Directions: No books or notes may be used during this exam. Important formulas are provided for you. Graphing calculators and palmtop or laptop computers are not allowed. Write everything on the exam booklet provided. Always include three significant digits in your numerical answers.

\[
\begin{align*}
\ddot{\omega}_{AVE} &= \frac{\Delta \ddot{\theta}}{\Delta t} \quad \ddot{\alpha}_{AVE} = \frac{\Delta \ddot{\alpha}}{\Delta t} \\
\ddot{\theta} &= \ddot{\theta}_i + \ddot{\theta}_i \Delta t + \frac{1}{2} \dddot{\alpha}(\Delta t)^2 \\
\ddot{\omega}_f &= \ddot{\omega}_i + \dddot{\alpha} \Delta t \\
\omega_f^2 &= \omega_i^2 + 2 \alpha \Delta \theta \\
\ddot{\omega}_{AVE} &= \frac{\ddot{\omega}_f + \ddot{\omega}_i}{2}
\end{align*}
\]

\[
\ddot{\omega}(t) = \frac{d^2 \ddot{\theta}(t)}{dt^2} \quad \ddot{\alpha}(t) = \frac{d^2 \dddot{\alpha}(t)}{dt^2} \\
\ddot{\omega}(t) = \int \ddot{\alpha}(t) dt \\
\ddot{\theta}(t) = \int \ddot{\omega}(t) dt \\
\bar{r} = \bar{r} \times \bar{F} \\
I = \int r^2 dm \\
I = I_{cm} + Md^2 \\
\bar{\sigma} = I \ddot{\alpha} \\
K_{ROT} = \frac{1}{2} I \omega^2
\]

\[W_{ROT} = \bar{\tau} \cdot \Delta \ddot{\theta} \quad W_{ROT} = \int \bar{\tau} \cdot d \ddot{\theta} \quad P_{ROT} = \bar{\tau} \cdot \ddot{\omega} \quad \bar{L} = I \ddot{\omega} \quad \bar{L} = \bar{r} \times \ddot{p} \quad \int \bar{\tau} = \frac{d \bar{L}}{dt}
\]

**Question 1:** WRITE THE FORM DESIGNATOR FOR THIS EXAM (A) IN THE ANSWER BOX FOR QUESTION #1 ON THE FIRST PAGE OF THE EXAM BOOKLET.

Questions 2-6 (5 points each) Multiple Choice. You will be graded on your answer only. It is not necessary to show your work for these problems. Put the answer for each question in the proper numbered box on the first page of your test booklet.

2. Could a force with a smaller magnitude produce the same torque as a force with a larger magnitude? (A) Yes, but only if the two forces are in the same direction. (B) Yes, but only if the two forces are in opposite directions. (C) Yes, but only if the two forces are perpendicular. (D) No, it could never do that. (E) None of the other answers are correct.

3. For a wheel that is rolling without slipping on flat, level ground, what is the relationship between the speed of its center of mass \( v_1 \) and the speed of a point on the top of the wheel \( v_2 \)? (A) \( v_1 = v_2 \) (B) \( v_1 < v_2 \) (C) \( v_1 > v_2 \).

4. A particle of mass \( m \) and speed \( v \) is moving in the +x-direction along the line \( y = d \), where \( d > 0 \). What is its angular momentum measured with respect to an axis perpendicular to the xy-plane passing through the origin? (A) \( mv \), clockwise (B) \( mv \), counterclockwise (C) \( mvd \), clockwise (D) \( mvd \), counterclockwise.

5. A motor accelerates a wheel from rest. After 10.0 seconds it's spinning at 100 rad/s, but its center-of-mass remains at rest. The moment of inertia of the wheel is 10.0 kg m². What was the average power output of the engine during this time? Assume constant acceleration. (A) 50.0 W (B) 100 W (C) 500 W (D) 1000 W (E) 5,000 W (F) 10,000 W (G) 50,000 W.

