I. A uniform disk of radius $R$ and mass 5 kg is pivoted such that it rotates freely about its central axis as shown in the diagram. A string wrapped around the disk is pulled with a force of 20 N. The disk accelerates at 25 rad/s².

a) If the disk starts from rest, determine its angular displacement after 3s.

$$\alpha = 25 \text{ rad/s}^2$$
$$\omega_0 = 0$$
$$t = 3 \text{ s}$$

$$\Delta \theta = \omega_0 t + \frac{1}{2} \alpha t^2$$

$$\Delta \theta = \left( \frac{1}{2} \right) (25)(3)^2 = 112.5$$

$$\Delta \theta = 110 \text{ rad}$$

b) Find the radius of the disk.

$$\alpha = I \alpha$$
$$\omega = F \cdot r$$
$$I = \frac{1}{2} m R^2$$

$$F \cdot r = \frac{1}{2} m R^2 \alpha$$

$$R = \frac{2F}{m \alpha} = \frac{(2)(20)}{(5)(25)} = 0.32 \text{ m}$$

$$\text{Radius} = 3.2 \text{ cm} = 0.032 \text{ m}$$

c) At $t=3$ s the string comes off the cylinder and a braking force of 10 N is then applied at the outside edge of the disk. How long will it take for the wheel to stop after the brakes are applied?

In first 3 seconds:

$$\omega_f = \omega_0 + \alpha t \Rightarrow \omega_f = 75 \text{ rad/s}$$

After brakes are applied

$$\omega_0 = 75 \text{ rad/s}$$
$$\omega_f = 0$$

$$(\text{since the force is half as big, momentum else unchanged})$$

$$t_{stop} = 6 \text{ s}$$

This makes sense b/c the brake, torque is half as large as the accelerating torque.
II. One mole of a monatomic ideal gas goes through a thermodynamic cycle consisting of two isobaric and two isothermal processes. The cycle consists of four parts: 1 → 2 is isobaric, 2 → 3 is isothermal, 3 → 4 is isobaric, 4 → 1 is isothermal.

a) Complete the table to determine the pressure and volume (in terms of $P_o$ and $V_o$) at each of the four points 1, 2, 3, 4, and then plot the cycle on the P-V diagram to the right and label the points with their number.

<table>
<thead>
<tr>
<th></th>
<th>$P$</th>
<th>$V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>$P_o$</td>
<td>$V_1$</td>
</tr>
<tr>
<td>$P_2$</td>
<td>$P_o$</td>
<td>$V_2$</td>
</tr>
<tr>
<td>$P_3$</td>
<td>$P_o/3$</td>
<td>$V_3$</td>
</tr>
<tr>
<td>$P_4$</td>
<td>$P_o/3$</td>
<td>$V_4$</td>
</tr>
</tbody>
</table>

b) If $P_o = 1.01 \times 10^5$ Pa and $V_o = 2.2 \times 10^{-2}$ m$^3$, determine the minimum and maximum operating temperatures.

$$T \propto PV \Rightarrow T_{\text{max}} \propto (PV)_{\text{max}} \Rightarrow \frac{PV}{nR}$$

$$T_{\text{max}} = \frac{2P_oV_o}{nR}$$

$$T_{\text{min}} = \frac{P_oV_o}{3nR}$$

$$T_{\text{min}} = 267 \text{ K}$$

$$T_{\text{max}} = 535 \text{ K}$$

c) How much work was done in each leg of the cycle and in the whole cycle? $\text{Express answer in terms of } P_oV_o$.

- **1 → 2**: $P \Delta V = P_o V_o$
- **2 → 3**: $+ 2P_o/3V_o /\ln 3 = + 2.2P_oV_o$
- **3 → 4**: $P \Delta V = \left(\frac{P_o}{3}\right)(-3V_o) = - P_oV_o$
- **4 → 1**: $P_oV_o /\ln (1/3) = - P_oV_o$

<table>
<thead>
<tr>
<th>Cycle leg</th>
<th>Work done</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 → 2</td>
<td>$+ P_oV_o$</td>
</tr>
<tr>
<td>2 → 3</td>
<td>$+ 2.2P_oV_o$</td>
</tr>
<tr>
<td>3 → 4</td>
<td>$- P_oV_o$</td>
</tr>
<tr>
<td>4 → 1</td>
<td>$- P_oV_o$</td>
</tr>
<tr>
<td><strong>TOTAL WORK</strong></td>
<td>$+ 1.1P_oV_o$</td>
</tr>
</tbody>
</table>
III. Three successive harmonics for a certain air column are 40, 60, and 80 Hz.

a) Determine whether the air column has one end open and one end closed or both ends open.

