SDI LAB #4. ROTATIONAL DYNAMICS

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Last (Print Clearly) First (Print Clearly) ID Number

LAB SECTION ________________________LAB TABLE POSITION___________________________

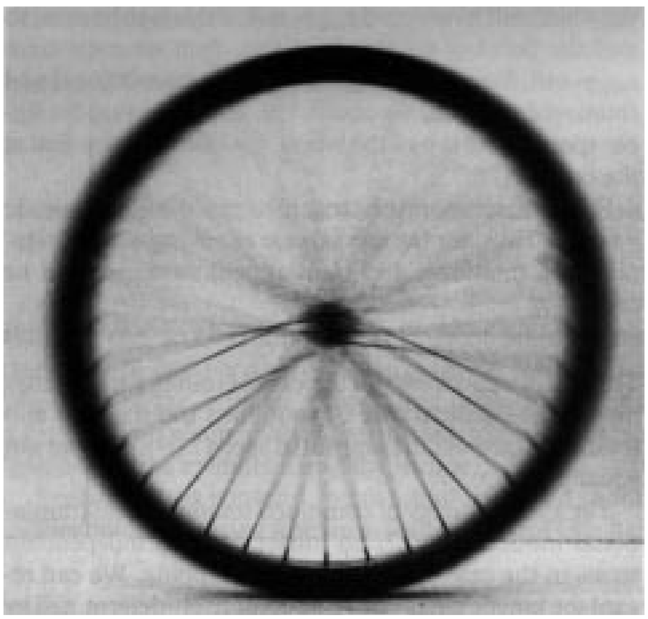

Fig. 1. Photograph of a rolling bicycle wheel from R. Resnick, D. Halliday, and K.S. Krane, Physics (4th ed., John Wiley& Sons, 1992), p. 259, Fig. 22, photo by Alice Halliday, © John Wiley & Sons, 1992. This material is used by permission of the copyright holder, John Wiley & Sons, Inc.

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I. INTRODUCTION

In this lab you strengthen your grasp of Newtonian mechanics by performing relatively simple experiments which can be understood on the basis of Newton's second law of rotational motion (N2R), $\vec{\tau}_o = I_o \vec{\alpha}_o$, and the expression for the rotational kinetic energy $K_R = (1/2)I_o \omega_o^2$. **(**In these expressions, the subscript "o" indicates the point about which the quantities are taken.**)**

A. OBJECTIVES

1. To understand the relationship of center-of- mass, tangential, rim, and angular velocities during rolling without slipping by (a) unrolling a tape from a hoop, and (b) rolling a hoop down an inclined plane.

2. To consider two rotational motion puzzles: "Mystery Batons" and the "Charwoman's Coup."

3. To understand how rotational kinetic energy considerations apply to the rolling of hoops, cylinders, spheres, soup cans, and yo-yos down inclined planes: the roller race.

4. To derive from energy considerations and then from Newton's second law of rotation an expression for the translational velocity of the center of mass of a yo-yo rolling from rest a distance L down a channel. To devise and execute an experimental check of this relationship. To consider the translational velocity of the yo-yo as it rolls on a table after its descent down the channel.

B. HOW TO PREPARE FOR THIS LAB

1. **Review the Sec. I-B "Ground Rules for SDI Labs," of SDI Lab #0.1.**

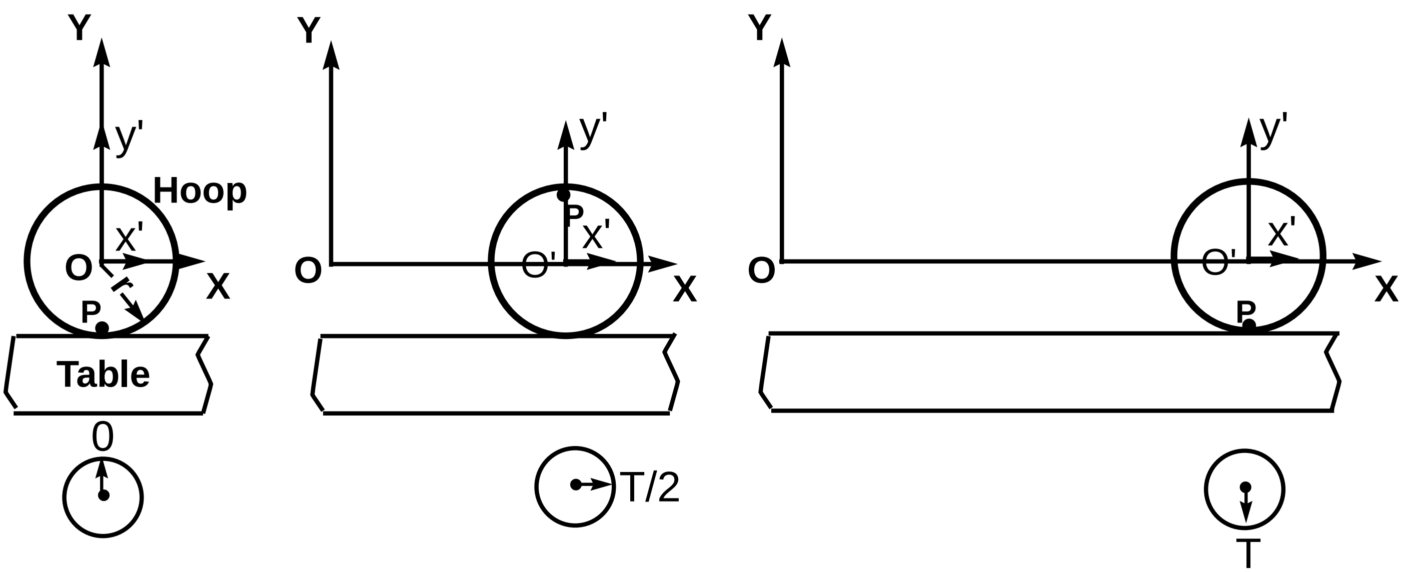
2. Before you begin, it will also help to study the following sections in the course text *Physics*, 4th ed. by Douglas Giancoli (or similar material in whatever text you are using): Chap. 5, "Circular Motion, Gravitation"; Chapter 8, "Rotational Motion." In addition please review ALL the material covered in lectures, labs, and homework on frictional forces, circular motion, and rotational dynamics.

II. CENTER-OF-MASS, TANGENTIAL, RIM, AND ANGULAR VELOCITIES DURING ROLLING WITHOUT SLIPPING (to be done by all students as the first experiment).

A. RELATIONSHIP OF THE CENTER-OF-MASS VELOCITY, $\vec{v}_{cm}$, TO THE ANGULAR VELOCITY $\vec{\omega}$ (CONSTANT $\vec{\omega}$ CASE)

1. Use the black tape and the hoop at your table: (a) affix one end of the tape to the outer surface of the hoop with drafting tape, (b) wrap the black tape once around the hoop, and (c) cut the black tape off so that it has a length equal to the outer circumference $C = 2\pi r$ of the hoop, where r is the outer radius of the hoop. Place a pencil mark on the rim of the hoop where the two ends of the tape meet. Call this point "P." Starting from a position with the CM of the hoop (i.e., the center of the hoop) slightly to the left of the t = 0 position (Fig. 2a), roll the hoop through one revolution so that it maintains *a nearly constant angular velocity* $\vec{\omega}$ over the time span $0 \leq t \leq T$ of Fig. 2 and the tape unwinds to lay in a straight line on the table (Fig. 2c). Here T is just the period for rotation of the hoop through one revolution.

A TAPE UNWINDS FROM A HOOP: START, MIDDLE, AND END OF THE <u>CONSTANT-ω</u> MOTION



2a. Start . 2b. Middle Fig. 2c. End

Fig. 2. A hoop rolls at constant angular velocity ω over the time span $0 \leq t \leq T$ so as to unwind a tape which encircles the hoop at t = 0.

2. Draw in the $\vec{\omega}$ vectors and the positions of the tape in Fig. 2a, b, c. For clarity show the tape as brown.