6. A gyroscope starts from rest at time \( t = 0 \) s and its angular acceleration as a function of time is \( \ddot{\alpha}(t) = 10t + 3 \), where the angular acceleration is measured in rad/s² and the time is measured in s. What is the angular speed of the gyroscope at \( t = 3.00 \) sec? (A) 9.00 rad/s (B) 30.0 rad/s (C) 45.0 rad/s (D) 54.0 rad/s (E) None of the other answers are correct.

**TURN THE PAGE OVER**
Solve the following three problems on the front of the next three pages of your exam booklet. Solve each problem on a separate page, in numerical order. For full credit, include the following:

1. Translate the problem statement from English into math. Write equations of the form "symbol equals number units". Include such equations for any constants used in the solution. Write "symbol equals ?" to indicate which quantity is to be determined.
2. Draw the physical representations (graph, diagram, free-body diagram, etc.). Include coordinate axis, if appropriate. Give each axis a label and indicate positive and negative directions, if appropriate.
3. Solve for the unknown quantity. For full credit, include the only mathematical representations which are used in the solution from the list of formulas on the other side of this exam.

7. (25 pts.) Standing on the Equator

In a reference frame in which the Earth is stationary, the acceleration of a person standing on the Earth's equator is 0 m/s². In a reference frame in which the axis of rotation that passes through the north and south poles of the Earth is stationary, and the Earth spins around this axis, what is the acceleration (both magnitude and direction) of a person standing on the Earth's equator? Assume the Earth spins at a constant rate, and that it has a constant radius of 6380 km.

8. (25 pts.) Rolling without Slipping

A solid 50.0-kg cylinder has a radius of 0.100 m, a moment of inertia of \((1/2)mr²\), and is initially at rest. How much energy is required to get it rolling without slipping at a rotational speed of 20.0 rad/s?

9. (25 pts.) Race Track

A race car of mass \(m\) travels at constant speed \(v\) around a circular track of radius \(r\). The track lies in the horizontal plane. It is not tilted or banked. The magnitude of the acceleration due to gravity is \(g\). What is the minimum value of the coefficient of static friction between the car's tires and the track so that the car stays on the track at that speed without skidding off? The answer will be a formula in terms of \(m\), \(v\), \(r\), and/or \(g\).

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\[
\begin{align*}
\ddot{\omega}_{AVE} &= \frac{\Delta \dot{\theta}}{\Delta t} \\
\ddot{\alpha}_{AVE} &= \frac{\Delta \ddot{\alpha}}{\Delta t} \\
\ddot{\theta} &= \ddot{\dot{\theta}} + \dddot{\theta} \Delta t + \frac{1}{2} \dddot{\alpha}(\Delta t)^2 \\
\ddot{\alpha} &= \ddot{\dot{\alpha}} + \dddot{\alpha} \Delta t \\
\ddot{\omega} &= \ddot{\omega} + \dddot{\omega} \Delta t \\
\ddot{\theta}_f &= \ddot{\theta}_i + \dddot{\theta}_i \Delta t + \frac{1}{2} \dddot{\alpha}(\Delta t)^2 \\
\ddot{\alpha}_f &= \ddot{\dot{\alpha}}_i + \dddot{\dot{\alpha}}_i \Delta t + \frac{1}{2} \dddot{\dddot{\alpha}}(\Delta t)^2 \\
\ddot{\omega}_f &= \ddot{\omega}_i + \dddot{\omega}_i \Delta t + \frac{1}{2} \dddot{\dddot{\omega}}(\Delta t)^2 \\
\ddot{\omega}_{AVE} &= \frac{\ddot{\omega}_f + \ddot{\omega}_i}{2}
\end{align*}
\]

