

# Classical Mechanics by John R. Taylor Problems

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# 1 Newton's Laws of Motion

## 1.1

$$\begin{aligned}
 \mathbf{b} + \mathbf{c} &= 2\hat{\mathbf{x}} + \hat{\mathbf{y}} + \hat{\mathbf{z}} \\
 5\mathbf{b} + 2\mathbf{c} &= 7\hat{\mathbf{x}} + 5\hat{\mathbf{y}} + 2\hat{\mathbf{z}} \\
 \mathbf{b} \cdot \mathbf{c} &= 1 \\
 \mathbf{b} \times \mathbf{c} &= \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{vmatrix} \\
 &= \hat{\mathbf{x}} - \hat{\mathbf{y}} - \hat{\mathbf{z}}
 \end{aligned}$$

## 1.5

$$\begin{aligned}
 \mathbf{v}_{\text{body}} &= \hat{\mathbf{x}} + \hat{\mathbf{y}} + \hat{\mathbf{z}} \\
 \mathbf{v}_{\text{face}} &= \hat{\mathbf{x}} + \hat{\mathbf{z}} \\
 \mathbf{v}_{\text{body}} \cdot \mathbf{v}_{\text{face}} &= v_{\text{body}} v_{\text{face}} \cos \theta \\
 2 &= \sqrt{6} \cos \theta \\
 \cos \theta &= \frac{2}{\sqrt{6}} \\
 \theta &= \arccos \frac{2}{\sqrt{6}} \\
 &= 35.26^\circ
 \end{aligned}$$

## 1.11

The particle moves counterclockwise in an ellipse of width  $2b$  and height  $2c$ . The angular speed is  $\omega$ .

## 1.23

$$\begin{aligned}
 \mathbf{v} &= v \cos \theta \frac{\mathbf{b}}{b} - v \sin \theta \frac{\mathbf{b} \times \mathbf{c}}{bc} \\
 &= \frac{\lambda}{b} \frac{\mathbf{b}}{b} - \frac{c}{b} \frac{\mathbf{b} \times \mathbf{c}}{bc} \\
 &= \frac{\lambda \mathbf{b} - \mathbf{b} \times \mathbf{c}}{b^2}
 \end{aligned}$$

## 1.25

$$\begin{aligned}
 \frac{df}{dt} &= -3f \\
 \frac{1}{f} \frac{df}{dt} &= -3 \\
 \ln f &= -3t + c \\
 f &= ce^{-3t}
 \end{aligned}$$

One constant.

1.35

$$\begin{aligned}
 F_x &= 0 \\
 ma_x &= 0 \\
 a_x &= 0 \\
 v_x &= c_1 \\
 &= v_o \cos \theta \\
 r_x &= v_o \cos(\theta)t + c_2 \\
 &= v_o \cos(\theta)t
 \end{aligned}$$

$$\begin{aligned}
 F_y &= 0 \\
 ma_y &= 0 \\
 a_y &= 0 \\
 v_y &= c_3 \\
 v_y &= 0 \\
 r_y &= c_4 \\
 r_y &= 0
 \end{aligned}$$

$$\begin{aligned}
 F_z &= -mg \\
 ma_z &= -mg \\
 a_z &= -g \\
 v_z &= -gt + c_5 \\
 &= v_o \sin \theta - gt \\
 r_z &= v_o \sin(\theta)t - \frac{1}{2}gt^2 + c_6 \\
 &= v_o \sin(\theta)t - \frac{1}{2}gt^2
 \end{aligned}$$

$$\begin{aligned}
 0 &= v_o \sin(\theta)t - \frac{1}{2}gt^2 \\
 t &= \frac{2 \sin(\theta)v_o}{g} \\
 r_x &= v_o \cos(\theta)t \\
 &= \frac{2 \cos(\theta) \sin(\theta)v_o^2}{g} \\
 &= \frac{\sin(2\theta)v_o^2}{g}
 \end{aligned}$$

**1.37**

(a)

$$\begin{aligned}F &= -mg \sin \theta \\ma &= -mg \sin \theta \\a &= -g \sin \theta \\v &= c_1 - gt \sin \theta \\&= v_o - gt \sin \theta \\x &= v_o t - \frac{1}{2}gt^2 \sin \theta\end{aligned}$$

(b)

$$t = \frac{2v_o}{g \sin \theta}$$

### 1.39

$$\begin{aligned}
 F_x &= -mg \sin \phi \\
 ma_x &= -mg \sin \phi \\
 a_x &= -g \sin \phi \\
 v_x &= c_1 - gt \sin \phi \\
 &= v_o \cos \theta - gt \sin \phi \\
 r_x &= v_o t \cos \theta - \frac{1}{2}gt^2 \sin \phi + c_2 \\
 &= v_o t \cos \theta - \frac{1}{2}gt^2 \sin \phi
 \end{aligned}$$

$$\begin{aligned}
 F_y &= -mg \cos \phi \\
 ma_y &= -mg \cos \phi \\
 a_y &= -g \cos \phi \\
 v_y &= c_3 - gt \cos \phi \\
 &= v_o \sin \theta - gt \cos \phi \\
 r_y &= v_o t \sin \theta - \frac{1}{2}gt^2 \cos \phi + c_4 \\
 &= v_o t \sin \theta - \frac{1}{2}gt^2 \cos \phi
 \end{aligned}$$

$$\begin{aligned}
 0 &= v_o t \sin \theta - \frac{1}{2}gt^2 \cos \phi \\
 t &= \frac{2v_o \sin \theta}{g \cos \phi}
 \end{aligned}$$

$$\begin{aligned}
 r_x &= \frac{2v_o^2 \cos \theta \sec \phi \sin \theta}{g} - \frac{2v_o^2 \sec \phi \sin^2 \theta \tan \phi}{g} \\
 &= \frac{2v_o^2 \sin \theta (\cos \theta \cos \phi - \sin \theta \sin \phi)}{g \cos^2 \phi} \\
 &= \frac{2v_o^2 \sin \theta \cos(\theta + \phi)}{g \cos^2 \phi}
 \end{aligned}$$

$$\begin{aligned}
\frac{dr_x}{d\theta} &= \frac{2v_o^2}{g \cos^2 \phi} [\cos \theta \cos(\theta + \phi) - \sin \theta \sin(\theta + \phi)] \\
&= \frac{2v_o^2 \cos(2\theta + \phi)}{g \cos^2 \phi} \\
0 &= \frac{2v_o^2 \cos(2\theta + \phi)}{g \cos^2 \phi} \\
&= \cos(2\theta + \phi) \\
2\theta + \phi &= \frac{\pi}{2} \\
\theta &= \frac{\pi}{4} - \frac{\phi}{2} \\
r_{x,\max} &= \frac{2v_o^2 \sin\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \cos\left(\frac{\pi}{4} - \frac{\phi}{2} + \phi\right)}{g \cos^2 \phi} \\
&= \frac{v_o^2(1 - \sin \phi)}{g \cos^2 \phi} \\
&= \frac{v_o^2}{g(1 + \sin \phi)}
\end{aligned}$$