3. How far does the center of mass (CM) of the hoop travel (translate) during one revolution? [HINT: Look at the tape.]

4. What, then, is the translational speed v_{cm} of the CM *with respect to* (wrt) *the lab frame of reference* Oxy?

5. Draw in the vectors $\vec{\mathbf{v}}_{cm}$ in the sketches of Fig. 2.

6. What would be the path of the point P *as seen by an observer in the reference frame* O′x′y′ *fixed to the CM and NOT rotating* (i.e., wrt O′x′y′) ? [Hint: Walk along beside the hoop as you roll it. Watch the point P.]

7. Would the path in "6" change if the hoop rotated about the CM and the CM were *stationary* wrt the lab frame? {Y, N, U, NOT} [Hint: Stand motionless in the lab frame of reference. Rotate the hoop with its CM stationary in the lab frame. Watch the point P.]

8. How far does point P travel during one revolution wrt O′x′y′? [Note that the *distance travelled* wrt O′x′y′ is NOT the same as the *displacement* wrt O′x′y′(the latter would be zero!).]

9. What then is the tangential speed $\vec{\mathbf{v}}_t$ of the rim of the hoop with respect to a coordinate system O′x′y′ moving with the center of mass? (NOTE: Here we *define* the *tangential* speed to be the speed of the rim of the hoop with respect to O′x′y′ fixed to the CM. Thus the tangential velocity vector $\vec{\mathbf{v}}_t$ is always tangent to the circumference of the hoop, even when the hoop is rolling.)

10. What then is the relationship between v_{cm} and v_t?

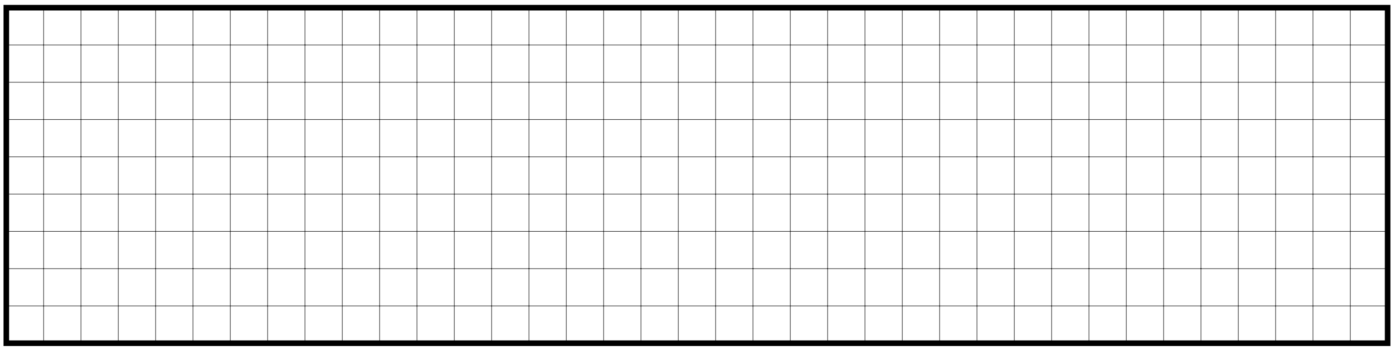
11. Can you derive the famous relation $v_t = \omega r$? {Y, N, U, NOT} [HINT: How is a small increment of angle $\Delta\theta$ at the center of the hoop related to the corresponding arc length Δs? What are the definitions of ω and v_t?]

DERIVATION OF THE FAMOUS RELATION $v_t = \omega r$

12. Since $v_t = \omega r$ and considering your answer to "10," above, how is the translational center-of-mass velocity v_{cm} related to the angular velocity ω?

13. Repeat part "1" above, except omit the tape and watch the pencil mark on the rim (point P) as the hoop rolls at constant angular velocity. Can you sketch the path of the point *as seen by an observer (you) fixed in the lab frame of reference* Oxy? {Y, N, U, NOT} [HINT: You may want to experimentally trace out the path on sheets of paper - can you think of a way to do this?]

PATH OF A POINT ON THE RIM OF A ROLLING HOOP AS SEEN BY A LAB OBSERVER



Do you know the name of this famous curve? {Y, N, U, NOT }

B. RELATIONSHIP OF THE MAGNITUDES OF THE CENTER OF MASS VELOCITY, $\vec{\mathbf{v}}_{cm}$, AND THE ANGULAR VELOCITY $\vec{\omega}$ (NON-CONSTANT $\vec{\omega}$ CASE)

1. Suppose ω in *not* constant as in part "A" above. A time-dependent ω would occur, for example, if the hoop rolled down the incline without slipping as in Fig. 3. Considering your work in part "A," what would be the relationship between the *instantaneous* magnitudes of the translational velocity of the center of mass $\vec{\mathbf{v}}_{cm}$, the tangential velocity $\vec{\mathbf{v}}_{t}$, and the angular velocity $\vec{\omega}$? [HINT: Consider performing the above experiment of Sec. A, parts 1-12, for a small fraction of a revolution requiring some small time interval Δt which is a small fraction of a period T. Then consider experiments as $\Delta t \rightarrow 0$.]

2. Roll the hoop down the incline at one of the lab tables. The snapshot sketches of Fig. 3 show the hoop *starting from rest* at t = 0 near the top of the incline, and then at later times rolling near the middle and bottom of the incline. In the latter two sketches qualitatively show the instantaneous center-of-mass velocity $\vec{\mathbf{v}}_{cm}$, the instantaneous angular velocity vector $\vec{\omega}$, and the instantaneous tangential velocity vectors $\vec{\mathbf{v}}_t$ ***on the rim*** **with their tails at four points: near the contact point, opposite the contact point, and at the two points of intersection of the rim and the x-axis.**

SHOW $\vec{\mathbf{v}}_{cm}$, $\vec{\omega}$, AND $\vec{\mathbf{v}}_t$ FOR THE ROLLING HOOP NEAR THE MIDDLE AND BOTTOM OF THE INCLINE. SHOW $\vec{\mathbf{v}}_t$ AT 4 POINTS ON THE RIM AS SPECIFIED ABOVE.