\[
\begin{align*}
\ddot{\theta}(t) &= \ddot{\dot{\theta}}(t) + \dddot{\dot{\theta}}(t) \Delta t + \frac{1}{2} \dddot{\dddot{\dot{\theta}}}(\Delta t)^2 \\
\ddot{\alpha}(t) &= \ddot{\dot{\alpha}}(t) + \dddot{\dot{\alpha}}(t) \Delta t + \frac{1}{2} \dddot{\dddot{\dot{\alpha}}}(\Delta t)^2 \\
\ddot{\omega}(t) &= \ddot{\dot{\omega}}(t) + \dddot{\dot{\omega}}(t) \Delta t + \frac{1}{2} \dddot{\dddot{\dot{\omega}}}(\Delta t)^2 \\
\ddot{\theta}(t) &= \ddot{\dot{\theta}}(t) + \dddot{\dot{\theta}}(t) \Delta t \\
\ddot{\alpha}(t) &= \ddot{\dot{\alpha}}(t) + \dddot{\dot{\alpha}}(t) \Delta t \\
\ddot{\omega}(t) &= \ddot{\dot{\omega}}(t) + \dddot{\dot{\omega}}(t) \Delta t
\end{align*}
\]

\[
\begin{align*}
\ddot{r} &= \dddot{r} \times \vec{F} \\
\ddot{I} &= \dddot{I} \times \vec{F} \\
\ddot{L} &= \dddot{L} \times \vec{F}
\end{align*}
\]

\[
\begin{align*}
\ddot{v} &= \frac{2\pi r}{T} \\
\ddot{r} &= \dddot{r} \times \vec{F} \\
\ddot{I} &= \dddot{I} \times \vec{F} \\
\ddot{L} &= \dddot{L} \times \vec{F} \\
\ddot{\theta} &= \dddot{\theta} \times \vec{F} \\
\ddot{\alpha} &= \dddot{\alpha} \times \vec{F} \\
\ddot{\omega} &= \dddot{\omega} \times \vec{F}
\end{align*}
\]

Question 1: WRITE THE FORM DESIGNATOR FOR THIS EXAM (B) IN THE ANSWER BOX FOR QUESTION #1 ON THE FIRST PAGE OF THE EXAM BOOKLET.

Questions 2-6 (5 points each) Multiple Choice. You will be graded on your answer only. It is not necessary to show your work for these problems. Put the answer for each question in the proper numbered box on the first page of your test booklet.

2. A gyroscope starts from rest at time \( t = 0 \) s and its angular acceleration as a function of time is \( \ddot{\alpha}(t) = 10t + 3 \), where the angular acceleration is measured in rad/s\(^2\) and the time is measured in s. What is the angular speed of the gyroscope at \( t = 3.00 \) sec? (A) 9.00 rad/s (B) 30.0 rad/s (C) 45.0 rad/s (D) 54.0 rad/s (E) None of the other answers are correct.

3. Could a force with a smaller magnitude produce the same torque as a force with a larger magnitude? (A) Yes, but only if the two forces are in the same direction. (B) Yes, but only if the two forces are in opposite directions. (C) Yes, but only if the two forces are perpendicular. (D) No, it could never do that. (E) None of the other answers are correct.

4. For a wheel that is rolling without slipping on flat, level ground, what is the relationship between the speed of its center of mass \( v_1 \) and the speed of a point on the top of the wheel \( v_2 \)? (A) \( v_1 = v_2 \) (B) \( v_1 < v_2 \) (C) \( v_1 > v_2 \)

5. A particle of mass \( m \) and speed \( v \) is moving in the +x-direction along the line \( y = d \), where \( d > 0 \). What is its angular momentum measured with respect to an axis perpendicular to the xy-plane passing through the origin? (A) \((mv, \text{ clockwise})\) (B) \((mv, \text{ counterclockwise})\) (C) \((mvd, \text{ clockwise})\) (D) \((mvd, \text{ counterclockwise})\).

6. A motor accelerates a wheel from rest. After 10.0 seconds it's spinning at 100 rad/s, but its center-of-mass remains at rest. The moment of inertia of the wheel is 10.0 kg m\(^2\). What was the average power output of the engine during this time? Assume constant acceleration. (A) 50.0 W (B) 100 W (C) 500 W (D) 1000 W (E) 5,000 W (F) 10,000 W (G) 50,000 W.

TURN THE PAGE OVER
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1. Translate the problem statement from English into math. Write equations of the form "symbol equals number units". Include such equations for any constants used in the solution. Write "symbol equals ?" to indicate which quantity is to be determined.
2. Draw the physical representations (graph, diagram, free-body diagram, etc.). Include coordinate axis, if appropriate. Give each axis a label and indicate positive and negative directions, if appropriate.
3. Solve for the unknown quantity. For full credit, include the only mathematical representations which are used in the solution from the list of formulas on the other side of this exam.