1.41

$$\begin{aligned}
F &= ma \\
T &= m \frac{v^2}{R} \\
&= m \frac{(\omega R)^2}{R} \\
&= m\omega^2 R
\end{aligned}$$

1.47

(a)

$$\begin{aligned}
\rho &= \sqrt{x^2 + y^2} \\
\phi &= \arctan \frac{y}{x} \\
z &= z
\end{aligned}$$

$\rho$  is the distance of  $P$  from the  $z$ -axis.

The use of  $r$  may be unfortunate because it suggests it's the distance of  $P$  from the origin.

- (b)  $\hat{\rho}$  points away from the  $z$ -axis,  $\hat{\phi}$  points counter-clockwise around the  $z$ -axis, and  $\hat{z}$  points in the positive  $z$  direction.

$$\mathbf{r} = \rho\hat{\rho} + z\hat{z} + \sqrt{x^2 + y^2}\hat{\rho} + z\hat{z}$$

(c)

$$\begin{aligned}\mathbf{v} &= \frac{d\mathbf{r}}{dt} \\ &= \dot{\rho}\hat{\rho} + \rho\frac{d\hat{\rho}}{dt} + \dot{z}\hat{z} + z\frac{d\hat{z}}{dt} \\ &= \dot{\rho}\hat{\rho} + \rho\dot{\phi}\hat{\phi} + \dot{z}\hat{z} \\ \mathbf{a} &= \frac{d\mathbf{v}}{dt} \\ &= \ddot{\rho}\hat{\rho} + \dot{\rho}\frac{d\hat{\rho}}{dt} + \dot{\rho}\dot{\phi}\hat{\phi} + \rho\ddot{\phi}\hat{\phi} + \rho\dot{\phi}\frac{d\hat{\phi}}{dt} + \ddot{z}\hat{z} \\ &= \ddot{\rho}\hat{\rho} + \dot{\rho}\dot{\phi}\hat{\phi} + \dot{\rho}\dot{\phi}\hat{\phi} + \rho\ddot{\phi}\hat{\phi} - \rho\dot{\phi}^2\hat{\rho} + \ddot{z}\hat{z} \\ &= (\ddot{\rho} - \rho\dot{\phi}^2)\hat{\rho} + (2\dot{\rho}\dot{\phi} + \rho\ddot{\phi})\hat{\phi} + \ddot{z}\hat{z}\end{aligned}$$

## 2 Projectiles and Charged Particles

### 2.1

$$\begin{aligned}1 &= (1.6 \times 10^3)Dv \\ v &= \frac{1}{(1.6 \times 10^3)D} \\ &= 8.9 \text{ mm/s}\end{aligned}$$

When  $v \gg 1 \text{ cm/s}$  the drag force can be treated as purely quadratic. For a beach ball this becomes  $v \gg 1 \text{ mm/s}$ .

### 2.3

(a)

$$\begin{aligned}\frac{f_{\text{quad}}}{f_{\text{lin}}} &= \frac{(1/4)\rho Av^2}{3\pi\eta Dv} \\ &= \frac{\rho\pi\left(\frac{D}{2}\right)^2 v}{12\pi\eta D} \\ &= \frac{\rho Dv}{48\eta} \\ &= \frac{R}{48}\end{aligned}$$



(b)

$$R = \frac{Dv\rho}{\eta} \approx 0.01$$

**2.5**

$$\begin{aligned} v_y(t) &= v_{\text{ter}} + (v_{y0} - v_{\text{ter}})e^{-t/\tau} \\ &= v_{\text{ter}} + (2v_{\text{ter}} - v_{\text{ter}})e^{-t/\tau} \\ &= v_{\text{ter}}(1 + e^{-t/\tau}) \end{aligned}$$

The velocity starts at  $2v_{\text{ter}}$  and asymptotically approaches  $v_{\text{ter}}$ .

**2.7**

$$\begin{aligned} F &= F(v) \\ m\dot{v} &= F(v) \\ m \frac{dv}{F(v)} &= dt \\ t &= \int_{v_0}^v m \frac{dv'}{F(v')} \end{aligned}$$

$$\begin{aligned} F &= F(v) \\ m\dot{v} &= F_0 \\ v &= \frac{F_0}{m}t + c \end{aligned}$$

## 2.11

(a)

$$m\dot{v} = -mg - bv$$

$$\dot{v} = -g - kv$$

$$\frac{1}{-g - kv}\dot{v} = 1$$

$$-\frac{1}{k}\ln(-g - kv) = t + c$$

$$\ln(-g - kv) = c - \frac{t}{\tau}$$

$$-g - kv = Ae^{-t/\tau}$$

$$v = \tau(-g - Ae^{-t/\tau})$$

$$= -v_{\text{ter}} - \tau Ae^{-t/\tau}$$

$$v_o = -v_{\text{ter}} - \tau A$$

$$A = -k(v_o + v_{\text{ter}})$$

$$v = -v_{\text{ter}} + (v_o + v_{\text{ter}})e^{-t/\tau}$$

$$y = -v_{\text{ter}}t - \tau(v_o + v_{\text{ter}})e^{-t/\tau} + c$$

$$0 = -\tau(v_o + v_{\text{ter}}) + c$$

$$c = \tau(v_o + v_{\text{ter}})$$

$$y = -v_{\text{ter}}t + \tau(v_o + v_{\text{ter}})(1 - e^{-t/\tau})$$

(b)