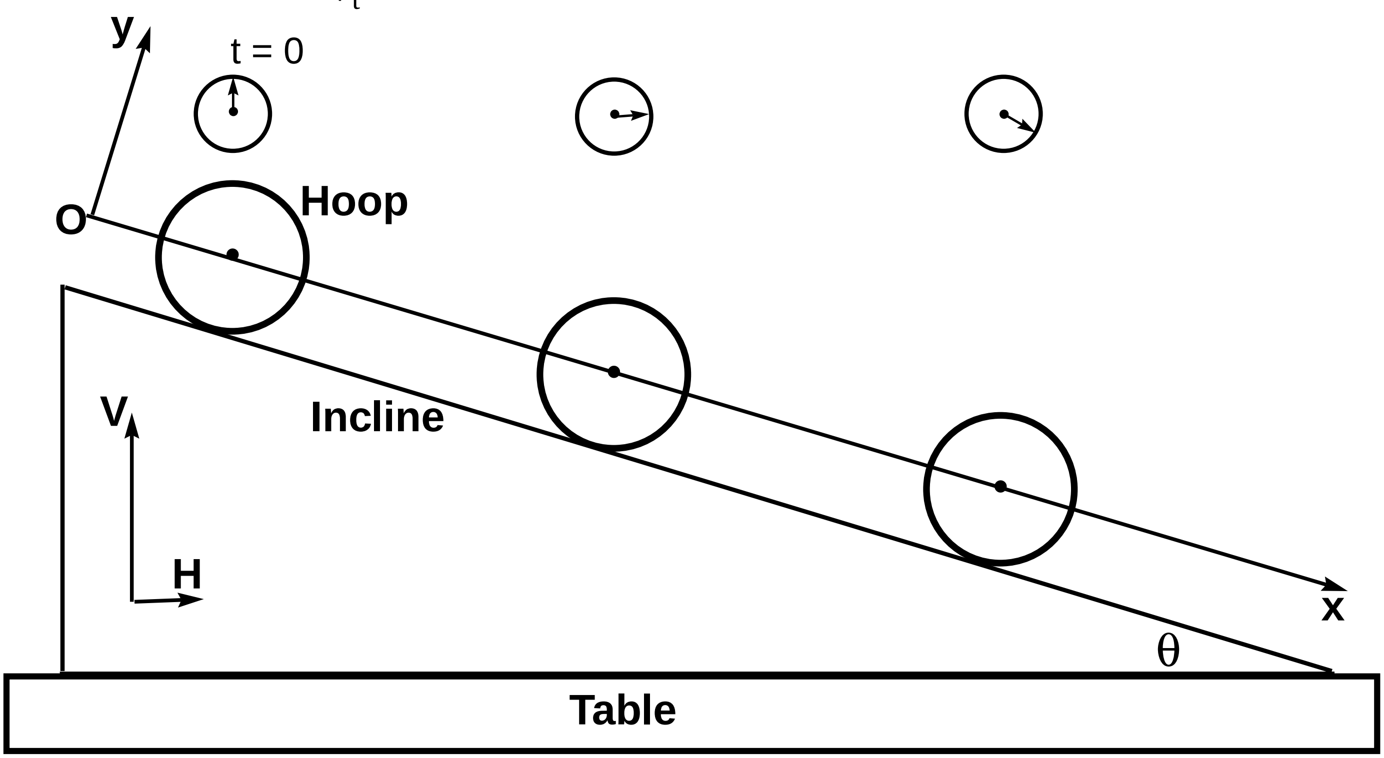


Fig. 3. Three snapshot sketches show the hoop near the top, middle, and bottom of the incline. Near the top at t = 0 the hoop is at rest. Not to scale. θ has been enlarged from the θ ≈ 10° used in the lab.

3. Complete the snapshot sketches in Fig. 4 on the next page, but now show only the instantaneous vector velocities $\vec{\mathbf{v}}_{rim}$ of points on the rim of the hoop *with respect to the laboratory frame* at the same four rim positions. [HINT #1: Consider the vector addition of velocities $\vec{\mathbf{v}}_{rim} \equiv \vec{\mathbf{v}}$ (rim with respect to lab), $\vec{\mathbf{v}}_t \equiv \vec{\mathbf{v}}$ (rim with respect to CM), and $\vec{\mathbf{v}}_{cm} \equiv \vec{\mathbf{v}}$ (CM with respect to lab). Write a *vector* equation connecting these three velocities, using the standard subscript notation.] [HINT #2: See Giancoli, p. 56 (or comparable equation in whatever text you are using), and his equation $\vec{\mathbf{v}}_{BS} = \vec{\mathbf{v}}_{BW} + \vec{\mathbf{v}}_{WS}$, where $\vec{\mathbf{v}}_{BS} \equiv$ velocity of <u>B</u>oat with respect to <u>S</u>hore, $\vec{\mathbf{v}}_{BW} \equiv$ velocity of <u>B</u>oat with respect to <u>W</u>ater, and $\vec{\mathbf{v}}_{WS} \equiv$ velocity of <u>W</u>ater with respect to <u>S</u>hore.]

SHOW ONLY $\vec{\mathbf{v}}_{rim}$ AT 4 POINTS ON THE RIM: CONTACT POINT (CP), OPPOSITE CP, AND AT THE POINTS OF INTERSECTION OF THE RIM AND THE X-AXIS

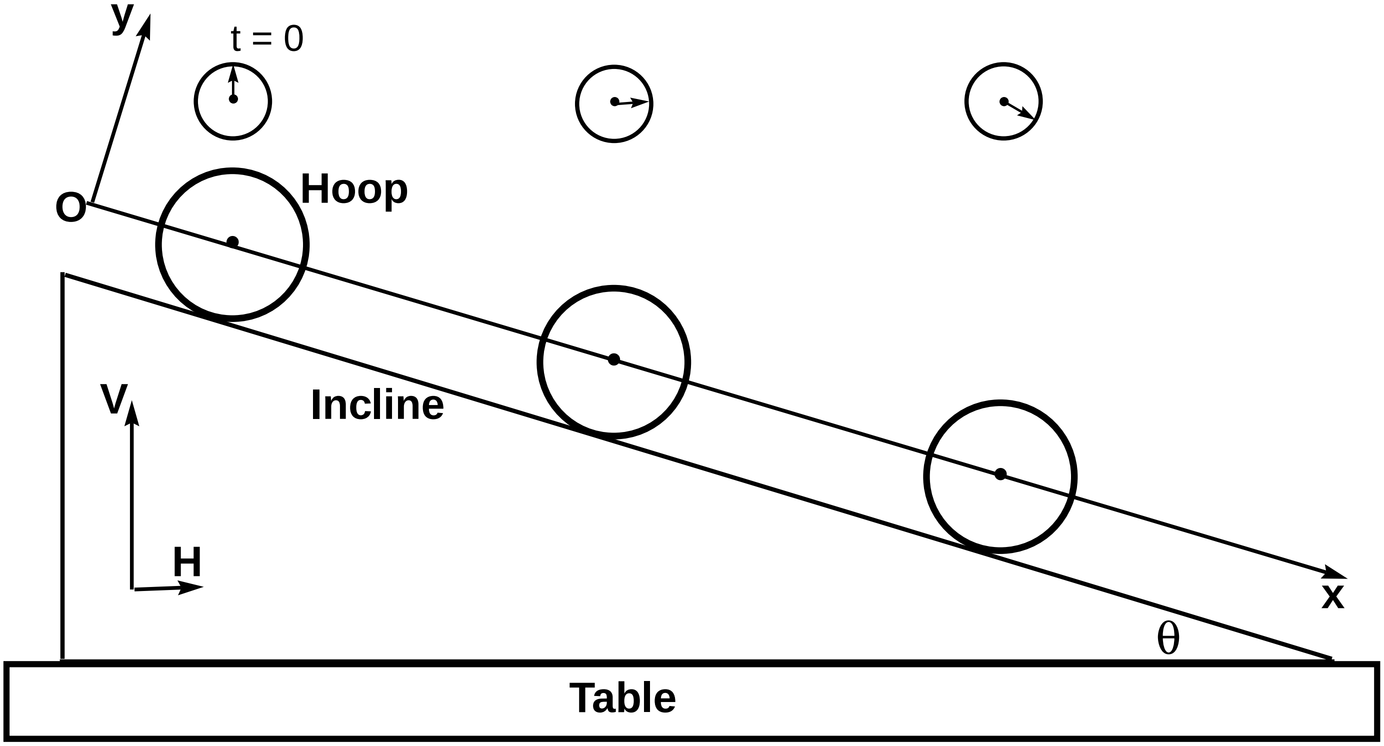


Fig. 4. A hoop starting from rest at t = 0 near the top of the incline, and then at later times rolling near the middle and bottom of the incline.

4. Do you see anything unusual about the photograph of the *rolling* bicycle wheel of Fig. 1 on p. 1? {Y, N, U, NOT}

5. Are the $\vec{\mathbf{v}}_{rim}$ vectors in Fig. 4 above consistent with the Fig. 1 photograph of the *rolling* bicycle wheel on p. 1? {Y, N, U, NOT}

6. Repeat the experiment of "2" above as a *thought experiment* in which there is *zero friction* at the hoop-incline interface. Complete the snapshot sketches of Fig. 5. Can you explain the physics indicated in your sketch? {Y, N, U, NOT}

ZERO-FRICTION MOTION OF A HOOP AT TOP, MIDDLE , AND BOTTOM OF INCLINE. SHOW $\vec{\mathbf{v}}_{cm}$, $\vec{\omega}$, AND $\vec{\mathbf{v}}_t$ FOR THE HOOP NEAR THE MIDDLE AND BOTTOM OF THE INCLINE. SHOW $\vec{\mathbf{v}}_t$ AT 4 POINTS ON THE RIM: CONTACT POINT (CP), OPPOSITE CP, AND AT THE POINTS OF INTERSECTION OF THE RIM AND THE X-AXIS