Taking the ratio of successive harmonics gives the ratio of the harmonics.

\[ \frac{60}{40} = \frac{3}{2} \quad \text{and} \quad \frac{80}{60} = \frac{4}{3} \quad \text{since they correspond to} \quad n = 2, 3, 4 \quad \text{the} \quad \text{both ends are open (even boundary conditions).} \]

b) Determine the fundamental frequency.

\[ f_{n+1} = f_n = (n+1) f_1 - n f_1 = f_1 \]

\[ f_1 = 20 \text{ Hz} \]

c) In the space below, draw the standing wave pattern for the 40 Hz resonance.

\[ f_2 = 2 f_1 = 40 \text{ Hz} \quad \text{and} \quad n = 2 \Rightarrow L = \lambda \]

\[ L = 2 \]
4. At the moment of a total eclipse, the moon lies along a line from the Earth to the sun. If your normal weight is 600 N, how much is your weight decreased by the combined pull of the sun and moon?

\[ M_{\text{sun}} = 2.0 \times 10^{30} \text{ kg}, \quad r_{\text{sun-E}} = 1.5 \times 10^8 \text{ km} = 1.5 \times 10^{11} \text{ m} \]
\[ M_{\text{moon}} = 7.4 \times 10^{22} \text{ kg}, \quad r_{\text{moon-E}} = 3.8 \times 10^8 \text{ km} = 3.8 \times 10^{12} \text{ m} \]

\[ F_{\text{net}} = F_{\text{moon on you}} + F_{\text{sun on you}} \]

(a) 9.0 N  
(b) 0.90 N  
(c) 90 N  
(d) 3.6 \times 10^6 N  
(c) 0.36 N

After the newton scale of a large

5. A potter’s wheel, with rotational inertia 39 kg\cdot m^2, is spinning freely at 4.2 rad/s. The potter drops a lump of clay onto the wheel, where it sticks a distance 1.1 m from the rotational axis. If the subsequent angular speed of the wheel and clay is 3.4 rad/s, what is the mass of the clay?

\[ L \text{ IS CONSERVED.} \quad I_f \omega_f = I_i \omega_i \]

(a) 7.6 kg  
(b) 5.9 kg  
(c) 6.4 kg  
(d) 4.6 kg  
(e) 3.2 kg

6. A coin with a radius R = 0.15 m rolls up a 30° inclined plane. The coin starts out with an initial angular speed of 60.0 rad/s and rolls in a straight line without slipping. If the moment of inertia of the coin is \( \frac{1}{2} MR^2 \), how far, s, will the coin roll up the inclined plane?

(a) 8.6 cm  
(b) 4.1 cm  
(c) 6.1 cm  
(d) 12 cm  
(e) 10 cm

\[ \frac{1}{2} mV_o^2 + \frac{1}{2} I\omega^2 = mg h \]
\[ \frac{1}{2} mV_o^2 + \frac{1}{2} \left( \frac{1}{2} mR^2 \right) \omega^2 = mg h \]
\[ h = \frac{1}{2} \left( \frac{\omega^2}{g} + \frac{1}{2} \frac{R^2 \omega^2}{g} \right) = \frac{3}{4} \frac{R^2 \omega^2}{g} \]
\[ s = \frac{h}{sin\theta} = 0.12 \text{ m} \]
7. A horizontal bar of length L = 3.0 m and of weight 200 N is supported by a wire that makes an angle $\theta = 40^\circ$ with the horizontal. A load of weight 300 N is placed on the bar at $x$. If the wire can withstand a maximum tension of 400 N, what is the maximum distance, $x$, at which the weight can be placed?

\[ y = \left( \frac{400L}{3m} \right) \sin 40^\circ = \frac{1.57}{8} m \]

- a) 2.2 m
- b) 1.3 m
- c) 1.6 m
- d) 0.8 m
- e) 0.5 m

8. A rock is thrown into a swimming pool that is filled with water at a uniform temperature. After the rock is completely under the surface, which of the following statements is true?