$$\begin{aligned}
0 &= -v_{\text{ter}} + (v_o + v_{\text{ter}})e^{-t/\tau} \\
e^{-t/\tau} &= \frac{v_{\text{ter}}}{v_o + v_{\text{ter}}} \\
-\frac{t}{\tau} &= \ln \frac{v_{\text{ter}}}{v_o + v_{\text{ter}}} \\
t &= -\tau \ln \frac{v_{\text{ter}}}{v_o + v_{\text{ter}}} \\
y_{\text{max}} &= -v_{\text{ter}} \left( -\tau \ln \frac{v_{\text{ter}}}{v_o + v_{\text{ter}}} \right) + \tau(v_o + v_{\text{ter}}) \left( 1 - \frac{v_{\text{ter}}}{v_o + v_{\text{ter}}} \right) \\
&= \tau v_{\text{ter}} \ln \frac{v_{\text{ter}}}{v_o + v_{\text{ter}}} + \tau(v_o + v_{\text{ter}} - v_{\text{ter}}) \\
&= \tau \left( v_o + v_{\text{ter}} \ln \frac{v_{\text{ter}}}{v_o + v_{\text{ter}}} \right) \\
&= \tau \left[ v_o - v_{\text{ter}} \ln \left( 1 + \frac{v_o}{v_{\text{ter}}} \right) \right]
\end{aligned}$$

(c)

$$\begin{aligned}
y_{\text{max}} &= \tau \left[ v_o - v_{\text{ter}} \ln \left( 1 + \frac{v_o}{v_{\text{ter}}} \right) \right] \\
&= \tau \left[ v_o - g\tau \ln \left( 1 + \frac{v_o}{g\tau} \right) \right] \\
&\approx \tau \left\{ v_o - g\tau \left[ \frac{v_o}{g\tau} - \frac{1}{2} \left( \frac{v_o}{g\tau} \right)^2 \right] \right\} \\
&= \tau \left( v_o - v_o + \frac{1}{2} \frac{v_o^2}{g\tau} \right) \\
&= \frac{1}{2} \frac{v_o^2}{g}
\end{aligned}$$

## 2.13

$$\begin{aligned}
 v^2 &= \frac{2}{m} \int_{x_0}^x -kx' dx' \\
 &= -\frac{2k}{m} \left( \frac{1}{2}x^2 - \frac{1}{2}x_0^2 \right) \\
 &= -\frac{k}{m}(x^2 - x_0^2) \\
 v &= \sqrt{\frac{k}{m}(x_0^2 - x^2)} \\
 &= \omega \sqrt{x_0^2 - x^2}
 \end{aligned}$$

$$\begin{aligned}
 \int_{x_0}^x \frac{1}{\sqrt{x_0^2 - x'^2}} dx' &= \int_0^t \omega dt \\
 \arctan \frac{x}{\sqrt{x_0^2 - x^2}} - \arctan \frac{x_0}{\sqrt{x_0^2 - x_0^2}} &= \omega t \\
 \arctan \frac{x}{\sqrt{x_0^2 - x^2}} &= \omega t + \frac{\pi}{2} \\
 \frac{x}{\sqrt{x_0^2 - x^2}} &= \tan \left( \omega t + \frac{\pi}{2} \right) \\
 &= -\cot \omega t \\
 \frac{\sqrt{x_0^2 - x^2}}{x} &= -\tan \omega t \\
 \sqrt{x_0^2 - x^2} &= -x \tan \omega t \\
 x_0^2 - x^2 &= x^2 \tan^2 \omega t \\
 x^2 &= \frac{x_0^2}{1 + \tan^2 \omega t} \\
 &= \frac{x_0^2 \cos^2 \omega t}{\cos^2 \omega t + \sin^2 \omega t} \\
 &= x_0^2 \cos^2 \omega t \\
 x &= x_0 \cos \omega t
 \end{aligned}$$

2.15

$$\begin{aligned}
a_y &= -g \\
v_y &= v_{y0} - gt \\
y &= v_{y0}t - \frac{1}{2}gt^2 \\
0 &= v_{y0}t - \frac{1}{2}gt^2 \\
t &= \frac{2v_{y0}}{g} \\
x &= v_{x0}t \\
R &= \frac{2v_{x0}v_{y0}}{g}
\end{aligned}$$

2.19

(a)

$$\begin{aligned}
x &= v_{x0}t \\
y &= v_{y0}t - \frac{1}{2}gt^2 \\
&= \frac{v_{y0}}{v_{x0}}x - \frac{1}{2}g\left(\frac{x}{v_{x0}}\right)^2
\end{aligned}$$

(b)

$$\begin{aligned}
y &= \frac{v_{y0} + v_{\text{ter}}}{v_{x0}}x + v_{\text{ter}}\tau \ln\left(1 - \frac{x}{v_{x0}\tau}\right) \\
&\approx \frac{v_{y0}}{v_{x0}}x + \frac{g\tau}{v_{x0}}x - g\tau^2\left[\frac{x}{v_{x0}\tau} + \frac{1}{2}\left(\frac{x}{v_{x0}\tau}\right)^2\right] \\
&= \frac{v_{y0}}{v_{x0}}x - \frac{1}{2}g\left(\frac{x}{v_{x0}}\right)^2
\end{aligned}$$

## 2.23

(a)

$$\begin{aligned}
 v_{\text{ter}} &= \sqrt{\frac{mg}{c}} \\
 &= \sqrt{\frac{mg}{\gamma D^2}} \\
 &= \sqrt{\frac{mg}{0.25D^2}} \\
 &= \sqrt{\frac{\rho \frac{4}{3}\pi \left(\frac{D}{2}\right)^3 g}{0.25D^2}} \\
 &= \sqrt{\frac{4\pi\rho Dg}{6}} \\
 &= 22 \text{ m/s}
 \end{aligned}$$

(b)

$$\begin{aligned}
 m &= \rho V \\
 &= \rho \frac{4}{3}\pi \left(\frac{D}{2}\right)^3 \\
 &= \frac{\pi\rho D^3}{6} \\
 D^2 &= \left(\frac{6m}{\pi\rho}\right)^{2/3} \\
 v_{\text{ter}} &= \sqrt{\frac{mg}{0.25D^2}} \\
 &= \sqrt{\frac{mg}{0.25(6m/\pi\rho)^{2/3}}} \\
 &= 140 \text{ m/s}
 \end{aligned}$$

