SI Physics - Full Discipline Demo

Torque and Equilibrium

Final Report - Answer Guide

Institution	Science Interactive University
Session	SI Physics - Full Discipline Demo
Course	SI Physics - Full Discipline Demo
Instructor	Sales SI Demo

Test Your Knowledge

Match each term to the best description.

Terms	Description	Answer
Center of mass	State of an extended object in which net force and net torque are equal to zero	1
Line of action	The twisting force that tends to cause rotation of an object	2
Pivot point	The average position of all parts of an object or system weighted according to mass	3
Radial distance	Distance between the pivot point and point of force application	4
Static equilibrium	Axis along which a force is applied	5
Torque	Axis of an object around which the object rotates	6

Correct answers:

1 Static equilibrium 2 Torque 3 Center of mass 4 Radial distance

5 Line of action 6 Pivot point

Identify each statement as true or false.

- A force applied parallel to the moment arm produces the largest possible torque.
- The rotational velocity must be zero during static equilibrium.
- Torque is a vector quantity.
- Torque is positive when it induces rotation in the clockwise direction.

True	False
1	2

Correct answers:

1 The rotational velocity must be zero during static equilibrium.

Torque is a vector quantity.

2

A force applied parallel to the moment arm produces the largest possible torque.

Torque is positive when it induces rotation in the clockwise direction.

Exploration

A force applied at a 90° angle to the moment arm produces the largest possible torque.

- True ✔
- False

Torque can be found using the equation _____.

- $\tau = rF_{\perp}$
- $\tau = r_{\perp}F$
- $\tau = rF\sin(\theta)$
- All of the above ✔

The _____ is the average position of all parts of the object or system weighted according to mass.

- center of gravity
- center of mass ✔
- pivot point
- None of the above

The moment of inertia depends on how the _____ of an object is distributed.

- gravity
- inertia
- mass ✔
- All of the above

_____ is the rotational equivalent of force and causes rotational motion.

- Center of mass
- Moment of inertia
- Torque ✔
- All of the above

Static equilibrium occurs when the _____ is zero.

- net force
- net torque
- velocity
- All of the above ✔

Exercise 1

Describe the conditions necessary for equilibrium on a balance.

For equilibrium to be achieved (1) the sum of the forces in the horizonal direction must be zero, (2) the sum of the forces in the vertical direction must be zero, and (3) the sum of the torques must be zero.

When the pivot point of a balance is not at the center of mass of the balance, how is the net torque on the balance calculated? When a force is applied directly to the pivot point of a balance, what is the torque due to that force?

When calculating the net torque of a system with the pivot point not placed at the center of mass, the weight of the balance contributes to the net torque. The torque due to the weight of the balance is found by applying the weight of the balance at the center of mass location. When a force is applied to the pivot point, there is no torque due to this weight because the radial distance *r* from the pivot point to where the force is applied is zero.

To maintain the same amount of torque due to a mass on a balance as the mass is increased, how should the position of the mass change? Use your measurements recorded in Data Table 3 to support your answer.

As the mass is increased, the radial distance from the mass to the pivot point must be decreased so the torque due to the mass remains constant. This is shown by comparing the radial distance r for a single washer of 10.55 cm to the distance for three washers of 3.4 cm when the ruler system was balanced by two washers on the other side of the center of mass, which was also the pivot point.

Why is the handle on a door far from the hinge? Use the definition of torque in your answer.

Torque is defined at $\tau = r*F$. Assuming the door takes a particular amount of torque to be opened, increasing r means a smaller force is required to open the door. A door handle is placed far from the hinges to increase the length of the lever/moment arm and decrease the applied force necessary to open the door.

What are the main experimental factors that contributed to the error you found in each part of your experiment?

Students answers will vary. Some possible factors are: the string was not perfectly vertical on the ruler (meaning the force may have been applied at a position different than that measured), the masses of the washers vary but the average mass was used, the string may have shifted during the experiment if not taped well, the spring scale was not zeroed correctly, the protractor was read incorrectly.