- a) The buoyant force on the rock is zero as it sinks.
- b) The buoyant force on the rock increases as it sinks.
- c) The buoyant force on the rock is constant as it sinks.
- d) The buoyant force on the rock decreases as it sinks.
- e) The buoyant force on the rock as it sinks is nonzero at first but becomes zero once the rock is falling at a constant velocity.

9. A heat engine takes 2 moles of an ideal gas through a reversible cycle 1→2→3→1 etc. The path 2→3 is an isothermal process. The temperature at 3 is 640 K and the volumes $V_1 = 0.03 \text{ m}^3$ and $V_3 = 0.22 \text{ m}^3$. The heat taken in during the leg 2→3 is closest to

- a) 9.5 kJ
- b) 10 kJ
- c) 0 kJ
- d) 21 kJ
- e) 32 kJ

\[ \Delta U = Q - W \]
\[ \text{ISOTHERMAL} \]
\[ \text{SO} \quad \Delta U = 0 \]
\[ Q = W_{\text{done by gas}} \]

\[ W_{\text{gas}} = nRT \ln \left( \frac{V_2}{V_1} \right) = (2)(8.31)(640) \ln \left( \frac{0.22}{0.03} \right) \]
\[ = 21,000 J \]
\[ Q = W \]
10. Of the heat engines below that are physically possible, which is the LEAST efficient?

<table>
<thead>
<tr>
<th></th>
<th>( T_H = )</th>
<th>( T_C = )</th>
<th>Work</th>
<th>Heat engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>480 K</td>
<td>320 K</td>
<td>625 J</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>500 K</td>
<td>240 K</td>
<td>500 J</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>650 K</td>
<td>250 K</td>
<td>800 J</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>550 K</td>
<td>250 K</td>
<td>450 J</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>700 K</td>
<td>350 K</td>
<td>200 J</td>
<td></td>
</tr>
</tbody>
</table>

By 1st Law: \( Q_H = Q_W \) 
By 2nd Law: \( \frac{Q_C}{Q_H} > \frac{Q_H}{T_H} \)

\( \varepsilon_{REAL} = \frac{W}{Q_H} \)
\( \varepsilon_B = \frac{300}{800} = 38\% \)
\( \varepsilon_C = \frac{200}{200} = 40\% \)

11. The graph shows a wave of frequency 1.5 Hz traveling to the right. The speed of this wave is

<table>
<thead>
<tr>
<th></th>
<th>6 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>12 m/s</td>
</tr>
<tr>
<td>c</td>
<td>0.6 m/s</td>
</tr>
<tr>
<td>d</td>
<td>2.4 m/s</td>
</tr>
<tr>
<td>e</td>
<td>1.2 m/s</td>
</tr>
</tbody>
</table>

\[ f = 1.5 \text{ Hz} \quad \lambda = 0.4 \text{ m} \quad V = f \lambda = 0.6 \text{ m/s} \]
12. You suspend a mass from a spring and make it oscillate above a motion detector (like you did in the workshop). The data are shown to the right for "Experiment A". You change the experiment for Experiment B and Experiment C.

\[ \text{SAME PERIOD, SAME MASS} \quad \left( \frac{T}{T_A} = \frac{1}{2} \right) \]

Compared to Experiment A,

<table>
<thead>
<tr>
<th>the hanging mass in Experiment B is...</th>
<th>The hanging mass in Experiment C is...</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) half as big as Experiment A</td>
<td>twice as big as Experiment A</td>
</tr>
<tr>
<td>b) the same as Experiment A</td>
<td>half as big as Experiment A</td>
</tr>
<tr>
<td>c) the same as Experiment A</td>
<td>one-fourth as big as Experiment A</td>
</tr>
<tr>
<td>d) twice as big as Experiment A</td>
<td>the same as Experiment A</td>
</tr>
<tr>
<td>e) twice as big as Experiment A</td>
<td>half as big as Experiment A</td>
</tr>
</tbody>
</table>

