# Drag Force; Interacting systems and Newton's 3rd Law (part 1)

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# Logistics on midterm 1

- Date and time: **Oct 8 (Tue), 7:30 – 9:30 PM**
- Venue: **Changhou Lecture Hall** (a.k.a. **SC 101**)
- Those who have conflict and/or accommodation will receive email from me on alternative date, time and venue

# Scope of midterm 1

- **Knight §1 – §7**, plus **supplementary notes on drag force**
- Lecture 1 – 13 (maybe also loose ends from 14)
- Homework 1 – 4
- Preflights to weeks 2 – 4

# Format of midterm 1

- There will be **4 short questions** (4 points each) and **3 long questions** (8 points each)
- Partial credits will be awarded
- Difficulty of questions on par with homework. However, **long questions will be broken down into parts**
- Question order will neither be related to difficulty nor "chronological"

# Regulations on midterm 1

- Formula sheets and scratch papers will be provided
- You can also bring in one letter-sized **handwritten** prep sheet
- You can bring a calculator. However, no “smart” device or internet access during the exam are allowed.
- **Important:** **do not** talk about the midterm afterwards until I say OK.

# Mock midterm exam 1

A **mock midterm exam** will be posted by Monday (if not earlier). It:

- Follows the format and length of the actual midterm
- Includes the actual instruction page
- Should be roughly as difficult as the actual midterm

**Formula sheets** for midterm 1 will be posted alongside the mock midterm. **Solutions** to the mock midterm will be posted by Wednesday (Oct 2)

# Outline

1. Drag force
2. Newton’s third law
3. Analyzing interacting systems

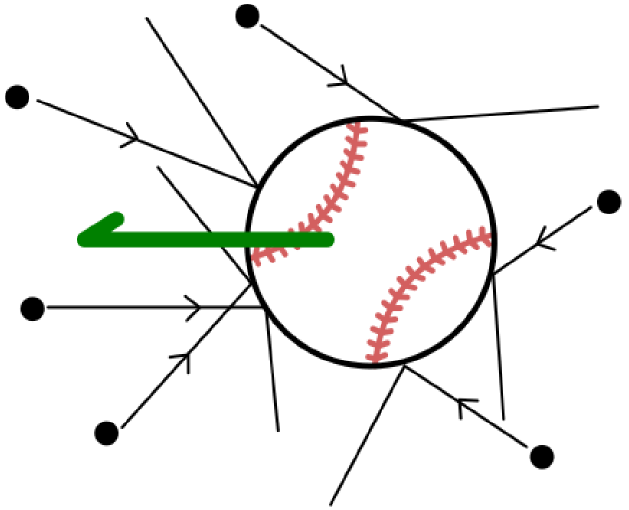
# 1. Drag force

# Catalogue of (macroscopic) forces

- Prescribed forces:
  - (Your push/pull, etc.)
- Forces determined by constraints:
  - Tension force $\vec{T}$
  - Normal force $\vec{n}$
  - Static friction $\vec{f}_s$
- Forces determined by formulas:
  - Gravitational force $\vec{F}_G$
  - Spring force $\vec{F}_{sp}$
  - Kinetic friction $\vec{f}_k$
  - Drag force $\vec{D}$

# Turbulent drag opposes motion relative to (non-sticky) fluid

- Applies to **“non-sticky”** situations
- Microscopic origin: collisions with fluid particles
- Direction: opposite to motion relative to the surrounding fluid
- Magnitude:

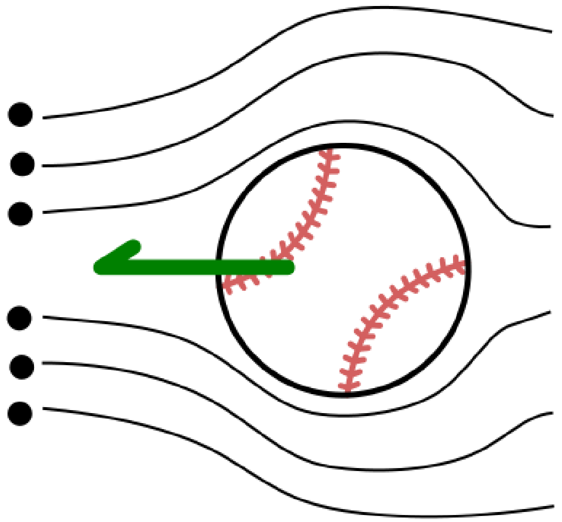


$$F_{\text{drag}} = \frac{1}{2}\rho C A v^2$$

| | Meaning | Unit |
|---|---|---|
| $\rho$ | density of fluid | kg/m$^3$ |
| $C$ | geometrical constant | 1 |
| $A$ | reference area | m$^2$ |
| $v$ | speed of object | m/s |

# Viscous drag opposes motion relative to (sticky) fluid

- Applies to **"sticky"** fluid
- Microscopic origin: shear against fluid particles
- Direction: opposite to motion relative to the surrounding fluid



- Magnitude:

$$F_{\text{visc}} = \mu c \ell v$$

| | Meaning | Unit |
|---|---|---|
| $\mu$ | viscosity of fluid | N·s/m² |
| $c$ | geometrical constant | 1 |
| $\ell$ | length (e.g. radius) | m |
| $v$ | speed of object | m/s |