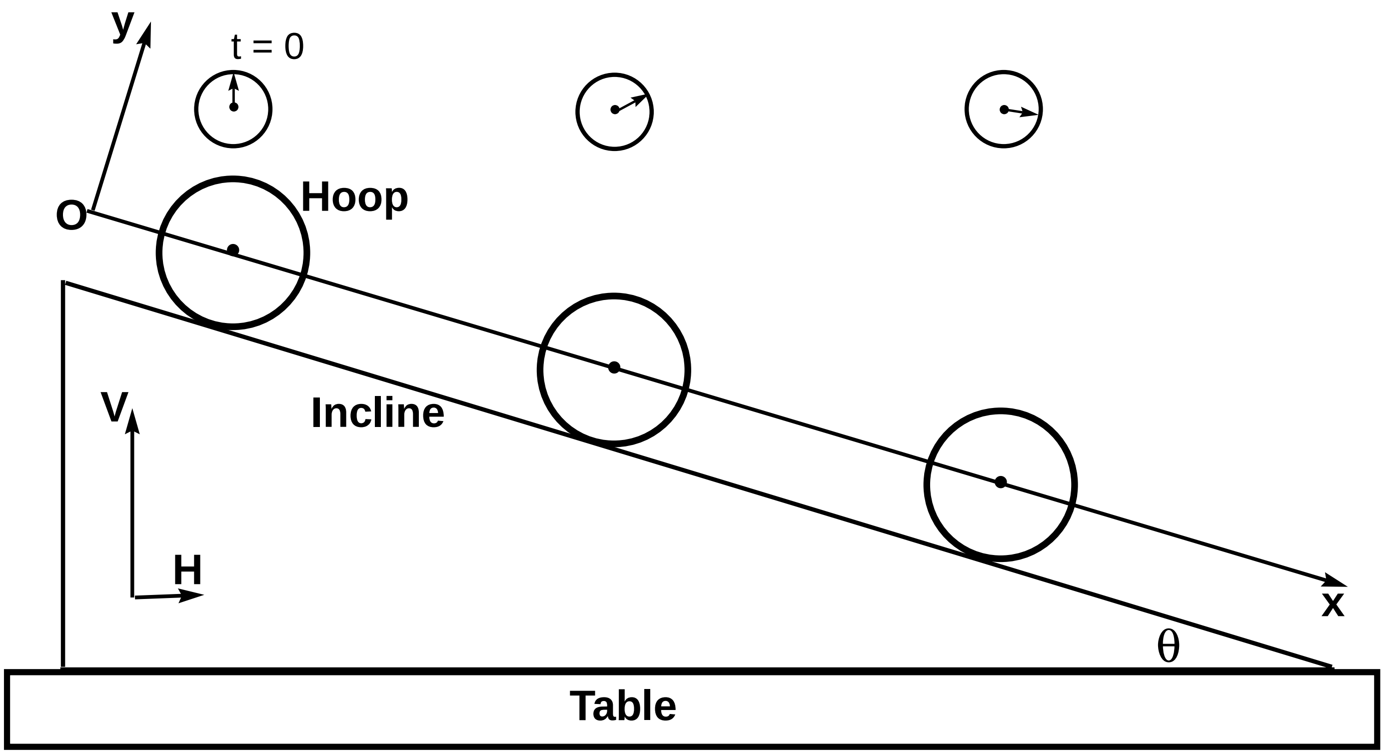


Fig. 5. Zero-friction motion of a hoop near the top, middle, and bottom of an incline showing $\vec{\mathbf{v}}_{cm}$, $\vec{\omega}$, and $\vec{\mathbf{v}}_t$ at four points on the rim. The hoop starts from rest at t = 0.

III. ROTATIONAL MOTION PUZZLES

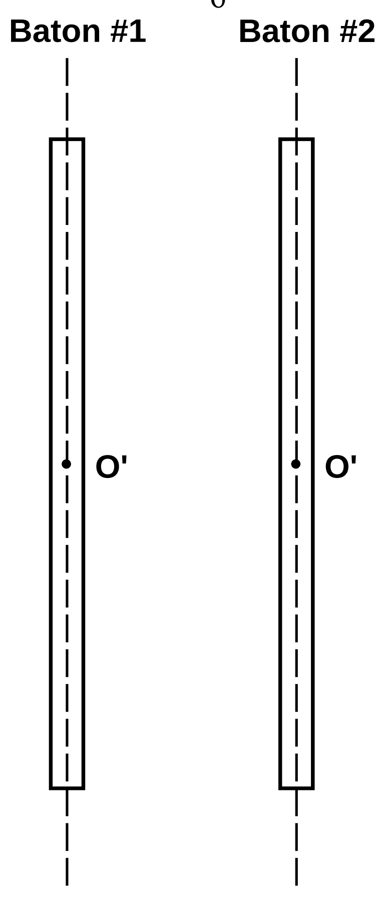
A. MYSTERY BATONS. Consider the two white plastic batons labeled #1 and #2.

1. Grasp each baton near its center, #1 in one hand and #2 in the other. Hold both batons stationary. Do you think the two batons weigh about the same? {Y, N, U, NOT}

2. Still grasping the two batons as in "1" above, *rotate them rapidly back and forth in vertical planes.* Do you sense any difference in the ease with which the two batons can be rotated rapidly back and forth? {Y, N, U, NOT}

If so, which baton, #1 or #2 (*Encircle One*) , is the easiest for you to rotate rapidly back and forth?

3. Can you give a possible explanation of your observations in part "2" in terms of the positions of metal weights (draw them in the figure below) and Newton's second law for rotational motion (N2R) †, $\vec{\tau}_o = I_o \vec{\alpha}_o$? {Y, N, U, NOT} [HINT: If you can answer this question, congratulations! You have *directly felt* and then understood the crucial importance of the moment of inertia I_o to the rotational acceleration $\vec{\alpha}_o$.]



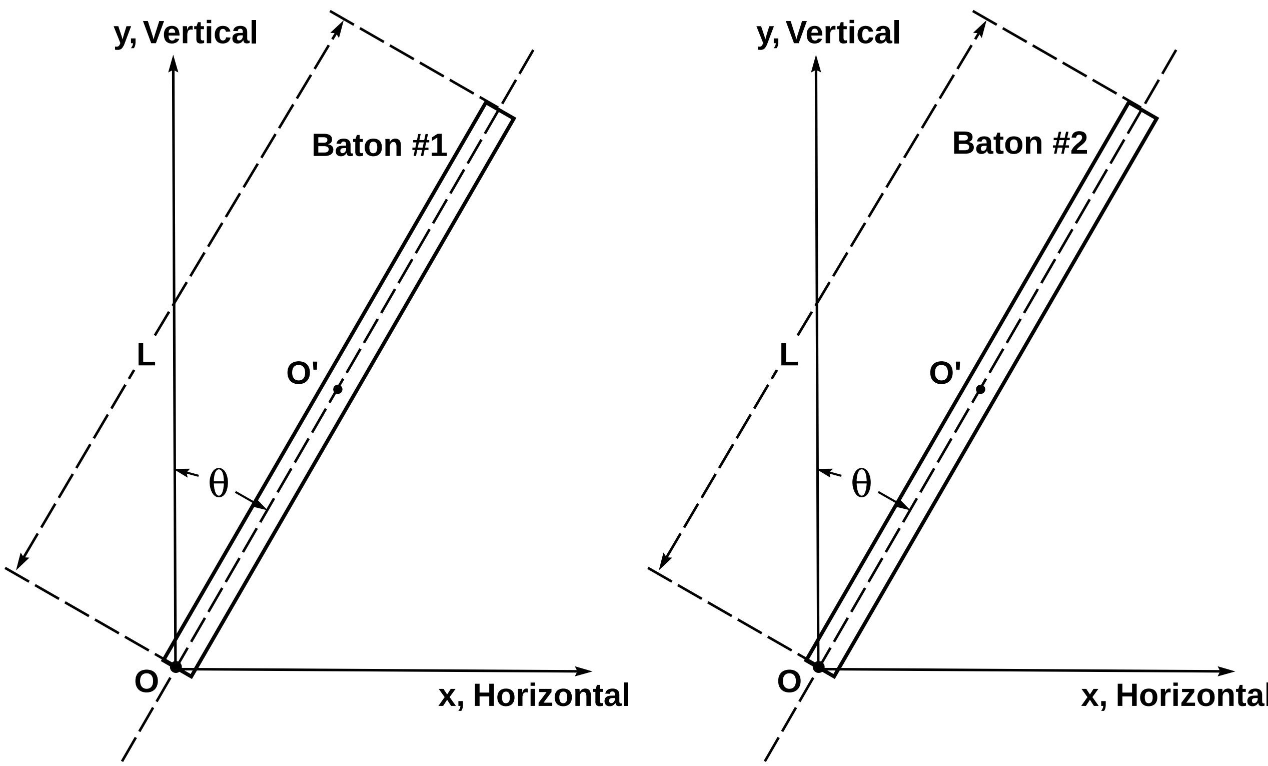
†In the N2R expression, the subscript "o" indicates the point about which the quantities are taken. The experiments of this lab satisfy the conditions (considered in more advanced courses -- see SDI Lab #5, p. 3) for the application of N2R in the above simple form with the moment of inertia I_o a scalar.