13. At an outdoor concert on a cold winter’s night, the speed of sound in the cold air is 330 m/s. An organ pipe open at both ends is 1.5 m long. A second organ pipe that is closed at one end and open at the other is 0.75 m long. Which of the following sets of frequencies consists of frequencies which can be produced by BOTH pipes?

a) 330 Hz, 440 Hz, 550 Hz
b) 330 Hz, 360 Hz, 1200 Hz
c) 330 Hz, 220 Hz, 330 Hz
d) 220 Hz, 440 Hz, 560 Hz
e) 110 Hz, 330 Hz, 550 Hz

14. A rocket has a sound level of 160 dB. What is the intensity in W/m²?

a) 1
b) 100

c) 100,000

d) 10,000

e) 1,000

\[ 160 \text{ dB} = 10 \ln \left( \frac{I}{I_0} \right) \]

\[ I_0 = 10^{-12} \text{ W/m}^2 \]

\[ I = (10^{12})(10^{-12}) = 10^4 \]
Use $g=10 \text{ m/s}^2$ throughout the exam (for simplicity)

I. A uniform disk of radius $R$ and mass $5 \text{ kg}$ is pivoted such that it rotates freely about its central axis as shown in the diagram. A string wrapped around the disk is pulled with a force of $20 \text{ N}$. The disk accelerates at $67 \text{ rad/s}^2$.

![Diagram of a disk with a force applied to the string and an angle θ]

a) If the disk starts from rest, determine its angular displacement after 5s.

\[ \omega_0 = \theta_0 = 0, \quad t = 5 \text{ s} \]
\[ \Delta \theta = \omega_0 t + \frac{1}{2} \alpha t^2 \]
\[ \Delta \theta = \frac{1}{2} (67)(5)^2 = 838 \text{ rad} \]
\[ \theta = \sqrt{838 \text{ rad}} \]

b) Find the radius of the disk.

\[ r = \frac{F}{m \alpha} = \frac{(2)(20)}{\left( \frac{1}{2} \right)(67)} = 0.12 \text{ m} \]

\[ RADIUS = 0.12 \text{ m} = 12 \text{ cm} \]

c) At $t=5$ s the string comes off the cylinder and a braking force of $10 \text{ N}$ is then applied at the outside edge of the disk. How long will it take for the wheel to stop after the brakes are applied?

Since nothing is different except for the size and direction
of the force, the magnitude of the acceleration is proportional to the force.

\[ \alpha = - \frac{10}{0.67} \]

\[ t_{stop} = \frac{\omega_f - \omega_0}{\alpha} = 10 \text{ s} \]
II. One mole of a monatomic ideal gas goes through a thermodynamic cycle consisting of two isobaric and two isothermal processes. The cycle consists of four parts: 1 → 2 is isobaric, 2 → 3 is isothermal, 3 → 4 is isobaric, 4 → 1 is isothermal.

a) Complete the table to determine the pressure and volume (in terms of \( P_0 \) and \( V_0 \)) at each of the four points 1, 2, 3, 4, and then plot the cycle on the P-V diagram to the right and label the points with their number.

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_1 = P_0 )</td>
<td>( V_1 = V_0 )</td>
</tr>
<tr>
<td>( P_2 = \frac{P_0}{2} )</td>
<td>( V_2 = 8V_0 )</td>
</tr>
<tr>
<td>( P_3 = P_0 )</td>
<td>( V_3 = 2V_0 )</td>
</tr>
<tr>
<td>( P_4 = \frac{P_0}{2} )</td>
<td>( V_4 = 4V_0 )</td>
</tr>
</tbody>
</table>

b) If \( P_0 = 1.01 \times 10^5 \text{ Pa} \) and \( V_0 = 2.2 \times 10^{-2} \text{ m}^3 \), determine the minimum and maximum operating temperatures.