7. (25 pts.) Standing on the Equator

In a reference frame in which the Earth is stationary, the acceleration of a person standing on the Earth's equator is 0 m/s². In a reference frame in which the axis of rotation that passes through the north and south poles of the Earth is stationary, and the Earth spins around this axis, what is the acceleration (both magnitude and direction) of a person standing on the Earth's equator? Assume the Earth spins at a constant rate, and that it has a constant radius of 6380 km.

8. (25 pts.) Rolling without Slipping

A solid 50.0-kg cylinder has a radius of 0.100 m, a moment of inertia of \((1/2)mr^2\), and is initially at rest. How much energy is required to get it rolling without slipping at a rotational speed of 20.0 rad/s?

9. (25 pts.) Race Track

A race car of mass \(m\) travels at constant speed \(v\) around a circular track of radius \(r\). The track lies in the horizontal plane. It is not tilted or banked. The magnitude of the acceleration due to gravity is \(g\). What is the minimum value of the coefficient of static friction between the car's tires and the track so that the car stays on the track at that speed without skidding off? The answer will be a formula in terms of \(m\), \(v\), \(r\), and/or \(g\).

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\[
\begin{align*}
\vec{\omega}_{AVE} &= \frac{\Delta\vec{\theta}}{\Delta t} \\
\vec{\alpha}_{AVE} &= \frac{\Delta\vec{\omega}}{\Delta t} \\
\Delta\vec{\theta} &= \vec{\theta}_f - \vec{\theta}_i + \vec{\omega}_t \Delta t + \frac{1}{2} \vec{\alpha} (\Delta t)^2 \\
\Delta\vec{\omega} &= \vec{\omega}_f - \vec{\omega}_i + \vec{\alpha} \Delta t \\
\omega_f^2 &= \omega_i^2 + 2\alpha \Delta \theta \\
\vec{\omega}_{AVE} &= \frac{\vec{\omega}_f + \vec{\omega}_i}{2} \\
\vec{\omega}(t) &= \vec{\omega}(0) + \int \vec{\alpha}(t) dt \\
\vec{\alpha}(t) &= \vec{\omega}(0) + \int \vec{\alpha}(t) dt \\
\vec{\omega}(t) &= \vec{\alpha}(t) dt \\
\vec{\alpha}(t) &= \vec{\omega}(t) dt \\
\theta(t) &= \int \vec{\alpha}(t) dt \\
\vec{\omega}(t) &= \int \vec{\alpha}(t) dt \\
s &= r\theta \\
v_r &= r\omega \\
a_r &= r\alpha \\
a_r &= \frac{v^2}{r} \\
\vec{\omega}^2 &= \omega^2 r \\
v &= \frac{2\pi r}{T} \\
\vec{t} &= \vec{r} \times \vec{F} \\
I &= \int r^2 dm \\
I &= I_{CM} + Md^2 \\
\sum \vec{t} &= I\vec{\omega} \\
K_{ROT} &= \frac{1}{2} I\omega^2 \\
W_{ROT} &= \vec{t} \cdot \Delta \vec{\omega} \\
W_{ROT} &= \int \vec{t} \cdot d\vec{\omega} \\
P_{ROT} &= \vec{t} \cdot \vec{\omega} \\
L &= I\vec{\omega} \\
L &= \vec{r} \times \vec{p} \\
\sum \vec{t} &= \frac{d\vec{L}}{dt}
\end{align*}
\]

Question 1: WRITE THE FORM DESIGNATOR FOR THIS EXAM (C) IN THE ANSWER BOX FOR QUESTION #1 ON THE FIRST PAGE OF THE EXAM BOOKLET.

Questions 2-6 (5 points each) Multiple Choice. You will be graded on your answer only. It is not necessary to show your work for these problems. Put the answer for each question in the proper numbered box on the first page of your test booklet.