# Sticky versus non-sticky—Reynolds number $Re$

- The viscosity $\mu$ (as in $F_{\text{visc}} = \mu c \ell v$) measures the stickiness of a fluid, but it is a **dimensionful** number
- We need a **dimensionless** measure of stickiness, and that's provided by the Reynolds number:

$$Re \equiv \frac{\rho \ell v}{\mu}$$

- Conclusion: situation is sticky if you are **small** or **slow (!)**

| | Meaning | Unit |
|---|---|---|
| $\rho$ | density of fluid | kg/m$^3$ |
| $\ell$ | typical length | m |
| $v$ | typical speed | m/s |
| $\mu$ | viscosity of fluid | N·s/m$^2$ |
| $Re$ | Reynolds number | 1 |

# Number sense: viscosity and Reynolds number

| Fluid | $\rho$ (kg/m³) | $\mu$ (N·s/m²) |
|---|---|---|
| Air | 1.204 | $1.81 \times 10^{-5}$ |
| Pure water | 998 | $1.002 \times 10^{-3}$ |
| Engine oil | 888 | 0.837 |
| Glycerine | 1264 | 1.519 |

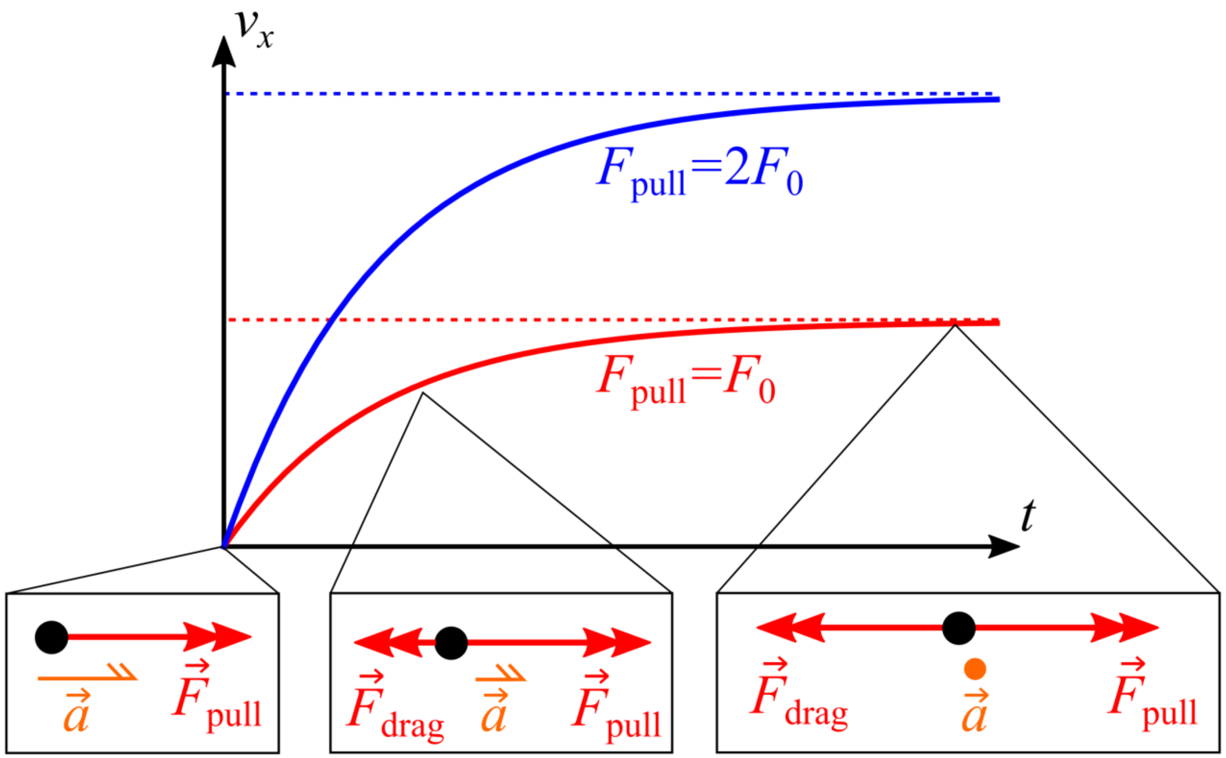
* **Sources:** Kundu *et. al.*, *Fluid Mechanics* (6th ed.)
Çengel and Cimbala, *Fluid Mechanics* (4th ed.)

| Situation | $Re$ |
|---|---|
| Bacterium swimming | $1 \times 10^{-4}$ |
| Pollen grain falling | $1 \times 10^{-2}$ |
| Fruit fly flying | 100 |
| Small bird flying | $1 \times 10^{5}$ |
| Large whale swimming | $1 \times 10^{8}$ |

* **Source:** Vogel, *Comparative Biomechanics* (2nd ed.)