\[
T = \frac{PV}{nR} \quad \Rightarrow \quad (PV)_{\text{max}} \rightarrow T_{\text{max}}
\]

\[
T_{\text{max}} = \frac{4P_0V_0}{nR} \quad \Rightarrow \quad T_{\text{min}} = \frac{P_0V_0}{nR}
\]

\[
T_{\text{min}} = 270 \text{ K}
\]

\[
T_{\text{max}} = 1070 \text{ K}
\]

c) How much work is done by the gas in each leg of the cycle and in the whole cycle? Express your answers in terms of \( P_0 \) and \( V_0 \) for simplicity (you do not need to plug in their values.) Let work done by the gas be positive.

\[
W_{1 \rightarrow 2} = PAV = P_0(3V_0) = 3P_0V_0
\]

\[
W_{2 \rightarrow 3} = 4P_0V_0 \ln 2 = 2.8P_0V_0
\]

\[
W_{3 \rightarrow 4} = PAV = (0.5P_0)(-6V_0) = -3P_0V_0
\]

\[
W_{4 \rightarrow 1} = P_0V_0 \ln \left( \frac{1}{2} \right) = -0.7P_0V_0
\]

\[
W_{\text{TOTAL}} = (3 + 2.8 - 3 - 0.7)P_0V_0
\]
Use \( g = 10 \text{ m/s}^2 \) throughout the exam (for simplicity)

III. Three successive harmonics for a certain air column are 60, 90, and 120 Hz.

a) Determine whether the air column has one end open and one end closed or both ends open.

\[
\text{Find ratios: } \frac{60}{90} = \frac{2}{3} \quad \frac{90}{120} = \frac{3}{4}
\]

So both ends open (both even and odd harmonics are present)

b) Determine the fundamental frequency.

\[60 \text{ Hz} = f_2 = 2f_1 \quad \therefore f_1 = 30 \text{ Hz}\]

c) In the space below, draw the standing wave pattern for the 60 Hz resonance.

\[n = 2\]

[Standing wave pattern diagram]
Use $g = 10 \, \text{m/s}^2$ throughout the exam (for simplicity)

4. At the moment of a total eclipse, the moon lies along a line from the Earth to the sun. If your normal weight is 600 N, how much is your weight decreased by the combined pull of the sun and moon?

$$M_{\text{SUN}} = 2.0 \times 10^{30} \, \text{kg}, \quad r_{S-E} = 1.5 \times 10^8 \, \text{km}$$
$$M_{\text{moon}} = 7.4 \times 10^{24} \, \text{kg}, \quad r_{\text{moon}} = 3.8 \times 10^9 \, \text{km}$$

a) $3.6 \times 10^5 \, \text{N}$

b) $0.36 \, \text{N}$

c) $9.0 \, \text{N}$

d) $0.90 \, \text{N}$

e) $90 \, \text{N}$

5. A large potter's wheel, with rotational inertia $39 \, \text{kg} \cdot \text{m}^2$, is spinning steadily at $4.2 \, \text{rad/s}$. After the motor has been turned off, the potter drops a lump of clay onto the wheel, where it sticks a distance $1.2 \, \text{m}$ from the rotational axis. If the subsequent angular speed of the wheel and clay is $3.4 \, \text{rad/s}$, what is the mass of the clay?

$$a) \quad 7.6 \, \text{kg}$$

b) $5.9 \, \text{kg}$

c) $6.4 \, \text{kg}$

d) $4.6 \, \text{kg}$

e) $3.2 \, \text{kg}$

6. A coin with a radius $R = .015 \, \text{m}$ rolls up a $30^\circ$ inclined plane. The coin starts out with an initial angular speed of $60.0 \, \text{rad/s}$ and rolls in a straight line without slipping. If the moment of inertia of the coin is $\frac{1}{2} \, MR^2$, how far, $s$, will the coin roll up the inclined plane?

a) $12 \, \text{cm}$

b) $10 \, \text{cm}$

c) $8.6 \, \text{cm}$

d) $4.1 \, \text{cm}$

e) $6.1 \, \text{cm}$
Use \( g = 10 \text{ m/s}^2 \) throughout the exam (for simplicity)

