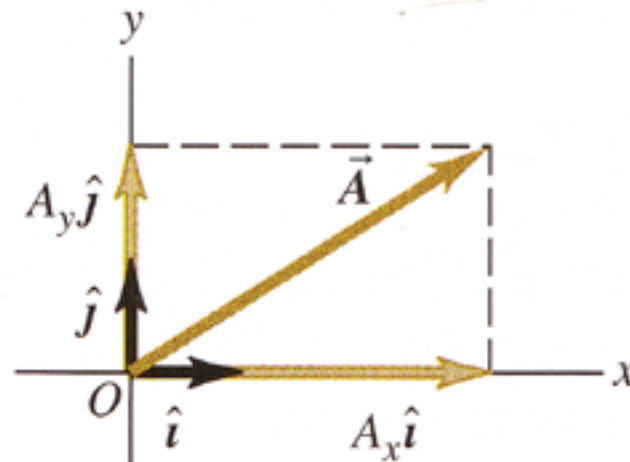


Are vector components vectors?
Yes on even pages, *no* on odd ones



Wait a minute...

23



1.18 Using unit vectors, we can express a vector \vec{A} in terms of its components A_x and A_y as $\vec{A} = A_x \hat{i} + A_y \hat{j}$.

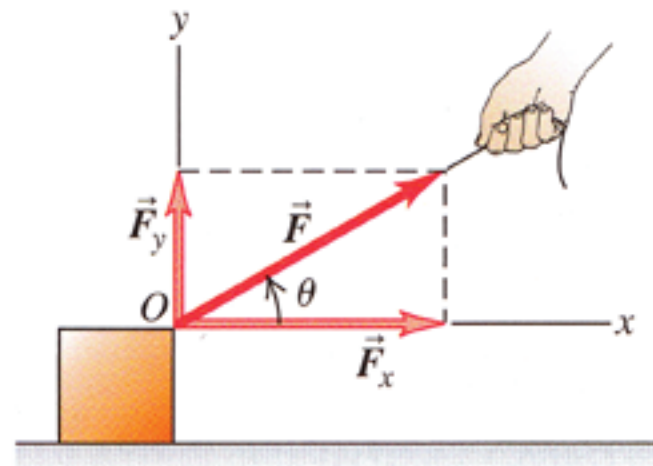


What about forces?



Yes

121



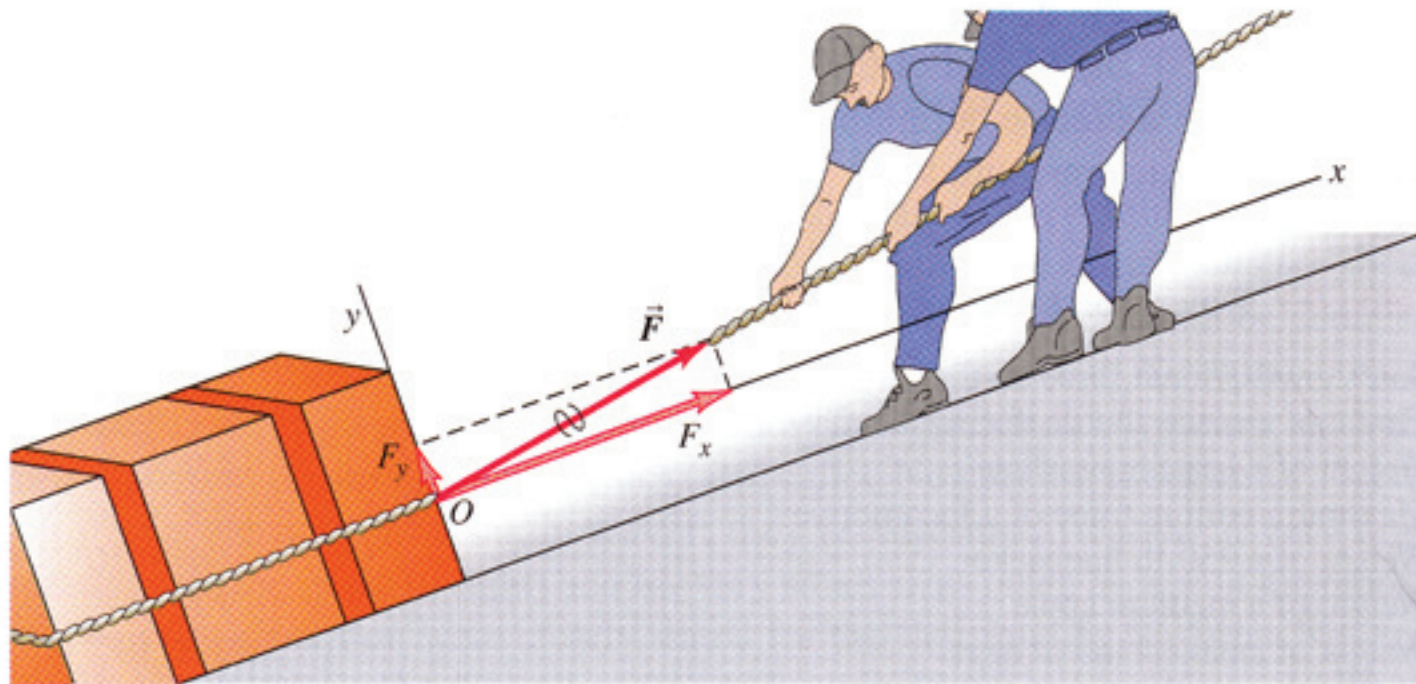
Component vectors: \vec{F}_x and \vec{F}_y
Components: $F_x = F \cos \theta$ and $F_y = F \sin \theta$

4.3 The force \vec{F} , which acts at an angle θ from the x -axis, may be replaced by its rectangular component vectors \vec{F}_x and \vec{F}_y .



No

122



4.4 F_x and F_y are the components of \vec{F} parallel and perpendicular to the sloping surface of the inclined plane.

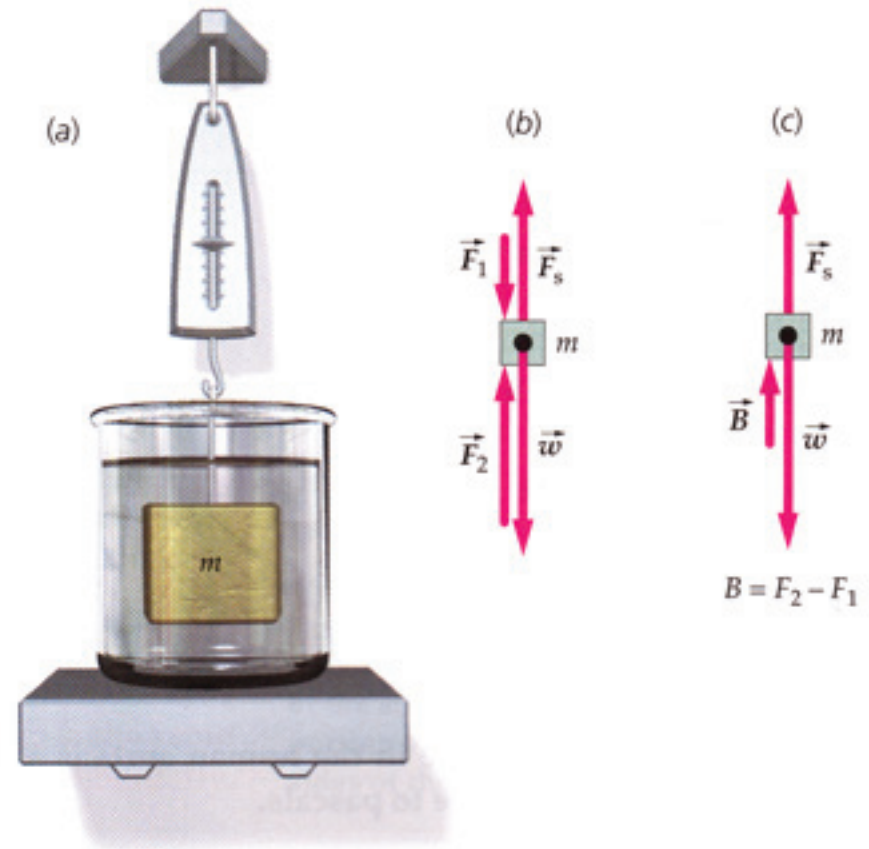


“I don’t understand vectors.”