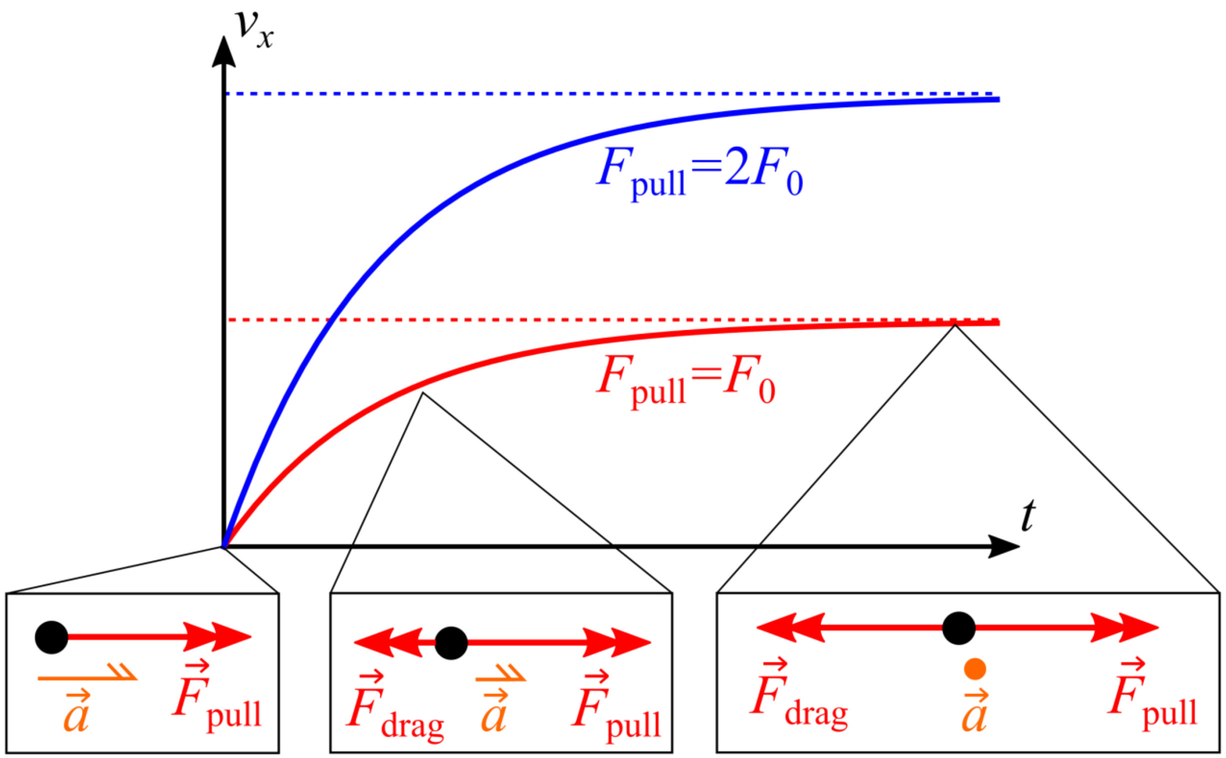
# Terminal velocity

- Consider constant pull in the presence of $v$-dependent drag
- $v_x$ increases until $F_{\text{pull}} = F_{\text{drag}}$
- The final $v_x$ attained is called the **terminal velocity** $v_{\text{term}}$



# Terminal velocity and naïve notion of force

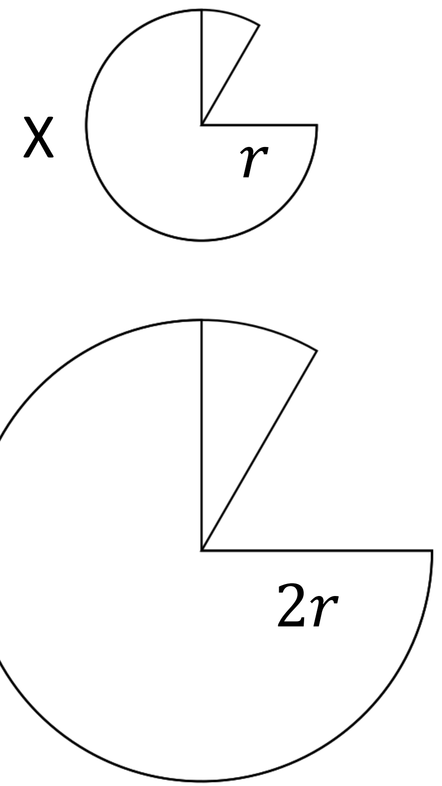
- Note that in the presence of drag, $F_{\text{pull}}$ leads to **constant** $v$
- Also, $F_{\text{pull}} \nearrow$ leads to $v_{\text{term}} \nearrow$
- Both agree with our **naïve** notion of force!