(c)

$$v_{\text{ter}} = 107 \text{ m/s}$$

## 2.27

$$\begin{aligned}
m\dot{v} &= -mg \sin \theta - cv^2 \\
-\frac{\sqrt{m} \arctan \frac{\sqrt{cv}}{\sqrt{gm \sin \theta}}}{\sqrt{cg \sin \theta}} &= t + c_1 \\
\arctan \frac{\sqrt{cv}}{\sqrt{gm \sin \theta}} &= \sqrt{\frac{cg \sin \theta}{m}}(c_1 - t) \\
\frac{\sqrt{cv}}{\sqrt{gm \sin \theta}} &= \tan \left[ \sqrt{\frac{cg \sin \theta}{m}}(c_1 - t) \right] \\
v &= \sqrt{\frac{gm \sin \theta}{c}} \tan \left[ \sqrt{\frac{cg \sin \theta}{m}}(c_1 - t) \right] \\
v_0 &= \sqrt{\frac{gm \sin \theta}{c}} \tan \left( \sqrt{\frac{cg \sin \theta}{m}}c_1 \right) \\
c_1 &= \sqrt{\frac{m}{cg \sin \theta}} \arctan \left( \sqrt{\frac{c}{gm \sin \theta}}v_0 \right) \\
v &= \sqrt{\frac{gm \sin \theta}{c}} \tan \left[ \arctan \left( \sqrt{\frac{c}{gm \sin \theta}}v_0 \right) - \sqrt{\frac{cg \sin \theta}{m}}t \right] \\
0 &= \sqrt{\frac{gm \sin \theta}{c}} \tan \left[ \arctan \left( \sqrt{\frac{c}{gm \sin \theta}}v_0 \right) - \sqrt{\frac{cg \sin \theta}{m}}t \right] \\
\sqrt{\frac{cg \sin \theta}{m}}t &= \arctan \left( \sqrt{\frac{c}{gm \sin \theta}}v_0 \right) \\
t &= \sqrt{\frac{m}{cg \sin \theta}} \arctan \left( \sqrt{\frac{c}{gm \sin \theta}}v_0 \right)
\end{aligned}$$

## 2.29

$$\begin{aligned}
v(t) &= v_{\text{ter}} \tanh \frac{gt}{v_{\text{ter}}} \\
v(1) &= 9.6 \text{ m/s} \\
v(5) &= 38 \text{ m/s} \\
v(10) &= 48 \text{ m/s} \\
v(20) &= 50 \text{ m/s} \\
v(30) &= 50 \text{ m/s}
\end{aligned}$$

**2.31**

(a)

$$\begin{aligned}
v_{\text{ter}} &= \sqrt{\frac{mg}{c}} \\
&= \sqrt{\frac{mg}{0.25D^2}} \\
&= 20.2 \text{ m/s}
\end{aligned}$$

(b)

$$\begin{aligned}
y &= -30 + \frac{v_{\text{ter}}^2}{g} \ln \left( \cosh \frac{gt}{v_{\text{ter}}} \right) \\
0 &= -30 + \frac{v_{\text{ter}}^2}{g} \ln \left( \cosh \frac{gt}{v_{\text{ter}}} \right) \\
t &= 2.78 \text{ s} \\
v(2.78) &= 17.6 \text{ m/s}
\end{aligned}$$

**2.33**

(b)

$$\begin{aligned}
\cosh z &= \frac{e^z + e^{-z}}{2} \\
&= \frac{1}{2} \left[ \left( 1 + z + \frac{z^2}{2} + \frac{z^3}{6} + \cdots \right) + \left( 1 - z + \frac{z^2}{2} - \frac{z^3}{6} + \cdots \right) \right] \\
&= 1 + \frac{z^2}{2} + \frac{z^4}{24} + \frac{z^6}{720} + \cdots \\
\cos iz &= 1 - \frac{(iz)^2}{2} + \frac{(iz)^4}{24} - \frac{(iz)^6}{720} + \cdots \\
&= 1 + \frac{z^2}{2} + \frac{z^4}{24} + \frac{z^6}{720} + \cdots \\
&= \cosh z \\
\sinh z &= -i \sin iz
\end{aligned}$$



(c)

$$\begin{aligned}\frac{d}{dz} \cosh z &= \frac{d}{dz} \left( \frac{e^z + e^{-z}}{2} \right) \\ &= \frac{e^z - e^{-z}}{2} \\ &= \sinh z \\ \frac{d}{dz} \sinh z &= \frac{d}{dz} \left( \frac{e^z - e^{-z}}{2} \right) \\ &= \frac{e^z + e^{-z}}{2} \\ &= \cosh z\end{aligned}$$

(d)

$$\begin{aligned}\cosh^2 z - \sinh^2 z &= \left( \frac{e^z + e^{-z}}{2} \right)^2 - \left( \frac{e^z - e^{-z}}{2} \right)^2 \\ &= \frac{1}{4} (e^{2z} + 2 + e^{-2z} - e^{2z} + 2 - e^{-2z}) \\ &= 1\end{aligned}$$

(e)

$$\begin{aligned}\int \frac{1}{\sqrt{1+x^2}} dx &= \int \frac{\cosh z}{\sqrt{1+\sinh^2 z}} dz \\ &= \int 1 dz \\ &= z \\ &= \operatorname{arcsinh} x\end{aligned}$$

## 2.35

(a)

$$\begin{aligned}
 m\dot{v} &= mg - cv^2 \\
 \dot{v} &= g \left( 1 - \frac{v^2}{v_{\text{ter}}^2} \right) \\
 \int_0^v \frac{1}{1 - v'^2/v_{\text{ter}}^2} dv' &= \int_0^t g dt \\
 v_{\text{ter}} \operatorname{arctanh} \frac{v}{v_{\text{ter}}} &= gt \\
 v &= v_{\text{ter}} \tanh \frac{gt}{v_{\text{ter}}} \\
 y &= \int_0^t v_{\text{ter}} \tanh \frac{gt'}{v_{\text{ter}}} dt' \\
 &= \frac{v_{\text{ter}}^2}{g} \ln \left[ \cosh \left( \frac{gt}{v_{\text{ter}}} \right) \right]
 \end{aligned}$$