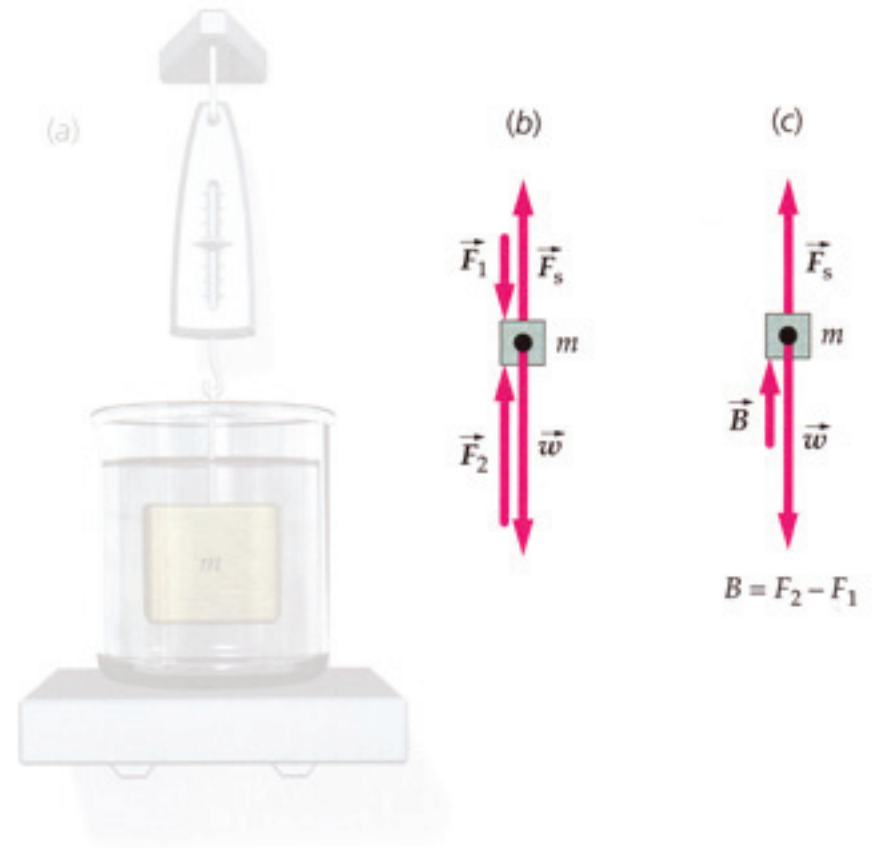
Working with vectors

We can derive Archimedes' principle from Newton's laws by considering the forces acting on a portion of a fluid and noting that in static equilibrium the net force must be zero. Figure 13-9b shows the vertical forces acting on an object being weighed while submerged. These are the force of gravity \vec{w} acting down, the force of the spring scale \vec{F}_s acting up, a force \vec{F}_1 acting down because of the fluid pressure on the top surface of the object, and a force \vec{F}_2 acting up because of the fluid pressing on the bottom surface of the object. Since the spring scale reads a force less than the weight, the force \vec{F}_2 must be greater in magnitude than the force \vec{F}_1 . The difference in magnitude of these two forces is the buoyant force $\vec{B} = \vec{F}_2 - \vec{F}_1$ (Figure 13-9c). The buoyant force occurs because the pressure of the fluid at the bottom of the object is greater than that at the top.



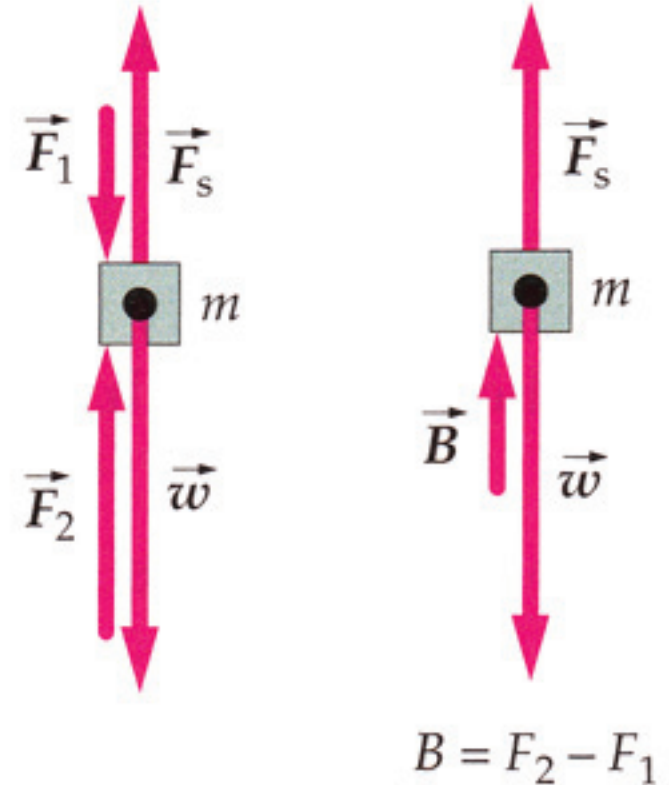
Working with vectors

We can derive Archimedes' principle from Newton's laws by considering the forces acting on a portion of a fluid and noting that in static equilibrium the net force must be zero. Figure 13-9*b* shows the vertical forces acting on an object being weighed while submerged. These are the force of gravity \vec{w} acting down, the force of the spring scale \vec{F}_s acting up, a force \vec{F}_1 acting down because of the fluid pressure on the top surface of the object, and a force \vec{F}_2 acting up because of the fluid pressing on the bottom surface of the object. Since the spring scale reads a force less than the weight, the force \vec{F}_2 must be greater in magnitude than the force \vec{F}_1 . **The difference in magnitude of these two forces is the buoyant force $\vec{B} = \vec{F}_2 - \vec{F}_1$** (Figure 13-9*c*). The buoyant force occurs because the pressure of the fluid at the bottom of the object is greater than that at the top.



Working with vectors

The difference in magnitude of these two forces is the buoyant force $\vec{B} = \vec{F}_2 - \vec{F}_1$ (Figure 13-9c).

