Lecture 13

Recap: Solid on Solid Friction

- force ∥ to interface between two surfaces that opposes relative motion
- can act in direction of motion (wrt. ground) [example: friction force from road on tire when car accelerates] or opposite to the direction of motion [example: friction force from road on tire when car brakes]

case ①: Static friction $\vec{f}_s$:

- no relative motion of surfaces in contact
- self-adjusts to prevent relative motion up to maximum value:

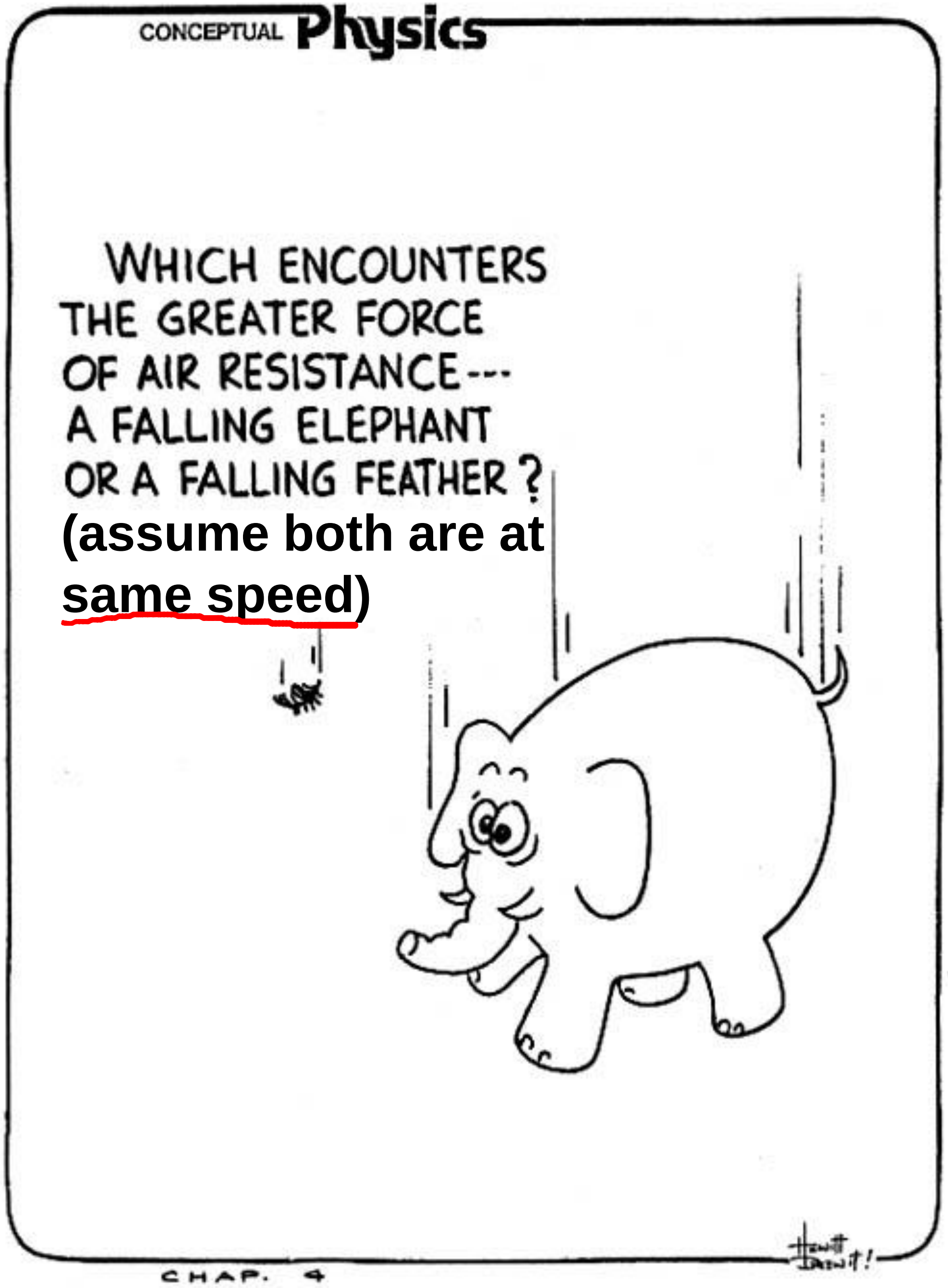
$$f_s \leq (f_s)_{max} = \mu_s N$$

← normal force

↖ coef. of static friction

case ②: Kinetic friction $\vec{f}_K$:

- for sliding of surfaces in contact
- $f_K = \mu_K N$, independent of other ∥ forces, rel. velocity



WHICH ENCOUNTERS THE GREATER FORCE OF AIR RESISTANCE--- A FALLING ELEPHANT OR A FALLING FEATHER?

(assume both are at same speed)

Elephant is large

⇒ has large cross-sect. area A

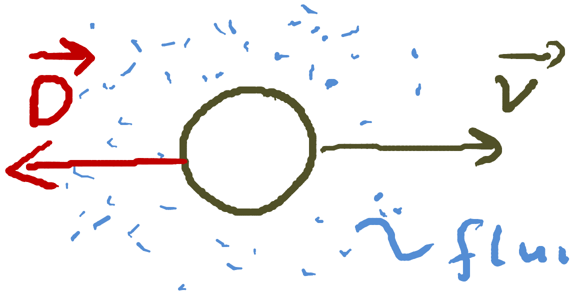
$D \propto A$

- [✓ **A.**] **Elephant**
- **B.** **Feather**
- **C.** **Same**

Today:

- **Fluid friction:**
  - **Viscous and turbulent drag**
  - **Turbulent drag force**
  - **Damage from hurricanes**
  - **Air drag**
  - **Fish and bird formations**
  - **Terminal speed**

Fluid-Solid Friction: "Drag force" $\vec{D}$



$\vec{D}$: Drag force exerted by the fluid on the object moving relative to it; opposes relative motion

$\vec{v}$: V_{object} relative to fluid

Two Regimes:

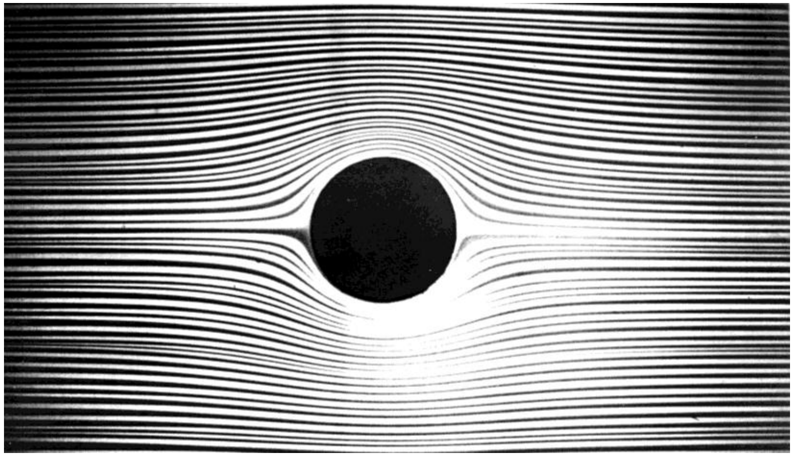
① Viscous Drag:

- tiny objects, tiny velocities and/or viscous (thick) fluids
  e.g. raindrops in clouds, bacteria in water

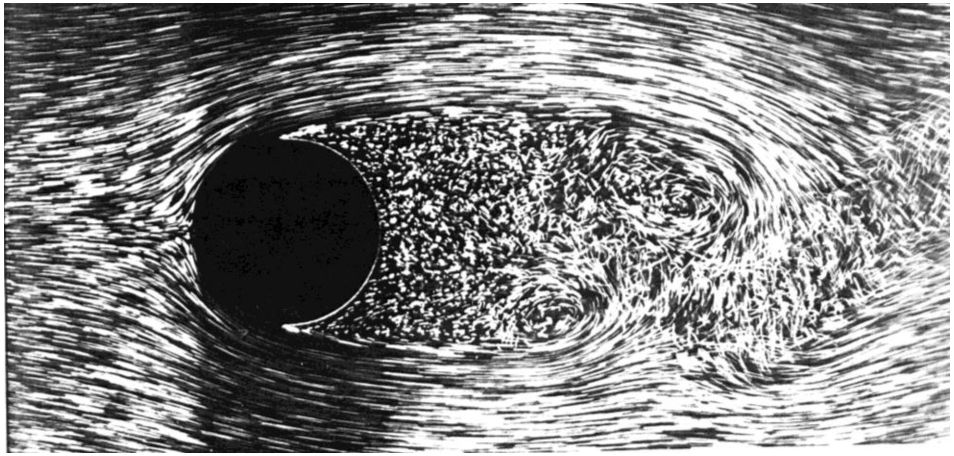
② Turbulent Drag:

- ordinary size objects, everyday to large velocities, fluids like air and water

Laminar Flow: Low velocities / small diameters / "thick" fluids ⇒ viscous drag



Turbulent flow: High velocities / larger dia-meters / "thin" fluids ⇒ turbulent drag



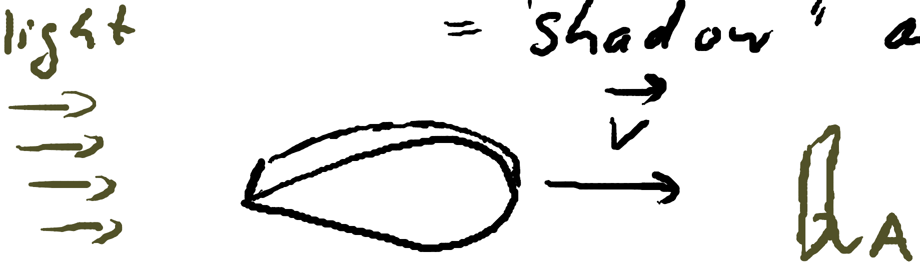
$\vec{D}$ due to turbulent drag

relevant factors:

- ρ_{fluid} : fluid density $[\rho] = kg/m^3$
- A_{object} : effective cross-sectional area of object

  = area swept out by the object that is $\perp$ to $\vec{v}$ as it moves through the fluid $[A] = m^2$

  = 'shadow' area



- v : speed of the object relative to fluid $[v] = \frac{m}{s}$

The force due to turbulent air drag depends on the density of the fluid ρ (in kg/m^3), the area A swept out by the object as it moves through the fluid (in m^2), and the object's speed v relative to the fluid (in m/s).

Using dimensional analysis, what is the relation between D, ρ, A, and v? $D \propto \rho^{\alpha} A^{\beta} v^{\gamma}$

D	ρ	A	v
$N = kg \frac{m}{s^2}$	$\frac{kg}{m^3}$	m^2	m/s

$\Rightarrow \alpha = 1 \qquad \gamma = 2 \qquad \beta = 1$

$\Rightarrow D \propto \rho A v^2$

- A. $D \propto \rho A v$
- [✓ B.] $D \propto \rho A v^2$
- C. $D \propto \rho A^2 v$
- D. $D = \rho A v$
- E. $D = \rho A v^2$

Detailed Analysis:

$\rho_{air} = 1.2 \text{ kg/m}^3$

$\rho_{water} = 1000 \text{ kg/m}^3$

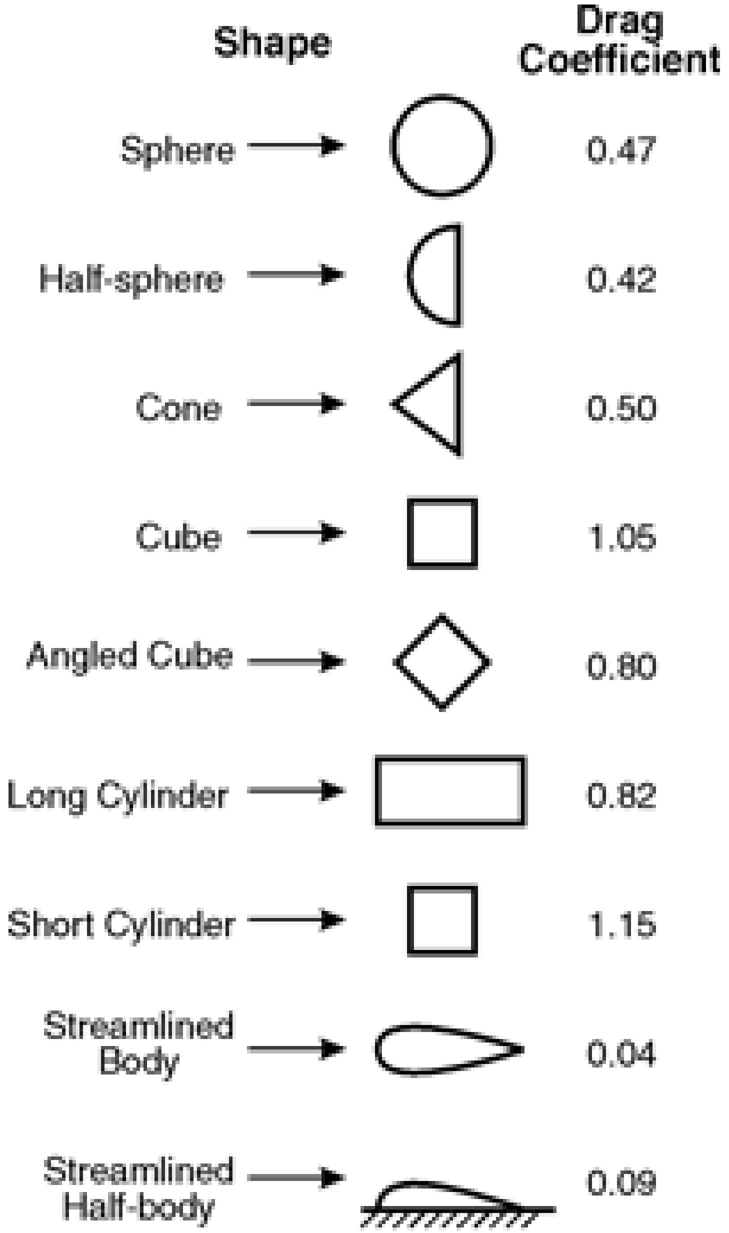
$$D_{\text{turbulent drag on object}} = \frac{1}{2} C_{obj} \rho_{fluid} A_{obj} V^2_{\text{object wrt. fluid}}$$