(b)

$$\begin{aligned}
 v &= g\tau \tanh \frac{t}{\tau} \\
 y &= g\tau^2 \ln \left[ \cosh \left( \frac{t}{\tau} \right) \right] \\
 v(\tau) &= g\tau \tanh 1 \\
 &= 0.76v_{\text{ter}} \\
 v(2\tau) &= 0.96v_{\text{ter}} \\
 v(3\tau) &= 0.99v_{\text{ter}}
 \end{aligned}$$

(c)

$$\begin{aligned}
 y &= g\tau^2 \ln \left[ \cosh \left( \frac{t}{\tau} \right) \right] \\
 &= g\tau^2 \ln \left( \frac{e^{t/\tau} + e^{-t/\tau}}{2} \right) \\
 &= g\tau^2 \ln \left( \frac{e^{t/\tau}}{2} \right) \\
 &= g\tau^2 (\ln e^{t/\tau} - \ln 2) \\
 &= g\tau t - g\tau^2 \ln 2 \\
 &= v_{\text{ter}} t - g\tau^2 \ln 2
 \end{aligned}$$

(d)

$$\begin{aligned}
 y &= \frac{(v_{\text{ter}})^2}{g} \ln \left[ \cosh \left( \frac{gt}{v_{\text{ter}}} \right) \right] \\
 &\approx \frac{(v_{\text{ter}})^2}{g} \ln \left[ 1 + \frac{1}{2} \left( \frac{gt}{v_{\text{ter}}} \right)^2 \right] \\
 &\approx \frac{(v_{\text{ter}})^2}{g} \frac{1}{2} \left( \frac{gt}{v_{\text{ter}}} \right)^2 \\
 &= \frac{1}{2} gt^2
 \end{aligned}$$

## 2.39

(a)

$$\begin{aligned}
 m\dot{v} &= -cv^2 - 3 \\
 \int_{v_0}^v \frac{m}{-cv'^2 - 3} dv' &= \int_0^t dt' \\
 \frac{m}{\sqrt{3}c} \left[ \arctan \left( \sqrt{\frac{c}{3}} v_0 \right) - \arctan \left( \sqrt{\frac{c}{3}} v \right) \right] &= t
 \end{aligned}$$

	Speed	Time
	15 m/s	6.34 s
(b)	10 m/s	18.4 s
	5 m/s	48.3 s
	0 m/s	142 s

## 2.41

$$\begin{aligned}
m\dot{v} &= -mg - cv^2 \\
\dot{v} &= -g \left[ 1 + \left( \frac{v}{v_{\text{ter}}} \right)^2 \right] \\
v \frac{dv}{dy} &= -g \left[ 1 + \left( \frac{v}{v_{\text{ter}}} \right)^2 \right] \\
\int_{v_0}^v \frac{v'}{1 + (v'/v_{\text{ter}})^2} dv' &= \int_0^y -g dy' \\
\frac{1}{2} v_{\text{ter}}^2 [\ln(v_{\text{ter}}^2 + v^2) - \ln(v_{\text{ter}}^2 + v_0^2)] &= -gy \\
\ln \frac{v_{\text{ter}}^2 + v^2}{v_{\text{ter}}^2 + v_0^2} &= -\frac{2gy}{v_{\text{ter}}^2} \\
\frac{v_{\text{ter}}^2 + v^2}{v_{\text{ter}}^2 + v_0^2} &= e^{-2gy/v_{\text{ter}}^2} \\
v &= \sqrt{(v_{\text{ter}}^2 + v_0^2)e^{-2gy/v_{\text{ter}}^2} - v_{\text{ter}}^2} \\
0 &= \sqrt{(v_{\text{ter}}^2 + v_0^2)e^{-2gy/v_{\text{ter}}^2} - v_{\text{ter}}^2} \\
v_{\text{ter}}^2 &= (v_{\text{ter}}^2 + v_0^2)e^{-2gy/v_{\text{ter}}^2} \\
\frac{v_{\text{ter}}^2}{v_{\text{ter}}^2 + v_0^2} &= e^{-2gy/v_{\text{ter}}^2} \\
-\frac{2gy}{v_{\text{ter}}^2} &= \ln \frac{v_{\text{ter}}^2}{v_{\text{ter}}^2 + v_0^2} \\
y &= -\frac{v_{\text{ter}}^2}{2g} \ln \frac{v_{\text{ter}}^2}{v_{\text{ter}}^2 + v_0^2} \\
&= \frac{v_{\text{ter}}^2}{2g} \ln \frac{v_{\text{ter}}^2 + v_0^2}{v_{\text{ter}}^2} \\
y_{\text{max}} &= 17.6 \text{ m}
\end{aligned}$$

## 2.45

(a)

$$\begin{aligned}
 z &= re^{i\theta} \\
 &= r(\cos \theta + i \sin \theta) \\
 &= \sqrt{x^2 + y^2} \left[ \cos \left( \arctan \frac{y}{x} \right) + i \sin \left( \arctan \frac{y}{x} \right) \right] \\
 &= \sqrt{x^2 + y^2} \left( \frac{1}{\sqrt{1 + \frac{y^2}{x^2}}} + i \frac{y}{x\sqrt{1 + \frac{y^2}{x^2}}} \right) \\
 &= \sqrt{x^2 + y^2} \left( \frac{x}{\sqrt{x^2 + y^2}} + i \frac{y}{\sqrt{x^2 + y^2}} \right) \\
 &= x + iy
 \end{aligned}$$

$r$  is the distance between  $z$  and the origin,  $\theta$  is the angle between the positive real axis and  $z$ .