2. A motor accelerates a wheel from rest. After 10.0 seconds it's spinning at 100 rad/s, but its center-of-mass remains at rest. The moment of inertia of the wheel is 10.0 kg m². What was the average power output of the engine during this time? Assume constant acceleration. (A) 50.0 W (B) 100 W (C) 500 W (D) 1000 W (E) 5,000 W (F) 10,000 W (G) 50,000 W.

3. A gyroscope starts from rest at time t = 0 s and its angular acceleration as a function of time is \( \vec{\alpha}(t) = 10t + 3 \), where the angular acceleration is measured in rad/s² and the time is measured in s. What is the angular speed of the gyroscope at t = 3.00 sec? (A) 9.00 rad/s (B) 30.0 rad/s (C) 45.0 rad/s (D) 54.0 rad/s (E) None of the other answers are correct.

4. Could a force with a smaller magnitude produce the same torque as a force with a larger magnitude? (A) Yes, but only if the two forces are in the same direction. (B) Yes, but only if the two forces are in opposite directions. (C) Yes, but only if the two forces are perpendicular. (D) No, it could never do that. (E) None of the other answers are correct.

5. For a wheel that is rolling without slipping on flat, level ground, what is the relationship between the speed of its center of mass \( v_1 \) and the speed of a point on the top of the wheel \( v_2 \)? (A) \( v_1 = v_2 \) (B) \( v_1 < v_2 \) (C) \( v_1 > v_2 \).

6. A particle of mass \( m \) and speed \( v \) is moving in the +x-direction along the line \( y = d \), where \( d > 0 \). What is its angular momentum measured with respect to an axis perpendicular to the xy-plane passing through the origin? (A) \( mv \), clockwise (B) \( mv \), counterclockwise (C) \( mvd \), clockwise (D) \( mvd \), counterclockwise.

TURN THE PAGE OVER
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2. Draw the physical representations (graph, diagram, free-body diagram, etc.). Include coordinate axis, if appropriate. Give each axis a label and indicate positive and negative directions, if appropriate.

3. Solve for the unknown quantity. For full credit, include the only mathematical representations which are used in the solution from the list of formulas on the other side of this exam.

7. (25 pts.) Standing on the Equator

In a reference frame in which the Earth is stationary, the acceleration of a person standing on the Earth's equator is 0 m/s². In a reference frame in which the axis of rotation that passes through the north and south poles of the Earth is stationary, and the Earth spins around this axis, what is the acceleration (both magnitude and direction) of a person standing on the Earth's equator? Assume the Earth spins at a constant rate, and that it has a constant radius of 6380 km.

8. (25 pts.) Rolling without Slipping

A solid 50.0-kg cylinder has a radius of 0.100 m, a moment of inertia of \((1/2)mr^2\), and is initially at rest. How much energy is required to get it rolling without slipping at a rotational speed of 20.0 rad/s?

9. (25 pts.) Race Track

A race car of mass \(m\) travels at constant speed \(v\) around a circular track of radius \(r\). The track lies in the horizontal plane. It is not tilted or banked. The magnitude of the acceleration due to gravity is \(g\). What is the minimum value of the coefficient of static friction between the car's tires and the track so that the car stays on the track at that speed without skidding off? The answer will be a formula in terms of \(m\), \(v\), \(r\), and/or \(g\).

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\[ \omega_{AVE} = \frac{\Delta \theta}{\Delta t}, \quad \ddot{\alpha}_{AVE} = \frac{\Delta \ddot{\theta}}{\Delta t}, \quad \ddot{\theta}_f = \ddot{\theta}_i + \ddot{\omega}_i \Delta t + \frac{1}{2} \ddot{\alpha}(\Delta t)^2, \quad \ddot{\omega}_f = \ddot{\omega}_i + \ddot{\alpha} \Delta t, \quad \omega_f^2 = \omega_i^2 + 2 \alpha \Delta \theta, \quad \ddot{\omega}_{AVE} = \frac{\ddot{\omega}_f + \ddot{\omega}_i}{2} \]