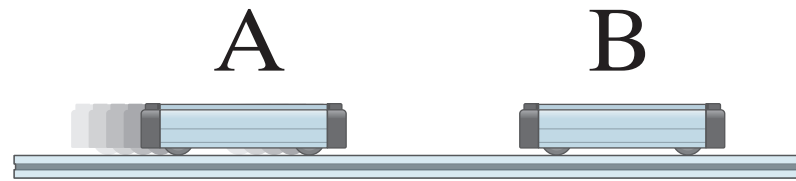


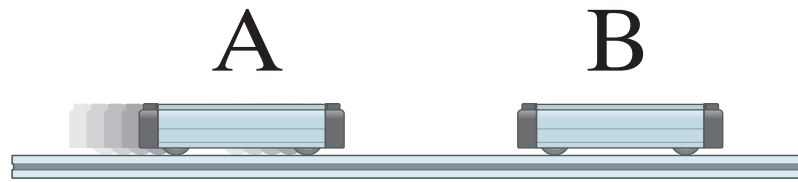
Because we know what is meant,
we are unconscious of errors



Conservation

Consider collision on low-friction track





“The momentum of cart B is not conserved”

“Momentum is conserved”

“The total momentum of the carts is constant”

“The momentum of carts A and B is conserved”



To the physicist, all make sense...



...but students are confused!



Conservation

“I am confused about conservation of momentum”

“Why is momentum not conserved in a nonisolated system?”

“Is momentum conserved in an inelastic collision?”

“I am confused as to how (and when) to apply conservation of momentum”



Conservation

Involves many concepts



Conservation

Involves many concepts

- System (universe, environment)



Conservation

Involves many concepts

- System (universe, environment)
- Extensive quantities



Conservation

Involves many concepts

- System (universe, environment)
- Extensive quantities
- Destruction/creation



Conservation

Involves many concepts

- System (universe, environment)
- Extensive quantities
- Destruction/creation
- Interactions (transfer, flow, boundary)



Conservation

Involves many concepts

- System (universe, environment)
- Extensive quantities
- Destruction/creation
- Interactions (transfer, flow, boundary)
- Constant (no change over time)



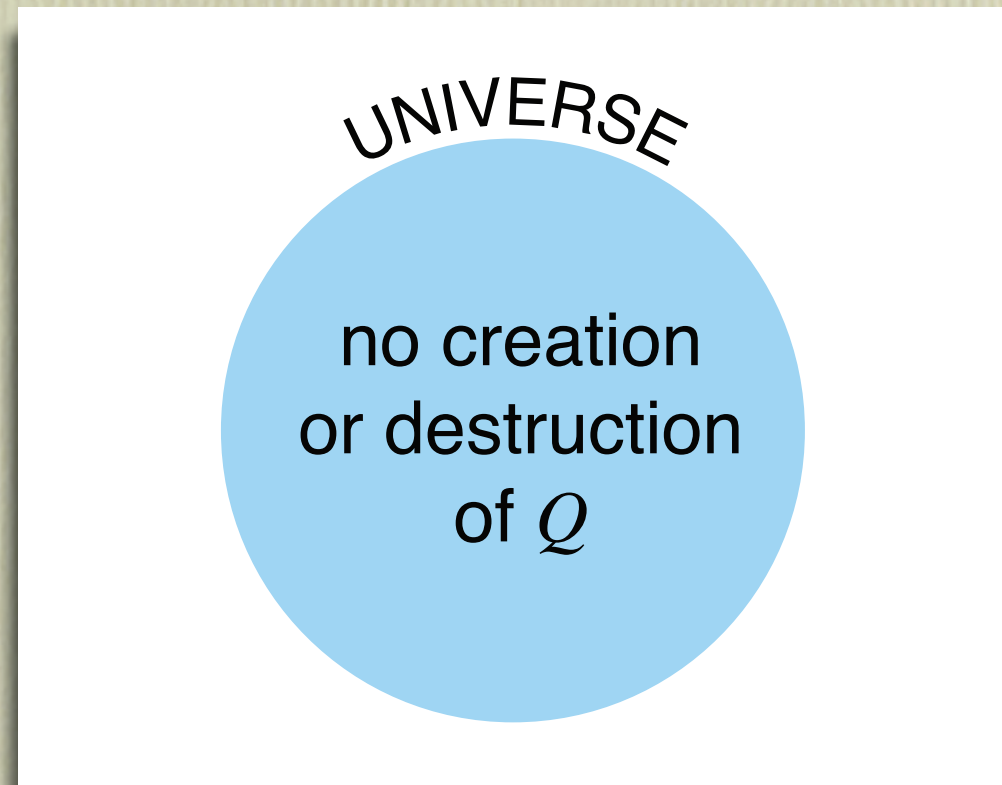
Conservation

How to express “conservation” of quantity Q ?



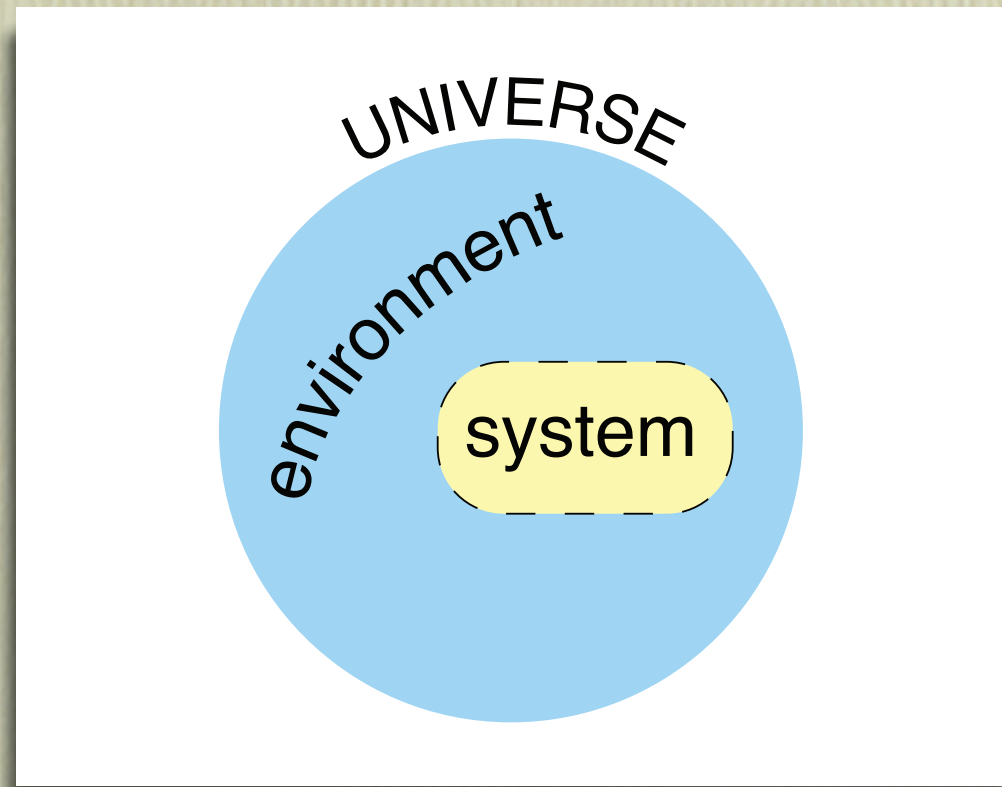
Conservation

How to express “conservation” of quantity Q ?