(b)

$$z = \sqrt{3^2 + 4^2} e^{i \arctan 4/3} = 5e^{0.927i}$$

(c)

$$z = 2 \cos -\frac{\pi}{3} + i 2 \sin -\frac{\pi}{3} = 1 - \sqrt{3}i$$

## 2.47

(a)

$$\begin{aligned}
 z + w &= 9 + 4i \\
 z - w &= 3 + 12i \\
 zw &= (6 + 8i)(3 - 4i) \\
 &= 18 - 24i + 24i + 32 \\
 &= 50 \\
 \frac{z}{w} &= \frac{zw^*}{ww^*} \\
 &= \frac{(6 + 8i)(3 + 4i)}{(3 - 4i)(3 + 4i)} \\
 &= \frac{18 + 24i + 24i - 32}{9 + 12i - 12i + 16} \\
 &= \frac{-14 + 48i}{25} \\
 &= -\frac{14}{25} + \frac{48}{25}i
 \end{aligned}$$

(b)

$$\begin{aligned}z + w &= \left(8 \cos \frac{\pi}{3} + i8 \sin \frac{\pi}{3}\right) + \left(4 \cos \frac{\pi}{6} + i4 \sin \frac{\pi}{6}\right) \\&= (4 + 2\sqrt{3}) + i(4\sqrt{3} + 2) \\z - w &= (4 - 2\sqrt{3}) + i(4\sqrt{3} - 2) \\zw &= 32e^{i\pi/2} \\&= 32i \\\frac{z}{w} &= 2e^{i\pi/6} \\&= \sqrt{3} + i\end{aligned}$$

## 2.49

(a)

$$\begin{aligned}z^2 &= (e^{i\theta})^2 \\&= e^{i2\theta} \\&= \cos 2\theta + i \sin 2\theta \\z^2 &= (\cos \theta + i \sin \theta)^2 \\&= \cos^2 \theta + 2i \cos \theta \sin \theta - \sin^2 \theta \\&= \cos^2 \theta + i \sin 2\theta - \sin^2 \theta\end{aligned}$$

$$\cos 2\theta = \cos^2 \theta - \sin^2 \theta$$

$$\begin{aligned}\cos 2\theta + i \sin 2\theta &= \cos^2 \theta + 2i \sin \theta \cos \theta - \sin^2 \theta \\i \sin 2\theta &= 2i \sin \theta \cos \theta \\\sin 2\theta &= 2 \sin \theta \cos \theta\end{aligned}$$

(b)

$$\begin{aligned}z^3 &= (e^{i\theta})^3 \\&= e^{i3\theta} \\&= \cos 3\theta + i \sin 3\theta \\z^3 &= (\cos \theta + i \sin \theta)^3 \\&= \cos^3 \theta + 3i \cos^2 \theta \sin \theta - 3 \cos \theta \sin^2 \theta - i \sin^3 \theta\end{aligned}$$

$$\begin{aligned}\cos 3\theta + i \sin 3\theta &= \cos^3 \theta + 3i \cos^2 \theta \sin \theta - 3 \cos \theta \sin^2 \theta - i \sin^3 \theta \\&= \cos \theta (\cos^2 \theta - 3 \sin^2 \theta) + i (3 \cos^2 \theta \sin \theta - \sin^3 \theta) \\&= \cos \theta (\cos^2 \theta - 3 \sin^2 \theta) + i [3(1 - \sin^2 \theta) \sin \theta - \sin^3 \theta] \\&= \cos \theta (\cos^2 \theta - 3 \sin^2 \theta) + i (3 \sin \theta - 4 \sin^3 \theta) \\\cos 3\theta &= \cos \theta (\cos^2 \theta - 3 \sin^2 \theta)\end{aligned}$$

$$\sin 3\theta = 3 \sin \theta - 4 \sin^3 \theta$$

### 2.53

$$\begin{aligned}
\mathbf{B} &= B_z \hat{\mathbf{z}} \\
\mathbf{E} &= E_z \hat{\mathbf{z}} \\
\mathbf{v} \times \mathbf{B} &= B_z v_y \hat{\mathbf{x}} - B_z v_x \hat{\mathbf{y}} \\
\mathbf{F} &= q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \\
&= qB_z v_y \hat{\mathbf{x}} - qB_z v_x \hat{\mathbf{y}} + qE_z \hat{\mathbf{z}}
\end{aligned}$$

$$\begin{aligned}
m\dot{v}_x &= qB_z v_y \\
\dot{v}_x &= \omega v_y
\end{aligned}$$

$$\begin{aligned}
m\dot{v}_y &= -qB_z v_x \\
\dot{v}_y &= -\omega v_x
\end{aligned}$$

$$\begin{aligned}
m\dot{v}_z &= qE_z \\
\dot{v}_z &= \frac{q}{m} E_z
\end{aligned}$$

$$\begin{aligned}
\frac{d}{dt} \begin{pmatrix} v_x \\ v_y \end{pmatrix} &= \begin{pmatrix} 0 & \omega \\ -\omega & 0 \end{pmatrix} \begin{pmatrix} v_x \\ v_y \end{pmatrix} \\
\begin{pmatrix} v_x \\ v_y \end{pmatrix} &= c_1 \left[ \begin{pmatrix} 0 \\ 1 \end{pmatrix} \cos \omega t - \begin{pmatrix} -1 \\ 0 \end{pmatrix} \sin \omega t \right] + c_2 \left[ \begin{pmatrix} -1 \\ 0 \end{pmatrix} \cos \omega t + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \sin \omega t \right] \\
&= \begin{pmatrix} c_1 \sin \omega t - c_2 \cos \omega t \\ c_1 \cos \omega t + c_2 \sin \omega t \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
x &= -\frac{c_1}{\omega} \cos \omega t - \frac{c_2}{\omega} \sin \omega t + x_0 \\
y &= \frac{c_1}{\omega} \sin \omega t - \frac{c_2}{\omega} \cos \omega t + y_0
\end{aligned}$$

$$\begin{aligned}
v_z &= \frac{q}{m} E_z t + v_{z0} \\
z &= \frac{q}{2m} E_z t^2 + v_{z0} t + z_0
\end{aligned}$$

The particle moves in a helix oriented along the  $z$ -axis.



2.55

(a)

$$\begin{aligned}
 \mathbf{B} &= B\hat{\mathbf{z}} \\
 \mathbf{E} &= E\hat{\mathbf{y}} \\
 \mathbf{F} &= q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \\
 &= Bqv_y\hat{\mathbf{x}} + q(E - Bv_x)\hat{\mathbf{y}} \\
 \dot{v}_x &= \frac{Bq}{m}v_y \\
 &= \omega v_y \\
 \dot{v}_y &= \frac{Eq}{m} - \frac{Bq}{m}v_x \\
 &= \frac{Eq}{m} - \omega v_x \\
 \dot{v}_z &= 0
 \end{aligned}$$

The net force has no  $\hat{\mathbf{z}}$  component, so the motion stays in the  $xy$ -plane.

