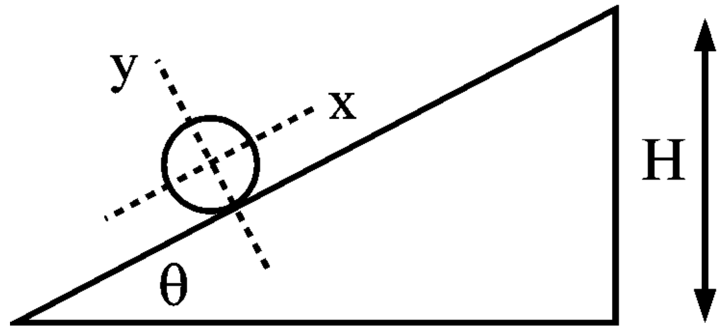
First Name: ____________________ Last Name:________________________________



A ball of mass M, radius R and moment of inertia I is smoothly rolling uphill. You will use this figure for the entire tutorial.

1. At this instant, what is the direction of the linear acceleration of the ball? Use the coordinate system shown and explain your reasoning.

2. At this instant, what is the direction of the angular acceleration of the ball? Use the coordinate system shown and explain your reasoning.

3. Draw a free body diagram (FBD) with qualitatively correct vector lengths for the ball.

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4. If you have drawn a friction force in Question #3, what type of friction force is it? Explain your reasoning.

To help determine whether your FBD in Question #3 is correct, you must check to see if it explains the answers you gave in Questions #1 and #2. It is possible that as you work through Questions #5-8, you may reach the conclusion that your FBD in Question #3 is incorrect. If so, you must fix it.

5. Do the forces in your FBD correctly explain the x-component of the acceleration (which was part of your answer to Question #1)? Explain why or why not.

6. Do the forces in your FBD correctly explain the y-component of the acceleration (which was part of your answer to Question #1)? Explain why or why not.

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7. For each force in your FBD in Question #3, determine if that force creates a torque about the center of mass of the ball. If it does, determine the direction of that torque in the original coordinate system. If it does not, explain why not.

8. Using the results from Question #7, does your FBD correctly explain the angular acceleration that you described in Question #2? Explain why or why not.

9. Hopefully, you now correctly understand the FBD (if not, please request help from a learning assistant). Redraw it here with qualitatively correct vector lengths.

It is now time to determine the size of the static friction force.

10. Write out Newton's 2nd Law along the x and y axes. Similarly, write out Newton's 2nd Law for rotation where you should calculate torques relative to the center of mass of the ball. Note that you may **not** assume that you have maximum static friction so the static friction force will have to be labeled as f_s.

11. Examine the equations you wrote in Question #10 and identify (circle them) all unknown quantities. Compare the number of equations to the number of unknowns. Would you be able to solve these equations at this point? Explain why or why not. If you need any additional equation(s), write them down and explain what they mean. Hint: don't forget that the ball is rolling smoothly.

12. Solve the equations in Questions #10-11 for the static friction force, the normal force, the linear acceleration of the ball and the angular acceleration of the ball.

13. Evaluate your answers to Question #12 in the specific case that the ball is a solid sphere with $I = \frac{2}{5}MR^2$.

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14. Imagine that the solid spherical ball has a linear speed of 5 m/s at the bottom of the incline. Also, assume that H=1.5 m. By the time this question is done, you will have calculated its linear speed at the top of the incline using two different methods:

    A: Determine the time to reach the top and the linear speed at the top using Newton's Laws (as you have throughout the entire tutorial) and kinematics.

    B: As you solved part A, there should have appeared to be two possible solutions. How did you know which one was correct and/or how did you eliminate the other one? Explain your reasoning.

C: Explain physically (not mathematically) why the linear speed at the top does not depend upon the angle of the incline.

D: Determine the linear speed at the top using energy conservation.

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Comments about this tutorial:

The dynamics of rolling is clearly one of the most challenging topics in introductory mechanics so there is no question that students will find this difficult. This is definitely intended for calculus-based physics courses. Since this covers the more challenging rolling uphill (since the static friction force is uphill) I think it is critical that they have already seen rolling downhill in a previous class.

Throughout the semester, I emphasize "Does your FBD accurately reflect what is happening to the object?" That is the point of the first eight questions. The majority of groups have trouble drawing the FBD correctly and also have trouble understanding whether their diagram accurately describes the actual acceleration/angular acceleration. I heard many interesting discussions during this tutorial both amongst students in the groups but also when they were being helped by one of the preceptors.

Question #2: Many students would like to answer this as counterclockwise but I really want to get them using the xyz labels.

Question #4: If you have talked enough about rolling smoothly in class, they will know it is static friction but otherwise they probably won't.

Questions #7-9: Many students will understand that their initial FBD was wrong but not understand how to fix it.

Question #11 clearly requires them to add the smoothly rolling condition $a = R\alpha$. It helps to have something with you that you can roll smoothly or not smoothly so they can see that this condition doesn't always apply.

Most groups were on Questions #11-13 after 50 minutes. There were a couple exceptional groups that finished the activity.

Question #12: Some get bogged down by algebra.

Since so few students get to the end, I can't really comment on their performance on the last question.

Tutorial source(s):

All questions were written by Drew Milsom

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