# Your turn: paper cones drop time

Consider two paper cones X and Y made out of the same piece of paper, except that cone Y has twice the radius of cone X. If both cones are dropped from rest, which one will land first? (**Hint:** we are in the turbulent regime)

A. Cone X will land first
B. Both will land at roughly the same time
C. Cone Y will land first



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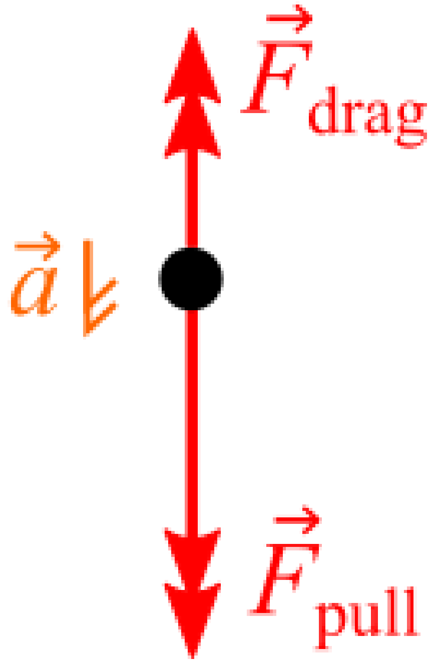



From Newton's 2nd Law:

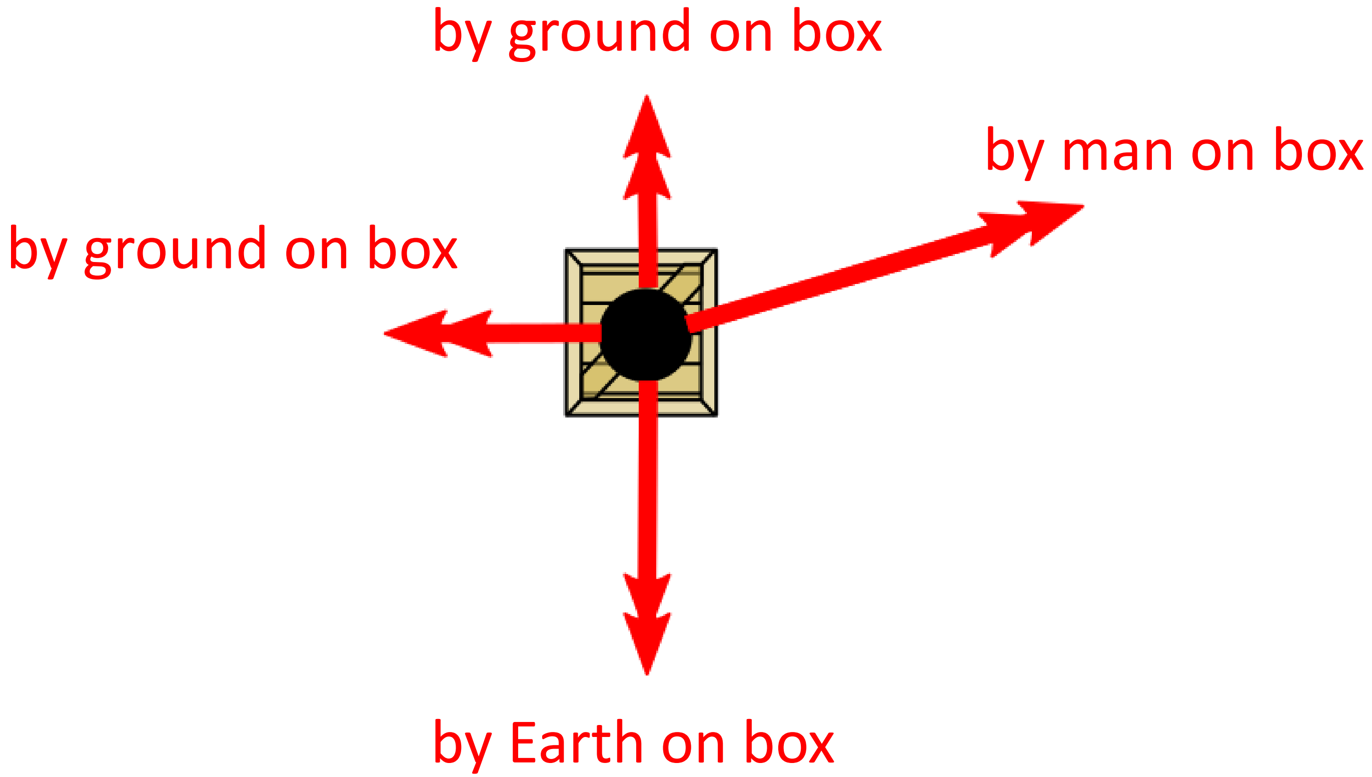
$$mg - \frac{1}{2}\rho C A v^2 = ma$$

Note that in this case $m \propto A$. Thus, all terms above $\propto A$

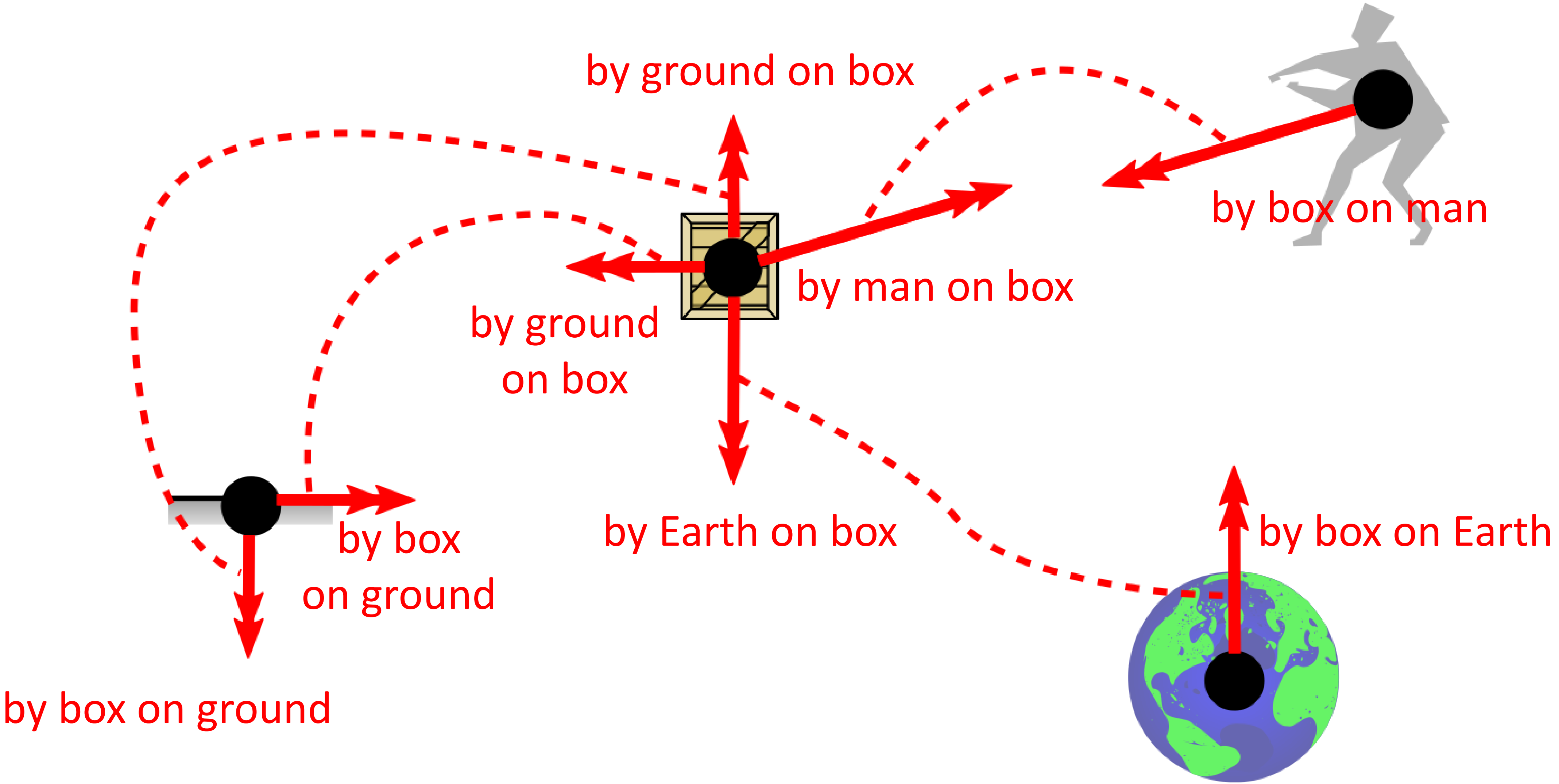
$\Rightarrow A$ drops out of the kinematics!

# 2. Newton’s third law

# Force acts on an **object** by an **agent**

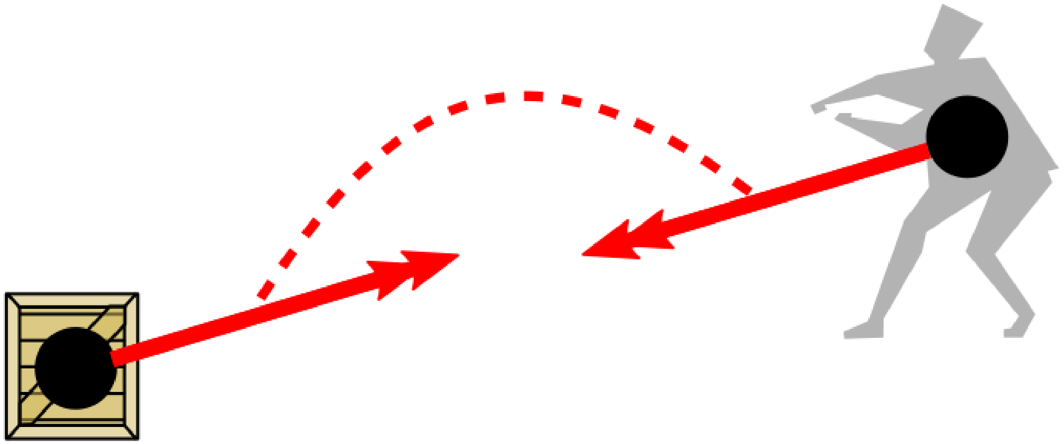


# Forces come in pairs

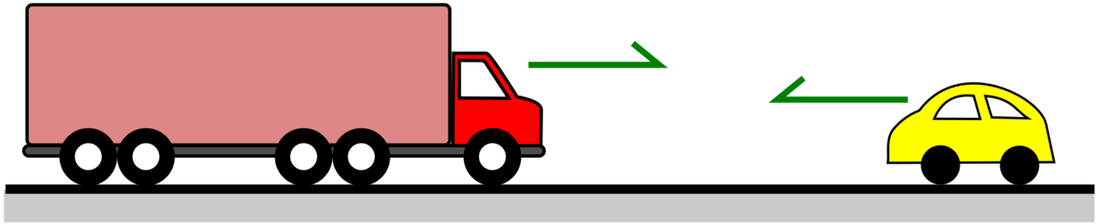


# Newton’s third law

- Every force is a member of an **action/reaction pair**
- The two members of the pair act on **different** objects
- The two members are **equal in magnitude** but **opposite in direction**



