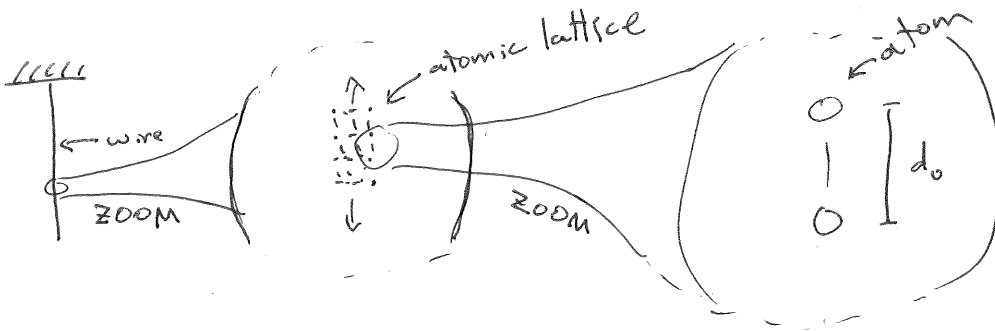


Forces of nature

EM } → ropes, chains, pushes, pulls
 Gravity } → gravity

Springs

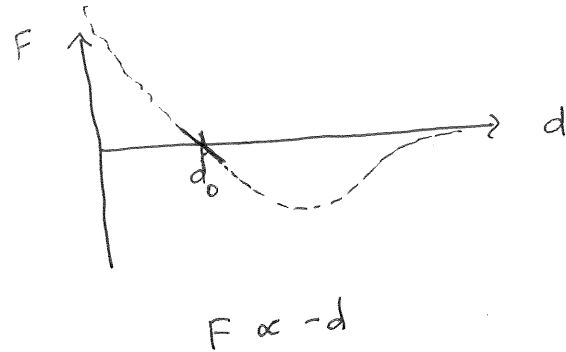


stretch wire: $\frac{x}{L}$

$\Rightarrow F \propto -x$

$$\vec{F} = -k\vec{x}$$

Hooke's Law

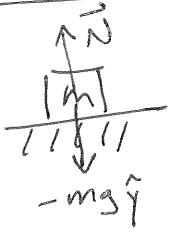


coiled up wire
 \Rightarrow spring

[Spring demo: add mass, $x \propto mg$]

Note: $\begin{cases} \vec{F}_s = -k\vec{x} \\ \vec{F}_g = m\vec{x} \end{cases} \Rightarrow \ddot{x} = \frac{-k}{m}x$ differential equation
 \rightarrow oscillatory motion as solution

Normal force



$N = mg$

[$m \rightarrow 2m \Rightarrow N \rightarrow 2N$]
How does the table know?

Spring-like:



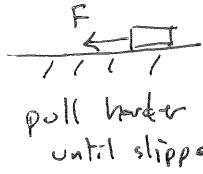
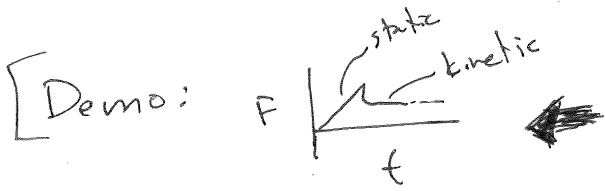
Friction



$(\max F_f) = \mu N$

$F_f \leq \mu_s N$

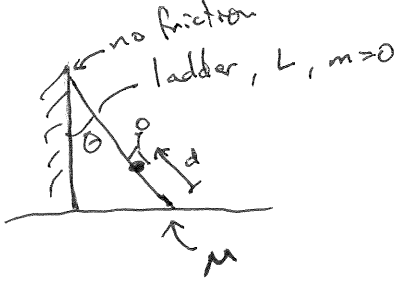
"static" friction



$F_f = \mu_k N$

"kinetic" friction

Example



when does it start slipping? ($d=?$)

y forces: $N - mg = 0$

x forces: $F_w - F_f = 0$
 $\Rightarrow F_w - \mu N = 0$



torque about bottom:

$F_w L \cos \theta - mg d \sin \theta = 0$

$\Rightarrow d_{\max} = \frac{L \mu}{\sin \theta}$

[PDF slides → EM] [multiple demos]

3

Drag

Stokes' drag: $\vec{F}_d = -6\pi R \eta \vec{v}$

radius
viscosity
velocity

$$\vec{F}_{grav} = -mg\hat{y} \Rightarrow v_t = \frac{mg}{6\pi R \eta}$$

→ demo

→ non-turbulent ("laminar") flow

↳ important in biology, with particulates & microorganism moving through fluids.

→ turbulent flow $\Rightarrow F_d \propto v^2$ (like on the quiz)

$$= \frac{1}{2} \rho C_d A v^2$$

density of fluid shape dependent velocity area

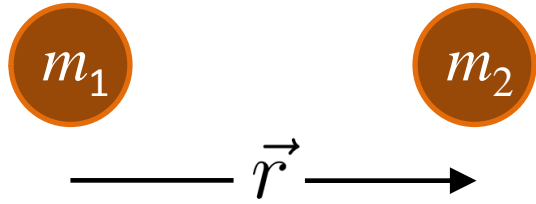
[Back to slides]

TABLE 6.1**KINETIC AND STATIC FRICTION COEFFICIENTS^a**

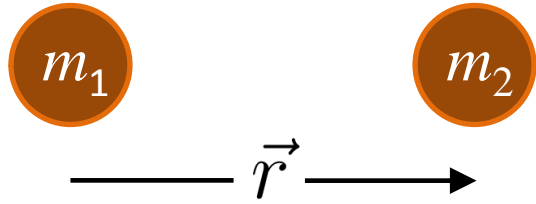
MATERIALS	μ_k	μ_s
Steel on steel	0.6	0.7
Steel on lead	0.9	0.9
Steel on copper	0.4	0.5
Copper on cast iron	0.3	1.1
Copper on glass	0.5	0.7
Waxed ski on snow		
at -10°C	0.2	—
at 0°C	0.05	—
Rubber on concrete	≈ 1	≈ 1

^aThe friction coefficient depends on the condition of the surfaces. The values in this table are typical for dry surfaces but not entirely reliable.