drag coefficient

- dimensionless
- typical : 0.1 → 1.2
- value depends on shape and surface texture of object
- flat plate : $C \sim 1.2$
- sphere : $C \sim 0.5$

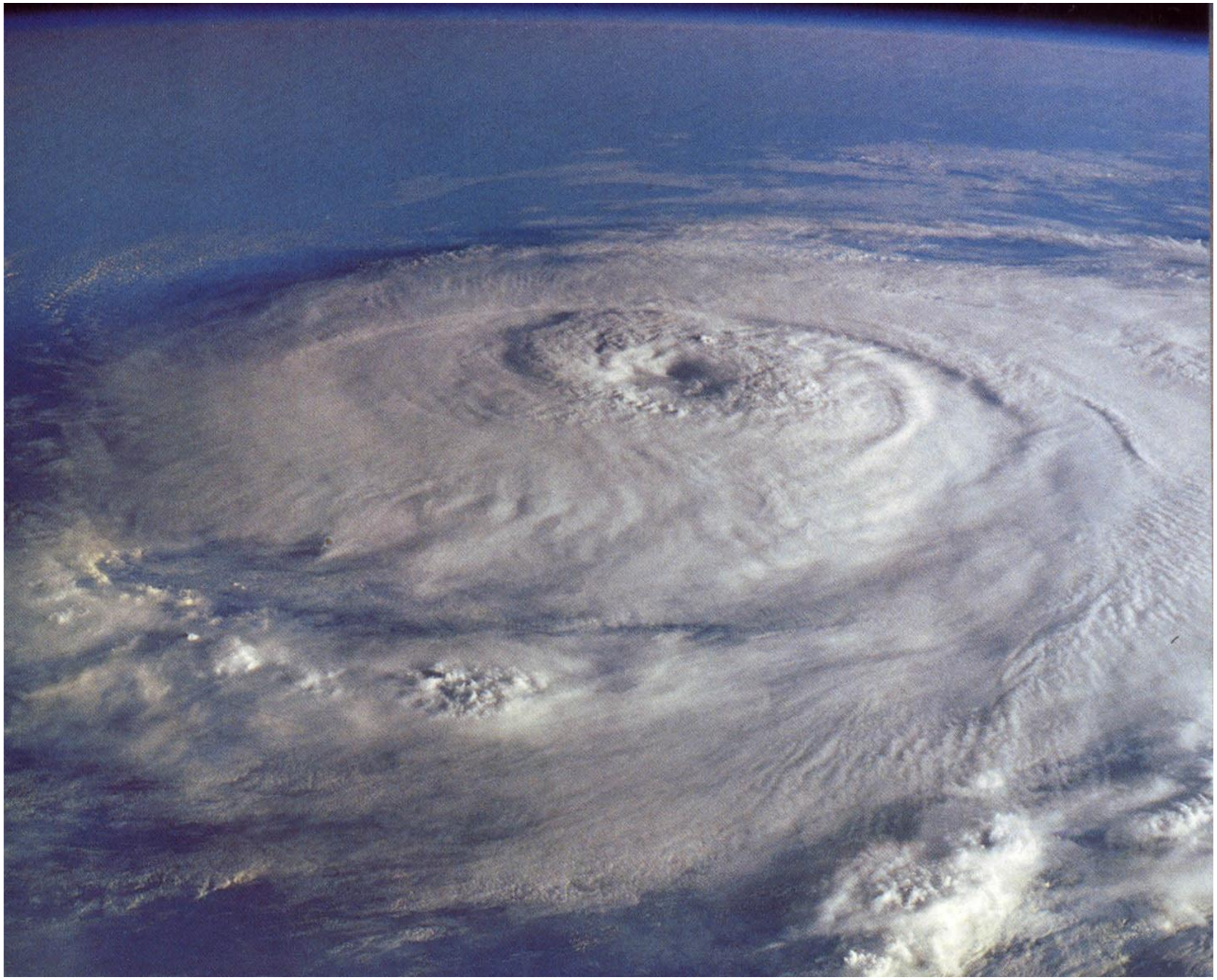
Note: $D \propto v^2$ } different than kinetic friction for solid on solid

$f_K = \mu_K \cdot N$



Measured Drag Coefficients

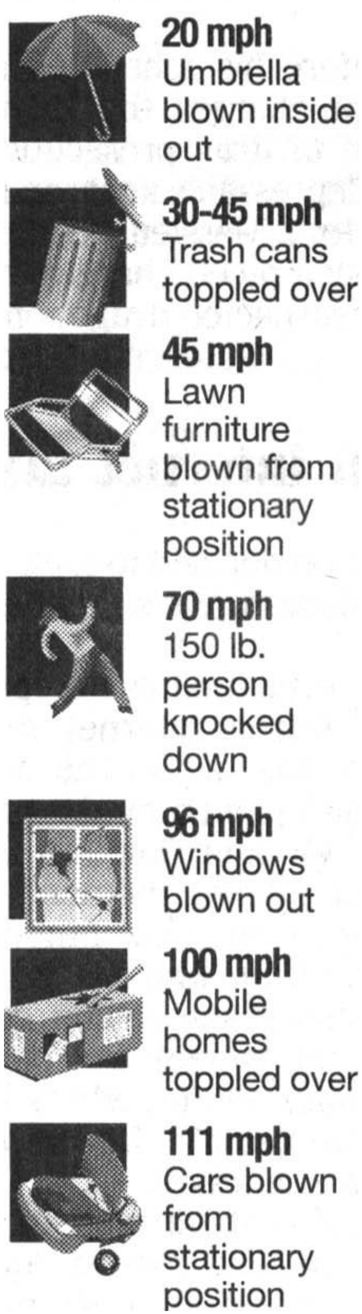
Damage from Hurricanes:



Wind Forces:

$$D=(1/2)\ C\ \rho\ A\ v^2,$$

Assume $C\approx1$



20 mph
Umbrella blown inside out

30-45 mph
Trash cans toppled over

45 mph
Lawn furniture blown from stationary position

70 mph
150 lb. person knocked down

96 mph
Windows blown out

100 mph
Mobile homes toppled over

111 mph
Cars blown from stationary position

A (m^2)	v (m/s)	D (N)	D (lb)
0.3	9	14	3
0.5	20	120	30
0.5	30	270	60
5	50	7500	1700

Damage from Hurricanes:

Damage from Hurricanes:

$D=(1/2)\ C\ \rho\ A\ v^2$, $\rho_{water} \sim 800\ \rho_{air}$

BILL WARREN / Journal Staff

Ithaca Firefighter Chris Kourkoutis, right, helps Allison Crouch cross Taughannock Creek after she got stranded with two others on the northern side of the creek Thursday afternoon at Taughannock Falls State Park. Trumansburg and Ithaca firefighters worked together to set up the rescue.

Trio rescued at Taughannock Creek

$\rho_w / \rho_{air} \approx 800$

What speed v_w of flowing water will exert approximately the **same drag force** on a Stop sign as the 160 mi/h wind from a hurricane?

Drag force: $$\underset{\text{same}}{D} = \frac{1}{2} \underset{\text{same}}{C} \overset{\text{varying}}{\rho} \underset{\text{same}}{A} \overset{\text{varying}}{v^2}$$

$$\Rightarrow D = \text{const} \propto \rho v^2$$

$$\Rightarrow v^2 \propto \frac{1}{\rho}$$ } for same drag force on stop sign

$$\Rightarrow \left(\frac{V_{water}}{V_{air}}\right)^2 = \frac{\rho_{air}}{\rho_{water}} = \frac{1}{800}$$

$$\Rightarrow \frac{V_w}{V_{air}} \approx \frac{1}{\sqrt{800}} \Rightarrow V_w \sim \frac{1}{30} V_{air} \approx 5 \ \text{mi/h}$$

v_w = ?

A. ~0.2 mi/h

[✓ B.] ~ 5 mi/h

C. ~ 20 mi/h

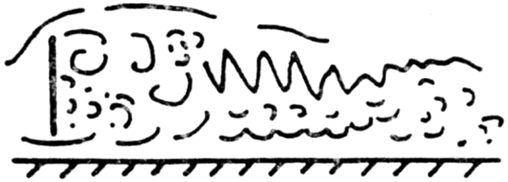
D. ~ 40 mi/h

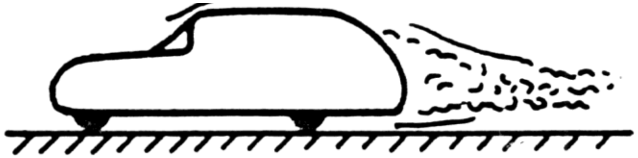
E. ~ 80 mi/h

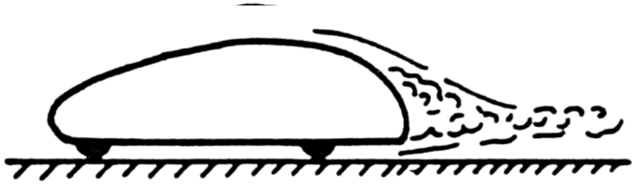
Air Drag in Auto Design:

$$D = (1/2)\ C\ \rho\ A\ v^2$$

C:







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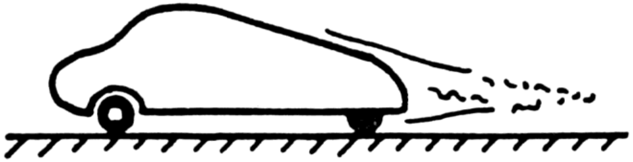


Air Drag in Auto Design:

$$D = (1/2)\ C\ \rho\ A\ v^2$$

Honda Insight: C_D=0.25, MPG = 70

Air Drag in Auto Design:

$$D = (1/2)\ C\ \rho\ A\ v^2$$

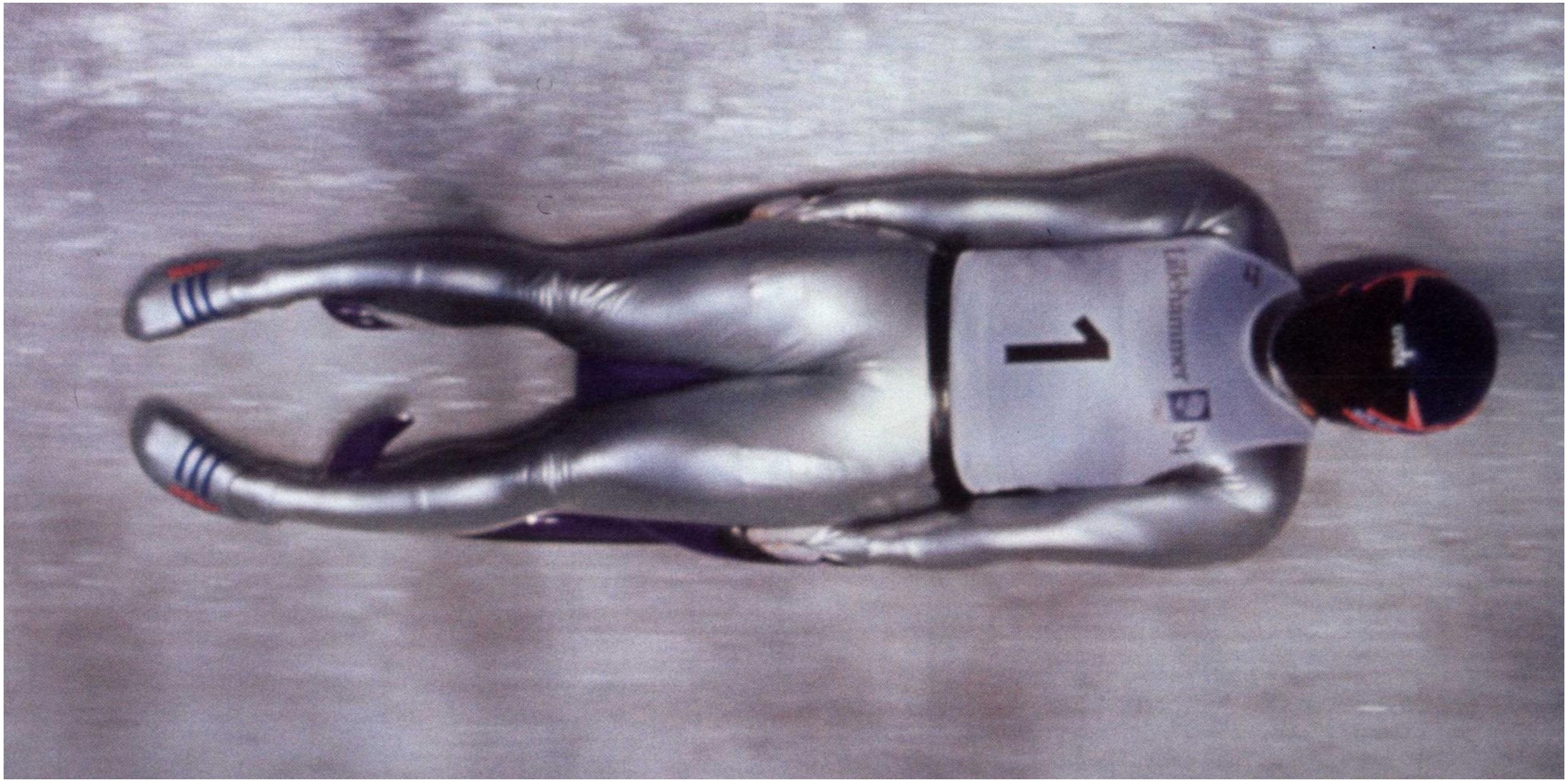
Jeep Cherokee: $C_D = 0.51$, MPG=21

Air Drag in Ski Jumping:

$$D = (1/2)\ C\ \rho\ A\ v^2$$

Air Drag in Luge:

$$D = (1/2)\ C\ \rho\ A\ v^2$$



Record luge speed: **85 mi/h**

Air Drag in Cycling:

$$D = (1/2)\ C\ \rho\ A\ v^2$$

Air Drag in Cycling:

$$D = (1/2)\ C\ \rho\ A\ v^2$$

World Speed Records:

200 m, flying start:
71.3 km/h (~45 mi/h)

1 hour:
56.4 km/h (~35 mi/h)

How does the **drag force** exerted on a cyclist moving at ***v* = 54 km/h** compare with the force exerted on a cyclist moving at ***v* = 27 km/h**?

$$D = \underbrace{\frac{1}{2} C \rho A}_{\text{same}} \, v^2 \quad \nwarrow \text{vary}$$

$$D \propto v^2$$

$$\frac{D(2v)}{D(1v)} = \left(\frac{2v}{v}\right)^2 = 2^2 = \underline{\underline{4}}$$

D (54 km/h) / D (27 km/h) = ?

A. 1/4

B. 1/2

C. 1

D. 2

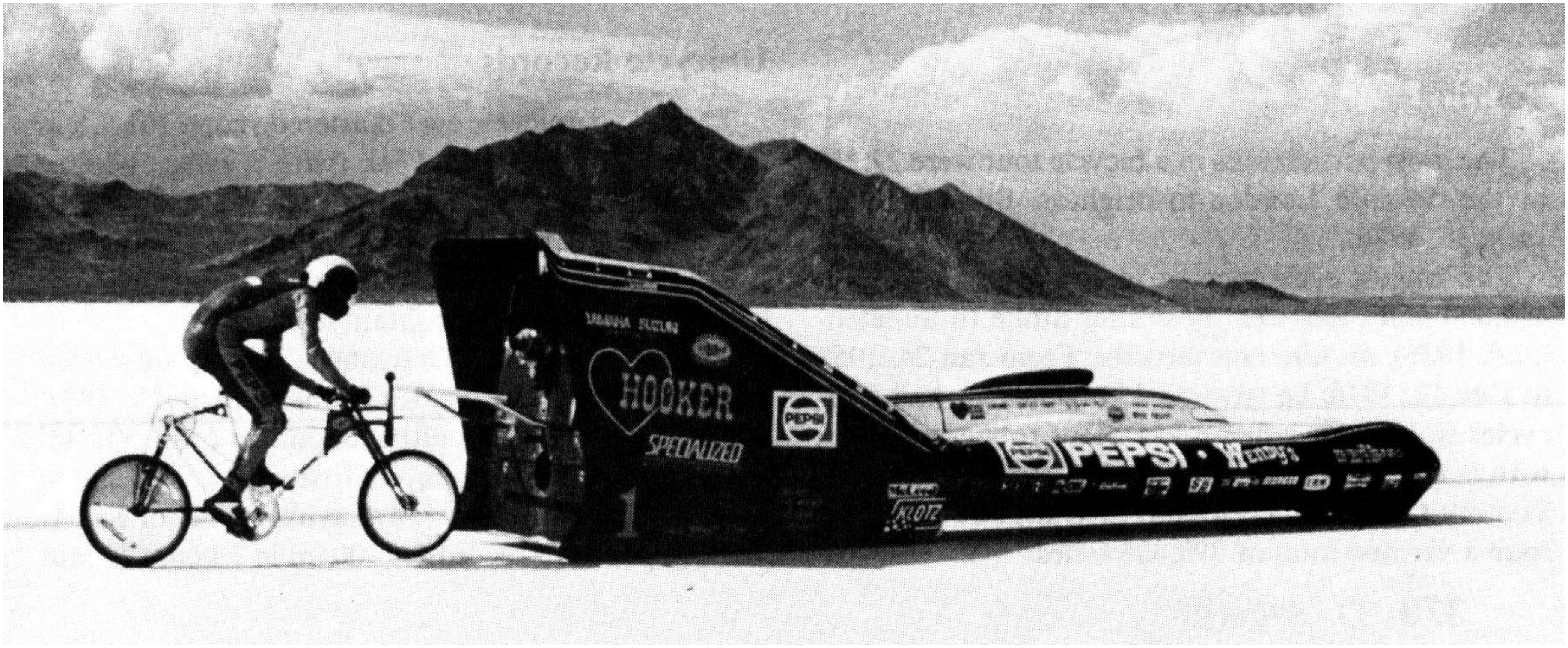
[✓ E.] 4

Air Drag in Cycling:

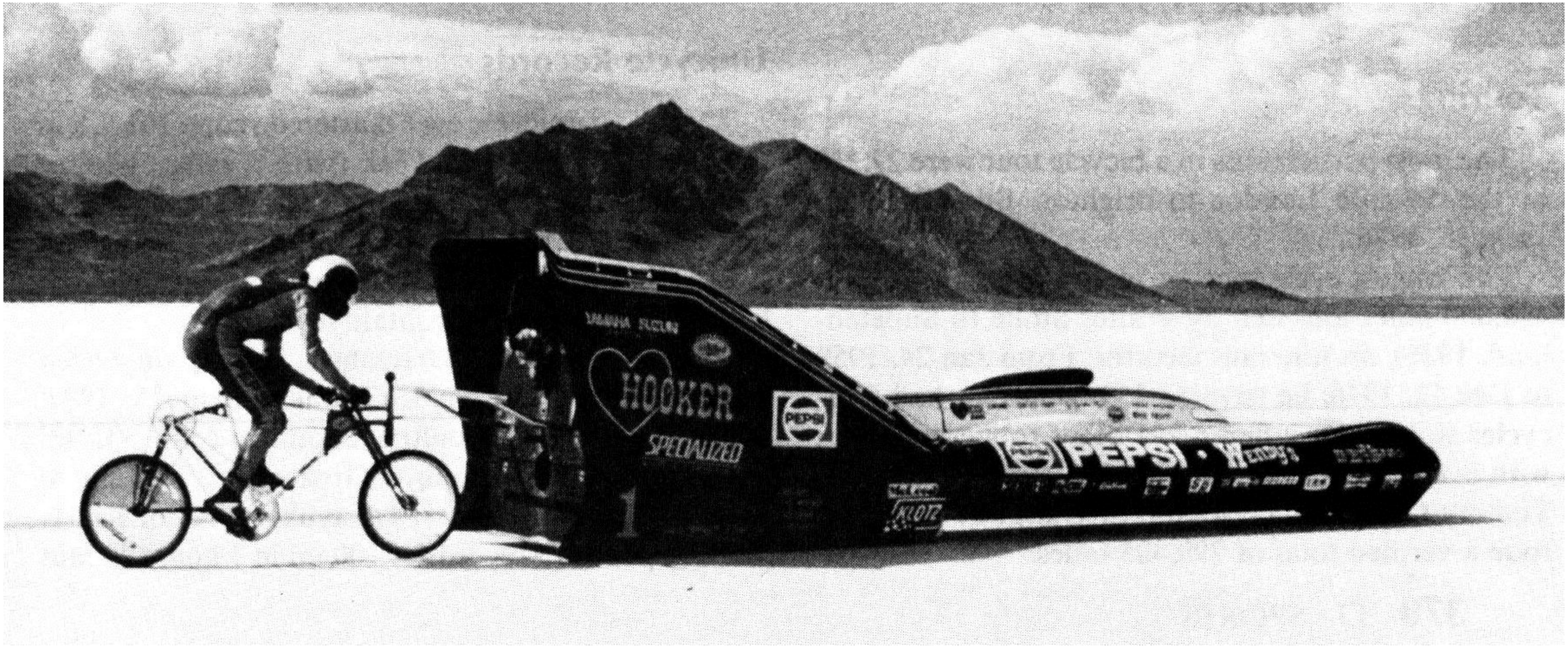
$$D = (1/2)\ C\ \rho\ A\ v^2$$

How fast could you cycle if you could eliminate air drag?

Bonneville Salt Flats, Utah:



Bonneville Salt Flats, Utah:

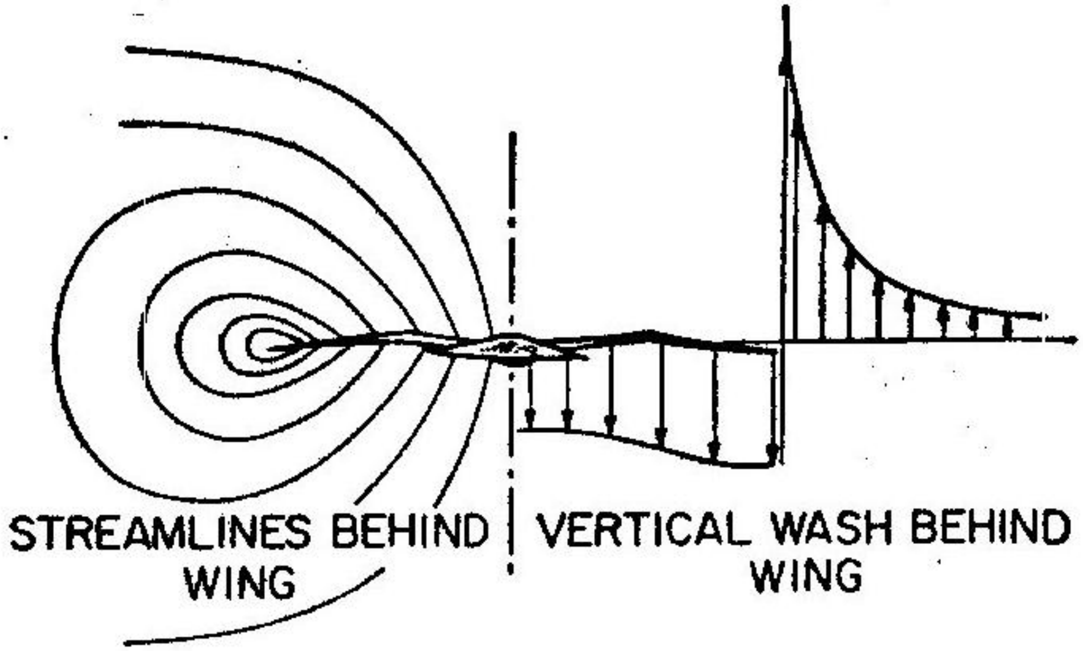


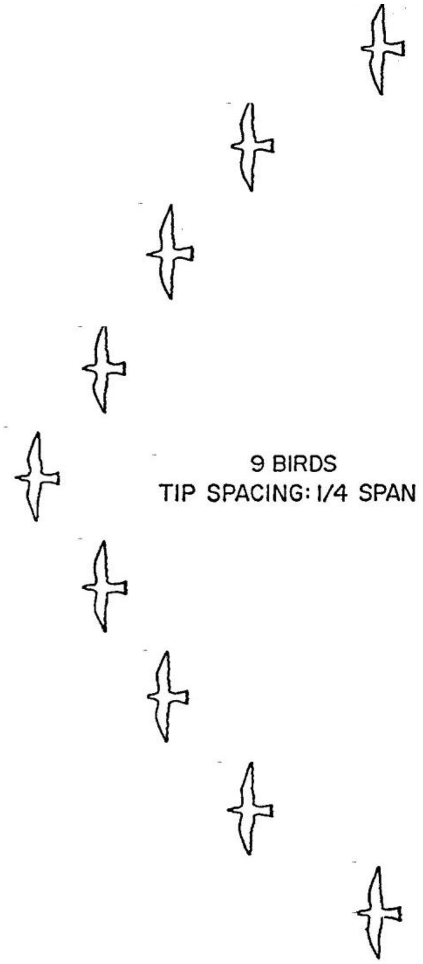
John Howard, USA, 1985: 152 mi/h

Fred Rompelberg, NL, 1995: 167 mi/h

(Rompelberg was 50 years old at the time.)