# Your turn: car and truck collision. SAD.



A moving truck collides with a moving car head-on :-/. Compare:

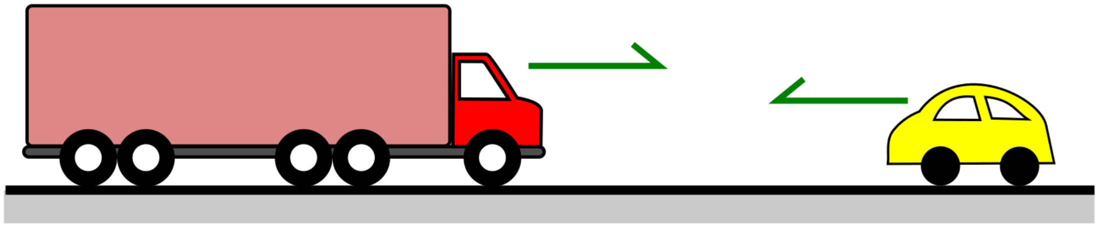
1. $F_{\text{on truck}}$ and $F_{\text{on car}}$ over the course of the collision

   A. $F_{\text{on truck}} > F_{\text{on car}}$  B. $F_{\text{on truck}} = F_{\text{on car}}$  C. $F_{\text{on truck}} < F_{\text{on car}}$

2. $a_{\text{truck}}$ and $a_{\text{car}}$ over the course of the collision

   A. $a_{\text{truck}} > a_{\text{car}}$  B. $a_{\text{truck}} = a_{\text{car}}$  C. $a_{\text{truck}} < a_{\text{car}}$

# Your turn: car and truck collision. SAD.



- By Newton's 3rd Law:

$$F_{\text{on truck}} = F_{\text{on car}}$$

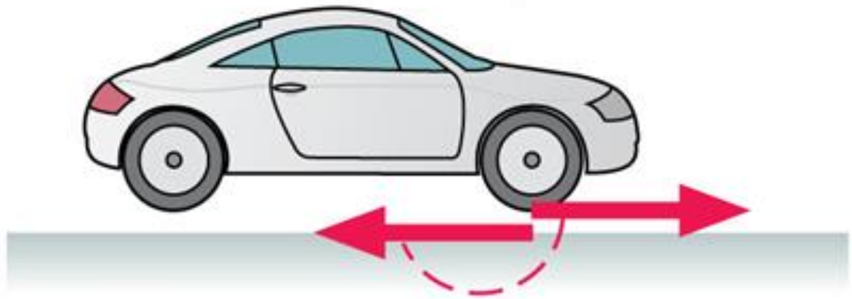
- Together with Newton's 2nd Law:

$$m_{\text{truck}}\, a_{\text{truck}} = m_{\text{car}}\, a_{\text{car}}$$

$$\Rightarrow a_{\text{car}} > a_{\text{truck}}$$

# Remark: propulsion

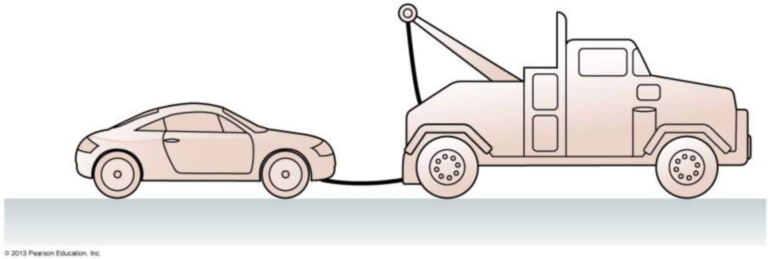
- When we walk, it is the static friction by the ground on us that pushes us forward!
- This is possible because our body is flexible (there are a lot of **internal forces** involved in the process!)
- Similarly, a car is propelled forward by the static friction between the ground and its driving wheels