\[ \ddot{\omega}(t) = \frac{d\ddot{\theta}(t)}{dt}, \quad \ddot{\alpha}(t) = \frac{d\ddot{\omega}(t)}{dt}, \quad \ddot{\omega}(t) = \int \ddot{\alpha}(t) dt, \quad \ddot{\theta}(t) = \int \ddot{\omega}(t) dt, \quad s = r \theta, \quad v_r = r \omega, \quad a_r = r \alpha, \quad a_r = \frac{v^2}{r} = \omega^2 r \]

\[ v = \frac{2 \pi r}{T}, \quad \ddot{\tau} = \ddot{r} \times \dddot{F}, \quad I = \int \rho^2 dm, \quad I = I_{CM} + Md^2, \quad \Sigma \ddot{\tau} = I \ddot{\alpha}, \quad K_{ROT} = \frac{1}{2} I \omega^2 \]

\[ W_{ROT} = \ddot{\tau} \cdot \Delta \ddot{\theta}, \quad W_{ROT} = \int \dddot{\tau} \cdot d\ddot{\theta}, \quad P_{ROT} = \ddot{\tau} \cdot \ddot{\omega}, \quad \ddot{L} = I \ddot{\omega}, \quad \dddot{L} = \ddot{r} \times \dddot{F}, \quad \Sigma \ddot{\tau} = \frac{d\ddot{L}}{dt} \]

Question 1: WRITE THE FORM DESIGNATOR FOR THIS EXAM (D) IN THE ANSWER BOX FOR QUESTION #1 ON THE FIRST PAGE OF THE EXAM BOOKLET.

Questions 2-6 (5 points each) Multiple Choice. You will be graded on your answer only. It is not necessary to show your work for these problems. Put the answer for each question in the proper numbered box on the first page of your test booklet.

2. A particle of mass \( m \) and speed \( v \) is moving in the \( +x \)-direction along the line \( y = d \), where \( d > 0 \). What is its angular momentum measured with respect to an axis perpendicular to the \( xy \)-plane passing through the origin? (A) \( mv \), clockwise (B) \( mv \), counterclockwise (C) \( mvd \), clockwise (D) \( mvd \), counterclockwise.

3. A motor accelerates a wheel from rest. After 10.0 seconds it's spinning at 100 rad/s, but its center-of-mass remains at rest. The moment of inertia of the wheel is 10.0 kg m². What was the average power output of the engine during this time? Assume constant acceleration. (A) 50.0 W (B) 100 W (C) 500 W (D) 1000 W (E) 5,000 W (F) 10,000 W (G) 50,000 W.

4. A gyroscope starts from rest at time \( t = 0 \) s and its angular acceleration as a function of time is \( \ddot{\alpha}(t) = 10t + 3 \), where the angular acceleration is measured in rad/s² and the time is measured in s. What is the angular speed of the gyroscope at \( t = 3.00 \) sec? (A) 9.00 rad/s (B) 30.0 rad/s (C) 45.0 rad/s (D) 54.0 rad/s (E) None of the other answers are correct.

5. Could a force with a smaller magnitude produce the same torque as a force with a larger magnitude? (A) Yes, but only if the two forces are in the same direction. (B) Yes, but only if the two forces are in opposite directions. (C) Yes, but only if the two forces are perpendicular. (D) No, it could never do that. (E) None of the other answers are correct.

6. For a wheel that is rolling without slipping on flat, level ground, what is the relationship between the speed of its center of mass \( v_1 \) and the speed of a point on the top of the wheel \( v_2 \)? (A) \( v_1 = v_2 \) (B) \( v_1 < v_2 \) (C) \( v_1 > v_2 \).

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In a reference frame in which the Earth is stationary, the acceleration of a person standing on the Earth's equator is $0 \text{ m/s}^2$. In a reference frame in which the axis of rotation that passes through the north and south poles of the Earth is stationary, and the Earth spins around this axis, what is the acceleration (both magnitude and direction) of a person standing on the Earth's equator? Assume the Earth spins at a constant rate, and that it has a constant radius of 6380 km.

8. (25 pts.) Rolling without Slipping

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9. (25 pts.) Race Track

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