Data Table 1: Mass of Washers and Ruler

(SAMPLE ANSWER BELOW)

Mass of 5 washers (g)	Average mass of 1 washer (g)	Mass of ruler (g)
30.5	6.1	38.0

Data Table 2: Initial Data

(SAMPLE ANSWER BELOW)

Center of mass position (cm)	Mass m_1 (g)	Ruler Position x_1 (cm)	Radial Distance r_1 (cm)	Torque τ_1 (Nm)
15.25	12.20	10.0	5.25	0.00628

Data Table 3: Measurements and Calculations for Torque About the Center of Mass

(SAMPLE ANSWER BELOW)

Number of washers for m_2	1	2	3
Mass m_2 (g)	6.10	12.20	18.30
Ruler position x_2 (cm)	25.8	20.25	18.65

Radial distance $r_{2,exp}$ (cm)	10.55	5.00	3.40
Torque $\tau_{2,exp}$ (Nm)	-0.0063	-0.0060	-0.0061
Torque $\tau_{2,theory}$ (Nm)	-0.0063	-0.0063	-0.0063
Radial Distance $r_{2,theory}$ (cm)	10.49	5.24	3.50
% Error	0.6	4.7	2.8

Data Table 4: Center of Mass Equilibrium with Hanging Mass

(SAMPLE ANSWER BELOW)

x_0 = 10.00 cm	Measured mass m (g)	Ruler Position x (cm)	Radial Distance r (cm)	Torque τ (Nm)	Calculated mass (g)	Percent error (%)
Ruler center of mass	38.00	15.25	5.25	-0.0191	37.18	2.2
4 washers	24.4	2.00	8.00	0.0191		

Data Table 5: Center of Mass Equilibrium with Vertical Spring Scale

(SAMPLE ANSWER BELOW)

x_0 = 10.00 cm	Ruler position x (cm)	Radial distance r (cm)	Spring scale reading or mass (g)	Torque $\tau_{,exp}$ (Nm)	Torque $\tau_{,theory}$ (Nm)	Percent error (%)
Spring scale	25.00	15.00	12.50	0.0184	0.0191	3.7
Ruler center of mass	15.25	5.25	38.00	-0.0191		

Data Table 6: Center of Mass Equilibrium with Spring Scale at an Angle

(SAMPLE ANSWER BELOW)

Location	Center of mass	Spring scale	Pivot point
Spring scale reading or mass (g)	38.00	15.00	
Angle θ (°)	90.0	60.0	70.0
Perpendicular Force $F_{\perp}$ (N)	-0.373	0.127	0.245
Parallel Force $F_{\parallel}$ (N)	0.0	0.0736	-0.0736
Net Force F_{net} (N)	0.373	0.147	0.256
Torque τ (Nm)	-0.0196	0.0192	0

Exercise 2

How can two objects with different masses be in balanced equilibrium on a beam with a pivot at the beam center of mass? Refer to your measurements recorded in Data Table 7 to support your answer.

Different masses can be in equilibrium on a balance if the torques are equal and opposite. This is done by utilizing the torque equation $\tau = r \times F$. Though the gravitational forces are different, the radial distance *r* can be adjusted such that the torques have equal magnitudes. Assuming the objects are on different sides of the pivot point, this ensures equilibrium is reached. The mass of the bricks recorded in Data Table 7 remained constant at 20 kg, but the torque due to the bricks changed because the radial distance was changed. The system could still be balanced as the mass of the unknown objects changed by changing the position of the bricks. The bricks moved closer to the pivot point as the mass of the object decreased with the smallest mass object (5 kg) having the bricks located the closest to the pivot point (0.25 m).

Describe how torque and equilibrium determine the mass of an unknown object.

Equilibrium requires that the torque due to all forces acting on a balance add up to zero. Therefore, the torque due to the weight of a single object resting on the balance can be determined if the torques due to any other objects acting on the balance are known. Once the torque due to the weight of the unknown object is determined, the mass can be found using the definition of torque $\tau = r \times F$, and the definition of weight $F = w = mg$ and solving for the mass.

Compare the mass measurements you made using the simulation in Exercise 2 to the mass measurement of the ruler you made in Exercise 1. How were the measurements similar, and how were they different?

The torque, mass, and position of the objects in the simulation in Exercise 2 were produced from precise measurements, whereas the values were computed by measurements with error when using the ruler in Exercise 1. In the simulation, the pivot point was set at the center of mass of the beam, so that the beam exerted zero torque on itself due to its weight. With the ruler, the pivot point was offset from the center of mass so that the weight of the ruler exerted a torque on the pivot point and therefore the torque due to the weight could be measured. The calculations of the weight and then mass in both exercises proceeded in the same manner, beginning with assuming static equilibrium and then solving for the mass from the torque due to the unknown weight in each circumstance.