Gravitational force

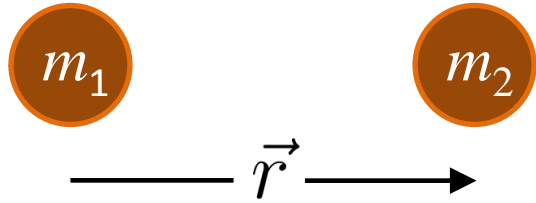


Gravitational force



$$\vec{F}_2 = -G \frac{m_1 m_2}{r^2} \hat{r}$$

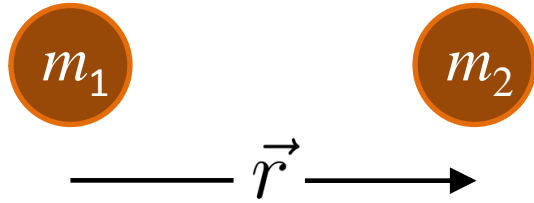
Gravitational force



$$\vec{F}_2 = -G \frac{m_1 m_2}{r^2} \hat{r}$$

$$G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2 / \text{kg}^2$$

Gravitational force

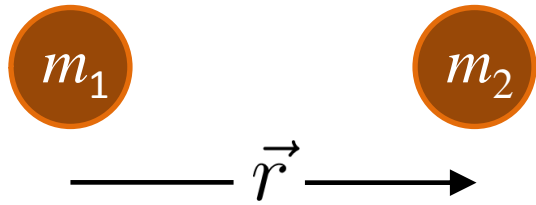


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attractive

Gravitational force

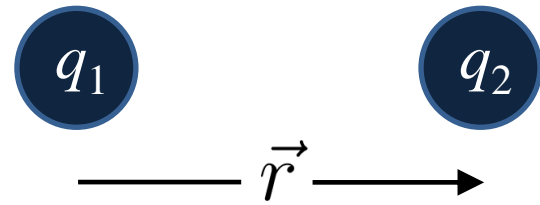


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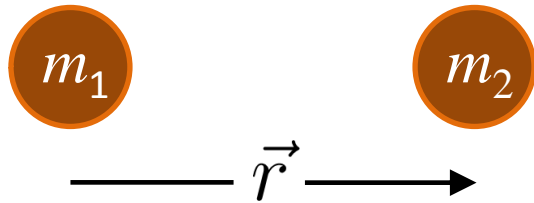
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attractive

Electrical force



Gravitational force

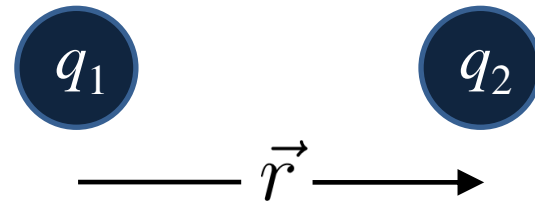


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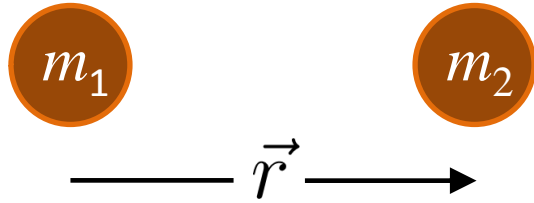
attractive

Electrical force



$$\vec{F}_2 = k_e \frac{q_1 q_2}{r^2} \hat{r}$$

Gravitational force

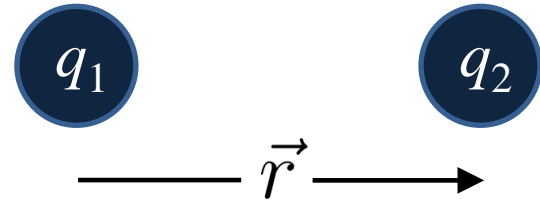


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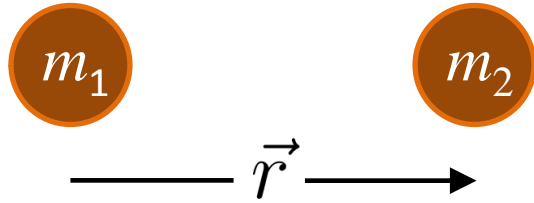
Electrical force



$$\vec{F}_2 = k_e \frac{q_1 q_2}{r^2} \hat{r}$$

$$k_e = 1 / (4\pi\epsilon_0) \\ = 8.988 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2$$

Gravitational force

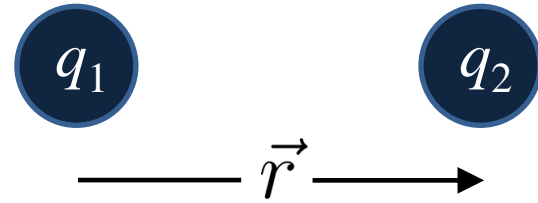


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attractive or repulsive

Relative strengths

Consider the forces between two electrons ...

$$\frac{F_{\text{grav}}}{F_{\text{elec}}} = \frac{Gm_e^2}{k_e q_e^2}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$q_e = 1.60 \times 10^{-19} \text{ C}$$

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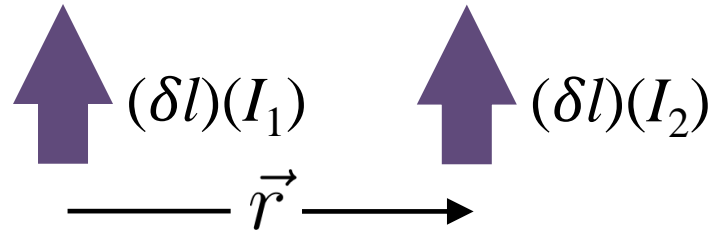
$$\frac{F_{\text{grav}}}{F_{\text{elec}}} \approx 2 \times 10^{-34}$$