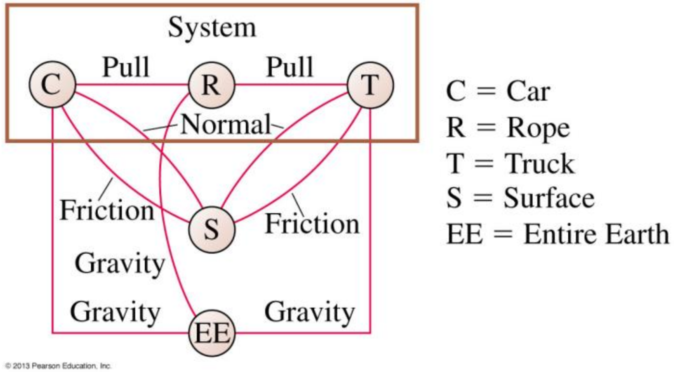


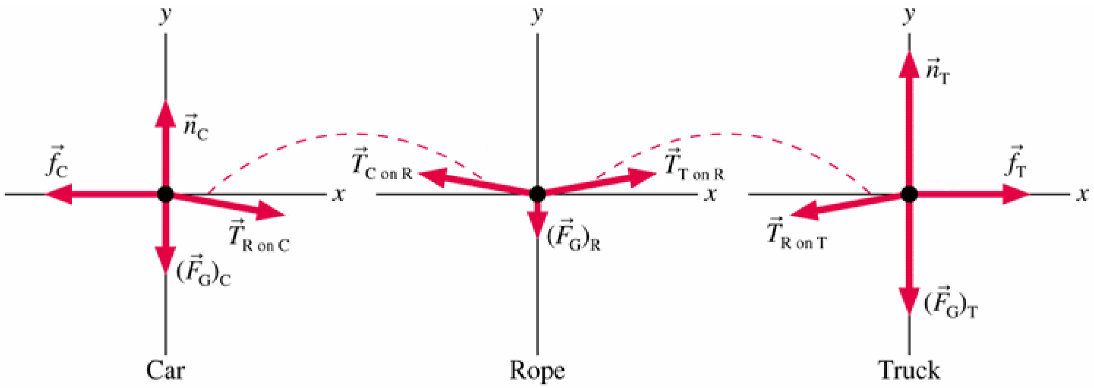
# 3. Analyzing interacting systems

# Framework for analyzing interactive systems

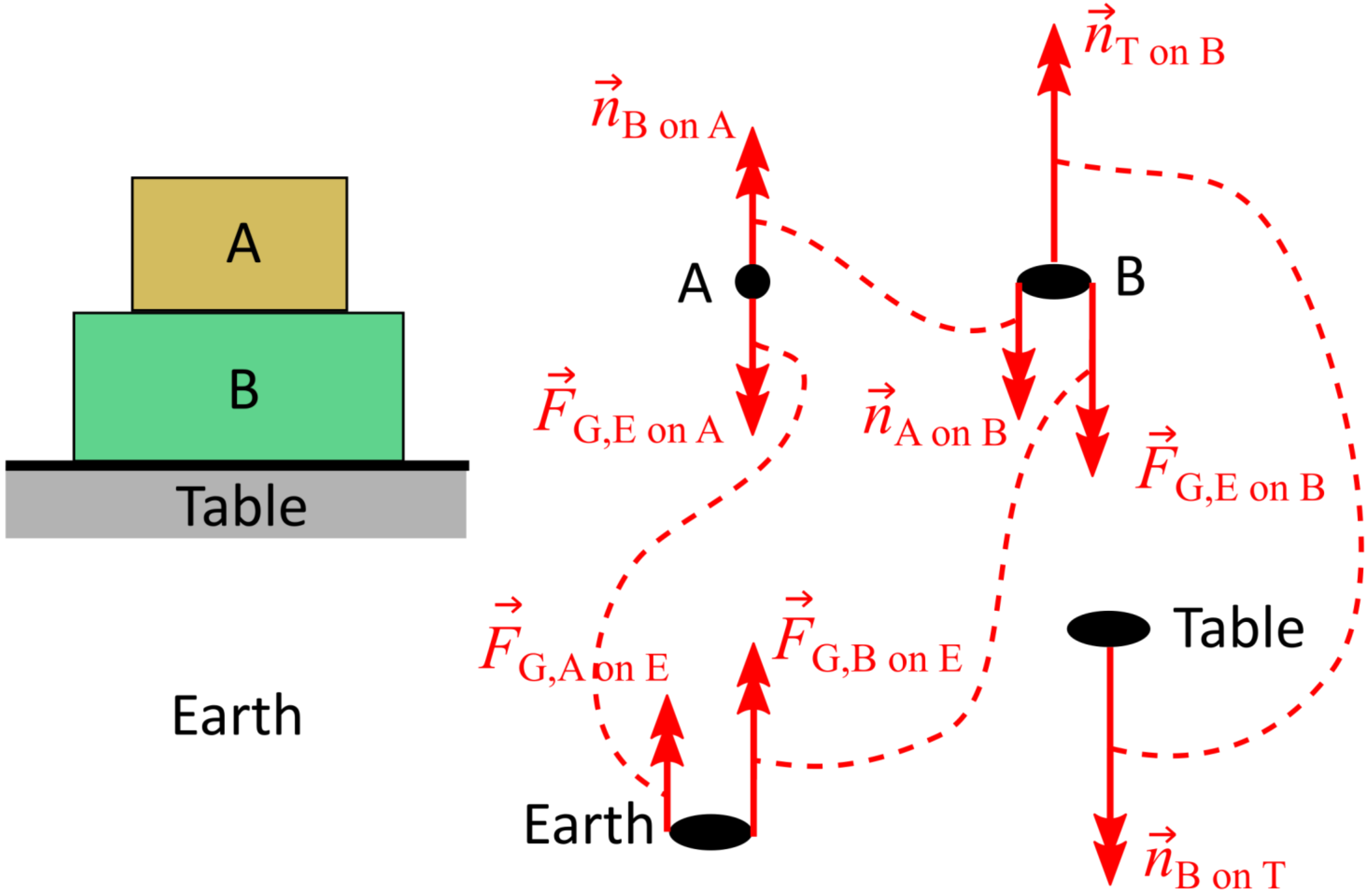
1. Identify objects involved in the situation
2. Identify interactions between the objects
3. Identify the system of interest
4. Construct free-body diagram for each object of the system



