MOMENTUM CENTRIC PEDAGOGY OF NEWTON'S LAWS

TATSU TAKEUCHI, VIRGINIA TECH

APRIL 22, 2017
JOINT SPRING MEETING OF THE APPALACHIAN & CHESAPEAKE SECTIONS OF THE AAPT
CONCORD UNIVERSITY, ATHENS, WV

WHAT IS "FORCE?"

- Randall D. Knight,
  Physics for Scientists and Engineers, a strategic approach, 3rd edition:
  "A force is a push or a pull" (page 117)
- Nicholas J. Giordano, College Physics, Reasoning & Relationships, 2nd edition:
  "A force is simply a push or a pull" (page 27)
- Debora M. Katz, Physics for Scientists and Engineers, Foundations and Connections with Modern Physics:
  "A force is a push or a pull that is required to make an object accelerate" (page 123)
- Young and Freedman,
  Sears & Zemansky's University Physics with Modern Physics, 13th edition:
  "A force is a push or a pull. A better definition is that a force is an interaction between two bodies or between a body and its environment" (page 105)
- Young & Stadler, Cutnell & Johnson Physics, 10th edition:
  "A force is a push or a pull" (page 79)

- Eric Mazur, Principles and Practice of Physics:
  "The force exerted on the object is the time rate of change in the object's momentum" (page 177)

PROBLEMS WITH "A PUSH OR A PULL"

- Vague and not quantitative. Unscientific!
- Leads to many misconceptions and confusions:
  1. You can "feel" it when you are being pushed or pulled, so a "force" is something that you can "feel"
     → You "feel" weightless on the ISS so how can there be a force acting on you?
  2. Newton's 3rd Law does not make any sense!
     - Pushing or pulling requires volition, so inanimate objects cannot supply a force
       → How can the wall push back when you push it?
     - How can action and reaction be of the same magnitude?
       → If the force with which the trailer is pulling the tractor is the same as the force with which the tractor is pulling the trailer, how can the two move at all?
- Does not explain why forces add like vectors

PROBLEMS WITH "A PUSH OR A PULL"

- Many textbooks try to overcome the various misconceptions by spending many pages or even chapters trying to guide, or indoctrinate the student into the correct understanding
- In the process, many authors inadvertently introduce many misconceptions of their own
- As a result, to the student, Newton's Laws seem like a confusing mess of definitions, caveats, laws and rules that only apply on a case by case basis

- Don't dig a hole (by defining "force" as "a push or a pull") and then try to dig yourself out of it later!

BETTER DEFINITION OF "FORCE"

- Newton's 2nd Law

$$\vec{F} = \frac{\Delta \vec{p}}{\Delta t}$$

  is not really a law but the definition of force
  (After all, force is NOT an observable quantity)
- The force of A on B is the rate of momentum transfer from A to B
- Force is a vector since momentum is a vector,
  and momentum is a vector since velocity is a vector,
  and velocity is a vector since displacement is obviously a vector!
- Teach momentum first and force later!

NEWTON'S LAWS IN MOMENTUM-CENTRIC LANGUAGE

- Newton's 1st Law (aka Law of Inertia)
  If an object does not exchange momentum with anything else, its momentum will remain unchanged

  → In Aristotle's "Physics," all objects come to rest because it is their "natural state," not because momentum is lost due to friction, i.e. in Aristotle's world view momentum is not conserved!

- Newton's 3rd Law (aka Action-Reaction Law)
  When momentum is exchanged between objects A and B, the momentum lost by A is exactly the same as the momentum gained by B. No momentum is lost in the transaction.

NEWTON'S 3RD LAW IN DETAIL

- When momentum is exchanged between objects A and B, the momentum lost by A is exactly the same as the momentum gained by B. No momentum is lost in the transaction.
- Let's say that A "pushes" B and momentum $\Delta\vec{p}$ is transferred from A to B:

$$\Delta\vec{p}_A = -\Delta\vec{p}, \qquad \Delta\vec{p}_B = \Delta\vec{p}$$

  Note that A lost momentum $\Delta\vec{p}$ because it gave $\Delta\vec{p}$ to B by "pushing" it. NOT because B "reacted" to the push and "pushed back." It is a single transaction.
- The rates of momentum transfer are:

$$\vec{F}_{B\to A} = \frac{\Delta\vec{p}_A}{\Delta t} = -\frac{\Delta\vec{p}}{\Delta t} = -\frac{\Delta\vec{p}_B}{\Delta t} = -\vec{F}_{A\to B}$$

- The "reaction force" is NOT the "reaction" to the "action force!"