4. Try to balance each baton *on end* (i.e., with the baton's long axis near the vertical) with a finger, a foot, or your nose. (Caution, these batons are highly breakable!). [HINT: Watch the *top* of the baton while balancing.] Which baton, #1 or #2 (*Encircle One*), is the easiest for you to balance? In the space below, can you give a possible explanation in terms of N2R, $\vec{\tau}_o = I_o \vec{\alpha}_o$, and the position of metal weights in the two batons? {Y, N, U, NOT }

HINT #1: Show on each of the diagrams below only that force which is most important in producing a torque *about the support point* O (consider the positions of the metal weights each of mass M). Show the torque, angular velocity, and angular acceleration vectors for rotational motion about O.

HINT #2: Find the angular accelerations $\vec{\alpha}$ for the two cases. (You can directly verify your conclusion about the relative magnitudes α by comparing the angular velocities as the two batons rotate from the vertical.) Would it be easier or harder (*Encircle One*) to balance the cylinder with the higher angular acceleration? Why?}

TWO BATONS EACH AT θ WITH VERTICAL SHOWING $\vec{F}$, $\vec{\tau}$, $\vec{\omega}$, AND $\vec{\alpha}$ AS INDICATED ABOVE



B. THE CHARWOMAN’S COUP

The sacred Aristotle University (AU) Scroll was enshrined in a $100,000 holy hollow platinum cylinder in the top spire of Plato Hall. One dark night the guard awoke to find that the platinum cylinder had been stolen. He tracked the thief to the rival Newton University (NU), seized the cylinder, and returned it to AU. Unfortunately, in the process, the guard inadvertently got the *hollow* platinum cylinder mixed up with a $2.00 decoy *solid* aluminum cylinder of *equal* mass, radius, height, and appearance.

The president of AU called the leading campus intellects to his office, hoping that they could advise him on how to distinguish the real and decoy cylinders. Even after many hours, these great thinkers remained hopelessly baffled. Then a charwoman (graduate of NU, working her way through medical school) overheard their futile deliberations (Fig. 6). She seized the cylinders and *within one minute* had singled out the platinum cylinder with the sacred AU scroll.

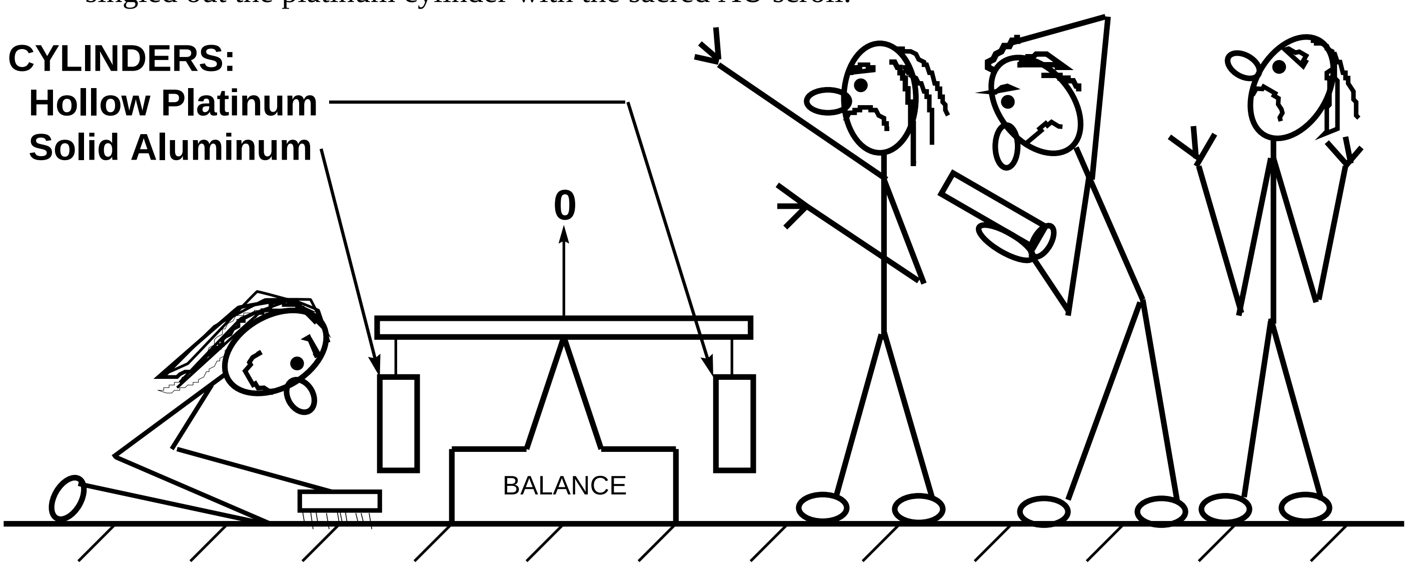


Fig. 6. The charwoman overhears the futile deliberations of the campus intellects.

Can you figure out how the charwoman pulled off her coup? {Y, N, U, NOT} (Simulations of the two cylinders are available for your inspection and testing at the front desk.) If you can’t quickly solve this puzzle, why not return to it after completing some of the experiments in Sec. IV?

DIAGRAM SHOWING HOW THE CHARWOMAN DISTINGUISHED THE TWO CYLINDERS

IV. ROLLER RACE

A. RACE OF CYLINDER, HOOP, AND SPHERE.

Pick out at random any solid cylinder, any hoop, and any solid sphere from the boxes at your table. (Henceforth in Sec. IV we shall omit the adjective "solid.") Suppose you were to race these three rolling objects from rest down the inclined plane shown in Fig. 7. Please predict the order in which they would finish:

PREDICTION: First _____________ ; Second ______________ ; Third______________.

Hold the above indicated race, but before starting, please test the incline for tilt along its short axis by attempting to roll a small steel sphere down the middle of the incline. If the sphere swerves markedly to the right or left, please notify an instructor who will show you how to level the incline. Reduce the influence of random variables by holding 3 or 4 such races. List below the overall finish order. Are your predictions verified? {Y, N, U, NOT} [NOTE: It's easiest to place the three objects behind a "starting gate" board and then suddenly lift the board. Here, as in a horse race, one concentrates on the position of the "noses" (not the midpoints) at the finish line.]

RESULTS: First ______________ ; Second ______________ ; Third______________.