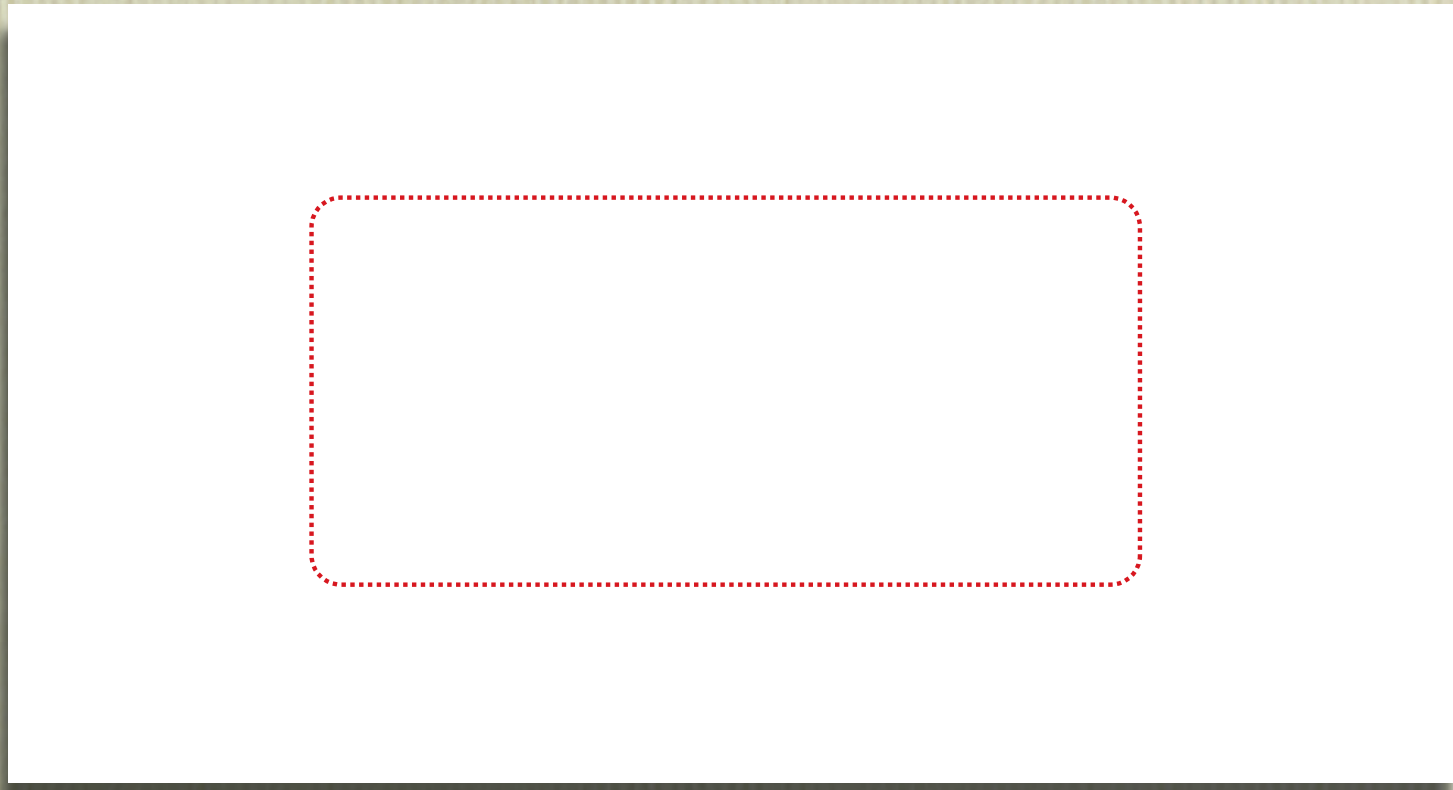
Conservation

How to express “conservation” of quantity Q ?



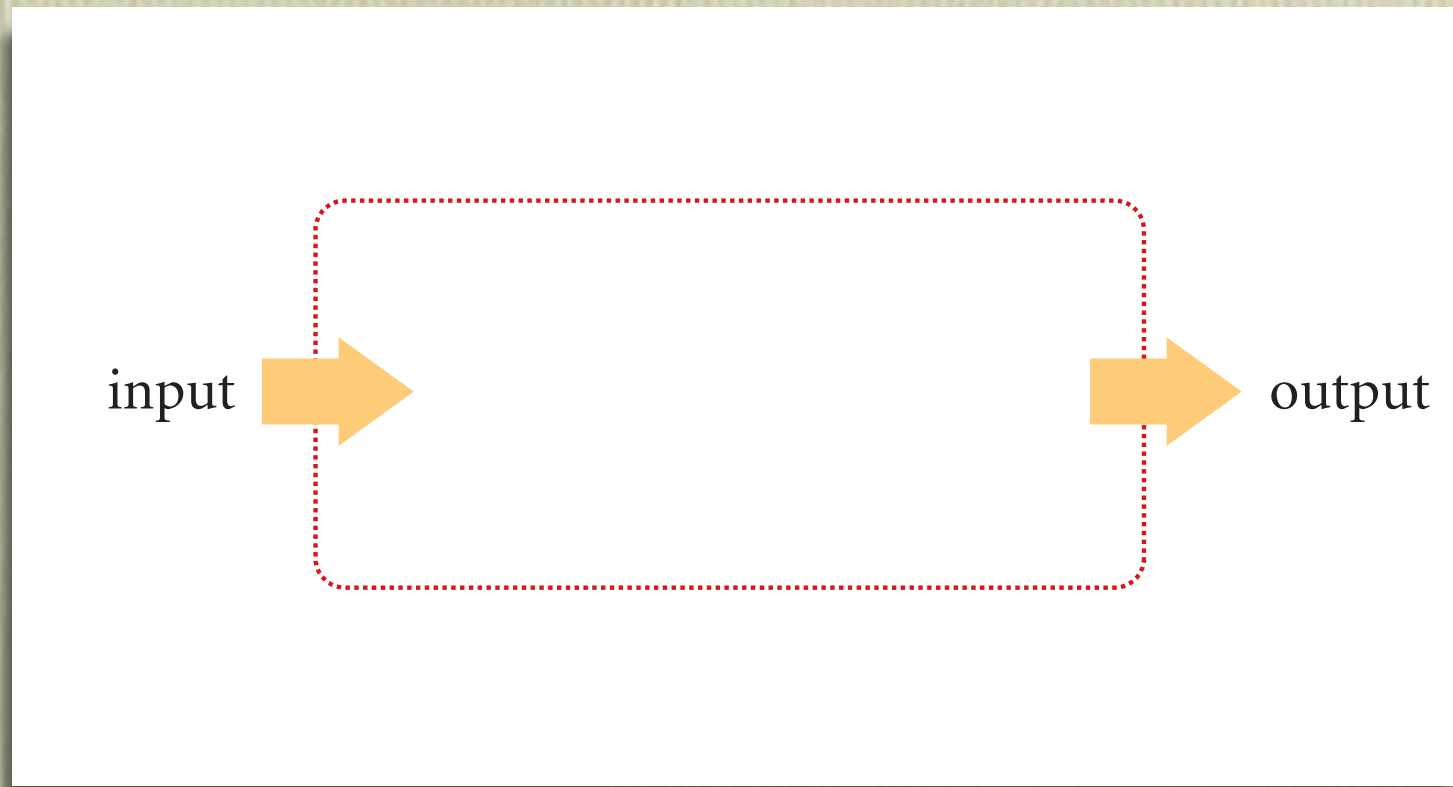
Conservation

How can Q change?