Coulomb force demo

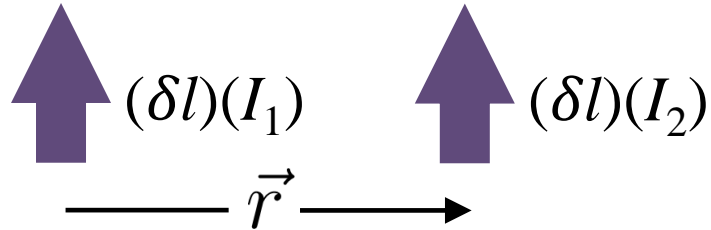
Magnetic force

between two short parallel wires



Magnetic force

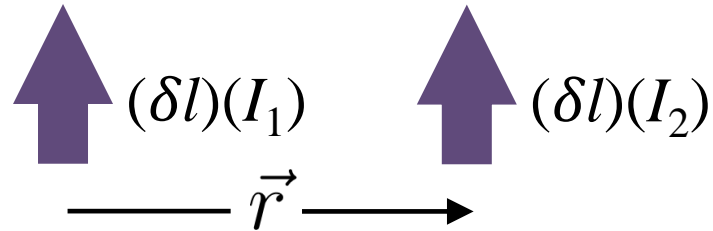
between two short parallel wires



$$\vec{F}_2 = -k_m \frac{(I_1 \delta l)(I_2 \delta l)}{r^2} \hat{r}$$

Magnetic force

between two short parallel wires

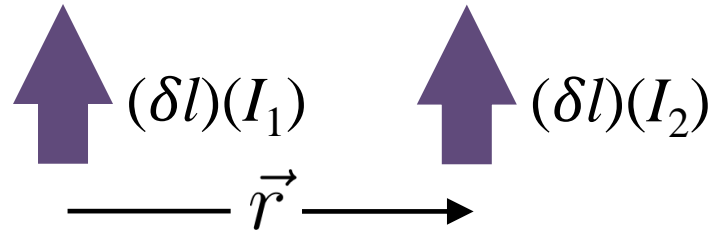


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$$\begin{aligned} k_m &= \mu_0 / (4\pi) \\ &= 10^{-7} \text{ N} / \text{A}^2 \end{aligned}$$

Magnetic force

between two short parallel wires



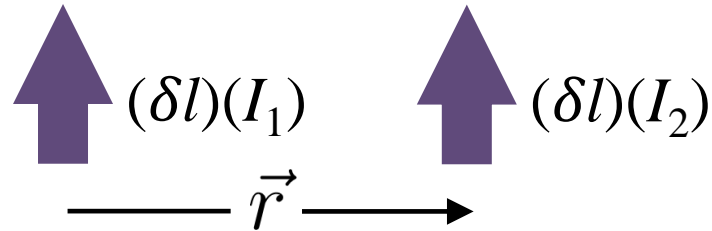
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(Magnetic force demos)

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$$\begin{aligned} k_e / k_m &= (8.988 \times 10^9 \text{ N} \cdot \text{m}^2 / \text{C}^2) / (10^{-7} \text{ N} / \text{A}^2) \\ &= 8.988 \times 10^{16} \text{ m}^2 / \text{s}^2 \\ &= c^2 \end{aligned}$$

Drag forces (blackboard and demo)

Fundamental forces

	<i>Relative strengths (at everyday energies)</i>	<i>Scaling with distance</i>
Gravity	10^{-36}	$1/R^2$
Electromagnetism	0.01	$1/R^2$

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Heavenly bodies' motions and apples falling → **gravity (1687)**

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SM and G → breaks horribly; active area of theoretical work