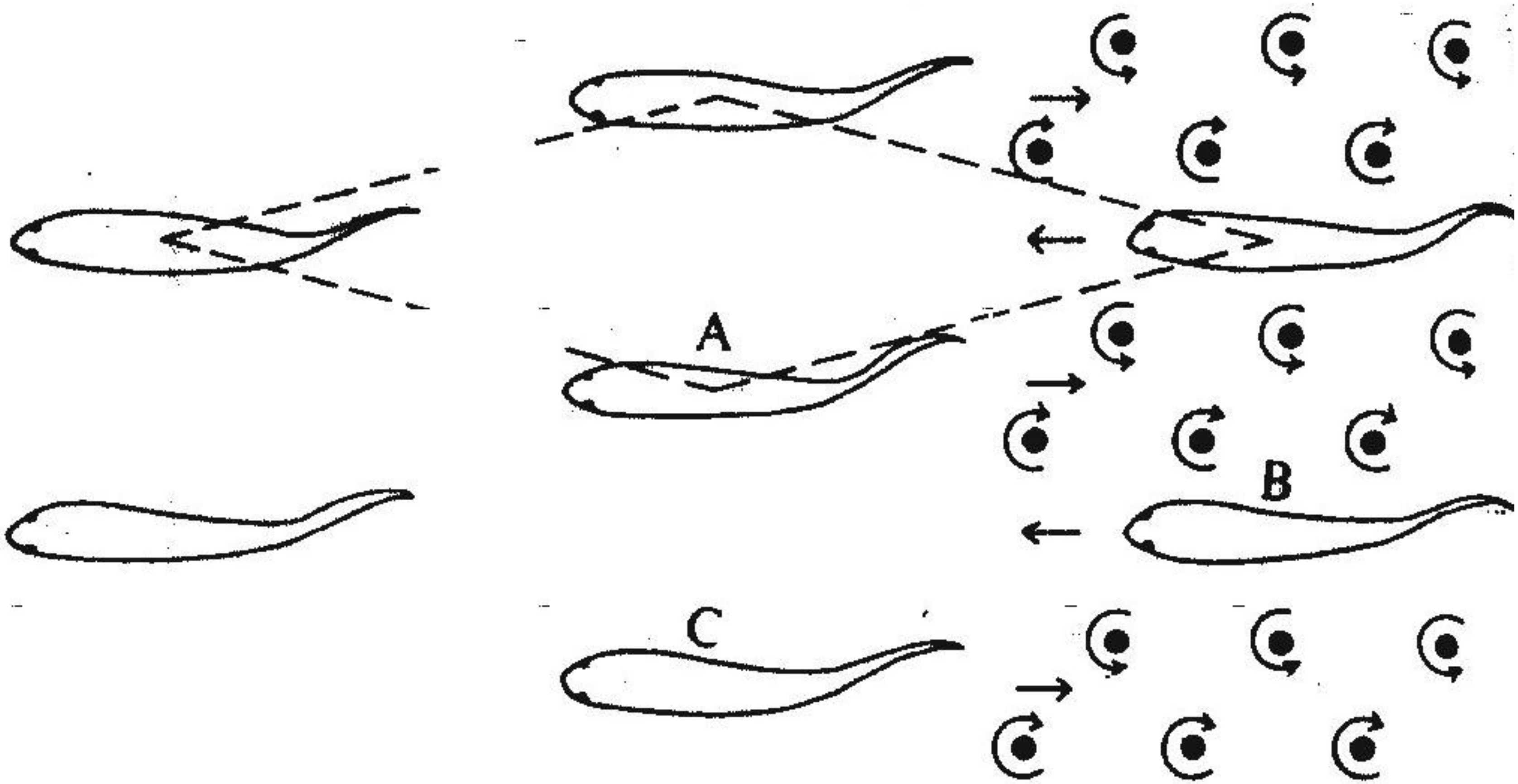
Bird Formations During Migration:





By taking advantage of **upward moving air** produced by their neighbors, **migrating birds traveling in “Vees" can travel 1.7 × as far as individual birds.** **(~40% energy savings/mile).**

Fish Schools



By **swimming in synchrony** in the correct formation, each fish can take advantage of **moving water created by the fish in front** to reduce drag.

Fish swimming in schools can swim 2 to 6 times as long as individual fish.

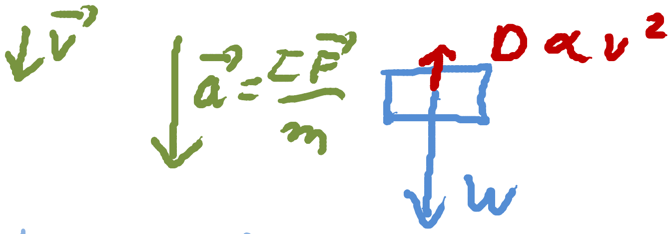
Terminal speed

Key idea: $D \propto v^2$ $\Rightarrow$ objects under influence of a drag force approach terminal speed $v_t = \text{const}$, i.e. $\vec{a} = 0$

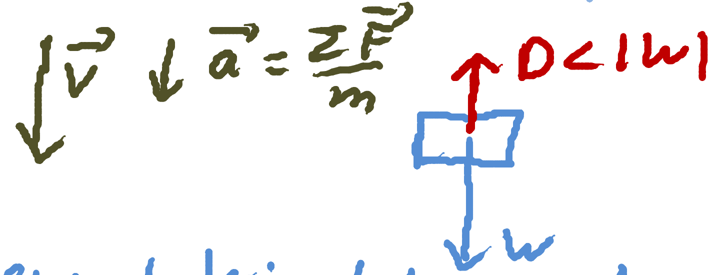
$$\underbrace{\sum \vec{F} = 0}_{\text{at } v = v_t}$$