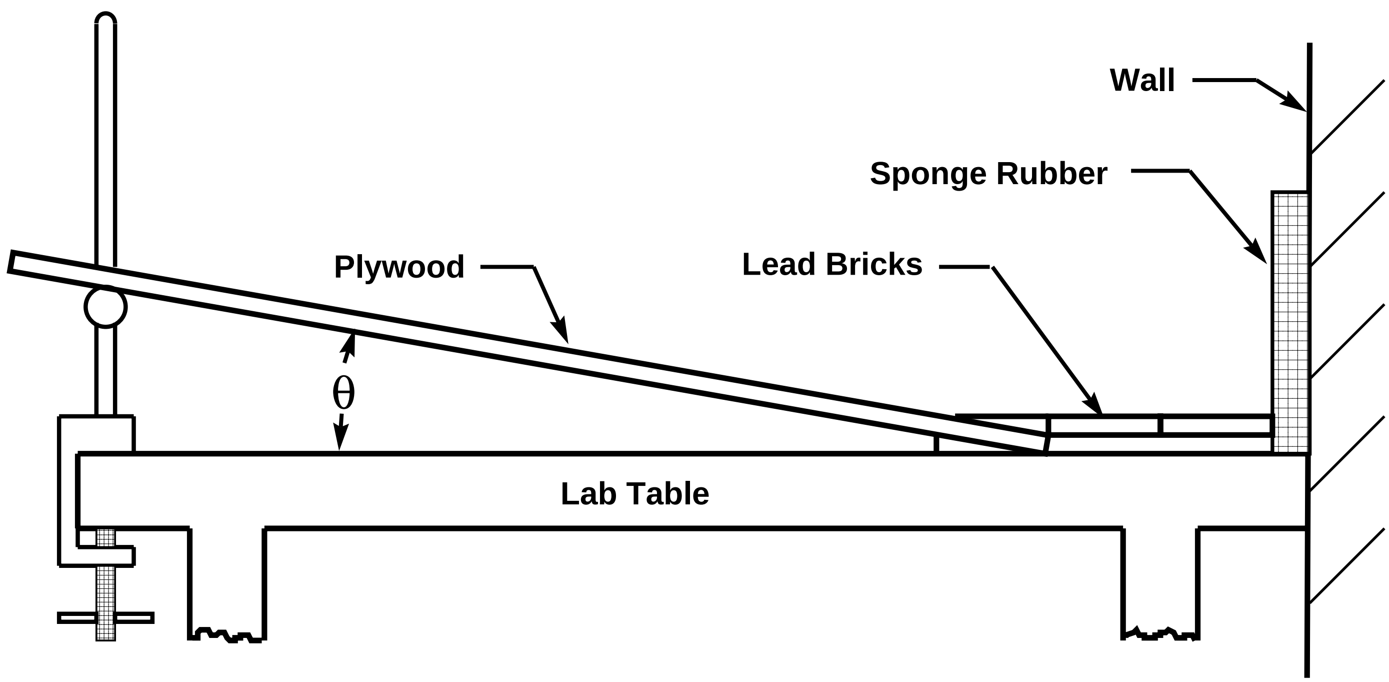


Fig. 7. The inclined-plane race course. The angle of incline θ is about 10°. The plywood incline is (3/4) x ≈14 x ≈59 in. Vertical plywood panels (not shown) enclose the incline and the bottom of the race course and are held in place by lead bricks (or other means). The latter also hold the sponge rubber against the wall.

B. RACE OF SPHERES.

Suppose a sphere with a relatively large mass M and radius R races a sphere with a relatively small mass m and radius r. Please predict the order in which they would finish:

PREDICTION: First ________________ ; Second ________________ .

Hold the sphere race indicated above. Reduce the influence of random variables by holding 3 or 4 such races. List below the overall finish order. Are your predictions verified? {Y, N, U, NOT}

RESULTS: First ________________ ; Second ________________ .

Race a variety of spheres of various masses and radii at once by placing them behind a starting gate and then suddenly lifting the gate. Reduce the influence of random variables by holding 3 or 4 such races. Can you make any general statement about the results?
{Y, N, U, NOT}

C. RACE OF THE HOOPS.

Race a variety of hoops of various masses and radii at once by placing them behind a starting gate and then suddenly lifting the gate. Reduce the influence of random variables by holding 3 or 4 such races. Can you make any general statement about the results?
{Y, N, U, NOT}

D. RACE OF THE CYLINDERS.

Race a variety of cylinders of various masses and radii at once by placing them behind a starting gate and then suddenly lifting the gate. Reduce the influence of random variables by holding 3 or 4 such races. Can you make any general statement about the results?
{Y, N, U, NOT}

E. RACE OF THE SOUP CANS

Suppose you were to race a can of bean soup, a can of onion soup, and an empty can from rest down the incline. Please predict the order in which they would finish (show your predictions):

PREDICTION: First ____________ ; Second _____________ ; Third_____________.

Hold the can race indicated above. Reduce the influence of random variables by holding 3 or 4 such races. List below the overall finish order. Are your predictions verified? {Y, N, U, NOT}

RESULTS: First _____________ ; Second _____________ ; Third_____________.

F. RACE RESULTS EXPLAINED BY ENERGY CONSERVATION.

Do this as **O**ut-of-**L**ab **P**roblem **OLP #11**. Can you explain the race results A - E above in terms of *energy conservation*? {Y, N, U, NOT}

HINT #1: Take into account both the *translational* kinetic energy $K_T = (1/2)\ Mv_{cm}{}^2$ and the *rotational* kinetic energy $K_R = (1/2)\ I\ \omega^2$ of the rolling bodies. Assume that the bodies roll without slipping.

HINT #2: Treat the case of the sphere, cylinder, and hoop all together by expressing the moments of inertia I_o about the CM's as βMr^2 where β (sphere) = 2/5, β (cylinder) = 1/2, and β (hoop) = 1.

EXPLANATION OF THE RESULTS OF THE CYLINDER - HOOP - SPHERE - SOUP RACES

G. A THOUGHT EXPERIMENT.

Repeat the races A - E above as *thought experiments* in which there is zero friction between the bodies and the inclined plane. Can you predict what the results would be? {Y, N, U, NOT}

H. THE DARK HORSE

Ask your instructor to lead *Black Disco*, the cylindrical dark horse in from her stall. Suppose *Black Disco* were to race the winner of Race A (Cylinder - Hoop - Sphere) above. Would you predict that she would win? {Y, N, U, NOT}.

After placing bets, hold the race. Are your predictions confirmed? {Y, N, U, NOT} Can you explain the result? {Y, N, U, NOT} (Dissection of the dark horse is *not* allowed!)