Data Table 7: Determining the Mass of a Mystery Object

(SAMPLE ANSWER BELOW)

Mystery object	Object distance (m)	Brick mass (kg)	Brick distance (m)	Brick torque (Nm)	Object mass (kg)	F_{object} (N)	F_{bricks} (N)	$F_{pivot\ point}$ (N)
A	1.00	20	1.00	-196.20	20	-196.20	-196.20	392.40
B	1.00	20	0.25	-49.05	5	-196.20	-49.05	245.25
C	1.00	20	0.75	-147.15	15	-196.20	-147.15	343.35
D	1.00	20	0.50	-98.10	10	-196.20	-98.10	294.30

Competency Review

_____ is calculated by finding the product of the applied force and the radial distance.

- Center of mass
- Moment of inertia
- Torque ✔
- All of the above

The _____ spans the distance from the _____ to the location of the applied force.

- moment arm; pivot point ✔
- moment of inertia; center of mass
- torque; center of mass
- None of the above

A net force of zero is the only requirement for static equilibrium.

- True
- False ✔

Torque can be calculated if the _____ and angular acceleration are known.

- mass
- moment arm
- moment of inertia ✔
- None of the above

Torque is the rotational equivalent of force and causes translational motion.

- True
- False ✔

A hanging system can only be balanced if the pivot point is placed at the center of mass.

- True
- False ✔

A door is pushed with a force of 5 N at a distance of 30 cm from the hinge. The torque is _____.

- 6 N/m
- 150 N m
- 1.50 N m ✔
- None of the above

A 40 cm ruler with non-uniform mass is hung from its center of mass, at 21 cm. A force is applied at the 40 cm mark of the ruler. The length of the moment arm is _____.

- 40
- 19 ✔
- 21
- None of the above

A 30 cm ruler is found to have a center of mass of 15.6 cm. The percent error of the center of mass is _____, if the ruler is assumed to have uniform mass.

- 0.48%
- 0.52%
- 4% ✔
- None of the above

The mass of a ruler can be determined by hanging the ruler from its center of mass.

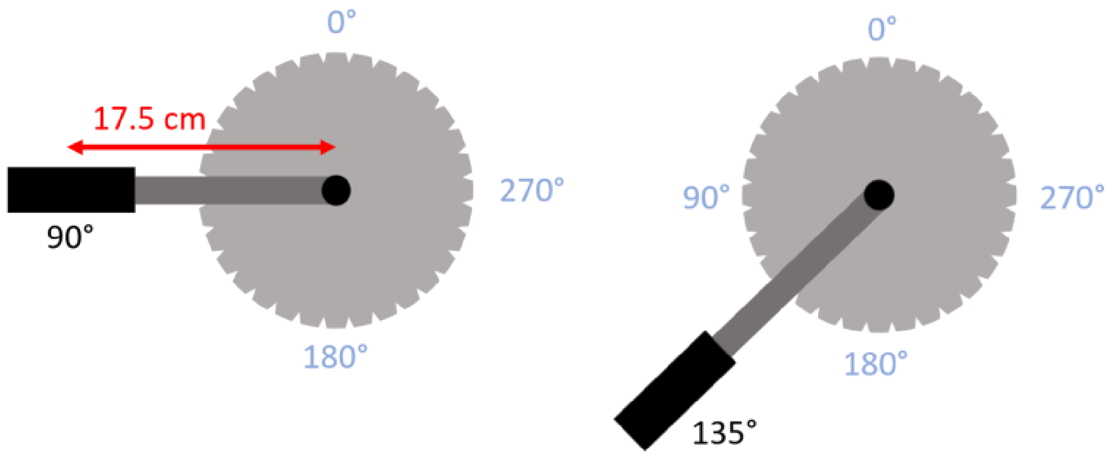
- True
- False ✔

A seesaw sits in static equilibrium. A child with a mass of 30 kg sits 1 m away from a pivot point. Another child sits 0.75 m away from the pivot point on the opposite side. The second child's mass is _____ kg.

- 20
- 30
- 40 ✔
- None of the above

Extension Questions

In cycling, the torque generated about the crank axis is determined by the magnitude of the force from a foot pushing the pedal as well as the angle between the crank arm and the force vector. The diagram shows the 17.5 cm crank pedal at two positions: 90 degrees and 135 degrees. What is the torque at each of the points if the foot applies a force of 800 N? Which position creates the larger torque? Note: Use the angle between the force application and crank arm in your calculations.



(SAMPLE ANSWER BELOW)

At 90 degrees, the torque is: tau=r*F*SIN(90)=0.175*800*1=140 N*m. At 135 degrees, the torque is: tau=r*F*SIN(135-90)=0.175*800*SIN(45)=99 N*m. Thus, the 90 degree position yields the greater torque. Note: The angle for the second calculation is 135-45 degrees due the geometry of the system. You must use the angle between the applied force and the crank. SIN(135) would give the component of the force parallel to the crank arm.