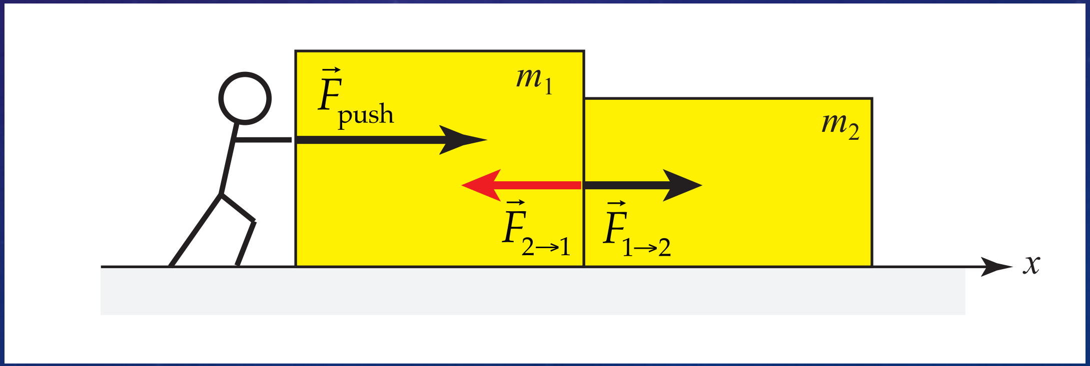
"ACTION" & "REACTION" ARE MISLEADING

- Proposal: rename the "action-reaction law" as the "credit-debit law"

$$\Delta\vec{p}_A = -\Delta\vec{p}, \qquad \Delta\vec{p}_B = \Delta\vec{p}$$

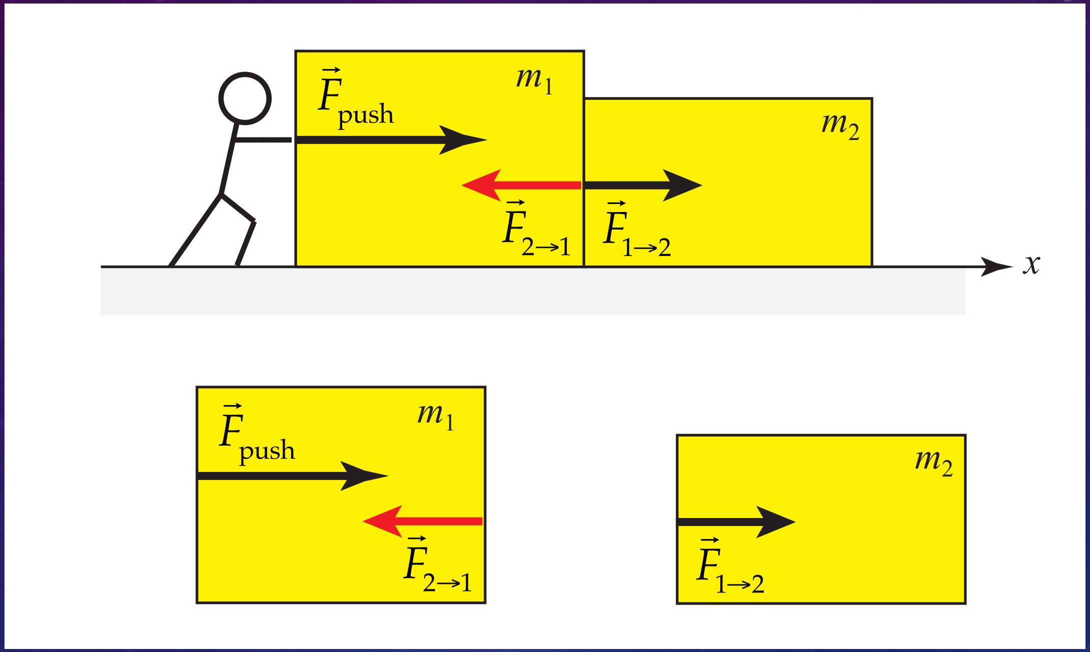
$\Delta\vec{p}$ appears as a credit on $\mathrm{B}'\mathrm{s}$ momentum account
$\Delta\vec{p}$ appears as a debit on $\mathrm{A}'\mathrm{s}$ momentum account

- A's debit must be the same as B's credit
- Use black and red arrows to indicate credit and debit forces:



"FREE BODY DIAGRAM" IS ALSO A WEIRD TERM

- Proposal: rename the "free body diagram" the "momentum accounting diagram"



OTHER BENEFITS

- "Impulse" becomes a redundant concept since it is the same thing as "momentum transfer"
  → when it is necessary to emphasize that Δt is small, call it the "instantaneous momentum transfer"
- No need to invoke the impulse-momentum law to derive the pressure of an ideal gas from the kinetic theory of gases
- Air drag/lift obviously has to be proportional to the velocity squared since the number of air molecules that you collide with per unit time, and the amount of momentum transferred to you from an air molecule per collision are both proportional to the velocity
- Internal forces of an extended object are irrelevant to the motion of its center-of-mass since they represent momentum transfer from one part of the object to another.