EXPLANATION OF WHY THE DARK HORSE (*ENCIRCLE*: DOES, DOES NOT) WIN THE RACE

V. YO-YO ON AN INCLINE

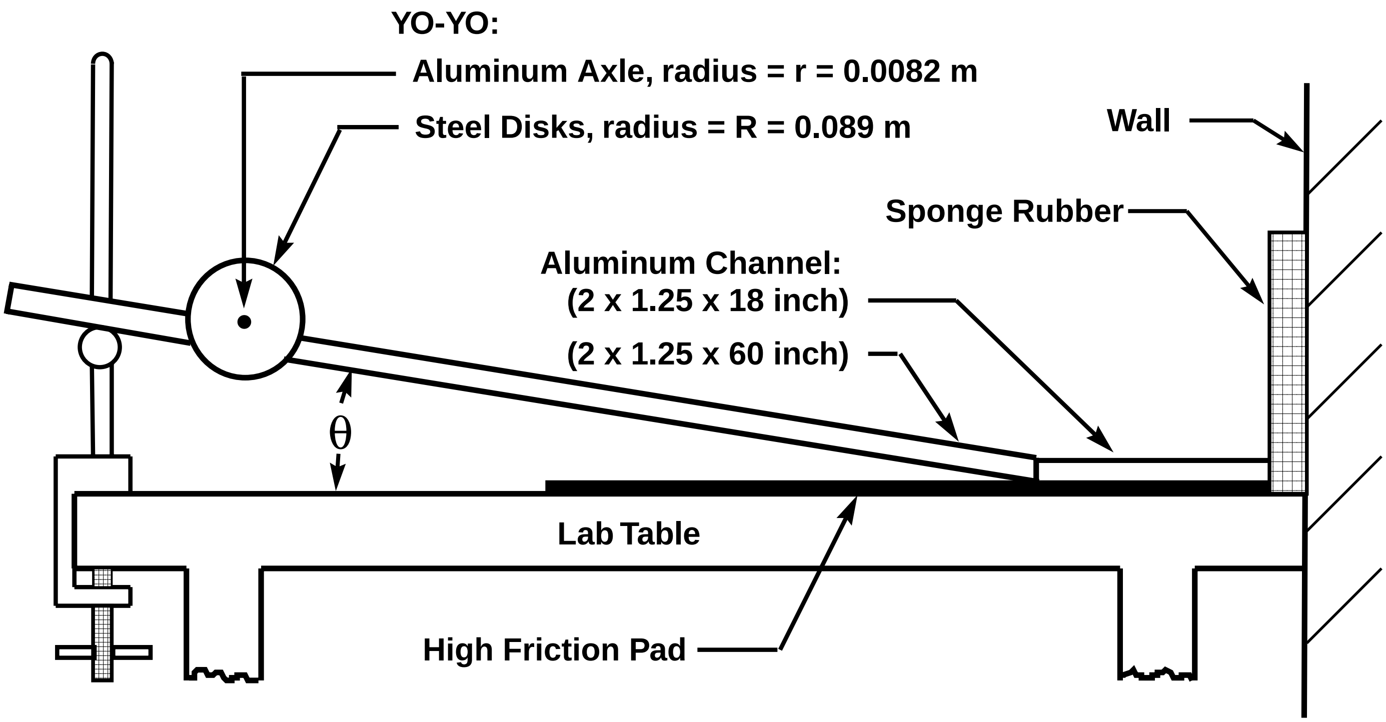


Fig. 8. The metal yo-yo descends to the lab table, riding on an aluminum channel inclined at an angle $\theta \approx 10°$. At the end of the descent, the time interval ΔT over which slipping by the rapidly rotating disks occurs is reduced by the high-friction pad. The yo-yo bounces off the sponge rubber and rolls part way back up the incline.

A. YO-YO RACE

1. Ask those doing the "Roller Race" (Sec. IV) for their Slowest Roller (SR). The SR will probably fit within the aluminum channel. Suppose you were to race the SR against the Yo-Yo down the inclined channel shown in Fig. 8 What is the geometry of your SR? ________________________________ . Please predict the order of the finish:

PREDICTION: First ________________ ; Second _______________ .

2. After placing bets, hold the race indicated above. Indicate the finish order. Are your predictions confirmed? {Y, N, U, NOT}

RESULTS: First ________________ ; Second _______________ .

Can you explain the results of this race on the basis of N2R? {Y, N, U, NOT} (You may wish to return to this question after completing out-of-lab assignment OLP #12.)

3. From your *qualitative observations* of the motion, *qualitatively* graph the yo-yo's center of mass (CM) translational speed v and CM translational acceleration a versus time from the time t = 0, when the yo-yo is released from rest at the top of the incline until it makes contact with the sponge rubber.***** To do this, first *estimate* the ratio v_r/v_b = ______ (insert), where v_r and v_b are, respectively, the speeds of the center of mass of the yo-yo as it **r**olls on the pad without slipping and just **b**efore it hits the pad. For simplicity regard the entire motion as one dimensional with positive v and a in the direction of motion. Let $t = T_1$ (reaches bottom of the incline), $t = T_2$ (makes contact with the sponge rubber); show t = 0, T_1, and T_2 on your graph).

QUALITATIVE GRAPH OF $|\vec{\mathbf{v}}_{cm}|$ and $|\vec{\mathbf{a}}_{cm}|$ vs t FOR THE YO-YO AS INDICATED ABOVE

*****Optional: The motion of the yo-yo during contact with the sponge rubber is complex, but if you desire a challenge, you can extend the time axis of the above graph to a time when the yo-yo has rebounded from the sponge rubber and is traveling back up the incline. If you do this let $t = T_3$ (has compressed sponge rubber to the maximum, $t = T_4$ (leaves contact with the sponge rubber, $t = T_5$ (starts back up the incline, $t = T_6$ (traveling back up the incline). Show t = T_1, T_2, T_3, T_4, T_5, T_6 on your graph. [HINT: While in contact with the sponge rubber assume that the motion of the CM of the yo-yo is similar to that of a mass moving horizontally with zero friction and compressing an ideal horizontal spring, i.e., assume that the motion is simple harmonic.]

4. Figure 9 shows a top and front view of the yo-yo at an instant of time when it is rolling down the channel. The axle has been enlarged in comparison with the discs so that the vectors may be more clearly indicated. Show ALL the force vectors **F** acting on the yo-yo; the translational velocity $\vec{\mathbf{v}}$ and translational acceleration $\vec{\mathbf{a}}$ of the center of mass; and the torque $\vec{\tau}$, angular velocity $\vec{\omega}$, and angular acceleration $\vec{\alpha}$ vectors about the center of mass.

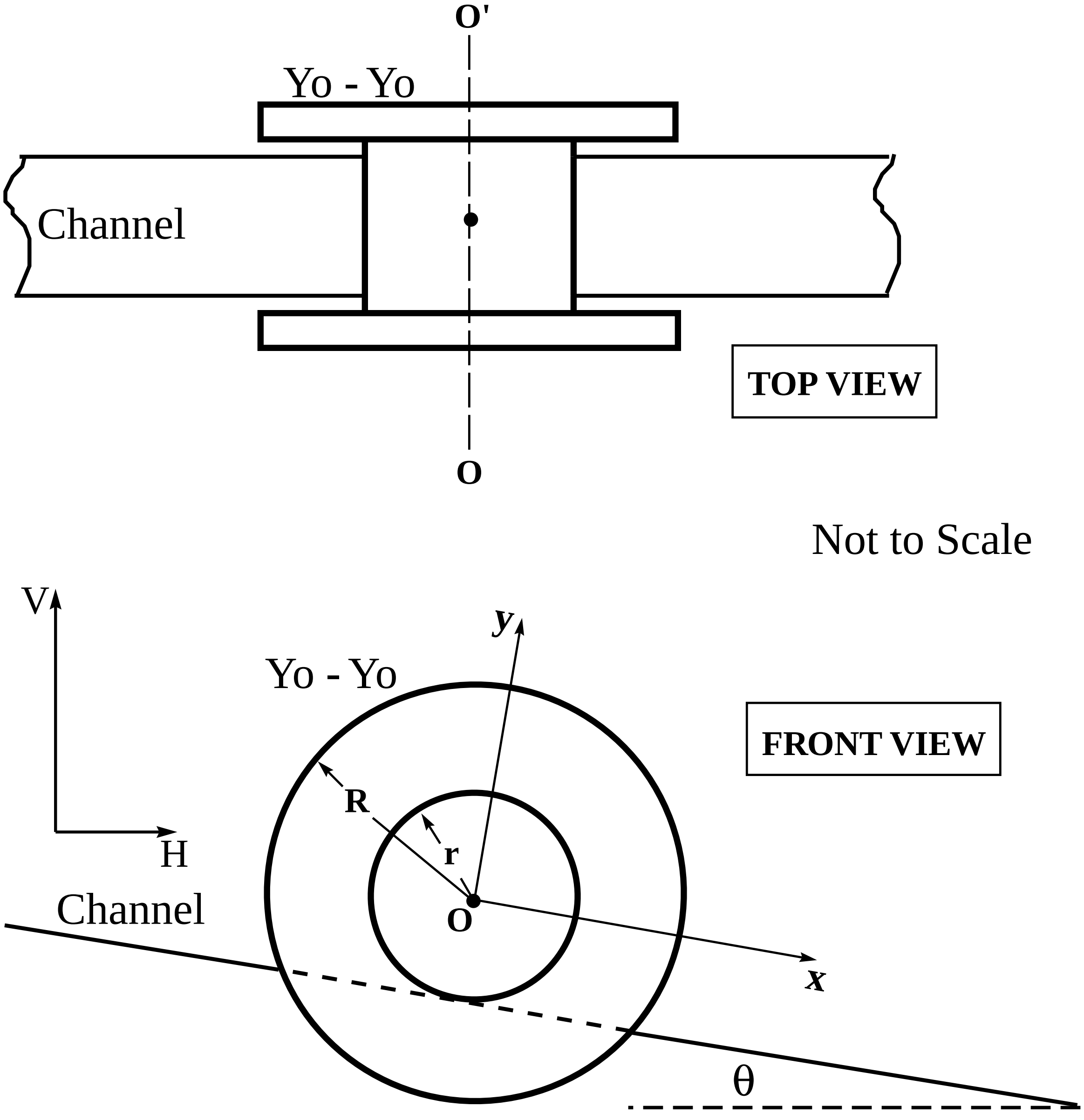


Fig. 9. Top and front views of the yo-yo at an instant of time when it is rolling down the channel.