(b)

$$\begin{aligned}
 0 &= \frac{Eq}{m} - \omega v_x \\
 v_x &= \frac{Eq}{\omega m} \\
 &= \frac{E}{B}
 \end{aligned}$$

(c)

$$\begin{aligned}
\begin{pmatrix} \dot{v}_x \\ \dot{v}_y \end{pmatrix} &= \begin{pmatrix} 0 & \omega \\ -\omega & 0 \end{pmatrix} \begin{pmatrix} v_x \\ v_y \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{Eq}{m} \end{pmatrix} \\
\mathbf{V}_c &= \begin{pmatrix} c_1 \sin \omega t - c_2 \cos \omega t \\ c_1 \cos \omega t + c_2 \sin \omega t \end{pmatrix} \\
\mathbf{V}_p &= \begin{pmatrix} c_3 \\ c_4 \end{pmatrix} \\
\begin{pmatrix} 0 \\ 0 \end{pmatrix} &= \begin{pmatrix} 0 & \omega \\ -\omega & 0 \end{pmatrix} \begin{pmatrix} c_3 \\ c_4 \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{Eq}{m} \end{pmatrix} \\
&= \begin{pmatrix} c_4 \omega \\ -c_3 \omega + \frac{Eq}{m} \end{pmatrix} \\
c_3 &= \frac{Eq}{m\omega} \\
&= \frac{E}{B} \\
&= v_{\text{dr}} \\
c_4 &= 0 \\
\mathbf{V}_p &= \begin{pmatrix} v_{\text{dr}} \\ 0 \end{pmatrix} \\
\mathbf{V} &= \begin{pmatrix} c_1 \sin \omega t - c_2 \cos \omega t + v_{\text{dr}} \\ c_1 \cos \omega t + c_2 \sin \omega t \end{pmatrix} \\
\begin{pmatrix} v_{x0} \\ 0 \end{pmatrix} &= \begin{pmatrix} -c_2 + v_{\text{dr}} \\ c_1 \end{pmatrix} \\
c_1 &= 0 \\
c_2 &= v_{\text{dr}} - v_{x0} \\
\mathbf{V} &= \begin{pmatrix} v_{\text{dr}} + (v_{x0} - v_{\text{dr}}) \cos \omega t \\ -(v_{x0} - v_{\text{dr}}) \sin \omega t \end{pmatrix}
\end{aligned}$$

(d)

$$\begin{aligned}
x &= v_{\text{dr}} t + \frac{v_{x0} - v_{\text{dr}}}{\omega} \sin \omega t + x_0 \\
y &= \frac{v_{x0} - v_{\text{dr}}}{\omega} \cos \omega t + y_0 \\
z &= z_0
\end{aligned}$$

## 3 Momentum and Angular Momentum

### 3.3

$$mv_0 = \frac{m}{3}(v_1 + v_2 \cos \theta + v_3 \cos \theta)$$

$$3v_0 = v_0 + \sqrt{2}v_2$$

$$2v_0 = \sqrt{2}v_2$$

$$v_2 = \sqrt{2}v_0$$

$$\mathbf{v}_2 = \sqrt{2}v_0 \left( \cos \frac{\pi}{4} \hat{\mathbf{x}} + \sin \frac{\pi}{4} \hat{\mathbf{y}} \right)$$

$$= v_0(\hat{\mathbf{x}} + \hat{\mathbf{y}})$$

$$\mathbf{v}_3 = v_0(\hat{\mathbf{x}} - \hat{\mathbf{y}})$$

### 3.7

$$v = v_{\text{ex}} \ln \frac{m_0}{m}$$

$$= 2079 \text{ m/s}$$

$$F = 25 \text{ MN}$$

$$W = 19.6 \text{ MN}$$

The thrust is 1.28 times the weight on Earth.

### 3.9

$$-\dot{m}v_{\text{ex}} = m_0g$$

$$v_{\text{ex}} = -\frac{m_0g}{\dot{m}}$$

$$= 2352 \text{ m/s}$$

### 3.11

(a)

$$m\dot{v} = -\dot{m}v_{\text{ex}} + F_{\text{ext}}$$

(b)

$$\begin{aligned}
 m\dot{v} &= -\dot{m}v_{\text{ex}} - mg \\
 \dot{v} &= -\frac{v_{\text{ex}}}{m}\dot{m} - g \\
 \int_0^t \dot{v} dt &= \int_0^t \left( -\frac{v_{\text{ex}}}{m}\dot{m} - g \right) dt \\
 \int_0^v dv' &= -v_{\text{ex}} \int_{m_0}^m \frac{1}{m'} dm' - \int_0^t g dt' \\
 v &= -v_{\text{ex}} \ln \frac{m}{m_0} - gt \\
 &= v_{\text{ex}} \ln \frac{m_0}{m} - gt
 \end{aligned}$$

(c)

$$v = 903 \text{ m/s}$$

It would be 2079 m/s without gravity (2.3 times larger).

(d) The rocket wouldn't take off until it was light enough (from burning fuel) that its thrust was greater than its weight.

### 3.13

$$\begin{aligned}
 v &= v_{\text{ex}} \ln \frac{m_0}{m} - gt \\
 &= v_{\text{ex}} \ln \frac{m_0}{m_0 - kt} - gt \\
 y &= v_{\text{ex}} t - \frac{mv_{\text{ex}}}{k} \ln \frac{m_0}{m} - \frac{1}{2}gt^2 \\
 y(2 \text{ min}) &= 40 \text{ km}
 \end{aligned}$$

### 3.15

$$\begin{aligned}M &= m_1 + m_2 + m_3 \\&= m_1 + m_1 + 10m_1 \\&= 12m_1 \\ \mathbf{R} &= \frac{1}{12m_1} \left[ m_1 \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} + m_2 \begin{pmatrix} 1 \\ -1 \\ 0 \end{pmatrix} + m_3 \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \right] \\&= \frac{1}{12m_1} \begin{pmatrix} 2m_1 \\ 0 \\ 0 \end{pmatrix} \\&= \begin{pmatrix} \frac{1}{6} \\ 0 \\ 0 \end{pmatrix}\end{aligned}$$

### 3.17

If we let Earth be at the origin, then

$$\begin{aligned}R &= \frac{dM_m}{M_e + M_m} \\&= 4630 \text{ km}\end{aligned}$$

The centre of mass is inside Earth.

### 3.19

- (a) No external forces apply during the explosion so the path of the centre of mass would be unchanged.
- (b) 100 m before the target.
- (c) No.