Example ①: free fall

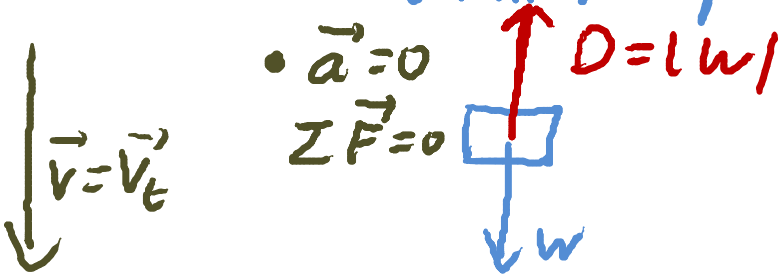
initial: low speed



later: increased speed



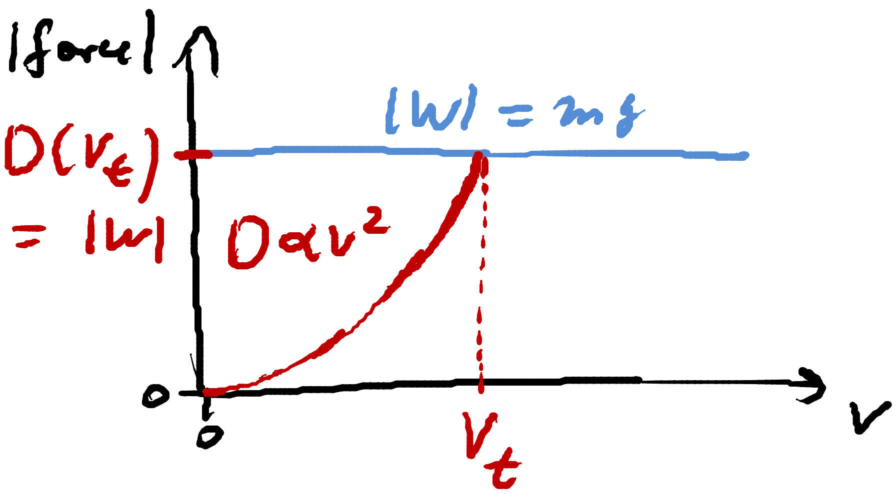
even later: at terminal speed

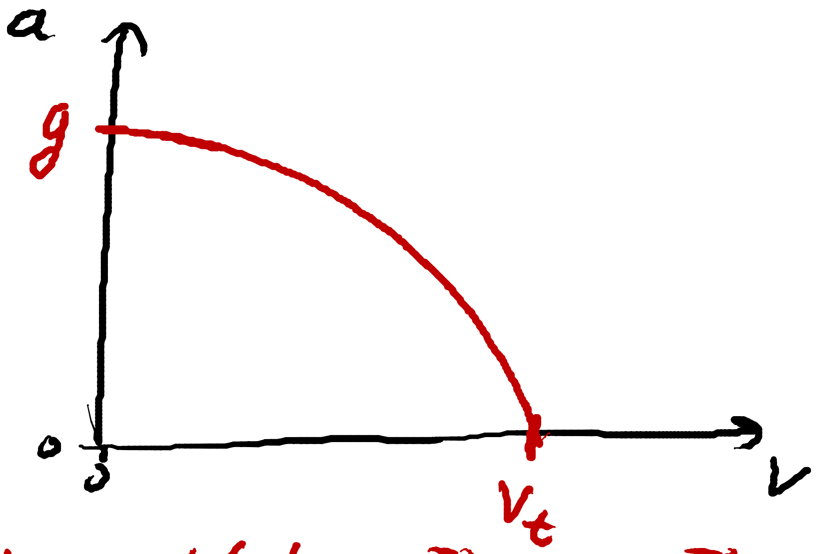


- $\vec{a} = 0$

$\sum \vec{F} = 0$

} stable equilibrium





at $v = v_t$: $D(v_t) = |W|$ so that $\sum \vec{F} = 0 \Rightarrow \vec{a} = 0$

$$\Rightarrow \frac{1}{2} C \rho_{fluid} A_{obj} v_t^2 = mg$$

$$\Rightarrow \underline{\underline{v_t}} = \sqrt{\frac{2 m_{obj} g}{C \rho_{fluid} A_{obj}}}$$

TABLE 6-1 SOME TERMINAL SPEEDS IN AIR

OBJECT	TERMINAL SPEED (m/s)	95% DISTANCE[a] (m)
16 lb Shot	145	2500
Sky diver (typical)	60	430
Baseball	42	210
Tennis ball	31	115
Basketball	20	47
Ping-Pong ball	9	10
Raindrop (radius = 1.5 mm)	7	6
Parachutist (typical)	5	3

[a] This is the distance through which the body must fall from rest to reach 95% of its terminal speed.

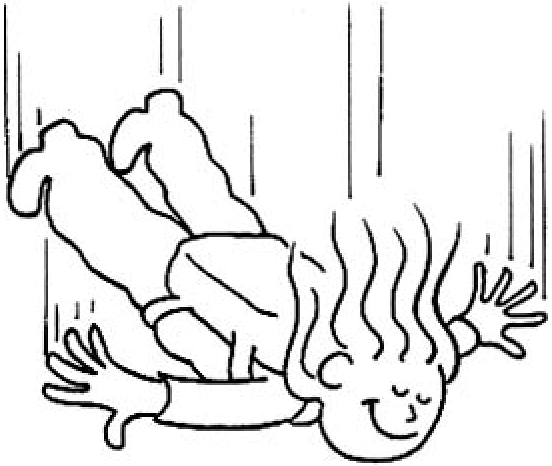
CONCEPTUAL **Physics**

As she falls faster and faster through the air, her acceleration

a) increases

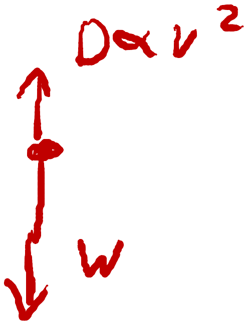
[✓ b) decreases]

c) remains the same



Hewitt Drew it!

CHAP. 4



faster → larger D

$\Rightarrow$ smaller $|\vec{a}| = \frac{|\Sigma \vec{F}|}{m}$

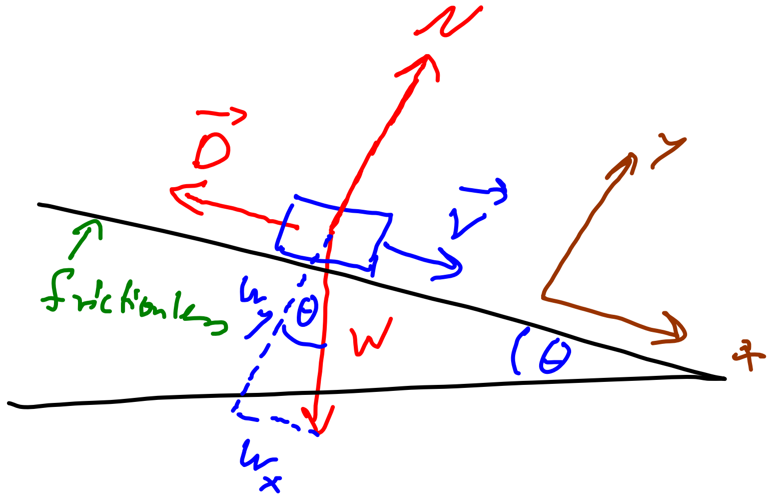
note:

at $v = v_t$

$|W| = |D|$

$\Rightarrow \vec{a} = 0$

Example ② of terminal speed:



at $v = v_t$: $\sum \vec{F} = 0$

$$\sum F_x = 0 = W_x - D(v_t)$$

$$\Rightarrow D(v_t) = W_x$$

$$\Rightarrow \frac{1}{2} C \rho A \underline{\underline{v_t}}^2 = mg\sin\theta$$

$$\Rightarrow v_t = \ldots$$