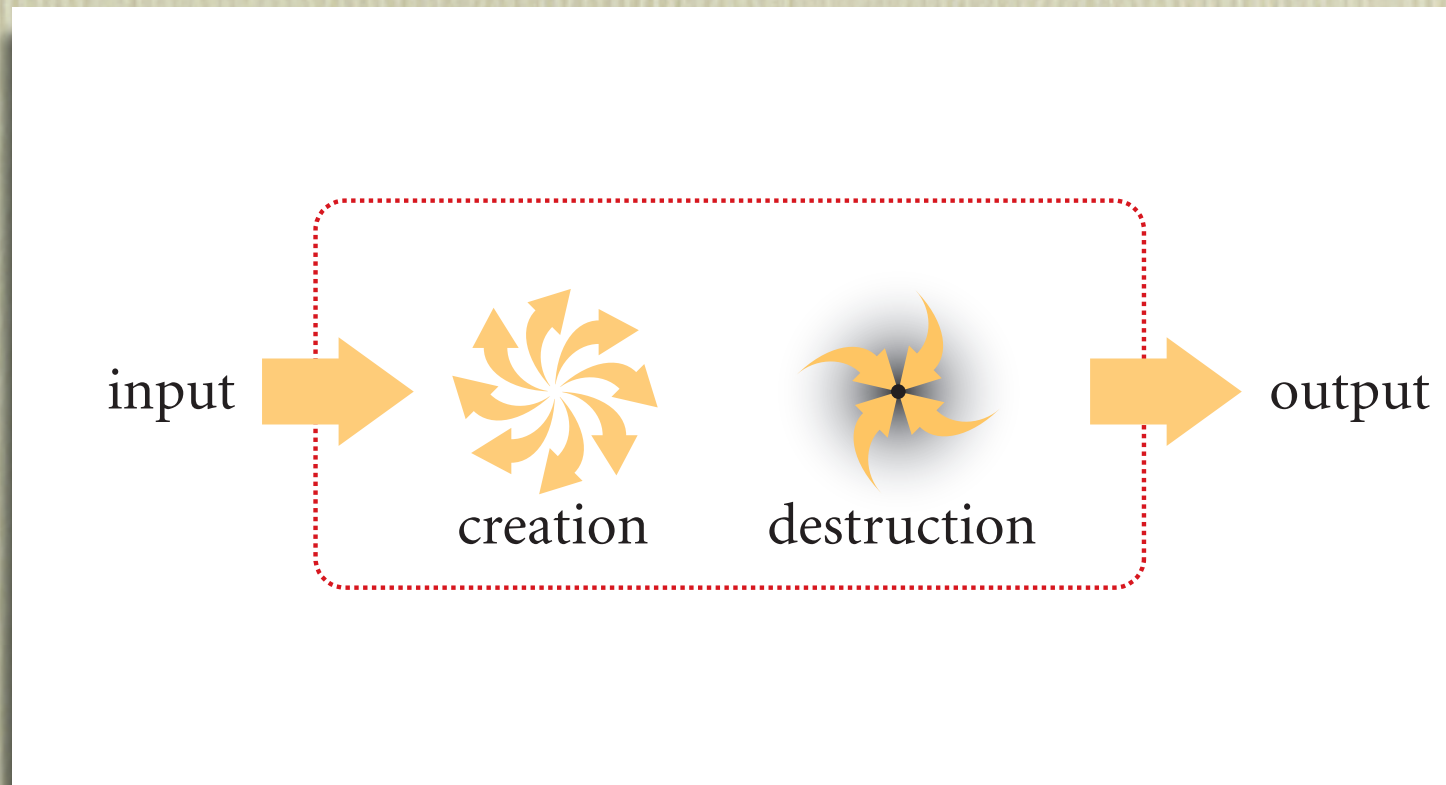
Conservation

How can Q change?



Conservation

How can Q change?



Conservation

$$\Delta Q = J_Q + S_Q$$



Conservation

If Q is “conserved”: $S_Q = 0$, and so $\Delta Q = J_Q$



Conservation

If system *also* isolated: $J_Q = 0$, and so $\Delta Q = 0$

Q cannot change



Conservation

conservation + isolation = no change

Q cannot change



Conservation

What I told my students:



Conservation

What I told my students:

I. Conservation laws most basic principles



Conservation

What I told my students:

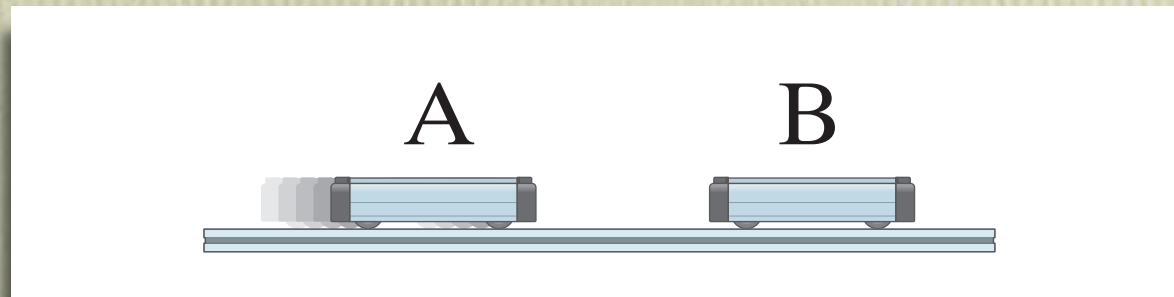
1. Conservation laws most basic principles
2. Momentum is conserved



Conservation

What I told my students:

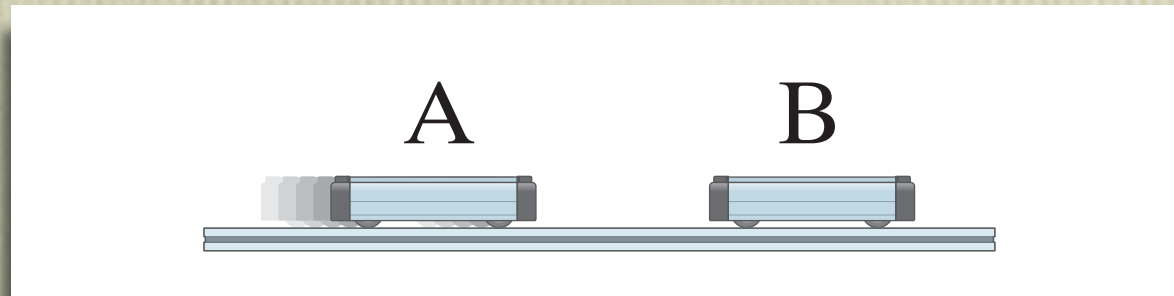
1. Conservation laws most basic principles
2. Momentum is conserved



Conservation

What I told my students:

1. Conservation laws most basic principles
2. Momentum is conserved



3. Momentum of cart *B* is not conserved



Dear Professor,

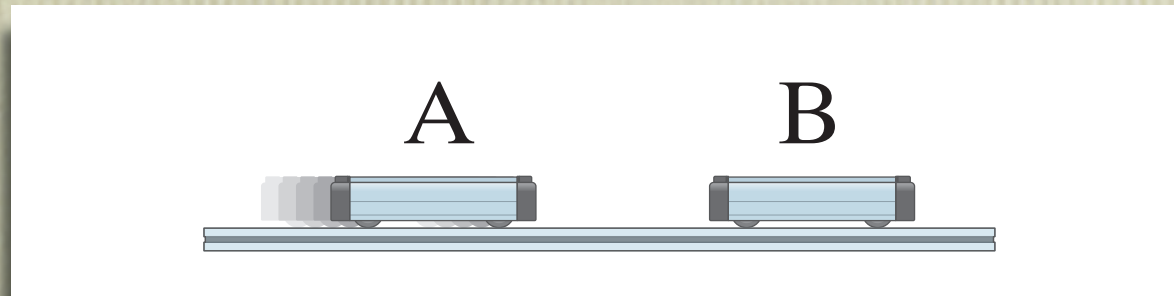
*If conservation is so fundamental,
then why is momentum
conserved only in certain cases?*