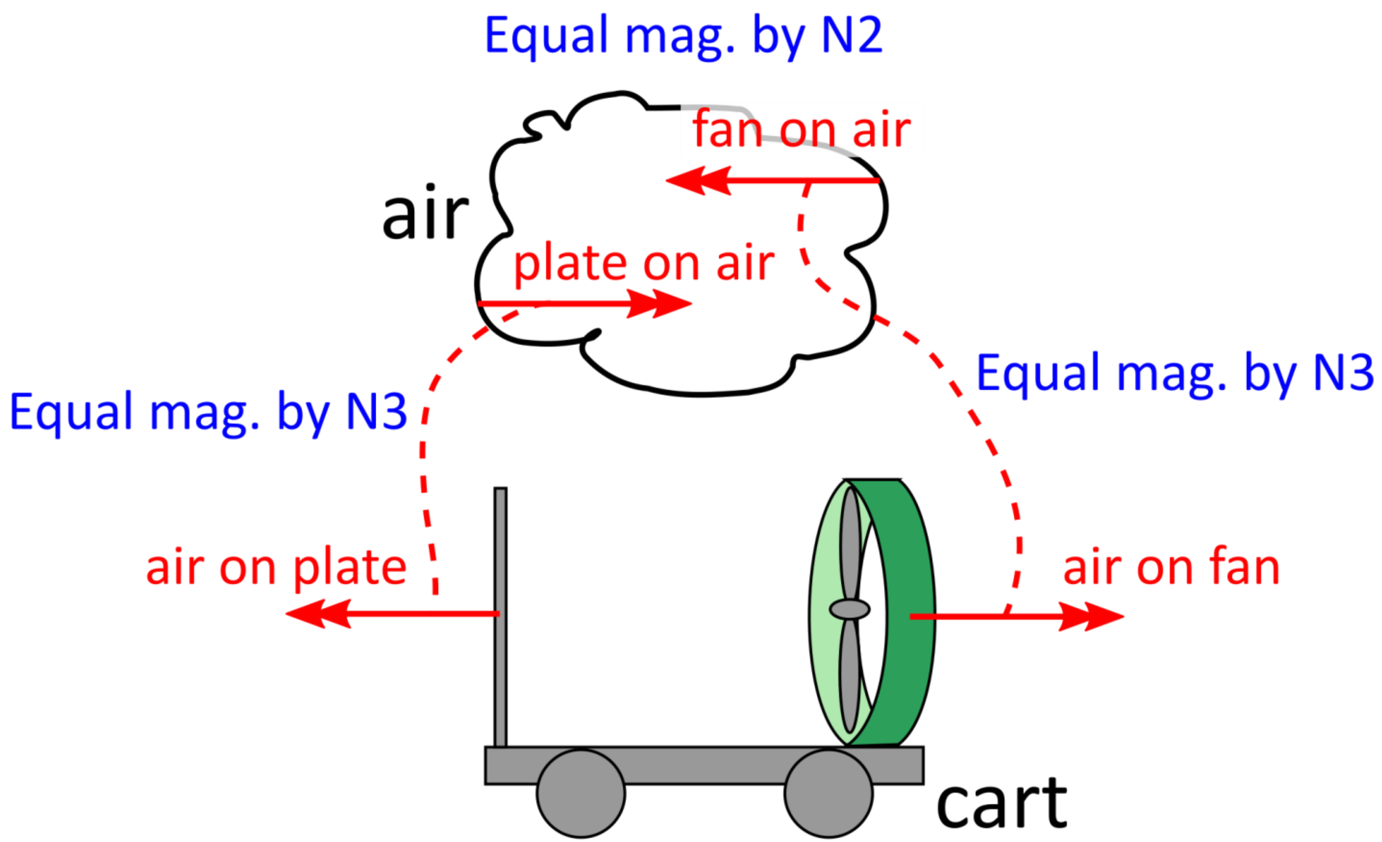



# Week 4 preflight Q2



# Demo: fan cart

- Question: why is the fan cart not moving?




# Your turn: equal by 2nd Law or 3rd Law?

You are pushing on a heavy block and the block remains still. Why are the following true?

(i) $f_{s\,(\text{block on grd})} = f_{s\,(\text{grd on block})}$

(ii) $F_{\text{me on block}} = f_{s\,(\text{grd on block})}$

A. (i) true by N2; (ii) true by N3

B. (i) true by N3; (ii) true by N2

C. Both (i) and (ii) true by N2

D. At least one of (i) and (ii) NOT true