### 3.21

$$\begin{aligned}
\mathbf{R} &= \frac{1}{M} \int \mathbf{r} \, dm \\
&= \frac{2}{\sigma \pi R^2} \int \mathbf{r} \sigma \, dA \\
&= \frac{2}{\pi R^2} \int_0^R \int_0^\pi \mathbf{r} r \, d\phi \, dr \\
&= \frac{2}{\pi R^2} \int_0^R \int_0^\pi r (\cos \phi \hat{\mathbf{x}} + \sin \phi \hat{\mathbf{y}}) r \, d\phi \, dr \\
&= \frac{2}{\pi R^2} \int_0^R r^2 \int_0^\pi (\cos \phi \hat{\mathbf{x}} + \sin \phi \hat{\mathbf{y}}) \, d\phi \, dr \\
&= \frac{2}{\pi R^2} \int_0^R r^2 [\sin \phi \hat{\mathbf{x}} - \cos \phi \hat{\mathbf{y}}]_0^\pi \, dr \\
&= \frac{4}{\pi R^2} \int_0^R r^2 \, dr \hat{\mathbf{y}} \\
&= \frac{4R}{3\pi} \hat{\mathbf{y}}
\end{aligned}$$

### 3.25

$$\begin{aligned}
L &= L_0 \\
I\omega &= I_0\omega_0 \\
mr^2\omega &= mr_0^2\omega_0 \\
\omega &= \left(\frac{r_0}{r}\right)^2 \omega_0
\end{aligned}$$

### 3.29

$$\begin{aligned}
I\omega &= I_0\omega_0 \\
\frac{2}{5} \left(\frac{4}{3}\pi R^3\rho\right) R^2\omega &= \frac{2}{5} \left(\frac{4}{3}\pi R_0^3\rho\right) R_0^2\omega_0 \\
\omega &= \left(\frac{R_0}{R}\right)^5 \omega_0
\end{aligned}$$

If the radius doubles the angular velocity is  $\omega_0/32$ .

**3.31**

$$\begin{aligned}
I &= \int r^2 dm \\
&= \int r^2 \sigma dA \\
&= \frac{M}{\pi R^2} \int_0^R \int_0^{2\pi} r^3 d\phi dr \\
&= \frac{1}{2} MR^2
\end{aligned}$$

**3.33**

$$\begin{aligned}
I &= \int r^2 dm \\
&= \int r^2 \sigma dA \\
&= \frac{M}{(2b)^2} \int_{-b}^b \int_{-b}^b (x^2 + y^2) dx dy \\
&= \frac{M}{4b^2} \int_{-b}^b \left[ \frac{1}{3} x^3 + xy^2 \right]_{-b}^b dy \\
&= \frac{M}{4b} \int_{-b}^b \left( \frac{2}{3} b^2 + 2y^2 \right) dy \\
&= \frac{M}{4b} \left[ \frac{2}{3} b^2 y + \frac{2}{3} y^3 \right]_{-b}^b \\
&= \frac{2}{3} Mb^2
\end{aligned}$$

### 3.35

(b)

$$\Gamma_{\text{ext}} = RMg \sin \gamma$$

$$\dot{L} = \Gamma_{\text{ext}}$$

$$I\dot{\omega} = RMg \sin \gamma$$

$$\frac{3}{2}MR^2\dot{\omega} = RMg \sin \gamma$$

$$\dot{\omega} = \frac{2g \sin \gamma}{3R}$$

$$\begin{aligned}\dot{v} &= R\dot{\omega} \\ &= \frac{2}{3}g \sin \gamma\end{aligned}$$

(c)

$$\begin{aligned}M\dot{v} &= Mg \sin \gamma - f \\ f &= M(g \sin \gamma - \dot{v})\end{aligned}$$

$$\begin{aligned}\Gamma_{\text{ext}} &= Rf \\ &= RM(g \sin \gamma - \dot{v})\end{aligned}$$

$$\dot{L} = \Gamma_{\text{ext}}$$

$$I\dot{\omega} = RM(g \sin \gamma - \dot{v})$$

$$\frac{1}{2}MR^2\dot{\omega} = RM(g \sin \gamma - \dot{v})$$

$$\dot{\omega} = \frac{2(g \sin \gamma - \dot{v})}{R}$$

$$\begin{aligned}\dot{v} &= R\dot{\omega} \\ &= 2(g \sin \gamma - \dot{v}) \\ &= \frac{2}{3}g \sin \gamma\end{aligned}$$



3.37

(b)

$$\begin{aligned}\sum m_{\alpha} r'_{\alpha} &= \sum m_{\alpha} (r_{\alpha} - R) \\ &= \sum m_{\alpha} r_{\alpha} - \sum m_{\alpha} R \\ &= MR - MR \\ &= 0\end{aligned}$$

## 4 Energy

4.3

(a)

$$\begin{aligned}\int_P^Q \mathbf{F} \cdot d\mathbf{r} &= \int_P^O \mathbf{F} \cdot d\mathbf{r} + \int_O^Q \mathbf{F} \cdot d\mathbf{r} \\ &= 0\end{aligned}$$

(b)

$$\begin{aligned}x &= 1 - t \\ y &= t \\ \mathbf{r} &= (1 - t)\hat{\mathbf{x}} + t\hat{\mathbf{y}} \\ d\mathbf{r} &= (-\hat{\mathbf{x}} + \hat{\mathbf{y}}) dt \\ \mathbf{F} \cdot d\mathbf{r} &= (x + y) dt \\ &= [(1 - t) + 1] dt \\ &= dt \\ \int_P^Q \mathbf{F} \cdot d\mathbf{r} &= \int_0^1 dt \\ &= 1\end{aligned}$$

(c)

$$\begin{aligned}\mathbf{r} &= \cos \phi \hat{\mathbf{x}} + \sin \phi \hat{\mathbf{y}} \\ d\mathbf{r} &= (-\sin \phi \hat{\mathbf{x}} + \cos \phi \hat{\mathbf{y}}) d\phi \\ \mathbf{F} \cdot d\mathbf{r} &= (\sin^2 \phi + \cos^2 \phi) d\phi \\ &= d\phi \\ \int_P^Q \mathbf{F} \cdot d\mathbf{r} &= \int_0^{\pi/2} d\phi \\ &= \frac{\pi}{2}\end{aligned}$$