Physics 201 Lab 10: Torque

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Theoretical Discussion

For each of the linear kinematic variables – displacement, velocity, and acceleration – there is a corresponding angular kinematic variable: angular displacement, angular velocity, and angular acceleration, respectively. Even the familiar dynamical variables – momentum and force – have rotational analogs: angular momentum and torque, respectively. Finally, the rotational analog of the inertial mass m is the moment of inertia I. These relationships are summarized in Table I.

Linear variables	**Rotational analog**
displacement $\vec{dr}$	angular displacement $\vec{d\theta}$
velocity $\vec{v} = \vec{dr}/dt$	angular velocity $\vec{\omega} = \vec{d\theta}/dt$
acceleration $\vec{a} = \vec{dv}/dt$	angular acceleration $\vec{\alpha} = \vec{d\omega}/dt$
momentum $\vec{p} = m\vec{v}$	angular momentum $\vec{L} = I\vec{\omega}$ [sometimes!]
force $\vec{F}$	torque $\vec{\tau}$

TABLE I: Linear variables and their rotational analogs.

Torque is the rotational analog of force: In other words, just as force acts to change the magnitude and/or direction of an object's linear momentum, torque acts to change the magnitude and/or direction of an object's angular momentum. The equation

$$\vec{\tau} = \frac{d\vec{L}}{dt} \tag{1}$$

is the dynamical 'law' of rotation, in the same way that Newton's 2nd law relates force to the rate of change of linear momentum. But unlike force, the torque of a force depends upon the reference point O about which the torque is computed. If the force is $\vec{F}$ and the displacement vector from O to the point where the force is applied is $\vec{r}$, then the torque of $\vec{F}$ about O is

$$\vec{\tau} = \vec{r} \times \vec{F} \tag{2}$$

The relationships between $\vec{F}$, $\vec{r}$, and $\vec{\tau}$ are shown in Figure 1. $r_\perp = r\sin\theta$ is the *moment arm* of the force, and can be used to calculate the magnitude of torque simply as $\tau = r_\perp F$.

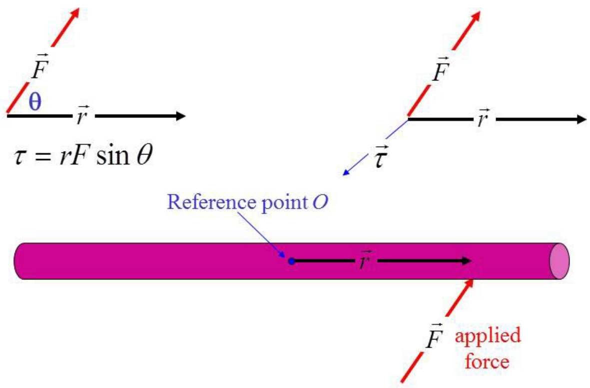

FIG. 1: Relationships between $\vec{F}$, $\vec{r}$, and $\vec{\tau}$.

So long as the total net force on an object is zero, the velocity of its center of mass will not change. However, it is possible for an object to have zero net force acting on it, but still be subject to a non-zero torque. Figure 2 shows one such scenario. The velocity of the center of mass of the object in Figure 2, acted upon by two equal and opposite forces, will remain constant, but since the torque is non-zero, it will spin about its axis at an ever-increasing rate of rotation. For an object to remain in *static equilibrium*, so that both the velocity of its center of mass and its angular velocity about any axis are constant, both the net force and the net torque on it must be zero:

$$\vec{F}_{\text{net}} = 0 \tag{3}$$
$$\vec{\tau}_{\text{net}} = 0 \tag{4}$$

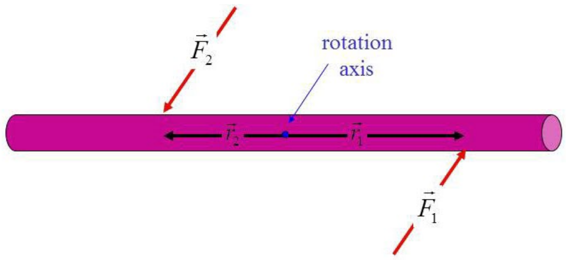

FIG. 2: Equal forces applied to opposite sides of a rotation axis.

Experimental Procedure

In today's experiment a rigid body (meter stick) is subjected to various combinations of forces in such a way that the body remains in equilibrium. One such arrangement is shown in Figure 3. For each case studied, the forces and torques exerted on the meter stick are calculated from data collected in the experiment. The calculated value of the net torque derived from the experiment is compared for consistency with the theoretical value [of zero]. Lastly, the equilibrium conditions are used to deduce the mass of an unknown object.

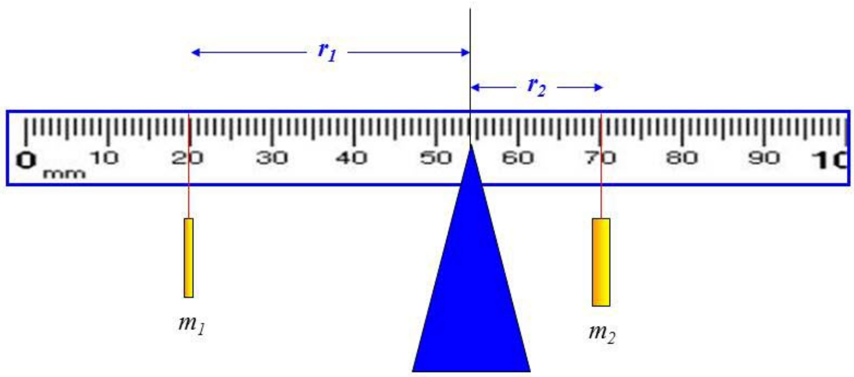

FIG. 3: A meter stick subject to four forces (can you identify them?). The stick is in equilibrium when there is no rotation about the pivot.

The particulars of the experiment are as follows:

1. Using the triple-beam balance, measure and record the mass of the meter stick. Remove the knife-edge attachment for this measurement, so the recorded mass is that of the stick alone.

2. Locate the center of mass of the meter stick by balancing the meter stick on the knife edge. When balanced, the stick is non-rotating and oriented horizontally. Record the position of the knife edge along the stick to the accuracy of your measurement.

3. Next, balance the meter stick when approximately 150 grams of mass are suspended from the 20.0 cm mark of the stick. Record the location of the knofe edge along the stick to 3-digit accuracy. Use the triple-beam balance to obtain an accurate (4-digit) value for the suspended mass (including any hangar that may have been used).

4. Repeat the previous step when approximately 150 grams of mass are suspended from the 20.0 cm mark and approximately 250 grams are suspended from the 70.0 cm mark of the meter stick. Again, use the triple-beam balance to obtain accurate values for the suspended masses.

5. For each of the previous trials, calculate the counterclockwise torque, the clockwise torque, and the net torque about the pivot point. Be sure to include the torque generated by the weight of the meter stick. Report the net torque [ideally zero] as a fraction (or percent) of the *average* of the counterclockwise and clockwise torques.

6. Suspend the metallic object from the 10.0 cm mark of the meter stick. Attach approximately 250 grams to that point on the stick such that the system of masses and the stick balances at the center of mass of the meter stick. Use this information in Equation 4 to deduce a theoretical value for the mass of the metallic object. Compare this with the value found using the triple-beam balance (conventional method), and report the difference as a fraction (or percent) of the triple-beam result.