Conservation

What I should have said instead:

1. Conservation laws most basic principles
2. Momentum is conserved



3. Momentum of cart *B* is not **constant**

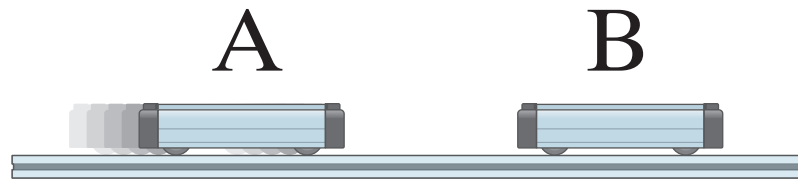


Conservation

A conserved quantity:

1. is *always* conserved
2. is *constant* (not *conserved*) for isolated systems
3. can *only* change due to transfer across boundary





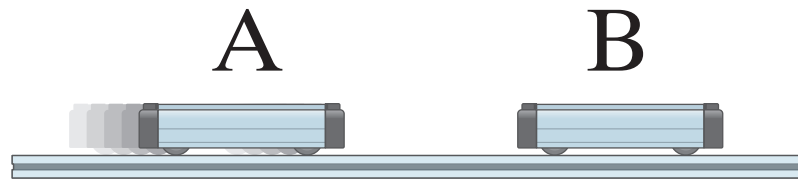
“The momentum of cart B is not conserved”

“Momentum is conserved”

“The total momentum of the carts is constant”

“The momentum of carts A and B is conserved”





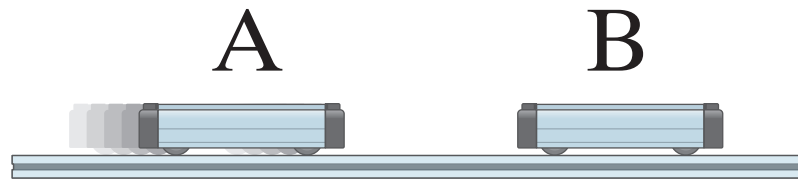
“The momentum of cart B is not **constant**”

“Momentum is conserved”

“The total momentum of the carts is constant”

“The momentum of carts A and B is conserved”





“The momentum of cart B is not **constant**”

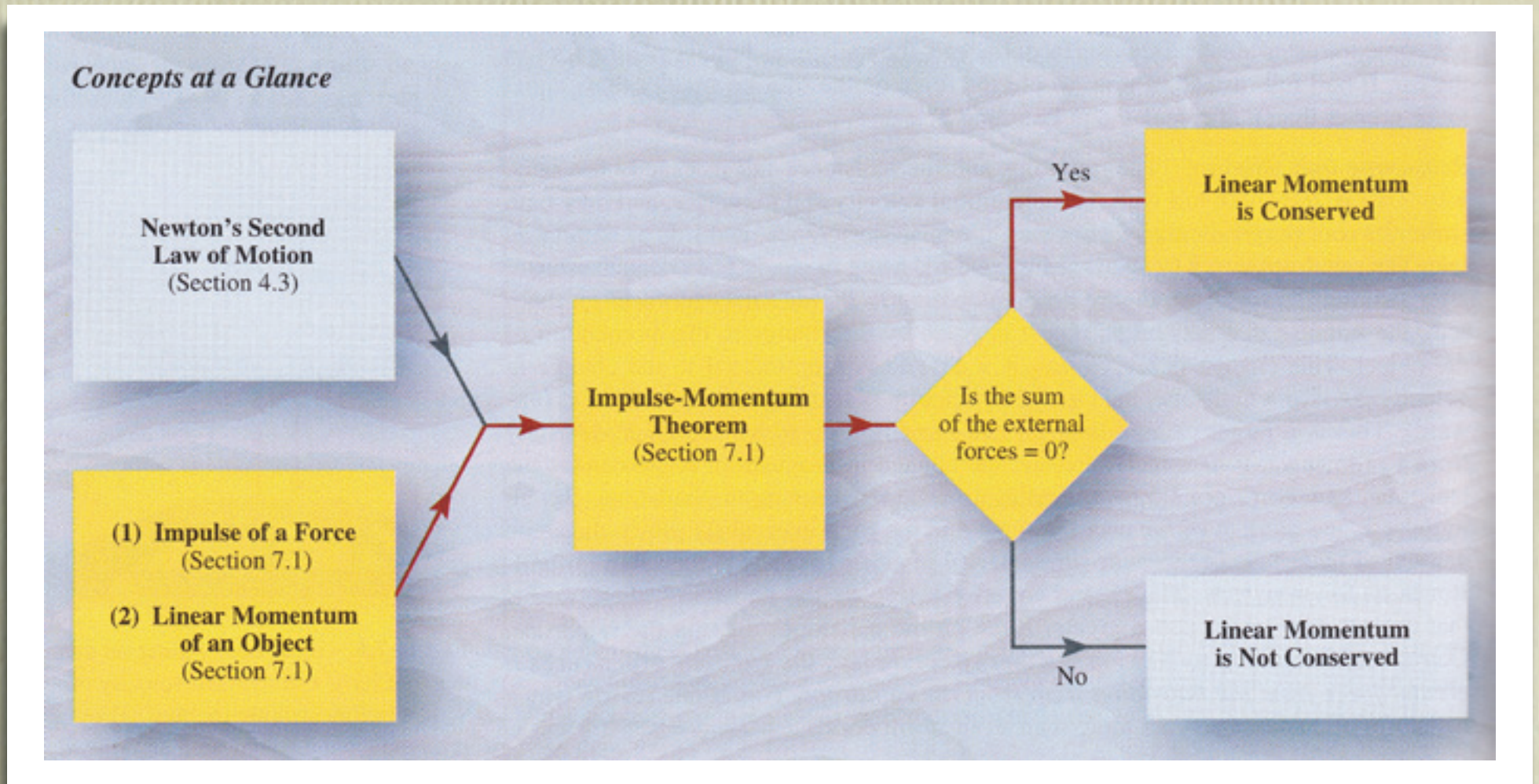
“Momentum is conserved”

“The total momentum of the carts is constant”