5. Which (if any) force(s) cause torque(s) *about the center of mass* of the yo-yo? What is (are) the magnitude(s) and directions(s) of the torque(s)?

6. (Do this as out-of-lab problem **OLP #12**) Suppose the yo-yo moves from rest a distance L down the incline. **Obtain an expression for the final speed v_f of the center of mass of the yo-yo after it has moved this distance L by invoking:**

a. the *conservation of mechanical energy*. [HINT: Here and in part "b" below, in calculating the moment of inertia of the yo-yo you may ignore (1) the moment of inertia of the small light, small-radius aluminum cylinder, (2) the small central holes in the steel discs.]

b. ***Newton's second law of rotational motion*** $\vec{\tau}_o = I_o \vec{\alpha}_o$. In the course of this derivation, obtain an expression for the magnitude of the translational acceleration $\vec{\mathbf{a}}$ of the center of mass. How does the magnitude of $\vec{\mathbf{a}}$ compare with g, the acceleration due to gravity?

7. (**OLP #13**) Is your expression for v_f in part "6" above physically reasonable? {Y, N, U, NOT} [HINT: As usual, consider dimensions and the predicted magnitude of the parameter in question (here v_f) for both realistic and extreme limiting conditions.]

8. Devise and execute an experimental check of the relationship derived in part "6" above. Find the relative % discrepancy between the measured and theoretically predicted values of v_f. This comparison will require measurement of (among other things) the angle of incline θ. This angle can be measured with sufficient accuracy with the rotatable level at your table.

9. Why does the yo-yo take off like a bat when the disks contact the high-friction pad? To answer this question, first derive an *upper limit* to the ratio v_r/v_b by assuming that the disks *do not slip* when they hit the pad. Here, as before, v_r and v_b are, respectively, the speeds of the center of mass the yo-yo as it **r**olls on the pad without slipping and just **b**efore it hits the pad. Show snapshot sketches of the yo-yo just before and just after the disks hit the pad. Plug numbers into your expression for v_b/v_r.

DERIVATION OF v_r/v_b ASSUMING THAT NO SLIPPING OCCURS

10. Are your qualitative observations of the motion of the yo-yo as diagrammed on p. 17 consistent with the assumption above that no slipping occurs when the disks hit the pad? {Y, N, U, NOT} [HINT: watch the red and blue "spokes" drawn on the side of the yo-yo as the yo-yo hits the pad.]

11. Figure 10 shows a top and front view of the yo-yo *at the instant it hits the pad.* The axle has been enlarged in comparison with the disks. Show ALL the force vectors $\vec{\mathbf{F}}$ acting on the yo-yo; the translational velocity $\vec{\mathbf{v}}$ and translational acceleration $\vec{\mathbf{a}}$ of the center of mass; and the torque $\vec{\tau}$, angular velocity $\vec{\omega}$, and angular acceleration $\vec{\alpha}$ vectors about the center of mass.

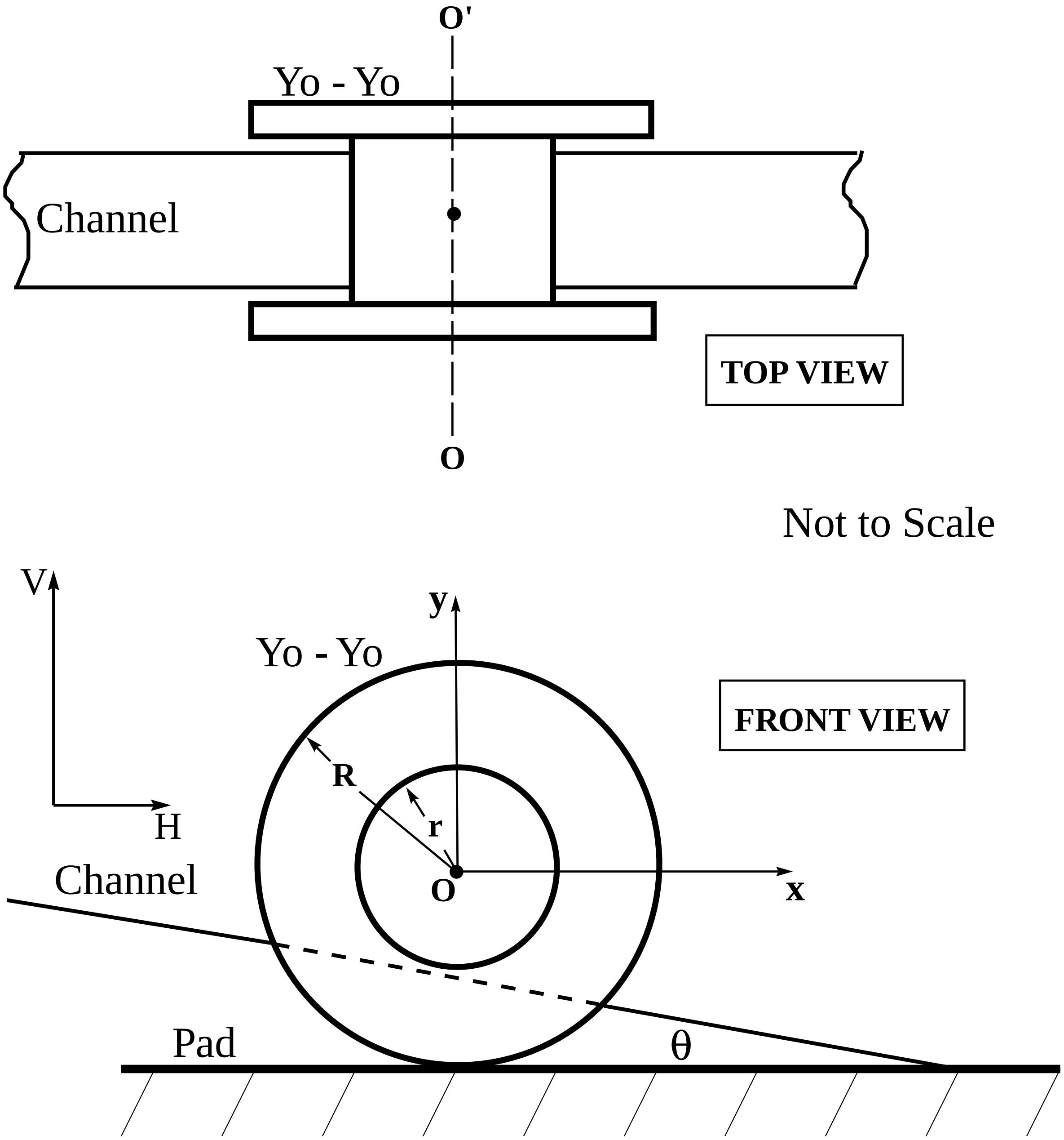


Fig. 10. Top and front views of the yo-yo at the instant it hits the pad.

12. Which (if any) force(s) cause torque(s) *about the center of mass* of the yo-yo? What is (are) the magnitude(s) and direction(s) of the torque(s)?

13. OPTIONAL (Do this as out-of-lab problem **OLP #14**.) Derive an expression for ratio v_r/v_b in which you DO *assume that slipping occurs* when the disks hit the pad. Here, as before, v_r and v_b are, respectively, the speeds of the center of mass the yo-yo as it rolls on the pad without slipping and just before it hits the pad. Plug reasonable numbers into your expression for v_r/v_b. [HINT: First find a and α in terms of one or more of M, R, μ (is it kinetic or static?), g, and v_b. What are the conditions on v_t and v_r for the yo-yo to roll without slipping? Calculate the time interval ΔT over which slipping occurs in terms of one or more of M, R, μ, g, and v_b. Then use ΔT to find v_r and then v_r/v_b.

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