7. A horizontal bar of length \( L = 3.0 \) m and of weight 200 N is supported by a wire that makes an angle \( \theta = 40^\circ \) with the horizontal. A load of weight 300 N is placed on the bar at \( x \). If the wire can withstand a maximum tension of 500 N, what is the maximum distance, \( x \), at which the weight can be placed?

\[
x = \frac{(500)(2) \sin 40^\circ - (200)(\frac{3}{2})}{300}
\]

\[x = 2.2 \text{ m}\]

b) \( 1.3 \) m
c) \( 1.6 \) m
d) \( 0.8 \) m
e) \( 0.5 \) m

8. A rock is thrown into a swimming pool that is filled with water at a uniform temperature. After the rock is completely under the surface, which of the following statements is true?

a) The buoyant force on the rock is zero as it sinks.

b) The buoyant force on the rock is constant as it sinks.

c) The buoyant force on the rock decreases as it sinks.

d) The buoyant force on the rock increases as it sinks.

e) The buoyant force on the rock as it sinks is nonzero at first but becomes zero once the rock is falling at a constant velocity.

9. A heat engine takes 3 moles of an ideal gas through a reversible cycle \( 1 \rightarrow 2 \rightarrow 3 \rightarrow 1 \) etc. The path \( 2 \rightarrow 3 \) is an isothermal process. The temperature at 3 is 640 K and the volumes \( V_1 = .03 \) m\(^3\) and \( V_3 = .22 \) m\(^3\). The heat taken in during the leg \( 2 \rightarrow 3 \) is closest to

\[
Q = (3)(8,315)(640)\ln\left(\frac{.32}{.03}\right)
\]

\[Q = 32 \text{ kJ}\]

A) 9.5 kJ
b) 10 kJ

\[\text{See \ V. I} \]

c) 0 kJ
d) 21 kJ
e) 32 kJ
Use $g = 10 \text{ m/s}^2$ throughout the exam (for simplicity)

10. Of the heat engines below that are physically possible, which is the MOST efficient?

a) A  
b) B  
c) C  
d) D  
e) E

11. The graph shows a wave of frequency 3.0 Hz traveling to the right. The speed of this wave is

\[ f = 3 \text{ Hz} \quad \lambda = 0.4 \text{ m} \quad \nu = f\lambda = 1.2 \text{ m/s} \]
Use $g=10 \text{ m/s}^2$ throughout the exam (for simplicity)

12. You suspend a mass from a spring and make it oscillate above a motion detector (like you did in the workshop). The data are shown to the right for “Experiment A”. You change the experiment for Experiment B and Experiment C.

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<td>b) twice as big as Experiment A.</td>
<td>half as big as Experiment A.</td>
</tr>
<tr>
<td>c) half as big as Experiment A.</td>
<td>twice as big as Experiment A.</td>
</tr>
<tr>
<td>d) the same as Experiment A.</td>
<td>half as big as Experiment A.</td>
</tr>
<tr>
<td>e) the same as Experiment A.</td>
<td>one-fourth as big as Experiment A.</td>
</tr>
</tbody>
</table>

13. At an outdoor concert on a cold winter’s night, the speed of sound in the cold air is 330 m/s. An organ pipe open at both ends is 1.5 m long. A second organ pipe that is closed at one end and open at the other is 0.75 m long. Which of the following sets of frequencies consists of frequencies which can be produced by BOTH pipes?

- a) 220 Hz, 660 Hz, 1100 Hz
- b) 330 Hz, 440 Hz, 550 Hz
- c) 110 Hz, 330 Hz, 550 Hz
- d) 110 Hz, 220 Hz, 330 Hz
- e) 220 Hz, 440 Hz, 660 Hz

See \( V. \) for solution.

14. A rocket has a sound level of 150 dB. What is the intensity in W/m²?

- a) 1
- b) 100
- c) 100,000
- d) 10,000
- e) 1,000

\[
150 = 10 \log \left( \frac{I}{I_0} \right)
\]

\[
15 = \log \left( \frac{I}{I_0} \right) \quad \frac{I}{I_0} = 10^{15}
\]

\[
I_0 = 10^{-12}, \quad \text{so} \quad I = 10^3
\]