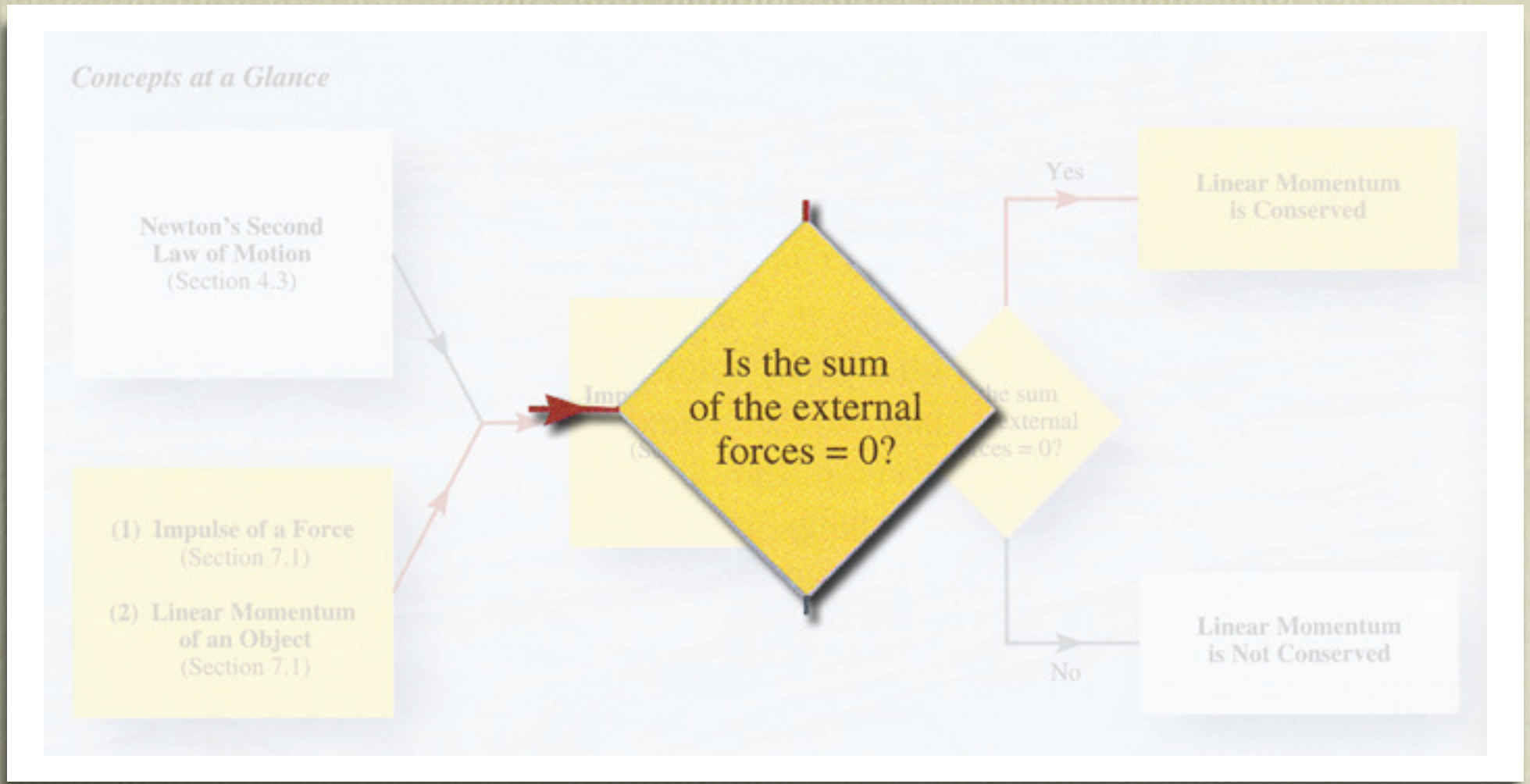
“The momentum of carts A and B is **constant**”



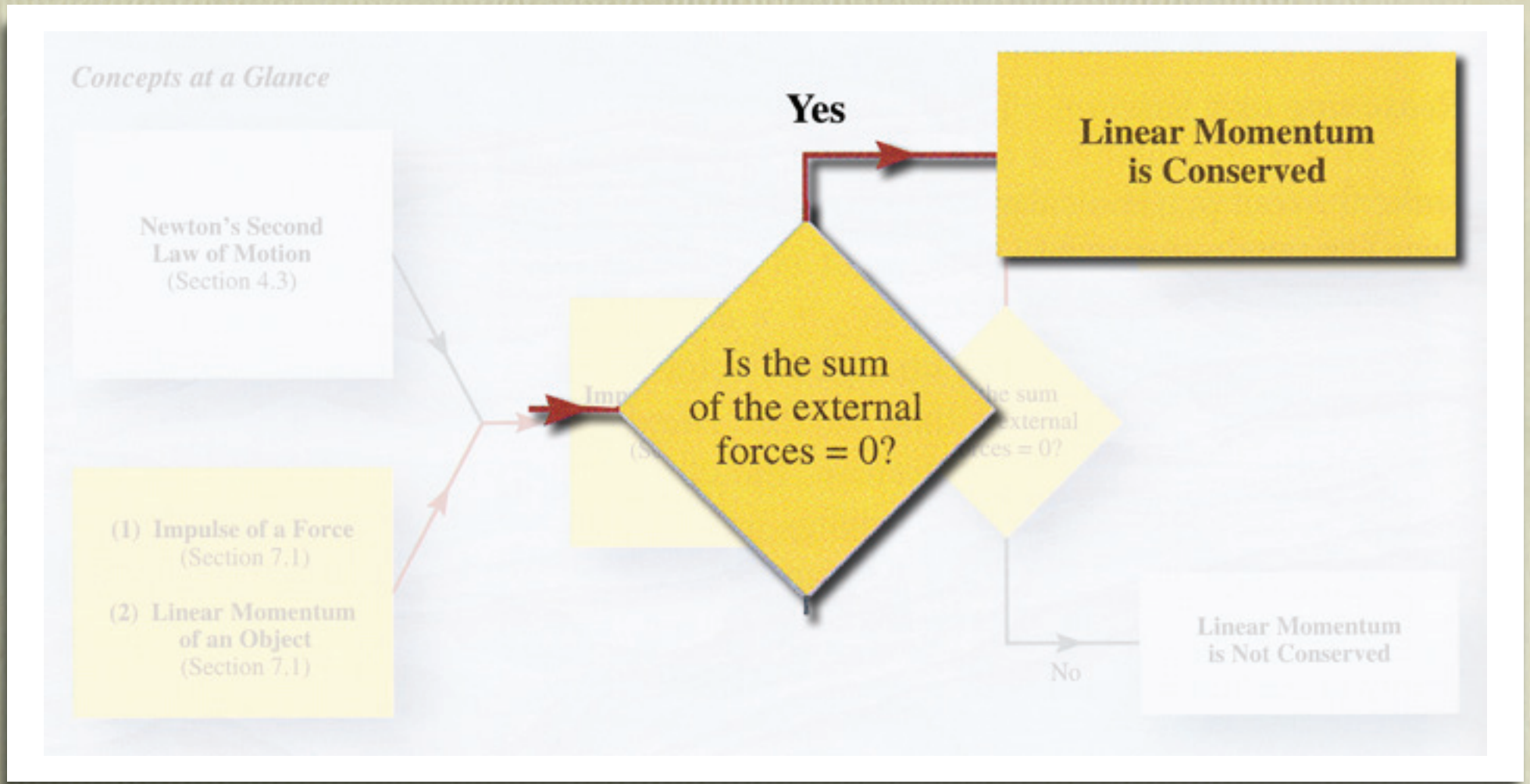
It's not just me!



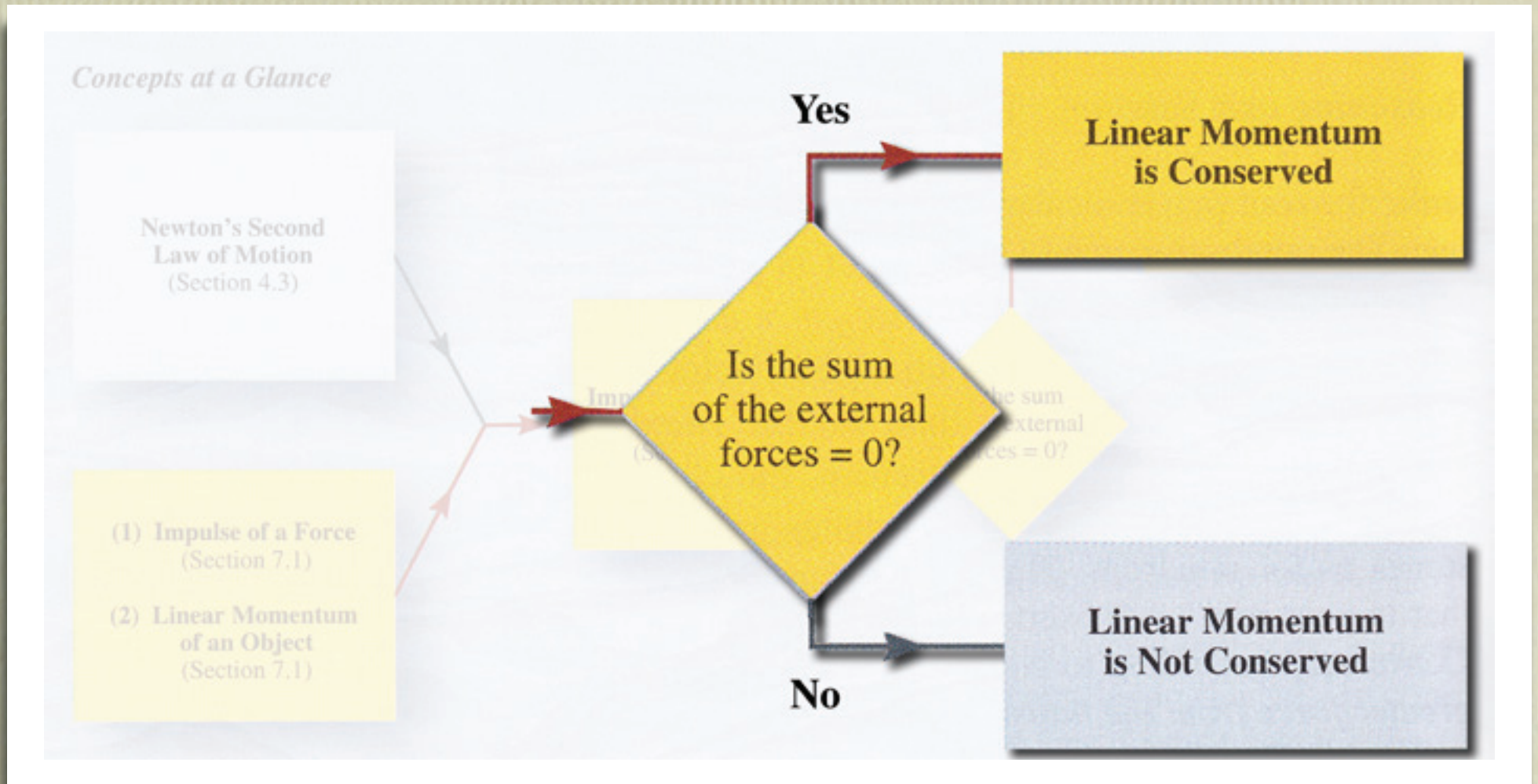
It's not just me!



It's not just me!




It's not just me!



Lack of precision leads to confusion

Summary

- Silly art makes us look weird
- Misplaced realism makes physics different
- Lack of precision confuses



We need to be more careful
with our own representations

Dear Professor,

Dear Professor,

*You keep saying that science
is all about proof.*

Dear Professor,

*You keep saying that science
is all about proof.*

*If you prove that what we believe is wrong,
we should change our minds.*

Dear Professor,

*You keep saying that science
is all about proof.*

*If you prove that what we believe is wrong,
we should change our minds.*

But minds don't change like that.

Dear Professor,

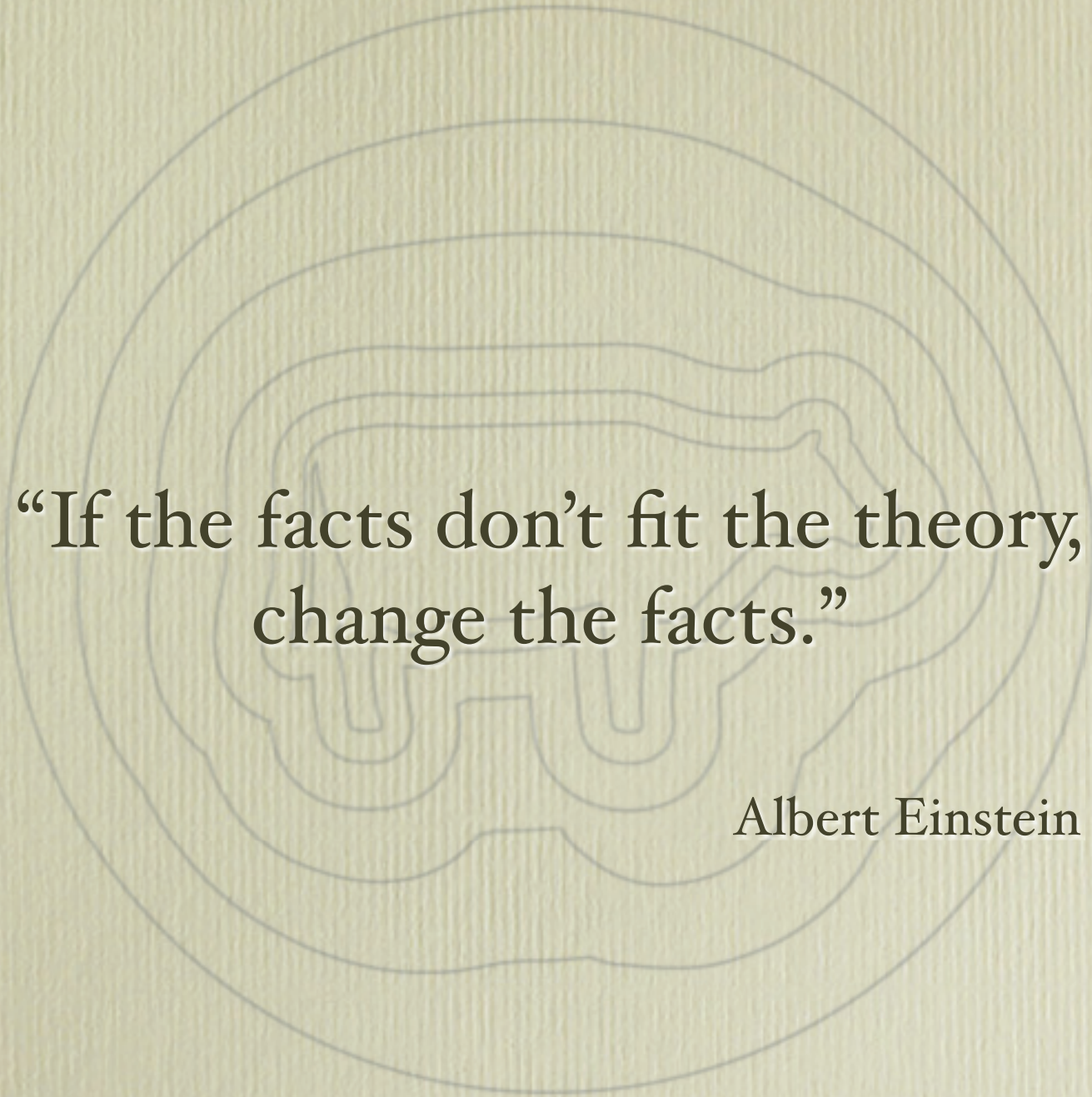
*You keep saying that science
is all about proof.*

*If you prove that what we believe is wrong,
we should change our minds.*

But minds don't change like that.

*We keep proving it
every time we take another test.*

Nin Andrews, *Dear Professor* (Subito Press, 2008)



“If the facts don’t fit the theory,
change the facts.”

Albert Einstein

